HYDROGEOLOGICAL EXPLORATION AND CHARACTERISATION OF THE AQUIFERS FOUND IN MIDDELBURG, EASTERN CAPE, FOR TOWN WATER SUPPLY

by

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DECLARATION

I, Reuben John Grobler, hereby declare that this dissertation submitted for the Magister Scientiae degree at the Department of Geohydrology, Faculty of Natural and Agricultural Sciences, University of the Free State in Bloemfontein, South Africa, is my own independent work and has not been submitted to any other institution of higher education. I further declare all sources cited have been acknowledged within the references section.

R. J. Grobler
June 2014

Keywords

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Preface

One of the core functions of a university is to generate knowledge. The purpose of this study, apart from fulfilling the requirements for a M.Sc. degree, was to generate new hydrogeological information for the Middelburg study area for future developments. Middelburg is a town of approximately 50 000 people whose only source of potable water is groundwater. When an evaluation of groundwater for so many people's livelihoods is performed, it can thus not simply be an overview type of study. The conclusions and recommendations at the end of each chapter provide the bottom line required by decision makers, whilst chapters have been divided into sections and sub-sections for scientists and engineers requiring specific information on a subject. Many of the methods and means used during the study are generic and can be applied to other groundwater resource development projects.

Table of Contents

1 INTRODUCTION 1

1.1 BACKGROUND 1
1.2 PROBLEM STATEMENT AND RATIONALE 2
1.3 AIM 2
1.4 OBJECTIVES OF THE STUDY 2
1.5 SCOPE OF THE STUDY AND CHAPTER OUTLINE 3
1.6 LOCATION OF THE STUDY AREA 3
1.7 RESEARCH QUESTION 4

2 LITERATURE STUDY 6

2.1 GEOLOGY 6
2.1.1 Geological overview 6
2.1.2 Karoo Supergroup 8
2.1.3 Cenozoic Deposits 15
2.1.4 Intrusive Rocks 18
2.1.5 Structural Geology 27
2.2 HYDROGEOLOGY 28
2.2.1 Karoo Supergroup aquifers 28
2.3 COMPARISON BETWEEN THE SOUTH AFRICAN AND AUSTRALIAN GROUNDWATER RESOURCE DEVELOPMENT METHODOLOGY 37
2.3.1 South African Groundwater Resource Development Methodology 37
2.3.2 The methodologies 41
2.3.3 Australian legislation and methodology 43
2.3.4 Methodology of Groundwater Resource Development in South Africa 47
2.3.5 Summary and conclusion from methodology comparison 49
2.4 REVIEW OF MIDDELBURG C.P. GEOHYDROLOGICAL INVESTIGATION. M.A.C. VANDOOLAEGHE. 1979. 51
2.4.1 Terms of reference and objectives 51
2.4.2 Scope of work 51
2.4.3 Topography and drainage 51
2.4.4 Geology 53
2.4.5 Geophysics 54
2.4.6 Drilling 55
2.4.7 Hydrocensus 56
2.4.8 Water quality 57
2.4.9 Pumping tests 59
2.4.10 Geohydrology 60
2.4.11 Groundwater balance 61

2.4.12 *Considerations for future groundwater exploitation* ... 62

3 HISTORIC GROUNDWATER LEVELS & ABSTRACTION ... 63

3.1 INTRODUCTION ... 63

3.2 HISTORIC TIME SERIES WATER LEVELS ... 63

3.2.1 *Closed stations* ... 63

3.2.2 *Locations of active monitoring boreholes* ... 65

3.2.3 *Q1N0042 – Bultfontein, Matjieskloof (Operational)* ... 68

3.2.4 *Q1N0050 – Grootfontein (Operational)* ... 70

3.2.5 *Q1N0507 – Nuwevlei (Operational)* ... 73

3.2.6 *Q1N0508 – Downstream of Zonnebloem municipal abstraction (Operational)* ... 75

3.3 ABSTRACTION FROM EXISTING MUNICIPAL WATER SUPPLY BOREHOLES ... 77

3.4 CONCLUSIONS ... 79

3.5 RECOMMENDATIONS ... 79

4 HYDROCENSUS ... 80

4.1 METHODOLOGY ... 80

4.1.1 *Hydrocensus* ... 80

4.1.2 *Data processing and database* ... 81

4.1.3 *Sub-catchment delineation* ... 81

4.1.4 *Hydrochemistry* ... 82

4.2 HYDROCENSUS RESULTS ... 84

4.2.1 *General statistics from hydrocensus* ... 84

4.2.2 *Hydrocensus water levels* ... 88

4.2.3 *Borehole depths from hydrocensus* ... 90

4.3 STUDY AREA DEFINITION ... 90

4.4 GENERAL GROUNDWATER QUALITY ... 91

4.4.1 *Overall water quality classification of boreholes sampled in hydrocensus* ... 92

4.4.2 *Electrical conductivity (EC)* ... 94

4.4.3 *Total and faecal coliforms* ... 95

4.4.4 *Total hardness* ... 97

4.4.5 *Fluoride* ... 98

4.5 CATCHMENTS AND SUB-CATCHMENT DELINEATION ... 99

4.5.1 *Sub-catchment delineation* ... 99

4.5.2 *Middelburg municipal sub-catchment* ... 101

4.5.3 *Dunblane sub-catchment* ... 101

4.5.4 *The Glen sub-catchment* ... 101

4.5.5 *Karmel sub-catchment* ... 101

4.5.6 *Lusernvlei sub-catchment* ... 102

4.5.7 *Grootfontein compartment sub-catchment* 102

5 GEOPHYSICS & EXPLORATION TARGET AREAS 104

5.1 INTRODUCTION 104
5.2 METHODOLOGY 104
5.2.1 *Georefencing of geological map and geology shapefiles* 104
5.2.2 *Remote sensing and further target area delineation* 104
5.2.3 *Magnetometer geophysics* 105
5.2.4 *Electromagnetic (EM) method and Frequency domain EM geophysics method* 107
5.2.5 *Resistivity geophysics* 109
5.2.6 *Digitizing of geophysical lines for presentation in maps* 110
5.3 RESULTS 111
5.3.1 *Geophysical profiles discussion* 116
5.3.2 *Target areas* 147

6 DRILLING 150

6.1 METHODOLOGY 150
6.1.1 *Rotary air-percussion drilling technique* 150
6.1.2 *Water hammer drilling technique* 151
6.2 DRILLING SUMMARY 151
6.3 BOREHOLE RESULTS AND DISCUSSION 156
6.3.1 *Phase 2 drilling: J & M Drilling* 156
6.3.2 *Drilling Difficulties* 166
6.3.3 *Phase 3 drilling: Steyns Drilling* 167
6.4 CONCLUSIONS ON DRILLING WORK 184

7 AQUIFER TESTING 186

7.1 METHODOLOGY 186
7.1.1 *Aquifer testing (Hydraulic tests)* 186
7.2 ASSUMPTIONS AND ANALYTICAL MODEL LIMITATIONS 188
7.3 HYDRAULIC TESTING RESULTS 189
7.3.1 *Existing boreholes tested* 189
7.3.2 *New boreholes tested* 197
7.3.3 *Aquifer mechanics and aquifer types* 207
7.4 PACKER ISOLATED WATER QUALITY TESTING 210
7.5 CONCLUSIONS 210

8 NEW MIDDELBURG GROUNDWATER MONITORING NETWORK 212

8.1 METHODOLOGY 215

8.2 RESULTS 215
8.2.1 Monitoring period December 2008 to March 2010 215
8.2.2 Recovered data: monitoring period July 2010 to March 2013 223
8.3 CONCLUSIONS 226

9 GROUNDWATER CHEMISTRY 227

9.1 METHODOLOGY 227
9.1.1 Sampling 227
9.1.2 Analysis and classification of results 228
9.2 RESULTS 230
9.2.1 Hydrocensus samples groundwater chemistry analysed 230
9.2.2 Groundwater chemistry results from hydraulic testing 230
9.3 DISCUSSION 237
9.3.1 Groundwater characterisation from hydrocensus samples 237
9.3.2 Borehole hydrochemical characterisation from hydraulic testing 238
9.3.3 Major ions 244
9.3.4 Minor ions 246
9.3.5 Deductions from groundwater characterisation 247
9.4 WATER QUALITY CLASSIFICATION 248
9.5 WATER TREATMENT OPTIONS 250
9.6 CHLORIDE INTERPOLATION OF NEW AND EXISTING BOREHOLES 250
9.7 CONCLUSIONS & RECOMMENDATIONS FROM HYDROCHEMISTRY 253

10 GROUNDWATER BALANCE 255

10.1 INTRODUCTION 255
10.2 METHODOLOGY 255
10.3 EXISTING MIDDELBURG STUDIES: VANDOOLEAGHE (1979) WATER BALANCE 256
10.4 WATER DEMAND 257
10.4.1 Current municipal abstraction 257
10.4.2 Current consumption per capita 257
10.4.3 Water supply phase 1: Immediate drought relief 257
10.4.4 Future 2024 water demand 257
10.5 RESULTS 258
10.5.1 Rainfall, assurance levels and groundwater recharge 258
10.5.2 Groundwater volume in storage 263
10.5.3 Dams seepage 265
10.5.4 Basic human needs (BHN) Reserve 265
10.5.5 Current borehole abstraction 265
10.5.6 Reported municipal abstraction 266

10.5.7 Total livestock farms water use *266*
10.5.8 Total mine usage *266*
10.5.9 Community groundwater use *266*
10.5.10 Wetland water use *266*
10.5.11 Spring flow *267*
10.5.12 Evapotranspiration *267*
10.6 DISCUSSION 268
10.6.1 Scenario 1: Present day GYMR 95% assured rainfall *270*
10.6.2 Scenario 2: Present day GYMR with MAP rainfall, both recharge estimates *274*
10.6.3 Scenario 3: Present day, comparison of 95% assured rainfall & CMB recharge vs. MAP rainfall & SVF recharge *277*
10.6.4 Scenario 4: Present day, the Glen implementation 20 ℓ/s drought relief *288*
10.6.5 Scenario 5: Future 2024 scenario *288*
10.7 CONCLUSIONS 291
10.8 RECOMMENDATIONS 294

11 SUSTAINABILITY VALIDATION: NUMERICAL MODELLING 296

11.1 INTRODUCTION 296
11.2 OBJECTIVES OF NUMERICAL MODELLING 296
11.3 METHODOLOGY 296
11.4 CONCEPTUAL MODEL AND DATA 297
11.4.1 Aquifer system framework *297*
11.4.2 Groundwater flow system *298*
11.4.3 Hydrological and hydrogeological boundaries *306*
11.4.4 Model domain *306*
11.4.5 Hydraulic properties *306*
11.4.6 Rainfall records *309*
11.4.7 Sources and sinks *309*
11.4.8 Water balance (water budget) *310*
11.5 GROUNDWATER FLOW MODEL CONSTRUCTION 312
11.5.1 Finite element mesh construction (model grid) *312*
11.5.2 Temporal dimensionality and discretisation *315*
11.5.3 Hydraulic parameters *315*
11.5.4 Boundary conditions *315*
11.5.5 Selection of calibration targets (initial conditions) *316*
11.6 CALIBRATION 316
11.6.1 Residual analysis *316*
11.6.2 Sensitivity analysis *325*

11.6.3 Model validation *331*
11.7 Scenario modelling (ASTM terminology: Predictive simulations) 345
11.7.1 Scenario 1: Present day existing abstraction, transient 100 year rainfall *345*
11.7.2 Scenario 2: The Glen implementation, transient 100 year simulation *356*
11.8 Conclusions 368
11.8.1 Assumptions and model limitations *369*
11.9 Recommendations 370

12 CONCLUSIONS, RECOMMENDATIONS & FUTURE PROSPECTS 371

12.1 Conclusions 371
12.2 Recommendations 374
12.3 Future Prospects: Artificial Recharge 377

13 REFERENCES 381
SUMMARY 388
OPSOMMING 390

List of Figures

Figure 1-1: Regional locality map for the Middelburg study area ... 4
Figure 1-2: Regional locality of the Middelburg study area ... 5
Figure 2-1: Regional 1:250 000 Geological map for the Middelburg study area ... 7
Figure 2-2: A vertical profile measured on a scarp slope of Bakenskop, Zuurplaats 35 farm representative of the Geology found in Middelburg Study area (after Cole *et al.*, 2004) ... 10
Figure 2-3: (a) En-echelon dyke emplacement mode; (b) dyke with vertical tectonic and horizontal thermal jointing and (c) Fissures relating to tectonic reactivation and jointing from weathering or erosional unloading (Woodford *et al.*, 2002: 53) ... 19
Figure 2-4: The 5 major ring and sill complex systems (mega basins) found in the western to eastern Karoo (Woodford *et al.*, 2002: 83) ... 21
Figure 2-5: The two proposed emplacement modes for dolerite ring/sill systems: (a) Ring dyke model after Chevallier and Woodford (1999) and (b) the laccolith model of Burger *et al.* (1981) [in Woodford *et al.*, 2002] ... 23
Figure 2-6: The fracture types associated with ring- and sill-complexes (after Chevallier *et al.*, 2001 in Woodford *et al.*, 2002: 89) ... 26
Figure 2-7: Groundwater flow to a borehole in an idealised dual porosity aquifer (after Van Tonder *et al.*, 2002: 2-10) ... 29
Figure 2-8: Relationships of South African legislation, policy and guidelines ... 42
Figure 2-9: Diagram of legal requirements of the Water Act when performing any groundwater resource development in the Northern Territory of Australia ... 46
Figure 2-10: Drainages, quaternary catchments and water management areas (WMAs) of the Middelburg area ... 52
Figure 2-11: Histogram of percentage water interceptions vs airlift yield tests (after Vandooleaghe, 1979) ... 56
Figure 2-12: Municipal annual abstraction volumes over time (after Vandoolaeghe, 1979: 38) ... 57
Figure 3-1: Grootfontein closed monitoring stations with groundwater levels from 1956 to 1967 ... 64
Figure 3-2: Closed monitoring station groundwater levels between 1987 and 1993 ... 66
Figure 3-3: Map showing operational DWA water level monitoring boreholes with municipal boreholes & abstraction ... 67
Figure 3-4: Water level over time for monitoring borehole Q1N0042 at Matjieskloof ... 69
Figure 3-5: Groundwater level over time for borehole Q1N0050 at Grootfontein Agricultural College ... 72
Figure 3-6: Water level over time for Q1N0507 at Nuwevlei ... 74
Figure 3-7: Groundwater level change over time for monitoring borehole Q1N0508 downstream of Zonnebloem abstraction ... 76
Figure 3-8: Monthly abstraction from municipal boreholes over time ... 78
Figure 4-1: The 1692 boreholes from the detailed hydrocensus of the Middelburg study area ... 84
Figure 4-2: Summation of different Site Types for Geosites surveyed ... 85
Figure 4-3: Bar graph count of each geosite purpose ... 85

Figure 4-4: Statistical distribution of the *Status* of each geosite surveyed 86
Figure 4-5: Installation types for geosites surveyed during hydrocensus 86
Figure 4-6: Map indicating borehole density around Middelburg using hydrocensus results 87
Figure 4-7: Histogram of distribution of 888 borehole water levels 88
Figure 4-8: Water level contour map interpolated from 885 boreholes with water levels 89
Figure 4-9: Map of Middelburg cadastral information of farms surveyed during Hydrocensus 91
Figure 4-10: Overall DWAF drinking water quality classification for 405 boreholes sampled 92
Figure 4-11: Point colour map of the overall water quality class for 405 boreholes in the study area 93
Figure 4-12: The electrical conductivity (EC) DWAF classification for 405 boreholes sampled in Middelburg.. 94
Figure 4-13: Total coliforms classified for boreholes sampled during hydrocensus 95
Figure 4-14: Faecal coliforms classified for boreholes sampled during hydrocensus 96
Figure 4-15: Total hardness classified for 405 boreholes sampled during hydrocensus 97
Figure 4-16: Fluoride classified for 405 boreholes sampled during hydrocensus 98
Figure 4-17: Quaternary catchments that the Middelburg study area intersects and falls over 100
Figure 4-18: Map showing the 6 final sub-catchments for the Middelburg study area with elevation and shaded relief 103
Figure 5-1: Regional map of all geophysics conducted in Middelburg study area in sub-catchments 112
Figure 5-2: Regional Landsat 7 imagery of Middelburg study area and sub-catchments; geophysical profiles in orange 113
Figure 5-3: Map showing geophysical lines conducted in Lusernvlei sub-catchment and showing new boreholes drilled in green 117
Figure 5-4: Profile P04 on the farm Buffelsvlei in the Dunblane sub-catchment (Coetzer, 2008) 118
Figure 5-5: Map showing profile P04 as it crossed the Oompies spruit drainage and the Dunblane dyke striking SSE-NNW 119
Figure 5-6: Profile P06 on Lusernvlei farm with drilling site selected at station 290 (Coetzer, 2008) 121
Figure 5-7: Profiles P07, P08 & P09 across Dunblane dyke (Coetzer, 2008) 122
Figure 5-8: Profiles P12, P13 and P14 correlated showing highly fractured zones in green either side of Dunblane dyke (Coetzer, 2008) 123
Figure 5-9: Profile P13 perpendicularly across the Dunblane dyke with fractures/ weathering on both sides... 124
Figure 5-10: Profile P12 across fracture zone next to Dunblane dyke (J. Coetzer, 2008) 125
Figure 5-11: Map showing profiles P07 – P15 and new boreholes on Dunblane dyke 126
Figure 5-12: Profile P15 across Dunblane dyke on Grootfontein farm in Dunblane sub-catchment (Coetzer, 2008) 127
Figure 5-13: Map of profiles P16 – P22 conducted to determine extension and orientation of Dunblane dyke beneath alluvium 128
Figure 5-14: Profile P23 first profile conducted in The Glen sub-catchment (Coetzer, 2008) 129
Figure 5-15: Profile P23 full magnetic and deep FDEM profiling (Coetzer, 2008) 130
Figure 5-16: Map showing Profiles P24, P25, P26 & P29 at Jones poort and The Glen sub-catchment 131

Figure 5-17: Profile P27 on Greyville farm, Dunblane sub-catchment (Coetzer, 2008) 132
Figure 5-18: Profile P29 through Jones Poort that borehole EC-Q14-1634 was sited on (Coetzer, 2008) 133
Figure 5-19: Profile P30 was used for siting borehole EC-Q14-1633 (Coetzer, 2008) 134
Figure 5-20: Profile P31 parallel to minor sill/ dolerite structure in The Glen sub-catchment (Coetzer, 2008) 136
Figure 5-21: P34 Contoured frequencies 150Hz, 75Hz & 37.5Hz from top to bottom-a higher conductance feature in green measured on P34 (Coetzer, 2008)... 136
Figure 5-22: Map of Profiles P31 – P36 investigating linear-like dolerite structure present parallel to southern part of P31 137
Figure 5-23: Profiles P37, P38 & P39 in The Glen sub-catchment parallel to dyke cutting through sill (Coetzer, 2008).. 139
Figure 5-24: Profile P40-P43 perpendicular across Dunblane dyke offshoot where Dunblane dyke cuts through The Glen dolerite ring structure (Coetzer, 2008).. 140
Figure 5-25: Map of Profiles P37 – P43 where Dunblane dyke offshoot cuts through The Glen ring structure indicated in blue.. 141
Figure 5-26: Profile P44 traverse across dolerite sill on The Glen farm in The Glen sub-catchment (Coetzer, 2008).. 142
Figure 5-27: Map showing profiles P23, P44 & P47 in The Glen sub-catchment.. 143
Figure 5-28: Profile P46 on Karmel/Waterkloof farms in Karmel sub-catchment (Coetzer, 2008)................. 145
Figure 5-29: Location of geophysical profiles conducted in Karmel sub-catchment – Profiles P45 & P46....... 146
Figure 5-30: Profile P48 E-W across the Dunblane dyke in Grootfontein sub-catchment 148
Figure 5-31: Location of Profile P48 in Grootfontein sub-catchment.. 149
Figure 6-1: Regional geology map showing all new boreholes drilling during the Middelburg groundwater investigation 152
Figure 6-2: Borehole lithology and construction log for EC-Q14-1631: part 1 of 2....................................... 159
Figure 6-3: Borehole lithology and construction log for EC-Q14-1631: part 2 of 2....................................... 160
Figure 6-4: Borehole lithology and construction log for EC-Q14-1632: part 1 of 3....................................... 162
Figure 6-5: Borehole lithology and construction log for EC-Q14-1632: part 2 of 3....................................... 163
Figure 6-6: Borehole lithology and construction log for EC-Q14-1632: part 3 of 3....................................... 164
Figure 6-7: Rock expelled from fracture found in EC-Q14-1636 at 122 mbgl 169
Figure 6-8: Chip (42mm dia.) from EC-Q14-1636 water strike at 122 mbgl with pyrite..................................... 170
Figure 6-9: Water Hammer operations at EC-Q14-1636.. 172
Figure 6-10: Borehole lithology and construction log for EC-Q14-1636: part 1 of 3 173
Figure 6-11: Borehole lithology and construction log for EC-Q14-1636: part 2 of 3 174
Figure 6-12: Borehole lithology and construction log for EC-Q14-1636: part 3 of 3 175
Figure 6-13: Borehole log EC-Q14-1655, Jones Poort, The Glen; log 1 of 3.. 181
Figure 6-14: Borehole log EC-Q14-1655, Jones Poort, The Glen; log 2 of 3.. 182
Figure 6-15: Borehole log EC-Q14-1655, Jones Poort, The Glen; log 3 of 3.. 183

Figure 7-1: Map of existing and new boreholes that pumping tests were performed on 191
Figure 7-2: Unconfined porous aquifer behaviour with delayed yield in existing borehole EC-Q14-192 constant discharge test 192
Figure 7-3: Fickson from AB Pumps at riser pipe yielding 25 ℓ/s from EC-Q14-1655 during its constant discharge test 197
Figure 7-4: EC-Q14-1631 CD test and recovery, line fitted on 1 no-flow boundary 202
Figure 7-5: Linear-log graph of constant discharge test for EC-Q14-1636 with fitted line at pseudo radial flow 204
Figure 7-6: Log-log graph of EC-Q14-1636 constant discharge test 204
Figure 7-7: Graph showing drawdown and poor recovery in EC-Q14-1636; observation borehole EC-Q14-1637 response during testing of EC-Q14-1636 205
Figure 7-8: Linear-log graph of EC-Q14-1655 constant discharge test at 25 ℓ/s and recovery 206
Figure 8-1: Installation of groundwater monitoring equipment by Mr. R. Haasbroek 212
Figure 8-2: Map of new groundwater monitoring borehole network 213
Figure 8-3: EC-Q14-482 and EC-Q14-371 monitoring boreholes in the western valley aquifer 216
Figure 8-4: Municipal sub-catchment groundwater level fluctuation, new monitoring holes 217
Figure 8-5: Middelburg Municipal deep aquifer monitoring from new exploration borehole 218
Figure 8-6: Dunblane sub-catchment new groundwater monitoring borehole responses 219
Figure 8-7: More distant monitoring boreholes EC-Q14-172 and EC-Q14-1047 fluctuations 220
Figure 8-8: Groundwater level from new monitoring borehole EC-Q14-1634 at Jones Poort, The Glen sub-catchment 221
Figure 8-9: Karmel sub-catchment monitored groundwater levels 222
Figure 8-10: Data showing logger battery failure in The Glen sub-catchment 223
Figure 8-11: EC-Q14-1634 The Glen sub-catchment recovered data and older data indicating rise in water level due to above MAP rainfall 224
Figure 8-12: EC-Q14-008 Municipal sub-catchment recovered data combined with older data showing abstraction and recharge 225
Figure 9-1: Piper diagram of groundwater chemistries of all existing boreholes sampled during hydrocensus (n = 402) 231
Figure 9-2: Piper diagram of existing boreholes sampled during hydraulic testing 234
Figure 9-3: Piper diagram of new boreholes drilled during the investigation 235
Figure 9-4: Map of new and existing boreholes hydraulically tested and hydrogeochemically interpreted 236
Figure 9-5: Kriging interpolation of all (n=415) chloride values sampled at boreholes, effectively representing a map of recharge 252
Figure 10-1: Time series water level data of borehole EC-Q14-968 on Greyville farm in the middle of the Dunblane sub-catchment 282
Figure 10-2: Map showing stress index of Present day scenario with SVF recharge and water level-Cooper & Jacob abstraction 286

FIGURE 10-3: MAP SHOWING STRESS INDEX OF PRESENT DAY SCENARIO WITH WOODFORD RECHARGE AND WATER LEVEL-COOPER & JACOB ABSTRACTION 287
FIGURE 11-1: MAP FOR CROSS-SECTION A-B FOR CONCEPTUAL MODEL 300
FIGURE 11-2: NW – SE SECTION CONCEPTUAL MODEL THROUGH THE GLEN SUB-CATCHMENT, GROOTFONTEIN COMPARTMENT AND SMALL PART OF THE MUNICIPAL SUB-CATCHMENT 301
FIGURE 11-3: MEASURED GROUNDWATER LEVELS VS. TOPOGRAPHY GRAPH AND CORRELATION (N = 378) 302
FIGURE 11-4: CONCEPTUAL MODEL AND CROSS SECTION E – W THROUGH THE GLEN SUB-CATCHMENT AND BOREHOLE EC-Q14-1636 303
FIGURE 11-5: CONCEPTUAL MODEL AND CROSS SECTION PERPENDICULAR TO DUNBLANE DYKE AT EC-Q14-1632 304
FIGURE 11-6: MAP SHOWING LOCATION OF ALL CROSS-SECTIONS FOR CONCEPTUAL MODELS 305
FIGURE 11-7: MIDDELBURG STUDY AREA HYDROGEOLOGICAL BOUNDARIES AND MODEL DOMAIN 308
FIGURE 11-8: ALL THE FEATURES USED IN THE FEFLOW SUPERMESH CONSTRUCTION 311
FIGURE 11-9: FEFLOW FINITE ELEMENT MESH 313
FIGURE 11-10: GEOLOGY, RIVERS AND ABSTRACTION BOREHOLES INCLUDED IN FE MESH (TABLE 11-4) 314
FIGURE 11-11: MODEL OBSERVATION BOREHOLES (N = 378) 317
FIGURE 11-12: SCATTER PLOT OF CALIBRATED STEADY STATE MEASURED VS. SIMULATED HYDRAULIC HEADS 319
FIGURE 11-13: BAR CHART OF CALIBRATED STEADY STATE MEASURED VS. SIMULATED HYDRAULIC HEADS 320
FIGURE 11-14: LINE GRAPH OF CALIBRATED STEADY STATE MEASURED VS. SIMULATED HYDRAULIC HEADS 321
FIGURE 11-15: RESIDUALS ANALYSIS: RESIDUAL DISTRIBUTION COMPARED TO TOPOGRAPHY 322
FIGURE 11-16: HISTOGRAM OF HYDRAULIC HEAD RESIDUALS FROM FINAL STEADY STATE CALIBRATION, SKEWED DISTRIBUTION DUE TO CONSERVATIVE APPROACH 323
FIGURE 11-17: MAP OF INTERPOLATED STEADY STATE MODEL RESIDUALS (N = 378) 324
FIGURE 11-18: SENSITIVITY ANALYSIS FOR GROUNDWATER RECHARGE ON FRACTURED HARD ROCK FORMATIONS THAT OUTCROP 326
FIGURE 11-19: GROUNDWATER RECHARGE SENSITIVITY ANALYSIS FOR ALLUVIUM, CALCRETE AND WEATHERED RIVER CHANNEL (GROUPED UNCONSOLIDATED) 327
FIGURE 11-20: SENSITIVITY ANALYSIS FOR TRANSMISSIVTY (T) OF FRACTURED HARD ROCK GEOLOGY TYPES 329
FIGURE 11-21: SENSITIVITY ANALYSIS FOR TRANSMISSIVTY (T) OF ALLUVIUM, CALCRETE AND WEATHERED RIVER CHANNEL ZONE 330
FIGURE 11-22: SIMULATED WATER LEVEL EC-Q14-101 COMPARED TO MONITORING BOREHOLE Q1N0508 331
FIGURE 11-23: TOTAL MODEL DOMAIN STORAGE OF 100 YEAR SIMULATION WITHOUT TIME SERIES ABSTRACTION 332
FIGURE 11-24: RAINFALL ANALYSIS: COMPARISON OF PATCHED RAINFALL SEQUENCE TO VARIOUS OTHER RAINFALL DATASETS.. 333
FIGURE 11-25: RECHARGE ADJUSTMENT EFFECT DURING HISTORY MATCHING AND Q1N0508 COMPARISON 335
FIGURE 11-26: SELECTED GROUNDWATER LEVELS FOR MUNICIPAL SUB-CATCHMENT; DIFFERENT DISTANCES FROM MUNICIPAL ABSTRACTION 337
FIGURE 11-27: SELECTED GROUNDWATER LEVELS FOR THE GLEN SUB-CATCHMENT/COMPARTMENT; NO IMPACT FROM CURRENT ABSTRACTION 338

Figure 11-28: Representative groundwater levels in the Karmel sub-catchment upstream of Municipal sub-catchment; no problems 340
Figure 11-29: Representative groundwater levels in Dunblane sub-catchment: some effects of adjacent municipal sub-catchment abstraction 341
Figure 11-30: Representative groundwater levels for Grootfontein catchment and history match DWA monitoring hole Q1N0050 342
Figure 11-31: Scenario 1 simulated hydraulic head distribution and location of selected boreholes for graphs 346
Figure 11-32: Scenario 1 transient 100 year simulated heads (mbgl) for the Middelburg Municipal sub-catchment 347
Figure 11-33: Scenario 1 transient 100 year simulated heads (mbgl) for The Glen sub-catchment/compartment 348
Figure 11-34: Scenario 1 transient 100 year simulated hydraulic heads (mbgl) for the Karmel sub-catchment. 349
Figure 11-35: Scenario 1 transient 100 year simulated hydraulic heads (mbgl) for the Dunblane sub-catchment 350
Figure 11-36: Scenario 1 transient 100 year simulated hydraulic heads (mbgl) for the Grootfontein compartment 351
Figure 11-37: Scenario 1 FE node hydraulic head residuals interpolated, note range of residuals 352
Figure 11-38: Scenario 2 simulated hydraulic head distribution for The Glen sub-catchment new boreholes implementation 357
Figure 11-39: Selected Municipal sub-catchment simulated hydraulic heads for Scenario 2 implementation of The Glen boreholes 358
Figure 11-40: Selected simulated hydraulic heads from The Glen sub-catchment for Scenario 2 implementation of The Glen new boreholes 359
Figure 11-41: Selected Karmel sub-catchment simulated hydraulic heads for Scenario 2 implementation of The Glen boreholes 360
Figure 11-42: Selected Dunblane sub-catchment simulated hydraulic heads for Scenario 2 implementation of The Glen boreholes 361
Figure 11-43: Selected Grootfontein compartment simulated hydraulic heads for Scenario 2 implementation of The Glen boreholes 362
Figure 11-44: Scenario 2 hydraulic heads minus history match final heads 2011: residuals/difference 363
Figure 11-45: Scenario 2 simulated heads minus calibrated steady state heads: residual/difference 364
Figure 11-46: Model domain groundwater volume fluctuations over time 367
Figure 12-1: Artificial recharge candidate area for in-channel gabion structure and sand dam in Grootfontein sub-catchment 378

List of Tables

Table 2-1: Stratigraphy of the Karoo Supergroup in the 3124 Middelburg geology map (Cole *et al.*, 2004) also representative of the study area stratigraphy ... 15
Table 3-1: Grootfontein closed stations summary table of details ... 65
Table 3-2: Summary table of various closed stations and their details ... 65
Table 3-3: Water level parameters for monitoring borehole Q1N0042, Matjieskloof ... 68
Table 3-4: Water level parameters for monitoring borehole Q1N0050, Grootfontein ... 71
Table 3-5: Summary water level parameters for Q1N0507 Nuwevlei ... 73
Table 3-6: Summary water level parameters for Q1N0508, near Zonnebloem 1 & 2 ... 75
Table 3-7: Annual volumes abstracted from municipal boreholes that are available ... 77
Table 4-1: Water quality classification and Assessment guide ... 83
Table 4-2: Study area sub-catchments information ... 99
Table 5-1: Summary table 1 of 2 of geophysical profiles conducted ... 114
Table 5-2: Summary table 2 of 2 of geophysical profiles conducted ... 115
Table 6-1: Drilling summary table of boreholes drilled & rehabilitated by J & M Drilling – Phase 2 ... 153
Table 6-2: Drilling summary table of boreholes drilled & rehabilitated by Steyns Drilling- Phase 3 ... 154
Table 6-3: Table with discussion of borehole targets and results as well as profiles/ stations boreholes were sited on ... 155
Table 7-1: Basic information of existing boreholes aquifer tested in Middelburg ... 193
Table 7-2: Pumping test information of the existing boreholes tested during the Middelburg groundwater investigation ... 194
Table 7-3: Table 1 of 2 aquifer parameters determined for existing boreholes aquifer tested in Middelburg ... 195
Table 7-4: Table 2 of 2 aquifer parameters determined for existing boreholes aquifer tested in Middelburg ... 196
Table 7-5: Basic information of new boreholes aquifer tested in Middelburg ... 198
Table 7-6: Pump testing information of the new boreholes tested during the Middelburg groundwater supply study ... 199
Table 7-7: Table 1 of 2 aquifer parameters determined for new boreholes aquifer tested in Middelburg ... 200
Table 7-8: Table 2 of 2 aquifer parameters determined for new boreholes aquifer tested in Middelburg ... 201
Table 8-1: New monitoring borehole network summary table ... 214
Table 9-1: DWA water quality classification system classes and colours (DWAF, 1998) ... 229
Table 9-2: Table 1 of 2 hydrochemistry results of existing and new boreholes sampled during hydraulic testing and drilling ... 232
Table 9-3: Table 2 of 2 hydrochemistry results of existing and new boreholes sampled during hydraulic testing and drilling ... 233
Table 9-4: DWA classification of existing and new boreholes ... 249
Table 9-5: Treatment options for problem constituents in recommended boreholes ... 251
Table 10-1: Comparison of recharge estimates obtained from different recharge calculations ... 263
Table 10-2: Groundwater volume in storage (m^3) for each sub-catchment ... 264

Table 10-3: Scenario 1(a) present day 95% assured rainfall with potential existing abstraction 270
Table 10-4: Scenario 1 (b): Present day 95% assured rainfall & AGES estimated abstraction 272
Table 10-5: Scenario 1 (c): AGES reported GYMR balance to DWA 272
Table 10-6: Scenario 2 (a): Present day MAP rainfall with CMB recharge and Potential existing abstraction ... 275
Table 10-7: Scenario 2 (a): Present day MAP rainfall with SVF recharge estimates and Potential existing abstraction 275
Table 10-8: Scenario 2 (b): Present day MAP rainfall with CMB recharge and AGES estimated abstraction 276
Table 10-9: Scenario 2 (b): Present day MAP rainfall with SVF recharge and AGES estimated abstraction 276
Table 10-10: Scenario 3 (a): Present day comparison of 95% assured rainfall & CMB recharge vs. MAP & SVF recharge, both with Potential abstraction volumes 278
Table 10-11: Scenario 3 (a): Present day MAP rainfall with SVF recharge estimates and Potential abstraction.... 279
Table 10-12: Scenario 3 (b): Present day MAP rainfall with SVF recharge estimates and AGES estimated abstraction 279
Table 10-13: Comparison of the three abstraction estimates 281
Table 10-14: Scenario 3 (c): Present day scenario with SVF-MAP recharge and water level-transmissivity estimated abstraction 283
Table 10-15: Present day scenario with Woodford trend line estimated recharge and water level-transmissivity estimated abstraction 285
Table 10-16: Scenario 4: Present day, The Glen implementation for immediate drought relief, SVF recharge and water level-Cooper & Jacob abstraction 289
Table 10-17: Scenario 4: Present day, The Glen implementation for immediate drought relief, Woodford recharge and water level-Cooper & Jacob abstraction 289
Table 10-18 Scenario 5 (a): Future 2024 scenario: SVF recharge and 153 ℓ/s municipal abstraction implemented 290
Table 10-19 Scenario 5 (b): Future 2024 scenario: Woodford recharge and 153 ℓ/s municipal abstraction implemented 290
Table 11-1: Hydraulic parameters used to determine initial transmissivity and specific yield 307
Table 11-2: Recharge estimation method results for sub-catchments and geomorphology 309
Table 11-3: Initial model water balance steady state 310
Table 11-4: Initial steady state hydraulic parameters 315
Table 11-5: Final steady state calibrated hydraulic parameters 318
Table 11-6: Model domain mean water budget results for scenario 1 353
Table 11-7: Water budget results from numerical model for sub-catchments, scenario 1 354
Table 11-8: Scenario 2 model domain mean water budget results 365
Table 11-9: Comparison of Scenario 3 model water budget results and GYMR water balance 366

List of Abbreviations

Abbreviation:	Description:
AGES	Africa Geo-Environmental Services
ARC	Agricultural Research Council
BHN	Basic Human Need
CMB	Chloride Mass Balance
DTM	Digital Terrain Model
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
EIA	Environmental Impact Assessment
EWR	Ecological Water Requirement
FCM	Flow Characteristic Method
FE	Finite Element
GRIP	Groundwater Resource Information Project
GYMR	Groundwater Yield Model for the Reserve
IGS	Institute for Groundwater Studies
IWRM	Integrated Water Resource Management
Ma	Million years
MAE	Mean Absolute Error
mamsl	metres above mean sea level
MAP	Mean Annual Precipitation
mbcl	metres below collar level
mbgl	metres below ground level
NEMA	National Environmental Management Act
NGI	National Geospatial Information
nT	nanotesla
RDM	Resource Directed Measures
SAWS	South African Weather Service
SVF	Saturated Volume Fluctuation
WR2005	Water Resources of South Africa, 2005 study
WRC	Water Research Commission

Notations and terminology

Advection is the process by which solutes are transported by the bulk motion of the flowing groundwater.

Anisotropy is an indication of some physical property varying between at least two dimensions.

An *aquifer* is defined as a saturated geological unit that can transmit viable quantities of groundwater under commonly found hydraulic gradients.

An *aquiclude* is defined as a saturated geological unit that cannot transmit economically viable or significant quantities of groundwater under commonly induced hydraulic gradients. Groundwater flow through an aquiclude is so slow that the flow is considered negligible.

Aquitard has been defined as the less permeable formations in a stratigraphic sequence that transmits enough groundwater to be recognised at regional flow scale, but is not permeable enough to locally transmit viable quantities of groundwater to justify an abstraction borehole.

Cone of depression is a depression in the groundwater table or potentiometric surface that has the shape of an inverted cone and develops around a borehole from which water is being withdrawn. It defines the area of influence of a borehole.

A *confined aquifer* is a formation in which the groundwater is isolated from the atmosphere at the point of discharge by impermeable geologic formations; confined groundwater is generally subject to pressure greater than atmospheric.

The *darcy flux*, is the flow rate per unit area (m/d) in the aquifer and is controlled by the hydraulic conductivity and the hydraulic gradient.

Dispersion is the measure of spreading and mixing of chemical constituents in groundwater caused by diffusion and mixing due to microscopic variations in velocities within and between pores.

Drawdown is the distance between the static water level and the surface of the cone of depression.

Effective porosity is the percentage of the bulk volume of a rock or soil that is occupied by interstices that are connected.

Elevation head (h_z) is the elevation (above chosen datum level) of the hydraulic head's point of measurement. Elevation head in practical terms is the elevation above mean sea level of the bottom opening of the piezometer, where the piezometer has no other screens along its length.

A *fault* is a fracture or a zone of fractures along which there has been geological displacement of the opposing rock blocks.

Hydraulic conductivity (K) is the volume of water that will move through a porous medium in unit time under a unit hydraulic gradient through a unit area measured perpendicular to the area [L/T]. Hydraulic conductivity is a function of the permeability and the fluid's density and viscosity.

Hydraulic gradient is the rate of change in the total head per unit distance of flow in a given direction.

Hydraulic head (h): Hydraulic head is a form of potential energy and is related to fluid potential (Φ) through $\Phi = gh$. Total hydraulic head, $h_T = h_z + h_p + h_v$. In practical terms, hydraulic head is simply the groundwater level measured and then related back to a common datum level, such as metres above mean sea level (mamsl).

Heterogeneous indicates non-uniformity in a formation or intrusion.

Karstic topography is a type of topography that is formed on limestone, gypsum, and other rocks by dissolution, and is characterised by sinkholes, caves and underground drainage.

Mechanical dispersion is the process whereby the initially close group of pollutants are spread in a longitudinal as well as a transverse direction because of velocity distributions.

Molecular diffusion is the dispersion of a chemical caused by the kinetic activity of the ionic or molecular constituents.

Observation borehole is a borehole drilled in a selected location for the purpose of observing parameters such as water levels.

Permeability (k) is related to hydraulic conductivity, but is independent of the fluid density and viscosity and has the dimensions [L^2]. Hydraulic conductivity is related to water and is therefore used in all the calculations.

Piezometric head is the sum of the elevation and pressure head. An unconfined aquifer has a water table and a confined aquifer has a piezometric surface, which represents a pressure head. The piezometric head is also referred to as the *hydraulic head (h)*.

Porosity (n) is the percentage of the bulk volume of a rock or soil that is occupied by interstices, whether isolated or connected.

Pressure head (h_p) is defined the amount of work done (elastic energy) to raise the fluid pressure from p_0 (atmospheric pressure) up to a point p. The groundwater level pushes up in unscreened piezometer from piezometer bottom to level above aquifer penetration if it's a confined aquifer.

Pumping tests (hydraulic tests) are performed on boreholes to determine aquifer parameters, sustainable yield and/or well (borehole) efficiency.

Recharge is the addition of water to the saturated zone; also, the amount of water added.

Sandstone is a sedimentary rock composed of abundant rounded or angular fragments of sand set in a fine-grained matrix (silt or clay) and more or less firmly united by a cementing material.

Shale is a fine-grained sedimentary rock formed by the consolidation of clay, silt or mud. It is characterised by finely laminated structure and is sufficiently indurated so that it will not fall apart on wetting.

Specific storage (S_0), of a saturated confined aquifer is the volume of water that a unit volume of aquifer releases from storage under a unit decline in hydraulic head. In the case of an unconfined (phreatic/water table) aquifer, specific yield is the water that is released or drained from storage per unit decline in the water table.

Static water level (SWL) is the level of water in a borehole that is not being affected by withdrawal or injection of groundwater.

Storativity/storage coefficient (S) is equal to S_0 multiplied by aquifer thickness (*b*).

Total dissolved solids (TDS) is a term that expresses the quantity of dissolved material in a sample of water.

Transmissivity (T) is the two-dimensional form of hydraulic conductivity and is defined as the hydraulic conductivity multiplied by the saturated thickness (b).

An *unconfined-*, *water table-* or *phreatic-aquifer* are different terms used for the same aquifer type, which is bounded at base by an impermeable layer. The upper boundary is the water table, which is in contact with the atmosphere so that the system is open.

Vadose zone is the zone containing water under pressure less than that of the atmosphere, including soil water, intermediate vadose water, and capillary water. This zone is limited above by the land surface and below by the surface of the zone of saturation, that is, the water table.

Velocity head (h_v) is the amount of work required to accelerate a fluid from $v = 0$ to velocity v (Freeze & Cherry, 1979). The work done is calculated through equation $w = (mv^2)/2$. In fluid flow through porous media, velocities are generally extremely low so that the h_v term in the total hydraulic head (h_T) equation can almost always be excluded.

Water table is the surface at which the water in the pores of the strata/deposit are exactly equal to atmospheric pressure. The groundwater table is directly associated with unconfined aquifers.

(AGES, 2010; Freeze & Cherry, 1979)

1 INTRODUCTION

1.1 Background

W.C. Handy said: “You’ll never miss the water ‘til the well runs dry.” It is also said that the wars of the next century will be fought over fresh water (Serageldin, 1995). All life on earth depends upon water. Globally, a steady decline in potable water has been seen and its scarcity in South Africa’s arid climate has become common knowledge. The most easily accessible sources of fresh water, namely surface water are now utilised to full capacity, forcing South Africa to have to explore new innovative ways of finding potable water. At the 2009 Groundwater Division Conference the keynote speaker, Mr. Johan van Rooyen of the Department of Water Affairs, noted that the golden age of dam building in South Africa is over. There is however still much potable water available in South Africa, in the form of groundwater. Groundwater as source is however frowned upon by many an engineer due to the large uncertainties associated with its sustainable supply. This is an artefact of inexperienced exploration and exploitation of the resource, with many ill prepared recommendations made to engineers, and the engineers and managers of the resource ending up with a resource unable to supply its demand. This single major obstacle can be overcome by realistic well proven management recommendations by hydrogeologists, that are neither too conservative to make the source unfeasible, nor too ambitious (due to financial gain) to result in failure of the source. If good recommendations are made by seasoned hydrogeologists and critically include the management of the aquifer by continued monitoring of the hydraulic heads (groundwater levels), there would be no reason why a large aquifer cannot be managed to a similar efficiency as a large surface water dam.

Middelburg is a typical small Karoo town situated in the centre of the palaeo basin of the Karoo Supergroup of rocks. Its sole source of potable water is groundwater as there are no large surface water bodies present in the area. Groundwater also has two distinct advantages in this area when compared to surface water: Construction of a large surface water dam in the area would be impractical due to 1) the evaporation rate (1850 mm/a; WR2005, 2007) of a large surface water dam is five times the mean annual precipitation (345 mm/a) and 2) aquifers are not exposed to contaminants from the atmosphere and inherently have in their geometry a natural filtering system, resulting in better quality water often not requiring treatment. Most bottled mineral water that is sold is of groundwater origin.

Middelburg has an almost ideal shallow aquifer system. Extensive exploitation of this shallow aquifer system for more than half a century has resulted in localised over-exploitation and water supply failure.

1.2 Problem statement and rationale

Middelburg is a Karoo town situated in the north-western part of the Eastern Cape Province and has a population of approximately 50 000 people. It is also, like many other Karoo towns, dependent on groundwater as its sole source of water supply, as no large surface water bodies are present in the area. In the past (1987), water supply from existing municipal production boreholes was adequate to supply the town, but in more recent years town growth has resulted in a water supply shortage. The shallow aquifer with alluvial character, currently used as sole source, is under stress and groundwater levels are declining steadily. Piping water from the Orange-Fish River scheme was considered, but this option was shown to be very expensive (±R180 million) compared to groundwater resource development (±R8 million).

1.3 Aim

To address the water supply shortage, the hydrogeological consulting firm AGES was appointed through a tender process and performed an initial groundwater exploration investigation. The aim was to evaluate the potential of the deep aquifers associated with the large dolerite ring- and sill-complex structures in the area. The author formed part of the project team for the investigation and was the main author of the bulk of the reports.

The aim of this study and investigation is to perform groundwater exploration, resource development and aquifer characterisation to ensure sustainable water supply to the town of Middelburg.

1.4 Objectives of the study

The following main objectives were defined for the study:

1. Evaluate whether groundwater is a viable source of water supply to Middelburg in terms of quantity and quality;
2. Evaluate the linkage between the shallow and deep aquifers;
3. Perform aquifer characterisation to determine:
    - Aquifer parameters with a higher degree of confidence;
    - Determine groundwater recharge to the aquifers with higher confidence;
4. Implement a monitoring network and monitoring protocol for the sustainable management of aquifers in the study area.

1.5 Scope of the study and chapter outline

The outline and scope of the dissertation can be summarised in the following main and specialised components of groundwater resource development:

- A literature study of existing information sources on geology, hydrogeology, groundwater methodologies, existing studies done in the area, etc.;
- Review and analysis of historic groundwater levels and municipal abstraction;
- Hydrocensus and sampling to obtain data and information on the status and utilisation of the aquifers in the study area;
- Geophysics performed for siting groundwater exploration boreholes;
- Drilling of new exploration boreholes and site conditions encountered;
- Aquifer testing of new and existing potential production boreholes;
- Groundwater chemistry and characterisation;
- Analytical groundwater balance with the Groundwater Yield Model for the Reserve (GYMR) method;
- Numerical groundwater modelling for high confidence sustainability validation;
- Conclusions, recommendations and future prospects for the study area.

1.6 Location of the study area

Middelburg is located in the Eastern Cape Province of South Africa; approximately 87 km south of Colesberg (see Figure 1-1). The study area can be roughly defined with a 30 km radius around Middelburg, and is exactly defined with the boundaries of farms included in the hydrocensus. Administratively, Middelburg is located in the Inxuba Yethemba Local Municipality (LM) that falls within the administrative boundaries of the Chris Hani District Municipality (DM) in the Eastern Cape Province.

Hydrologically, the study area is situated in the Fish to Tsitsikamma water management area (WMA). The study area falls predominantly within the Q14 tertiary catchment, but also has portions within the Q22 and Q11 tertiary catchments (see Figure 1-2). The main drainage that runs through the study area is the non-perennial Klein-Brak River and its tributary, the Oompiespruit River.

The closest significant surface water dam to Middelburg is the Gariep Dam, approximately 106 km northeast of Middelburg. The Orange-Fish River transfer scheme is realised by the Orange–Fish Tunnel (83 km in length) that transfers water from the Gariep Dam into the Teebus Spruit. The Teebus River runs from north to south, approximately 45 km east of Middelburg at its closest point. As mentioned, piping water from the Orange-Fish River scheme (Teebus River) is the most viable surface water supply option with a capital expenditure (CAPEX) cost estimate of ±R180 million (Thusanang Gast, 2006).

1.7 Research question

This study will address hydrogeological characterisation of the aquifers found in the Middelburg Eastern Cape study area for sustainable water supply to the town. The geometry of the aquifer and hydraulic parameters obtained will then be used to evaluate the sustainability of groundwater as water supply source. The knowledge is also provided for decision making in the future water supply to Middelburg.

This study aims to obtain results for a number of different sub-disciplines within hydrogeology, but finally the results are all used to answer the following research question: Based on groundwater exploration and aquifer characterisation, does Middelburg have enough groundwater resources within a 10 – 20 km radius to meet the town's projected future water demand, or is surface water supply the only future option?

Figure 1-1: Regional locality map for the Middelburg study area

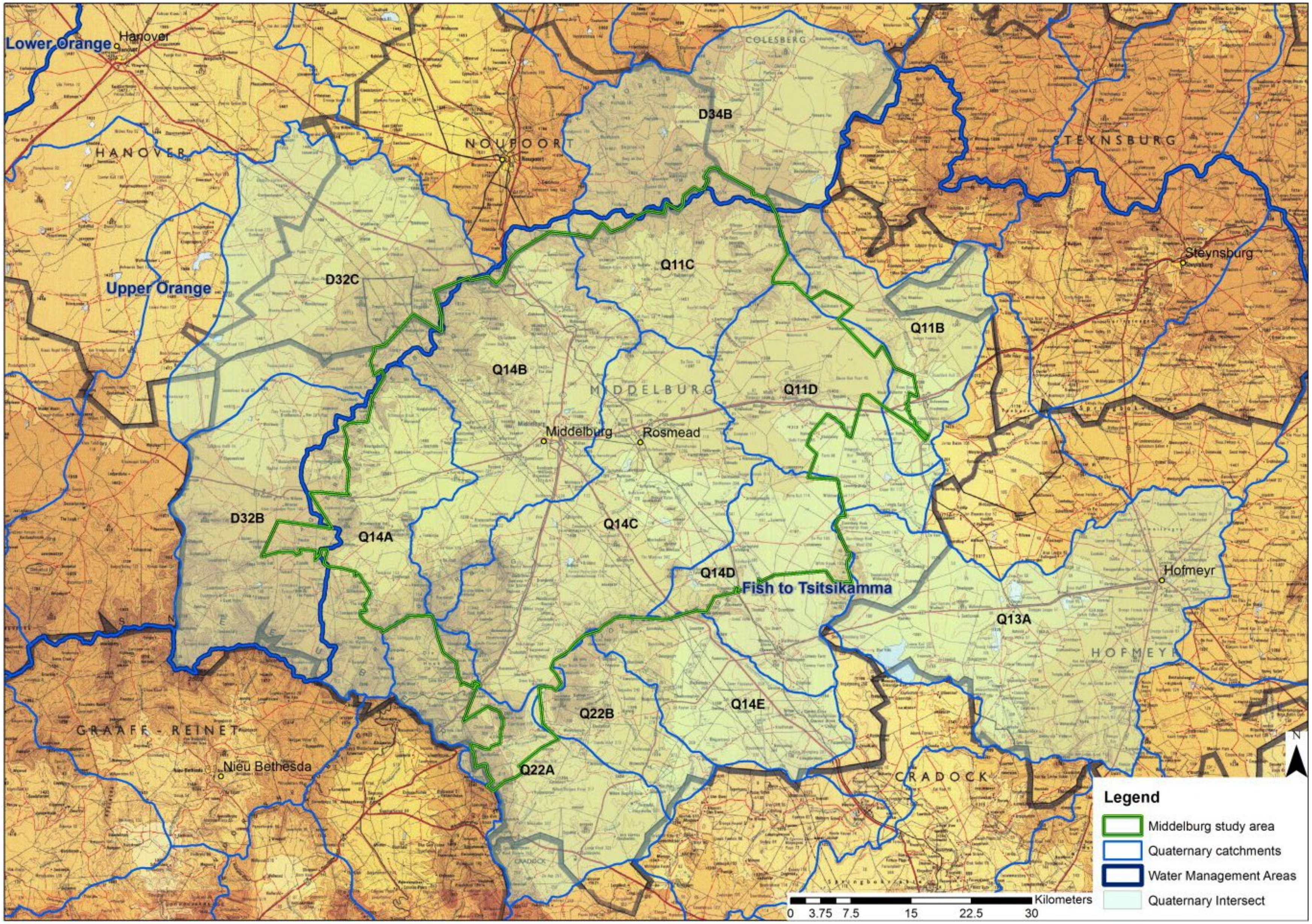


Figure 1-2: Regional locality of the Middelburg study area

2 LITERATURE STUDY

2.1 Geology

2.1.1 Geological overview

The Middelburg study area is primarily underlain by sedimentary rocks. Igneous rocks, mostly dolerite, make up the subordinate component of rocks in the study area (Council for Geoscience SA, 2004: IV). Few metamorphic rocks are present in the study area; their occurrence is limited to contact metamorphism zones between the dolerite intrusions and the sedimentary country rock. The sedimentary rocks of the study area belong to the Karoo Supergroup sequence of sedimentary rocks which underlie approximately 50% of the surface area of South Africa (Woodford *et al.*, 2002: 1). Refer to geology map in Figure 2-1.

Only formations of the Beaufort Group of the Karoo Supergroup occur in the study area. The two subgroups that are present are the Adelaide- and Tarkastad-Subgroups. Due to an absence of marker horizons in the Adelaide Subgroup in the study area, this subgroup has not been differentiated into its component formations. The Permian aged Adelaide Subgroup consists of mudstone with subordinate sandstone (Council for Geoscience, 1996; Council for Geoscience, 2004: 1). The Tarkastad Subgroup is of Triassic age (240-248 Ma) and it is only the Katberg Formation of this subgroup, that is present in the study area (Council for Geoscience, 1996). The Katberg Formation is sandstone rich with subordinate red and greenish-grey mudstone (Council for Geoscience, 2004: 3).

The igneous rocks in the study area were formed when magma intruded the Karoo sedimentary rocks and extruded onto the surface during a period of intense magmatic activity, presumably related to the tectonic movement and break-up of Gondwanaland (204 - 120 Ma) (Botha *et al.,* 1998: 25; Woodford *et al*., 2002: 12). This period of volcanism also created a large number of hypabassal dolerite dyke- and sill-intrusions that outcrop in an area equivalent to almost two-thirds of South Africa (Woodford *et al*., 2002: 12).

Cenozoic deposits cover the larger part of the study area in and around Middelburg. They consist mainly of alluvium and some calcrete to the west and southwest. According to Cole *et al.* (2004) these are only thin alluvial deposits found along valley areas.

As there were no significant mining activities ever undertaken in the Middelburg study area the best geological reference for the study area was the Explanation of the 1: 250 000 geological map of Middelburg 3124 by Cole *et al.* (2004).

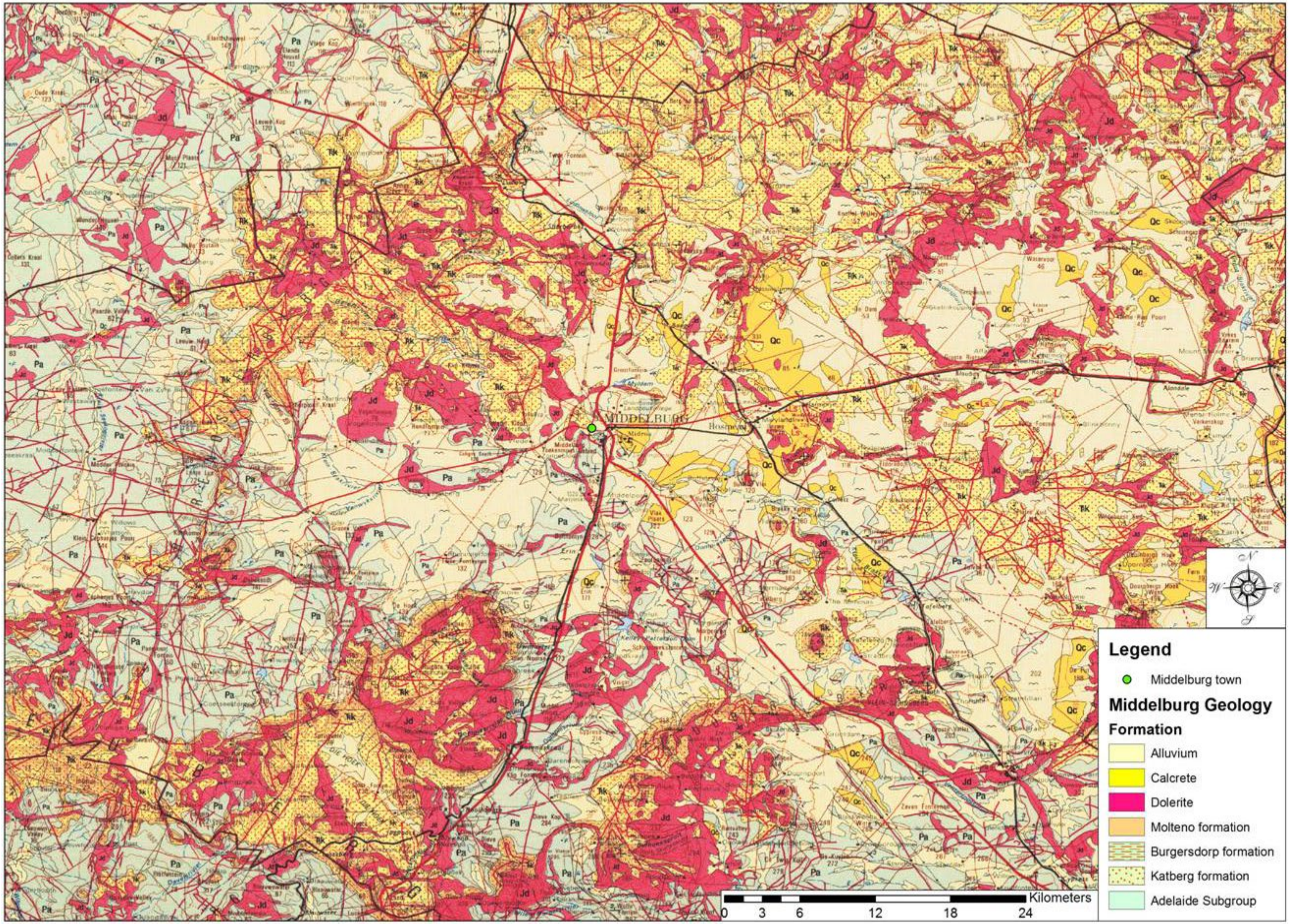


Figure 2-1: **Regional 1:250 000 Geological map for the Middelburg study area**

2.1.2 Karoo Supergroup

2.1.2.1 Beaufort Group

Adelaide Subgroup

Sedimentary formations of the Adelaide subgroup are found directly to the south and through to the west of Middelburg (GSSA, 1996). The Adelaide subgroup consists of up to 3 formations but these could not be differentiated in the study area due to the shortage of marker horizons (Cole *et al.*, 2004: 1). In the study area the subgroup is comprised of mudstone and subordinate sandstone with a sandstone-mudstone ratio of 1:6 (Cole *et al.*, 2004: 1). According to the Explanation of the 1:250 000 MIDDELBURG 3124 Geology map, the Adelaide subgroup is about 770 m thick in the northwest vicinity of the map, i.e. the vicinity of Hanover and thickens significantly southward to about 1400 m in the Graaff-Reinet area (Cole *et al*., 2004: 1; GSSA, 1996). According to Rubidge *et al.* (quoted by Cole *et al.*, 2004: 1) the significant northward thinning of the Adelaide Subgroup is due to younging of the Ecca Group in this direction. The Adelaide subgroup conformably overlies the Ecca Group (Cole *et al.*, 2004: 1).

The Katberg Formation of the Tarkastad Subgroup conformably overlies the Adelaide Subgroup where the contact between the two subgroups is discerned by the Katberg Formation consisting of noticeably more sandstone and a distinctly redder mudstone (Cole *et al.*, 2004: 1). The contact between the Adelaide Subgroup and the Katberg Formation of the Tarkastad Subgroup is defined as the horizon above which sandstone is relatively common according to Johnson as quoted by Cole *et al.* (2004: 1).

Colours of the mudstones are mostly greenish grey, grey to dark-grey, olive grey and less commonly reddish (Cole *et al.* 2004:1). Thickness of individual mudstone units has been noted to be as much as 40 m. In some places colours of these units alternate between red and greyish green (Cole *et al.*, 2004: 1).

The calcareous nodules that were commonly found were classified as pedogenic calcretes: Colour mottling, slickensided surfaces signifying multiple cycles of wetting and drying; occurrence of rizocretions indicating pedogenic modification of the original mud according to Smith (quoted by Cole *et al.* 2004: 3) and rarely found desert-rose clusters composed of quartz pseudomorphs after gypsum are all evidence of a warm paleoclimate with seasonal rainfall (Cole *et al*., 2004: 2).

Siltstone beds are up to 4 m thick and have varying shades of grey colour; from light to dark grey, greenish grey, dark greenish grey, yellowish grey and light olive grey (Cole *et al.,* 2004: 3). The siltstone beds are structure less, parallel laminated or ripple cross-laminated (Cole *et al.,* 2004: 3). Basal contacts of the siltstone with mudstone are mostly sharp and planar, where the siltstones fine upwards especially in their uppermost parts (Cole *et al.,* 2004: 3).

Sandstone units of the Adelaide subgroup are lenticular and tabular (Cole *et al.,* 2004: 3). They extend laterally for distances up to 20 km and according to Johnson, Dukas and Tordiffe (quoted by Cole *et al*., 2004: 3) reach thicknesses of up to 20 m. The colour of the buff weathered sandstone range from light grey to greenish grey. The texture of it varies from fine to very fine grained, with a medium grained texture noted in some places (Cole *et al.,* 2004 after Dukas (1978). The structure of the sandstone may be massive, display horizontal to low angle planar bedding, trough cross bedding, ripple cross-lamination and sometimes planar cross-lamination (Cole *et al.,* 2004: 5). Thicker and multi-storey sandstone units typically display upward fining cycles. The contacts between the basal sandstone and mudrocks are undulatory and erosional (Cole *et al.,* 2004: 5). The occurring mudstone-pebble conglomerates are normally a few centimetres thick, but attain a thickness of 2 m in some places. They usually occur in the basal parts of the sandstone bodies and also on scour or erosion surfaces within the sandstone bodies (Cole *et al.,* 2004: 5).

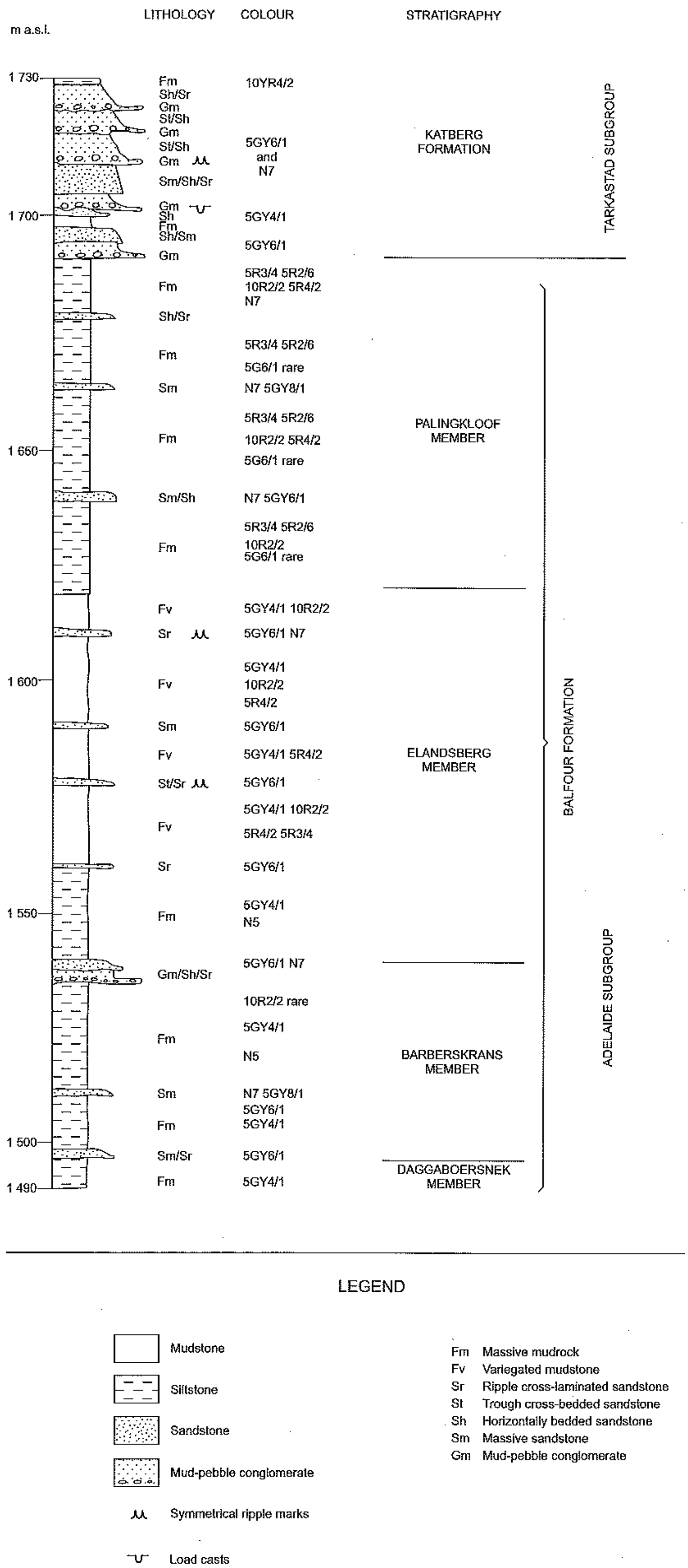


Figure 2-2: A vertical profile measured on a scarp slope of Bakenskop, Zuurplaats 35 farm representative of the Geology found in Middelburg Study area (after Cole *et al.*, 2004)

A petrographic study of the Adelaide sandstones found that rock fragments of felsite and micas are in abundance and less commonly found were granite-, chert-, porphyritic igneous- and schist-grains. These fragments total more than 40% of the rock (Cole *et al.*, 2004: 5). Mineral and physical composition of the sandstones show feldspar (plagioclase > K-feldspar) 27%, quartz 16.5%, matrix 11%, cement (predominantly calcite) 2% and accessory (heavy minerals included) minerals 2.5% (Cole *et al.*, 2004: 5).

Depositional environment

Various hypotheses have been proposed by a number of authors for the formation/deposition/origin of the Adelaide Subgroup. The most accepted hypothesis or theory is one that is shared by Cole *et al.* (2004: 10).

Evidence such as colour mottling and desert roses indicate that the Adelaide Subgroup accumulated in a terrestrial environment under warm climatic conditions (Cole *et al.*, 2004: 8 after Smith, 1990). Cole *et al.* (2004) also stated that: “Suspension settling of mud in floodplain and lacustrine environments produced the abundant mudstone, whereas the sandstones, which commonly fine upwards, represent meandering-river deposits” (Cole et al, 2004 after Johnson, 1976; Dukas, 1978; Tordiffe, 1978; Visser & Dukas, 1979; Visser & Loock, 1979; Jordaan, 1990).

There are visible traces of sedimentary cyclicity within the Adelaide Subgroup from sandstone packages and overlying mudrock showing upward-fining megacycles of up to 500 m in thickness (Tordiffe, 1978 quoted by Cole *et al*., 2004: 10).

A mechanism that has been suggested for the formation of the sandstone packages in the Adelaide subgroup is differential subsidence rates between adjacent areas of the basin. Cole *et al.* (2004:10) postulated that: “Low rates of subsidence cause reworking of flood-basin sediments and increased continuity of sandstone bodies; high rates result in the accumulation of thick flood-basin mud units and produce discontinuous sandstone bodies.” This is similar to the character of the Adelaide subgroup in the Middelburg Geological map area. The only extensive sandstone package in the Middelburg 3124 Geologic map area is the Barberskrans member.

Tarkastad Subgroup

Sedimentary formations that outcrop to north of Middelburg belong to the Tarkastad Subgroup while the Adelaide Subgroup sedimentary formations outcrop to the south of the town.

The Early Triassic aged Tarkastad Subgroup overlies the Adelaide Subgroup and the contact between the two subgroups is conformable (Cole *et al.*, 2004:10). The Tarkastad Subgroup consists of the lower sandstone-rich Katberg Formation and the upper mudstone-rich Burgersdorp Formation (Cole *et al.,* 2004:10). Within the study area the mudstone dominated Burgersdorp Formation has been weathered away and is no longer present. Sandstone prevails within the Tarkastad Subgroup and the subgroup is characterised by a distinctly redder mudstone that is present above the contact between the two subgroups (Cole *et al.,* 2004:10). The boundary between the two formations within the Tarkastad Subgroup is transitional over a thickness of 100 m. Above this transitional boundary between the two formations, mudstone is visibly more abundant signifying the Burgersdorp Formation (Cole *et al.,* 2004:10).

Katberg Formation

The Katberg Formation has a thickness of 260 m at Carlton Heights, 20 km north of Middelburg (Cole *et al*., 2004: 10). It is comprised of buff weathered, greenish-grey and light-grey tabular and minor ribbon-shaped tabular sandstone bodies that have a maximum thickness of 30 m (Cole *et al.*, 2004: 10). These sandstone bodies are interbedded with units of red, greyish-red and less frequently greenish-grey and dark greenish-grey mudstone. The mudstone units themselves contain thin (less than 2 m) greenish-grey and light-grey sandstone, and grey or greenish-grey siltstone beds (Cole *et al.*, 2004: 10).

The sandstone bodies in the Katberg formation are multi-storey and individual storeys display upward-fining sequences grading from fine to medium grained at the base to very fine grained at the top, with ranging thickness from 1 to 7 m (Cole *et al*., 2004: 11). The basal contacts between the sandstone bodies and the underlying mudstone are undulatory and erosional. The basal part of the typical sandstone body consists of a mudstone-pebble conglomerate up to 1 m thick (Cole *et al.,* 2004:11). The basal part of the Katberg formation itself consists of thick, cliff forming multi-storey sheet sandstone, especially prevalent along the scarp slopes of the Sneeuberge (Cole *et al.*, 2004:11). The boundary between the two subgroups of the Beaufort Group is transitional in places over a few tens of metres, with the lower Katberg Formation comprised of upward-thickening sandstone sheets north of Middelburg town in the vicinity of Noupoort (Cole *et al*., 2004). The sandstone is moderately sorted and predominantly massive or otherwise horizontally bedded, trough cross-bedded and in rare cases planar cross-bedded and ripple cross-laminated (Cole *et al*., 2004: 11 after Johnson 1976; 1984).

Mudstone of the Katberg formation is massive, contains some calcareous nodules as well as isolated trace fossils of burrows. The mainly reddish colour of the mudstone is evidence of oxidising depositional conditions and the calcareous nodules are most likely examples of pedogenic calcrete.

The Petrographic analysis of the composition of sandstone of the Lootsberg pass is: 30% quartz, 21% feldspar, 34,5% lithic fragments, 12,5% matrix, 1% accessory minerals and 1% secondary cement. Accoring to Johnson as quoted by Cole *et al.* (2004: 11), this composition makes it lithofeldspathic sandstone.

Burgersdorp Formation

There is an almost complete absence of the Burgersdorp Formation overlying the Katberg formation in the study area, except for some “koppies” or mesas in the area. Outside of the study area the Burgersdorp Formation is known to be approximately 450 m thick near Steynsburg (Cole *et al*, 2004:10). According to Catuneanu *et al*. (1998) and Hancox (1998) as quoted by Cole *et al*. (2004:12), the upper contact between the Burgersdorp Formation and the Molteno Formation is disconformable. The boundary above which the Molteno Formation is discerned from the Burgersdorp Formation is distinguished by an almost complete absence of red mudstone and calcareous concretions as well as the coarseness of the sandstone. Within the Molteno Formation there is a scattered occurrence of coal seams and carbonaceous shale as well as a presence of exotic pebbles, cobbles, boulders and fossilised plants instead of vertebrate fossils (Cole *et al*., 2004: 12 after Johnson, 1976).

The Burgersdorp Formation is characterised by abundant red, greenish-red and, less commonly, greenish-grey and grey mudstone. The mudstones also consist of sandstone bodies up to 10 m in thickness, which increase in abundance towards the upper and lower contacts of the formation (Cole *et al*., 2004: 12). According to Cole *et al*. (2004) after Groenewald (1996) there is also a sandstone rich unit in the upper part of the Burgersdorp Formation. The general sandstone-mudstone ratio of the formation is approximately 1:3.3 but varies and increases to around 1:0.8 at Steynsburg. Mudstone units themselves are up to 30 m thick, are massive, and contain minor worm burrows, calcareous concretions as well as desiccation cracks (Groenewald, 1996 as quoted by Cole *et. al.*, 2004: 12). Siltstone beds with greenish-grey, medium-grey and medium light-grey colouring are up to 0.5 m thick are present within the formation. They have sharp planar bases and gradational or sharp tops (Cole *et al*., 2004: 12).

Depositional Environment and provenance of the Tarkastad Subgroup

The depositional environment of the Tarkastad Subgroup is that of an oxidised terrestrial paleo-environment with sandy sedimentation in fluvial channels, muddy sedimentation in overbank floodplains and lacustrines. The paleo-environmental nature of this subgroup is supported by the following characteristics:

- The presence of pedogenic calcrete and red mudstone,
- The presence of sub-aerial desiccation cracks, fining upward immature sandstones with erosional bases and mudstone-pebble conglomerate, and
- Unimodal palaeocurrent directions (Cole *et al*., 2004: 13 after Johnson 1976, Hiller and Stavrakis, 1984, Groenewald, 1996).

From these and other observations it was deduced that the climate was arid and only seasonal rainfall occurred, with extended droughts. The palaeo-environment became more and more arid across the boundary between the Permian-Triassic time periods, below the Katberg Formation. This was gathered from the wet hydromorphic to dry flood-plain palaeosols, which are the result of rising and falling groundwater tables (Smith, 1995 quoted by Cole *et al.*, 2004: 13). According to the postulation of Hiller and Stavrakis (1984) as quoted by Cole *et al.* (2004: 13), the Cape Fold Belt uplift created a rain shadow, which was responsible for the increasing aridity. This uplift, corresponding to the orogenic paroxysm dated at 247+-3 Ma by Halbich *et al.* (1983), is presumed to be responsible for a rapid influx of sand during deposition of the Katberg Formation (Cole *et al*., 2004: 14). The subsequent removal of material by erosion and weathering resulted in a decrease in the slopes of the source area, and in turn caused the distal flood plain and lacustrine muddy facies to shift back toward the source area i.e. the Burgersdorp Formation (Cole *et al.*, 2004: 14 after Hiller and Stavrakis, 1984).

Table 2-1: Stratigraphy of the Karoo Supergroup in the 3124 Middelburg geology map (Cole *et al.*, 2004) also representative of the study area stratigraphy

Ma	AGE	GROUP	SUB-GROUP	FORMATION	LITHOLOGY AND CORRELATION	BIOSTRATIGRAPHIC ASSEMBLAGE ZONE
225	LATE TRIASSIC			Molteno	Fine- to coarse-grained sandstone and less abundant mudrock	
230						
235	MIDDLE TRIASSIC					
240						
	EARLY	BEAUFORT	TARKA-STAD	Burgersdorp	Red mudstone and subordinate fine-grained sandstone	*Cynognathus*
245	TRIASSIC			Katberg	Fine- to medium-grained sandstone and subordinate red and greenish-grey mudstone	*Lystrosaurus*
250	LATE PERMIAN		ADELAIDE	Balfour*	Grey, greenish-grey and subordinate red mudstone and fine-grained sandstone. Red mudstone in *Lystrosaurus* zone correlates with Palingkloof Member. Discontinuous sandstone package in upper part of *Dicynodon* zone correlates with Barberskrans Member.	*Dicynodon* *Cistecephalus*
				Teekloof* Abrahams-kraal*	As above. Lenticular package west of Hanover in *Pristerognathus* zone correlates with Poortjie Member (Teekloof Formation).	*Tropidostoma* *Pristerognathus*
255						

*Not distinguished on map

2.1.3 Cenozoic Deposits

2.1.3.1 Alluvium

Alluvium can generally be discerned from the other types of geological units in the study area as consists of unconsolidated sediments. The sediments in alluvium can range in diameter and normally consists of particles of gravel, sand, silt and even clay. The term 'unconsolidated' implies that the particles are not bound or hardened by mineral cement or other mechanisms such as pressure or thermal alteration of the grains (Freeze & Cherry, 1979: 147).

Alluvium can also further be typed as a fluvial deposit. Fluvial deposits are rock- and mineral-clasts or grains that have been lain down by the physical flow processes found in river channels or flood plains (Freeze & Cherry, 1979: 147). These deposits are also known as alluvial deposits.

Alluvial deposits cover an extensive part of the study area and create the main aquifers that Middelburg town and its farmers have depended for on many years. The alluvium is at its thickest in the valleys surrounded by high mountains. Alluvium in the study area is mainly associated with valleys of the local rivers draining the catchments. Where alluvium occurs in the valleys of mountainous terrain the depth of the alluvium can easily exceed 15 m.

The valley-fill alluvium found in the study area are generally made up of cyclic units of coarse-grained, reddish sand with scattered pebbles, grading upward into clay (Cole *et al*., 2004: 29). The colour of the clay units, particularly in high lying valleys close to the escarpment, is dark-brown to black created by the very rich organic material it contains (Cole *et al*., 2004: 29). Colours of clay units in less elevated valleys are more distinctly reddish to yellowish (Cole *et al*., 2004: 29).

The alluvial deposits found on the pediplain are primarily associated with well-established drainage systems and are mainly comprised of medium- to fine-grained sand (Cole *et al*., 2004: 29). These sandy deposits have a pale-yellow to orange colour and clay units are commonly absent within them (Cole *et al.*, 2004:29). Pebbles of up to 30 mm in diameter are found with the coarser grained sand. Calcrete is also quite common in the upper one to one and a half metres of the coarse-grained pediment alluvium profiles conducted by Cole *et al.* (2004: 29).

Valley alluvium is believed to have been formed from cut-and-fill processes and was deposited by steep, swiftly flowing mountain streams. Alluvium in the pediment areas were deposited by sheet wash processes (Cole *et al.*, 2004:29).

Warmer and humid climatic conditions during the Holocene followed the cooler, drier Pleistocene conditions, causing deep weathering of the bedrock (Partridge, 1993 quoted by Cole *et al.*, 2004: 30). According to Bousman *et al.* (1988) products from the former mentioned chemical processes stayed behind as alluvial valley deposits (Cole *et al.*, 2004:

30). The sandy alluvium found on the pediplains that border closer proximity valleys of larger rivers of South-Africa, i.e. the Sundays, Orange and Fish Rivers are quite possibly older than the cut-and-fill valley deposits and could date back to Early Pleistocene or Pliocene (De Wit, 1993 quoted by Cole *et al.*, 2004: 30).

2.1.3.2 Calcrete

Calcrete forms part of the type of geological formation generally known as pedocretes. According to Woodford *et al*. (2002: 167) pedocretes are soils that have to some extent been cemented or replaced by carbonates (calcrete), iron oxides (ferricrete, plinthite or laterite), silica (silcrete), phosphate (phoscrete), manganese-oxides (manganocrete), gypsum (gypcrete) or magnesite (magnesicrete). Two basic origins have been hypothesized for calcrete, namely:

(1) Groundwater. Groundwater type carbonate is said to be precipitated above a fluctuating, shallow water-table or by lateral seepage of the groundwater (Woodford *et al.*, 2002: 167).

(2) Pedogenic. In pedogenic calcrete, carbonate is transported down through the soil by infiltrating rainwater (Woodford *et al.,* 2002: 167).

The carbonate transported during this process may have soil as its source or it may be transported on dust particles or in the rain itself (Woodford *et al.,* 2002: 168). The formation of calcrete can either be due to the aridity of a region or as a weathering product of dolerite. According to Woodford *et al.* (2002: 168), the calcrete in the Middelburg vicinity is geographically bound by the Middelburg dolerite mega-ring complex.

Looking at calcrete in the study area from the geological map of Middelburg 3124 and according to Cole *et al.* (2004: 31), calcrete commonly occurs on the pediplains and is associated with alluvium where the alluvium consists of medium to coarse-grained sand and is more than one metre in thickness (see 1.3.1). Calcrete found on the pediplain varies from calcified soil to honeycomb calcrete (Cole *et al*., 2004: 30 after Netterberg, 1980). Composition of the calcrete in the Middelburg map area is comprised of calcified soil that is cemented by $CaCO_3$ into a stable and well bound sand or sandy gravel deposit (Cole *et al,.* 2004: 31). Scattered calcrete nodules are present in the upper one to one and a half metres of soil profiles conducted by Cole *et al.* (2004). In places where calcrete nodules and fine-grained calcareous particles are cemented together, calcified soil in some places grade into honeycomb calcrete, creating a hard calcrete layer, that is in most places less than 0.3 m thick (Cole *et al.,* 2004: 31). Another type of calcrete, powder calcrete, is commonly found near natural springs (Netterberg, 1980 quoted by Cole *et al.*, 2004: 31).

Cole *et al*. (2004: 31) states that formation of calcrete on the pediplains of the Middelburg geological map (Tordiffe *et al.*, 1983) area is due to a fluctuating water table under the influence of a semi-arid climate, with rainfall of 550 mm or less. Groundwater continually evaporates through the porous surface alluvium leaving a $CaCO_3$ precipitate (Cole *et al.*, 2004: 31). Calcium in the calcrete of the study area presumably originates from weathered plagioclase in the nearby dolerite (Cole *et al*., 2004: 31).

2.1.4 Intrusive Rocks

2.1.4.1 Dolerite

From a South African perspective, the early stages (190 – 160 Ma) of the break-up of Gondwanaland was accompanied by a period of intense magmatic activity during which mid-Jurassic aged basalt extruded onto the Karoo sediments (Woodford *et al.*, 2002: 12). The magmatic activity took place over the whole southern African sub-continent and given an estimated volume of 10 million km^3 that was extruded, it is of the largest flood basalt outpourings in the history of the world. The magmatic activity is widely accepted to have been the result of large mantle plumes driven by convection cells within the mantle. This caused the upwelling of unusually hot material from the base of the lithosphere (Woodford *et al.*, 2002: 12). Storey and Kyle (1997) as noted by Woodford *et al*. (2002:12) proposed that the mantle plume responsible for the magmatic activity was situated just off the eastern coast of South Africa.

The magma responsible for the volcanism and flood basalt extrusion was transported through the crust of the earth by an interconnected network of dykes (vertical linear intrusive structures), sills (horizontal intrusive structures) and complex saucer shaped ring- and sill-structures. These structures intruded into sub-vertical fractures, lateral contacts between sedimentary formations and forced their way through the crust driven by magma pressure. According to Johnson *et al.* (2006), flood basalts are formed by fissure eruptions - eruptions from dykes - and the dyke and sill network may be interpreted as the sub-volcanic plumbing system of the flood basalts that formed the Drakensberg lavas.

The town of Middelburg, as it is aptly named, is recognised as being in the centre of the Main Karoo Basin, at least when it comes to defining the Western and Eastern Karoo (Chevallier and Woodford, 2001; Cole et al., 2004). According to Cole *et al.* (2004) the dykes in the Middelburg area follow two major structural trends identified by Chevallier and Woodford (2001) for the Western Karoo. These trends are E-W and NNW-SSE (Chevallier and Woodford, 2002: 50).

The E-W trend is characterised by extensive continuous dykes that can be followed for up to 500 km in the Western Karoo. Two such E-W dykes can at length be followed west of Middelburg between Latitudes 31°30' and 31°50' S (Cole *et al.,* 2004: 32). The primary structure they intruded into was along a major right lateral E-W dislocation zone (Woodford *et al.*, 2002: 50 after Woodford and Chevallier, 2001). E-W dykes are well developed in the western Karoo, but they progressively disappear eastwards towards Middelburg (Cole *et al.*, 2004). The type of emplacement mode for E-W dykes is characterised by the *En-échelon* mode of emplacement (Woodford *et al*., 2002: 53).

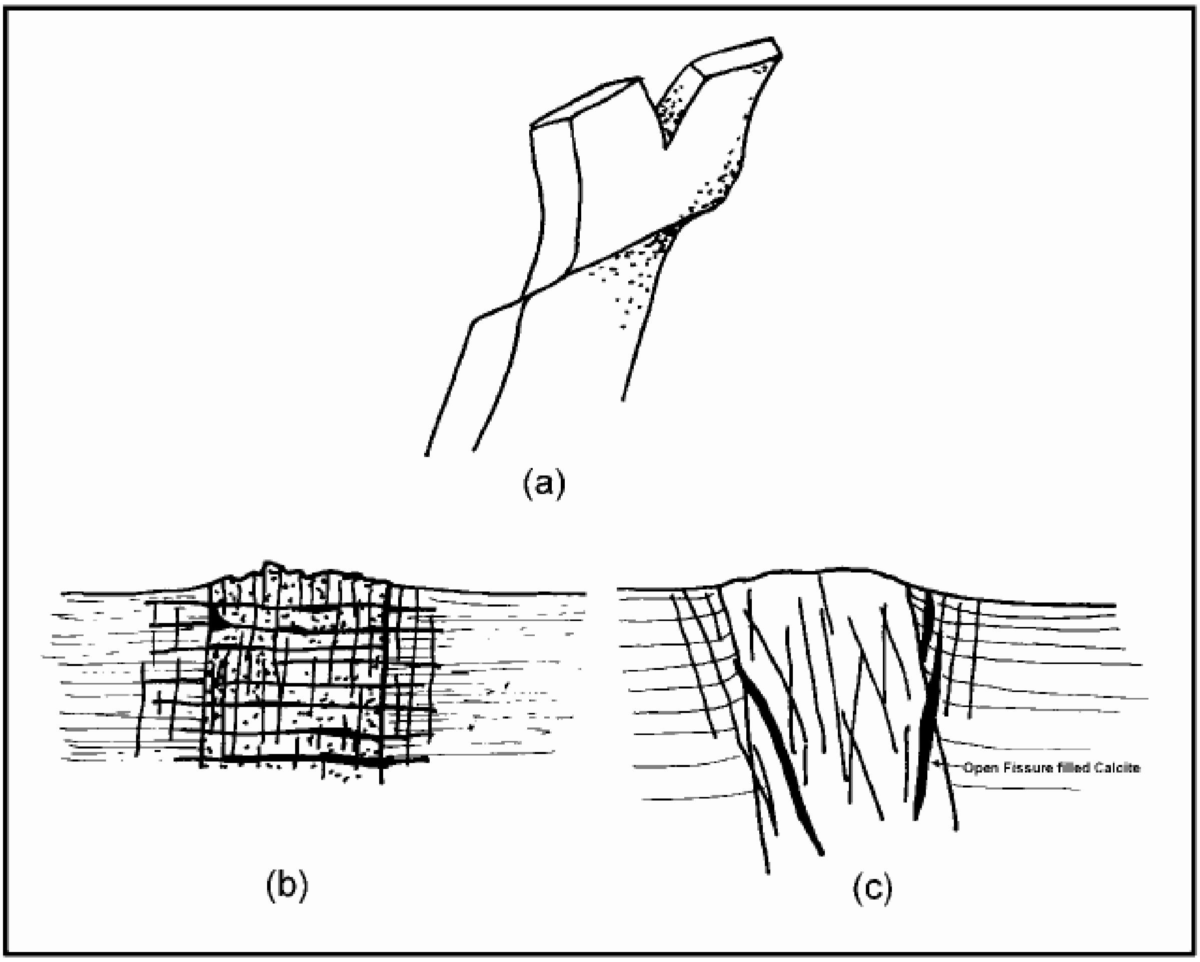


Figure 2-3: (a) En-echelon dyke emplacement mode; (b) dyke with vertical tectonic and horizontal thermal jointing and (c) Fissures relating to tectonic reactivation and jointing from weathering or erosional unloading (Woodford *et al.*, 2002: 53)

The NNW trend is an especially prominent tectonic direction in the study area and on a regional level represents evenly spaced from east to west extensive NNW structures. With emphasis on the study area, the Middelburg dyke system is especially well developed (Woodford *et al.*, 2002: 53). The Dunblane dyke intrusion is easily visible from simple satellite imagery, is 150 km long, approximately 100 m wide and runs through Middelburg town (Cole *et al.,* 2004). The Dunblane dyke crosses the entire 3124 Geological map area and continues at least 50 km south of 32° latitude. It must be noted here that different thicknesses of the Dunblane dyke are proposed by different references. Cole *et al.* (2004) proposed a thickness of a 100 m as stated above, while Vandoolaeghe (1979) who conducted an in-depth geohydrological investigation in the area proposed a constant thickness of approximately 20 m as will be seen later in this chapter. Based on what has been observed in the study area a thickness of 20 to 30 m is accepted and the Dunblane dyke thickness of 100 m proposed by Cole *et al.* (2004) is regarded as being representative of the Dunblane dyke further south on the 3124 Geological map.

It has been observed that many dykes do not follow the regional trends in the study area, but rather form short or jagged and curved smaller features along, or parallel to, dolerite ring structures. These features have been interpreted as feeder dykes to the rings (Cole *et al.,* 2004).

In the study area, dyke widths can vary from 0.5 to 100 m (Cole *et al*., 2004). Their attitude is generally sub-vertical with a dip angle rarely below 70°, although the attitude of dykes often changes with depth. The former has been postulated as being a result of either from vertical offsetting, which was caused by vertical en-echelon segmentation or it could have been the result of dykes interconnecting in between sedimentary layers and formations. (Woodford *et al.*, 2002: 53).

Dolerite Ring and Sill complexes

The Middelburg study area is riddled with dolerite dykes, sills and saucer shaped complex ring structures. The sills and ring structures, due to their more resistive nature to weathering, control the geomorphology of the study area to a great extent, forming topographic highs where dolerite intrusions are present at surface. It therefore controls the drainage of the catchments. The study area also falls within one of the five mega-ring basins, in this case the Middelburg mega ring structure (Figure 2-4) that is approximately 170 km in diameter (Woodford *et al*. 2002: 83).

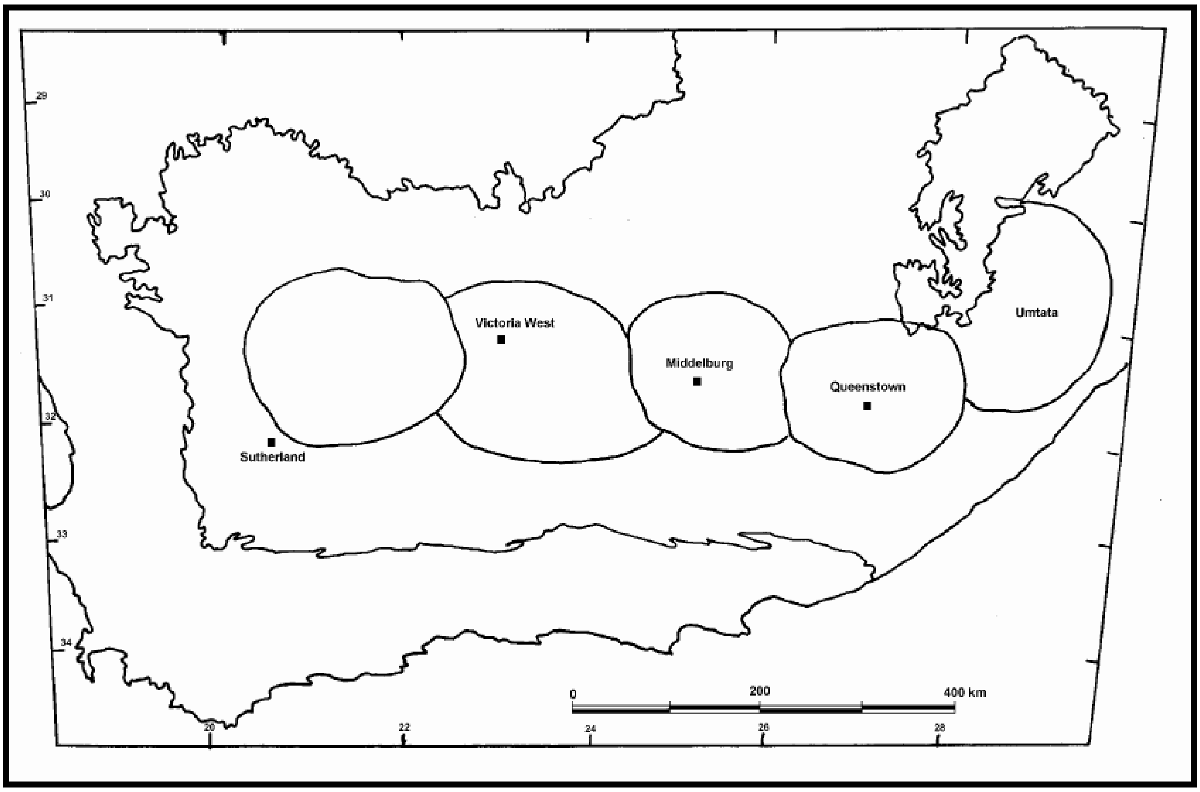


Figure 2-4: The 5 major ring and sill complex systems (mega basins) found in the western to eastern Karoo (Woodford *et al.*, 2002: 83)

Dolerite ring structures are markedly more abundant than normal sills in the study area. The dolerite ring structures display a sub-circular saucer-like shape, where the rims are exposed as topographical highs. Woodford *et al.* (2002: 80) stated that at a regional scale the sill structures display as "large coalescing circular, oval or kidney-shaped structural units". Each unit in itself may contain several sub-units smaller in size that are in turn composed of even smaller sub-units, creating the "ring within a ring" effect (Woodford *et al.*, 2002: 80). The rings and sills may also display important vertical stacking (Woodford *et al.*, 2002). Chevallier and Woodford (1999) in Woodford *et al.* (2002: 86) identified four distinctive morpho-tectonic units that a typical dolerite ring and sill complex is made of:

a) A **horizontal flat lying inner sill** that forms the bottom of the saucer, commonly 30- to 60- to 100 m thick and confirmed by extensive evidence from boreholes. These sills can however be thicker.
b) A **flat lying outer sill** with markedly extensive fracturing and jointing. These outer sills are the thick sills which intruded into the base of the Karoo basin and can extend for hundreds of kilometres. The outer sill extends from the ring and forms the outer rim of the saucer. It intruded at a higher altitude than the inner sill. The thickness of the outer sill, some 50-100 m, does not seem to differ much from the thickness of the inner sill.

c) A peripheral **inclined sheet** dipping at an angle of up to 60° towards the centre of the ring or basin, leaving a topographic ring after erosion. Vandoolaeghe found dips of the inclined sheet to be between 3° and 70° in the Middelburg area. The inclined sheet has a thickness of between 20 and 40 m, but can be more than that of the sills.

d) **Feeder dykes** associated with the ring and sill complexes are common and branch into or out of the ring and sill complexes, or in some cases cut through the complexes.

According to Cole *et al*. (2004) inner sills are rarely exposed in the 1:250 000 Middelburg geological map area. Feeder dykes may be seen to merge with sill and ring complexes in the study area. The relationship between dykes and sill/ ring complexes is very intricate, as dykes feeding into the inclined sheet for instance control the shape of the ring and in places result in a jagged rim (Cole *et al.,* 2004; Woodford *et al*., 2002).

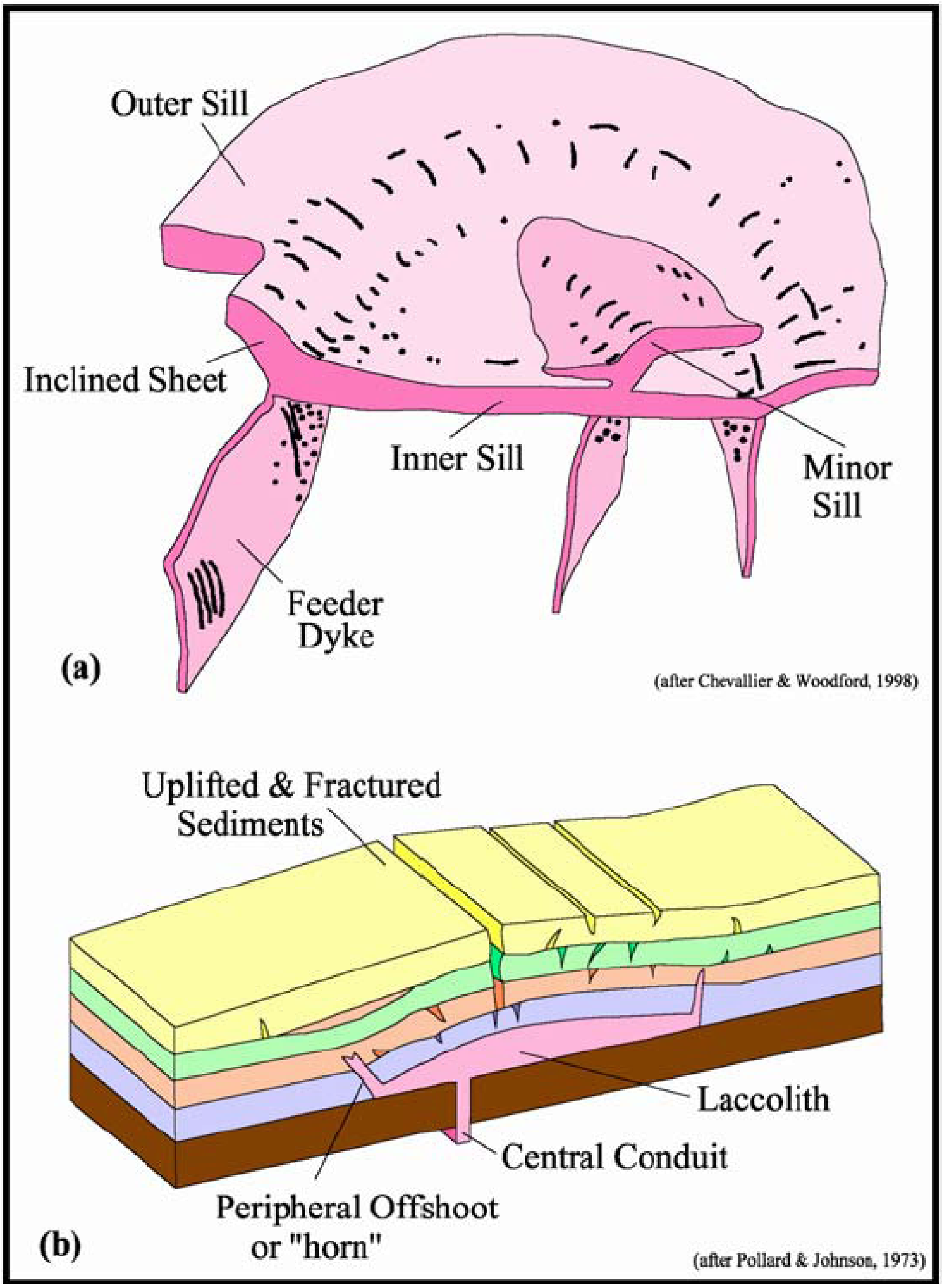


Figure 2-5: The two proposed emplacement modes for dolerite ring/sill systems: (a) Ring dyke model after Chevallier and Woodford (1999) and (b) the laccolith model of Burger *et al.* (1981) [in Woodford *et al.*, 2002]

The emplacement of dolerite sill- and ring-structures shows regional variation in the Karoo basin and different mechanisms of the emplacement of these dolerite sills have been proposed by different authors. The most recent mechanism of emplacement based on extensive geomorphological analysis, geological observation and evidence from drilling is proposed by Chevallier and Woodford (1999) in Woodford *et al*. (2002: 89). They propose a feeding system of magma along the inclined sheet or ring itself, using the coalescing ring-dyke network. In other words, ring dykes feed inclined sheets which in turn feed the flat-lying sheet in the centre (Woodford *et al.,* 2002; Cole *et al*., 2004).

Within the Eastern Cape Province dykes often cut through or transgress rings or sills and are clearly of a younger age than the rings or sills (Woodford *et al*., 2002).

The petrographic analysis of Karoo dolerites result in a variety of compositions. The types include; Olivine dolerite, dolerite without olivine, leucocratic dolerite, orthopyroxene dolerite and picrite. Dolerite intrusions in the Karoo generally have a fine grained porphyritic and melanocratic (60-90% dark minerals) composition on the chill zones of an intrusion (Woodford *et al.*, 2002: 57). The central portion of the dolerite has a medium- to coarse-grained texture and usually has a mesocratic (30-60% dark minerals) and sometimes leucocratic composition (Woodford *et al.*, 2002: 57). Minerals in general in dolerite are predominantly pyroxene and plagioclase feldspar, clinopyroxene and plagioclase phenocrysts in cases of low magnesium or MgO (Johnson et al., 2009: 512; Cairncross, 2004: 250). According to Cole *et al.* (2004: 33), a leucocratic (0-30% dark minerals) variety of dolerite occurs in the Middelburg area as mapped for the 3124 Geological map. As described from a sill in the area, leucocratic dolerite has characteristic intergrowths of quartz and plagioclase, which become more common towards the top of the sill where quartz crystals are also more abundant (Cole et al., 2004: 34 after Tordiffe, 1978). A picrite sill ±30 m thick was identified 14 km north of Middelburg by Walker and Poldervaart (1942) as referred to by Cole *et al*. (2004: 34). The rock is comprised of more than 50% magnesium olivine (Fa_{18}) crystals in a matrix of plagioclase. Other minerals within the rock include augite and subordinate orthopyroxene.

Dolerite intrusions resulted in contact metamorphism with the adjacent country rock. In this case the country rock was Karoo Supergroup strata, where the mudstone was more affected than the sandstone (Cole *et al*., 2004: 34). At locations of dipping dyke intrusions, localised upwarping of the host rock is often visible (Woodford *et al*., 2002: 54). This is commonly the result of supergene formation of clays near surface, with a high expansion coefficient causing “swelling” of the rock mass (Woodford *et al*., 2002: 54).

In almost all cases one can observe marked chilling and the baked zone of the country rock adjacent to where dolerite magma has been injected. The baked zone shows the effects of contact metamorphism: Argillites are altered to hornfels or lydianite and areanaceous units are recrystallised to quartzite (Woodford *et al*., 2002). According to Enslin and Van Wyk in

Woodford *et al.* (2002) the jointed contact zone is less than 30 cm wide irrespective of dyke thickness.

Fracturing associated with dolerite dykes

The country rock where a dyke is emplaced is often fractured during or after the emplacement. Woodford *et a*l. (2002: 54) observed the following three types of fracturing that commonly occur in the case of dykes and their intrusion:

(1) Fractures within the country rock form a set of master joints parallel to the strike over a distance roughly similar to the thickness of the dyke (5-15 m).

(2) Dolerite dykes are affected by columnar- and thermal-jointing perpendicular to their margins.

(3) Thermal joints extend into the host rock over a distance that does not exceed 0.3 to 0.5 m from the contact.

Fracturing associated with dolerite sills and rings

Chevallier *et al*. (2001) in Woodford *et al.* (2002) also identified three major fracturing types associated with dolerite sill- and ring-complexes:

(1) Vertical columnar jointing; well developed within the flat lying sill.
(2) Fractures parallel to the strike of the intrusion within the inclined sheet. The inclined sheet is often the most fractured part of the complex.
(3) Well developed, sub-horizontal or oblique open fractures develop in curved portions of the sill. These fractures are often filled with calcite in the western Karoo. Vandooleaghe (1980) made the same observations in the eastern Karoo (see Figure 2-6).

In addition, conjugated vertical jointing is commonly observed in the country rock above the sill or inclined sheet.

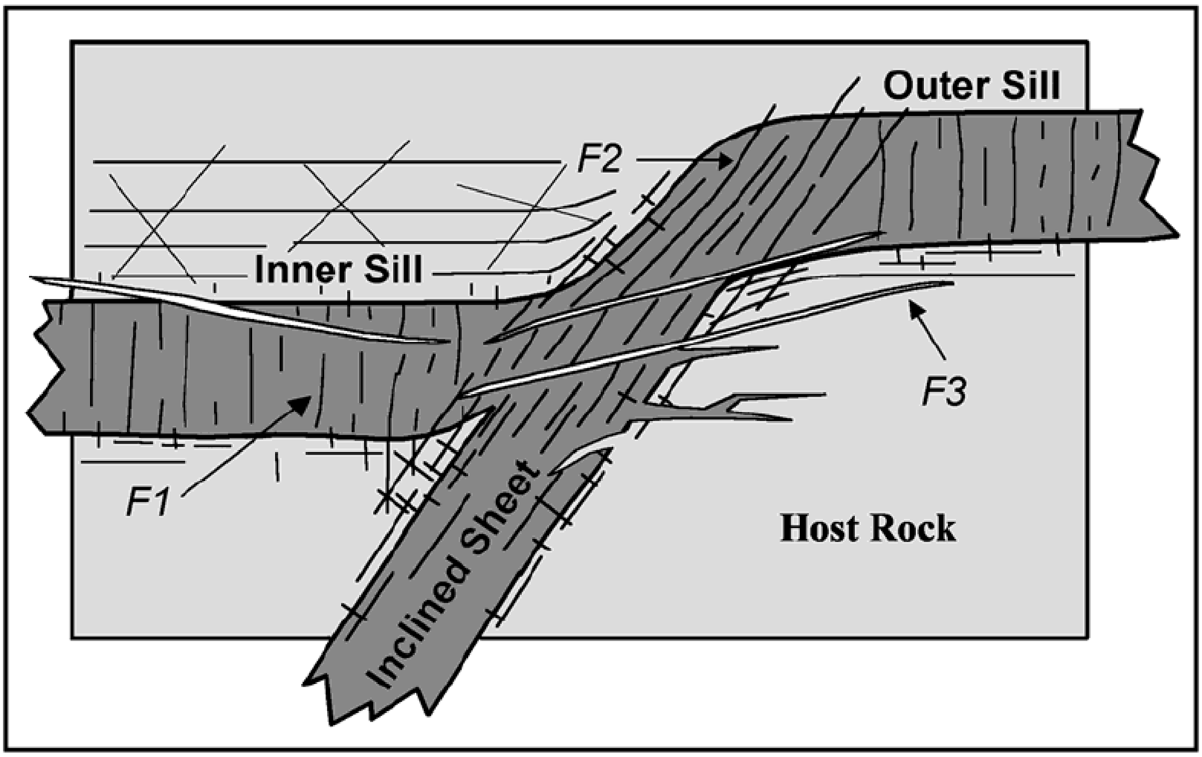


Figure 2-6: The fracture types associated with ring- and sill-complexes (after Chevallier *et al.*, 2001 in Woodford *et al.*, 2002: 89)

Petrography and dyke weathering

Variable cooling of dykes after intrusion also has an apparent effect on the way that they weather according to Woodford *et al*. (2002: 57). Dyke weathering processes may be grouped for thick dykes and thin dykes.

Thick dykes (>8 m) generally have a marked chill margin comprised of fine grained-porphyritic, melanocratic dolerite weathering to well-rounded, small, white-speckled boulders known as spheriodal weathering. The former mentioned zone normally has a width of no more than 0.5-1.5 m and displays well-developed thermal shrinkage joints. The dyke's central portion consists of medium- to coarse-grained mesocratic, occasionally leucocratic dolerite that weathers to produce a uniform gravelly material, exhibiting an exfoliation type pattern. Woodford et al. (2002) made no mention of sill weathering, but it is expected that sills should weather in the same manner as thick dykes.

Thin dykes (<3 m) are generally comprised of fine-grained, porphyritic and melanocratic dolerite. They tend to be more weather resistant than thicker dykes and in an outcrop display a uniform pattern of shrinkage joints. This type of dyke weathers to small rounded, white speckled boulders set in a finer angular groundmass.

2.1.5 Structural Geology

The formations and strata of the Karoo Supergroup sedimentary rocks are generally horizontal in the study area. According to the Explanation of the 3124 Geological map of Middelburg the strata are generally horizontal or have low dip angles, less than 5° (Cole *et al.*, 2002).

The upwarping of country rock near dolerite intrusions, as mentioned earlier, may result in larger dip angles such as Naudesberg Pass, where an angle of 10° was measured by Cole *et al.* (2004).

Also from the literature on the Geological map area of Middelburg 3124, an elongated centrocline was recognised in the central map area, deepening towards Lesotho and has resulted in low (1° to 3°), east-northeasterly regional dips down the axis of this centrocline in the central part of the map area (Cole et al.,2004: 35).

Faulting is not common in the study area, and from the most recently published Geological map (Tordiffe *et al.*, 1983) there are no faults in the study area. According to Cole et al. (2004) fault planes within the Geological map area are normally associated with dolerite dykes that present shear zones and slickensides along their contacts with the sedimentary rocks.

2.2 Hydrogeology

2.2.1 Karoo Supergroup aquifers

The Beaufort Group is the major group of formations within the Karoo Supergroup (Botha *et al*., 1998) and its hydrogeological character is similar to that of the Karoo Supergroup. For this reason the Beaufort Group's basic hydrogeology will be discussed in unison with that of the Karoo aquifers.

The Karoo Supergroup sequence of rocks are characterised as hard rocks. The origin and depositional environment of these rocks will show that they consist chiefly of fine-grained mudstones, siltstones and shales, with interbedded sandstones of which grain sizes may vary from fine to coarse (Woodford *et al.*, 2002; Botha *et al.*, 1998). The sedimentary rocks therefore originally had a high primary porosity, but this porosity was significantly reduced by cementation and compaction of the sediments (Botha *et al.,* 1998). The consequence is that the pores and micro-fractures found in the Karoo sedimentary rocks today are usually very small. An estimated general primary porosity for the Karoo Supergroup of rocks is 5% (Van Tonder *et al*., 2002). Expected hydraulic conductivities for the unfractured rock are less than 1 m/d (Van Tonder (*personal communication)*, 2009). The storage coefficient for the rocks is in the order of 1 x 10^{-3} (Van Tonder *et al.*, 2002).

The rocks however also have secondary porosity that developed after the rocks were formed. These voids were created from weathering, faulting, dissolution and in many cases fracturing caused by occurrences such as magma and dolerite intrusion.

Extensive studies of water supply in the Karoo, hydrogeological investigations and field evidence have revealed the fractured nature of the Karoo Supergroup and its associated hydrogeological properties. Aquifers found within the Karoo Supergroup are classed as fractured rock aquifers and compared to porous aquifers; these aquifers display a complex geometry and hydraulic function.

The campus of the University of the Free State, South Africa, has a groundwater and Karoo aquifer test site. Botha *et al.* (1998) conducted a detailed study of some Karoo aquifer formations at this test site. This campus test site is underlain by the Adelaide subgroup of the Beaufort group, the same subgroup found in the Middelburg study area. According to Botha *et al.* (1998) Karoo aquifers are multi-layered, multi-porous aquifers within which bedding parallel fractures are the dominant water bearing fractures. From the in-depth investigation they also found that there are two types of flow present in Karoo aquifers namely, bedding plane fracture flow and matrix (country rock) flow (in this case flow through the interconnected interstices or voids between cemented sedimentary particles of the sedimentary rock formation).

These bedding plane fractures act as the main conduits for water to boreholes intersecting them. They were also found to control the behaviour of the boreholes during abstraction (Botha *et al*., 1998: 87).

2.2.1.1 Theoretical model for Karoo fractured rock aquifers

The theoretical aquifer flow model that basically describes the Karoo fractured rock aquifers is the dual-porosity model, as first postulated by Barenblatt *et al.* in 1960 (Botha et al., 1998).

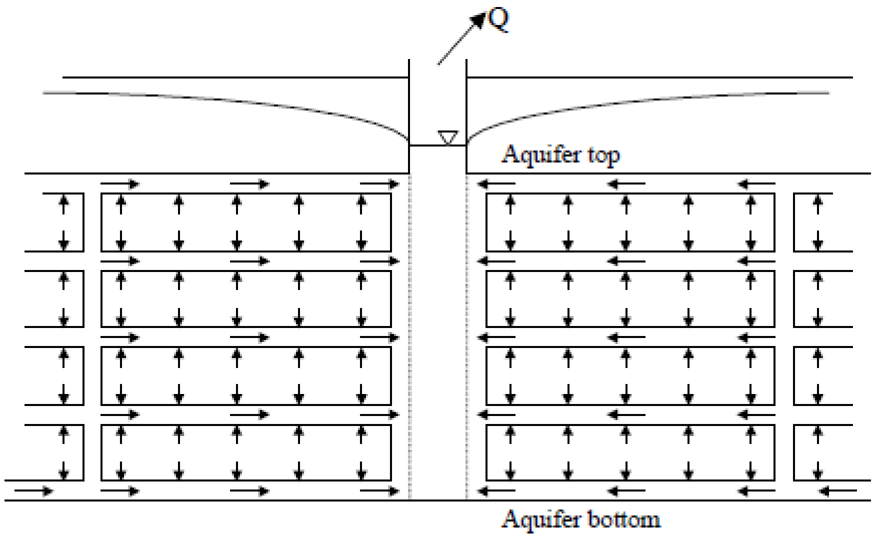


Figure 2-7: Groundwater flow to a borehole in an idealised dual porosity aquifer (after Van Tonder *et al.*, 2002: 2-10)

The double- or dual-porosity medium approach assumes a uniform distribution of matrix blocks and fissures throughout the aquifer. This model includes single-fractured models and multi-porosity/multi-permeability models. For Karoo aquifers the model was further developed by identifying the approach of Warren & Root (1963) where flow from the matrix block to the fissure occurs under steady state conditions. Moench (1984) as described by Woodford *et al.* (2002: 190) further refined the model by introducing the idea of a "thin skin of low-permeability material deposited on the surface of the blocks that serves to impede the free exchange of fluid between the blocks and the fracture". This so called 'fracture skin' delays flow from the matrix blocks to the fracture, causing a pressure response similar to that predicted under conditions of pseudo steady-state flow (Woodford *et al.*, 2002:190 after Moench; 1984). Moench argued that by reducing the gradient of the hydraulic head in the compressible matrix blocks, the fracture skin provided theoretical justification for the pseudo-steady state flow approximation used in the model of Warren and Root (Woodford *et al.,* 2002: 190).

Furthermore, Bourdet and Gringarten (1980) demonstrated that dual porosity behaviour of a fractured rock aquifer occurs only in a restricted part of the aquifer around the pumped borehole. Outside of this restricted area, i.e. for λ-values greater than 1.78 (λ-values obtained from equation of their curve-fitting method presented in fissure volume and block size determination paper, refer to Kruseman & de Ridder (2000) or Bourdet and Gringarten (1980) for full description of equation), the drawdown behaviour is similar to that of an equivalent porous medium (Kruseman & de Ridder, 2000: 253; Woodford *et al.,* 2002: 190).

During other investigations, Gringarten & Ramey (1974) developed a model for unsteady state-pressure distributions of a well penetrating a single horizontal fracture. Woodford *et al.* (2002) found during constant discharge tests conducted on 50 boreholes distributed across the Karoo that water-level responses were near 'textbook' examples of this model. Botha *et al.* (1998) however observed that at late time the water level started to deviate from the Gringarten & Ramey model during constant discharge rate tests. Botha *et al.* (1998) thought that causal factors for this phenomenon could either be an insufficient water supply from the rock matrix to the fracture or possible deformation of the fracture and/or aquifer. Woodford *et al.* (2002) argued that this deviation is due to the inability of the Gringarten and Ramey model to take variations in the vertical flow field into account; in this case variations in vertical flow from the rock matrix to the fracture.

In light of the above and observed at a larger radius of influence, the hypothesis put forward by Bourdet and Gringarten (1980) is probably the best approach for determining the behaviour of a borehole in the Karoo aquifers that is to be abstracted from for an extended period of time. It is also due to this late-time behaviour of the cone of depression, that the Cooper-Jacob approximation of the Theis equation was used for analysing boreholes drilled in fractured rock aquifers during this investigation (see Chapter 7).

2.2.1.2 Groundwater flow in Karoo fractured rock aquifers

Detailed geological assessments of Karoo formations that were conducted by Woodford *et al.* (2002), indicate two consequences for the behaviour of Karoo aquifers that are of great importance.

1) At regional scale, flow in Karoo formations very much resembles flow in a porous medium and as such, it must obey Darcy's Law (Q = KiA).
2) Formations within Karoo aquifers may contain large quantities of water, but the water in the formations cannot readily be released over such small areas, as the circumference of a borehole.

Van Tonder (2002) in Woodford *et al.* (2002: 180) describes the hydraulic dynamics that occur when the abstraction pump in a borehole in a typical Karoo aquifer is switched on as follows: The moment the pump is switched on the borehole will receive all its water from the fracture as the fracture has a high permeability compared to the very low permeability of the surrounding rock matrix. This will cause a drop in piezometric pressure within the fracture and consequently a pressure imbalance will result in the flux of water across the contact between the fracture and the matrix. The imbalance will cause a flux of water from the matrix to the fracture for as long as a pressure gradient exists between the rock matrix and the fracture, according to Darcy's law. This flux of water may be small, but if the fracture is continuous over a larger area, the volume of water from the flux may be considerable. From these accounts of hydraulic behaviour in stressed Karoo aquifers, matrix flow from the matrix to the fracture will be the predominant type of flow unless the fracture is very large both in aperture and areal extent.

The typical main stages of flow that have been identified during abstraction from a borehole in Karoo aquifers by van Tonder *et al.* (2002) are:

1) Water during the first few minutes of the pump's activation comes from storage in the borehole itself (well bore storage).
2) Thereafter water is supplied from the fracture(s) intersected by the borehole (linear flow).
3) As water is removed from the fracture the pressure difference that is created between the fracture and the rock matrix will cause a flux of water from the matrix to the fracture (bi-linear flow).
4) As the cone of depression and radius of influence grow larger, it approaches a circular shaped area as seen in planar view, and water is drained from the included matrix and fractures. The area influenced by abstraction is not simply the fracture

and its immediately surrounding rock-matrix, but a larger volume of rock matrix is also influenced and drained towards the fracture. At this point piezometric pressures between the fracture(s) and rock-matrix do not differ that much anymore, flow within the radius of influence displays a radial pattern and the system reaches a pseudo steady-state, similar to that found in porous flow aquifers (pseudo radial flow).

All the above flow stages or phases occur in the described order if the borehole is not over-abstracted and the fracture(s) dewatered. In the case of fracture dewatering or deformation, the average transmissivity obtained from the combined flow of the matrix and fracture is significantly reduced as the functioning transmissvity is now only that of the rock matrix, which is much lower than the average transmissivity gained from both the fracture and the matrix. Another important fact is that during fracture dewatering, the cohesive forces between water molecules are broken as the water in the matrix is not connected to water in the fracture, as there is no water in the fracture. A negative pressure gradient from cohesion is therefore lost and the only forces now draining water from the matrix to the fracture is gravity and possible outside matrix pressures.

2.2.1.3 Hydrogeological properties of the Beaufort Group

In the explanation of the Middelburg Geological map Cole *et al.* (2004: 37) the Beaufort Group is characterised as having a virtual absence of primary porosity and permeability, while their geometry is further complicated by changes in lateral facies. According to Cole *et al.* (2004: 37) frequent recharge to the Beaufort Group is critical for the lifespan of a borehole situated in the non-fractured, unweathered part of the formations. If the Beaufort Group is uninfluenced by alluvium or fracturing, but weathered to 20 or 30 m, borehole yields in the order of 0,5 to 1,0 ℓ/s can be expected if the aquifer is recharged frequently (Cole *et al*., 2004: 37). Weathering of the top part of Beaufort Group formations increases the aquifer’s yielding ability and where the upper part of the formation is weathered and the lower unweathered part of the formation is fractured, potentially high yielding aquifers develop. The dominant type of weathering found in the Beaufort Group in the study area is chemical weathering.

Katberg Formation

The predominantly outcropping hard rock in the study area is the Katberg Formation of which up to 90% is quartzitic sandstone. Both the effective primary porosity and permeability of the sandstone is much better than that of siltstone or mudstone and fractured sandstone aquifers are normally good aquifers. The Katberg formation in the study area is however limited in thickness, but where fractured it can create good shallow aquifers.

Adelaide Subgroup

A smaller southern part of the Middelburg study area is directly underlain by the Adelaide Subgroup consisting of mudrock and subordinate sandstone. When considering groundwater exploration it must be remembered that although the Katberg Formation of the Beaufort Group covers a larger surface area in the study area, it again is underlain by a much thicker succession of units from the Adelaide Subgroup, and at reasonable depth they will form the primary groundwater reservoir if dolerite is absent. The effective primary porosity and permeability of the predominantly mudstone Adelaide Subgroup does not generally create as good an aquifer as the Katberg predominantly sandstone aquifer would. This was important information to the Middelburg groundwater investigation and directly influenced deeper borehole yields (see Chapter 6).

2.2.1.4 The influence of a dolerite dyke on the hydrogeology

Dolerite dykes are linear intrusion structures. They are discontinuous in nature and this creates a thin linear zone of relatively higher permeability along their strikes that act as conduits for groundwater flow within the aquifer (Woodford *et al.*, 2002: 58). Dolerite dykes have always been and still are the preferred groundwater targets in the Main Karoo Basin (van Tonder, 2003).

Van Wyk (1963) states in Woodford *et al.* (2002: 59) that the high permeability encountered in dyke contact zones results from shrinkage joints developed during the cooling of the intrusion. He found that two types of jointing typically developed: (1) columnar joints that are roughly 120° to the contact and (2) joints that are parallel to the contact (Woodford *et al.,* 2002 after van Wyk, 1963).

Contact metamorphism plays an important role in the success of a borehole drilled to target a dolerite dyke. Various hydrogeologists propose various thicknesses for this zone. The contact zone represents a zone of higher porosity and permeability as found by van Wyk (1963) and described in Woodford *et al.* (2002: 59). The zone of contact metamorphism is commonly found to be less than or equal to the dyke thickness (Woodford *et al.,* 2002: 63). A maximum width for the contact zones of not more than three metres seemed to be a common thickness of this zone (Woodford *et al*., 2002 after Campbell 1975:60).

Woodford & Chevallier (2001) in Woodford *et al.* (2002) found no significant correlation between dyke width and groundwater yield when a sample of 539 privately owned boreholes were studied for such relationships.

In the Explanation of the Geological Map of Middelburg 3124, Cole *et al.* (2004) noted that the E-W dykes commonly display an En-échelon pattern. The hydrogeological significance of the En-échelon dyke formations is the vertical offsets that occur due to lateral displacement which is associated with intense fracturing and also high yields (Woodford *et al.*, 2002: 71).

A transgressive fracture can roughly be defined as a fracture that transgresses a dyke and extends into the country rock for some distance, normally up to 15 m away from the dyke (Woodford *et al.*, 2002). Large volumes of water are often intercepted in disrcrete, open transgressive fractures. According to Woodford *et al.* (2002: 71) these fractures are normally sub-horizontal in attitude with dip angles < 50°.

The most prominent dyke in the Middelburg study area is undoubtedly the Dunblane dyke, and it is a typical example of a dyke that has been transgressed by a fracture. The fracture transgresses the 20 m thick Dunblane dyke and has been reported to extend up to 90 m away from the dyke into the country rock (Woodford *et al.*, 2002). Transgressive fractures typically form near the surface, where advanced stages of weathering have already taken place (Woodford *et al.*, 2002: 71).

Where dykes as the younger structures cut across sills, good targets for groundwater are often found, especially in a valley-bottom scenario were the material of the sill is commonly highly weathered (Woodford *et al.*, 2002). According to Woodford et al. (2002) after work done by Paver *et al.* (1943) and Van Wyk (1963), the dyke/sill contact is in most cases not as wide or permeable as dyke contacts with country rock. Another reason why dyke/ sill contacts may form good targets for groundwater is the fact that transgressive fracturing is often found at these contacts (Woodford *et al.*, 2002).

From the Geological map (Tordiffe *et al.*, 1983) of Middelburg the Dunblane dyke is seen transgressing some of the dolerite sill- and ring-structures in the study area.

2.2.1.5 The influence of a dolerite sill on the hydrogeology

To date, extensive groundwater source development has not been conducted on dolerite ring- and associated sills-complexes. Woodford *et al.* (2002: 90) states the reasons for overlooking these structures are due to their size, thickness, rock hardness and structural complexity.

Due to the limited work done on these structures, the detailed hydrogeological descriptions that are typically available for dykes such as best targeted depth, fracturing and expected yields are absent in the literature. A handful of exploration drilling projects have however been conducted on dolerite sill- and ring-structures and their findings are discussed below.

Results from exploration drilling projects on a few ring structures in the Karoo have provided useful information regarding hydrogeologically significant zones within the dolerite ring- and sill-complexes. As reviewed in Woodford *et al.* (2002: 110) open water-bearing fractures are formed at specific locations within the dolerite and surrounding country rock. Such locations are:

(1) At the junction between the feeder dyke/ inclined sheet and a sill,
(2) in the sediment above an up-stepping hill or;
(3) at the base of an inner-sill.

At the first mentioned location fracturing is very localised. In the sediment above an up-stepping hill or at the base of an inner-sill open and shear fractures can extend for some distance into the country rock from the dolerite/country rock contact (Woodford *et al.*, 2002: 110).

During the comprehensive geohydrological investigation conducted in Middelburg, Eastern Cape by Vandoolaeghe (1979) as described in Woodford *et al.* (2002: 109) and Cole *et al.*, (2004: 38), high yields (up to 50 ℓ/s) were obtained in the lower-contact of an inclined-sheet which is part of the Matjieskloof ring-complex.

The three zones identified above occur at depths of 200 to 350 mbgl and represent challenging targets that will require deeper than normal drilling (Woodford *et al.*, 2002: 110).

2.2.1.6 Hydrogeological properties of Cenozoic deposits

The largest part of the Middelburg study area is covered by cenozoic deposits, primarily unconsolidated alluvium and secondarily by cemented and indurated calcrete. From the types of aquifers found within the study area, unconsolidated sediment porous aquifers form arguably the best aquifers, but the calcrete also has favourable groundwater flow and storage characteristics. The large amounts of alluvium found in the study area have a high effective porosity and permeability. According to Cole *et al.* (2004: 29) the alluvium is restricted to river valleys as would be logical, but observing from the surface area coverage of alluvium in the study area, this is certainly not a restricted area. Vandoolaeghe (1979) as described in Cole *et al.* (2004: 37) found that the alluvium has a thickness of up to 25 m in places. The alluvium shows a cyclic pattern of coarse sand and scattered pebbles fining upwards into clay (Cole *et al.*, 2004: 29). The deeper part of the alluvium, defined by scattered pebbles and coarse sand holds the promise of a very a high transmissivity and storativity aquifer if the water level is shallow and if the aquifer is not over exploited.

According to Vandoolaeghe (1979) in his geohydrological investigations in the Middelburg study area as described in Cole *et al.* (2004: 37), the boreholes with the highest yields are located along the Klein-Brak River and its tributaries in the alluvial valleys where they tap the shallow porous aquifer.

One advantage of unconsolidated sediment aquifers vs. hard rock aquifer types such as the Beaufort Group is that unconfined porous aquifers are not subject to permanent aquifer deformation, which in most cases destroys the aquifer’s ability to yield economically viable amounts of water to the borehole.

2.2.1.7 Summary of hydrogeology in the Middelburg study area

The main types of aquifer found in the study area are the unconsolidated deposits of alluvium as well as the fractured rock aquifers caused by dolerite intrusions. The alluvium presents an aquifer of high hydraulic conductivity and storativity but is limited in thickness. There is significant dolerite intrusion structures present in the study area. The dyke related fracturing is significant to groundwater as illustrated by the extensive Dunblane dyke. There is large groundwater potential in the number of dolerite sill- and ring-structures found in the study area, but will require some experienced drilling techniques as well as good geohydrological borehole siting. Where alluvium has been deposited against outcropping dolerite intrusions to form a dolerite embankment with alluvial reservoir, very high yields have been recorded when drilled on the contact aureole (Cole *et al.*, 2004: 37). There are a number of springs (18) in the Middelburg catchment area as noted by Cole *et al.* (2004: 38), although most of them are non-perennial. Three cases are mentioned where perennial spring exist namely, the weir spring at Grootfontein located just north of the Middelburg ring and spring at Onbekendt and Wolwekop respectively (Cole *et al.*, 2004). The weir spring is a result of groundwater damming created by large dolerite structures (Cole *et al.*, 2004).

2.3 Comparison between the South African and Australian Groundwater Resource Development Methodology

2.3.1 South African Groundwater Resource Development Methodology

South Africa is well noted for having one of the best Constitutional documents in the world and is also noted for having a good Water Act what water reform is concerned. The constitution and Water Act are examples of the post 1994 legislation that were designed with a global perspective after the best international legislation was reviewed and used as framework for the South African legislation.

Groundwater Resource development is governed by two major legislative documents namely the Constitution and the National Water Act of 1998. Section 27 of the constitution states that: "...Everyone has the right to have access to sufficient food and water..." (RSA, 1996). The actual development of a groundwater resource falls under the National Water Act (NWA) and the National Environmental Management Act (NEMA), while any development of infrastructure beyond the development of the resource itself falls under the Water Services Act of 1997. The National Water Act does not make provision for quantifying at which point an Environmental Impact Assessment (EIA) is needed due to abstraction volumes. NEMA refers to EIA regulations with which scheduled activities determine whether a Basic EIA is required and when not.

2.3.1.1 Law

The Constitution

It is the single over-arching law and document which supersedes all other law in South Africa and from which all other relevant Water Law and policy flow.

In particular, Section 27(1(b)) of the constitution of South Africa states:
"Everyone has a right to sufficient food and water;
27(2): "The state must take reasonable legislative and other measures, within its available resources, to achieve the progressive realization of each of these rights."

Section 24: "Environment – Everyone has a right-
(a) to an environment that is not harmful to their health or well-being; and

(b) to have the environment protected, for the benefit of present and future generations, through reasonable legislative and other measures that –

(i) prevent pollution and ecological degradation;

(ii) promote conservation; and;

(iii) secure ecologically sustainable development and use of natural resources while promoting justifiable economic and social development."

(Constitution of South Africa, 1996)

The National Water Act No. 36 of 1998

The National Water Act is the document which provides the base for water reform in South Africa and provides directive framework to the forming of various statutory water management bodies, strategic documents and defines water uses. It is, like the Constitution a law based on the principles of equity, sustainability and integrated management. The document recognizes that water in South Africa is an unevenly distributed resource, but all of the water forms part of a single coherent water cycle. Of relevance to water use, it defines water uses requiring licensing and water uses that are permissible from licensing, which fall under general authorizations (NWA, 1998).

The National Water Services Act No. 108 of 1997

Applicable to groundwater resource development the National Water Services Act describes the rights of access to basic water supply and basic sanitation, makes provision for the setting of national standards as well as norms and standards for water and sanitation related tariffs. Furthermore it provides for water services development plans as well as the gathering of information in a national information system (National Water Services Act, 1997).

The National Environmental Management Act (NEMA) No. 107 of 1998

The National Environmental Management Act addresses fully section 24 of the Constitution as one of its main purposes. It also provides that the law should develop a framework for integrating good environmental management into development activities and that law should through the state enforce environmental laws. The act states in its list of desirable actions that law should also"…establish principles guiding the exercise of functions affecting the environment." (NEMA, 1998)

2.3.1.2 Policy

National Water Policy, 1997, White Paper

The purpose of this white paper is to address the management of the quantity and quality of South Africa's water resources. This policy preceded the National Water Act and in many cases it addressed the then unformalised parts of the now established Water Act. Key proposals from the National Water Policy are: formalising the status of the South Africa's water resources as an indivisible national asset, the confirmation of the government as the national custodian of all water resources of South Africa and that its power will be exercised in the manner of a public trust. Only water that is required for basic human needs and for ecological sustainability will be guaranteed as a right and this component will be known as the Reserve, the riparian system of water allocation is discontinued and the Catchment is accepted as water management unit with its management operation. Groundwater is to be used in the context of an adequate Catchment Management Plan. (National Water Policy, 1997).

Reconstruction and Development Programme, 1994, White Paper

Community water supply and sanitation in South Africa is chiefly addressed and driven by the Reconstruction and Development Programme (RDP), defining a list of services required to improve the quality of life, especially for previously disadvantaged South Africans and strike at the heart of poverty. It is designed to meet its main goals and those of the constitution, which are in essence an approach to development and development programmes in an integrated, sustainable and principled manner. The RDP uses 5 key programs to achieve its goals. These are: (1) Meeting Basic Needs; (2) Developing human resources; (3) Building the economy; (4) Democratising the State and Society and (5) implementing the RDP.

Water Supply and Sanitation Policy, 1994, White Paper

The main focus of the Community Water Supply and Sanitation White Paper is to set out policy on water supply and sanitation services. Key purposes of the paper includes putting forward certain basic policy principles, outlining the institutional framework for water supply and sanitation services and provision for standards and guidelines for basic service delivery. An important function of this white paper is that it gives definition to many rights and laws set out in the Constitution and relevant Acts. One of these aspects that is of paramount importance and is used in many stages of water supply and reserve determination projects, is quantification of the volume of water for basic human need. In this paper, Basic Water supply is defined in terms of its quantity, maximum distance that cartage of the source is required, availability and assurance of the source to name a few. Basic water supply quantity is defined in this white paper as a minimum of 25 litres per person per day. This amount is considered the minimum for direct consumption essential for life, for food preparation and personal hygiene and is not necessarily seen as an adequate volume for a full, healthy and productive life (National Water Supply and Sanitation Policy, 1994).

2.3.1.3 Strategic documents from Implementing Authority

The National Water Resource Strategy 2004

The National Water Resource Strategy provides the public with detail on how the government through the Department of Water Affairs and Forestry (now the Department of Water Affairs) plans to give effect to the protection, use, development, conservation, management and control of South Africa's water resources (NWRS, 2004). In short, the NWRS is a statement of how South Africa's water resources will be managed in order to meet the objectives of the National Water Act (Integrated Water Resource Management: Groundwater Management Strategy, 2004). A new National Water Resource Strategy is currently being written.

IWRM [Integrated Catchment Management 2004]

Integrated Catchment Management (ICM) is seen as the "ideal" methodology for water management. This approach has however been replaced by the Integrated Water Resource Management (IWRM) approach, as South Africa at present is not yet ready for the ICM approach according to the DWA due to the absence of the necessary statutory and institutional structures needed to drive the ICM approach (Ashton, P.)

2.3.1.4 Standards and guideline documents from Implementing Authority

Minimum standards and guidelines for groundwater resource development for the Community Water Supply and Sanitation Programme, 1997

This is the most relevant and definitive guide to the community groundwater resource development process and when adhering to the minimum standards and guidelines set by the Department of Water Affairs for this activity. The document serves as a framework methodology which can be used for a groundwater resource development project. Although the methodology presented in this document is intended for Community Water Supply, the basic actions are the same for larger scale groundwater resource development such as the development conducted on this case study project for Middelburg, Eastern Cape. The actions for groundwater resource development included in this paper must therefore not be seen as exhaustive as there are other very important actions, such as water balances which definitely need to be carried out for projects which are of the magnitude of this case study for instance. The purpose of this guideline is defined as: "…an indication of the administrative structures, scope of work and methodology required to successfully implement and execute such projects." (Hobbs *et al*., 1997)

A guideline for the assessment, planning, and management of groundwater resources in South Africa, 2008

More recently, a document entitled: *A guideline for the Assessment, Planning and Management of Groundwater Resources of South Africa,* was published in 2008. This is an extensive work including all aspects of groundwater resources compared with the above standards and guidelines document of 1997, which only elaborates on groundwater source development for community water supply. The document's main objective is to streamline the whole groundwater management process.

2.3.2 The methodologies

A Visual representation of the processes followed by South Africa and Australia is the most effective means of conveying the information.

In the diagram in Figure 2-8, writing policy, white papers and drafting legislation takes place before laws are enacted. The laws however hold higher legislative power than the policies, so in a hierarchical relationship laws would be above policy.

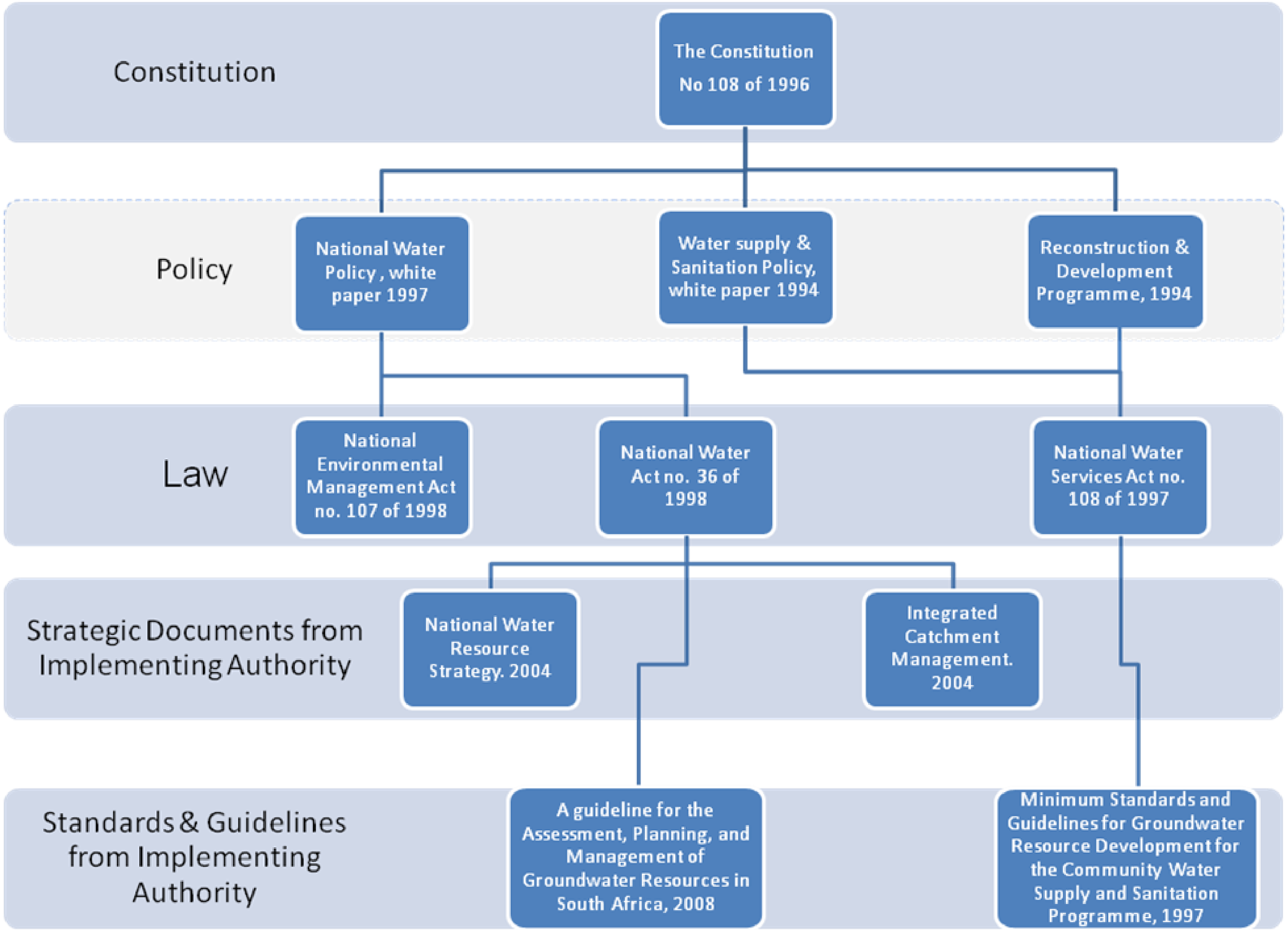


Figure 2-8: Relationships of South African legislation, policy and guidelines

2.3.3 Australian legislation and methodology

Australia has a climate which is similar to that of South Africa and as such lends itself to being a good candidate for comparison with South Africa what groundwater resources are concerned. Australia is governed by a Federal sovereign system in which each of its six states are governed independently as a sovereign state, much like a country on its own. The Northern Territory State will be used during this comparison. The Northern Territory functions as a sovereign state the same way as the other states do, except that any of its legislation can be overridden by Federal legislation if there is ever a need. When states are compared to territories in a legal manner, only state legislation set out in Section 51 of the Australian Constitution can be overridden by Federal legislation.

Groundwater constitutes approximately 17% of Australia's accessible water resources and constitutes approximately 30% of its total water consumption (The National Water Commission, 2010). Australia has its largest major aquifer situated in the central part of the country called the Great Artesian Basin. Thousands of boreholes have been drilled into this aquifer and many of them were not used, but also not sealed. Huge amounts of water from this aquifer was wasted when boreholes were left decanting, while the artesian aquifer lost much of its pressure and many other Artesian Basin boreholes that were used in other parts have dried up as a result.

The Northern Territory is a large Territory although not as densely populated as the Australian Capital Territory (ACT) for instance and has a relatively low intensity of land use. The Northern Territory obtains 90% of all the water it uses from groundwater and compared to other states it is the largest user of groundwater (NRETAS, 2010).

Australia is currently involved in a large-scale movement towards groundwater protection and sustainable groundwater management. Rather than focusing on developing new groundwater sources for water supply their entire focus is almost only on the management of existing groundwater sources, gaining complete understanding of Australian Hydrogeology and groundwater-surface water interaction and protecting groundwater sources from contamination (NWC, 2010). This is evident from the National Water Commission's website.

The Australian government (the Commonwealth) have invested greatly through the National Water Commission in projects and initiatives aimed at addressing the sustainable management of Australian Water Resources. One such initiative is the National Groundwater Initiative for which the National groundwater Action Plan is being developed.

For this initiative there has also been investment in a suite of projects aimed at addressing Key factors for which water reform and knowledge development is required (National Water Commission, 2010).

Australia currently does not have a national document dealing specifically with groundwater resource development that is comparable with the 1997 Minimum Standards and Guidelines document of South Africa (*pers. comm.* Peter Hyde, 2010; NWC, 2010). It can be argued that this is in larger part due to the different needs for groundwater resources in Australia compared to South Africa. South Africa has a development driven approach to natural groundwater resources whilst Australia has a sustainable management and protection approach.

Australia does however make consideration for development of protocols and methodology for development of groundwater resources in their newest Water Act, the Water Amendment Act, by declaring that the applicable authority may develop protocols for certain water works or activities (The Commonwealth, 2008). One example is the Sydney Groundwater Handbook developed by the Sydney Coastal Councils Group for Local Government.

The Northern Territory as State case study example also currently does not have a document that sets out a protocol for groundwater resource development. The applicable Northern Territory document that currently comes closest to this purpose is the strategic document entitled, *An Approach to Water Allocation Planning in the Northern Territory* (Hamstead Consulting, 2008; *pers. comm.* Peter Hyde, 2010). According to Peter Hyde (pers. comm. 2010) from the National Groundwater Commission (NWC) the Federal government in conjunction with State governments will in near future produce a set of planning documents for this purpose.

Even without a clear document defining how groundwater resource development is to be conducted nationally and in many cases state wise, Australia and the Northern Territory have ample groundwater protection laws and guideline documents to protect and manage groundwater resources such as the *Guidelines for Groundwater Protection in Australia* published in September 1995 which was part of the development of the National Water Quality Management Strategy (Agriculture and Resource Management Council of Australia and New Zealand, 1995).

Australia also has good guidelines for the construction of boreholes in the document *Minimum Construction Requirements for Water Bores in Australia*, although this document is not law (National Minimum Bore Specifications Committee, 2003; *pers. comm.* Peter Hyde, 2010). For Aquifer Testing there is the *AS 2368 – 1990 Test Pumping of Water Wells* Australian Standards document available which is similar to our SABS series of standards.

The Water Act of 1992 of the Northern Territory applies and provides for the investigation, allocation, use, control, management, protection and administration of water resources (Hamstead *et al.*, 2008). It defines a licence or permit requirement for almost every step of a new groundwater resource development as mentioned above. Figure 2-9 below describes the laws and licences as they apply to groundwater resource development in the Northern Territory.

Under the Northern Territory Water Act of 1992 (Northern Territory of Australia, 2009) the Minister for Natural Resources, Environment, The Arts and Sport must appoint The Controller of Water Resources. The Minister and the Controller are then the two chief consent authorities under the Act, although both may delegate their powers.

A Water Allocation Plan (WAP) may be developed for Beneficial Uses as set out in the Water Act of 1992 (Hamstead *et al.*, 2008: 23). Such a plan must according to the Act ensure that water is allocated within the estimated sustainable yield to *beneficial uses*. A WAP can apply legally for up to 10 years and it is the Minister's responsibility that the WAP be reviewed at intervals of no longer than 5 years. A WAP is typically developed for a *Water Control District.* A WAP does however not have to apply to a whole Water Control District and can be developed for a significant aquifer for instance the Katherine Tindall Limestone Aquifer in the Northern Territory. A person or persons may take groundwater under section 14 of the Act if it is for domestic, stock watering or watering of garden purposes given that the garden is no larger than 0.5 ha and pertains specifically to the dwelling (Northern Territory of Australia, 2010: 11). Any other uses for groundwater extraction will require a license. A licence to take or use water is granted for no longer than 10 years. The right to take or use water under a licence can also be traded in part or in full so as to cater for water user needs that could arise from future variables (e.g. climate) within the term of the current WAP. A new borehole cannot be drilled or constructed without a borehole construction permit and without the drilling contractor having a drilling licence.

Existing water use licences and new water entitlements/ new licence applications are generally reviewed at the end of the old WAP term for the beginning of a new WAP term. The Controller of Water Resources can under the current Act however review and amend a licence at any time if he feels it is required e.g. climate variability or risk to aquatic ecosystems. The process of allocating water use licences for a new WAP basically encompasses that the sustainable yield be scientifically determined for each new WAP or 5 year revision thereof and that extensive groundwater monitoring data be evaluated. This is done to determine whether current groundwater use is sustainable and whether there is enough additional groundwater recharge left for new licences after environmental contributions have been subtracted from the Total groundwater recharge.

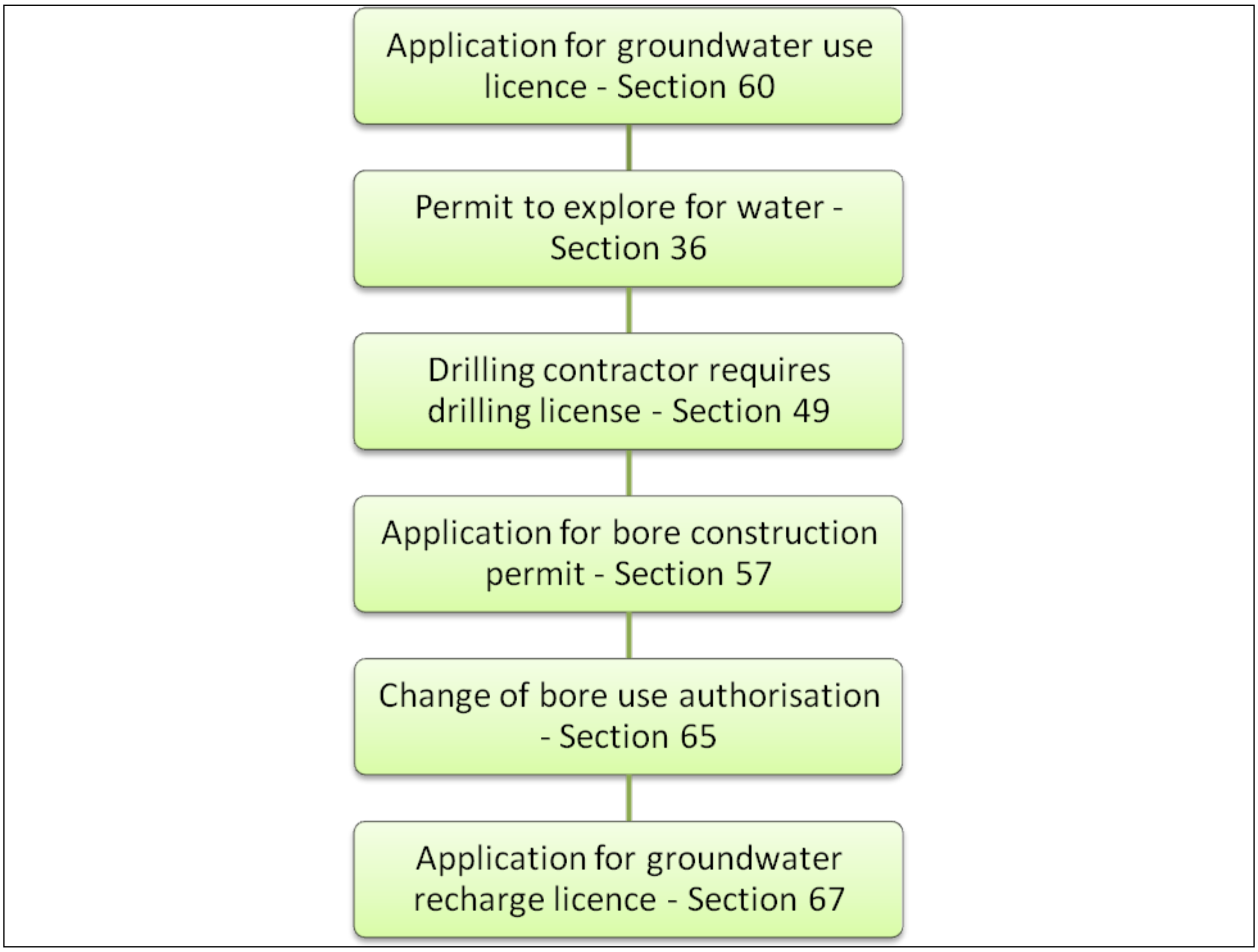


Figure 2-9: Diagram of legal requirements of the Water Act when performing any groundwater resource development in the Northern Territory of Australia

2.3.4 Methodology of Groundwater Resource Development in South Africa

In the Minimum standards and guidelines for groundwater resource development document of 1997, an institutional framework is first defined for the role players during groundwater resource development. This defines local government as third tier, provincial government as second tier and central government as first tier. Communities will have representation on a District Council or Transitional Local Council (TLC). The TLC in turn will have representation by the Local Water Committees for instance of communities. This structure allows for communities to make public a water shortage or need that they have and apply for government assistance in this regard (DWAF, 1997).

The main role players in the activation of a Groundwater Resource Development project are:

(1) The Activating Agency – The community which the groundwater development will serve.

(2) The Implementing Authority – The institution which is responsible for the provision of potable water within a defined area of jurisdiction. This is for instance the Local Municipality. If a local government structure is absent, the responsibility falls either on the district, provincial or central government.

(3) The Executive Agency – The organisation(s) that are responsible for the actual execution of the project and carry out the work on behalf of the Implementing Authority. In view of this task the Executive Agency may also be called the Implementing Agency. The Executive Agency may consist of a number of specialist firms or organisations, each acting under a separate appointment of the Implementing Authority. It can also be a single organisation conducting all project activities under a single appointment.

(DWAF, 1997: 2-2)

The typical broad groundwater resource development actions described in the guidelines as well as their sequence can be summarised as follows:

1. Project Inception and Foundation
    1.1. The verification of needs
    1.2. Communication and liaison with the community
    1.3. Familiarisation with the project area

2. Borehole Siting
    2.1. Purpose and scope
    2.2. Approach and personnel
    2.3. Techniques
    2.4. Geophysical surveying
    2.5. Protocols
    2.6. Marking of borehole site(s)
    2.7. Documentation of geophysical data

3. Borehole Drilling
    3.1. Purpose and scope
    3.2. Approach and responsibility
    3.3. Techniques
    3.4. Equipment and materials
    3.5. Workmanship and performance
    3.6. Borehole construction
    3.7. Data recording and reporting
    3.8. Down-the-hole loss of equipment
    3.9. Down-the-hole borehole measurements
    3.10. Rehabilitation of existing boreholes
    3.11. Final acceptance

4. Borehole Testing
    4.1. Purpose and scope
    4.2. General approach and methodology
    4.3. Equipment and materials
    4.4. Arrive-on-site actions
    4.5. Test pump installation
    4.6. Equipment set-up and pre-test actions

   4.7. Final pre-test measurements
   4.8. Data recording
   4.9. Groundwater sampling
   4.10. Aborted tests and breakdowns

5. Borehole Utilisation Recommendations
   5.1. Use application
   5.2. Equipment installation details
   5.3. Borehole operation details
   5.4. Groundwater quality

6. Reporting
   6.1. Progress reporting
   6.2. Technical report

(DWAF, 1997: 7)

These are the main actions described in the 1997 Standards and Guidelines document, although each of these actions have subordinate smaller tasks involved. For a detailed overview of all activities in the methodology above please refer to the *Minimum Standards and Guidelines Document* (1997) as referenced. All actions and their details are described in the Minimum Standards and Guidelines document, so that a professional practitioner without much groundwater experience can have a general guideline of the life cycle of a groundwater resource development project. Even an experienced groundwater practitioner can use this guideline document to optimise some aspects of an already developed groundwater resource development project life cycle.

2.3.5 Summary and conclusion from methodology comparison

The sharpest contrast resulting from the Groundwater Resource Development (GRD) methodology comparison is that South Africa follows a development driven groundwater resource approach, while Australia follows a groundwater protection and management approach. South Africa does not have all the legal requirements in its GRD approach, but has well developed methodologies and protocols for developing and assessing groundwater resources. For new GRD in Australia and the Northern Territory as case study, various licences are required at various stages of the GRD process, such as groundwater resource investigation permit and a borehole construction permit. Australia and the Northern Territory do not have a document similar to the Minimum Standards and Guidelines document of South Africa that states a protocol or methodology on how GRD is to be conducted. At national level, they do however have documents on segments of the GRD process such as the *Minimum Construction Requirements for Water Bores in Australia* (2003) and the Australian Standards document, *AS 2368 – 1990 Test Pumping of Water Wells*.

The extensive regulation of activities surrounding the drilling of a borehole in the Northern Territory and Australia is in stark contrast to South Africa where a licence is not even required to drill a borehole let alone carry out a geophysical investigation. In Australia only licensed drilling contractors can perform drilling under the laws of the Federal Government as well as the Northern Territory. The regulation of the drilling of boreholes is a good means to perform aquifer and catchment management and to quantify GRD for planning at provincial and national level. It allows the regulation and protection of groundwater resources in areas where aquifers are classified as stressed and where more abstraction is not sustainable. This kind of regulation of GRD does however require a significant human capital investment in a country's governmental department in charge of water resources.

2.4 Review of Middelburg C.P. Geohydrological Investigation. M.A.C. Vandoolaeghe. 1979.

The area under investigation was the catchment of the Klein-Brak River and its tributaries around Middelburg.

2.4.1 Terms of reference and objectives

Purpose and origin: The project was initiated by the Middelburg town council during 1973/1974, who envisaged expansion of the town primarily through industrial development and needed information on the available groundwater resources in the vicinity of Middelburg. A reconnaissance survey by the Groundwater section of the Geological Survey was completed in 1975 which found evidence of favourable groundwater conditions in the Middelburg area. This was followed by the Geohydrological Investigation on Middelburg C.P. The important results of this investigation will be summarised below. The investigation was conducted by the Division of Geohydrology of the Department of Water Affairs with the purpose of groundwater exploration and water supply to Middelburg town. Shortly after project inception the study was given a research purpose as well.

2.4.2 Scope of work

The investigation consisted of the main geohydrological actions below:

- Hydrocensus and catchment delineation;
- Geological mapping, site characterisation and geohydrological description;
- Geophysics and research and exploration borehole siting;
- Water balance;
- Aquifer testing with development of a test site and observation boreholes for each test sites.
- Detailed conceptualisation of each test site and the underlying aquifer(s);
- Groundwater quality sampling and hydro-geo-chemical description;
- Detailed documenting of findings, results and recommendations.

2.4.3 Topography and drainage

According to the Vandooleaghe (1979: 1) investigation, Middelburg was a middle-sized Karoo town and investigation was carried out on the drainage sub-region of the Klein-Brak River and its tributaries which formed the catchment that was studied (see Figure 2-10).

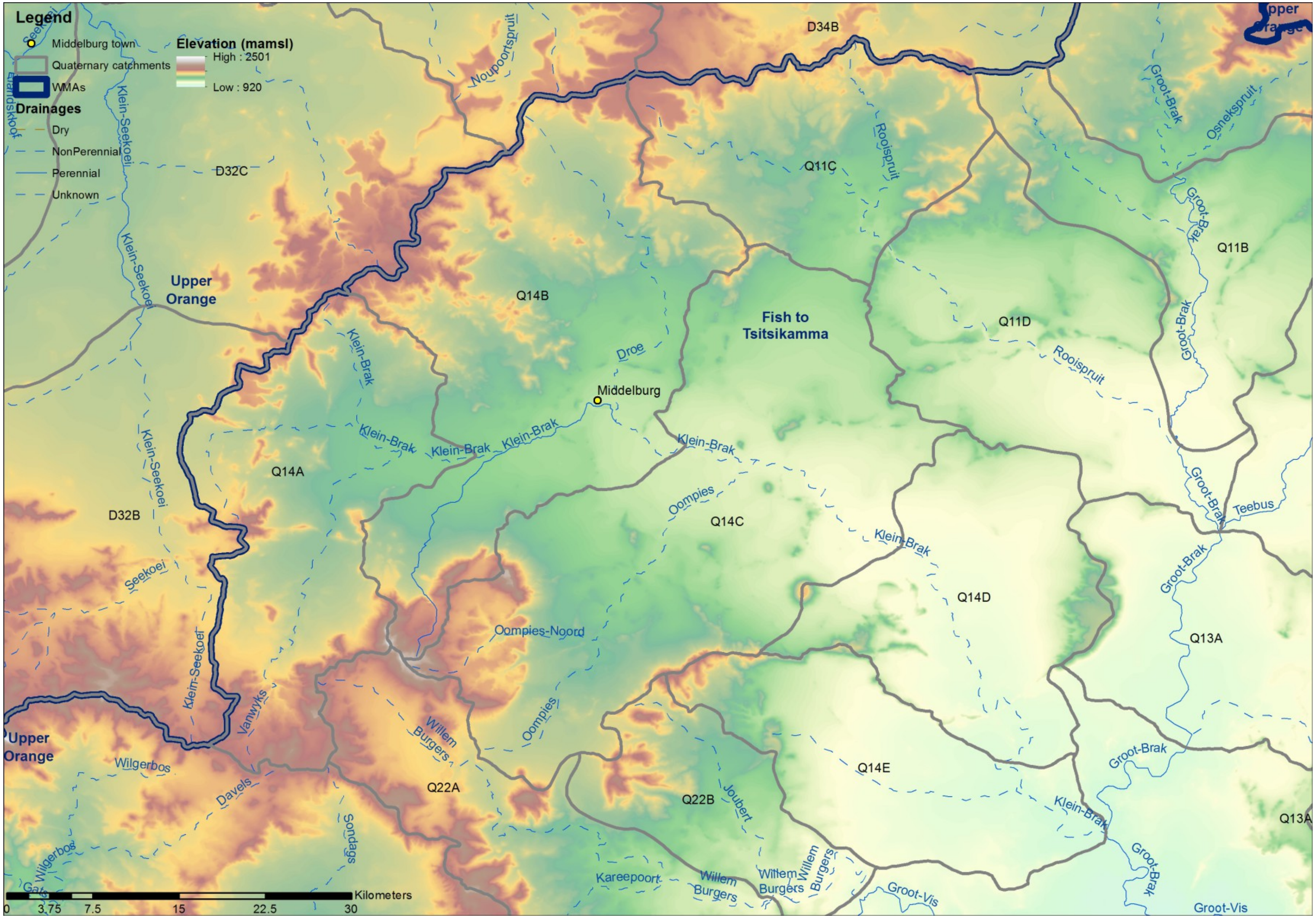


Figure 2-10: Drainages, quaternary catchments and water management areas (WMAs) of the Middelburg area

The Klein-Brak River and its tributaries are part of the Great Fish River drainage system. The former mentioned catchment had a surface area of 1740 km^2 while the actual catchment that was studied had a surface area of 1065 km^2. The emphasis of Vandooleaghe's (1979) study was on the alluvial valley of the Klein-Brak River and on valleys in the north and southwest. The mentioned study area is enclosed by a ring of mountains which forms the Hydrological divide. These mountains are the Joubertsberge, Renosterberg (highest point 2300 mamsl), Agter-Renosterberg, Carlton Hills and Kikvorsberge. The topography opens up to the east where the boundary of the Catchment here is formed by the dolerite-capped inselbergs: Wolweberg, Folminkskop and Tafelberg (Vandoolaeghe, 1979). The valley areas have elevations ranging from 1500 mamsl in the piedmont areas of Twistkraal, Schorpioenkraal and Tweefontein that drop to 1180 mamsl where the Klein-Brakriver leaves the study area (Vandoolaeghe, 1979: 2).

2.4.4 Geology

During the time of Vandooleaghe's (1979) investigation no geological maps or papers existed that dealt with the geology encountered in the study area, thus a great deal of work went into the compilation of geological maps and the understanding of the geohydrology of the study area.

2.4.4.1 Beaufort Group sediments

Stratigraphy:

As Vandoolaeghe's geology was done in 1979 it is considered dated and much has been done on the Karoo Supergroup since then. More detailed and relevant geology is discussed in the geology section of this report. Only what are considered important findings from Vandooleaghe's report are discussed here.

According to Vandoolaeghe (1979: 6) the Balfour formation of the upper Adelaide Subgroup and the Katberg formation of the lower Tarkastad Subgroup are found in the Middelburg vicinity. The Balfour formation is comprised of grey sandstone and red- and greyish-red –mudstone and the ratio of sandstone to mudstone is estimated at about 0.6 :1 here. Vandoolaeghe noted that shaly mudstones do occur in the study area and are often pyritic (Vandooleaghe, 1979: 6). The Katberg formation was defined as a predominantly sandy lithostratigraphic sequence with an approximately 80% sandstone- and 20% mudstone -composition. All sandstones in the study area are feldspathic (Vandoolaeghe, 1979:6).

2.4.4.2 Dolerite

The dolerite ring-shaped intrusions form oval to near circular structures that enclose horizontally-bedded sediments and formations (Vandooleaghe, 1979: 7). According to Vandoolaeghe (1979: 7) long-axis orientations of the oval-shaped intrusions have north-north-westerly to north-north-easterly trends and coincide with the major joint directions. Some dykes in the study area intersect dolerite ring structures and are then of younger age. Other dykes were found to be clearly linked with ring structures and were considered off-shoots. Vandoolaeghe (1979:7) described the Dunblane dyke as almost vertical and with a constant width of 20 m. Dolerite intrusions had and still have a great influence on the formation of the alluvium as well as the geohydrology.

2.4.4.3 Superficial deposits

During the geological study Vandoolaeghe(1979) concentrated on the superficial alluvial deposits as well as the dolerite intrusions. Time was spent analysing the bedding structure of the alluvium as well as performing a granulometric analyses on the deposits. The valleys of Klein-Brak River and its tributaries have, when compared in the Karoo, thick and extensive alluvial deposits. A general fining upwards cycle of the sediments was noted. The channel fill represents the whole grain size range of detrital material as investigated during the study (Vandoolaeghe, 1979: 11). Clean gravel is encountered in the bottom of the channel. The sequence of material between the bottom and top are fairly heterogeneous and poorly sorted. The top of the alluvial sequence is generally composed of the finest material. Near the top of the alluvial sequence, silty and sandy layers are sometimes very calcareous. Strong lateral variations and a decreasing thickness occur within the unconsolidated sediment sequences from west to east.

Travertine or CaCO3 deposits have formed below springs where dolerite intrusions have forced the groundwater table upward (Vandooleaghe,1979).

2.4.5 Geophysics

Vandoolaeghe applied both the electrical resistivity method as well as the magnetic geophysical method during the investigation. The electrical resistivity was applied to (1) determine the depth and geometry distribution of the unconsolidated sediment aquifer throughout the study area and (2) attempt to find a correlation between the surface measured parameter S (longitudinal conductance = electrical conductivity x thickness) and the pumping test derived parameter Transmissivity (T) (Vandoolaeghe, 1979: 15). Point 2 would enable lateral mapping of T in the alluvial aquifer throughout the studied area. The magnetic method was used an exploration tool to site boreholes in dolerite intrusions as well as determine the geometry of the dolerite dykes and ring structures.

An interpolated isopach map of the depth distribution of the unconsolidated sediment aquifer throughout the study area was created as one of the outputs from the geophysics. This map was also calibrated where possible using additional information from private- and calibration boreholes. The calculated T from surface measured electrical parameter S gave a measure of the infiltration time of the unsaturated superficial deposits. This value was however recognised as strongly dependent on the amount of soil moisture and sub-surface moisture present at the time of measurement (Vandoolaeghe, 1979).

2.4.6 Drilling

A total of 81 boreholes were drilled during the investigation of which 39 were classified as exploration boreholes and 42 as observation boreholes. Test wells were selected from the exploration boreholes, reamed and fitted with 204 mm or 256 mm flame-slotted steel casing (Vandoolaeghe, 1979:27). Most of the observation boreholes were fitted with 107 mm American piping to save some of the much used 165 mm casing.

The fine-grained upper part of the alluvial aquifer was prone to collapsing and frequently casing had to be driven in whilst drilling, causing many problem hours (Vandoolaeghe, 1979: 27). The total accumulated drilling depth was 2808 m with a total drilling depth for exploration boreholes being 1640 m and 1168 m for observation boreholes. The average exploration borehole depth was 54.5 m and the average observation borehole depth 27.8 m. The highest yields of groundwater were struck within the first 12 m below the water level. The boreholes G31580 and G31584 were drilled close to two of the strongest boreholes in the Middelburg area (Vandoolaeghe 1979:29).

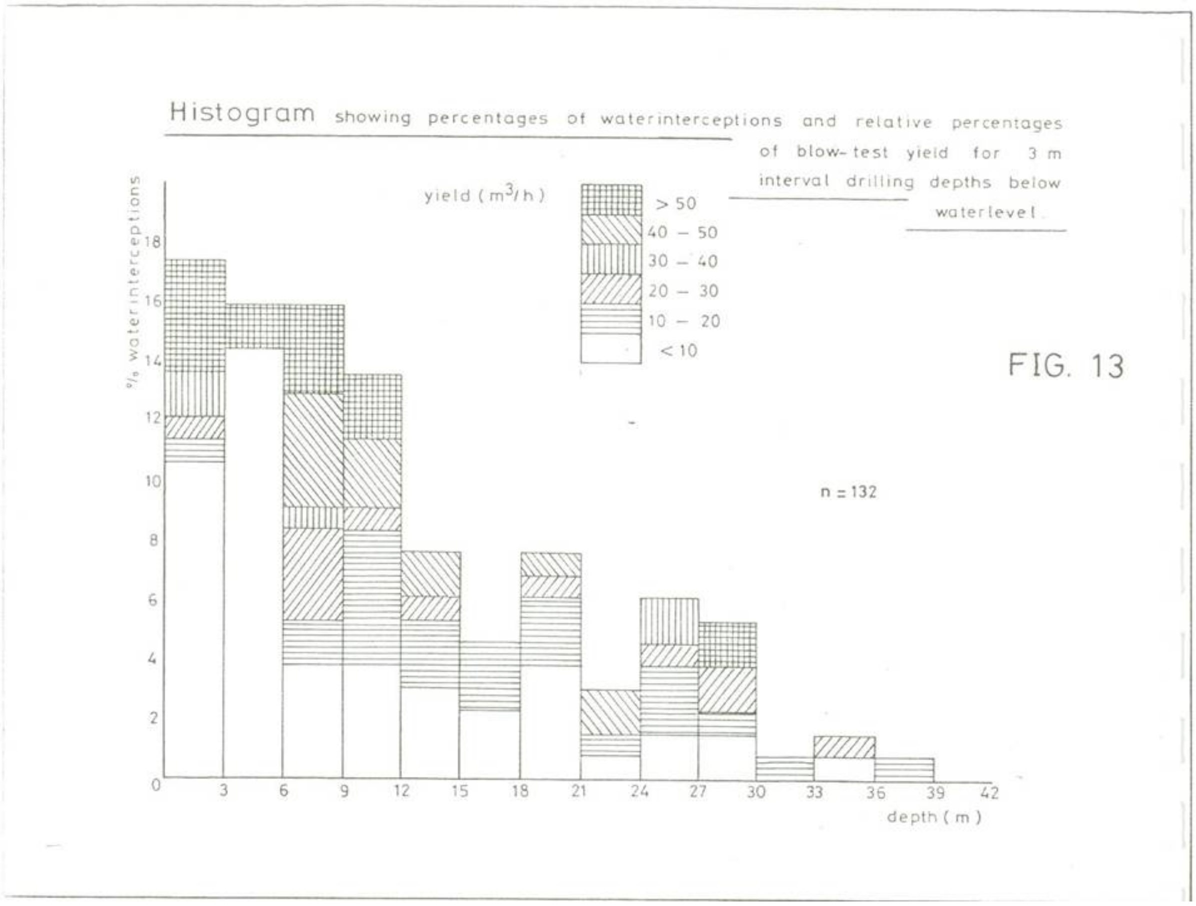


Figure 2-11: Histogram of percentage water interceptions vs airlift yield tests (after Vandooleaghe, 1979)

2.4.7 Hydrocensus

A comprehensive Hydrocensus for the 1979 investigation was conducted in the Middelburg vicinity from October 1977 to August 1978. It covered a surface area of approximately 1065 km^2. Priority was given to the farmlands in the alluvial valleys according to the aims of the project. 42 Individual farms were visited during the Hydrocensus and a total of 690 private boreholes were visited, marked and their water levels measured where possible (Vandoolaeghe, 1979: 31). Information gathered during this time from farmers indicated that the surface area under irrigation is approximately 1660 ha, which was felt to be a rather over-estimated figure. Crops cultivated in the area were lucern (80%) as main crop, followed by wheat, barley, rye, oats and mixed vegetables. The water used for irrigation purposes were supplied by springs, weirs, boreholes, the Klein-Brak River itself and dams in the wet season (Vandoolaeghe, 1979: 32). Dry lands made up only about 300 ha in the study area. During the borehole survey information for the water balance was also gathered based on abstraction rates, types of pumps, pump inlet depth and pipe size. A total annual water consumption for the year 1977 was estimated at 12 801.3 x 10^3 m^3 / a, although

Vandoolaeghe (1979: 35) clearly stated that there is an over estimation on some abstraction components such as wind pumps. The Grootfontein Agricultural College's water consumption was being monitored at its reservoir outlet by the department of Public Works and the annual abstraction figures for 1976, 1977 and 1978 were 12 632.8 m^3, 14 887.3 m^3 and 15 169.7 m^3 respectively. These figures were noted to be absolute minimums and the water was being abstracted from three 50 mm turbines of which only two were working simultaneously.

Municipal water was being supplied mostly from the Nuwe vlei pump station and the Ou Vlei weir. The pump stations Matjieskloof, Newman, Midros I and Midros II could be considered as standby sources which at the time only operated during summer months December to March (Vandoolaeghe, 1979:38). It is noted in the geohydrological report that abstraction increased considerably over the past couple of years. Figure 2-12 from the original investigation illustrates this fact and gives the annual abstraction volumes in m^3 x10^4 (Vandoolaeghe, 1979:38).

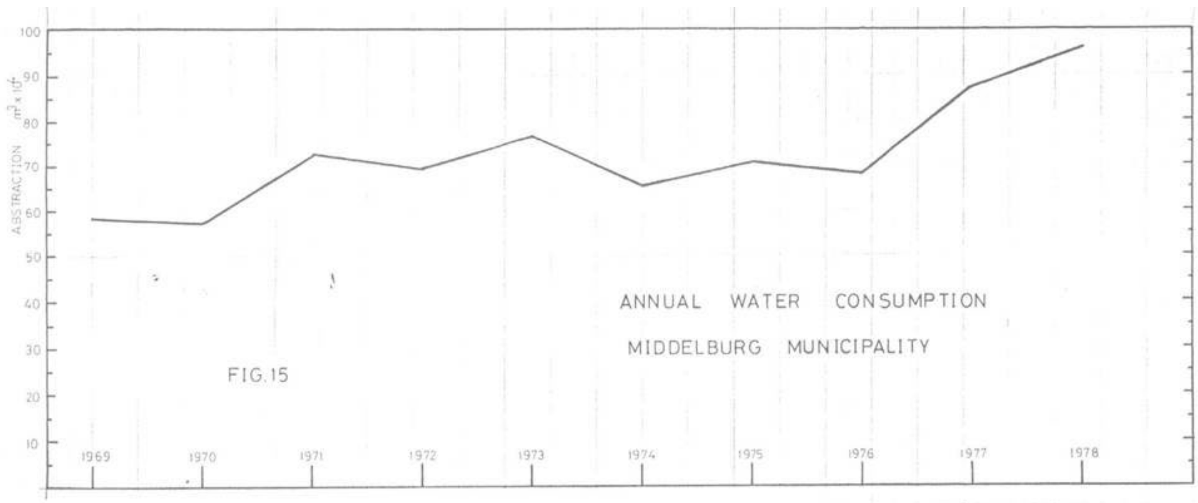


Figure 2-12: Municipal annual abstraction volumes over time (after Vandoolaeghe, 1979: 38)

2.4.8 Water quality

The water quality study that was done during the investigation consisted of approximately 490 field conductivity measurements and 152 complete hydrochemical analyses. From the results it was noted that the mineralisation increases in the direction of groundwater flow and was more or less in agreement with the water table gradient (Vandoolaeghe, 1979: 41). The deterioration was more evident in the alluvial waters than in the weathered or jointed zone. Areas that generally measured a lower conductivity (less than 1000 microSiemens/cm) correlated to the highlands and bordering piedmont zones. Specific zones noted to have exceptionally high conductivity (above 2000 microSiemens/cm) values, mostly above the SABS limit, were found to be (1) a zone of very high mineralisation extending from the farm Groote Valley to the farm Rietfontein, (2) the flat area associated with the Buffels Valey farm and the area enclosed by the Middelburg ring-shaped intrusion (Vandoolaeghe, 1979:41).

Another important aspect was the vertical variation in groundwater conductivity. According to Vandooleaghe (1979:42) the highly mineralised waters were in most cases confined to the fine grained upper part of the alluvial sediments and the weathered Beaufort sediments that border the alluvial valleys. The deterioration in water quality was thought to be more likely associated with the clay deposits and/or the pyritic argillaceous Beaufort sediments rather than low watertable gradients (Vandoolaeghe, 1979: 42).

The recharge line, i.e. mountainous areas and bordering areas, were classified with a dominant Ca/Mg HCO_3 groundwater character and coincide with areas of low mineralisation. The Mg ion dominates over the Ca ion in boreholes drilled into- or near –dolerite intrusions.
In summary regarding the Hydrochemistry, Vandoolaeghe (1979:45) noted the following findings. It appeared that two hydrochemical sequences existed in the study area. A “high permeability” sequence was locally represented by the Ca/Mg HCO_3 and $NaHCO_3$ groundwater groups where the latter group is typical of a dynamic underflow system. Another sequence was noted to be associated with the alluvial aquifers especially their fine grained upper part where a whole sequence from Ca/Mg HCO_3 to Na_2SO_4/ NaCl was observed. The succession was thought to be most likely accelerated by irrigation along the valley.

One explanation to the presence of SO_4 in the second “low permeability” sequence was that it was derived from the oxidation of pyrite, locally present in the argillaceous Beaufort sediments, also proposed earlier by Johnson (1975).

For the consideration of use of groundwater, Vandoolaeghe noted that young waters with low mineralisation are acidic, while alluvial waters are incrusting due to their hardness. The water from jointed aquifers was thought to be best suited for water supply. Extended duration of abstraction would induce greater hardness in the water as well as higher pH in places where an alluvial aquifer is also present. The overall groundwater quality was not stated as being excellent, but well within the health limits (Vandoolaeghe, 1979: 49).

2.4.9 Pumping tests

During the investigation nine Constant Discharge (CD) tests and seven well-production tests were performed (Vandoolaeghe, 1979: 50). The purpose of the pumping tests was to do detailed site characterisation at each test site. Consideration for well field test sites included (1) that sites had to be spread out as much as possible across the total Catchment area, (2) all types of aquifers found in the study area had to be included and (3) the tested formation had to representative for a large part of the global aquifer found in the study area (Vandoolaehge, 1979: 51). The majority of the test sites were located along the valleys of the Klein-Brak River and its tributaries. Each test site was properly set up with a number of observation boreholes drilled at various depths and distances from one production borehole, which was fitted with larger diameter casing. For each test site a CD test (duration ranging from 45 hours to 168 hours) was conducted to determine aquifer parameters as well as aquifer geometry. From the results a cross section of each test site was conceptualised and graphically represented, indicating different aquifers, their depth and other geohydrological information. In most cases at least 6 observation boreholes were drilled for each test site. Findings from each test site will not be repeated here, but important geohydrological findings from all the tests will be noted in the Geohydrology section of the Vandoolaeghe study.

The following test sites were characterised by full pump test and observation borehole setups (Vandoolaeghe, 1979):

1. Bultfontein (Matjieskloof) [CD test – 72 hours, pumped simultaneously: 145 m^3/h];
2. Municipal Allotment area (Nuwe Vlei) test [CD test – 168 hours, simultaneous 62 m^3/h];
3. Rietfontein test [CD test - , 75 m^3/h approximately 48 hours];
4. Grootfontein [100 m^3/h];
5. Buffels Valey (Dunblane) well-site [60 m^3/h for 116 hours];
6. Bultfontein (Middelpos) [69 hours @ 92 m^3/h];
7. Twee Fonteynen tests [98 m^3/h];
8. Buffels Valey (Buffelskop) [47 hours @ 75 m^3/h];
9. Onbekendt Tests [approx 45 hours @ 60 m^3/h].

2.4.10 Geohydrology

Vandoolaeghe (1979: 85) defined the following aquifers found in the Middelburg study area from his site characterisation results.

2.4.10.1 The unconfined aquifer

The principal aquifer in the Middelburg area was found to be unconfined and from top to bottom composed of:

1. An unconsolidated argillaceous sequence
2. An unconsolidated granular sequence
3. A weathered or weathered/ jointed argillaceous or arenaceous zone of the Beaufort Group sediments

(Vandoolaeghe, 1979: 85)

A maximum thickness for the unconsolidated aquifer was recorded as 25 m. Groundwater flow though the aquifer is predominantly (1) primary low permeability flow, (2) granular flow and (3) secondary permeability flow (fissure-flow or granular flow) (Vandoolaeghe, 1979: 85).

The unconfined aquifer is divided into a number of compartments of which the dolerite intrusions form compartment boundaries. According to Vandoolaeghe (1979: 85) the dolerite intrusions do not act as true impervious barriers. Groundwater flow from one compartment to a lower-lying one occurs through permeable or semi-permeable sections of the intrusions as seepage-, granular- or fissure-flow. Transport of groundwater through spring discharge into river flow was not considered very important, as much of this spring water is lost to evapotranspiration, partly as river run-off to the southeast (Vandoolaehge, 1979: 85). Flanks of the alluvial valley were thought to act as barrier boundaries, due to the great differences in permeability between the alluvial deposits and the adjacent fresh or weathered Beaufort sediments.

The aquifer was classified with Transmissivity values ranging from 200 to 1800 m^2/d, depending on the thickness and local flow mechanism (Vandoolaeghe, 1979: 86). Specific yield values were found to range between 1,3 x 10^{-2} and 6,5 x 10^{-2}, which are figures typical of an unconfined aquifer. Proper well screens with gravel packing instead of slotted casing were recommended for boreholes in the unconfined aquifer, which would increase their yield and their well efficiency.

2.4.10.2 Semi-confined aquifer

A semi-confined aquifer with fissure-flow was found to underlay the unconfined aquifer. The semi-confined layer is a horizontal, fractured layer and leakage occurs vertically to the semi-confined aquifer from the overlying unconfined aquifer. A Storage Coefficient (S) of 2.6 x 10^{-3} for the semi-confined aquifer at the Buffels Valley pump test supported its definition. A Transmissivity of about a 100 m^2/d was calculated for this layer at Buffels Valley. It was thought that these semi-confined aquifers could be associated with dolerite intrusions, although local evidence was too scarce to substantiate this point. The groundwater exploitation potential of these aquifers would however be limited by their transmissivity, recharge and well efficiency according to Vandoolaeghe (1979: 87).

2.4.10.3 Dyke-contact aquifers

In the alluvial valleys the weathered dyke contact's permeability was found to be lower than the adjacent formations, and dyke-contact aquifers are thus not a suitable target in the valleys (Vandoolaeghe, 1979: 87) Away from the valley areas they were however found to be the preferred targets. During Vandoolaeghe's investigation, yields exceeding 25 m^3/h associated with these aquifers were not recorded.

2.4.10.4 Weathered Beaufort aquifer

The least suitable aquifer for groundwater supply was noted as the weathered Beaufort rock away from the dolerite and alluvium. Their flow mechanism is one of secondary permeability and their yields are normally only sufficient for wind pump abstraction (Vandoolaeghe, 1979: 87).

2.4.10.5 Groundwater gradients

Even though Vandoolaehge stated that unconfined aquifer flow occurs through the semi-pervious and pervious dolerite intrusions, he also mentions that the groundwater gradient is definitely influenced by the dolerite intrusions.

2.4.11 Groundwater balance

Vandoolaeghe (1979: 95) calculated a groundwater balance estimate for the Middelburg Geohydrological investigation to get an idea of the "quantities of water involved". Most of the information was obtained during the borehole survey. Some notes on how he calculated the groundwater balance were given in this section of his detailed report.

The surface of the entire catchment was used as 1740 km^2, with a total precipitation volume of 6.19 x 108 m^3/a based on a MAP figure of 356 mm/a (Vandoolaeghe, 1979:95). An infiltration figure of 4% was used resulting in a recharge volume of 2.48 x 10^7 m^3/a that could reach the aquifer(s). The western valley was delineated as a sub-catchment and its water balance calculated with more detail. A 7% infiltration figure was used for the mountainous areas while a 2% infiltration rate was used for the valley parts of the compartment.

If total catchment abstraction figures obtained during the borehole survey are added up then: For the private boreholes in the study area a figure of 12 801.3 x 10^3 m^3/a applies, for Grootfontein the 1978 measured consumption figure was 15 169.7 m^3/a and for the Municipal water supply a figure of 95 x 10^4 m^3/a results. The total abstraction for the studied area of Middelburg was then approximately 13.77 x 10^6 m^3.

The conclusion reached on the water balance estimate during the 1979 investigation was that during years with average rainfall, the resulting balance would be a gain in the groundwater volume in the order of 10^6 m^3/ a (Vandoolaeghe, 1979: 95).

2.4.12 Considerations for future groundwater exploitation

In the report a few recommendations are made as to the location and type of aquifer that can most effectively be used for water supply to Middelburg town.

- The Grootfontein compartment was noted as largely under-used, although due to much of the land belonging to the agricultural college, it could not be considered as a first choice by the Municipality (Vandoolaeghe, 1979: 99).
- The Eastern valley was concluded as the only long term solution to water supply.
- A final conclusion was made that given the sensitivity of the quality of groundwater, the composition of the soil and the sensitive groundwater balance, opportunity for further agricultural expansion was not envisaged as any further agricultural expansion would have a detrimental effect on the water supply of the town in the distant future (Vandoolaeghe, 1979: 100).
- The groundwater sources were recommended to be diversified as far as water supply to the town was concerned (Vandoolaeghe, 1979: 101).

3 HISTORIC GROUNDWATER LEVELS & ABSTRACTION

3.1 Introduction

The groundwater level (hydraulic head, water level) is the most fundamental and only directly measurable water quantity parameter in the field of groundwater science. A groundwater level over time is even more valuable and can be regarded as the 'vital sign' of an aquifer.

3.2 Historic time series water levels

Historic time series water level data was received from Mr. Cobus Ferreira of the Department of Water Affairs (DWA) in Cradock, for Middelburg monitoring boreholes operated by DWA. The author's gratitude is expressed towards Mr. Ferreira for his efficient help.

Water level logger data was evaluated and gaps or blanks in the data were removed to create a continuous graph line for each monitoring borehole. Graph lines were evaluated for display with or without the inclusion of gaps in the data. Graph lines were better understood when gaps were not included in the lines. Important gaps in the data have been indicated on the graphs of currently operational monitoring stations. Operational monitoring station locations are shown in Figure 3-3.

3.2.1 Closed stations

There were various water level monitoring stations in the Middelburg vicinity which operated at some point, but they have been closed down for whatever reason. The water level measurements for these stations were however conserved, archived and made available by the Department of Water Affairs.

Two graphs, namely Figure 3-1 and Figure 3-2 were drawn for two groups of stations that operated at two distinctly different time periods namely 1956 - 1967 and 1987 - 1993. The group of stations that were monitored between 1956 and 1967 are all located on the Grootfontein farm and were presumably monitored by the Grootfontein Agricultural College (see Table 3-1 and Figure 3-1). Data from the two groups of stations that operated in these two time periods are shown with basic line extrapolation by line connection between gap points as well as consecutive points. Markers (points) on each monitoring borehole graph indicate where water level measurements were taken.

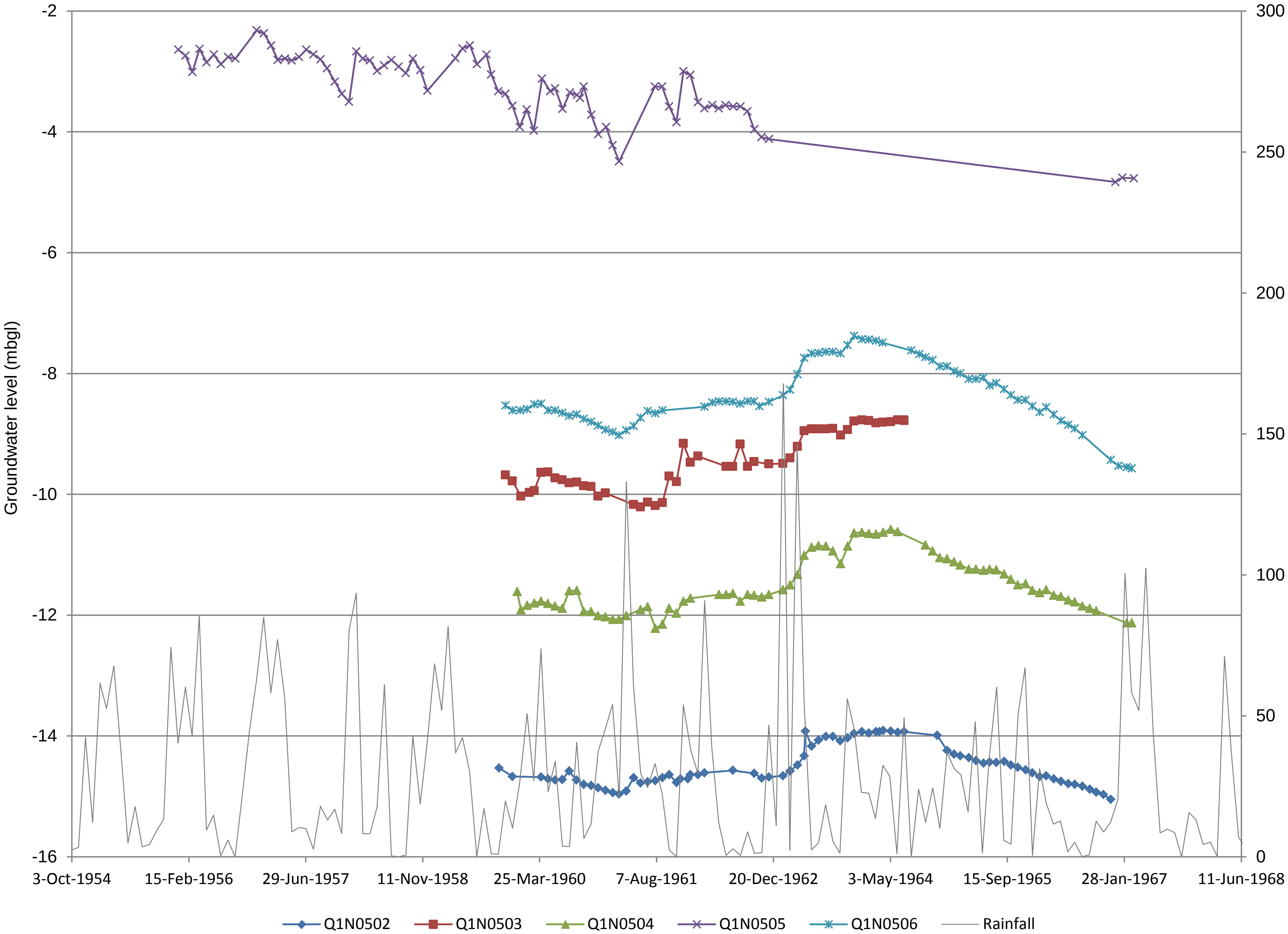


Figure 3-1: Grootfontein closed monitoring stations with groundwater levels from 1956 to 1967

Table 3-1: Grootfontein closed stations summary table of details

Borehole No.	Farm	First WL recording		Last WL recording		Lowest (mbgl)	Highest (mbgl)	Water level change (m)
		Date	Level (mbgl)	Date	Level (mbgl)			
Q1N0502	Grootfontein	1959/10/03	-14.530	1966/12/01	-15.050	-15.050	-13.910	-0.520
Q1N0503	Grootfontein	1959/10/31	-9.680	1964/07/01	-8.780	-10.210	-8.770	0.900
Q1N0504	Grootfontein	1959/12/20	-11.610	1967/03/01	-12.130	-12.220	-10.580	-0.520
Q1N0505	Grootfontein	1956/01/01	-2.640	1967/03/10	-4.770	-4.830	-2.320	-2.130
Q1N0506	Grootfontein	1959/10/31	-8.530	1967/03/01	-9.570	-9.570	-7.380	-1.040

Groundwater level trend analysis of the closed down Grootfontein monitoring stations show that from around 1964, there was a decline in all groundwater levels monitored until the stations closed.

The other group closed groundwater monitoring stations (boreholes) that operated between 1987 and 1993 are shown in Table 3-2. The time series water levels that have been recorded are plotted in Figure 3-2. These water levels as a whole show a rise in groundwater levels in all but one monitoring borehole.

Table 3-2: Summary table of various closed stations and their details

Borehole No.	Farm	First WL recording		Last WL recording		Lowest (mbgl)	Highest (mbgl)	Water level change (m)
		Date	Level (mbgl)	Date	Level (mbgl)			
Q1N0061	Bultfontein	1987/09/14	-4.230	1993/01/05	-3.470	-4.900	-2.160	0.760
Q1N0065	Middelburg Allotment	1987/09/14	-17.700	1993/02/03	-14.580	-17.700	-10.380	3.120
Q1N0066	Grootfontein	1987/09/14	-4.280	1993/01/06	-3.920	-4.570	-2.220	0.360
Q1N0068	Rietfontein	1987/11/18	-5.510	1993/02/03	-5.240	-5.910	-4.010	0.270
Q1N0072	Buffels vallei	1987/09/14	-6.640	1993/02/03	-5.380	-6.810	-4.990	1.260

3.2.2 Locations of active monitoring boreholes

The locations of currently active monitoring boreholes with electronic water level loggers are shown in Figure 3-3. This figure also shows the relative amounts of the mean yearly volume of groundwater abstracted by each municipal borehole by the size of the blue circular buffer around it. The mean annual abstraction was calculated from the available municipal abstraction volumes for the time period between Jan 2001 to June 2006. The monthly abstraction volumes for the former mentioned period are the only abstraction volumes that could be obtained from the Middelburg municipality. The map also gives some indication of how the boreholes are located in terms of geology and the localized area around Middelburg town itself.

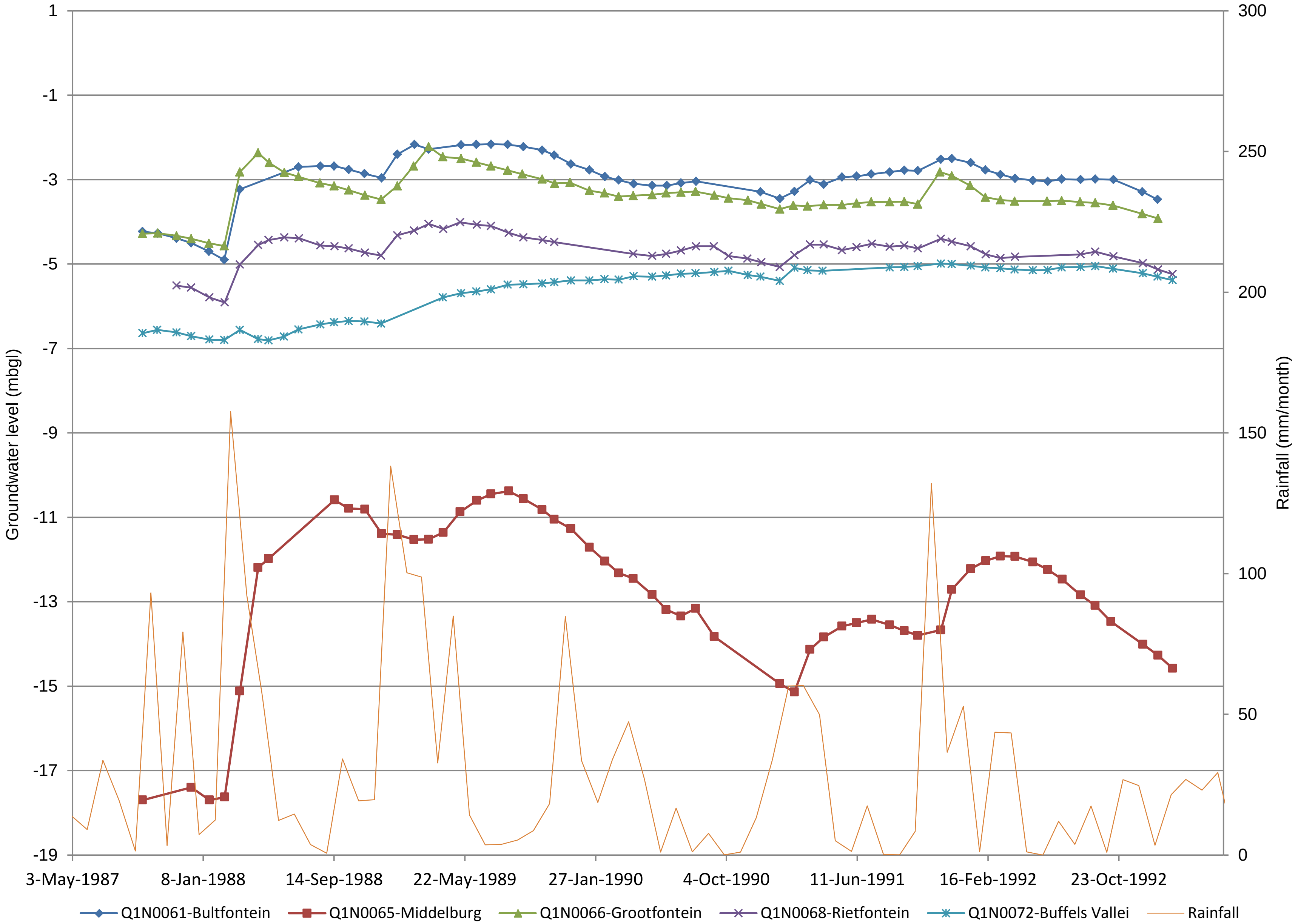


Figure 3-2: **Closed monitoring station groundwater levels between 1987 and 1993**

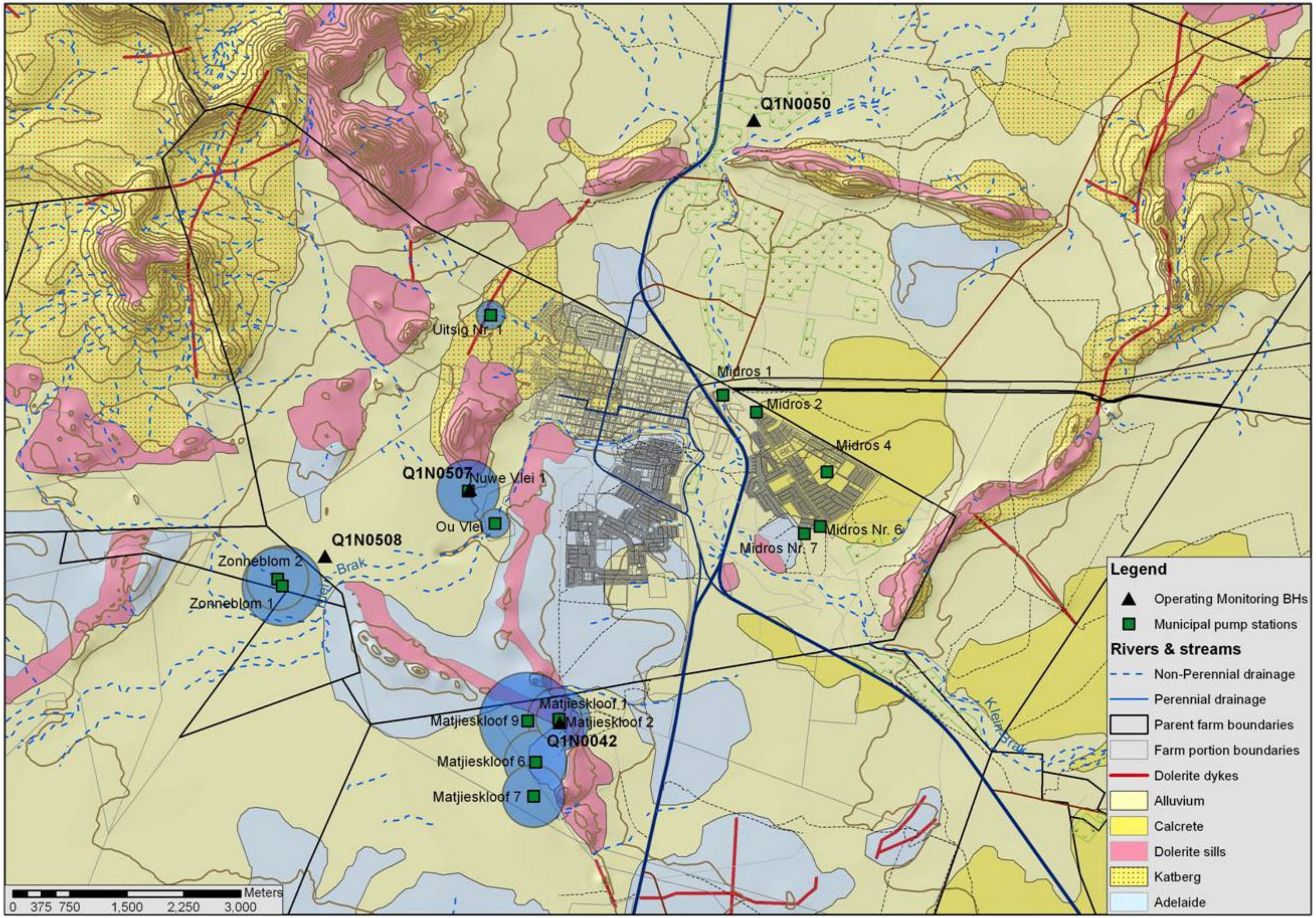


Figure 3-3: Map showing operational DWA water level monitoring boreholes with municipal boreholes & abstraction

3.2.3 Q1N0042 – Bultfontein, Matjieskloof (Operational)

The logger started operation on 22 August 1978 and is still in operation. Water level information for this logger was obtained until 13 August 2013. The water level was at -2.51 mbgl on 22 August 1978 and the water level measured on 22 August 2010 was -23.195 mbgl, while the water level on 13 August 2013 was -11.710 mbgl. The water level drop taken in the same season over exactly 32 years (1978 - 2010) was -20.685 m, which is significant and accounts for more than two thirds of the alluvial shallow aquifer. There are no gaps in the whole dataset greater than 31 days which is impressive considering the 35 years of water level measurements. The data has been audited and verified as good by Mr. Cobus Ferreira.

The water level graph in Figure 3-4 is perhaps the most disconcerting and at the same time positive water level of all historic water levels showed. Although the noise from a close abstraction borehole disguises to some degree the water level decline, if the water level and its axis scale are compared to other water levels and their axes on the other graphs, it is startling to see at what depth the Q1N0042 water level started and at what level it was during 2010. The contrary is to see how well the water level has recovered since 2010 (see Table 3-3). The highest (maximum) water level for the data set was -2.30 mbgl on 27 April 1987 while the lowest (minimum) water level was -25.903 mbgl on 29 December 2005. Based on the given water level information, this aquifer is constantly overstressed and is not sustainable with current management practices. Due to the significant water level decline, the municipality has also decided to pump this borehole intermittently, thus causing large fluctuations in the water level and putting a higher stress on the aquifer when the pump is started each time, than the stress that would be put on the aquifer if the abstraction would continue on a 24 hour duty cycle (water quality/dissolved oxygen- and cone of depression-implications). On a constant and lower abstraction rate in a 24 hour duty cycle, the hydraulic head would to some extent be able to stabilise with the negative pressure caused by the abstraction. The aquifer is probably situated in a compartment with outer boundaries (see Figure 3-3).

Table 3-3: Water level parameters for monitoring borehole Q1N0042, Matjieskloof

	Starting parameters		Last recording		Total water level change		Average change	
Name	Date	water level	Date	water level	Total time years (same month)	level (m)	Up to date	Change (m/a)
Q1N0042	22/08/1978	-2.510	23/11/2010	-22.815	32	-18.464	22/08/2010	-0.577
Q1N0042	23/11/2010	-22.815	13/08/2013	-11.710	3	11.105	22/08/2010	3.702

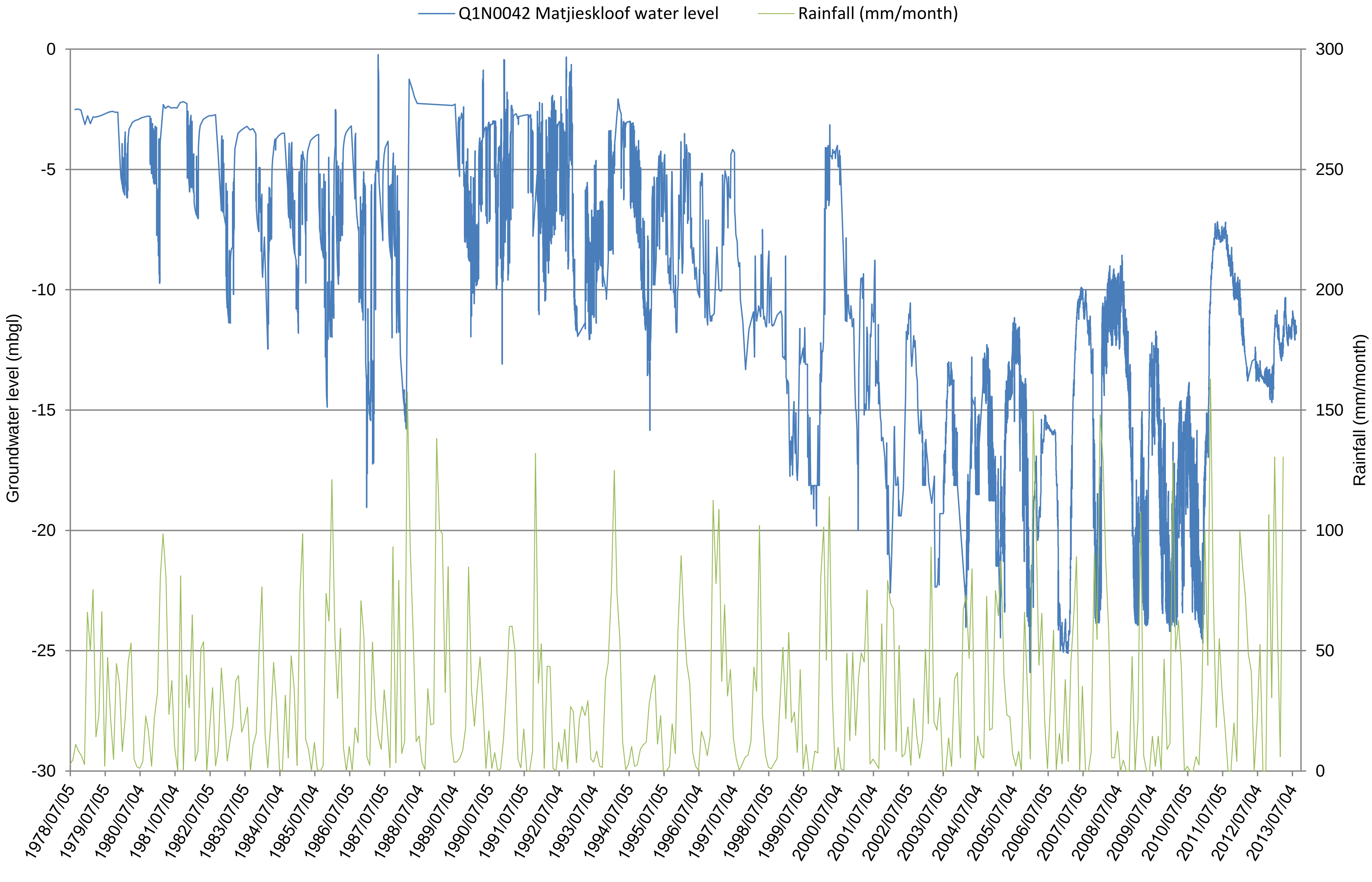


Figure 3-4: Water level over time for monitoring borehole Q1N0042 at Matjieskloof

3.2.4 Q1N0050 – Grootfontein (Operational)

Grootfontein water level monitoring started on 26 October 1959. Water levels are still being recorded (at high frequency) at this site and data was obtained up to 23 November 2010. This groundwater level monitoring borehole is located within the Grootfontein compartment/ sub-catchment while the other three operational DWA monitoring boreholes are located within the Middelburg sub-catchment (Figure 3-3). The monitoring borehole is also located within the Grootfontein Agricultural College well field (closest abstraction borehole ± 45 m away) with five boreholes in close proximity used in rotation to fill the College's concrete reservoir.

It is assumed that water level measurements were done by hand during the first years of water level monitoring, judging by the time between water level measurements (Figure 3-5). The first few years (1959 - 1978) have 29 large (average 217 days; gaps larger than 2 months) gaps in between them up to 24 February 1978. After 24 February 1978 there are 2 gaps not longer than 3 months each, between readings and one larger gap of 153 days (approximately 5 months) between 2 January 1997 and 4 June 1997. Water levels are still being recorded (at a high interval) at this site and water level data was obtained up to 23 November 2010.

The water level was at -9.730 mbgl on 26 October 1959 and the water level measured on 26 October 2010 was -5.830 mbgl, while the water level on 23 November 2010 was -5.90 mbgl. The highest (maximum) water level for the data was -1.190 mbgl on 30 August 1981 while the lowest (minimum) water level was -10.63 mbgl on 3 March 1971.

The water level rise taken in the same season over exactly 51 years was 3.9 m, although it is not considered representative due to the anomalies in the graph such as the one between 24 and 28 February 1978. It also has to be noted that the hydrogeologic conditions around the borehole is suspected to have changed or the manner in which the water level was being measured must have changed. There was an abrupt rise in water level between gaps 11 October 1973 and 1 May 1974 and 6 December 1974. There was again an abrupt rise in water level between 24 February 1978 with water level at -6.5 mbgl and 28 February 1978 with water level at -1.5 mbgl, presumably with the installation of a water level logger instrument. As mentioned earlier, after 28 February 1978 the water level readings were taken at high frequency and the graph makes more sense.

The water level trend in Figure 3-5 after 28 February 1978 is still disconcerting.

A large recharge event during the 2007/2008 rainy season (October – end March) and another during the 2010/2011 rain season lifted the water level by about 0.5 m and 1 m respectively and are clearly visible in Figure 3-5.

Table 3-4: Water level parameters for monitoring borehole Q1N0050, Grootfontein

Name	Starting parameters		Last recording		Total water level change		Average change	
	Date	water level	Date	water level	Total time years (same month)	level (m)	Up to date	Change (m/a)
Q1N0050	26/10/1959	-9.730	23/11/2010	-5.900	51	3.900	26/10/2010	0.076
Q1N0050	13/08/2010	-5.730	13/08/2013	-3.290	3	2.440	13/08/2013	0.813

When data is evaluated from 28 February 1978 (water level at -1.50 mbgl) onwards, the groundwater level declines to a maximum depth of -7.31 mbgl on 31 March 2007, a decrease of -5.81 m. After the 31 March 2007, the water level recovers due to the two large recharge events mentioned above to a current level of -3.28 mbgl measured on 13 August 2013, a water level increase of 4.03 m.

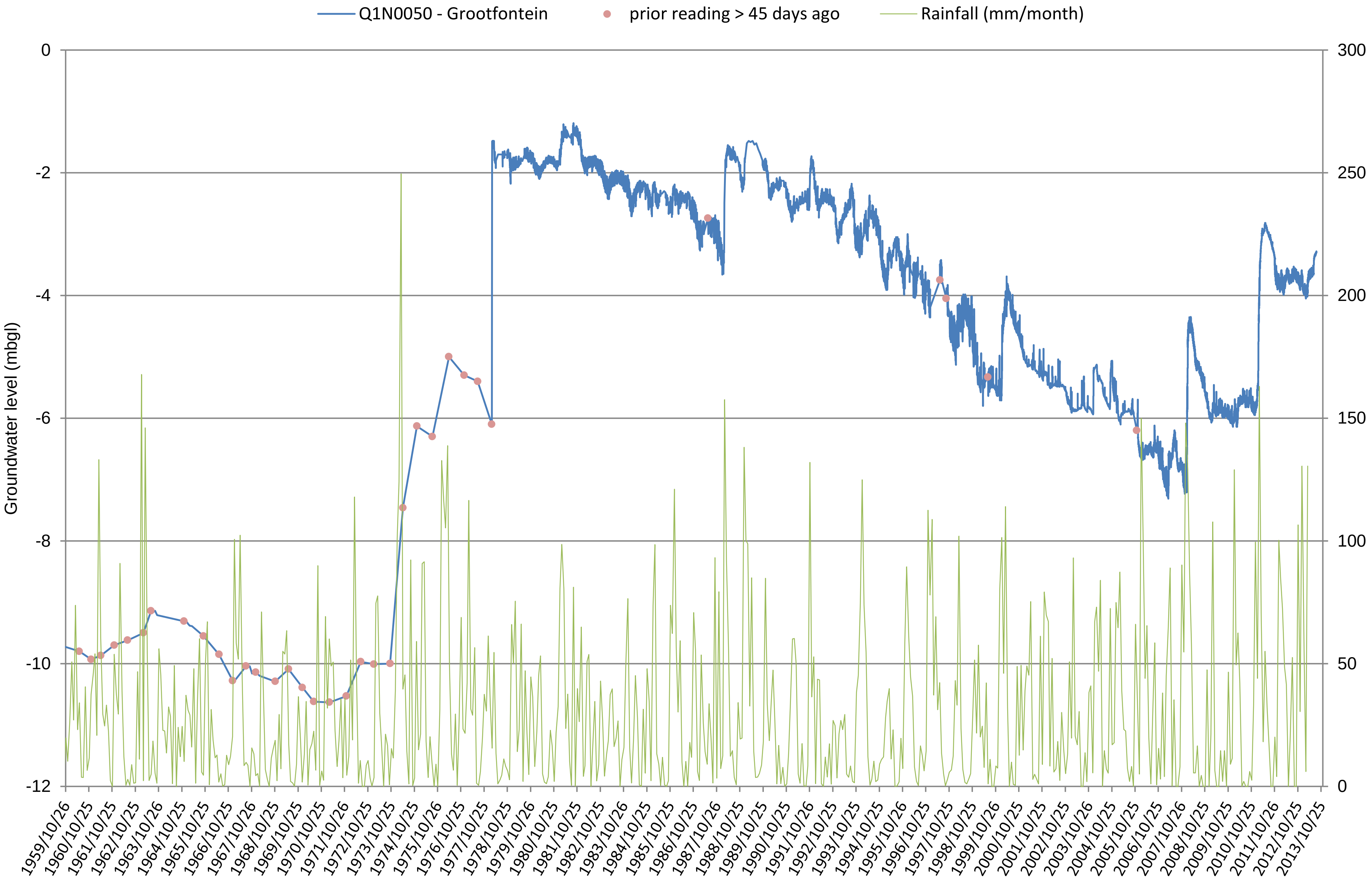


Figure 3-5: Groundwater level over time for borehole Q1N0050 at Grootfontein Agricultural College

3.2.5 Q1N0507 – Nuwevlei (Operational)

The water level logger started operating on 7 July 1966 and is still in operation. Water level information for this logger was obtained until 13 August 2013. The water level was at -7.60 mbgl on 7 July 1966 and the water level measured on 7 July 2010 was -10.15 mbgl, while the water level on 13 August 2013 was -9.61 mbgl. The water level drop taken in the same season over exactly 44 years was -2.55 m. It has to be taken into account however that the Nuwevlei pump station for the municipality is not pumped at full capacity anymore. There were four gaps greater than 4 months and two gaps greater than 2 months, but less than 3 months (Table 3-5).

Other minor gaps in the data are less than two months between 2 consecutive water level readings which is considered acceptable given the total length of time of monitoring.

Table 3-5: Summary water level parameters for Q1N0507 Nuwevlei

	Starting parameters		Last recording		Total water level change		Average change	
Name	Date	water level	Date	water level	Total time years (same month)	level (m)	Up to date	Change (m/a)
Q1N0507	07/07/1966	-7.600	23/11/2010	-10.490	44	-2.550	07/07/2010	-0.058
Q1N0507	13/08/2010	-10.090	13/08/2013	-9.610	3	0.480	07/07/2010	0.160

The highest (maximum) water level for the dataset was -3.470 mbgl on 16 August April 1977 while the lowest (minimum) water level was -12.210 mbgl on 17 September 1999.

The Q1N0507 monitoring borehole is located approximately 27 m away from the Nuwevlei 1 abstraction borehole (pumping station) as seen on Figure 3-3.

The initial rapid decline of the groundwater level can be seen in Figure 3-6 from 1966 to January 1974 where after two major recharge events between 1974 – 1976 and 1988 – 1990 respectively took place to recharge the aquifer to greater than its initial water level volume. Significant abstraction from Nuwevlei production sites however decrease the water level each time, until at a point in the graph a lowest level is reached, where the level does not decline anymore.

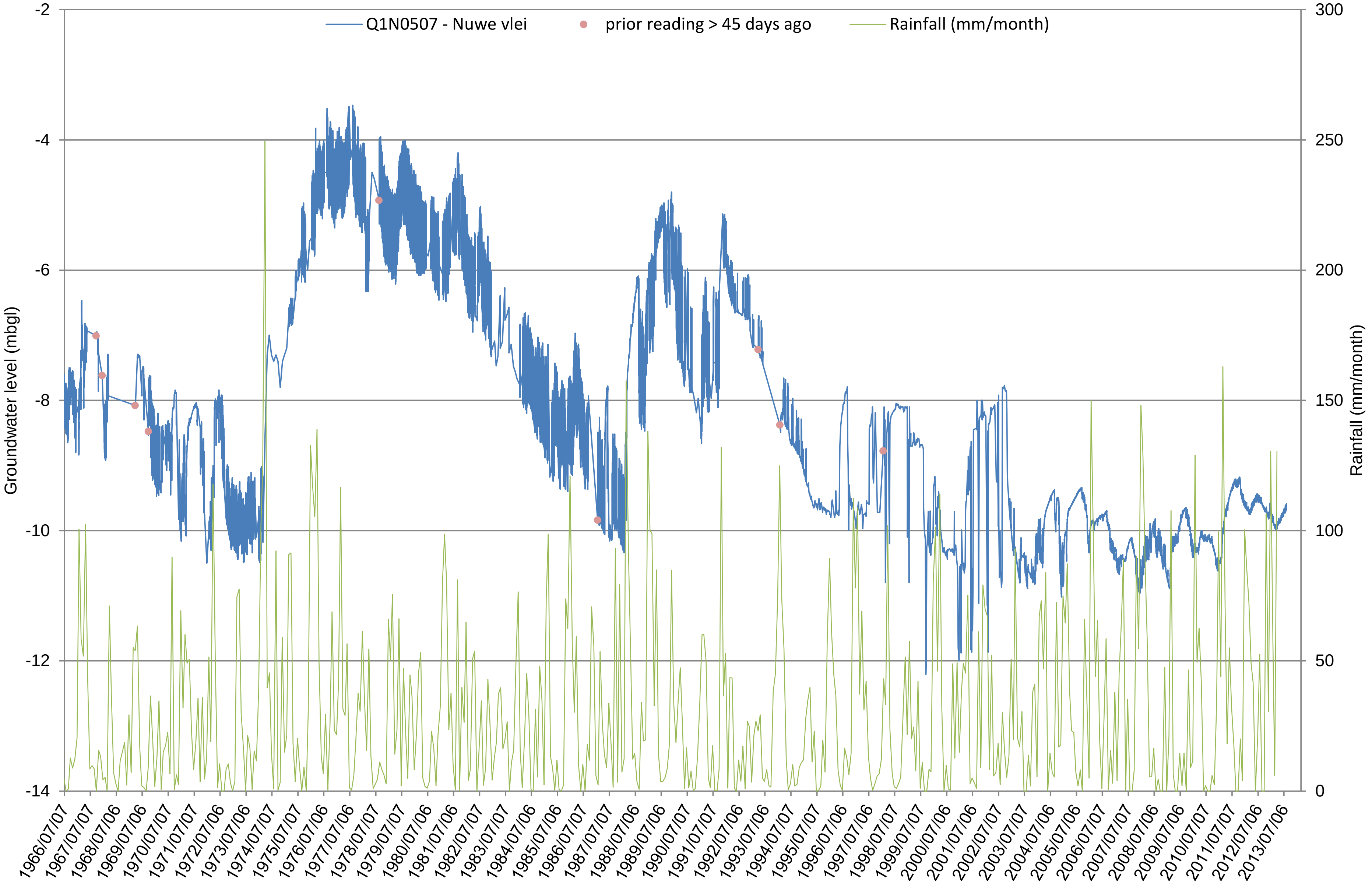


Figure 3-6: Water level over time for Q1N0507 at Nuwevlei

3.2.6 Q1N0508 – Downstream of Zonnebloem municipal abstraction (Operational)

The logger started operation on 19 September 1987 and is still in operation. Water level information for this logger was obtained until 27 June 2013. The water level was at -5.040 mbgl on 19 September 1987 and the water level measured on 19 September 2012 was -7.382 mbgl, while the last recorded water level on 27 June 2013 was -6.750 mbgl. The water level drop taken in the same season over exactly 25 years was -2.342 m. A graph of the groundwater level change over time for Q1N0508 is shown in Figure 3-7. This station is located approximately 620 m downstream of Zonnebloem 1 and Zonnebloem 2 municipal abstraction boreholes (see Figure 3-3). There are no gaps in the dataset greater than one month from 19 September 1987 to 27 June 2013. The lowest recorded water level was -10.230 mbgl on 31 August 2007 while the highest recorded water level was -3.111 mbgl on 18 November 1991.

Table 3-6: Summary water level parameters for Q1N0508, near Zonnebloem 1 & 2

	Starting parameters		Last recording		Total water level change		Average change	
Name	Date	water level	Date	water level	Total time years (same month)	level (m)	Up to date	Change (m/a)
Q1N0508	19/09/1987	-5.040	23/11/2010	-9.160	23	-3.890	19/09/2010	-0.169
Q1N0508	23/11/2010	-9.160	23/11/2012	-7.250	2	1.910	19/09/2010	0.955

From 18 November 1991 there was a dominant declining trend in the groundwater level until 31 August 2007. After 31 August 2007, there was a large recharge event in the 2007/2008 rainy season (started in October 2007) that reversed the declining trend into a recovering/ rising groundwater level trend. Clearly an above average rainfall hydrological year occurred in 2007/2008. During the 2008/2009 and 2009/2010 hydrological years rainfall recharge was not enough to counter abstraction and the trend started to turn again. Another two above average rainfall years occurred in 2010/2011 and 2011/2012, that again resulted in a rising groundwater level trend. This is confirmed in the SAWS rainfall figures with 598.4 mm (2007/2008), 214 mm (2008/2009), 358 mm (2009/2010), 535.6 mm (2010/2011) and 444.5 mm (2011/2012).

The groundwater level change in the Q1N0508 monitoring borehole downstream of the Zonnebloem municipal abstraction boreholes is different from the other three operational DWA monitoring stations discussed above. Q1N0508 is 620 m downstream of the abstraction boreholes and its graph is more gradual with less noise, providing a clear representation of the water level fluctuation in the shallow aquifer itself (see Figure 3-7).

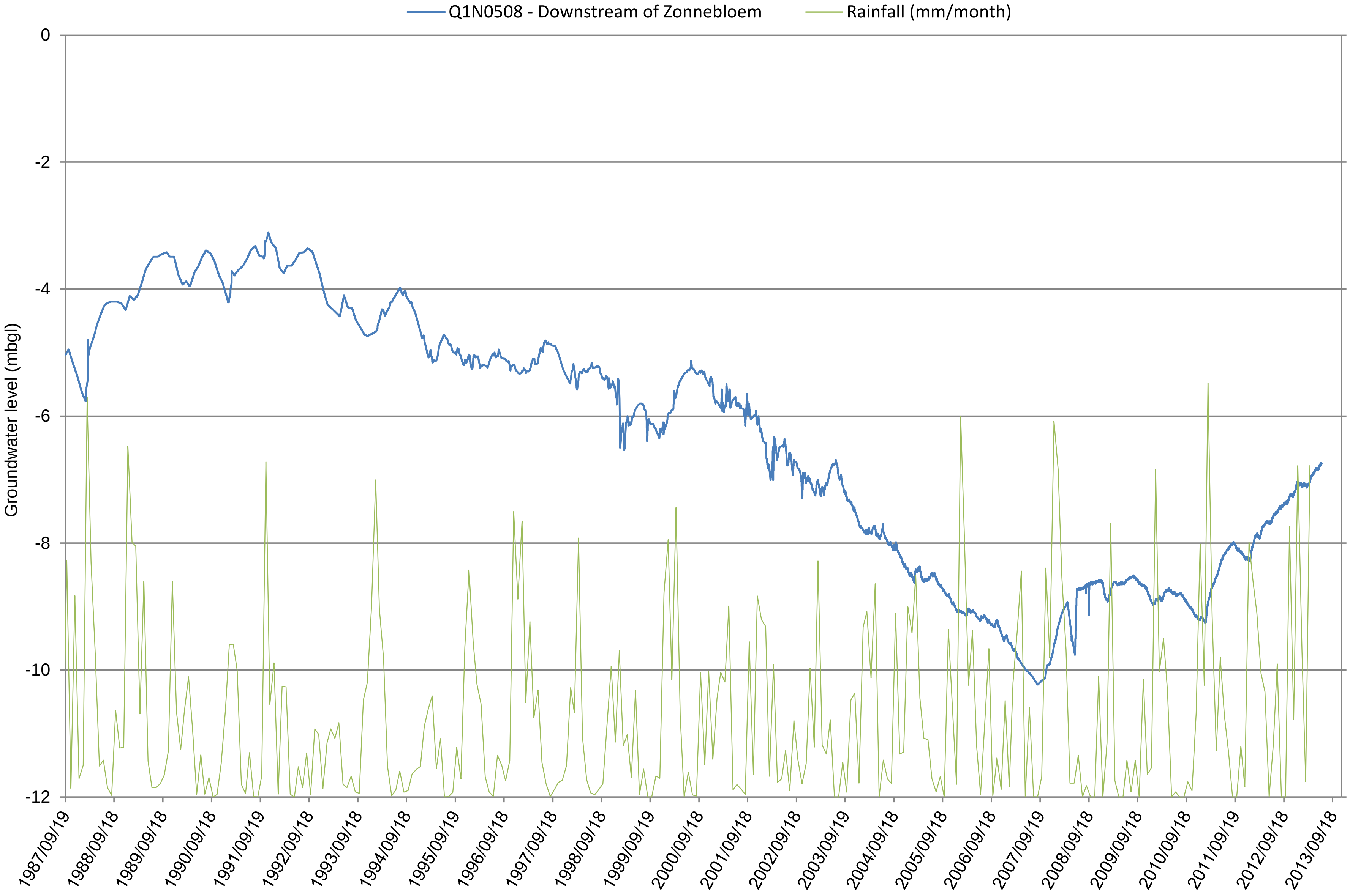


Figure 3-7: Groundwater level change over time for monitoring borehole Q1N0508 downstream of Zonnebloem abstraction

3.3 Abstraction from existing municipal water supply boreholes

Volumes abstracted from existing municipal production boreholes are summarised in Table 3-7. Monthly volumes from abstraction boreholes were available from January 2001 to July 2006 and are provided in Appendix A (see CD in enclosure). A bar chart in Figure 3-8 was also drawn to show the change of annual abstraction volumes from municipal abstraction boreholes over time.

Table 3-7: Annual volumes abstracted from municipal boreholes that are available

GEOSITE ID	NAME	2001 (m^3/a)	2002 (m^3/a)	2003 (m^3/a)	2004 (m^3/a)	2005 (m^3/a)
EC-Q14-019	Midros 1	58 303	36 303	15 692	11415	18 949
Midros 2	Midros 2	48 558	31 382	13	0	0
EC-Q14-866	Midros 4	9 481	6 257	0	0	0
EC-Q14-016	Midros 6	46 214	75 877	131 878	274945	272 741
EC-Q14-015	Midros 7	96 273	182 183	166 372	77081	134 587
EC-Q14-031	Matjieskloof 1	315 279	5 596	23 255	40673	19 540
EC-Q14-030	Matjieskloof 2	148 286	228 170	146 798	120250	119 132
EC-Q14-029	Matjieskloof 6	195 602	260 054	135 785	27800	29 212
EC-Q14-028	Matjieskloof 7	48 034	94 780	48 047	180233	193 271
EC-Q14-033	Matjieskloof 9	638 653	430 284	305 048	267321	236 299
EC-Q14-026	Ou Vlei	20 530	44 048	62 099	44378	61 767
EC-Q14-025	Nuwe Vlei	105 481	113 417	328 732	78150	12 727
EC-Q14-020	Uitsig	21 608	21 803	32 451	47864	9 928
EC-Q14-104	Zonnebloem 1	172 622	258 200	279 413	281135	273 606
EC-Q14-103	Zonnebloem 2	86 747	113 239	149 357	218490	285 368
TOTAL		2 011 671	1 901 593	1 824 940	1 669 735	1 667 127

It can be observed that there was a general decrease in total annual volumes pumped from municipal boreholes from 2001 to 2006. Thus from the water level data and municipal abstraction volumes there is an overall correlation of declining trend, indicating that as the groundwater volume in storage gets less (shown by water levels) the yields that can be sustained by the municipal abstraction boreholes decrease. This is an important conclusion regarding the local shallow aquifer with alluvial character and the reason the groundwater investigation for wider exploration of new groundwater sources was needed. A less obvious increasing trend in the volumes pumped from the Zonnebloem stations compared to a general decreasing trend of the other pumping stations was also noted. The Zonnebloem abstraction boreholes are newer boreholes compared to the other municipal abstraction boreholes. More importantly, they are located in a thick alluvial valley and are not bounded by outer boundaries as the Matjieskloof boreholes are. Matjieskloof boreholes have at least 1 semi-permeable boundary formed by a dolerite sill as shown from the geology in Figure 3-3. Matjieskloof 9 is also a newer abstraction borehole.

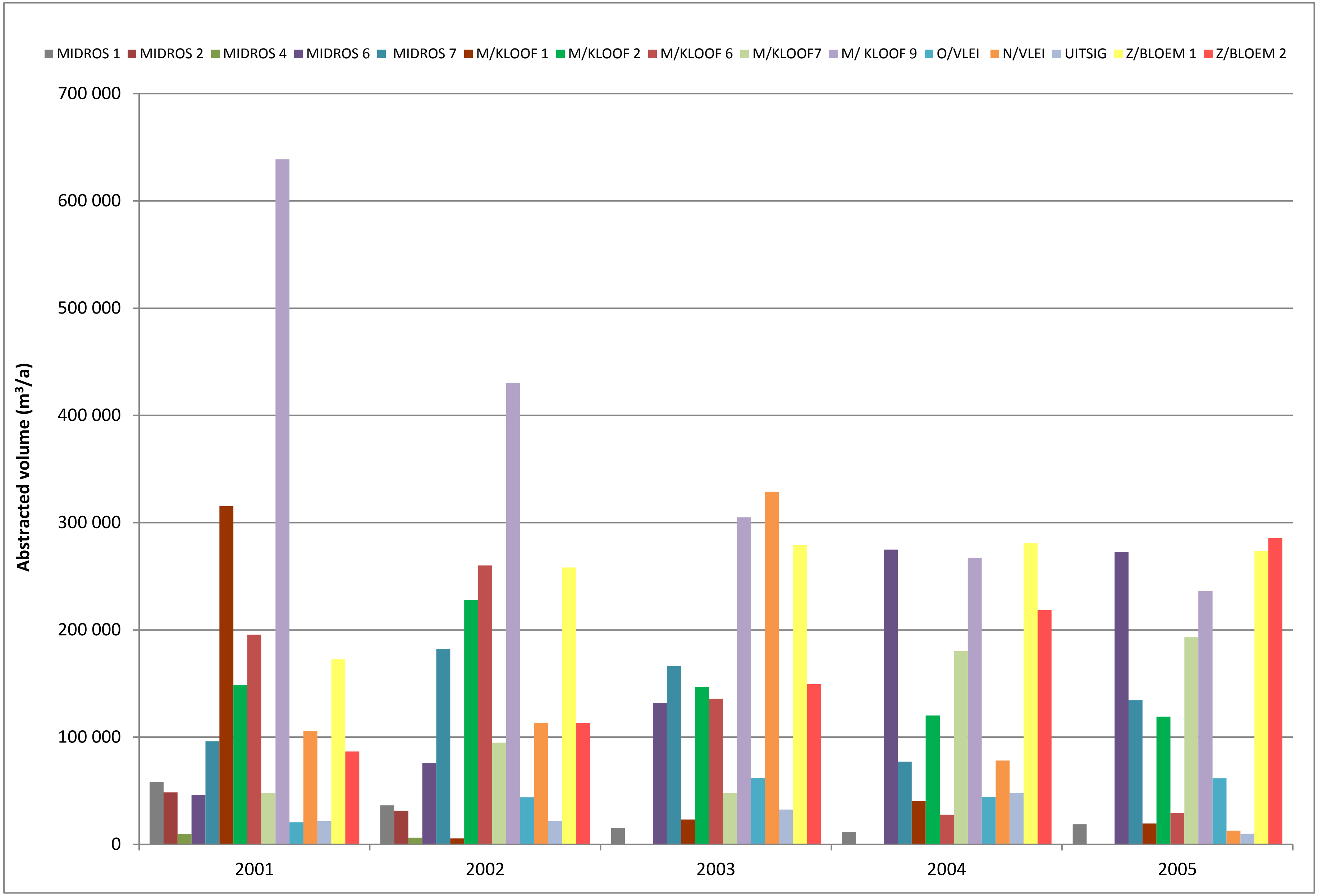


Figure 3-8: Monthly abstraction from municipal boreholes over time

3.4 Conclusions

All hydraulic heads (water levels) measured in operational DWA monitoring boreholes show responsive behaviour to abstraction and are representative of hydraulic head change over time. In addition, good maintenance of the monitoring equipment and auditing of the data was carried out by DWA.

There has been a definite decline in hydraulic heads in all operational DWA monitoring boreholes. The monitoring boreholes began operation at different times in the past, but water level declines range between -2.990 m and -23.195 m up to either the 2007/2008 rainy season or the 2010/2011 rainy season (October to March). After these dates groundwater levels in monitoring boreholes show an overall rise in water level between 0.480 m and 11.105 m, with a general rise in water levels of about 2 m. The rise in water levels have been shown to be a direct result of above average rainfall years.

3.5 Recommendations

It is clear that current (2001 – 2006) abstraction rates are not sustainable within the Municipal sub-catchment and that additional groundwater resource development at some distance from the current abstraction is required. When these new groundwater resources are introduced into the reticulation network, municipal over-abstraction in the Middelburg Municipal sub-catchment should be reduced.

It is recommended that electronic record be kept of monthly abstraction volumes of all municipal abstraction boreholes using the installed flow meters.

4 HYDROCENSUS

4.1 Methodology

4.1.1 Hydrocensus

“Hydrocensus surveys involve the location of geosites within a certain area to be captured into a database for usage in hydrogeological investigations. This involves the incorporation and assessment of existing databases containing borehole information, but finally physical site visits locate and confirm all boreholes and geosites in a given study area. Middelburg in the Eastern Cape was identified by The Department of Water Affairs (DWA) as a crisis area (hotspot), based on suspected over abstraction by the groundwater users from the shallow aquifer. DWA suggested a comprehensive hydrocensus be done in a 30 km radius around Middelburg to verify all groundwater use and to quantify the groundwater uses for a groundwater balance of the area. A comprehensive hydrocensus was undertaken in a 30 km radius area around Middelburg. This hydrocensus was then structured to provide maximum efficiency and results pertaining to the objectives of the study. The hydrocensus was structured by assigning weight and prioritising certain areas according to:

1. 30 km radius around Middelburg;
2. Catchments and sub-catchments that recharge the aquifer systems underlying Middelburg and the surrounding areas within a 30 km radius;
3. Target areas with high groundwater potential based on desktop study results as well as research and studies previously done in and around the area of interest;
4. Hydrocensus of farms in identified catchments and target areas;
5. Door to door hydrocensus in Middelburg town itself.

The identification and logging of the boreholes themselves were conducted according to the DWAF GRIP (Groundwater Resource Information Project) standards during the hydrocensus. This entailed that for each borehole identified, a detailed hydrocensus form be filled in, capturing many types of information about the borehole itself, such as the exact borehole location, equipment and the condition of the borehole. Captured boreholes are then renumbered according to the logical DWAF GRIP EC numbering system, whereby a borehole is captured on the database and receives a borehole number for example:

EC-Q14-195

This borehole number can be seen as a qualitative borehole number, first indicating that the borehole is in the Eastern Cape (**EC**), then it indicates in which tertiary catchment (**Q14**) it is, after which a normal sequence number follows (**195**).

During the hydrocensus other information of significance to the Groundwater balance model was also gathered as farms were surveyed. Such information included quantifying the irrigation area as well as obtaining borehole yield information where possible."
(Grobler *et al.*, 2008: 4)

The GRIP hydrocensus data used in this chapter can be obtained from the DWA GRIP Eastern Cape website: www.gripec.co.za or by logging a request at ngaur@dwa.gov.za for the data in catchments of interest or to create an account for the GRIP EC website.

4.1.2 Data processing and database

Since location is the most important information of a geosite surveyed, that data had to be cleaned to some extent primarily based on Geosite name and location. Geosite records with blank or erroneous names or coordinates were removed from the data set and also excluded from all statistics. In total three geosite records were removed from the database of 1695 records to leave a total of 1692 records. Also to take note is that some types of information such as borehole depth and water level cannot always be obtained and is then not available for every geosite.

4.1.3 Sub-catchment delineation

Prior to sub-catchment delineation, hydrocensus results were evaluated to ascertain where high density abstraction is taking place as well as where high borehole densities occur. Hydrocensus water quality results were also screened with GIS maps to determine if there are any zones in the study area with serious water quality problems, which would need to be excluded from groundwater exploration target areas.

The approach for sub-catchment delineation for groundwater exploration was to explore on a more regional scale (geological structures within a 30km proximity of Middelburg) and to also perform deep (300 mbgl) groundwater exploration. Sub-catchments were delineated based on the structural geology that is synonymous with the igneous dolerite intrusions in the Karoo, forming a multitude of sill- and ring-complexes as well as some large linear structures in the form of dykes (J. Myburgh *pers. comm.*, 2008). Geological maps, orthorectified aerial photographs and Aster satellite imagery was used to identify specific dolerite sill- and ring-complexes to be targeted at depth. The sill- and ring-complex structures also to a large degree control the geomorphology of the study area and thus also form the prominent watersheds in the area. Sub-catchments were also delineated to target the dyke lineaments that are very prominent in the study area, such as the Dunblane dyke.

Hydrological principles were further applied to delineate the sub-catchments sensibly based on the topography and drainage of the study area.
The Middelburg project study area was very slightly modified where it was in close proximity to sub-catchment and quaternary catchment boundaries so that the complete sub-catchment polygons were contained in the study area. The study area boundary, based on farm boundaries did not at minor points coincide with the watershed boundaries i.e. the catchment boundaries. This amendment to the project area was necessary in order to process and clip features such as the contour lines, catchments and the Digital Terrain Model (DTM).

4.1.4 Hydrochemistry

During the hydrocensus groundwater samples were taken at boreholes where an open stream of water was available to fill the bottle as the water was being pumped from the borehole or wind pump. The sampling protocol was further conducted according to the groundwater sampling manual by Weaver *et al.* (2008).

Groundwater samples from the boreholes were submitted to the SANAS accredited Talbot & Talbot laboratories to be analysed for physical parameters, macro- and trace-elements as well as microbiological constituents as they are applicable to potable water guidelines.

Results from the analysis were evaluated and interpreted by using the DWA guideline document entitled *Quality of Domestic Water Supplies: Assessment Guide, Volume* 1(2nd ed., 1998) published by the Water Research Commission. The Assessment guide provides a practical and implementable framework and classification system for the DWAF South African Water Quality Guidelines for domestic use 2nd ed. (1996). The SA Water Quality Guidelines (1996) were determined and compiled by studying and implementing various industry standards for allowable concentrations of chemical and microbiological constituents in drinking water. These guidelines and standards include from the international community; the World Health Organisation (WHO) Drinking Water Guidelines, The European Community Drinking Water Standards and the United States Environmental Protection Agency's (US EPA) quality criteria for domestic water supplies to name a few. The international guidelines for constituents were adapted for the South African water quality context and problems and national guidelines and standards were also used such as the SABS, Specification for Water for Domestic Supplies (1984).

The classification system in the DWAF Assessment guide shows the different effects on the water user for a range of concentrations for constituents commonly found in drinking water. The basic classification and associated type of water quality is shown in Table 4-1.

Table 4-1: Water quality classification and Assessment guide

Class 0	Ideal water quality	Natural water. Suitable for lifetime use
Class 1	Good water quality	Suitable for use, rare instances of negative effects.
Class 2	Marginal water quality	Conditionally acceptable. Negative effects may occur in some sensitive groups.
Class 3	Poor water quality	Unsuitable for use without treatment. Chronic effects may occur.
Class 4	Dangerous water quality	Totally unsuitable for use. Acute effects may occur.

The DWA water quality guidelines were also chosen above the SABS guidelines as the project was conducted for the Department of Water Affairs and the results could more easily be integrated with their existing systems and planning structures than would be possible with SABS standards.

For the Middelburg hydrocensus chemistry results, the concentrations of constituents per borehole were captured from the lab results and processed into spreadsheets with automatic calculation of classes for 10 boreholes per Excel workbook. Due to the nature of importance of the hydrocensus sampled concentrations for the task of identifying major water quality problems, statistics and piper diagrams were not done for these results. Proper hydrochemical analyses and piper diagrams were however drawn for the new boreholes drilled and aquifer tested later during the investigation and are shown in Chapter 9.

4.2 Hydrocensus results

A total of 1695 Geosites were surveyed, coordinates taken and details noted during the hydrocensus between 24 January 2007 and 20 September 2007. As discussed in the methodology data, cleaning was done to ensure an accurate dataset. In total three geosite records were removed from the database of 1695 records to leave a total of 1692 records (Figure 4-1).

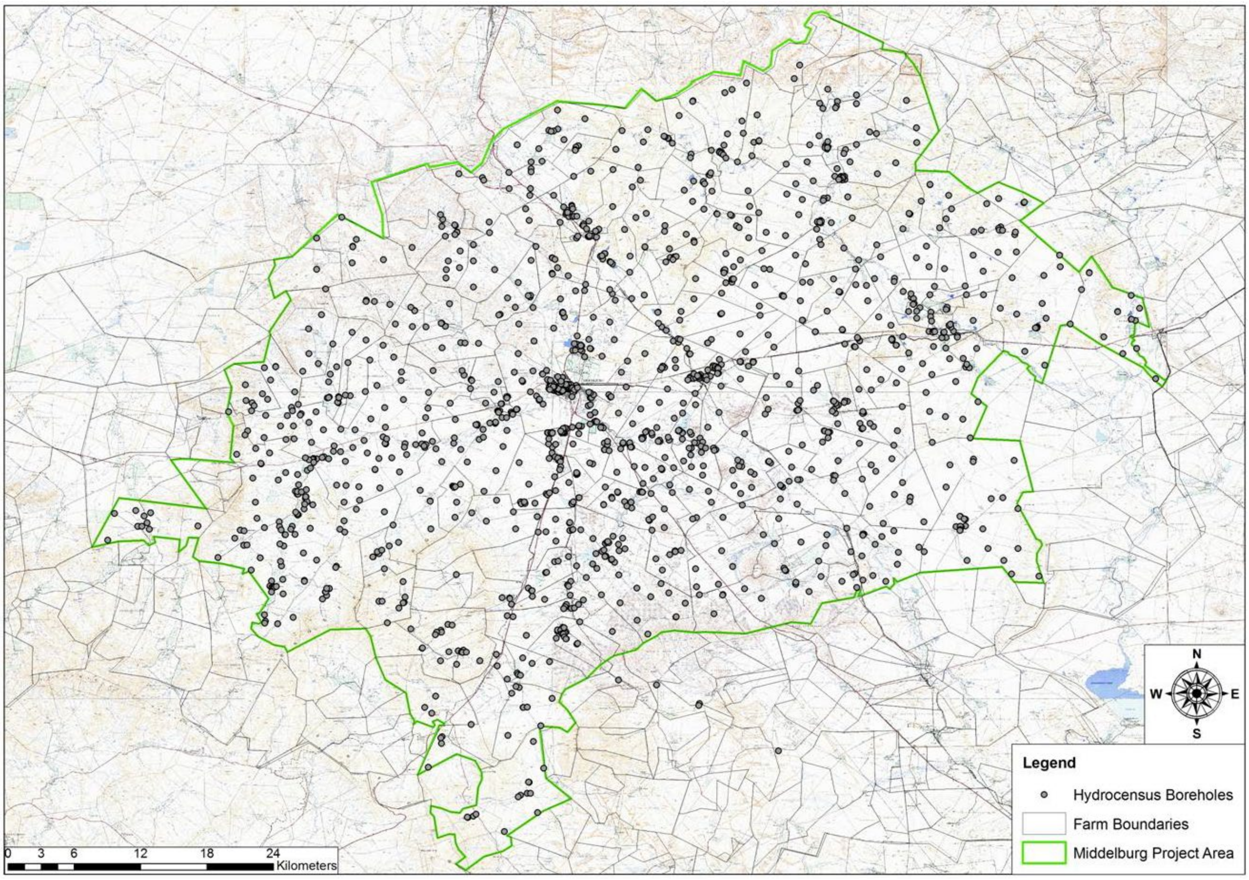


Figure 4-1: The 1692 boreholes from the detailed hydrocensus of the Middelburg study area

4.2.1 General statistics from hydrocensus

The geosite *Site Type* attribute was used to categorise the geosites surveyed and from the 1692 geosites identified, 1616 were boreholes, 45 fountains were found and 24 geosites were classified as a large diameter dug well type (Figure 4-2). The large amount of shallow dug wells and presence of a number of springs in the Middelburg area indicate that a very shallow a water level is present in many areas.

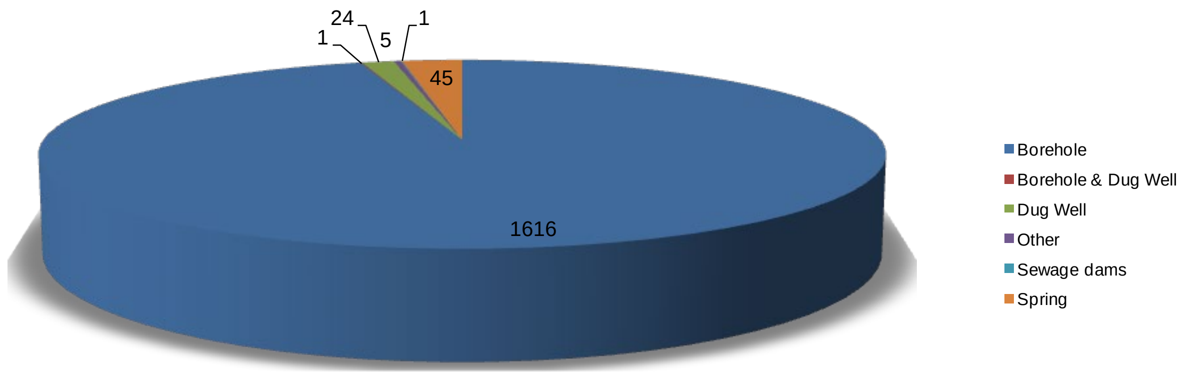


Figure 4-2: Summation of different Site Types for Geosites surveyed

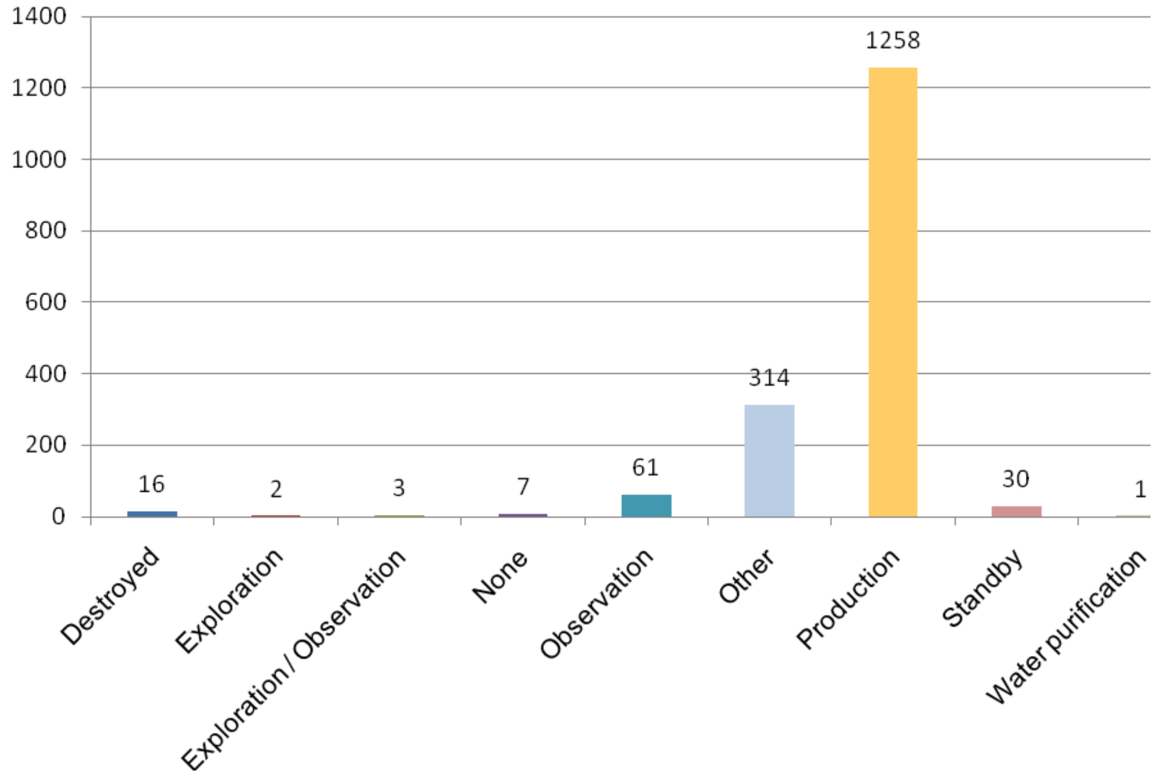


Figure 4-3: Bar graph count of each geosite purpose

Figure 4-3 displays the distribution in classes of purpose for all geosites. Production boreholes by far outnumber any other purpose classes. According to this bar chart there are 61 observation boreholes, which is contradictory to the amount of boreholes for which recorded water levels could be aquired (See Chapter 3). The information regarding observation boreholes was however gathered in the field during liaison with many farmers. It must then be concluded that a few farmers are being proactive and monitor the water levels in their own production or unused boreholes.

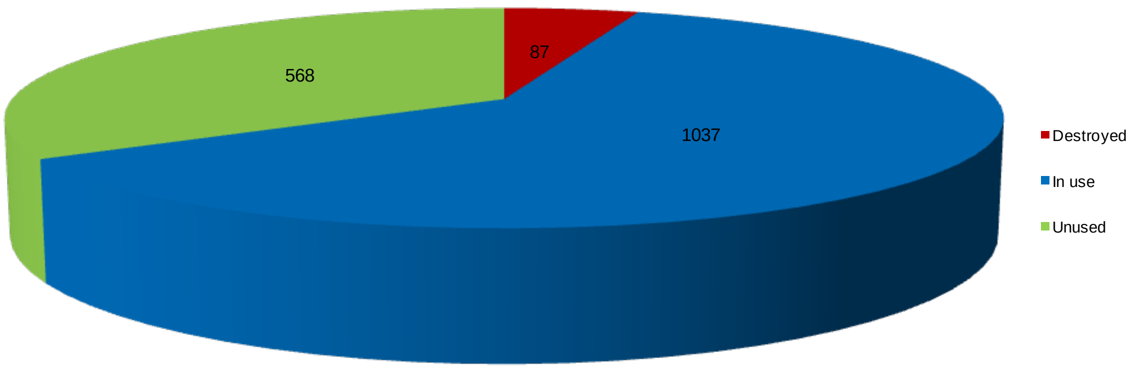


Figure 4-4: Statistical distribution of the *Status* of each geosite surveyed

Results in the pie chart in Figure 4-4 show that from the 1692 geosites surveyed in the data set, 34% or a third of boreholes are unused.

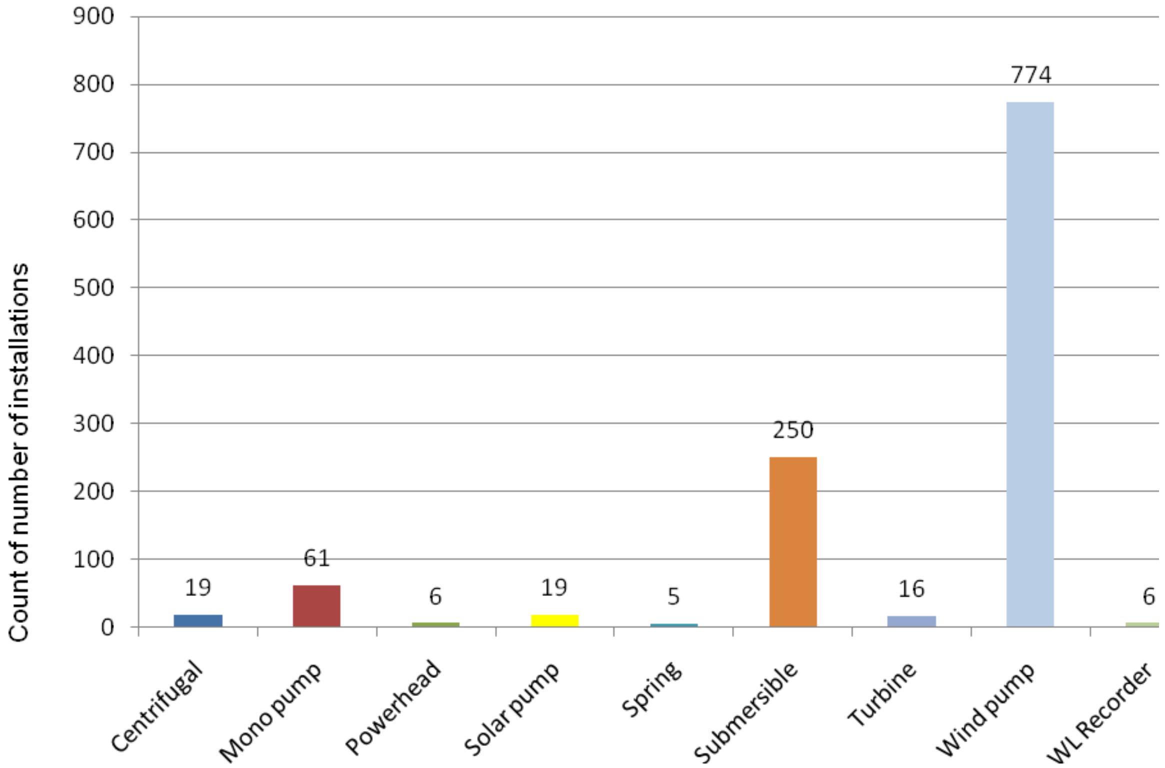


Figure 4-5: Installation types for geosites surveyed during hydrocensus

Where the status of a borehole is 'unused' or 'destroyed', or the borehole is not equipped for instance, such records were removed before plotting the bar chart for installation type in Figure 4-5. The chart shows that by far the dominant type of borehole installation is a wind pump installation. This result is expected to be because most of the farm land in the area is for sheep and cattle grazing and therefore a wind pump installation will yield enough groundwater for dams and for stock watering. Based on the results in the graph in Figure 4-5 one could argue that the area of Middelburg is actually proactive from a renewable energy point of view. The second largest count (250) of installations is that of submersibles, which yield and use significantly more groundwater than wind pumps. Third in count are 61 mono type pump installations. Mono, submersible, centrifugal and turbine type installations are disconcerting in terms of groundwater use.

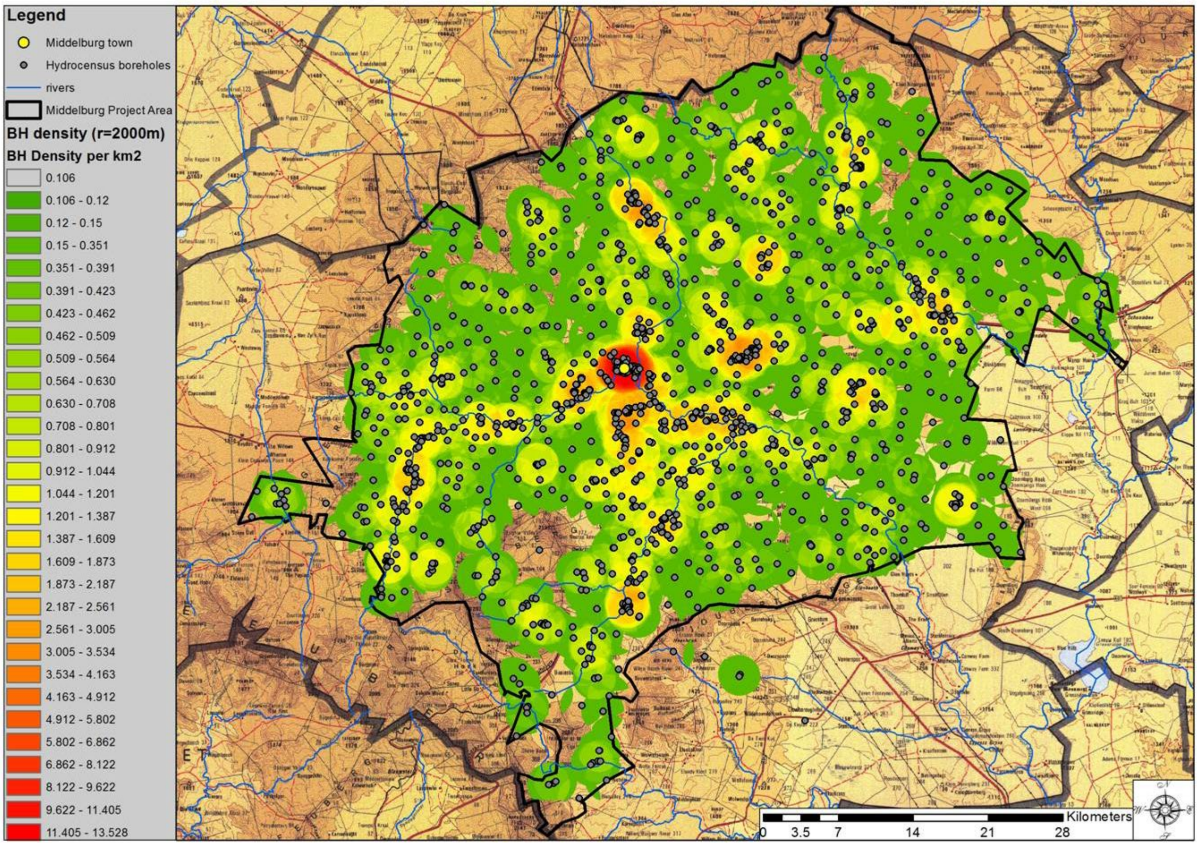


Figure 4-6: Map indicating borehole density around Middelburg using hydrocensus results

As part of the sub-catchment- and target area-delineation for groundwater exploration, the hydrocensus was key in identifying areas where too much abstraction could already be taking place. The borehole density map in Figure 4-6 helped identify areas where there is already a lot of groundwater activity/abstraction. What is striking from this map is an obviously too high density of boreholes in Middelburg town and immediate vicinity, but also the pattern of higher density from boreholes following the regional drainages and rivers.

4.2.2 Hydrocensus water levels

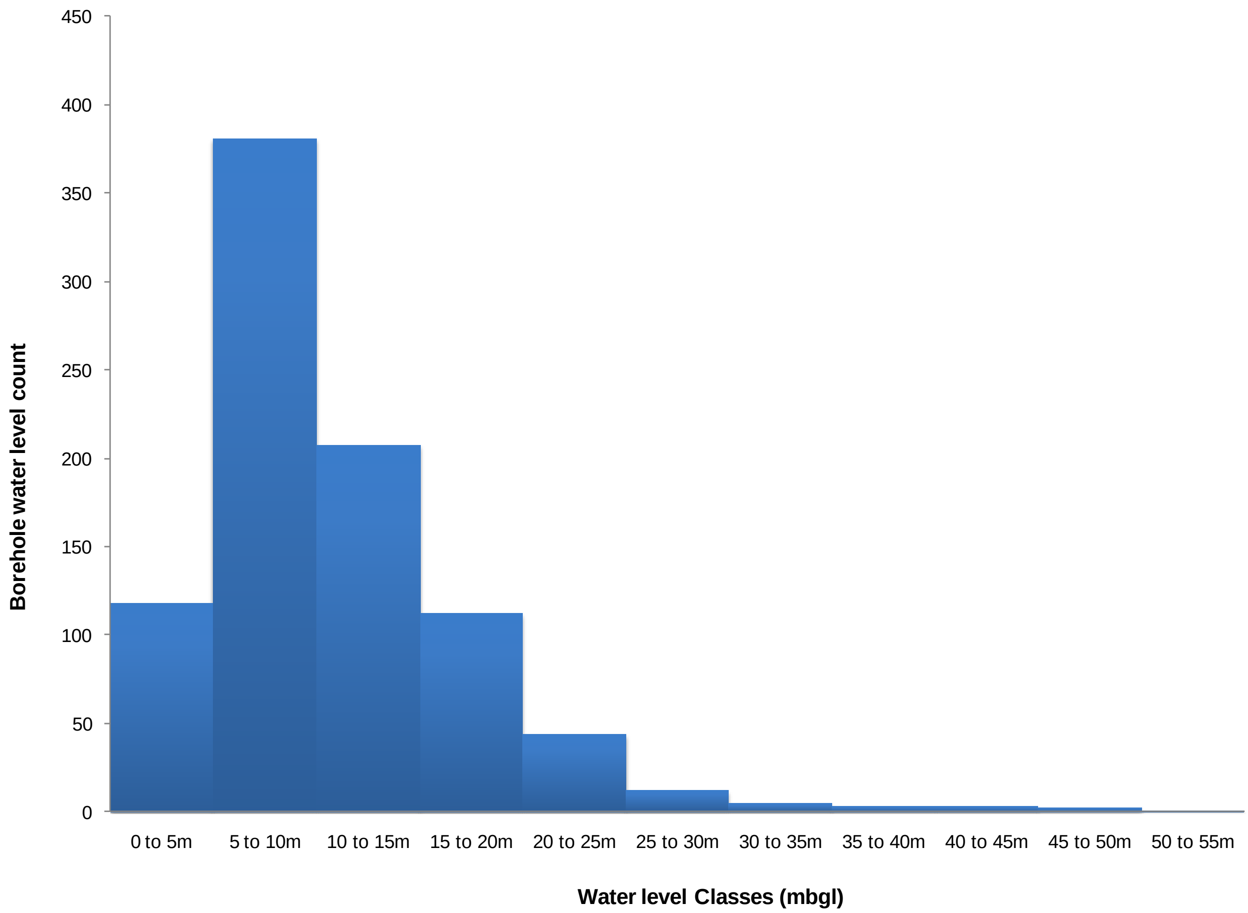


Figure 4-7: Histogram of distribution of 888 borehole water levels

The hydrocensus database of 1692 records was again filtered to provide only boreholes where groundwater levels (water levels) could be measured. Outlier records or records with erroneous and suspicious water level readings were removed or cleaned if minor errors were obvious. Finally, a database subset of 888 boreholes with water levels was used for water level statistics for the Middelburg study area. In Figure 4-7 a histogram with 11 classes represents the water level distribution for Middelburg and surrounds. The Middelburg study area has a minimum water level of 0.0 mbgl i.e. artesian and a maximum water level depth of 51.43 mbgl. An average water level of 10.78 mbgl was determined for the Middelburg data set as well as a standard deviation of 6.65 m. The histogram in Figure 4-7 is competent in giving some indication that the dominant aquifer in the area is the shallow primary alluvial aquifer and that the general water level has not declined below this aquifer.

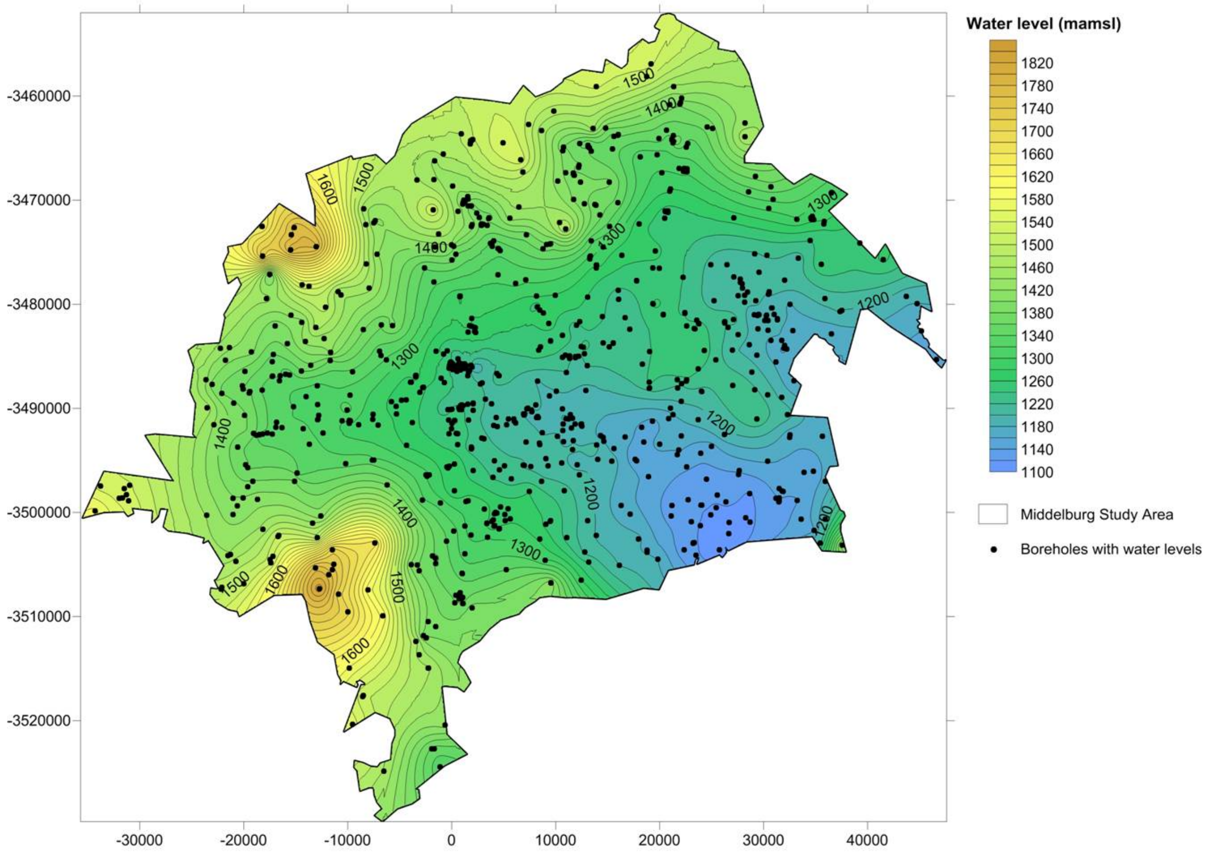


Figure 4-8: Water level contour map interpolated from 885 boreholes with water levels

In Figure 4-8 the water levels for 888 boreholes were contoured in metres above mean sea level (mamsl). From this map the general groundwater flow can be inferred as moving in a south-easterly direction. A few interpolation methods were evaluated before the final contoured water level map was created with the Kriging interpolation method. Kriging interpolation is a flexible interpolation method in the sense that it will generally create a good interpolation if data points are regularly spaced (continuous) or if the data points are unevenly distributed. Another advantage of the Kriging method is that it can extrapolate the given Z variable beyond a data set's XY field limits. The Inverse Distance Weighted (IDW) to a power interpolation method was tested, but it tended to create a 'bull's eye' effect of concentric circles around some boreholes and cannot extrapolate the water level beyond the XY field limits of the data points. The Natural Neighbour Method was also tested as it works well when data sets have many data points in some places while data points are sparse in other places (Golden Software, 2011). This method however only interpolates within the XY field of the data set and cannot extrapolate beyond it (Golden Software, 2011). This presented a problem at some parts of the study area boundary, thus the water level field interpolated with the Natural Neighbour method did not cover the full study area.

4.2.3 Borehole depths from hydrocensus

Borehole depth information was obtained for a final total of 473 geosites and the basic statistics calculated. From the survey done in the Middelburg study area the minimum depth for a borehole or dug well was 1 mbgl, the maximum depth for a borehole was 170 mbgl and a mean borehole depth of 31.63 mbgl was calculated. The mean borehole depth for the dataset confirms existing information that most boreholes are drilled in the alluvium where the borehole depth indicated where the alluvium/ weathered zone of the Beaufort Group generally stops. Reported and existing information also indicates that most boreholes were drilled with a cable tool or “jumper” drilling rig, explaining why the rigs could drill into the soft alluvium and weathered Beaufort zone, but struggled to drill further into the fresh sedimentary and dolerite rocks.

4.3 Study area definition

The preliminary study area was initially based on a 30 km radius around the town of Middelburg. The hydrocensus was conducted by surveying boreholes door to door in the town and farm by farm, in and around Middelburg. As the hydrocensus progressed within the 30 km radius around Middelburg the outer farm boundaries of completed farms became the preliminary study area boundary. The final study area boundary is an outline following the outer boundaries of the furthest farms out that was surveyed during the hydrocensus around Middelburg. All farms within the study area boundary were surveyed.

In total 847 individual farm portions and 229 parent farms were surveyed for boreholes and geosites during the hydrocensus. The farm portions and parent farm boundaries are indicated in Figure 4-9 as well as the final Middelburg study area boundary as determined by the farms surveyed.

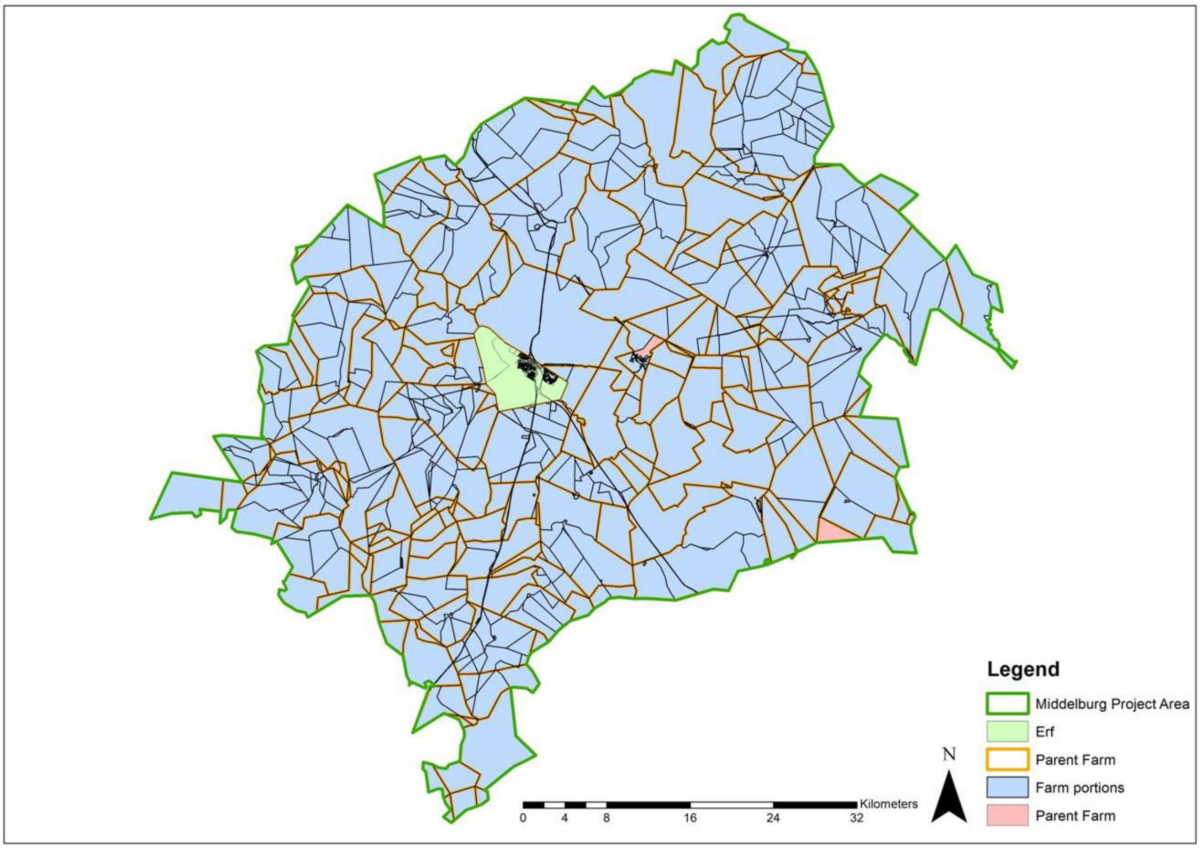


Figure 4-9: Map of Middelburg cadastral information of farms surveyed during Hydrocensus

4.4 General groundwater quality

During the hydrocensus within the Middelburg study area, samples were taken at groundwater sources where water was pumped from the borehole and an open water stream was available to fill the sample bottles.

A Total of 416 boreholes were sampled during the hydrocensus, their hydro-chemistries analysed and their results interpreted according to the DWAF Minimum standards and guidelines. The samples were analysed at Talbot & Talbot SANAS accredited laboratory for microbiological and macro element constituents.

The database with 416 records of water chemistry results and interpretations was checked for accuracy, gaps in data, duplicates and other errors. A final database with 405 borehole sample results was used for representing water quality results and in performing statistical analysis.

4.4.1 Overall water quality classification of boreholes sampled in hydrocensus

The overall DWAF water quality classification for the 405 boreholes sampled during the hydrocensus is DWAF Drinking Class 2 (Marginal water quality). This classification is mostly due to total hardness (calcium- and magnesium- carbonate) as well as total coliforms. The graph in Figure 4-10 represents the interpretation of the hydrochemistry results statistically.

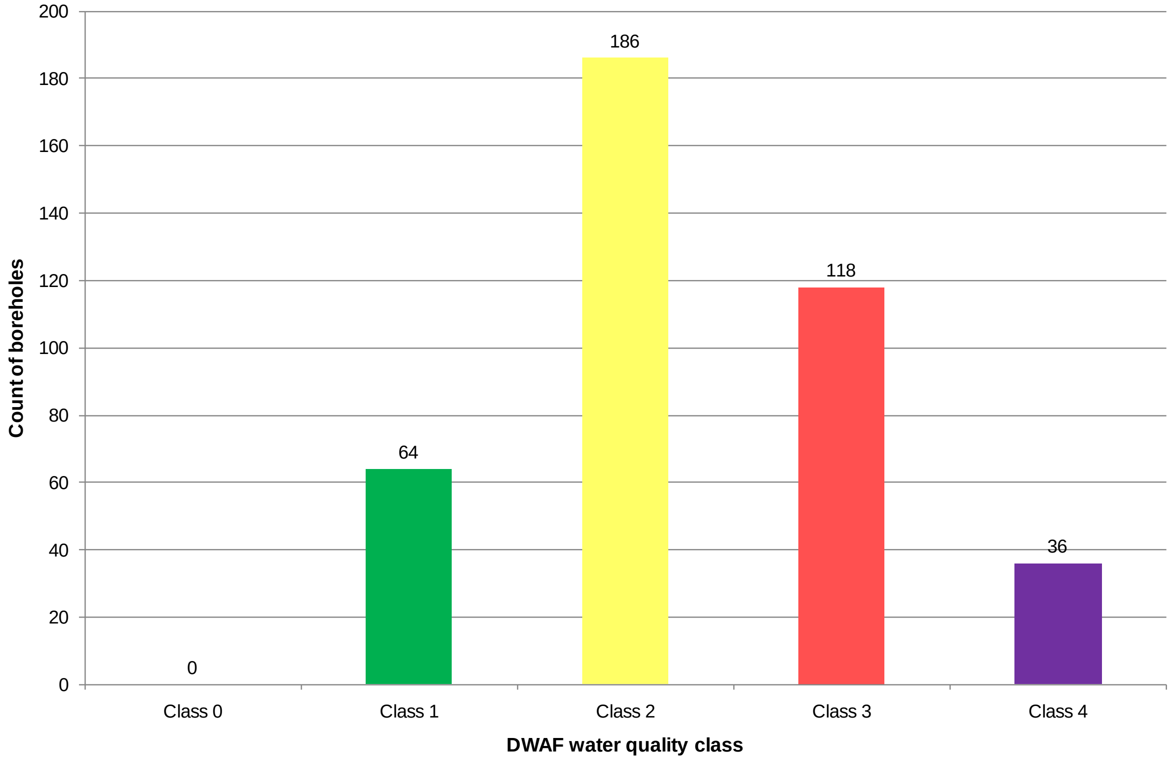


Figure 4-10: Overall DWAF drinking water quality classification for 405 boreholes sampled

A description of the DWA drinking water quality classes and their effect on human health are given in Table 4-1.

For more information regarding the setting of the DWAF drinking water quality classes, their health and aesthetic effects per constituent as well as treatment options the reader is referred to the document *Quality of domestic water supplies. Volume 1: Assessment guide* (DWA, 1998). The former mentioned assessment guide can be opened and used alongside this document to more carefully assess the water quality class per constituent in the hydrocensus results.

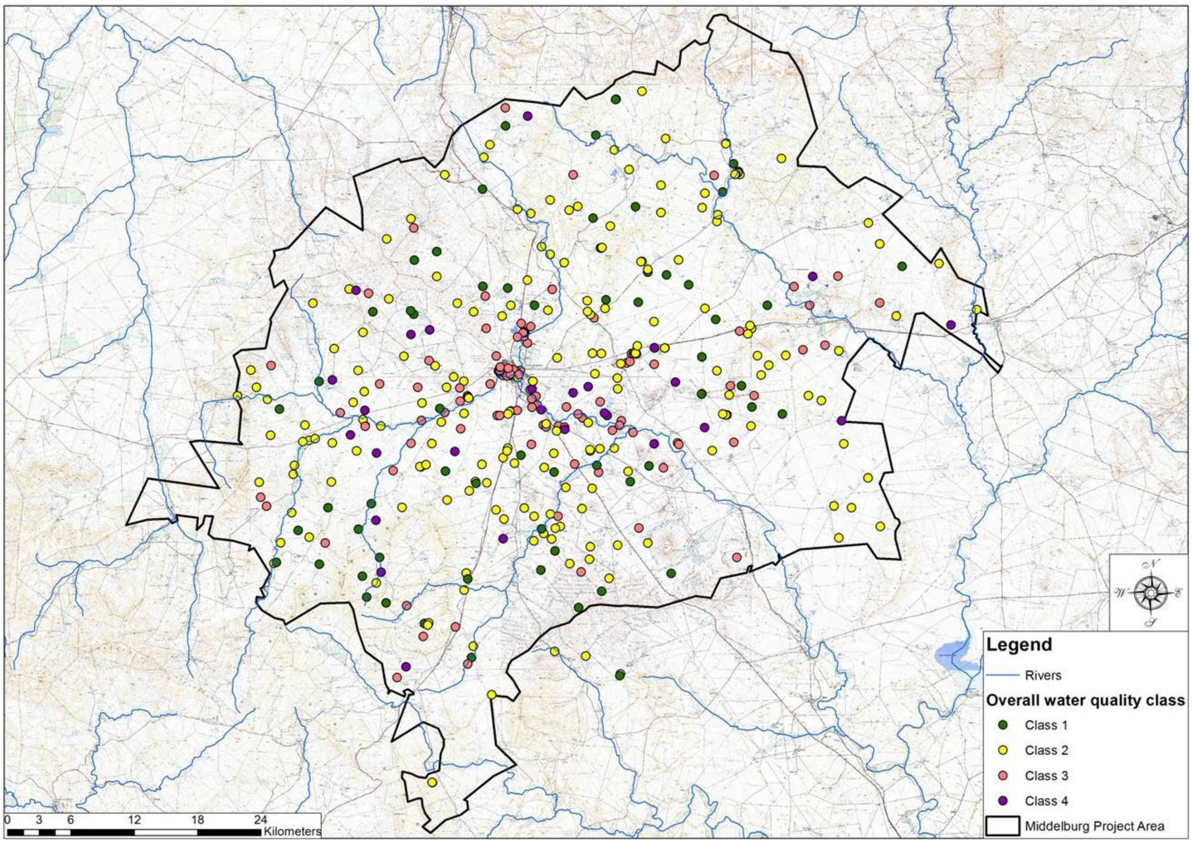


Figure 4-11: Point colour map of the overall water quality class for 405 boreholes in the study area

In Figure 4-11 a spatial presentation of the overall groundwater quality classes is given in a map of the study area and the distribution of the set of 405 boreholes sampled during the hydrocensus. A pattern that emerges from this map is the poorer water qualities associated Middelburg and with boreholes in the drainages and rivers for the study area, especially downstream of Middelburg. The higher mineralisation of downstream groundwater was also noted by Vandoolaeghe (1979) in his geohydrological investigation of Middelburg (see Chapter 2). The areas of the drainages are also the areas, which in most cases have the thicker alluvial aquifers. It can be argued that due to prolonged groundwater abstraction in these valleys the minerals have built up and concentrated in these waters and interstices of the porous aquifer. Contamination from surface water during floods, runoff from agricultural activities using fertilisers and sewerage discharge events can also not be excluded as possible contributors to these water quality results.

4.4.2 Electrical conductivity (EC)

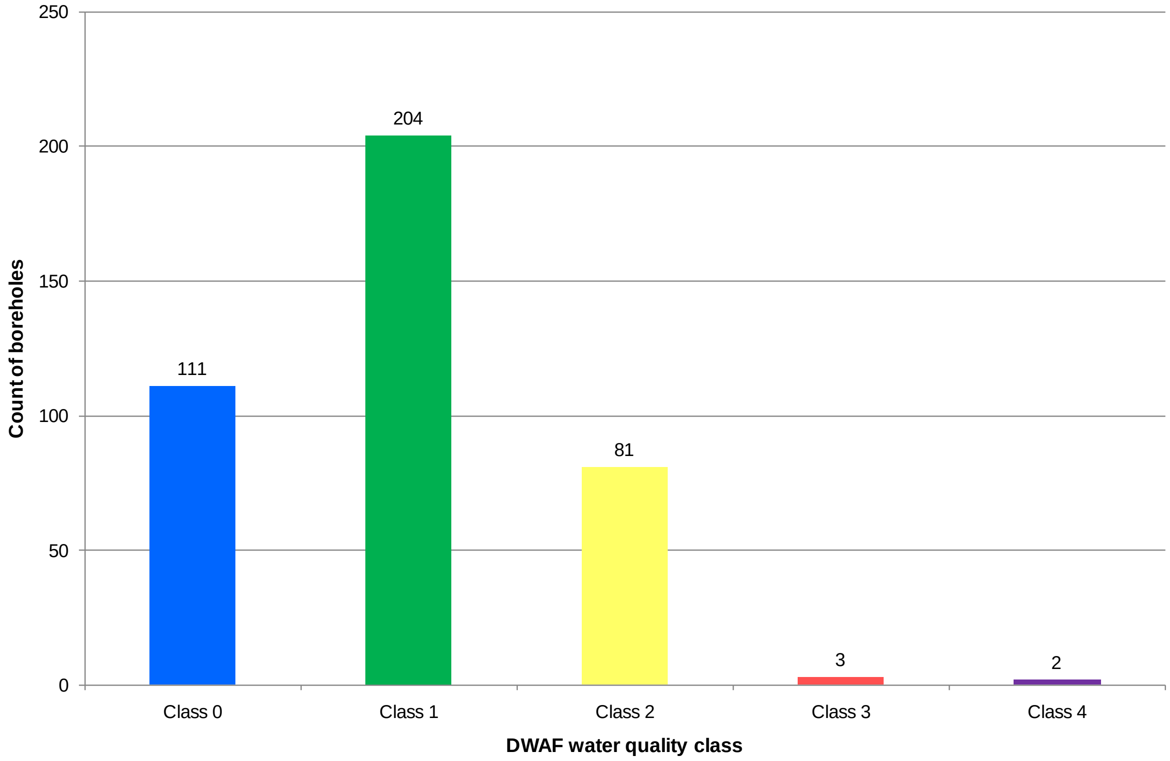


Figure 4-12: The electrical conductivity (EC) DWAF classification for 405 boreholes sampled in Middelburg

Generally the 405 boreholes sampled show good quality water in terms of electrical conductivity, as electrical conductivity (EC) is often used as a general indicator of water quality. EC reflects the amount of dissolved minerals in the water and as such is an indicator of the hydro-chemical quality of the water. EC is however not an indicator of mircobiological quality of the water, nor is it influenced in many cases by the turbidity of the water.

4.4.3 Total and faecal coliforms

Both total- and faecal-coliforms were tested for during analysis of the samples from the hydrocensus. The results of the former mentioned constituents can however only be regarded as a general statistical guideline for the area, as it was not always possible for the persons in the field to get the samples to the lab within 4 hours.

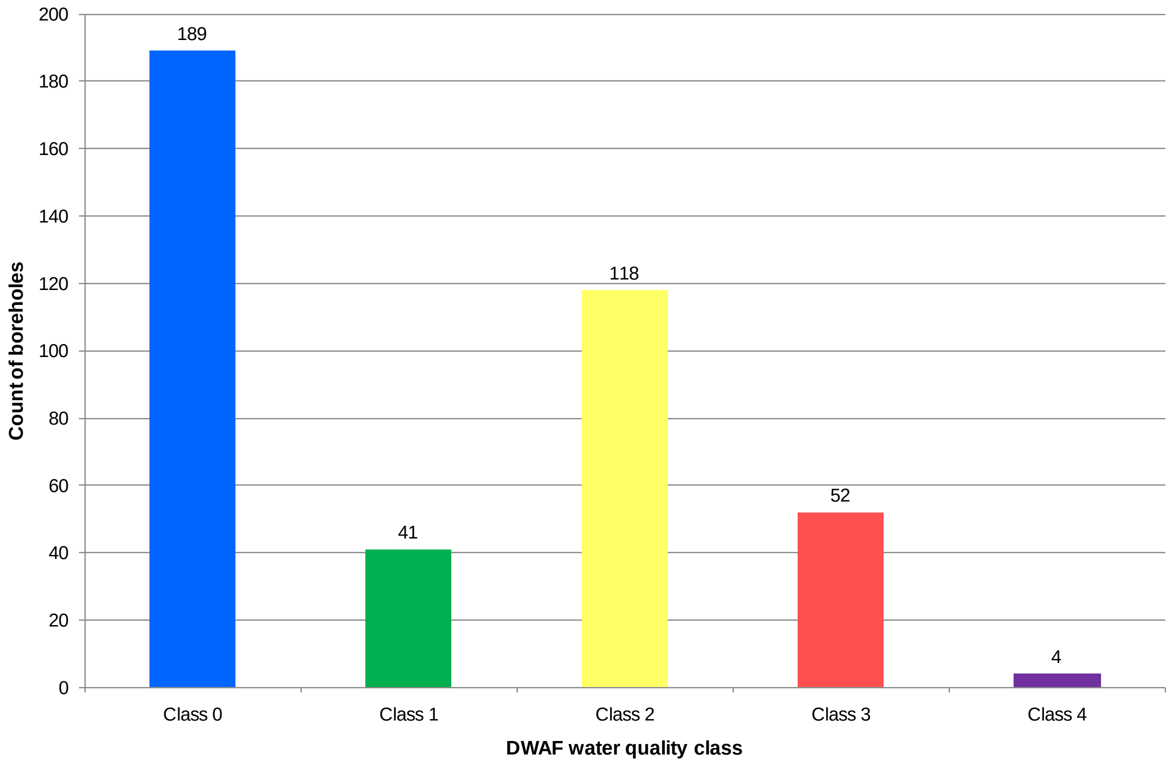


Figure 4-13: Total coliforms classified for boreholes sampled during hydrocensus

Total coliform counts are often also associated with microbiological colony growth within pipeline networks whereas faecal coliform count is more directly related to groundwater contamination from livestock pens directly above an aquifer or sewerage systems such as septic tanks contaminating the aquifers for instance. High Total coliform counts are also normally associated with slow flowing or standing surface water, which is prone to contamination from micro-organisms from prolonged direct contact with the atmosphere.

It is thought that the higher total coliform counts are the result of microbiological exposure and contamination in many of the pipes from the borehole pumps. The constant moisture in and around the pipes as well as leaks could create favourable environments for microbiological growth. Algal growth is often seen at joints and leaks on reticulation pipes from borehole pumps on farms.

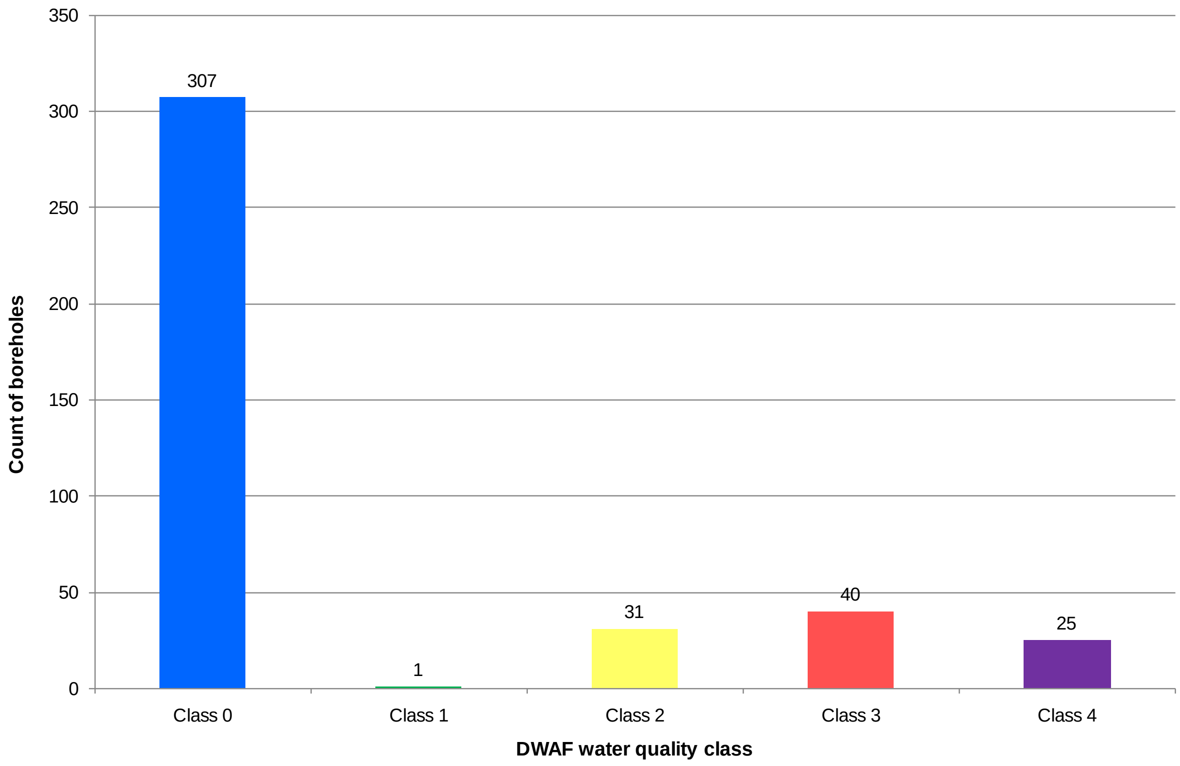


Figure 4-14: Faecal coliforms classified for boreholes sampled during hydrocensus

As can be seen from Figure 4-13 and Figure 4-14 there is much less contamination from faecal coliforms than total coliforms.

It is thus seen that even though the agricultural area around Middelburg is highly productive in terms of livestock farming, livestock pens and the livestock farming does not amount to significant faecal coliform contamination.

4.4.4 Total hardness

Total hardness was identified from the hydrocensus sample analysis as a constituent which in many cases had a DWA drinking water classification of more than Class 1, i.e. Class 2 and Class 3 mostly. None of the boreholes sampled were Class 4 however. The carbonate is thought to originate from the large amount of calcrete and alluvium in the study area while the magnesium is thought to a weathering product of the minerals in the dolerite intrusions and the Beaufort Group sedimentary rocks underneath the alluvium.

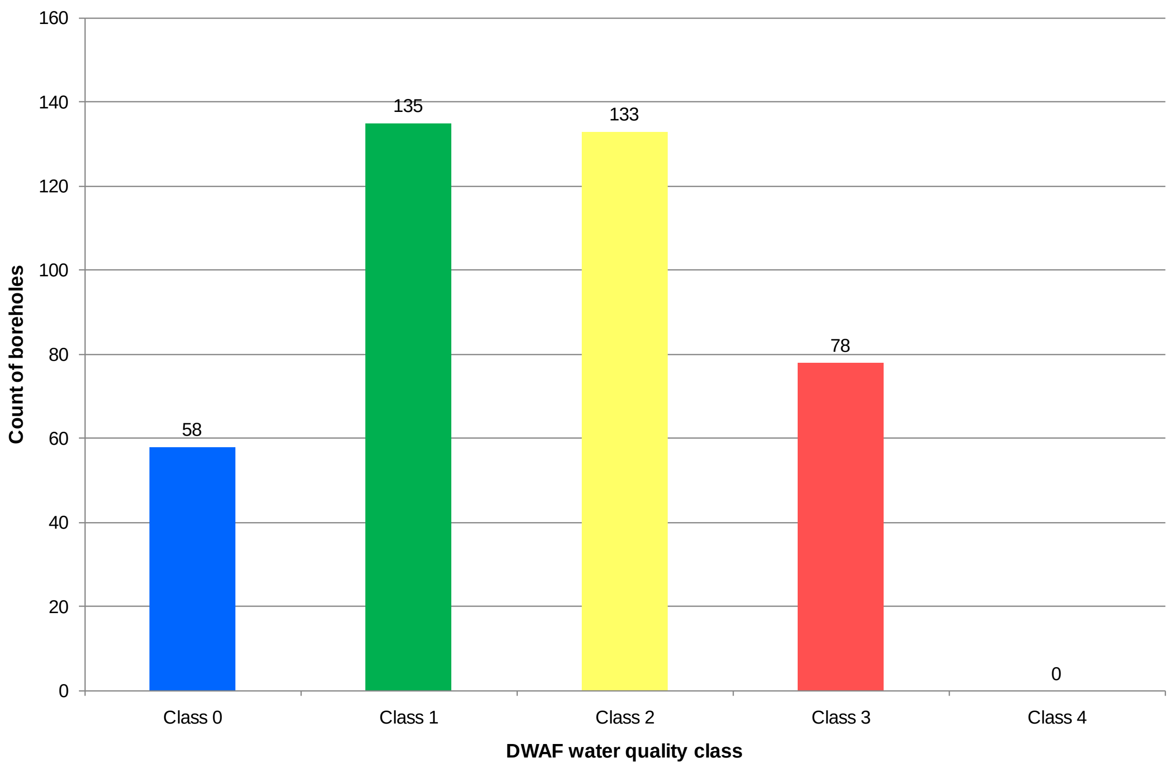


Figure 4-15: Total hardness classified for 405 boreholes sampled during hydrocensus

4.4.5 Fluoride

The results for fluoride are important because if there is an area where fluorides are high, that area needed to be excluded from groundwater exploration. These areas needed to be excluded, because currently fluoride is difficult to treat, requiring bone char or activated alumina in its treatment processes, which are relatively complex expensive treatment methods compared to some other methods required for other constituents.

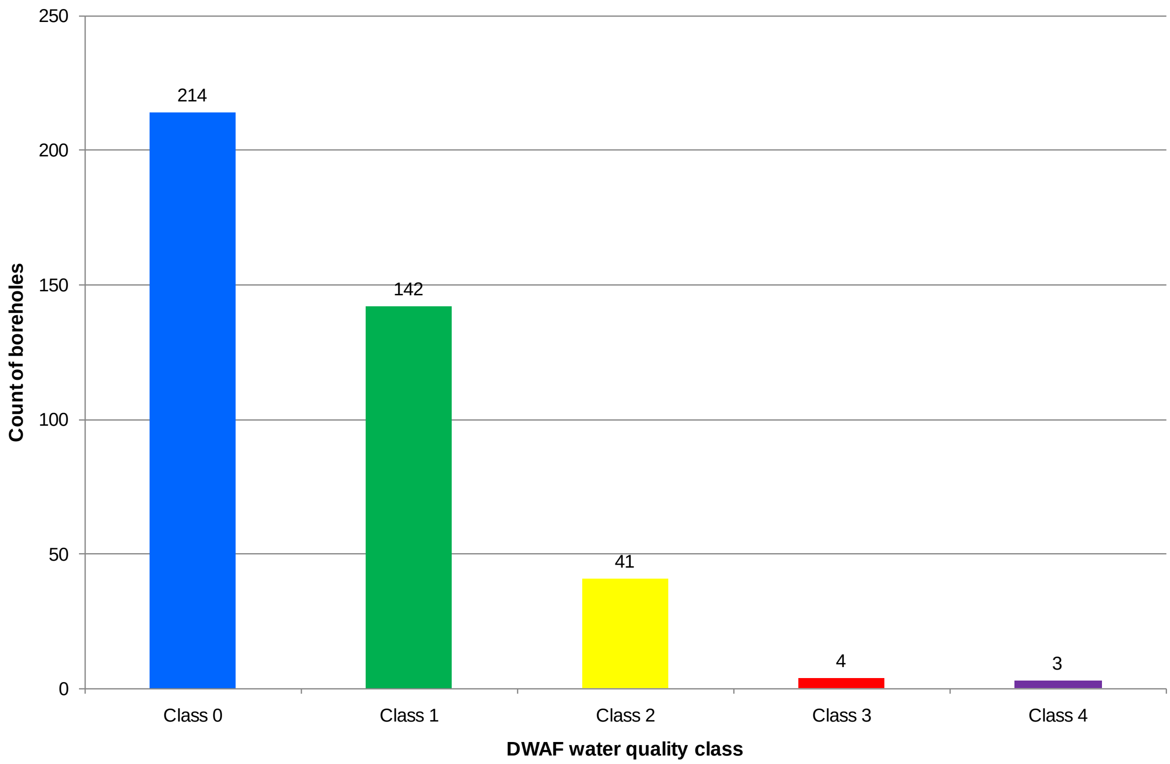


Figure 4-16: Fluoride classified for 405 boreholes sampled during hydrocensus

4.5 Catchments and sub-catchment delineation

As mentioned in Chapter 1, the Middelburg study area is situated almost completely in the Fish to Tsitsikamma Water Management Area (WMA). Very small parts (approximately 5%) of the study area on the northern side fall in the Upper Orange Water Management Area. The study area fell over 14 Quaternary Catchments (See Figure 4-17). Finally only Q14A, Q14B, Q14C and Q11D were considered in the groundwater balance as these quaternary catchments contained the sub-catchments that were finally considered for the future groundwater exploration and development work. The hydrocensus results could be used to efficiently steer the sub-catchment delineation process by highlighting areas of intensive abstraction, poor water quality or undeveloped areas.

4.5.1 Sub-catchment delineation

A total of 6 sub-catchments were delineated based on hydrogeology and groundwater potential. Only 5 sub-catchments were initially delineated, but later during the investigation, the Grootfontein compartment was also delineated due to a suggestion from Dr. Van der Ahee Coetzee and cooperation with the Grootfontein Agricultural College. The 6 sub-catchments are graphically represented in Figure 4-18. These sub-catchments were delineated as general target areas for groundwater exploration and development due to the hydrogeologically significant dolerite sill- and ring-complexes as well as large dyke formations associated with them (see section 4.1.3). The sub-catchments (excluding Middelburg Municipal) also had a lower density of abstraction boreholes, compared to the Middelburg Municipal sub-catchment. The Middelburg Municipal sub-catchment is centrally located with regards to Middelburg and already has a large number of abstraction boreholes including those the Municipality already uses for water supply to the town. The Middelburg municipal sub-catchment had to be delineated to determine an aquifer stress estimate with the Groundwater Yield Model (GYM) groundwater balance and to make a decision whether to exclude it from the groundwater exploration programme or not. It was delineated based on the Middelburg ring structure that surrounds it and forms topographical highs or the watersheds for it.

Table 4-2: Study area sub-catchments information

NO.	SUB-CATCHMENT	AREA (KM^2)	GEOHYDROLOGICAL FEATURE BASED ON
1	Middelburg Municipal	133.34	Shallow alluvial porous aquifer
2	Dunblane	286.23	Dunblane dyke intrusion
3	The Glen	108.05	sill- and ring- complex structure
4	Karmel	82.34	sill- and ring- complex structure
5	Lusernvlei	123.51	Dolerite ring structure
6	Grootfontein	143.13	Compartment formed by surrounding structures

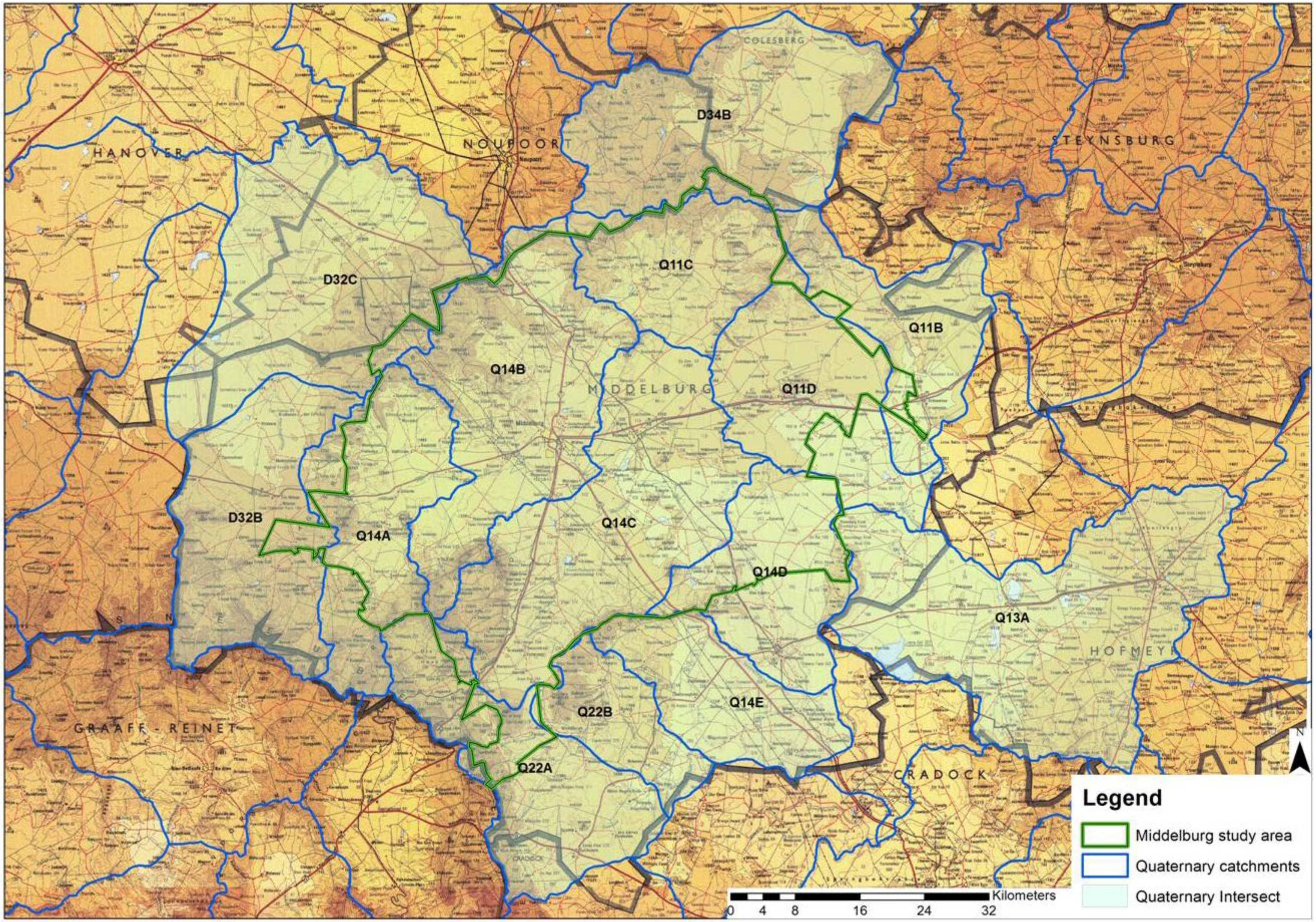


Figure 4-17: Quaternary catchments that the Middelburg study area intersects and falls over

4.5.2 Middelburg municipal sub-catchment

The Middelburg municipal sub-catchment was delineated for the purposes of demarcating the area of high borehole density and groundwater abstraction as well as delineating the shallow alluvial aquifer that is currently over-exploited. Almost all of the municipality's high yielding boreholes are located in this catchment in the alluvial aquifer close to the Klein-Brak River.

4.5.3 Dunblane sub-catchment

The Dunblane sub-catchment was delineated based on the definite groundwater potential of the Dunblane dyke. The dyke runs in a NNW direction through the southern and central part of the sub-catchment, which represents a few target locations for deep borehole drilling for intersection. This is by far the largest sub-catchment of the six sub-catchments with a surface area basically double that of the second largest sub-catchment.

4.5.4 The Glen sub-catchment

Represents a unique situation where the Dunblane dyke cuts through a sub-circular, almost rectangle shaped sill- and ring-structure. The sub-catchment was delineated based on the latter mentioned ring structure, which also has an associated inner sill as seen on the geology map and verified in the field. This sub-catchment also had very little boreholes in it as well as groundwater abstraction, implying that it could be a good area for future groundwater development for water supply to the town. Later during the investigation it was also determined that the electricity lines going from town into this northern catchment basically stops at the catchment's most southerly boundary, meaning that boreholes located in the catchment cannot use submersible pumps or electrically driven mono (progressive cavity)-, turbine- or centrifugal pumps. It is therefore unlikely that most of the few boreholes present in the catchment can abstract large volumes of water associated with the prior mentioned borehole installations.

4.5.5 Karmel sub-catchment

The Karmel sub-catchment was delineated based on another dolerite sill- and ring-structure located adjacent and to the left of the Glen sill- and ring-structure. The Karmel and the Glen sub-catchments are separated by the inclined sheet(s) of the two associated sill- and ring-structures. Karmel also has very little abstracting boreholes compared to its size as determined during the hydrocensus.

4.5.6 Lusernvlei sub-catchment

Lusernvlei was delineated on what is probably the most definite and morphologically prominent ring structure in the study area. It is located to the far east-northeast of Middelburg within the study area and its proximity is distal compared to the other sub-catchments. It did however represent exactly the kind of structure that was planned to be targeted at depth and also generally, had only a few boreholes.

4.5.7 Grootfontein compartment sub-catchment

As the Middelburg water supply project went on, Dr. Van der Ahee Coetzee became involved in a review and advisory role as he is an experienced geohydrologist and also the largest land owner in the Middelburg vicinity. Dr. Coetzee suggested that we also look at a compartment which is formed between the Glen sub-catchment and the Middelburg Municipal sub-catchment. The Grootfontein weir perennial spring is located on the northern boundary of the Municipal sub-catchment and the southern boundary of the Grootfontein compartment. The spring is caused by a natural embankment resulting from a dolerite ring structure/inclined sheet, which forces the southerly moving groundwater upwards and creates the spring. The water from this spring is kept in the Grootfontein compartment alluvial reservoir and judging by the perennial nature of the spring, there is enough groundwater to dam up to almost ground level. The reason why this sub-catchment was not investigated earlier for groundwater potential was due to the land being owned by the Grootfontein Agricultural College. AGES liaised with the College, and as the College is using the groundwater in the area only for stock watering and domestic supply to the college, they agreed to groundwater exploration, development and supply to the town, lest the groundwater levels being monitored in the sub-catchment did not drastically decline due to this possible future groundwater abstraction for water supply.

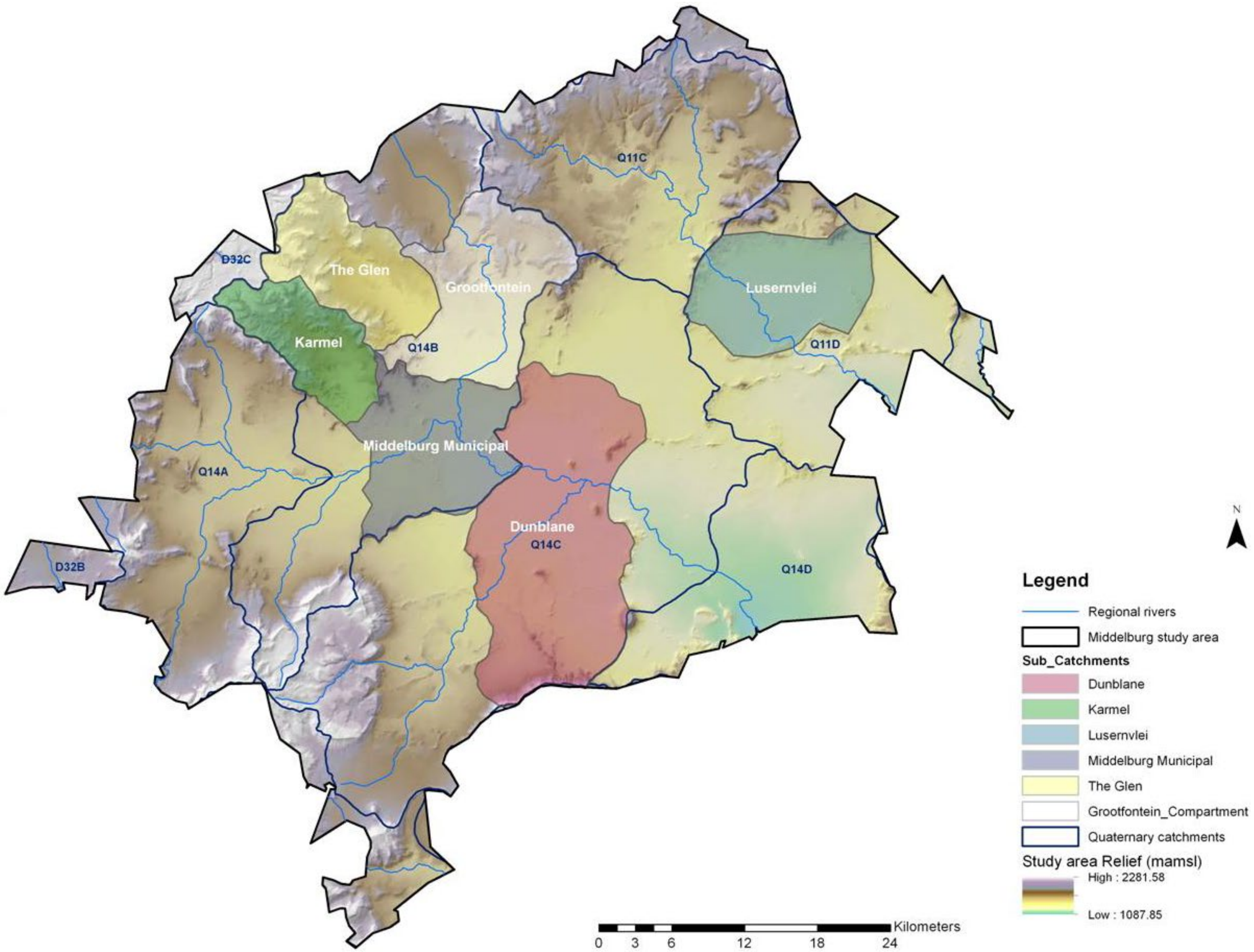


Figure 4-18: Map showing the 6 final sub-catchments for the Middelburg study area with elevation and shaded relief

5 GEOPHYSICS & EXPLORATION TARGET AREAS

5.1 Introduction

After the comprehensive hydrocensus and preliminary groundwater flow balance was completed, specific target areas for geophysical investigation were chosen. The specific target areas for geophysics were chosen in the sub-catchments where favourable groundwater flow balances were calculated. The target areas for geophysics were selected based on remote sensing and information from previous studies. A sub-contractor, namely Mr. Japie Coetzer, was appointed to carry out geophysics surveying and interpret the profiles from his field experience side. He could also be on site in Middelburg for the duration of the geophysical surveying and carefully interpret field conditions.

5.2 Methodology

5.2.1 Georefencing of geological map and geology shapefiles

A digital copy of the 1: 250 000 geology map of MIDDELBURG 3124 was obtained from the Council for Geoscience (CGS, 1983). The map was projected to the WGS84 Datum and plotted in GIS with the Middelburg study area layer. All the geology within the Middelburg study area was then digitised and the shapefile databases updated accordingly. When the geological raster map and shapefiles were compared with the correctly georeferenced ortho photos of Middelburg and a close up georeferenced image from Google Earth, it was observed that the geological map did plot correctly even after projection to the correct Datum. There was a slight misalignment with some geological structures. Trig beacon shapefiles and trig beacons indicated on the geological map were used to determine the X and Y error on the geological map. Clear geomorphological features such as mesas and koppies also provided good areas to measure the XY error. Finally the XY error was determined and the geological map and geology shapefiles were shifted -200 m (west) in the X direction and 60 m (north) in the Y direction. To use the geology map as received from the GCS would only have created confusion when comparing dykes with geophysical results.

5.2.2 Remote sensing and further target area delineation

Sub-catchments were firstly delineated based on geological structures and geomorphological watersheds that were regionally prominent. Such geological structures were the number of dolerite sill- and ring- structures as well as regionally continuous dolerite dykes. The sub-catchments formed obvious areas for further investigation given the approach of regional and deep targeting of dolerite ring and dyke structures for groundwater exploration. If fracturing could be found at greater depth within or along these structures, a greater aquifer thickness could be used than the current ~40 m used by Middelburg and the surrounding farmers. It was also thought that the deeper fractured fresh sedimentary formations and dolerite structures could provide a deep aquifer that would be confined from the upper shallow alluvial and weathered Beaufort Group aquifer. If proven to be confined, this deep regional aquifer would be unimpacted by existing use and supplying water from it would not impact on the current existing shallow aquifer groundwater use.

For the geophysical investigation, specific areas on the dolerite sill- and ring- structures were chosen that showed good fracturing, faulting and groundwater potential from a structural geology point of view. These specific target areas for geophysics were selected using remote sensing techniques applied to the 1: 250 000 geological map of Middelburg, ortho-rectified aerial photos, Landsat 7- and Aster- satellite images. As fractures are known to form conduits for groundwater flow in Karoo fractured rock aquifers (Botha *et al*, 1998; Van Tonder *et al.* 2002; Woodford *et al.*, 2002), areas on the geological structures where fracturing have been shown and are expected to be most intense were chosen. These areas have been described in the Literature study in Chapter 2 according to previous investigation by Woodford *et al.* (2002). The specific areas chosen were investigated using different groundwater geophysical methods.

5.2.3 Magnetometer geophysics

A proton magnetometer was used during the geophysical investigation. A magnetometer is used for geophysical exploration when the minerals magnetite, pyrrhotite and ilmenite are expected to be present in geological formations, ore bodies or geological structures in the area investigated.

Magnetite is the most common magnetic mineral and occurs in iron ore deposits, in different concentrations in igneous and metamorphic rocks, in direct or close association with metallic sulphide ores and even finely distributed in some sedimentary rocks.

Due to the earth's ever present magnetic field, magnetic minerals such as magnetite may act like magnets or electromagnets and become aligned with the earth's magnetic field (Roux, 1980: 7). In this manner the geological formation or structure that contain the magnetic mineral(s) will become magnetised and have its own magnetic field (Roux, 1980: 1). This magnetic field is very local, but at its location will be superimposed on the earth's magnetic field and create a departure (positive or negative) from the earth's normal magnetic field.

These departures (also called anomalies) from the earth's undisturbed magnetic field can be small or large, depending on the depth of burial, degree and direction of magnetisation as well as the strike of the formation in relation to the direction of the earth's magnetic field in that locality (Roux, 1980: 1). Metallic objects such as cars, fences or borehole casings can also act as "electro-magnets" through induced magnetism from the earth's magnetic field and are in most cases picked up in readings during a magnetometer geophysical survey.

Induced magnetism works in much the same way as an electro-magnet works. When a piece of soft iron is placed within a magnetic field it will draw the lines of magnetic force towards it and will take on the properties of a magnet with a north- and a south- pole (Roux, 1980: 7). In the case of an electro-magnet, when the current is switched on a magnetic field is created by the current flowing through the windings and the magnetic field is concentrated in the iron core, which then becomes a magnet (Roux, 1980: 7). When the current is switched off there is no longer a magnetic field. The earth's magnetic field induces magnetism into rocks and other iron objects in a similar manner as in the case of the electro-magnet. The earth's magnetic field is however a comparably weak field when compared to an electro magnet and the degree of magnetisation depends on the intensity of the earth's magnetic field at a given location as well as a property of the rock called a magnetic susceptibility.

Some rocks and minerals may also possess remanent magnetism caused by the remanent magnetism of their constituent ferromagnetic grains (Roux, 1980: 7). Remanent magnetism can completely dominate the induced magnetism in some rocks and minerals and the magnetic field of these rocks and minerals can be in a completely different direction than the earth's magnetic field and even oppose it. This is due to the fact that when these rocks and minerals were magnetised, the earth's magnetic field was in a different direction compared to the earth's present day magnetic field direction.

Remnant magnetism results from one or a combination of the following causes: (1) Molten rock cooling down in the presence of a magnetic field; (2) the chemical formation and crystallisation in a magnetic field; (3) Magnetic grains that tend to be orientated in the direction of the earth's magnetic field during sedimentation; and (4) the reorientation of magnetic grains as a result of great pressure (Roux, 1980: 7).

Different types of magnetometers are available and these also function on different principles. As mentioned, a proton magnetometer was used during this investigation. A proton magnetometer normally consists of two essential parts namely a battery pack with an integrated electronic console and processor for processing the readings, and a sensor that is connected to the electronic console by means of an electrical cable.

The sensor consists of a container filled with proton-rich fluid usually kerosene (paraffin) around which a coil of wire is wound (Roux, 1980: 14). The protons in the kerosene act like small spinning magnets. The spin axes of the protons precess about the direction of the earth's magnetic field in a similar manner as a gyroscope precesses about the direction of the earth's gravity field (Roux, 1980: 14). The direction of the spin axes of the numerous protons are randomly orientated under normal conditions and will have no effect on the coil.

When a current is applied to the coil a strong magnetic field is created and the axes of the protons align with this magnetic field. When the current is switched off the axes of all the protons will then precess about the earth's magnetic field and together induce an oscillating voltage in the coil (Roux, 1980: 14). The frequency of the oscillating voltage will be equal to the precession rate of the protons' spin axes and is directly proportional to the earth's magnetic field (Roux, 1980: 14).

The electronic console provides the power and current to create a pulse in the coil of the sensor, creating the strong magnetic field. The electronic console also has the electronics to measure or record the earth's magnetic field through the oscillating voltage induced by the precession of the protons after the pulse is switched off. Both the pulse and oscillating voltage is transferred or recorded through the electrical cable, connecting the separate electronic console and sensor.

The magnetometer is an excellent tool for determining the positions and geometries of dolerite structures in the Karoo Supergroup of rocks as the dolerite contains magnetite and the country rock is basically devoid of any magnetic minerals. Since the geological targets were dolerite sill- and ring-complex structures as well as large dykes, the magetometer was extensively used to determine to some extent the geometry of these complex structures. During the Middelburg investigation a station spacing of 5 m was used.

5.2.4 Electromagnetic (EM) method and Frequency domain EM geophysics method

According to Faraday's law, a time-varying magnetic field will cause a circulating electric field in a circuit (if the circuit is of conductive material) (IGS, 2008). This is the main concept of electromagnetic induction and can be more formally defined. A time-varying magnetic flux through a surface (conductor) induces a circulating electric field in that surface. This concept

can be extended to EM induction in prospecting and geohydrological investigations. The principles of this concept also apply to solid bodies (such as subsurface geological bodies).
A time varying or alternating (ac) primary current flowing through a primary circuit will cause a primary time-varying magnetic field perpendicular to the current in that circuit. The primary time-varying magnetic field will create a primary time-varying magnetic flux through a secondary circuit (conductive body) in the vicinity. This magnetic flux will induce an electromotive force (emf) in the secondary circuit (conductive body in the vicinity of the magnetic flux). The emf that is induced in the conductive body (geological body for instance) will cause a current to flow in the body (circuit) in the same way as if a battery was introduced to the circuit. This induced time-varying secondary current in the secondary circuit will in turn cause a secondary time-varying magnetic field (IGS, 2008).

When EM induction is employed during an EM geophysical survey, a source circuit, receiver circuit and model circuit (modelling the subsurface conductor) set up is used. This circuit configuration is referred to as the equivalent circuit model. The receiver circuit is used to measure the magnitude and phase difference between the primary (source) magnetic field and secondary (model) magnetic fields. The secondary magnetic field created by the induced current in the secondary (model) circuit lags behind the primary magnetic field and a phase difference in the magnetic fields can be computed. For good subsurface conductors (model circuits) the secondary magnetic field lags behind the primary (source) magnetic field by approximately πradians and the two fields are said to be in-phase. For poor conductors the phase difference is approximately $\pi 2$ radians and the two fields are said to be out-of-phase. It can thus be seen that by comparing the recorded magnitude of the in-phase and out-of-phase signal, an estimate of the conductivities of the subsurface conductors can be made. Moderately conductive subsurface bodies give in-phase and out-of-phase anomalies of the same order of magnitude.

A Frequency Domain Electromagnetic (FDEM) instrument was used during the geophysical investigation in the Middelburg study area. The frequency domain EM method makes use of a sinusoidal (ac) current as discussed in this section. The time domain EM (TDEM) method makes use of a number of pulses in a modulated current. The biggest difference between the two methods is that in the frequency-domain method we are working with functions expressed in terms of frequency and measurement of sinusoidal responses are made (IGS, 2008). In the time-domain method we are working with functions of time, the input current has the form of a series of pulses and the output is an induced emf that is measured at the number of time intervals in between the pulses (IGS, 2008;). The decay of the secondary magnetic field is measured as a function of time in the times between the pulses, referred to as the off-times. The Fourier Transforms can be used to transform measurements and functions from time-domain to frequency-domain and vice versa.

During the EM survey in the Middelburg study area, the FDEM measurements were taken with station spacing every 10 m on the lines set out (J. Coetzer, 2008). The FDEM instrument that was used employs 8 different frequencies in order to compensate for the range of different conductivities found in geological bodies. 20 m and 40 m coil separations were used to obtain different depth penetration into the subsurface on the traversed geophysical lines.

5.2.5 Resistivity geophysics

The direct current (DC) resistivity method is based on the fact that the different geological units or bodies are either more or less resistive to electrical current flow when compared to each other (Fourie, 2007). The resistivity method is practically applied by injecting a DC or slowly varying alternating current (AC) into the earth by means of grounded (Galvanic contact) current electrodes (Fourie, 2007). The voltage drop is then measured between a pair of grounded potential electrodes at a selected position. The voltage drop measured is dependent on the resistivities of the materials through which the currents are flowing. The assumption is then made that the earth is homogeneous and isotropic, and measurements of the injected electrical current and voltage drop, as well as the distances between the different electrodes may be used to calculate an apparent resistivity for the subsurface of the earth at a specific position (Fourie, 2007). The apparent resistivities as formerly mentioned can be inverted to obtain a model of the resistivity distribution within the subsurface of a measured location. The model resistivity distribution can now be interpreted in terms of the local geological conditions by incorporating known information on the geology and hydrogeology of the measured location or site (Fourie, 2007).

There are two electrode configurations used with the DC resistivity method namely the Wenner configuration and the Schlumberger configuration. The Wenner configuration uses an equal spacing between each of the four electrodes used and is convenient for profiling where the electrodes are moved forward each time after a measurement is taken along a geophysical survey line. The Schlumberger configuration uses a smaller fixed voltage electrode separation while the current electrodes are moved further away at equal current electrode distances from the voltage electrodes for each measurement. This kind of resistivity survey is referred to as sounding and performed at a specific location to obtain more precise geometries of the underlying geological units. The Wenner configuration was used during the Middelburg investigation as it has been shown by the DWA to have great success in siting boreholes especially in layered formations such as the Karoo sedimentary rocks with their typical bedding plane fractures. Electrode spacings of 40 m and 60 m was used during the geophysical investigation for Middelburg.

5.2.6 Digitizing of geophysical lines for presentation in maps

Since Mr J. Coetzer carried out the geophysical investigation all of the data from the investigation was collected by him. He later kindly provided AGES with a report on the geophysical investigation and drilling of the first five boreholes as well as an Excel file with appendixes. The start coordinates for all lines were provided, but unfortunately the middle and end line coordinates were not given through. During correspondence in 2010 with Mr. Coetzer, an attempt was made to obtain the end line coordinates for geophysical profiles, but the end line coordinates could not be found. This presented a challenge in displaying all 48 of the geophysical profiles set out, but with other information such as boreholes sited on selected lines as well as accurate directions and lengths of profiles, the problem was overcome to a large extent. Approximate positions of geophysical profiles set out were digitized with some lines more accurate due to drilling positions, geophysical stations and lengths of each geophysical line being available for most profiles. The methodology used in delineating the geophysical profiles in GIS later will be briefly described in the following paragraph.

The geophysical profiles set out were digitized as accurately as possible using the available starting coordinates and profile lengths available for all geophysical profiles. As a second tier of accurate data that could be used, drilling sites that were selected on a specific station on each of the 13 selected geophysical profiles could be used to orientate the direction of the profile line. Boreholes drilled later and not shown in the data given through could also be used to orientate geophysical profiles. If sited boreholes were not available profile directions and descriptions were used where available. Field measured directions indicated on graphs that were compared with 8 geophysical profiles with known orientation, show an average deviation of 3.1 degrees, with a minimum deviation 0 degrees and an outlier maximum deviation of 14 degrees. The outlier deviations of 14 degrees and 6 degrees were included in the average calculation. A map compiled by Mr. Coetzer for profiles 32 to 43 was also georeferenced and used to digitize these profile lines. Finally a full set of the 47 geophysical profile lines were digitized in shapefile format and was available for the compilation of geophysical target area maps.

5.3 Results

A total of 47 geophysical profile survey lines were laid out during the geophysical investigation (see Figure 5-1 and Figure 5-2 as well as Table 5-1 and Table 5-2 for overview summary of geophysics performed). The magnetic method was a commonly used method due to the focus on targeting dolerite structures at depth. A total of 38 profile lines were traversed with the G5 Proton magnetometer resulting in a total magnetic traversed length of 30285 m.

The FDEM instrument for electromagnetic geophysical method was employed and 10 m station spacings were used on both 20 m and 40 m coil separation. A total of 45 profiles were traversed of the 47 profile lines that were laid out, resulting in a total EM traversed length of 32125 m.

A Geotron electrical resistivity instrument was used only where the objective was to gain more precise geometry of the subsurface or structure at selected geophysical target areas. The resistivity instrument is used less frequently because it is a time consuming and laborious method. A total of 11 profile lines were traversed with the resistivity instrument. A total profiling length of 3010 m was traversed with a 40 m electrode separation and a total profiling length of 2950 m was traversed with a 60 m electrode separation (AGES, 2010).
All anomalies in the profiles were noted as well as suspicious readings and anomalies caused by man-made objects and human interference.

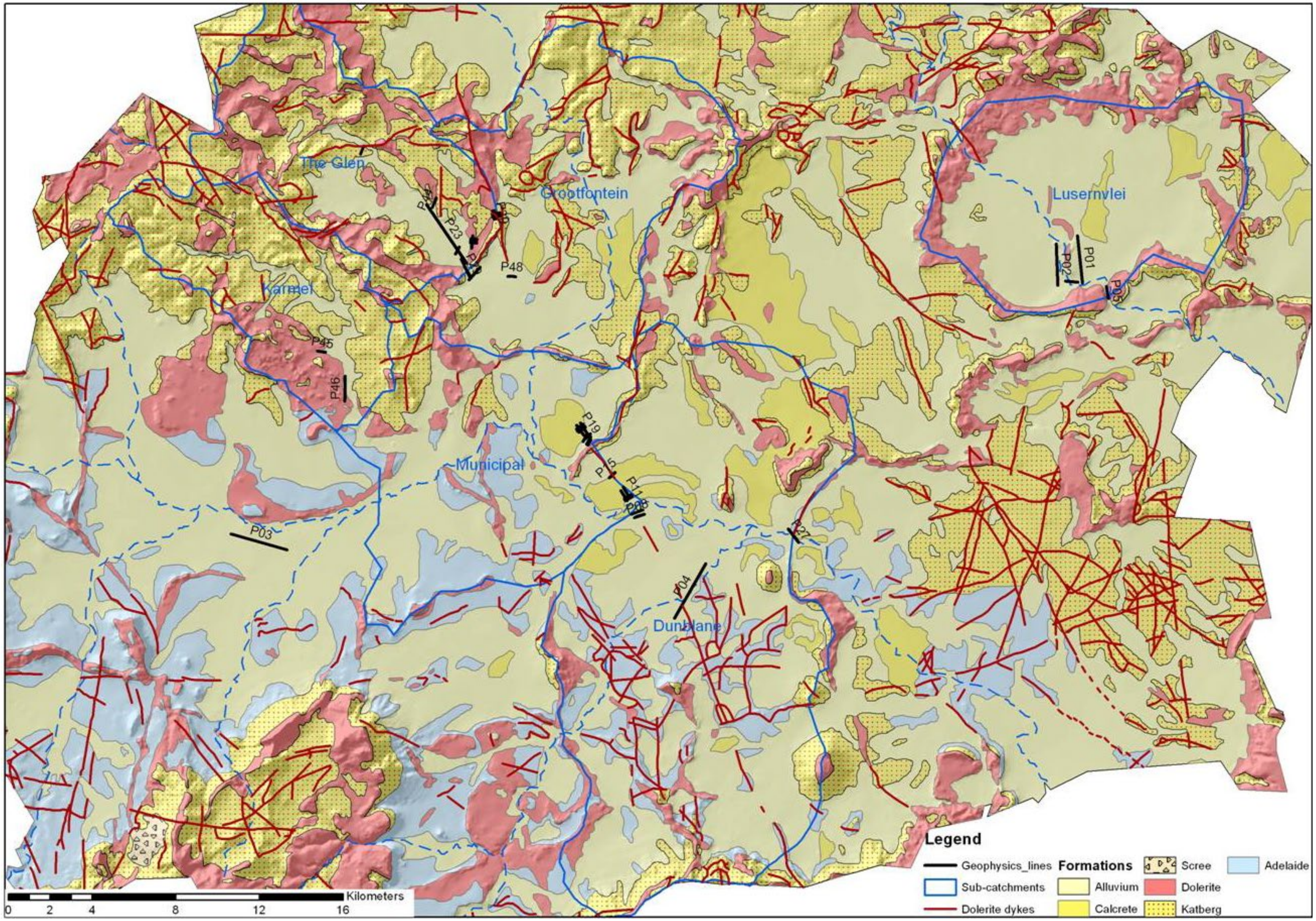


Figure 5-1: Regional map of all geophysics conducted in Middelburg study area in sub-catchments

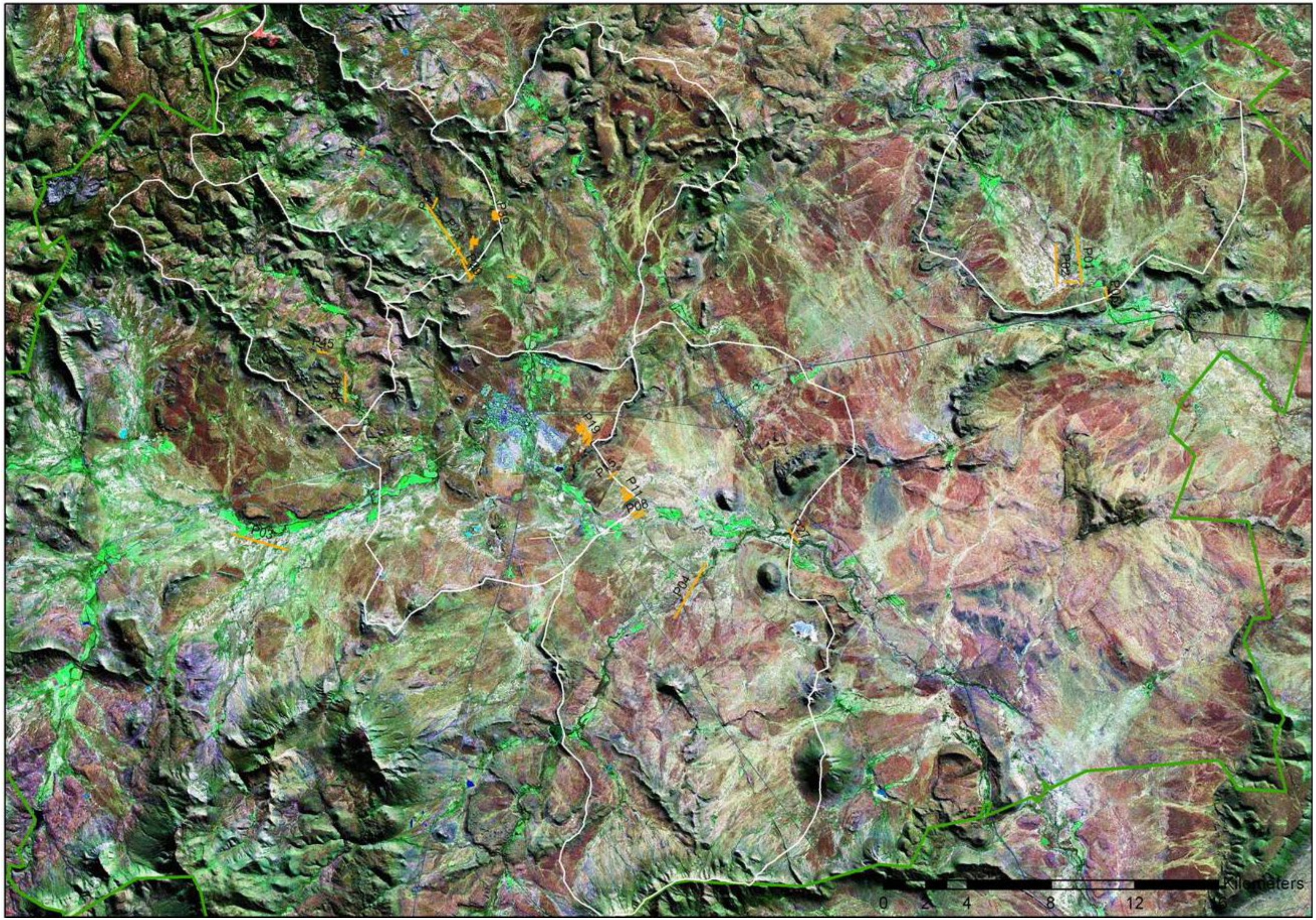


Figure 5-2: **Regional Landsat 7 imagery of Middelburg study area and sub-catchments; geophysical profiles in orange**

Table 5-1: Summary table 1 of 2 of geophysical profiles conducted

Profile no	Start Co-ordinates	Farm name / Area description	Method used				Target	Site Selected	Site Co-ordinates	Borehole no.
	Latitude(S); Longitude E		Mag	FDEM	Resistivity				Latitude(S); Longitude (E)	
	dd.dddd				40m	60m		Sta no.	dd.ddddd	EC-Q14-
P01	S31.41763 E25.29346	Lusernvlei	2360	2360			Fracturing due to dolerite intrusion			
P02	S31.42111 E25.28278	Lusernvlei	2140	2140			Fracturing due to dolerite intrusion			
P03	S31.54578 E24.86840	Platberg	3080	3080			Dolerite contact zones and fracturing			
P04	S31.55850 E25.10705	Buffelsvlei	3080	2760			Dolerite contact zones and fracturing	P04/2200	S31.57554 E25.09564	
P05	S31.43922 E25.30805	Alfalfa	600	600	180	120	Ring structure			
P06	S31.43699 E25.28741	Lusernvlei	600	600	230	200	Dolerite contact zones and fracturing	P06/290	S31.43735 E25.29029	
P07	S31.53547 E25.07546	Dunblane	600				Dolerite contact zones and fracturing			
P08	S31.53729 E25.07610	Dunblane	400	400			Dolerite contact zones and fracturing			
P09	S31.53778 E25.07521	Dunblane	400	400			Dolerite contact zones and fracturing			
P10	S31.52718 E25.06444	Dunblane		560			Fracturing due to dolerite intrusion			
P11	S31.52575 E25.06559	Dunblane		600			Fracturing due to dolerite intrusion			
P12	S31.53154 E25.06665	Dunblane	400	400	190	190	Dolerite contact zones and fracturing	P12/210	S31.53056 E25.06852	1630
P13	S31.53124 E25.06631	Dunblane	390	390	210	210	Dolerite contact zones and fracturing	P13/190	S31.53032 E25.06802	1631
P14	S31.53077 E25.06606	Dunblane	400	400			Dolerite contact zones and fracturing			
P15	S31.52171 E25.05856	Grootfontein - Dunblane	375	375	280	280	Dolerite contact zones and fracturing	P15/195	S31.52057 E25.06010	1632
P16	S31.50737 E25.04711	The Glen	400	400			Dolerite contact zones and fracturing			
P17	S31.50617 E25.04530	Commonage	400	400			Dolerite contact zones and fracturing			
P18	S31.50352 E25.04582	Commonage		600			Dolerite contact zones and fracturing			
P19	S31.50278 E25.04752	Commonage		600			Dolerite contact zones and fracturing			
P20	S31.50224 E25.04328	Commonage		400			Dolerite contact zones and fracturing			
P21	S31.50164 E25.04250	Commonage	400	400			Dolerite contact zones and fracturing			
P22	S31.50092 E25.04199	Commonage	400	400			Dolerite contact zones and fracturing			
P23	S31.40441 E24.96668	Commonage	3400	3400	130	110	Dolerite contact zones and fracturing	P23/2640 & P26/200	S31.42398 E24.98226	
P24	S31.43100 E24.98574	The Glen	600	600			Fracturing due to dolerite intrusion			
P25	S31.43138 E24.99370	The Glen	800	800			Fracturing due to dolerite intrusion			
P26	S31.42563 E24.98118	The Glen	380	380			Fracturing due to dolerite intrusion			

(Coetzer, 2008)

Table 5-2: Summary table 2 of 2 of geophysical profiles conducted

Profile no	Start Co-ordinates	Farm name / Area description	Method used				Target	Site Selected	Site Co-ordinates	Borehole no.
	Latitude(S); Longitude E		Mag	FDEM	Resistivity				Latitude(S); Longitude (E)	
	dd.dddd				40m	60m		Sta no.	dd.ddddd	EC-Q14-
P27	S31.54362 E25.14856	Greyville	800	800	310	290	Ring structure	P27/450	S31.54696 E25.15155	
P28	S31.50532 E25.04592	Commonage	400	400	150	150	Dolerite contact zones and fracturing			
P29	S31.42792 E24.98424	Grt- The Glen	980	980	780	780	Ring structure	P29/415	S31.43121 E24.98600	1634
P30	S31.50774 E25.04788	Grt- Dunblane	300	400			Ring structure	P30/220	S31.50590 E25.04889	1633
P31	S31.42328 E24.98942	Grt- The Glen	600	600	180	260	Fracturing due to dolerite intrusion	P31/360	S31.42001 E24.98975	
P32	S31.42112 E24.99182	Grt- The Glen		280			Fracturing due to dolerite intrusion			
P33	S31.42067 E24.99179	Grt- The Glen		280			Fracturing due to dolerite intrusion			
P34	S31.42021 E24.99191	Grt- The Glen	300	280			Fracturing due to dolerite intrusion			
P35	S31.41976 E24.99191	Grt- The Glen		280			Fracturing due to dolerite intrusion			
P36	S31.41938 E24.99203	Grt- The Glen		280			Fracturing due to dolerite intrusion			
P37	S31.40712 E25.00087	Grt- The Glen	400	400			Dolerite contact zones and fracturing			
P38	S31.40713 E25.00033	Grt- The Glen	400	400			Dolerite contact zones and fracturing			
P39	S31.40721 E24.99985	Grt- The Glen	400	400			Dolerite contact zones and fracturing			
P40	S31.41000 E25.00014	Grt- The Glen	400	400			Ring structure			
P41	S31.40953 E24.99997	Grt- The Glen	400	400			Ring structure	P41/190	S31.40934 E25.00198	
P42	S31.40899 E24.99980	Grt- The Glen	400	400			Ring structure			
P43	S31.40849 E24.99966	Grt- The Glen	400	400			Ring structure			
P44	S31.40576 E24.96964	The Glen	500	500			Fracturing due to dolerite intrusion	P44/440	S31.40230 E24.97133	
P45	S31.46732 E24.91187	Karmel	400	400			Ring structure			
P46	S31.47810 E24.92579	Karmel	1200	400	180	180	Ring structure	P46/730	S31.48460 E24.92575	
P47	S31.37938 E24.93532	Groothoek	400		190	180	Dolerite contact zones and fracturing			
		Totals (m)	30285	32125	3010	2950				

(Coetzer, 2008)

5.3.1 Geophysical profiles discussion

5.3.1.1 Profile P01 and P02

These profiles were conducted on the farm Lusernvlei and the geophysics thus started in the Lusernvlei sub-catchment. A prominent dolerite feature striking in a N-S direction was identified as a feeder dyke to Lusernvlei dolerite ring structure and was investigated. The two geophysical profiles P01 and P02 were conducted on either side of this structure and parallel to it (see Figure 5-3). The aim of this survey was to explore for fracturing along the sides of the feeder dyke and the presence of a possible fault from the intrusion (Coetzer, 2008). This would increase the possibility of groundwater flow at depth. P01 was surveyed with a magnetometer traverse of 2360 m as well as an FDEM traverse of the same length on the eastern side of the feeder dyke. Combining the different geophysical methods on the same profile line has been proven to enhance the identification and interpretation of the subsurface characteristics and geometry. Profile P02 was surveyed with a magnetometer traverse of 2140 m as well as an FDEM traverse of the same length on the western side of the feeder dyke. Both profiles were traversed in a N to S direction. No correlation was found between the different instruments and only shallow fracturing was observed in the results (Coetzer, 2008). This shallow fracturing did not warrant drilling as the goal was to target deep, fractured zones. The geophysical results of the profiles are shown in Figure 2-1 and Figure 2-2 in Appendix B: Geophysics. The Appendices for all chapters in the report are written to CD that can be found in an enclosure at the back of this document.

5.3.1.2 Profile 3

This profile was set out approximately 14 km WSW of Middelburg town and the traverse was started on the farm Platberg (Coetzer, 2008). The aim of this traverse was to explore a contact zone for possible fracturing on the southern side of the dolerite ring structure where the fractures would probably cut perpendicularly through the dolerite (Coetzer, 2008). The profile was surveyed with a magnetometer traverse of 3080 m and an FDEM traverse of the same length, both in an ESE direction. No fracturing through the dolerite was observed in the geophysical results (Coetzer, 2008). Figure 2-3 in Appendix B shows the graph results of this profile.

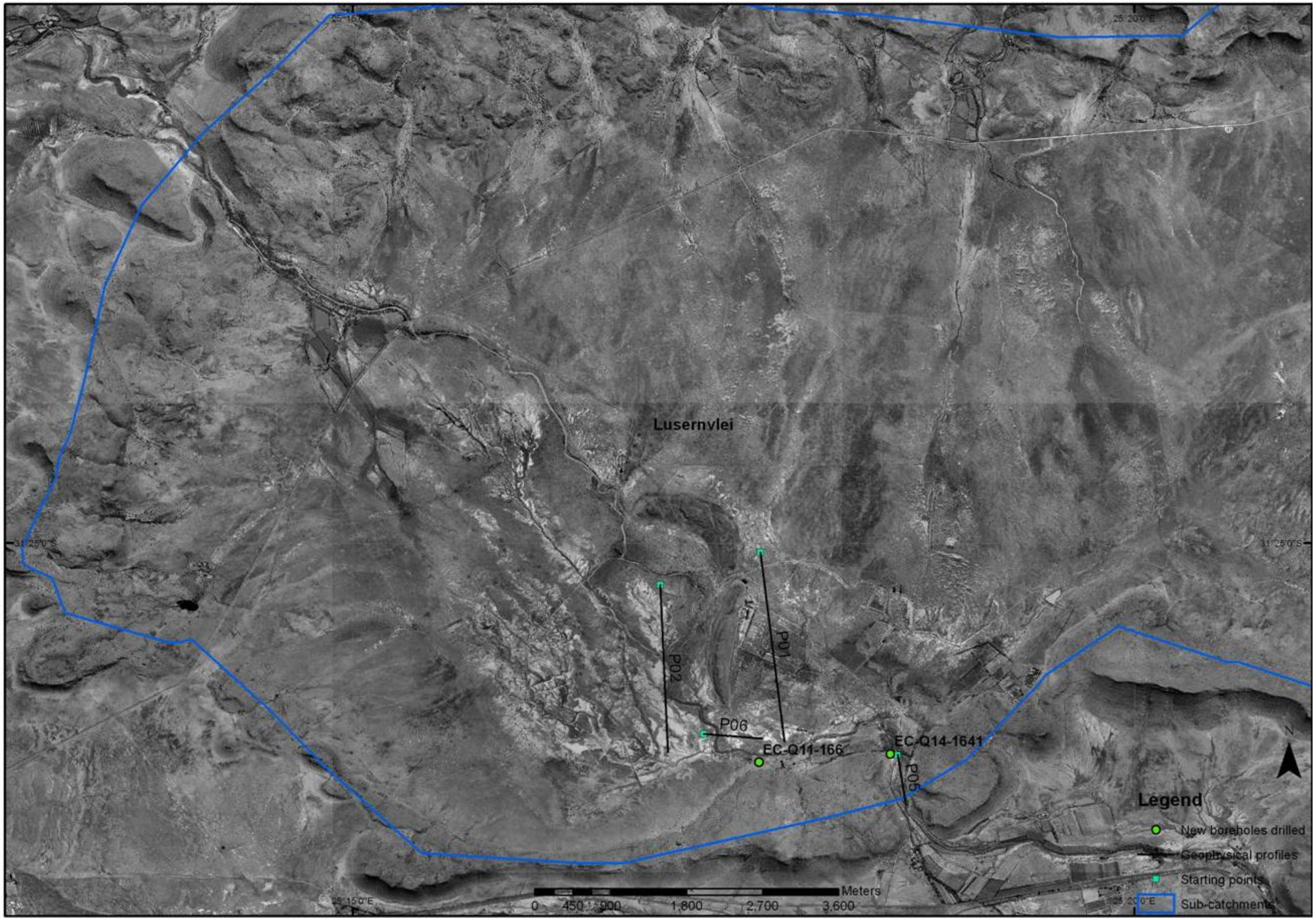


Figure 5-3: Map showing geophysical lines conducted in Lusernvlei sub-catchment and showing new boreholes drilled in green

5.3.1.3 Profile P04

Profile P04 was set out approximately 11.8 km from Middelburg on the farm Buffelsvlei. The profile was laid out in NE – SW direction in order to identify any dolerite dyke intrusions or fracturing associated with it. The profile was laid out more specifically to identify the major Dunblane dyke and it was expected the dyke would be identifiable with the alluvium cover on top of it (See map in Figure 5-5). Also to be noted from the profile in Figure 5-5 is that it crosses the Dunblane dyke approximately where the dyke underlies the non-perennial Oompiespruit drainage. It can thus be hypothesised that the Oompiespruit is a natural accumulation point and flow line for both surface and groundwater and that it would recharge any possible fractures associated with the Dunblane dyke cutting underneath it. Profile P04 was surveyed with a magnetic traverse of 3080 m and an FDEM traverse of 2760 m in a SE direction. A positive magnetic anomaly at 2260 m and a negative FDEM anomaly just before it were observed and the Dunblane dyke positively identified. A drilling site was selected at station 2200 m based on the anomalies. An existing Department of Water Affairs (DWA) borehole drilled in the 1990’s was however observed close to station 2200. The DWA borehole was identified for inclusion in the existing borehole aquifer testing program to determine if it would be necessary to drill another borehole (Coetzer, 2008). The geophysical results for P04 are illustrated in Figure 5-4.

Figure 5-4: Profile P04 on the farm Buffelsvlei in the Dunblane sub-catchment (Coetzer, 2008)

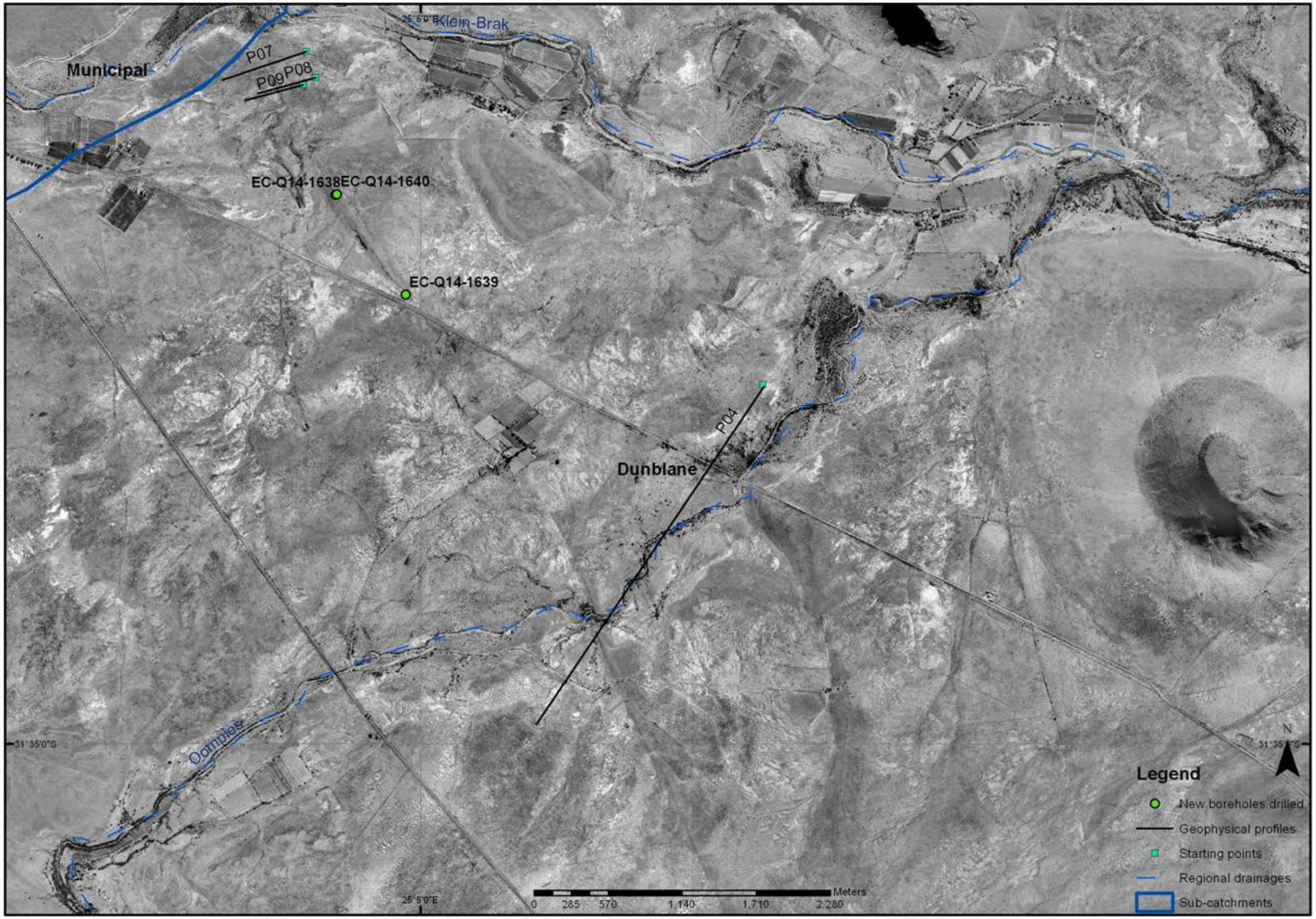


Figure 5-5: **Map showing profile P04 as it crossed the Oompies spruit drainage and the Dunblane dyke striking SSE-NNW**

5.3.1.4 Profile P05

The geophysical investigation was continued in the Lusernvlei sub-catchment on the farm Alfalfa approximately 28.8 km ENE of Middelburg town. The dolerite ring structure that forms the Lusernvlei sub-catchment was now investigated at a lowest elevation where it forms a ‘poort’ with the Rooispuit as non-perennial drainage also running through it. The objective was to determine the geometry of the dolerite at depth for the ring structure at this point. Profile P05 included a magnetic traverse and FDEM traverse of 600 m as well as resisitivity profiling of 180 m with a 40 m electrode separation and profiling of 120 m with a 60 m electrode separation (Table 5-1, Figure 5-3). None of the geophysical methods could identify the presence of any solid formations although the traverses were conducted between major dolerite intrusions. The conclusion that was reached was that the dolerite dips steeply towards the south to a point where a marshland or wetland is formed and no geophysics or drilling could take place (Coetzer, 2008). This could also indicate the very deeply weathered nature of the dolerite ring structure in the ‘poort’ and would in future present interesting possibilities for drilling at depth slightly upstream of the ‘poort’ that is formed. For the current Middelburg investigation no drilling site was selected on Profile P05 and the results are presented in Figure 2-4 in Appendix B.

5.3.1.5 Profile P06

Profile P06 continued the work in the Lusernvlei sub-catchment on the farm Lusernvlei. Again the aim was to determine the geometry of the dolerite ring structure at depth, but this time more towards the inside of the ring structure and also where the N-S feeder dyke perpendicularly links to the E-W inclined sheet of the ring structure (Figure 5-3). Profile 6 was set out in an E-W direction perpendicularly across the assumed underlying feeder dyke, where profiles P01 and P02 were to the north and parallel to the feeder dyke. Profile P06 was traversed to explore for fracturing at depth along the inclined sheet and contact with the country rock (sandstone) as well as fracturing associated with thermal jointing between the feeder dyke, country rock and inclined sheet of the ring structure. Profile P06 comprised 600 m magnetic and FDEM traverses as well as resistivity profiling of 230 m with a 40 m electrode separation and 200 m resistivity profiling with a 60 m electrode separation, all profiles in a W to E direction. Positive anomalies in the magnetic traverse, 40 m resistivity and 60 m resistivity were observed, all at approximately the same distance and station of the geophysical profile. Since the geophysical work was conducted in a W – E direction, it is thought that the anomalies clearly identified the location of the feeder dyke. A drilling site was selected on station 290 of the geophysical profile (See Figure 5-6) based on the anomalies and geology discussed above.

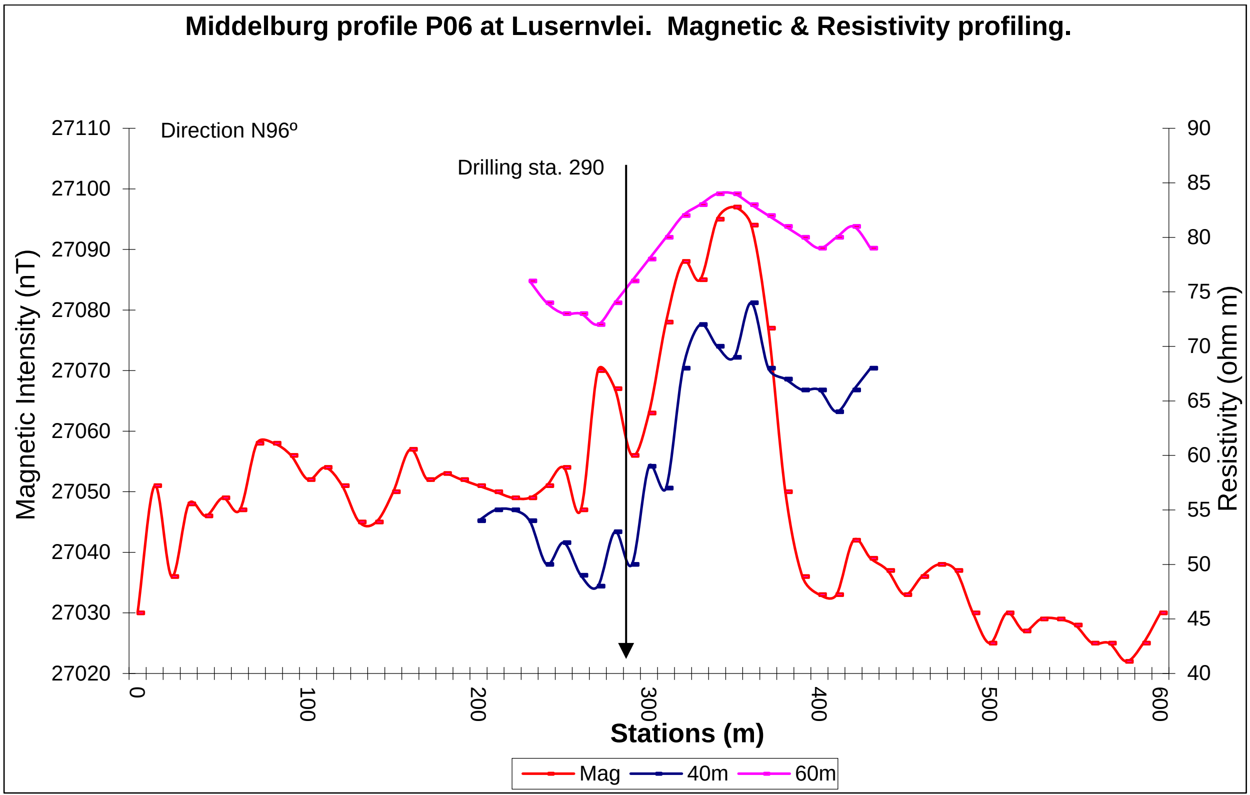


Figure 5-6: Profile P06 on Lusernvlei farm with drilling site selected at station 290 (Coetzer, 2008)

5.3.1.6 Profiles P07, P08 and P09

These profiles were laid out approximately 7.8 km SE of Middelburg town within the Dunblane sub-catchment. The goal of profiles P07, P08 and P09 was to establish the more exact location of the Dunblane dyke and its geometry, strike and attitude (Coetzer, 2008). Determining the more exact location of where the dyke passes through was also important for the extension of the geophysical investigation of the Dunblane dyke. The survey could then also be used to explore for fracturing associated with groundwater along or within the Dunblane dyke. Profile P07 was surveyed with a magnetic traverse of 600 m in a WSW direction. Profile 08 was surveyed with magnetic and FDEM traverses, each 400 m in length and in a WSW direction, approximately 200 m S and parallel to Profile 07. Profile 09 was surveyed with magnetic and FDEM traverses, each 400 m in length and in a WSW direction, approximately 28 m S of Profile 08 and parallel to it. Four boreholes that were drilled by DWA for the Vandoolaeghe (1979) investigation were located in close vicinity of these profiles. These Vandoolaeghe boreholes were G31594, G31610, G31611 and G31614

(Coetzer, 2008). Profile P09 covers two of these boreholes and was traversed to evaluate the necessity of drilling at this location (Coetzer, 2008). The DWA boreholes were however only drilled to ~40 m depths. No drilling site was selected based on these profiles and one or two of these existing boreholes would be included in the existing borehole aquifer testing program. The geophysical work performed is displayed in Figure 5-7 and the positions of these profiles are shown in Figure 5-11.

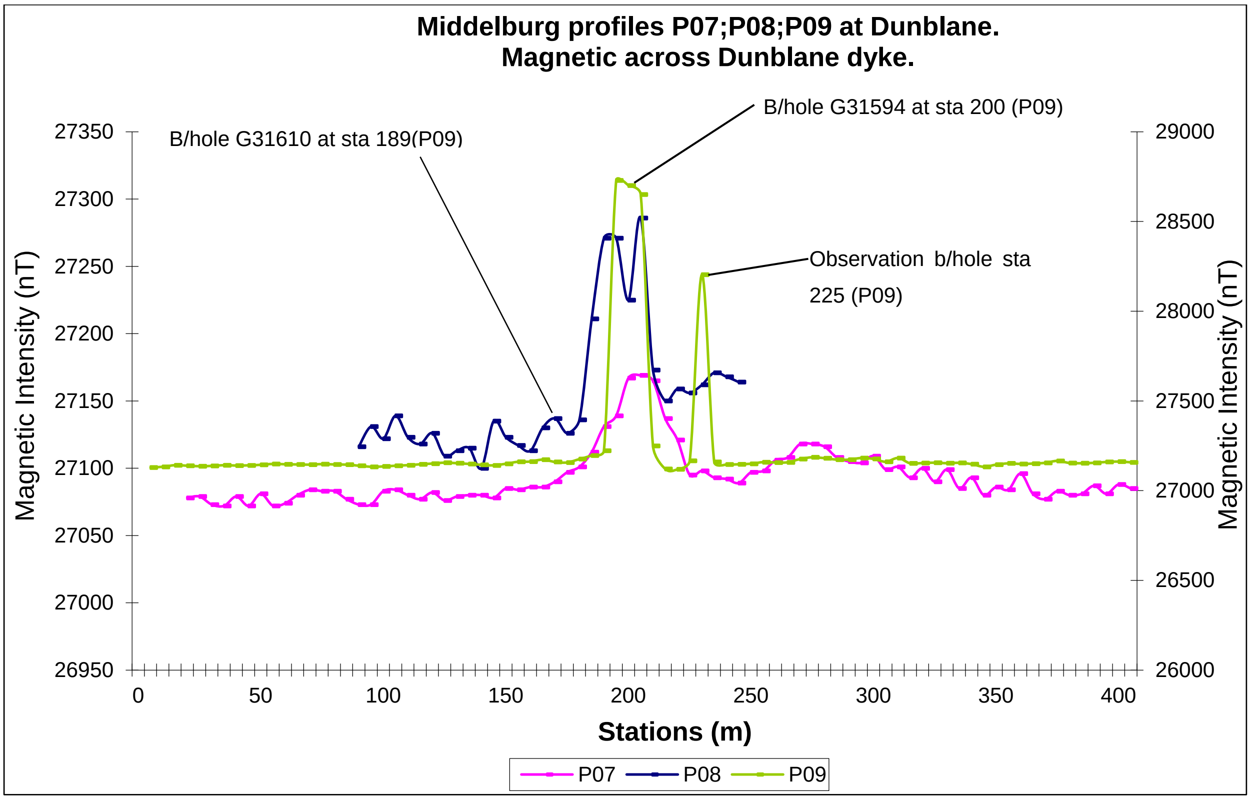


Figure 5-7: Profiles P07, P08 & P09 across Dunblane dyke (Coetzer, 2008)

5.3.1.7 Profiles P10 to P14

Profiles P10 to P14 were laid out on the farm Dunblane approximately 750 m NNW of the profiles P07 to P09, but these profiles were in the most eastern point of the Middelburg Municipal sub-catchment bordering the Dunblane sub-catchment. The objective of these profiles were again to clearly determine the more exact location of the Dunblane dyke as it was covered by alluvium at this location. Based on these profiles the first drilling site would possibly be selected due to easy access for the drilling rig (Coetzer, 2008). Profiles P10 (560 m) and P11 (560 m) were laid out parallel to the strike of the dyke on the east and west respectively, to investigate for possible fracturing and transgressive fractures perpendicular to the strike of the dyke. The profiles P10 and P11 were traversed in a SSE direction with the FDEM instrument and at a distance of 550 m the highest water bearing fracture possibilities were identified. Accordingly profiles P12, P13 and P14 were laid out perpendicularly to profiles P10 and P11, in the region indicating the highest possibility of water bearing fractures. The three former mentioned profiles could also be used to determine the exact position of the Dunblane dyke as they crossed it perpendicularly. The results of the geophysical traverses are shown in Figure 5-8 to Figure 5-10 as well as P11 in Figure 2-5 in the Appendix B. The data for the eight different frequencies generated by the FDEM, were plotted in the Surfer contouring software package to identify the concentration of the highest conductance measured on profiles P12, P13, P14 and the results are portrayed in Figure 5-8 (Coetzer, 2008). The graphs compiled for P13/180 are indicated in Figure 5-9.

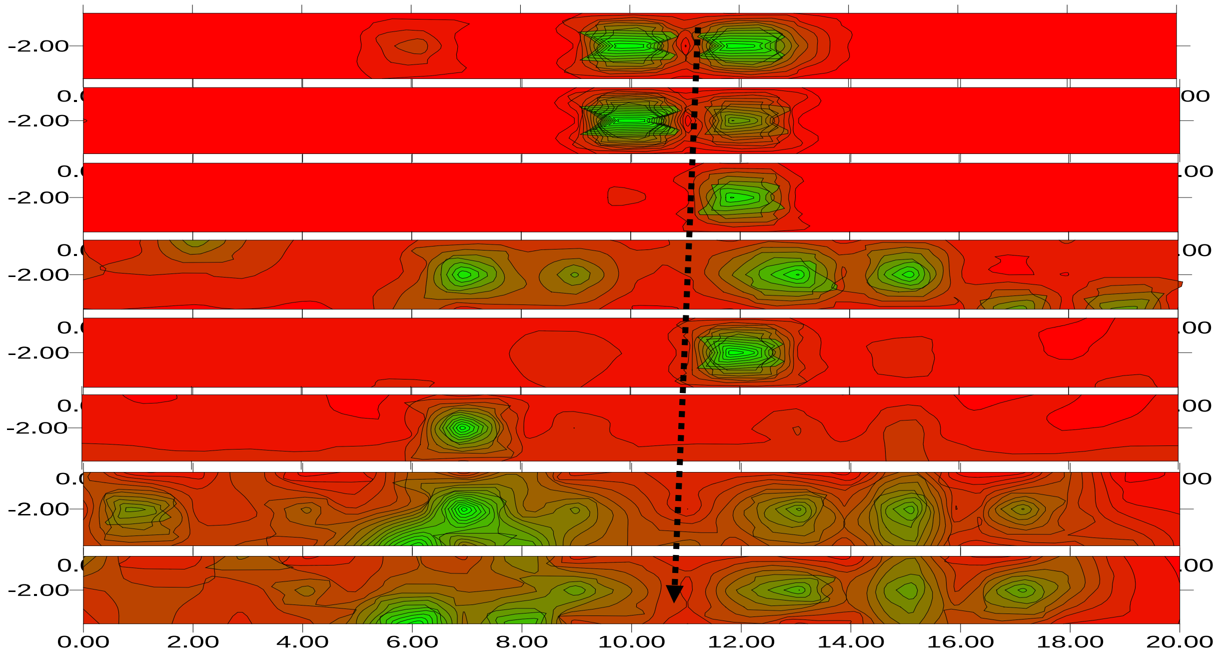


Figure 5-8: Profiles P12, P13 and P14 correlated showing highly fractured zones in green either side of Dunblane dyke (Coetzer, 2008)

In Figure 5-8 the closely spaced contours highlighted by green colour indicate the areas of high conductance measured by FDEM which correlate with water bearing fractured rock (Coetzer, 2008). Each of the eight segments of the contour graph in Figure 5-8 above represents a different frequency (from low to high) used by the FDEM instrument for different depth penetration, for each of the three profiles traversed. The dotted arrow line is an indication of a zone of lower conductance measured that can be associated with solid fresh formation like dolerite (Coetzer, 2008). The most fractured area in depth is indicated on station 9 (on the lowest segment) or 180m from the starting point and a drilling site was selected accordingly (Coetzer, 2008).

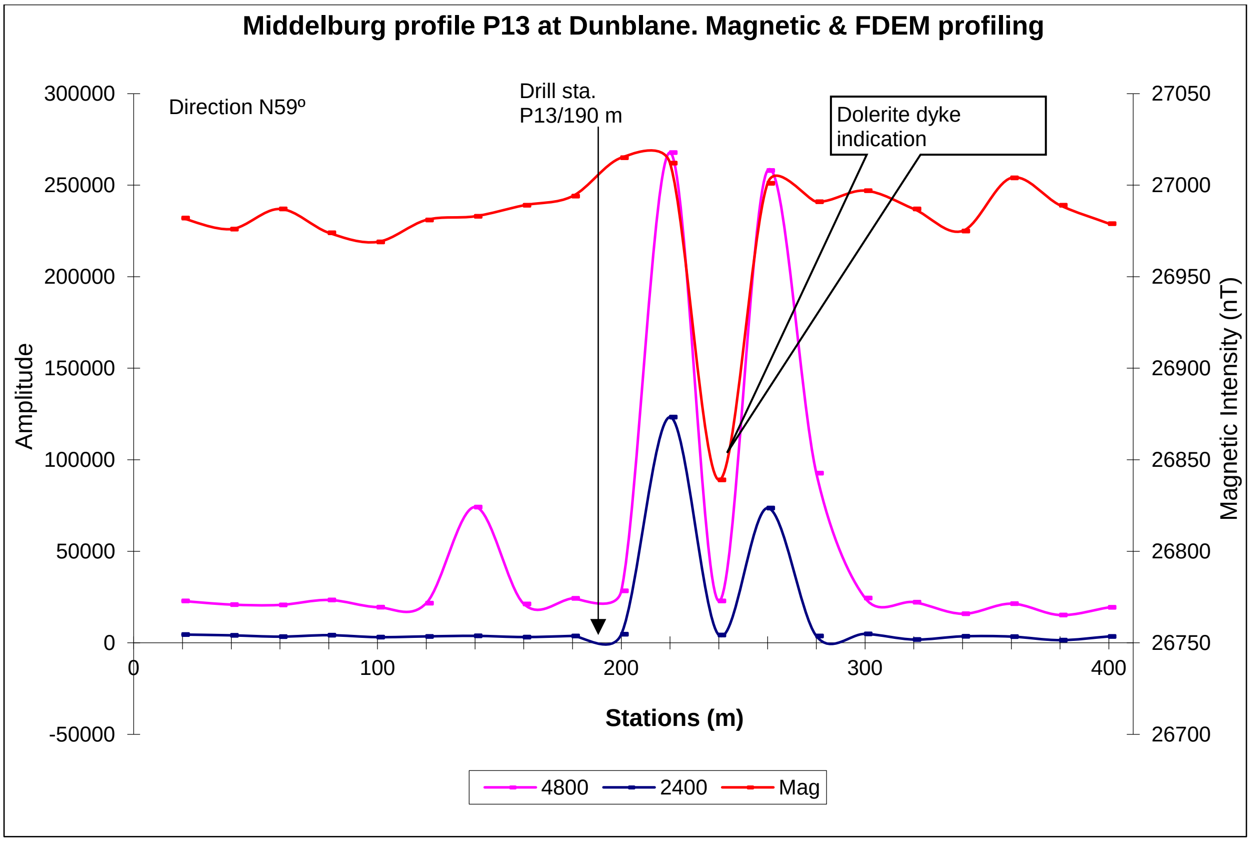


Figure 5-9: Profile P13 perpendicularly across the Dunblane dyke with fractures/ weathering on both sides

The first borehole drilling site was selected on profile P13, based on the FDEM contoured results indicating fracturing at depth. The geophysical surveys conducted on P13 comprised magnetic and FDEM traverses 390 m in length in a NE direction as well as resistivity profiling of 210 m with both 40 m and 60 m electrode separation. Based on the geophysical results in Figure 5-8 and Figure 5-9, the drilling site was selected on station 190 or a 190 m into the profile. The borehole EC-Q14-1630 was drilled and is discussed in the Drilling chapter.

A drilling site was selected on P12 to target the fractured zone next to the Dunblane dyke. The aim of this drilling site was to penetrate the dyke at a depth greater that 150m (Coetzer, 2008). Profile P12 was laid out 50m SSE of P13 and parallel to it. Borehole EC-Q14-1631 was drilled on station 210 of P12 and will be discussed in the Drilling chapter. The geophysical results of P12 are shown in Figure 5-10.

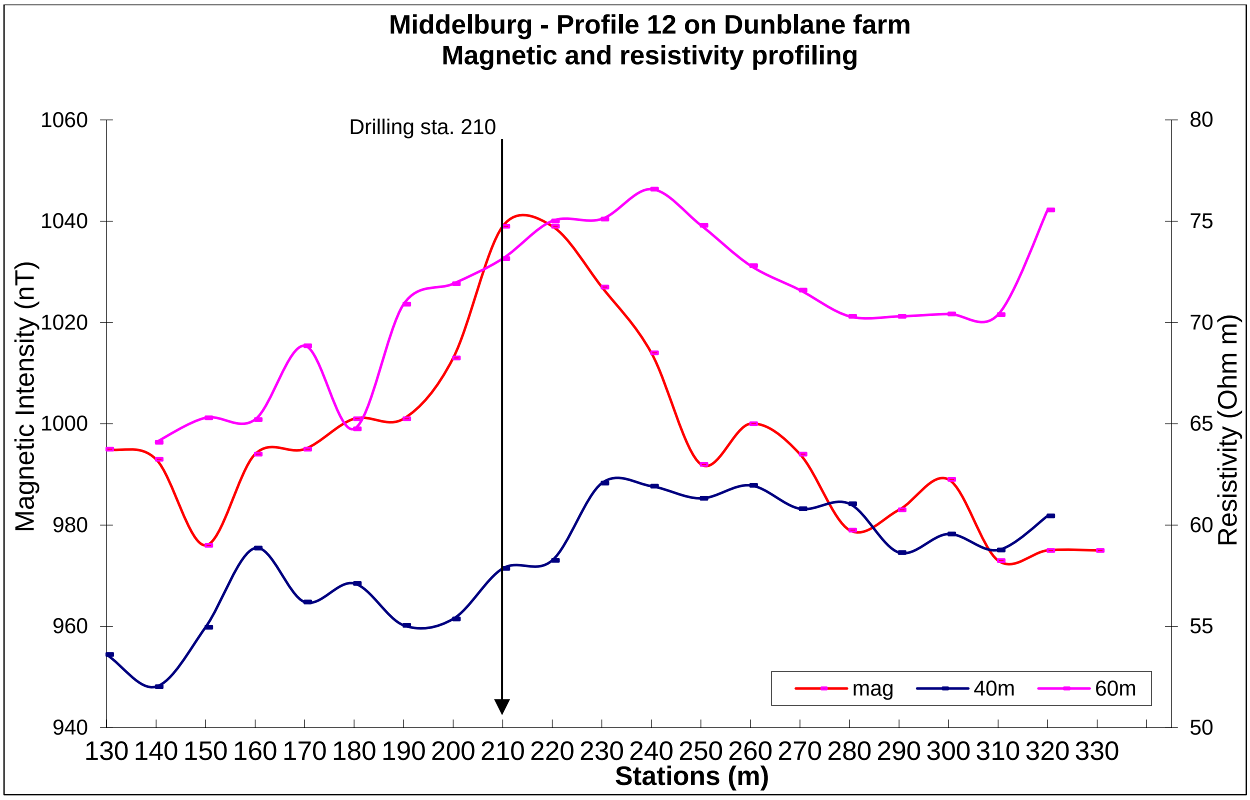


Figure 5-10: Profile P12 across fracture zone next to Dunblane dyke (J. Coetzer, 2008)

Geophysical work on Profile P11 comprised only an FDEM traverse of 600 m in order to pick up the most highly fractured zone parallel to the Dunblane dyke. This was successfully done with 3 FDEM frequencies clearly indicating such a zone that is thought to be a transgressive fracture. The results on P11 are presented in Figure 2-5 in Appendix B and no drilling site was selected, however P12 – P14 was laid out based on the anomalies on P11.

5.3.1.8 Profile P15

Profile P15 was set out approximately 1260 m NNW of profile P14 on the Grootfontein farm of the Grootfontein Agricultural College within the Dunblane sub-catchment. Profile P15 was also set out perpendicular to the expected strike of the Dunblane dyke. To the NNW and SSE of this location the Dunblane dyke outcrops above the ground level with at least 3 – 5 m. At the specific location of P15 however there is a small ‘poort’ formed that also serves as an access road past the Dunblane dyke. The Middelburg groundwater exploration project turned from an exploration project into a drought relief project at the time when P15 was traversed and the option of developing a well field next to the Dunblane dyke started taking effect (Coetzer, 2008). Profile P15 included magnetic and FDEM traverses 375 m in length as well as resistivity profiling of 280 m with both 40 m and 60 m electrode separation. A drilling site was selected on Station 195 at the confluence of anomalies and the borehole EC-Q14-1632 was drilled (Figure 5-12).

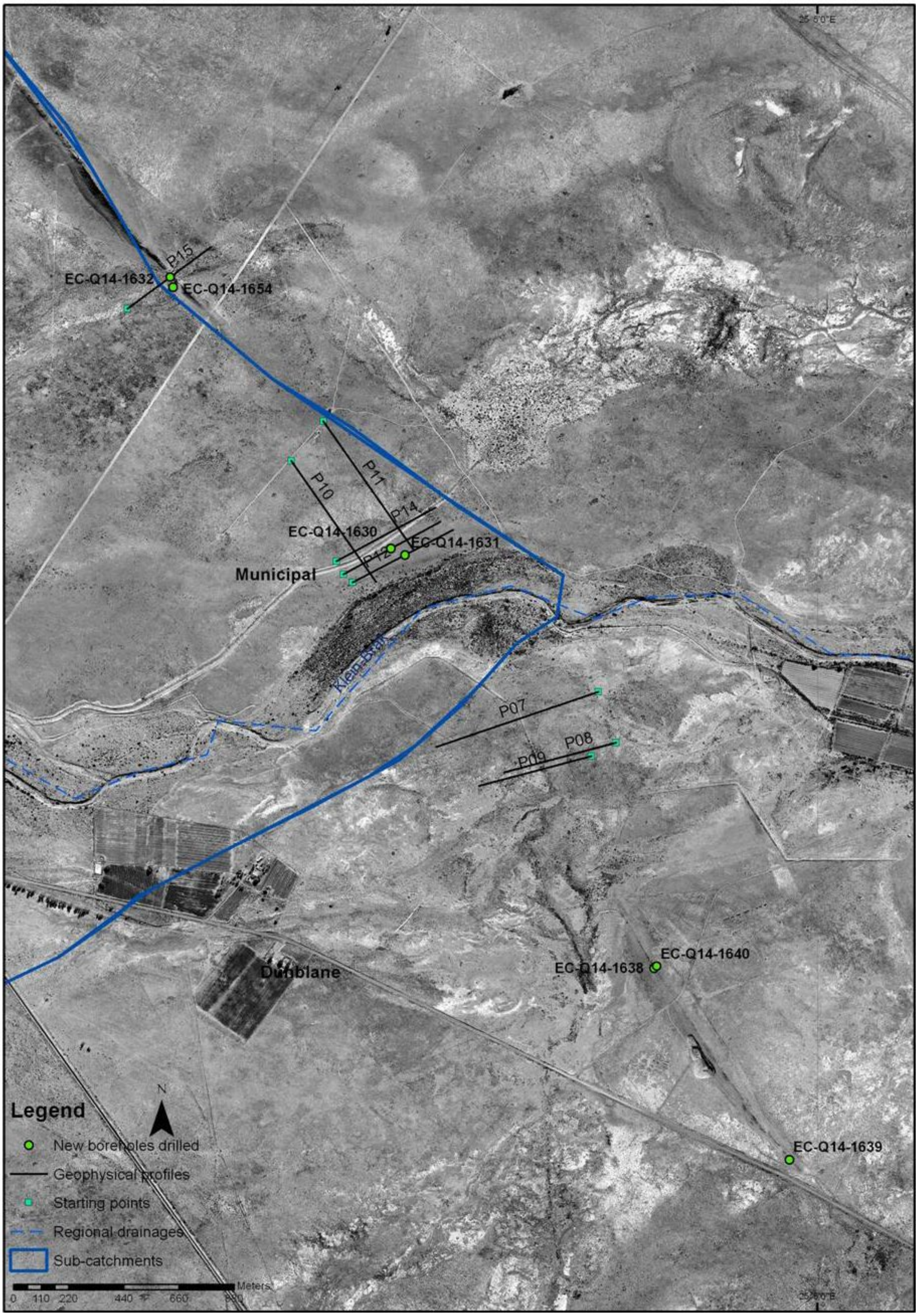


Figure 5-11: Map showing profiles P07 – P15 and new boreholes on Dunblane dyke

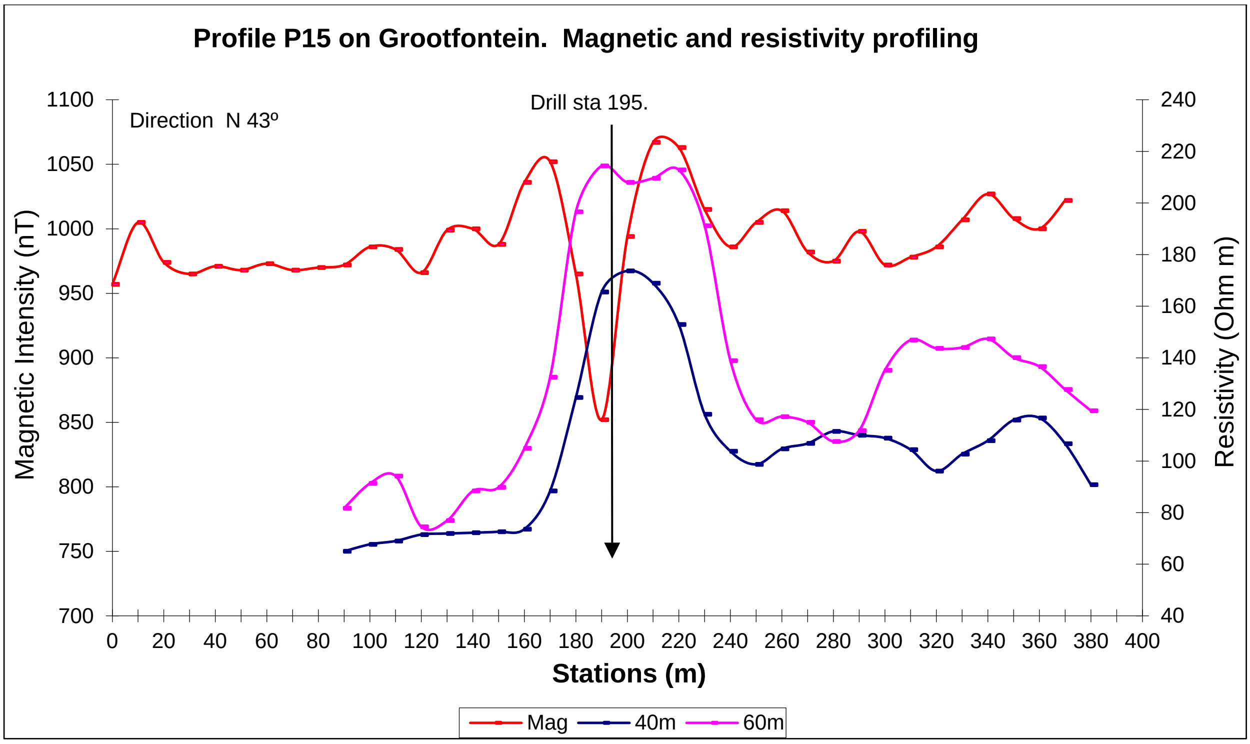


Figure 5-12: Profile P15 across Dunblane dyke on Grootfontein farm in Dunblane sub-catchment (Coetzer, 2008)

5.3.1.9 Profile P16 to P22

Profiles P16 – P22 were set out on the Municipal allotment area within the Middelburg Municipal sub-catchment, approximately 3.7 km E of Middelburg town. The goal was not to drill in this area, but to investigate the extension and strike of the Dunblane dyke in a northern direction, at this location where it is covered by alluvium (Coetzer, 2008). There were also some municipal boreholes in the proximity of these profiles and drilling in this area could result in over abstraction taking place in combination with the municipal boreholes. The length and traverse type conducted on these profiles is summarised in Table 5-1 and the geophysical results summarised in Figures 2-6 to 2-12 in Appendix B (CD enclosure). The positions of profiles P16 – P22 are shown in Figure 5-13.

Figure 5-13: Map of profiles P16 – P22 conducted to determine extension and orientation of Dunblane dyke beneath alluvium

5.3.1.10 Profile P23

Profile P23 started the work in the Glen sub-catchment on the Glen farm, and it is also the longest single profile laid out during the investigation at 3400 m. The objective of this profile was to detect the presence of dolerite in the basin of the ring structure i.e. the inner sill and also to correlate a highly fractured zone picked up by the FDEM at the station at 2600 m to station 2660 m (Coetzer, 2008). The profile was surveyed with magnetic and FDEM traverses of 3400 m length as well as resistivity profiling of 130 m with a 40 m electrode separation and 110 m with a 60 m electrode separation. The alluvium encountered in this part of the basin was however dominant and the electrical currents could not reach great depths, which resulted in the characterisation of low resistance layers only (Coetzer, 2008). A possible drilling site was selected based on the FDEM results as well as the assumed geometry of the ring structure and its inclined sheet. A possible drilling site was selected at 2640 m and the geophysical results are shown in Figure 5-14 and Figure 5-15.

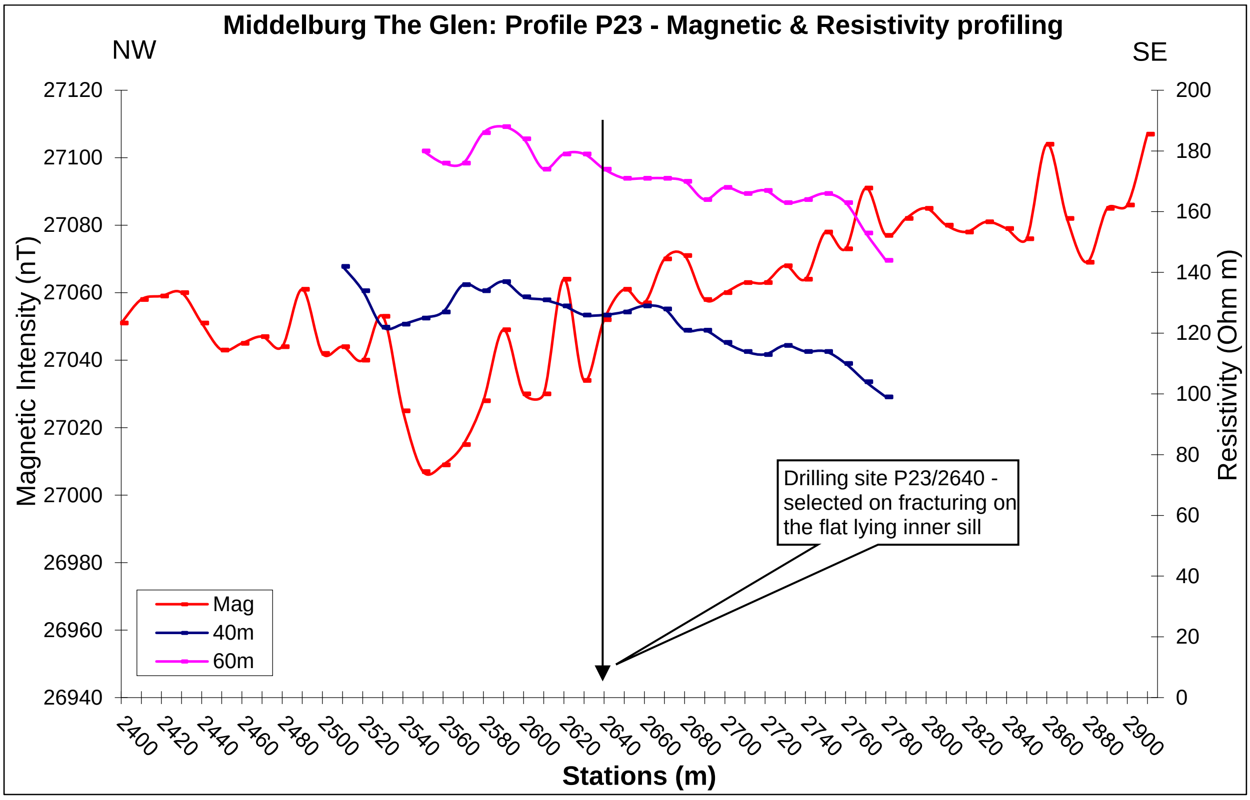


Figure 5-14: Profile P23 first profile conducted in The Glen sub-catchment (Coetzer, 2008)

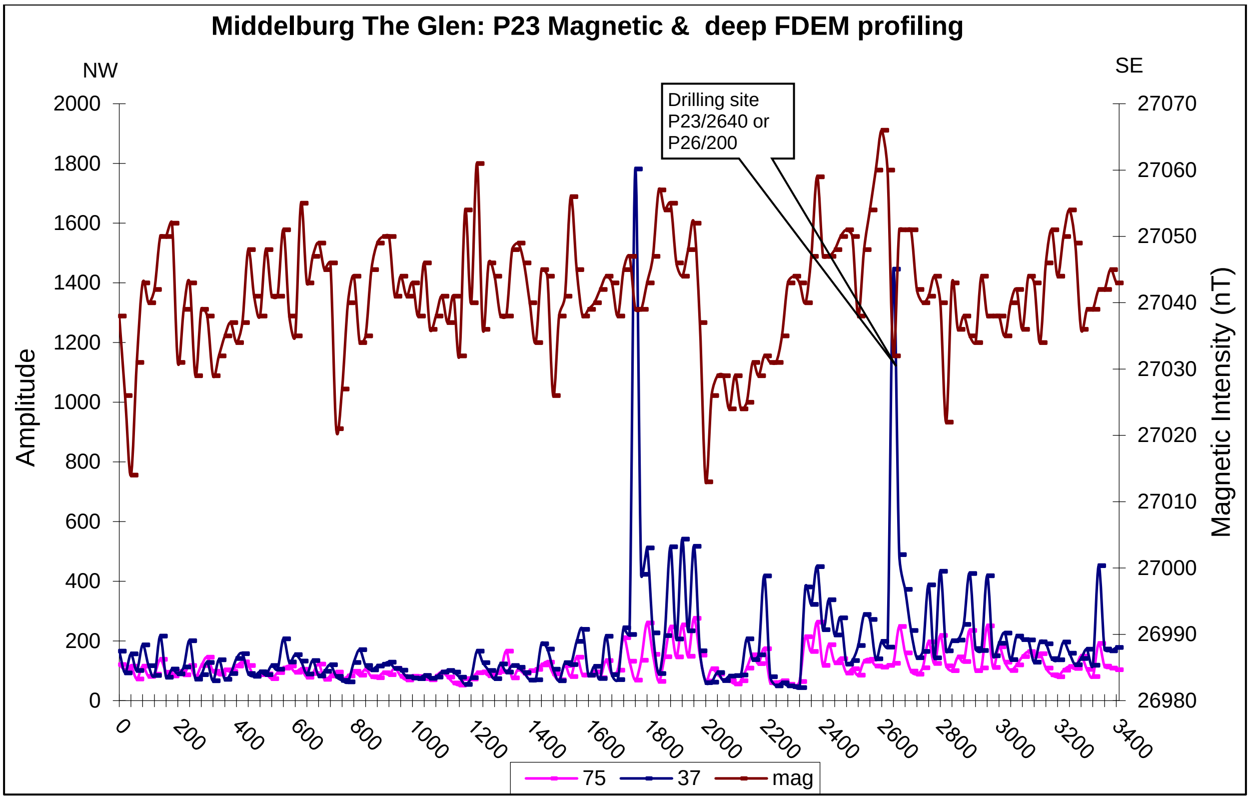


Figure 5-15: Profile P23 full magnetic and deep FDEM profiling (Coetzer, 2008)

5.3.1.11 Profiles P24 to P26

Profiles P24 to P26 were conducted on the farm the Glen in the Glen sub-catchment close to the southern part of P23. The objective of the profiles was to investigate a prominent inclined sheet at this part of the farm and possible fracturing associated with the intrusion of the inclined sheet. Profile P24 was an extension of P23 and was laid out through the 'poort' known as Jones Poort as the lowest point of the sub-catchment and ring structure. P24 comprised 600 m magnetic and FDEM traverses in a SE direction. P25 was laid out on the outside of the inclined sheet to investigate for any fractures that could have developed during or after the intrusion as well as any lineaments extending through Jones Poort. P26 was laid out perpendicularly to P23 on the inside of the inclined sheet in the Glen sub-catchment southern basin to evaluate fracturing there. The graph results of these profiles are presented in Figure 2-13 to 2-15 in the Appendix B. The locations of these profiles are shown in Figure 5-16.

Figure 5-16: **Map showing Profiles P24, P25, P26 & P29 at Jones poort and The Glen sub-catchment**

5.3.1.12 Profile 27

The geophysical investigation then shifted again to Dunblane sub-catchment to the farm Greyville approximately 14.5 km SE of Middelburg. The aim of this profile was to identify the presence and position of dolerite where a dolerite ring structure was evident on the geological map, but was covered by alluvium along the river where the profile was traversed. The profile was surveyed with magnetic and FDEM traverses of 800 m length each as well as resistivity profiling of 310 m with a 40 m electrode separation and 290 m with a 60 m electrode separation. The geophysics was successful with magnetic and resistivity results complementing each other well as can be seen in Figure 5-17 and the dolerite ring structure could be identified. A possible drilling site could be selected based on the anomalies observed.

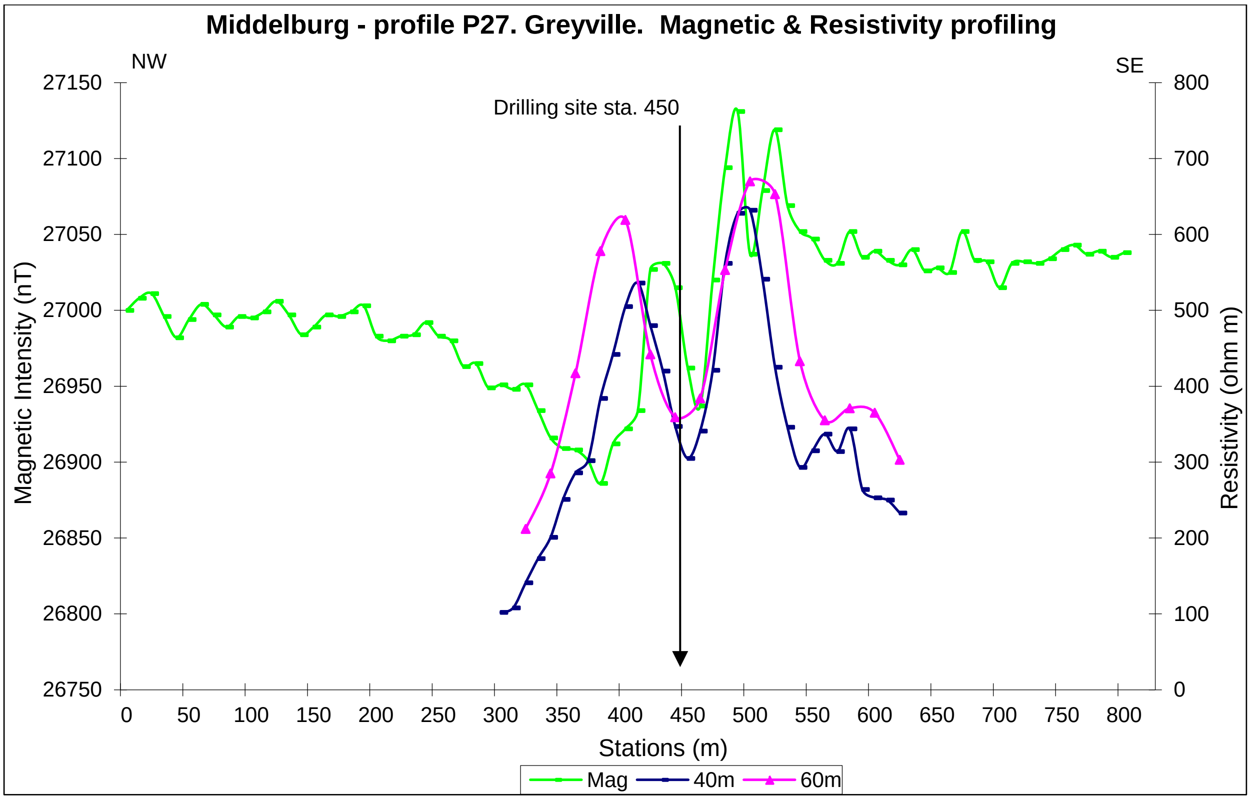


Figure 5-17: Profile P27 on Greyville farm, Dunblane sub-catchment (Coetzer, 2008)

5.3.1.13 Profile 28

Profile 28 was conducted in the immediate vicinity of profiles P16 – P22 on the municipal allotment area within the Middelburg Municipal sub-catchment (Figure 5-13). It was necessary to expand the geophysical investigation in this area after additional information on the existing municipal boreholes became available (Coetzer, 2008). At this location the Dunblane dyke is covered by alluvium and it was necessary to again determine its exact location for further investigation to the north (Coetzer, 2008). The profile extended across existing boreholes to determine their position with respect to the dyke. P28 was surveyed with 400 m magnetic and FDEM traverses in a NE direction as well as resistivity profiling of 150 m in both 40 m and 60 m electrode separation. The geophysical results are portrayed in Figure 2-16 in Appendix B.

5.3.1.14 Profile 29

Profile P29 continued the work on the Glen farm in the Glen sub-catchment. P29 was practically and extension of P24 as the results obtained from P24 were not what was expected and it was necessary to expand the investigation (Coetzer, 2008). Profile P29 was surveyed with magnetic and FDEM lines of 980 m each as well as resistivity profiling of 780 m with both 40 m and 60 m electrode separation. The geophysics proved successful and a drilling site could be selected at station 415 m based on the magnetic anomaly and complementing resistivity anomalies. The borehole EC-Q14-1634 was drilled at this station. Figure 5-18 shows the geophysical results of profile P29 and the location of the profile is shown in Figure 5-16.

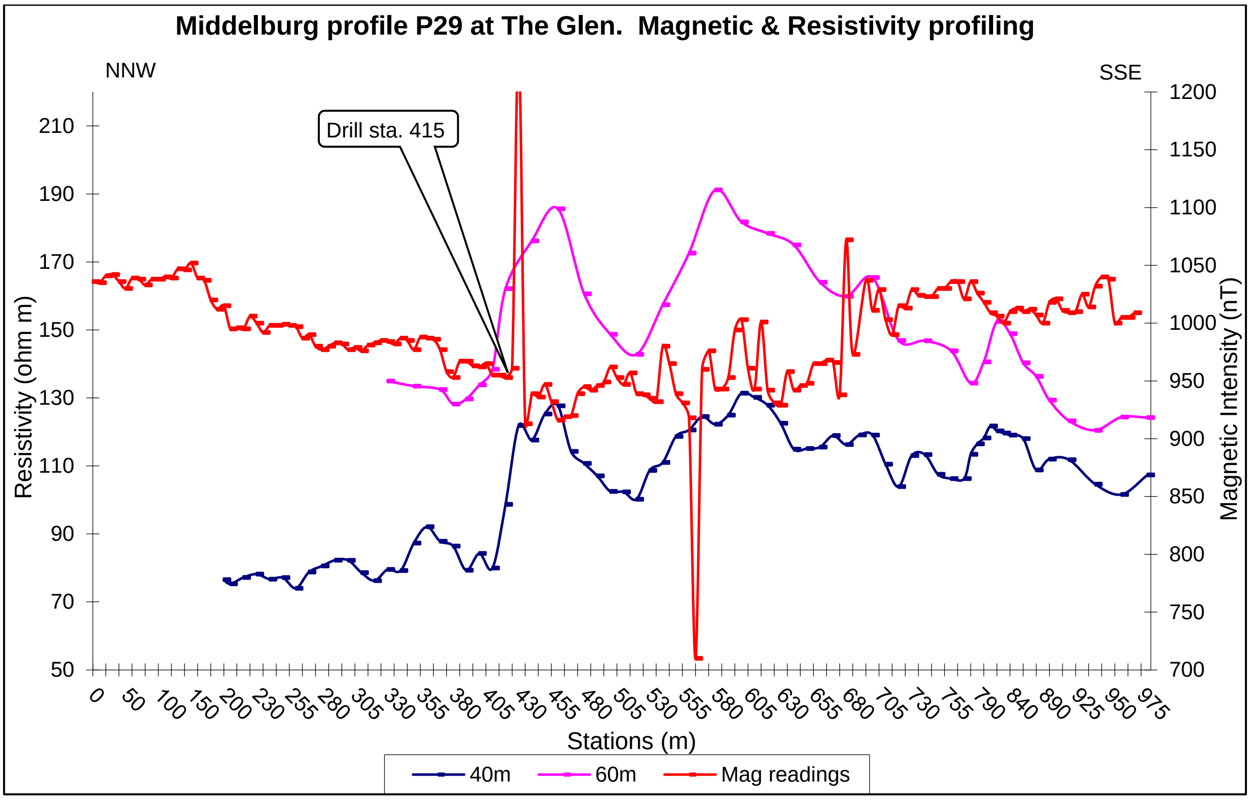


Figure 5-18: Profile P29 through Jones Poort that borehole EC-Q14-1634 was sited on (Coetzer, 2008)

5.3.1.15 Profile P30

Profile P30 was conducted on the municipal allotment within the Middelburg municipal sub-catchment. P30 is approximately 235 m south of P28 (Figure 5-13). The aim was to site and drill a borehole on the dipping side of the Dunblane dyke where it cuts through the dolerite ring structure. The dyke and the inclined sheet of the ring structure would be targeted at depth. Profile P30 was surveyed with a magnetic traverse 300 m in length and a FDEM traverse 400 m in length, both in a NE direction. The geophysical methods proved successful and a borehole could be sited on the geophysical results (Figure 5-19). Borehole EC-Q14-1633 was drilled on the profile 220 m from its starting point, based on a magnetic anomaly.

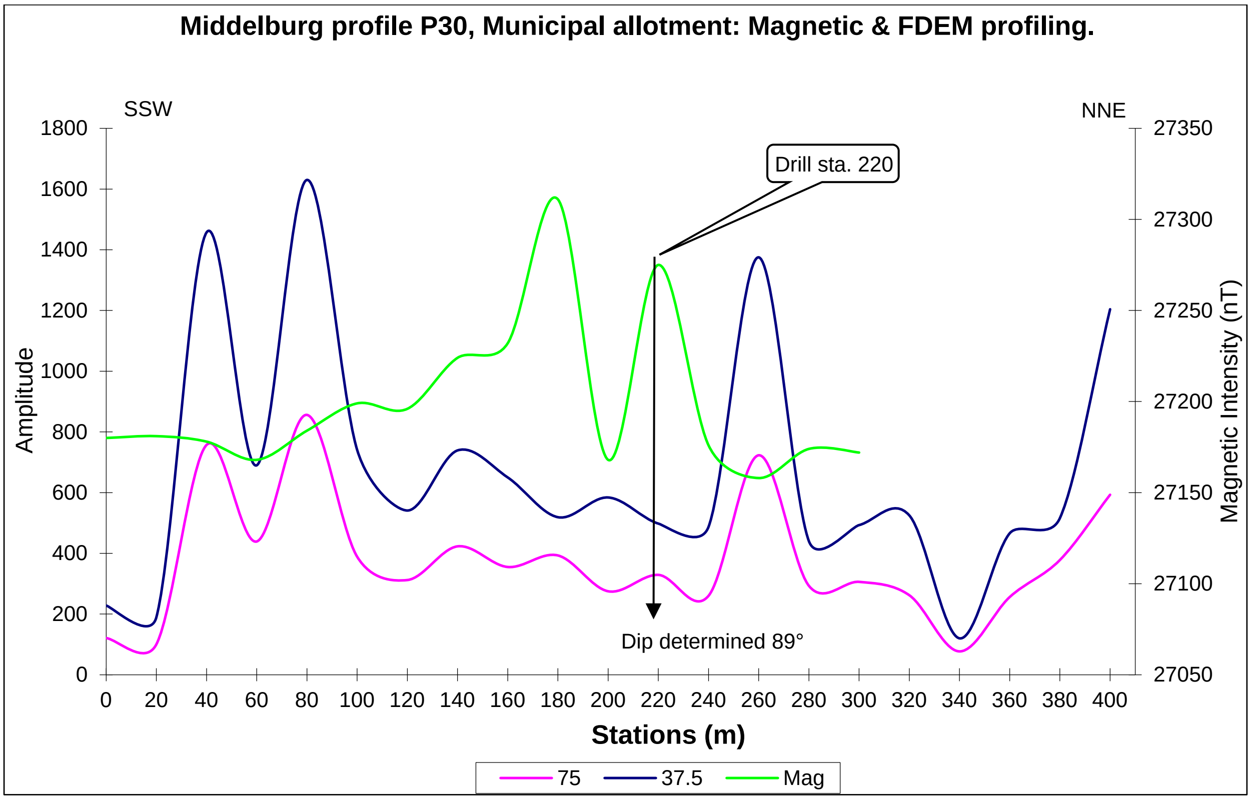


Figure 5-19: Profile P30 was used for siting borehole EC-Q14-1633 (Coetzer, 2008)

5.3.1.16 Profiles P31 to P36

These profiles were conducted on the farm Grootfontein approximately 8.5 km N to NNW of Middelburg, within the Glen sub-catchment. Complex geology was present at this location with visible fracturing features (Coetzer, 2008). The objective was then to delineate the type and geometry of the dolerite structure present in order to site a possible borehole. P31 was taken parallel to the dolerite structure where it outcrops at one point and is covered by alluvium at the other (Coetzer, 2008). Profiles P32 to P36 were set out perpendicularly to profile P31 to determine whether a dyke or a sill is present (see map in Figure 5-22). All length and types of the geophysical traverses are summarised in Table 5-2. Prominent fracturing could be discerned with the resistivity and electromagnetic methods and a drilling site could be selected. The geophysical results are presented in Figure 5-20 and Figure 5-21. The borehole EC-Q14-1637 was later drilled on profile P31 at 360 m from the starting point of the line. The geophysics data for P32, P33, P35 and P36 could not be supplied by Mr. Japie Coetzer.

The frequencies for deeper penetration (i.e. 150 Hz, 70 Hz and 37,5Hz) are contoured in Figure 5-21 for Profile P34. Figure 5-21 shows linear fracturing in an E-W direction that correlates well with the lower resistivity measured at station 360 m on profile P31 (Figure 5-20).

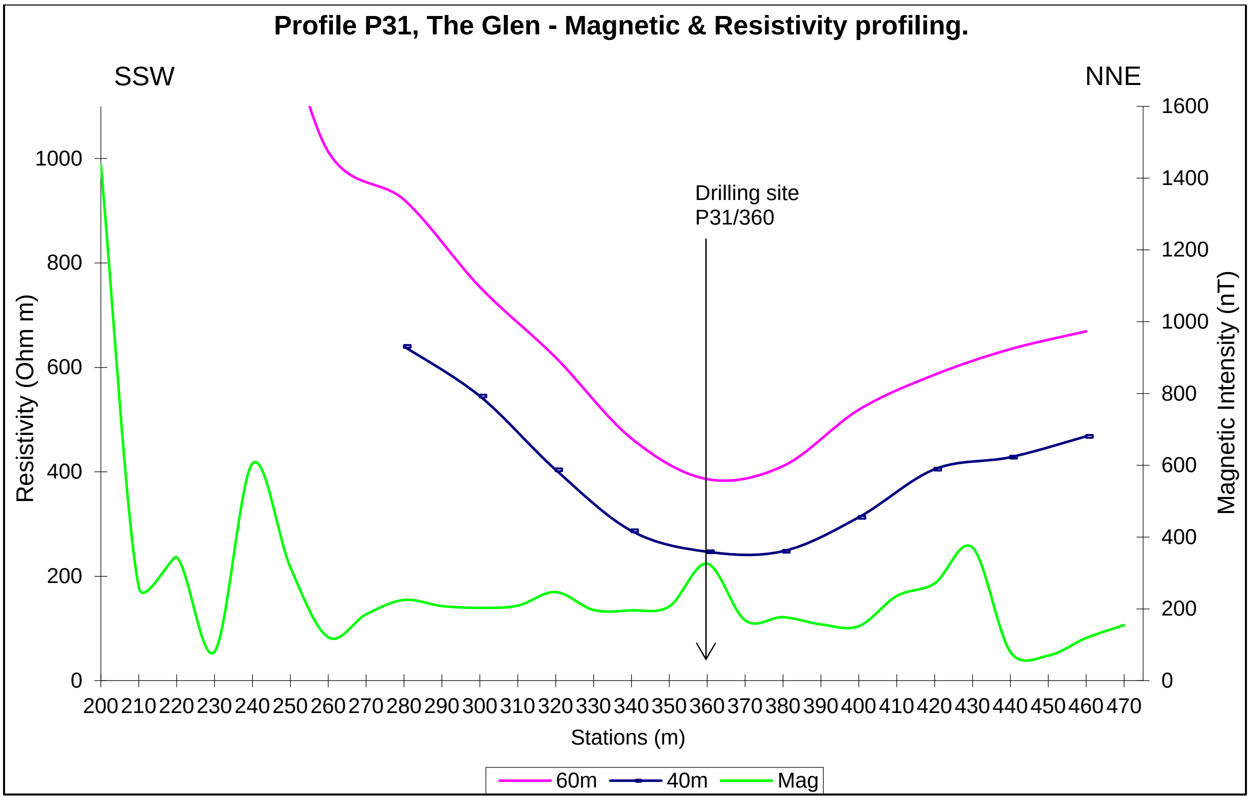


Figure 5-20: Profile P31 parallel to minor sill/ dolerite structure in The Glen sub-catchment (Coetzer, 2008)

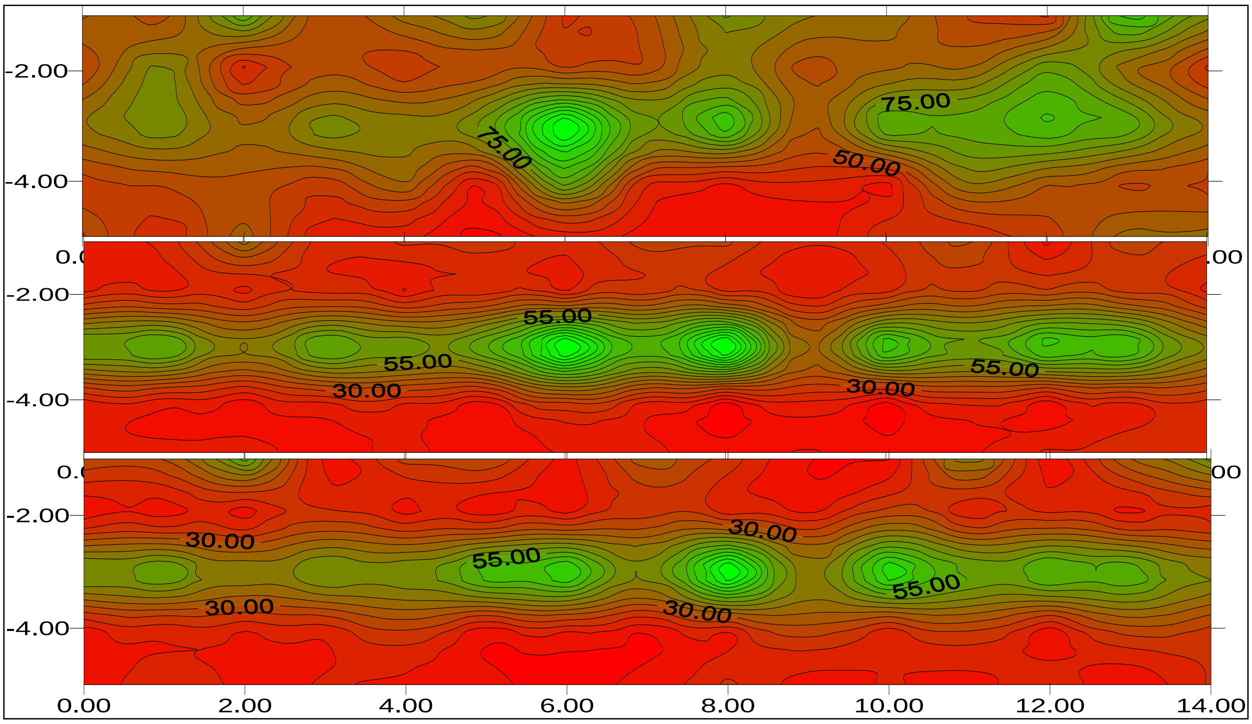
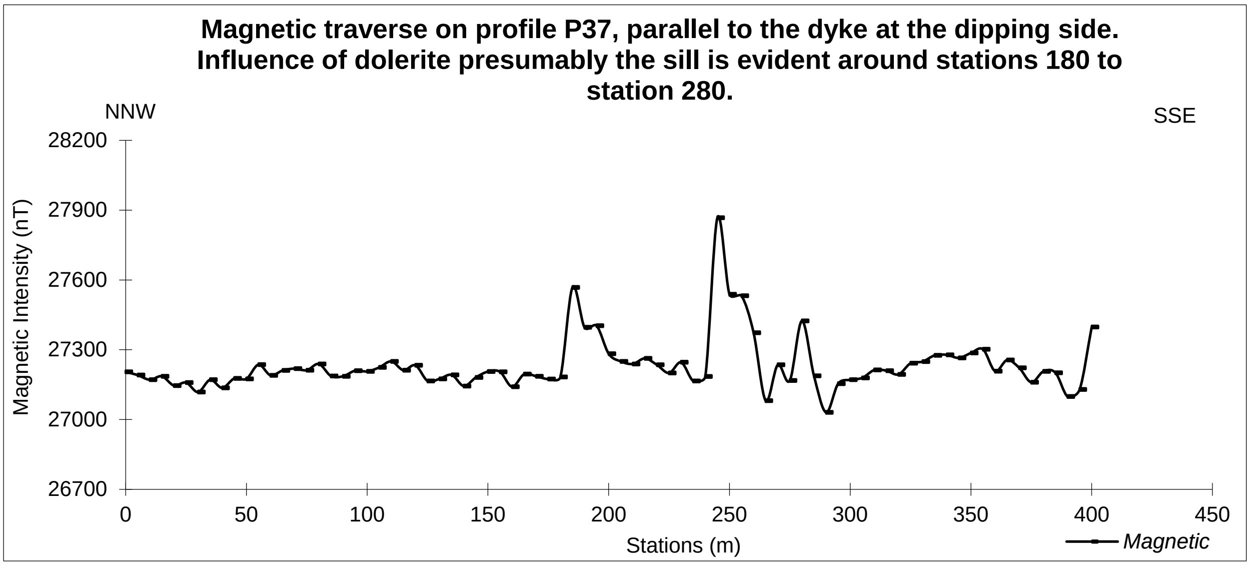


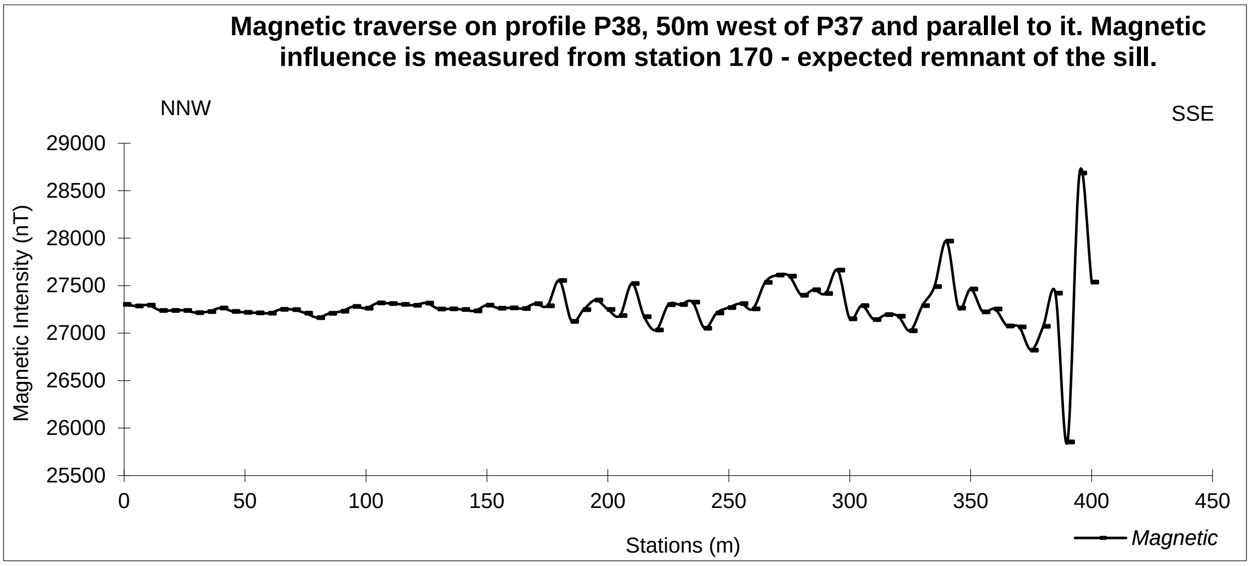
Figure 5-21: P34 Contoured frequencies 150Hz, 75Hz & 37.5Hz from top to bottom-a higher conductance feature in green measured on P34 (Coetzer, 2008)

Figure 5-22: Map of Profiles P31 – P36 investigating linear-like dolerite structure present parallel to southern part of P31

5.3.1.17 Profiles P37 to P43

Profiles P37 – P43 continued the work on Grootfontein farm in the Glen sub-catchment. The specific area under geophysical investigation here also presents complex geology where a dolerite dyke or an offshoot of the Dunblane dyke cuts through the inclined sheet of the dolerite ring structure forming the watershed of the Glen sub-catchment (Figure 5-25). The objective of the geophysics was to site and drill a borehole into the fracture zone on the side of the dyke and then secondly to drill into the sill at depth (Coetzer, 2008). Profiles P37 – P39 were laid out in a NNW – SSE direction parallel to the dyke where it was visible, up to the point where it was covered by alluvium (Coetzer, 2008). The type and length of these profiles are summarised in Table 5-2. The magnetic work in P37 – P39 in Figure 5-23 revealed remnants of what were expected to be part of the dolerite sill (Coetzer, 2008).





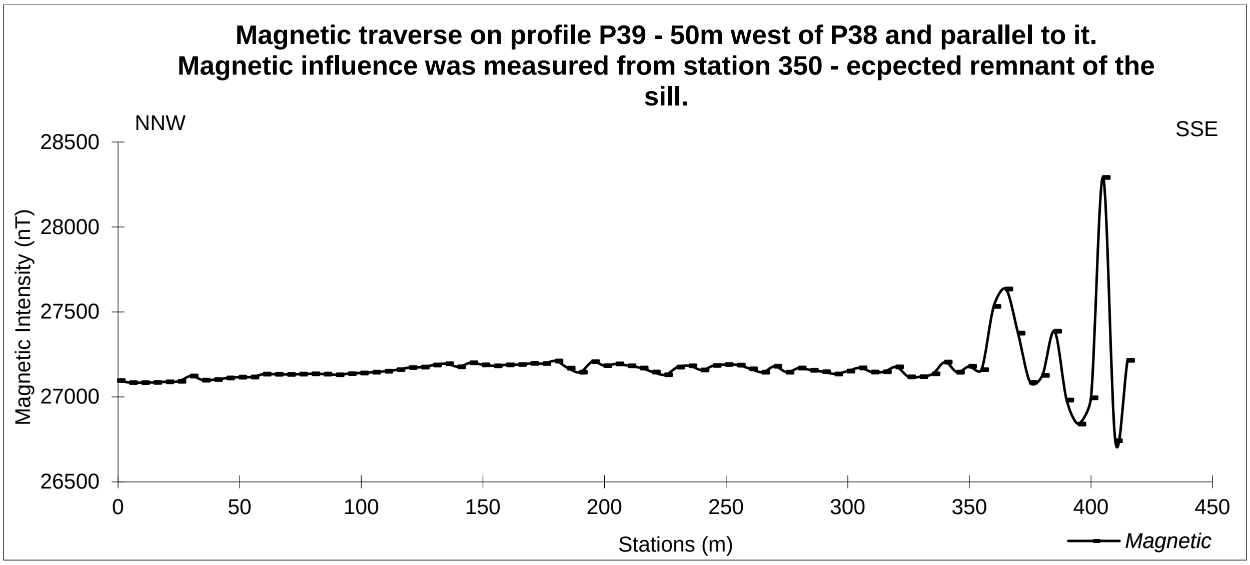
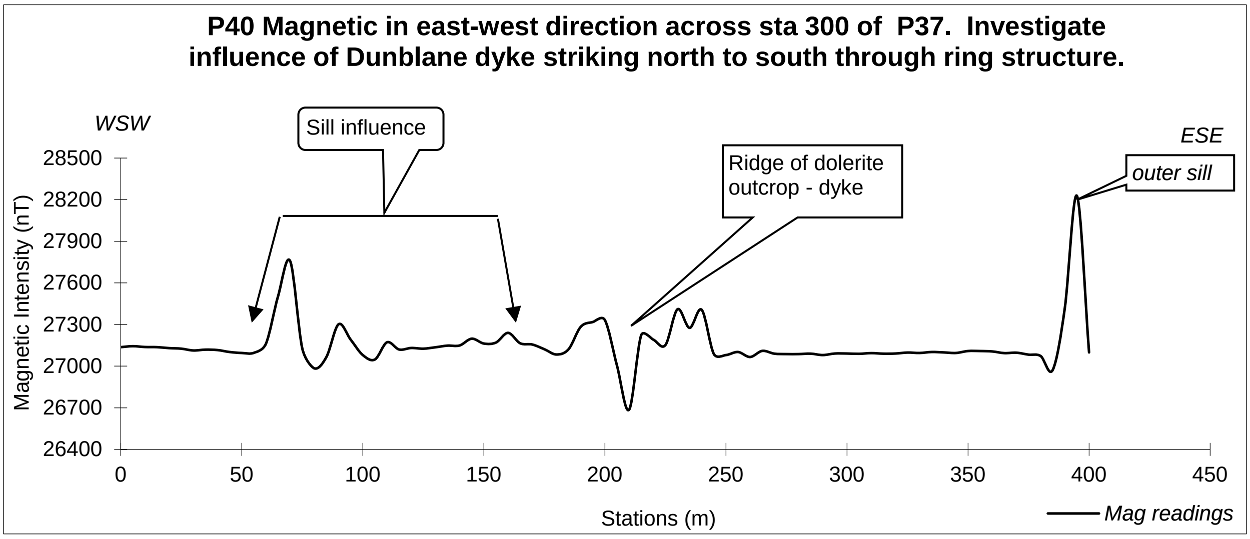


Figure 5-23: Profiles P37, P38 & P39 in The Glen sub-catchment parallel to dyke cutting through sill (Coetzer, 2008)

The profiles P40 – P43 were laid out perpendicular to P39 across the dyke at sections where the most conductance and fracturing was measured with the FDEM readings on profiles P37 – P39. The dolerite sill was detected during the magnetic surveys, but the dolerite dyke was more prominent and could be easily identified (Coetzer, 2008). A drilling site was selected on the dipping side of the dolerite dyke on profile P40 where the sill could also still be identified on the geophysics. Profiles P37 – P39 are presented in Figure 5-23. The presence of dolerite registered more prominently on the southern side of these profiles as these were closer to the outcropping dolerite. Geophysical readings for profiles P40 – P43 are presented in the graphs of Figure 5-24. The borehole EC-Q14-1636 was sited and drilled on station 210 of profile P40.



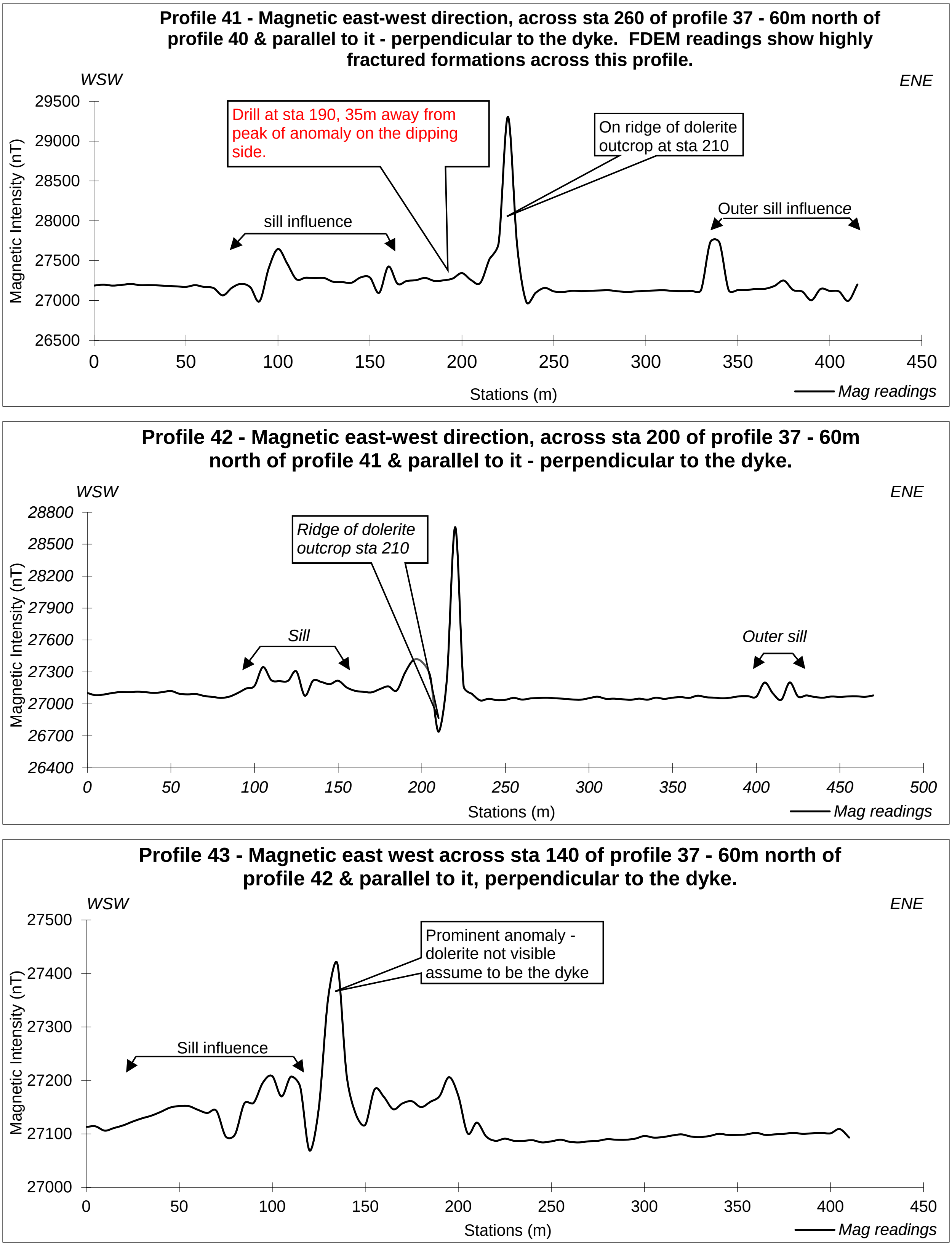


Figure 5-24: Profile P40-P43 perpendicular across Dunblane dyke offshoot where Dunblane dyke cuts through The Glen dolerite ring structure (Coetzer, 2008)

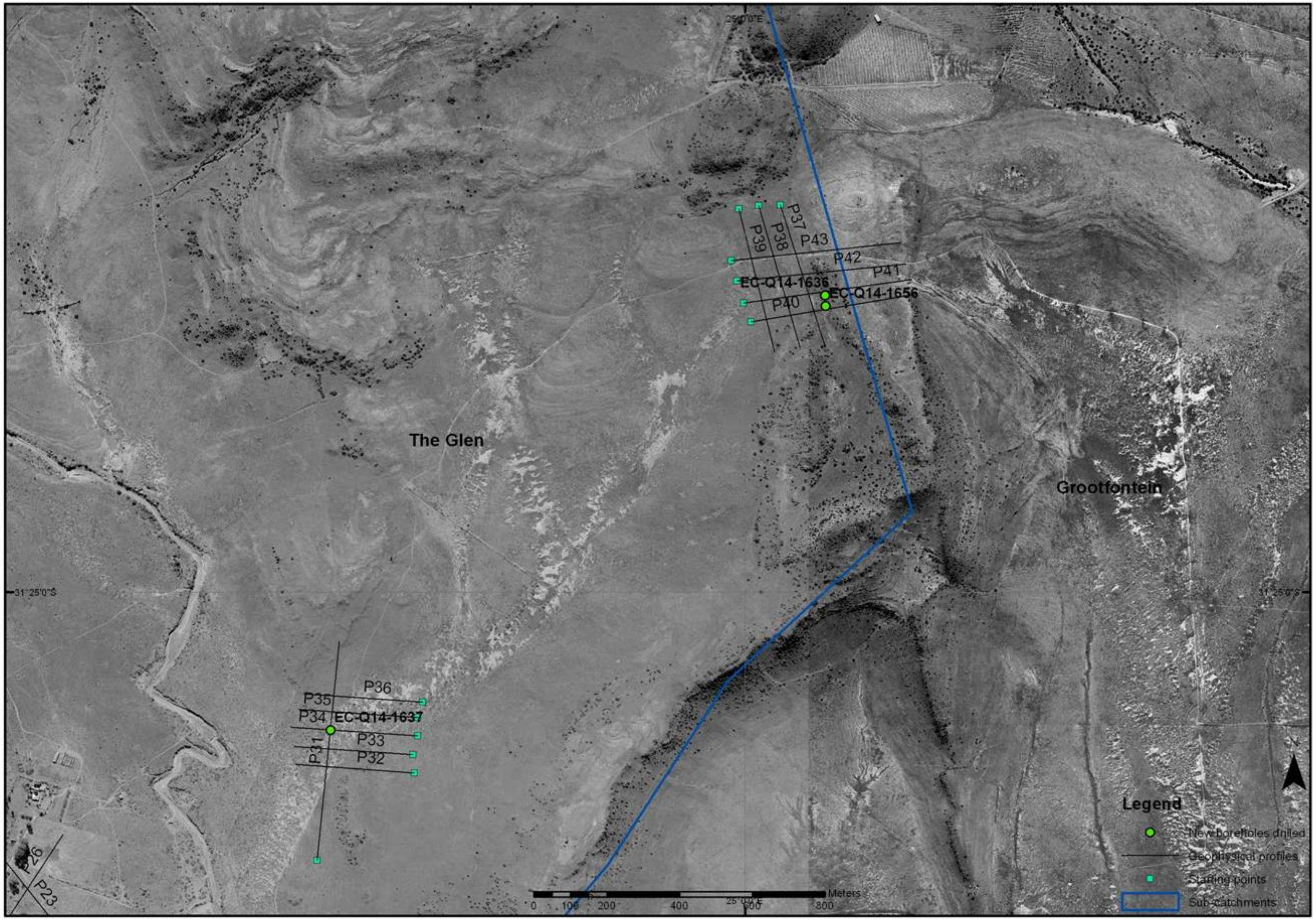


Figure 5-25: Map of Profiles P37 – P43 where Dunblane dyke offshoot cuts through The Glen ring structure indicated in blue

5.3.1.18 Profile P44

This profile was set out as a separate profile in The Glen sub-catchment on the Glen farm. A structure assumed to be a dolerite sill was noted on the geological map, but the full extent of the structure was covered by alluvium (Figure 5-27). The aim of the profile was to determine the geometry of the sill, penetrate the sill with expected fracturing at a depth of approximately 200 m while the alluvium would then recharge the deeper fractures that were targeted at depth (Coetzer, 2008). The profile was surveyed with a magnetic and FDEM traverse, each 500 m in length. Shallow fracturing was found as well as deeper resistive layers, assumed to be the dolerite sill (Coetzer, 2008). A possible drilling site was selected 440 m into the profile where the FDEM picked up a highly fractured zone and the magnetometer registered a clear anomaly. The geophysical results are shown in Figure 5-26.

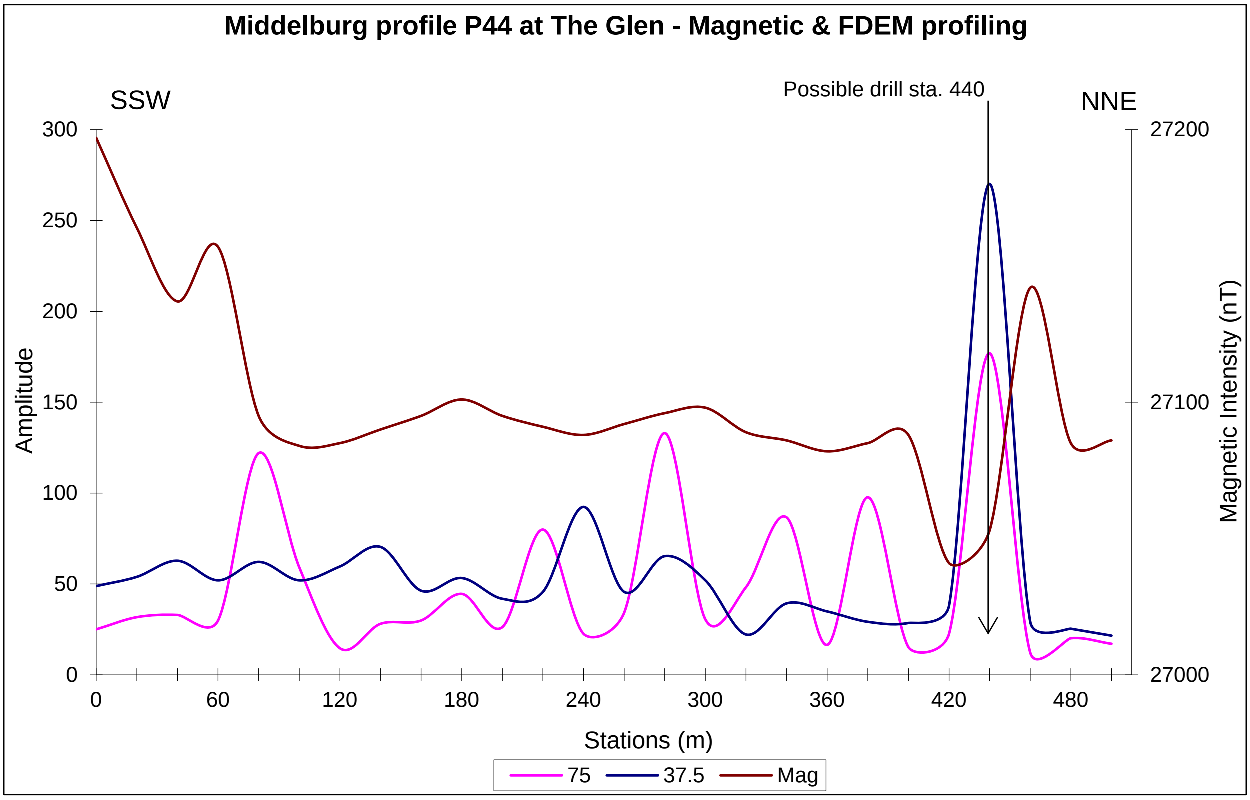


Figure 5-26: Profile P44 traverse across dolerite sill on The Glen farm in The Glen sub-catchment (Coetzer, 2008)

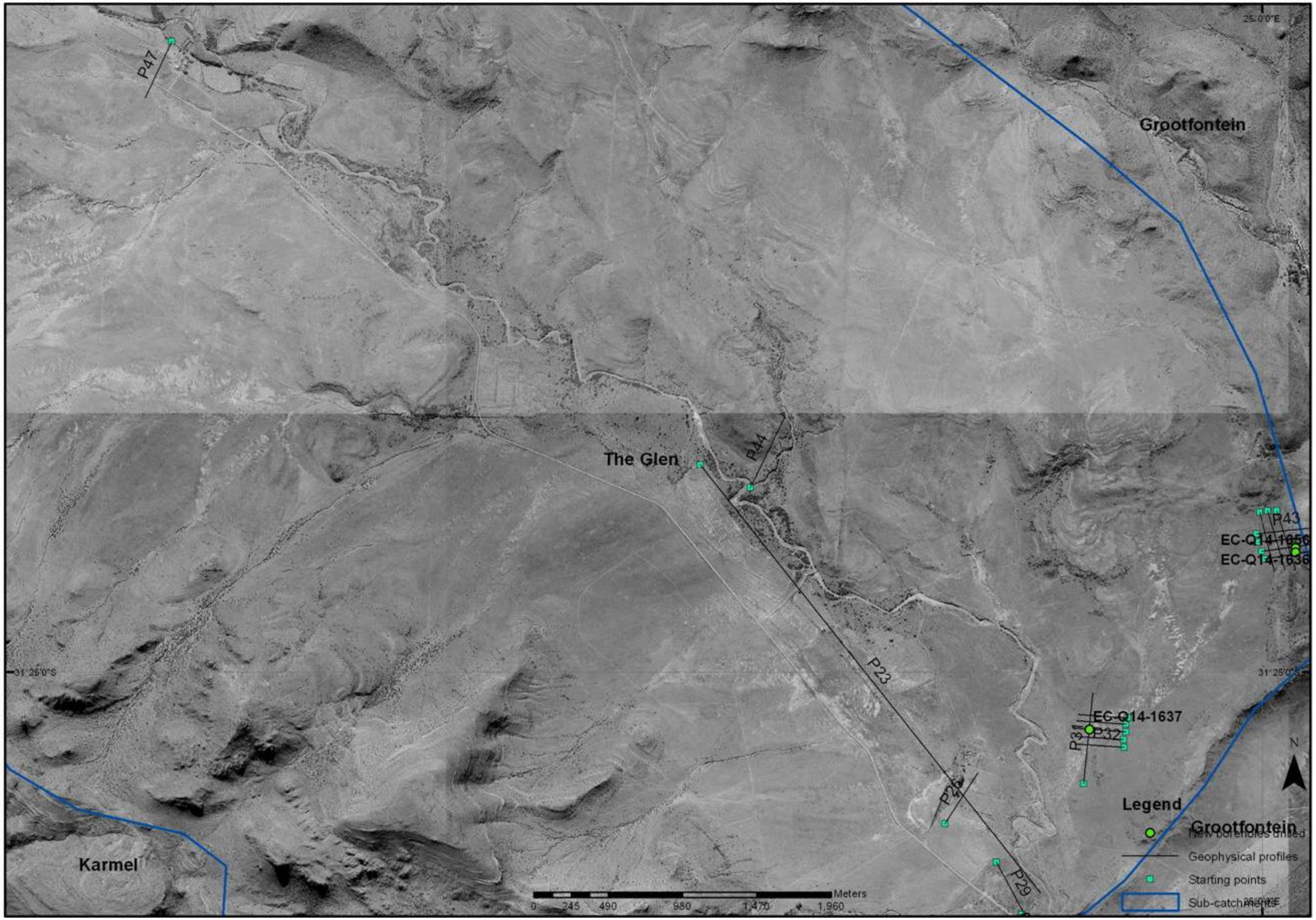


Figure 5-27: Map showing profiles P23, P44 & P47 in The Glen sub-catchment

5.3.1.19 Profiles P45 and P46

The geophysical investigation for the first time moved to the Karmel sub-catchment and profiles P45 and P46 were set out on the farm Karmel, approximately 8.5 km WNW of the town. The farm is encircled by a very rugged and prominent dolerite complex sill- and ring-structure that also forms the watershed for the Karmel sub-catchment. The objective of these profiles was to target the dolerite sill or inclined sheet in depth at the contact with the country rock to search for any possible fracturing. Profile P45 was chosen where the dolerite seemed to have been fractured and the profile was set out accordingly to evaluate the presence of any fractures or faults (Coetzer, 2008). No significant evidence of major fracturing or faulting was observed. Profile P45 was traversed with magnetic and FDEM traverses 400 m in length in an ESE direction. The geophysical results and data for this profile could not be obtained from Mr. J Coetzer.

Profile P46 was started approximately 1.8 km SE of P45 and was set out in a direction almost perfectly orientated south. The Dails River drains toward the south at this location and cuts through the dolerite, -an indication of the fracturing that took place here (Coetzer, 2008). Profile P46 was surveyed with a magnetic traverse 1200 m in length, a FDEM traverse 400 m in length as well as resistivity profiling of 180 m with both a 40 m and 60 m electrode separation. The profile was completed on the farm Waterkloof of which the owner also owns the farm Karmel and the fence between the two farms was not really visible (Coetzer, 2008). The geophysical work revealed the contact of the dolerite and a drilling site was selected at station 730. The geophysical results are portrayed in Figure 5-28. The positions of P45 and P46 are shown in Figure 5-29.

5.3.1.20 Profile P47

Profile P47 was laid out on the farm Groothoek in the northern part of The Glen sub-cacthment, approximately 14.6 km SSE of Middelburg. The main drainage of The Glen sub-catchment that also flows past borehole EC-Q14-1634, cuts across a dolerite dyke at the location of profile P47, according to the geological map. The profile was laid out along the banks of this stream and perpendicular to the strike of the dyke. The profile was surveyed with a 400 m magnetic traverse, resistivity profiling of 190 m with a 40 m electrode separation and 180 m resistivity with a 60 m electrode separation. The geophysical work did not reveal the expected geology and no drilling site was selected (Coetzer, 2008). The geophysical results are shown in Figure 2-17 in Appendix B and the position of P47 is shown in Figure 5-27.

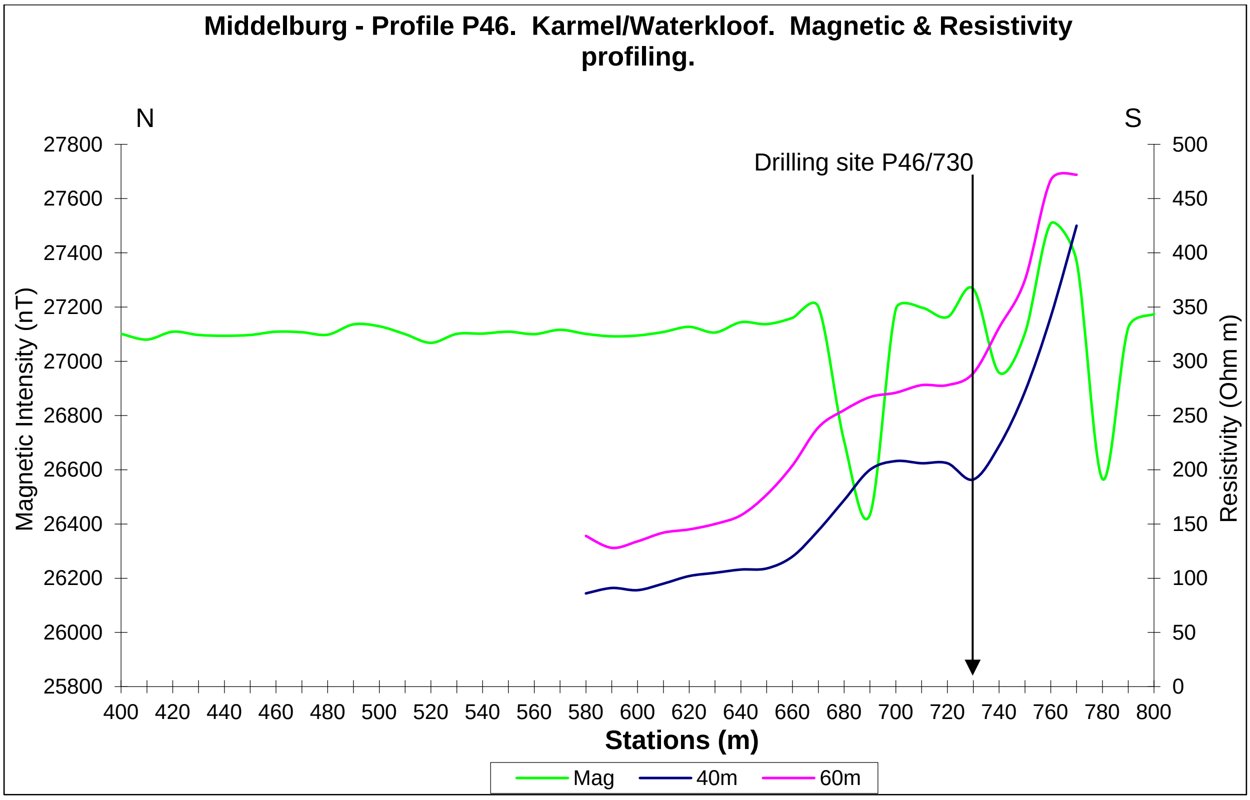


Figure 5-28: Profile P46 on Karmel/Waterkloof farms in Karmel sub-catchment (Coetzer, 2008)

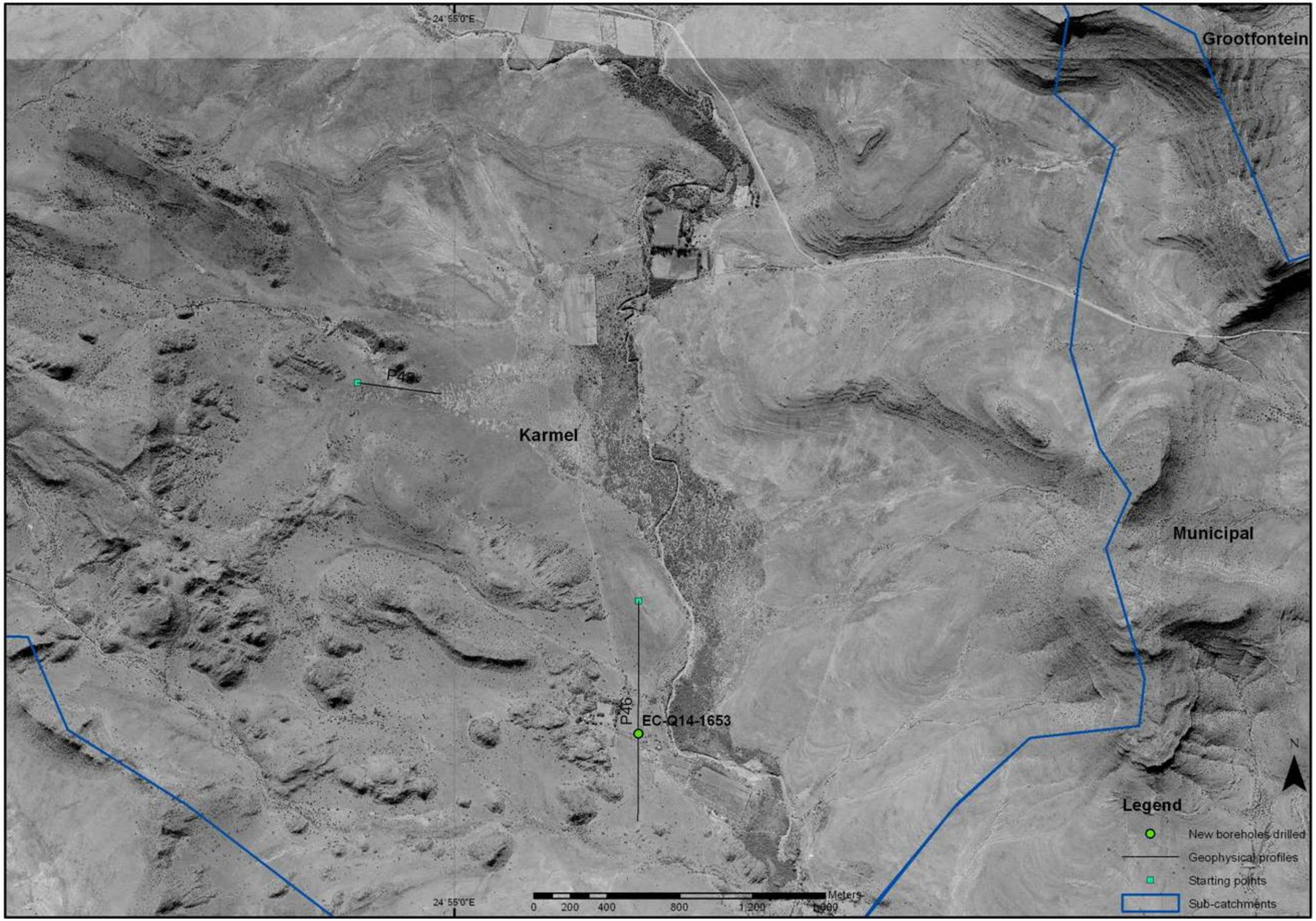


Figure 5-29: Location of geophysical profiles conducted in Karmel sub-catchment – Profiles P45 & P46

5.3.1.21 Profile P48

Later during the geohydrological investigation, negotiations between the Middelburg municipality and Grootfontein Agricultural College had taken place and the College agreed that there could be explored for groundwater on the northern part of the Grootfontein farm. This part covered a large previously excluded sub-catchment named the Grootfontein sub-catchment (See Figure 5-1). The Dunblane dyke is prominent at the Grootfontein sub-catchment's northern boundary with The Glen sub-catchment, but disappears under the alluvium when it is followed south towards Middelburg.

The objective of profile P48 was to determine the exact position, dip and geometry of the Dunblane dyke within the Grootfontein alluvium basin, and to target the contact zone fracturing at depth and then drill into or through the dyke, depending on the success of the borehole. The location of profile P48 is shown in Figure 5-31.

Profile P48 was initially named Profile 6 and 7 for resistivity and magnetometer surveys respectively, but was renamed. Profile P48 was surveyed with a magnetometer traverse of 210 m to only determine the more precise position of the Dunblane dyke and resistivity profiling of 400 m with a 40 m electrode separation was performed to explore for fracturing associated with the dyke. The magnetic and resistivity work was all done from E – W perpendicular to the strike of the dyke. The geophysical work successfully determined the position and dip of the dyke and a drilling site could be selected. The drilling site was selected at station 155 m and is indicated on the geophysical results in Figure 5-30.

5.3.2 Target areas

Each sub-catchment has been defined associated with specific primary hydrogeological targets. Exploration targets associated with each sub-catchment have been described in section 4.5 of Chapter 4: Hydrocensus and now the different profiles within the different sub-catchments have also been discussed.

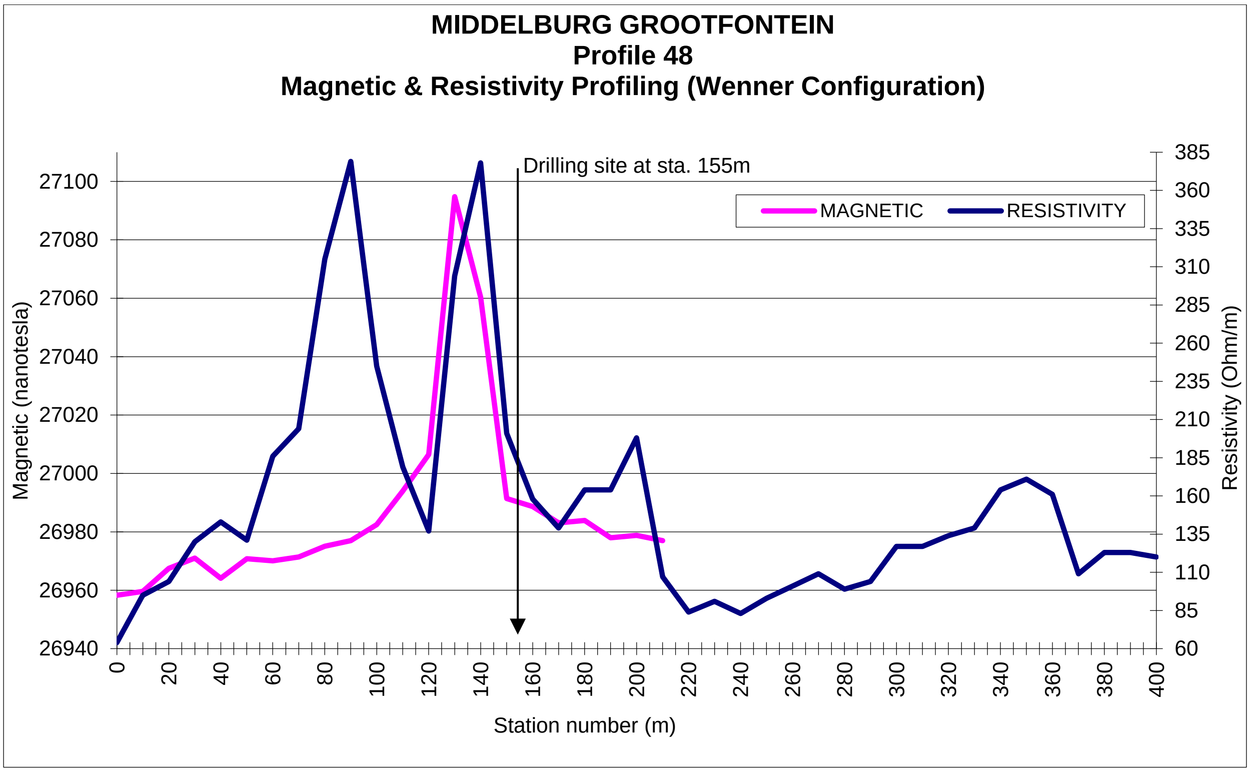


Figure 5-30: **Profile P48 E-W across the Dunblane dyke in Grootfontein sub-catchment**

Figure 5-31: Location of Profile P48 in Grootfontein sub-catchment

6 DRILLING

6.1 Methodology

6.1.1 Rotary air-percussion drilling technique

The rotary air-percussion or air rotary down-the-hole (DTH) hammer drilling method was predominantly used during the investigation. A tophead drilling rig was used where the up- and downwards moving tophead on the mast of the rig is coupled to the air compressor via swivel hose to the tophead (Sterrett *et al.*, 2007). The drilling method uses components described from bottom to top; a button bit with a hammer cylinder fitted on top of it followed by a drill string of pipes connected to the tophead. The tophead controls rotation of the drill string, hammer and drill bit and air is also forced in through the tophead into the pipes of the drill string down through the hammer towards the drill bit. The compressed air exits through small ports or holes in the drill bit at the bottom of the hole, and drill chips or tailings are removed from the bottom of the hole by the compressed air transporting it upwards in between the outside of the hammer, drill string pipes and the inside of the borehole. The drill chips are the blown out of the borehole and deposited on the ground around the borehole. When water is encountered during borehole drilling, greater air pressure is needed to overcome the pressure head of water accumulating in the borehole, in order to expel the water and chips from the borehole.

Drilling was conducted according the DWA minimum standards and guidelines for groundwater resource development (DWA, 1997). This resulted in the borehole being drilled and constructed using the specified materials, equipment and methods under strict supervision of the hydrogeological consultant. Casing was installed to stabilise loose shallow formations and was inserted into at least 6 m of solid formations. Each production borehole was delivered with a sanitary seal to prevent the ingress of surface water that could cause possible contamination of the aquifer and with a concrete collar to prevent surface erosion around the casing.

A GRIP borehole number was obtained from the Department of Water Affairs in Port Elizabeth for each new borehole drilled. A metal borehole number stake was planted approximate 5 m north of the newly drilled borehole. The borehole was capped to avoid vandalism and prevent the pollution of the ground water until utilisation.

6.1.2 Water hammer drilling technique

The W150 Wassara water hammer system was used briefly during the investigation. The water hammer drilling technique is a down-the-hole (DTH) technology that basically functions in the same way an air percussion rig would, but instead of using air to lift the drilling chips out of the borehole, water is used. A high pressure water pump provides water to the water hammer at a typical pressure of 15 MPa (Wassara, 2010). The high pressure water pump has to have a constant water supply to it of at least 5 ℓ/s. The constant high pressure water delivered to the drilling hammer should result in a much higher penetration rate and also enable much greater depths to be reached more efficiently, than would be possible with a normal rotary air percussion rig. For more information regarding the Wassara water hammer DTH drilling systems see their website at: www.wassara.com

6.2 Drilling summary

A total of 18 new boreholes were drilled during the Middelburg groundwater exploration and water supply investigation with an accumulated drilling depth of 3727 m. The boreholes had a minimum drilled depth of 63 mbgl (EC-Q14-1656-water hammer supply and monitoring borehole) and a maximum drilled depth of 298 mbgl (EC-Q14-1634 Monitoring borehole). A mean borehole drilling depth of 207.1 mbgl was calculated for the new boreholes. The total accumulated airlift yield from the boreholes drilled during the project was greater than 186.7 ℓ/s excluding smaller yields. Two existing boreholes were also cleaned/rehabilitated during the investigation. To provide some overview of the work done, an attempt has been made to summarise all the exploration and water supply drilling work to three tables (Table 6-1: J&M Drilling, Table 6-2: Steyns Drilling and Table 6-3: Targets).

Figure 6-1 shows at a regional scale the locations of all 18 new boreholes drilled during the investigation. For detail geological and structural geology settings of these boreholes the reader is referred to Table 6-3 also showing profiles and stations that these boreholes were drilled on. The profiles and areas drilled can then be used to view detail hydrogeological settings in the orthorectified photo maps of these profiles and boreholes in the Geophysics chapter.

Section 6.3 provides a detail description of the drilling, conditions and practicalities encountered at each borehole. Borehole logs for each new borehole drilled can be reviewed in the Drilling chapter Appendix C.

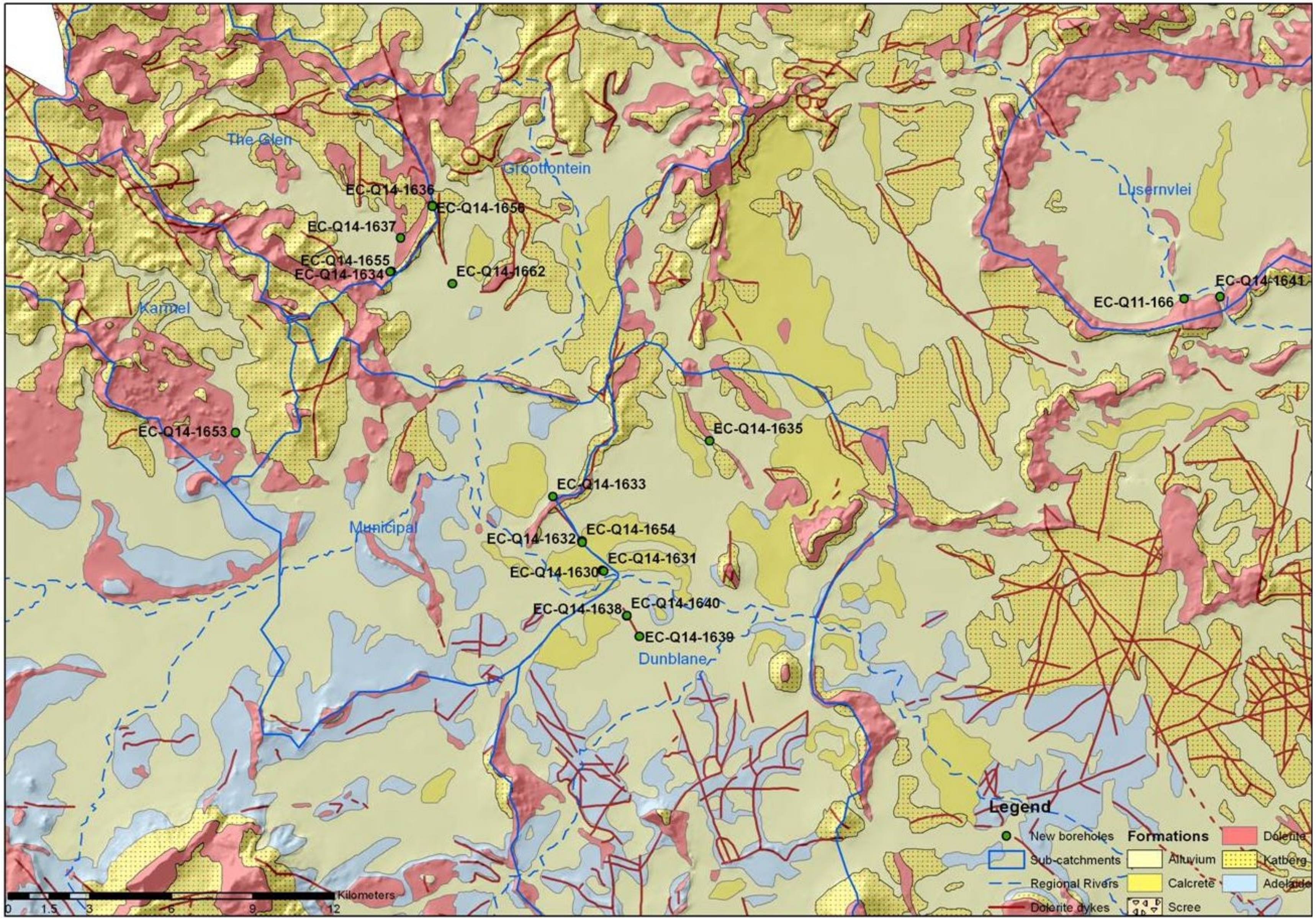


Figure 6-1: Regional geology map showing all new boreholes drilling during the Middelburg groundwater investigation

Table 6-1: Drilling summary table of boreholes drilled & rehabilitated by J & M Drilling – Phase 2

GRIP Borehole Number	Alternative Borehole Number	Borehole Status	Sub Catchment	Farm	Latitude	Longitude	Date Drilling Completed	Depth (m)	Water strikes mbgl Strike yield (l/s) Combined yield [ ]	Casing installed - Solid (m)	Casing installed - Perforated (m)	Airlift yield (l/s)
EC-Q14-1630	-	New Borehole	Dunblane	Dunblane	-31.53032	25.06802	14-Sep-2007	220	16(mudflow); 20(3.4); 22(6.8) [10.2]; -cased off- 34, 70, 118 [9.6]	0-9.57(254mm); 0-28(203mm)	0	10.20
EC-Q14-1631	-	New Borehole	Dunblane	Dunblane	-31.53056	25.06852	-	127	14(2.55); 23(1.87) - cased off; 34(7.65); 82(4.43); 117(8.2)	0-11(254mm); 0-28(219mm)	0	>24.7
EC-Q14-1632	-	New Borehole	Middelburg Municipal	Grootfontein	-31.52057	25.06010	10-Oct-2007	236	14(1.5); 66 (3.5) [5] - cased off; 79(6);159(6); 236 (4) [16]	0-9(254mm); 0-76(219mm)	0	>16
EC-Q14-1633	-	Monitoring Borehole	Middelburg Municipal	Grootfontein	-31.50590	25.04889	27-Sep-2007	256	61(0.5); 123(3) [2.5] 157(1.5) [4];	0-2(310 mm); 0-20(254mm)	0	4.00
EC-Q14-1634	-	Monitoring Borehole	Middelburg Municipal	Grootfontein	-31.43121	24.98600	26-Nov-2008	298	15(2); 29(4.4); 38(2); 43(6); 162(0.5); 181(2); [10] after in-situ perforation	0-5 (310mm); 0-18(305mm); 0-28(254mm)	25-46(219mm)	10.00
-	G31594	Existing/ Rehabilitated	Dunblane	Dunblane	-31.53831	25.07322	28-Oct-2007	40	Rehabilitation of Existing Borehole	-	-	2.90
											TOTAL	**64.90**

Table 6-2: Drilling summary table of boreholes drilled & rehabilitated by Steyns Drilling- Phase 3

GRIP Borehole Number	Alternative Borehole Number	Borehole Status	Sub Catchment	Farm	Latitude	Longitude	Date Drilling Completed	Depth (m)	Water strikes mbgl (l/s) Combined yield [ ]	Casing installed - Solid (m)	Casing installed - Perforated	Airlift yield (l/s)
EC-Q14-1635	-	Monitoring Borehole	Dunblane	Rosmead	-31.48739	25.10955	29-Apr-2008	120	15(0.1)	0-4(254)	0	0.10
EC-Q14-1636	-	New Borehole	The Glen	Grootfontein	-31.40934	25.00198	18-Apr-2010	271	31(0.5); 62(1.6); 112(1.6); 122(22) [>25];	0-6(254mm)	0	31.36
EC-Q14-1637	-	New Borehole	The Glen	Grootfontein	-31.42006	24.98976	27-May-2008	258	18(0.1)- cased off; 61(6.5); 75(3.4) [10];	0-15(254); 0-20(175)	0	10.00
EC-Q14-1638	-	New Borehole	Dunblane	Dunblane	-31.54539	25.07747	28-May-2008	228	14(0.5);	0-6(254)	0	0.80
EC-Q14-1639	-	New Borehole	Dunblane	Dunblane	-31.55227	25.08233	29-May-2008	138	37(0.5); 109(0.8);	0-6(254)	0	1.30
EC-Q14-1640	-	New Borehole	Dunblane	Dunblane	-31.54533	25.07756	2-Jun-2008	252	98(1.3)	0-3(254)	0	1.30
EC-Q14-1641	EC-Q14-1641	New Borehole	Lusernvlei	Redlands	-31.43910	25.30730	14-Jun-2008	200	3(7)- cased off; 33(0.5); 84(2); 92(4.4) [6.94];	16.5(254)	0	6.94
EC-Q11-166	EC-Q14-1652	New Borehole	Lusernvlei	Alfalfa	-31.43999	25.29330	19-Jun-2008	194	19(0.2); 57(5.4); 174(2.9); 192(3.6); [12.1] 7 l/s cased off	0-2.5(254mm); 0-24(175mm);	0	12.10
EC-Q14-1653	-	New Borehole	Karmel	Waterkloof-Karmel	-31.48460	24.92575	26-Jun-2008	132	34(0.5); 129(11.6) [12.1];	0-12 (175mm);	0	12.10
EC-Q14-1654	-	New Borehole	Dunblane	Grootfontein	-31.52093	25.06019	2-Jun-2008	200	13(0.5); 78(14);	0-16(175mm);	0	14.80
EC-Q14-1655	-	New Borehole	The Glen	Grootfontein	-31.43127	24.98580	23-Mar-2010	282	12(0.5); 14(1.4); cased off to 19m; 43.1(4.4); 100(2.6);	0-21(254mm); 0-18 (187mm uPVC); 36-38(187mm uPCV)	18-36 (187mm uPVC)	21.75
EC-Q14-1656	-	WH supply/ monitoring	The Glen	Grootfontein	-31.40960	25.00199	3-Feb-2010	63	32(1.26); 59(1); 62(8) [10.17]	0-2 (254mm)	0	10.17
EC-Q14-1662	-	New Borehole	Grootfontein	Grootfontein	-31.43534	25.00983	24-Jan-2010	252	23(0.8); 25(0.5) [1.27]; increased to final [2.55]	0-24 (254mm)	0	2.55
EC-Q14-1668	G31587 (Vandoolaeghe)	Existing/ Cleaned	Grootfontein	Grootfontein	-31.43521	25.00851	5-Feb-2010	24	-	-	-	-
											TOTAL	**121.77**

Table 6-3: Table with discussion of borehole targets and results as well as profiles/ stations boreholes were sited on

GRIP Borehole Number	Geophysical Profile/ Station for drilling site	Geohydrological Target	Target hit or missed	Comments	BH Status/ purpose	Sub Catchment	Depth (m)	Airlift yield (l/s)
EC-Q14-1630	P13/ 190	Fractured zone upstream side of Dublane dyke	Hit		Exploration	Dunblane	220	10.20
EC-Q14-1631	P12/ 210	Contact zone Dunblane dyke & country rock at depth	Hit	High yields obtained within fractured dolerite of Dunblane dyke	Exploration/ Production	Dunblane	127	>24.7
EC-Q14-1632	P15/ 195	Contact zone Dunblane dyke & country rock at depth	Hit	Drilled with planned Dunblane dyke well field in mind	Well field	Middelburg Municipal	236	>16
EC-Q14-1633	P30/ 220	Ring structure at depth where Dunblane dyke cuts through	Missed	Drilled with planned Dunblane dyke well field in mind	Well field/ Monitoring	Middelburg Municipal	256	4.00
EC-Q14-1634	P29/ 415	Weathered dolerite ring structure at depth	Hit	Borehole was grouted due to high water pressure and little progress, again perforated	Exploration/ Production	Middelburg Municipal	298	10.00
EC-Q14-1635	No geophysics info	Dolerite sill on downstream side	Missed		Monitoring Borehole	Dunblane	120	0.10
EC-Q14-1636	P41/ 210	Stress zones where Dublane dyke cuts through ring structure	Hit	Borehole was very successful, but limited reservoir found or catchment too small	Exploration/ Production	The Glen	271	31.36
EC-Q14-1637	P31/ 360	Dolerite sill dyke structure, presumably inner sill	Hit		Exploration/ Production	The Glen	258	10.00
EC-Q14-1638	No geophysics info/ Field observations	Dunblane dyke and contact zone fracturing	Missed	Missed presumably due to no geophysics done	Exploration	Dunblane	228	0.80
EC-Q14-1639	No geophysics info/ Field observations	Dunblane dyke and contact zone fracturing	Missed	Missed presumably due to no geophysics done	Exploration	Dunblane	138	1.30
EC-Q14-1640	No geophysics info/ Field observations	Dunblane dyke and contact zone fracturing	Missed	Missed presumably due to no geophysics done	Exploration	Dunblane	252	1.30
EC-Q14-1641	P05 info/ Field observations	Inclined sheet of dolerite ring structure at depth	Hit	Largest water strike at 92mbgl on contact with dolerite & sandstone	Exploration	Lusernvlei	200	6.94
EC-Q11-166	P06/ 230	Dolerite structure within ring structure - minor sill	Hit	Geophysics coordinates & Borehole coordinates do not correlate	Exploration/ Production	Lusernvlei	194	12.10
EC-Q14-1653	P46/ 730	Fractured zone on contact with dolerite & country rock	Hit	Very large fracture/ largest water strike at 129m depth	Exploration	Karmel	132	12.10
EC-Q14-1654	geophysics/drilling info - field conditions	Fractured zone/ transgressive fracturing next to Dunbl. dyke	Hit	Based on info from EC-Q14-1632/ water hammer supply borehole/ monitoring	WH supply/ monitoring	Dunblane	200	14.80
EC-Q14-1655	P24 Existing geophysics/ drilling info/field observations	Weathered dolerite ring structure in Jones Poort	Hit	Very good borehole also close to topographical low point of The Glen catchment	Exploration/ Production	The Glen	282	21.75
EC-Q14-1656	Drilling info/ P40/ P41/ field observations	Stress zones where Dublane dyke cuts through ring structure	Hit	Borehole approximately 30m from EC-Q14-1636, same fractures intersected	WH supply/ monitoring	The Glen	63	10.17
EC-Q14-1662	P48/ 155	Dunblane dyke/ contact zone at depth	Hit/ Unsuccessful	interception depth of contact zone perfect, but no fractures found	Exploration/ Monitoring	Grootfontein	252	2.55

6.3 Borehole results and discussion

6.3.1 Phase 2 drilling: J & M Drilling

The drilling contractor, J&M Drilling from Pretoria was assigned to perform the drilling at Middelburg. Drilling started on the 12th of September 2007 at the farm Dunblane on profile P13 station 180. Five boreholes were completed with the rotary air percussion method, until the 27th November 2007. Due to the possibility to drill deep to penetrate contact zones of the ring structures at expected depths of 200 m and even 300 m, the methodology for drilling took up several options. Shallow high yielding fractures up to a depth of a 100 m caused different kinds of problems. The methodology had to be practically adapted for each borehole due to the high yields and different types of geology penetrated. The general geology encountered was clayish alluvium, gravely alluvium, boulder alluvium, highly fractured sedimentary rock, highly fractured dolerites, and solid sedimentary rock with joints as well as solid dolerite with joints.

- Boreholes drilled in clayey alluvium going over to boulder alluvium needed to be started with 380 mm drill bit, to a depth were the boulder alluvium is still stable. Insert solid casing with an inside diameter of 355 mm. Care should be taken not to disturb the boulder alluvium too much with high pressure air lifting. Use the drill-and-drive method to drill through the boulder alluvium to a stable depth of the sedimentary, or dolerite rock and insert 254 mm solid casing. Continue drilling with the 254 mm drill bit as described above.
- Drill samples were taken at 1m intervals to give a geological profile of the formation penetrated. This information is combined to provide a lithological log for each borehole. Water strikes were measured with a 90º v-notch and are recorded at each depth of strike to identify main aquifers and ensure a proper yield test. A water sample was taken at some water strikes for chemical analyses and will be discussed in the hydrochemistry chapter, to follow.
- A penetration rate per meter drilling was tabled and could be used for different decision making options.
- The solid casing were in some cases slotted or “in situ” perforated at water strike depths for 2 m on either side of water strikes. Gravel pack was then inserted on the outside (to form a natural filter), for depths 5 m below and 5 m above the perforated areas, to prevent sandy material and any loose material from entering the borehole;

- The boreholes were developed by using the surge-plunge method by means of compressed air, which entailed the flushing-out of all loose material from the borehole when the desired depth has been reached or before a borehole was abandoned. This is done to ensure that the borehole is free of any sand or any other loose material that can damage the pumping equipment in the borehole, and to ensure a free flow of water from behind the gravel pack.
- A sanitary seal of up to 3 mbgl was inserted in each successful borehole to prevent any surface contaminants from entering the borehole.
- The successful boreholes were also equipped with a concrete collar, capped with a steel lid and numbered with a welding rod on top of the steel lid.

(Coetzer, 2008)

EC-Q14-1630

This was the first borehole to be drilled on the project, started on 12 September 2007 and was based on geophysical correlation of a highly fractured zone identified on the upstream side of the Dunblane dyke. The planned depth of drilling was to be executed to a depth of around 300 mbgl, but due to a shortage of drilling rods on site the final depth reached was 220 mbgl. The first water strike was intersected at 16 mbgl via a fracture, at 20 mbgl a joint in the geology was opened and yielded 3.4 ℓ/s. The next joint in the geology was opened at 22 mbgl and water poured into the borehole at an additional 10.2 ℓ/s. At this stage drilling became difficult due to unstable formations resulting in the compressed air being blown into the hole not being able to remove all the drilling debris.

254 mm inside diameter (ID) solid steel casing was installed up to 10m to allow for further drilling with the 254 mm drill bit. Solid steel casing with inside diameter of 203 mm was installed up to 28 mbgl to counter borehole instability and rock debris falling down and accumulating on top of the drill hammer. The 203 mm casing was then also supposed to seal off the shallow water strikes encountered, as the goal was to target deeper fractured areas.

Drilling continued with a the 203 mm drill bit to 116 mbgl at which stage the drilling operation was further complicated by the fact that the 203 mm ID casing did not seal of the water strikes properly. The air lift process whereby debris is expelled from the borehole and drill bit was equalised by a water pressure head formed on top of the drilling hammer due to shallow water strikes leaking past the 203 mm casing. From

116 mbgl the borehole was further drilled with a 167 mm drill bit to a final depth of 220 m. The borehole had a final airlift yield of 10.2 ℓ/s.

The drilling contractor stated he would, if need be return to the borehole with sufficient supply of drilling rods, but for the time being proceeded to the next borehole. For borehole log of the borehole see Appendix C.
(Coetzer, 2008)

<u>EC-Q14-1631</u>
EC-Q14-1631 was selected on profile P12 and is about 50 m away from profile P13 on which borehole EC-Q14-1630 was drilled. Drilling of the borehole was started on the 15th of September 2007 to further ascertain if large water bearing fractures and joints could be opened at depths exceeding 200 mbgl on the dolerite contacts found between the Dunblane dyke and the country rock. The borehole lithology and construction logs are provided in Figure 6-2 and Figure 6-3.

Initial drilling at this site was characterised by sandy-, clayish- and later boulder-alluvium that had to be drilled through before the dolerite contacts with the Karoo formations could be targeted. The first water strike was reached at 14mbgl within the Alluvium formations. Further down into the weathered dolerite multiple water bearing fractures and joints were opened at 23, 34, 82 and 117 mbgl with a combined airlift yield in excess of 24 ℓ/s. The borehole was drilled to a final depth of 127 m.

254 mm casing was inserted to 11mbgl to case off the unstable alluvium with a water strike at 14 mbgl. Stable formation was reached at 28 mbgl and 215 mm inside diameter casing could be inserted from ground level to 28 mbgl to case off alluvium and water strikes between 11-16 mbgl. Drilling proceeded with the 167 mm drill bit to 127 m. The borehole was reamed with the 203 mm drill bit in an attempt to gain greater depth further down the hole, but reaming succeeded to only 116 mbgl where the 203 mm drill bit could not pass a big fracture in the dolerite at such a depth.
(Grobler *et al.*, 2010)

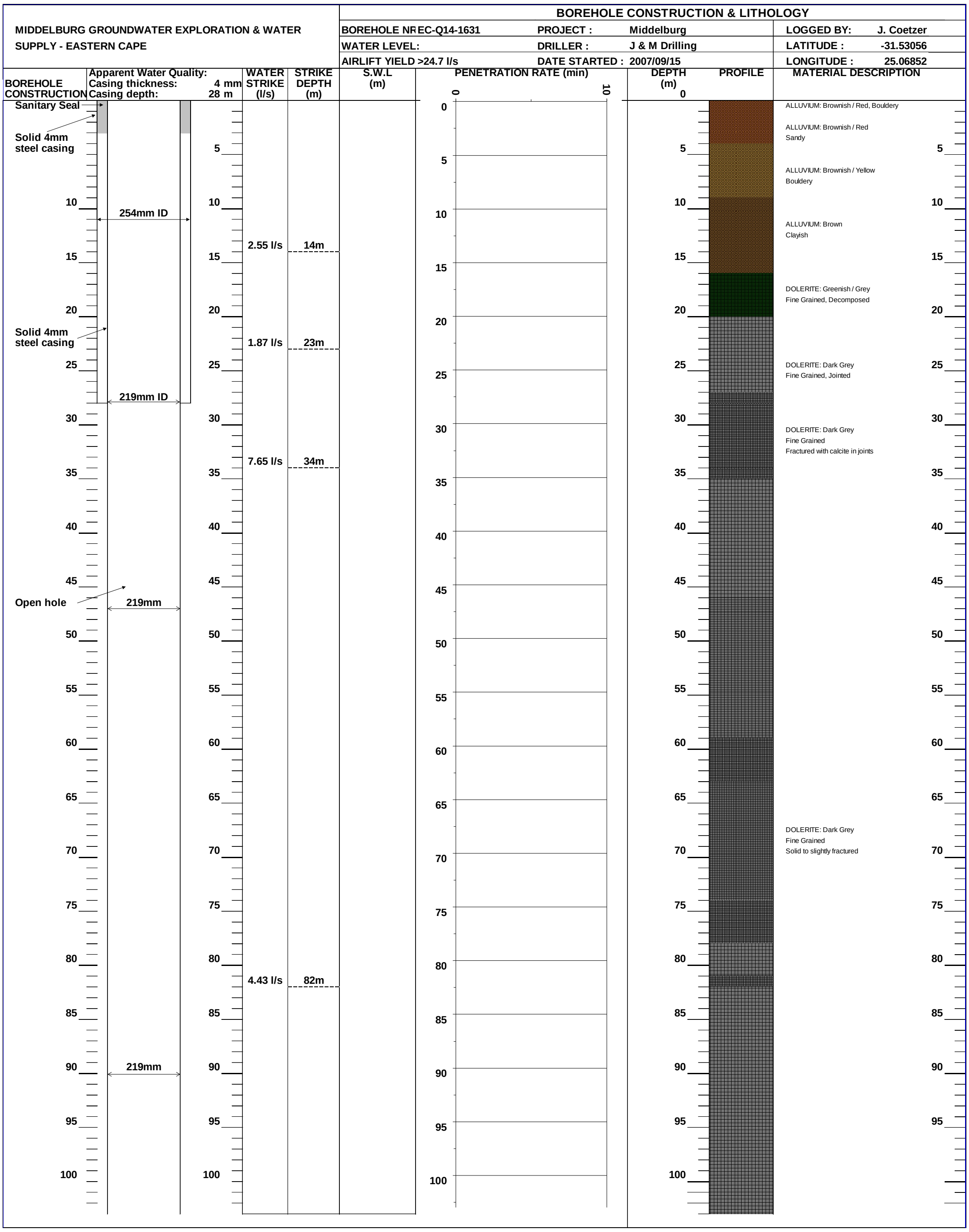


Figure 6-2: Borehole lithology and construction log for EC-Q14-1631: part 1 of 2

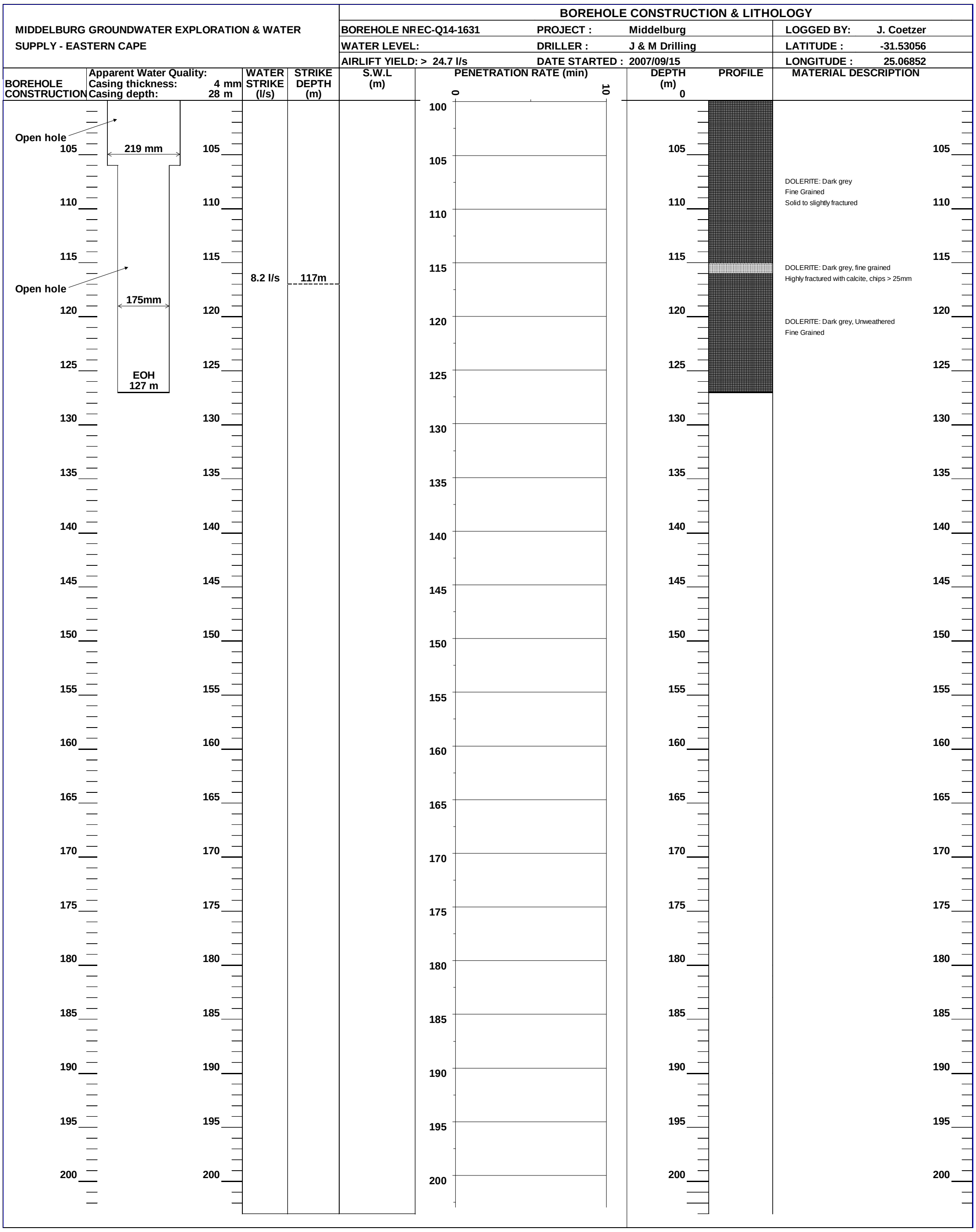


Figure 6-3: Borehole lithology and construction log for EC-Q14-1631: part 2 of 2

EC-Q14-1632

Up to this stage, the drilling program was for groundwater exploration, but with the water supply crisis in Middelburg town, it changed to a drought relief drilling program (Coetzer, 2008). The planning also changed to the idea of creating a well field next to the Dunblane dyke. The site of the next borehole EC-Q14-1632 was then based on geophysical profiles conducted in the vicinity of the Dunblane dyke. The drilling site chosen is located 1.4 km NNE of borehole EC-Q14-1631. The drilling of EC-Q14-1632 took place in the time period between 28 September 2007 and 10 October 2007. The borehole lithology and construction logs for EC-Q14-1632 are provided in Figure 6-4 to Figure 6-6 below.

The borehole was drilled to 236 mbgl and delivered a final airlift yield of 16 ℓ/s. Drilling was started with the 305 mm scraper bit to a depth of 9 mbgl where they encountered weathered dolerite and could not continue with the scraper bit. 254 mm inside diameter solid steel casing was installed up to 9mbgl and drilling continued with the 254 mm drill bit to 76 mbgl. 215 mm inside diameter casing was also installed to stabilise the borehole wall and provide air-pressure integrity for removing borings from the borehole. Drilling continued to 236 mbgl with 203 mm drill bit, at which depth drilling could not continue primarily due to the weight of the water pressure head building up and secondly due to unstable formations. A booster pump was needed to supplement the air-compressor in able to remove the pressure head of water, but there was no booster pump available on site. At this stage the airlift yield was 16 ℓ/s, but whether it was solely from a deep water strike or also from shallow water strikes that could not be cased-off properly, was unknown. Possible deflection of the drill bit from alluvium boulders could result in casing not sealing-off properly. Water strikes in the form of geological joints were intersected at 66, 79, 159 mbgl as well as 236 mbgl (there wasn't certainty that the blow yield was from a water strike at this depth or if the water could be coming from 76 mbgl where the casing did not seal-off properly).

Great difficulty was encountered with alluvium boulders at shallow depth causing a range of problems such as air compression lost, more stable parts of the alluvium being washed out in the borehole wall as well as boulders falling into the borehole during drilling which were very hard to excavate and may have caused deflection of the drill bit. This may have resulted in the borehole being slightly off-centre and casing not sealing off properly.
(Coetzer, 2008)

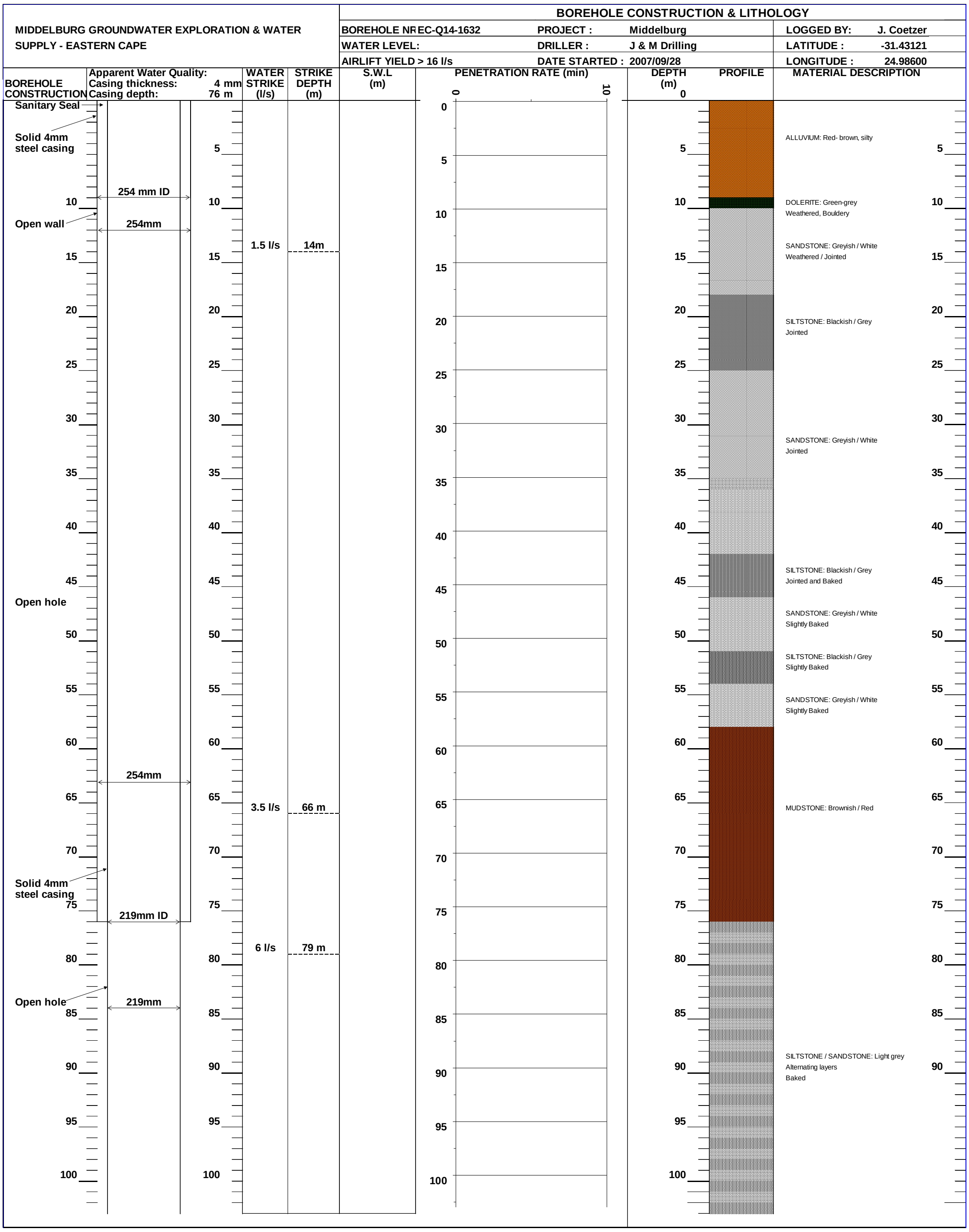


Figure 6-4: Borehole lithology and construction log for EC-Q14-1632: part 1 of 3

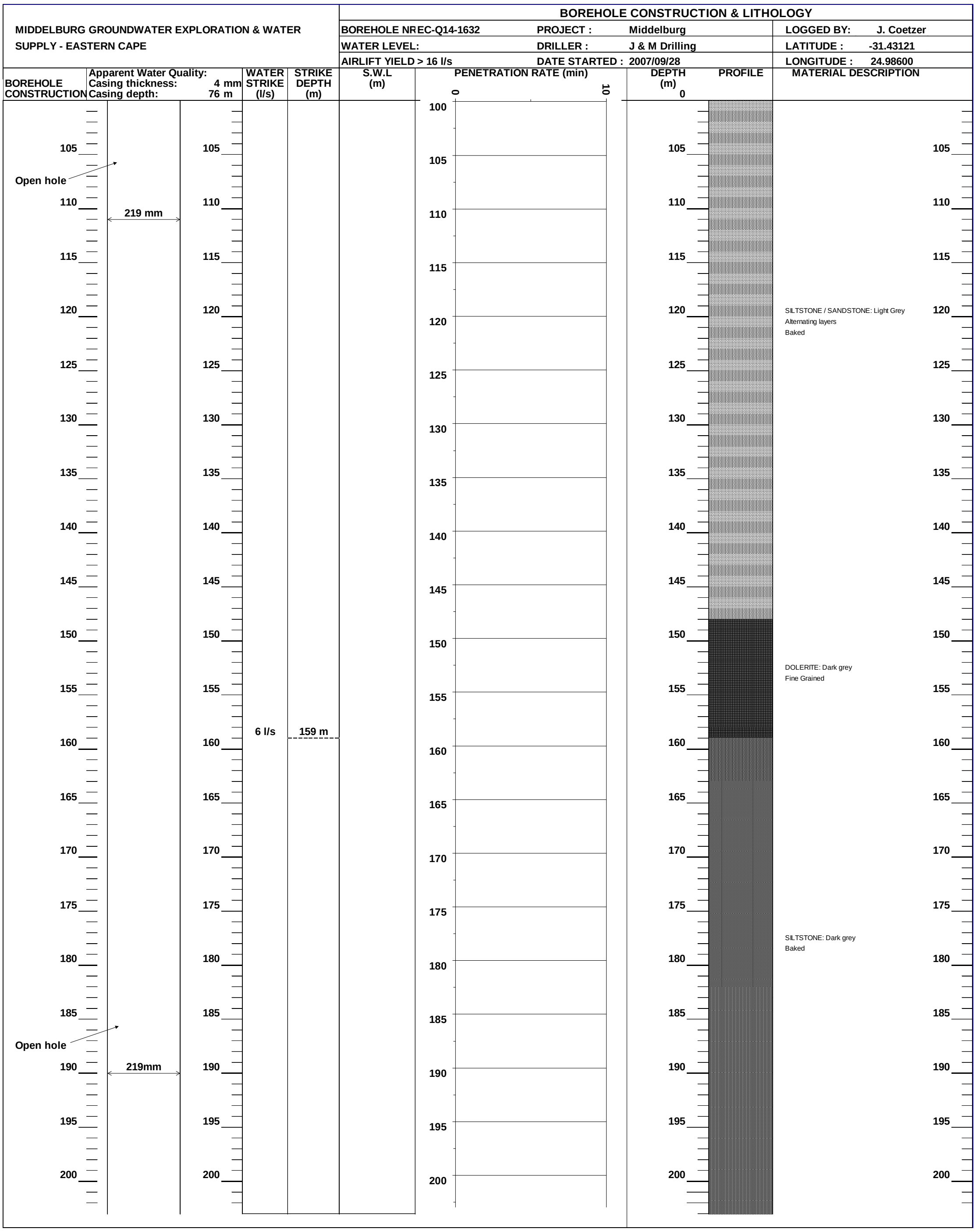


Figure 6-5: Borehole lithology and construction log for EC-Q14-1632: part 2 of 3

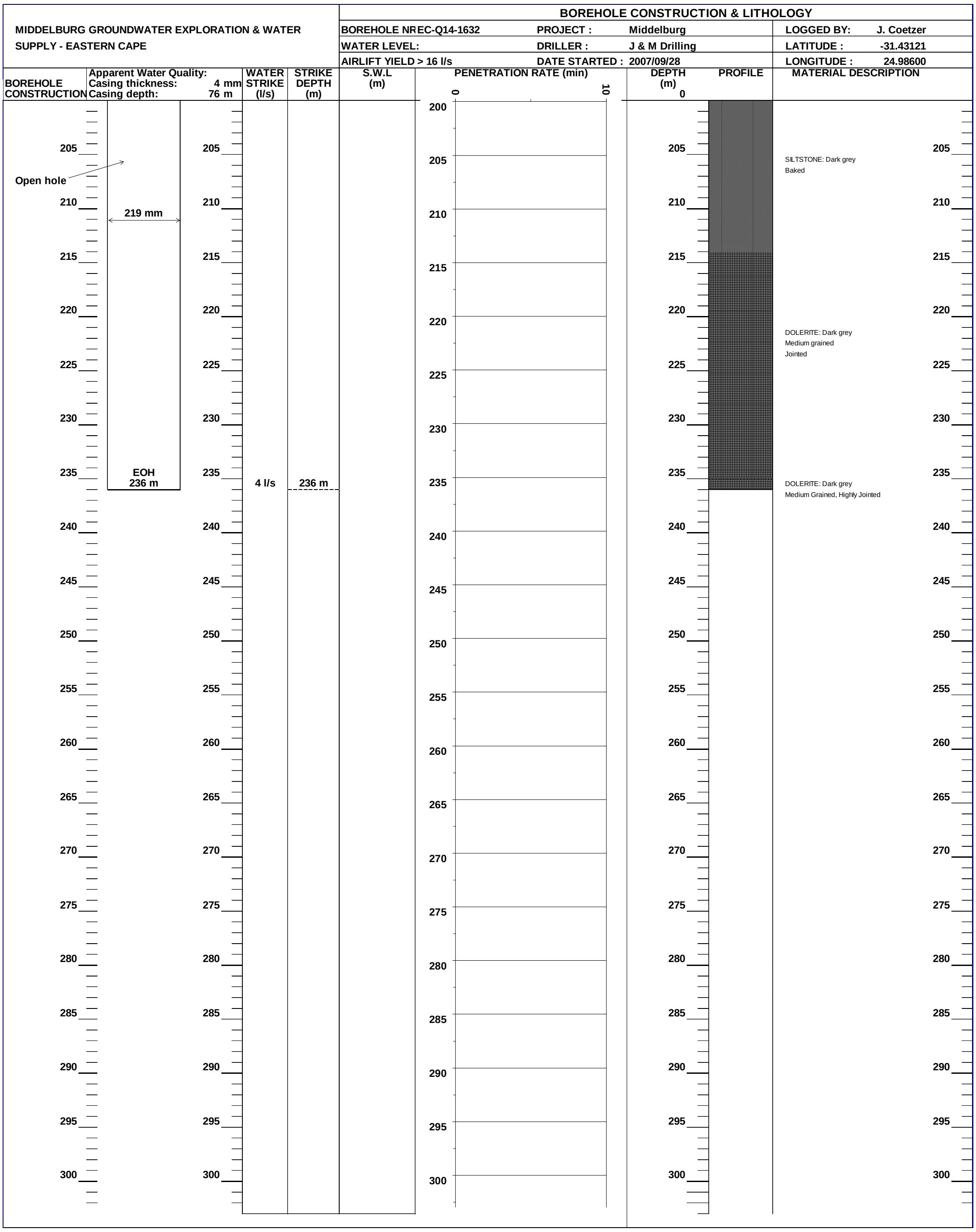


Figure 6-6: Borehole lithology and construction log for EC-Q14-1632: part 3 of 3

EC-Q14-1633

Borehole EC-Q14-1633 targeted a ring structure where the Dunblane dyke cuts across a ring structure approximately 1.9 km NNE from EC-Q14-1632. The goal was to target a dolerite ring structure at depth while close enough to town, keeping in mind the idea of creating an accessible well field for drought relief for Middelburg. Drilling of borehole EC-Q14-1633 was started on 11 October 2007 and ceased on the 27th of October 2007.

The borehole was drilled to a depth of 256 m and delivered a final airlift yield of 4 ℓ/s. To drill through the uppermost alluvium layer, a 355 mm drill bit was used drill up to 9 mbgl. The hole became too large to create a significant pressure cylinder for the borings and drilled rock pieces to be blown from the hole. 350 mm steel casing was inserted up to 9 mbgl. Drilling continued with a 254 mm drill bit up to 92 mbgl where the geology at this stage was dolerite. The 216 mm drill bit was fitted and drilling continued to a depth of 222 mbgl. From this depth drilling was conducted with a 167 mm drill bit up to 256 mbgl. The drilling rig operator at this stage recognised that some geology from much shallower depths were falling onto the drilling hammer and the drilling was stopped due to the possibility that the rock material falling from the borehole wall could get the drill hammer stuck at the bottom of the hole.

Water strikes were encountered at 61(0.51 ℓ/s), 123(2.5 ℓ/s) and 157(0.51 ℓ/s) mbgl generally within fractures found in the dolerite at these depths. A combined total airlift yield from these water strikes were measured at 4 ℓ/s.
(Coetzer, 2008)

EC-Q14-1634

A drilling site north of town on the property of the Grootfontein Agricultural College was chosen for borehole EC-Q14-1634. Here a weathered dominant dolerite ring structure forms a “poort” and drains a significant amount of the water of The Glen sub-catchment, extending to the north. The main objective was still to target the dolerite ring structure at depth. Drilling began on the 28th of October 2007 and was completed on the 26th of November 2008.

Drilling was started with a 355 mm drill bit and the borehole was drilled to 16 mbgl through clayey alluvium and boulder alluvium at 15 mbgl. 355 mm inside diameter casing was installed up to 5 mbgl to stabilise the top portion of the borehole. The drill bit size was changed to 305 mm and drilling continued to 28 mbgl with the 305 mm drill bit. 305 mm casing was installed but could only be lowered to 18 mbgl although the borehole had been reamed with the 305 mm drill bit to 28 mbgl. The drill and drive technique was applied to install 254 mm inside diameter casing inside 305 mm casing up to reamed depth of 28 mbgl. The 254 mm drill bit was used to drill further to a depth 100 mbgl. Water strikes were intersected at 15 m (2 ℓ/s); 29 m (4.4 ℓ/s); 38 m (2 ℓ/s); 43 m (6 ℓ/s).

Due to shallower water strikes the water pressure at this stage became too heavy for proper airlift operation to expel drilled rock material. Drilling progress in depth also declined where the penetration rate decreased to 25.47 min/m for the metre of drilling from 99-100 m. 219 mm casing was installed to only 58 mbgl where it resisted to being installed further. With some hammering and effort the casing went down to 66 mbgl where it became evident that the casing could not be lowered more. Excessive hammering could cause the welding between casings to break or split resulting in casing that does not seal properly or worse, the casing could fall and the borehole would be lost.

In order to seal off the shallower water strikes to drill further a decision was made to back-fill the borehole with drill chips to a point where the borehole could be grouted with cement and close the influx of water at 66 mbgl, to where the casing was installed. The borehole was back-filled and grouted with cement and left to stand for 3 days to dry. The drilling team returned, rehabilitated the borehole and drilling continued to a depth of 298 mbgl with the 203 mm drill bit. The borehole was "in-situ" perforated between 25 mbgl and 46 mbgl with a special tool and gravel pack was installed between the 254 mm casing and the borehole outer wall.

The borehole was drilled to a final depth of 298 mbgl and delivered a final airlift yield of 10 ℓ/s.
(Coetzer, 2008)

6.3.2 Drilling Difficulties

During drilling of these first 5 boreholes some general difficulties were encountered with some pertaining to the study area and others pertaining to the above normal depth being drilled. Most of the difficulties worked in unison against the drilling process:

- Boulder alluvium encountered at a deeper level within the alluvium caused problems with air compression being lost and stable parts of the alluvium being washed out. Some of the boulders also fell down onto the hammer head before the hole could be properly cased which could have caused the drill hammer head to become permanently stuck and in some instances did cause it to become temporarily stuck. Boulders falling down and next to the drill hammer also caused a probable deflection from true centre which in turn could have caused some of the steel casings not to seal-off properly in one or two instances. Water strikes that were sealed-off were still leaking water and air compression could be lost within gaps where casing did not seal on reamed ledge or on other casing.

- The more specialised Telescopic drilling method had to be used and consequently the contractor had to find large diameter drill bits (355 mm – 380 mm) to start the borehole off with. Because of larger volumes being created with larger diameter boreholes, air compression within the borehole was much less than a normal 165 mm borehole and blowing out drill chips, water and drilled rock material was much harder.
- A very heavy water pressure column formed on top of the drill hammer because in most cases multiple water strikes were found so that blowing out the water and drilled rock material was troublesome. There was also no booster pump available on site for the air compressor rig to help with extra compression.

6.3.3 Phase 3 drilling: Steyns Drilling

Steyns Drilling, the drilling contractor based in Port Elizabeth, was appointed to the Middelburg project on 17 January 2008 and drilled all the projects' boreholes in Middelburg that followed after borehole EC-Q14-1634. Most of the problems encountered during the drilling of the first five boreholes like drilling in alluvium, pressure equalisation due to the amount of water encountered and boulder alluvium, were also encountered during Phase 3 of the drilling and consequently the details will not be repeated in the following borehole descriptions.

The Telescoping drilling method although successful at drilling to great depths was however found to present some problems due to the many diameter changes. This resulted in borehole straightness problems in some cases where casing had difficulty in sealing off properly at casing joints and casing that could also not be installed at depth. With the experience of Steyns Drilling in the Eastern Cape and Karoo formations, larger diameters were drilled deeper in order to be able to also install larger diameter pumps at greater depths.

Some of the boreholes drilled by Steyns Drilling were also spaced over 2 stages, due to the year-long halt in the project. With the project activation a decision was made to only complete boreholes that had greatest potential in the applicable sub-catchment, namely The Glen.

EC-Q14-1635

The borehole was drilled in the Dunblane sub-catchment to a final depth of 120 mbgl and delivered a final airlift yield of 0.1 ℓ/s. The only water bearing fracture was intersected 15 mbgl, on a contact between the sandstone upper formation and the dolerite lower formation. The borehole was drilled with a 305 mm drill bit from 0 – 4 mbgl and from 4 – 120 mbgl the borehole was drilled with a 165mm drill bit. Solid steel casing with 254 mm ID was installed from 0 – 4 mbgl. A sanitary seal was installed into at least 3 m of solid formations between the casing and borehole outside wall, to prevent the ingress of surface water and possible contamination of the aquifer. The borehole was capped with an Allan key lock-bolt type steel cap to prevent vandalism and excessive exposure to atmospheric conditions.

EC-Q14-1636

This borehole was identified as one of the main production boreholes for Middelburg Water supply in The Glen sub-catchment. The borehole was drilled in two stages. Stage 1 was prior to the halt in the project and stage 2 was when the project re-activated and completed. It was started on 30 April 2008 and the 1st stage of the borehole's drilling was completed on 26 May 2008.

Stage 1

The borehole was started on the 30th of April 2008 and the 1st stage of the borehole's drilling was completed on 26 May 2008. During this stage the borehole was drilled to a depth of 126 mbgl and delivered a final airlift yield of 31.36 ℓ/s. Water bearing fractures were intersected 31 m(0.5 ℓ/s), 62m(1.6 ℓ/s), 112 m(1.6 ℓ/s) and 122 m (22 ℓ/s). The first three fractures are smaller stress fractures and thermal joints in the dolerite itself while the water strike at 126 mbgl originates from a zone of fracturing and one large fracture on the contact between the dolerite and sandstone below it.

Drilling was started with a 305 mm diameter and drilled from 0-4 m with this drill bit. The borehole was initially drilled with a 165 mm diameter to a depth of 126 mbgl. It was then reamed from 4 to 18 m with a 254 mm diameter and thereafter it was reamed from 18 m to 125 m with a 216 mm diameter. The drilling contractor reported no progress in drilling at the depth of 126 mbgl due to the large amount of water encountered at 122 mbgl. A decision was made to install a 100 kg of bentonite into the bottom of the borehole in an attempt to stop some of the water from entering the borehole so that drilling progress can be made and drilling chips expelled from the borehole. The bentonite was left to settle for 10 days and the rig was de-established.

When the rig returned and drilling resumed there was initially no flow from the borehole with the drill bit set up to 115 m. When the drill bit was lowered to 121 m, water began to flow from the borehole again during air-lifting and all the bentonite was blown out of the borehole. As no progress could be made with the current drilling set-up due to the large volumes of water, the borehole was abandoned and the contractor would return with the water hammer configuration to drill the borehole to a depth of approximately 300 mbgl.

Figure 6-7: Rock expelled from fracture found in EC-Q14-1636 at 122 mbgl

Figure 6-7 shows one of the larger chips/ rocks expelled from the borehole EC-Q14-1636 when the water strike at 122 mbgl was encountered. From the rock it is obvious that the fracture at 122 mbgl is comparably large as the relatively thick layer of quartz crystals that has formed on the fracture plane is very visible and had space and time to grow. The small shiny particles within the quartz precipitation are pyrite crystals. On other chips from the same fracture in Figure 6-8 the pyrite crystals are in abundance and well cubically formed. It is thought that the large amount of pyrite crystals formed as chemical precipitation took place from groundwater containing an abundant amount of dissolved Fe and S. The source of the pyrite is thought to be the sedimentary formations of the Beaufort Group.

Figure 6-8: Chip (42mm dia.) from EC-Q14-1636 water strike at 122 mbgl with pyrite

Stage 2

After the Middelburg project re-activated the drilling of borehole EC-Q14-1636 was resumed on the 24th of March 2010 with the water hammer installation and the borehole was completed on 20 April 2010. The borehole was drilled to a maximum depth of 271 mbgl and delivered an intermittent final airlift yield of 19 ℓ/s. No further obvious fractures were intersected from 126 mbgl to 271 mbgl, but with the intermittent nature of the airlift yield and water flowing from the borehole, it would be difficult or impossible to tell if another water strike was encountered.

The borehole drilling was resumed in Stage 2 with the water hammer installation with a 164 mm drill bit diameter (Figure 6-9). The water hammer technique was however not successful due to the complex nature of the aquifer and extensive fracture network, with the input of the 5 ℓ/s water by the water hammer, never flowing out of the top of the borehole. The implication was that drilling material and chips could not be removed from the borehole and the moment that the drilling would stop, the chips would settle on the drilling hammer (water hammer) and the hammer would become permanently stuck. The hammer would be lost and the borehole as well. As a test, the lay-flat pipe from the water supply borehole (EC-Q14-1656) being pumped for water hammer supply was directly inserted into the EC-Q14-1636 borehole mouth and water was pumped into the borehole at approximately 8 ℓ/s for 15 minutes. The water never flowed out of the borehole. The drilling contractor however proceeded to drill 1 m with the water hammer for testing purposes and the water hammer did have a rapid penetration rate.

Consequently the water hammer drill bit was taken out and changed to a 165mm Mincon High Capacity air percussion drill bit which the drilling contractor had acquired recently and had tested with good results on other projects. A larger air compressor than that used in Stage 1 was also on site. Drilling was started on 127 mbgl with the high capacity hammer and the drilling team was successful in airlifting the water from the borehole. Drilling could continue and the borehole was drilled to a final depth of 271 mbgl where the borehole penetration rate also decreased to around 30 min/m. The borehole was reamed with a 305 mm diameter to 10 m and was reamed with 254 mm diameter to a 110 mbgl. Reaming to 110 mbgl was done to accommodate a 152.4 mm (6'') installation for aquifer testing purposes.

It is possible that during drilling past 127 mbgl, when dolerite was exited into sedimentary rock again, a bedding plane or contact fracture was found and that water from the upper high yielding fractured dolerite aquifer was leaking through this sedimentary fracture to another aquifer or some point of lower hydraulic head. This could be what caused the intermittent final airlift yield in borehole EC-Q14-1636. Another more probable possibility is that the high yielding fracture and aquifer penetrated by EC-Q14-1636 is of limited aerial extent. The transmissivity of the fractured aquifer itself is very high, but groundwater flow to this aquifer is very slow or the catchment of this high yielding aquifer is too small.

Figure 6-9: Water Hammer operations at EC-Q14-1636

The borehole lithology and construction logs for EC-Q14-1636 are provided in Figure 6-10 to Figure 6-12.

EC-Q14-1637

The borehole numbered EC-Q14-1637 in The Glen sub-catchment was drilled to a final depth of 258 mbgl and delivered a final airlift yield of 10 ℓ/s. Water bearing fractures were intersected at 18 m (0.1 ℓ/s), 61 m (6.5 ℓ/s) and 75 m (3.4 ℓ/s), generally within the weathered dolerite and contact zones between the mudstone, siltstone and dolerite. 254 mm ID solid steel casing was installed from 0 to 15 mbgl into at least 3 mbgl of solid formations to stabilise the borehole in the looser alluvium formations. Solid steel casing with 177 mm ID was also installed from 0 to 20 mbgl to stabilise the section from 15 to 20 m in the weathered dolerite. A concrete collar was installed to prevent the ingress of surface water into the borehole which may lead to groundwater contamination and structural instability of the casing. The borehole was sealed with a 6 mm Allan key borehole cap to prevent vandalism and excessive exposure to the atmosphere until equipping of the borehole could be done.

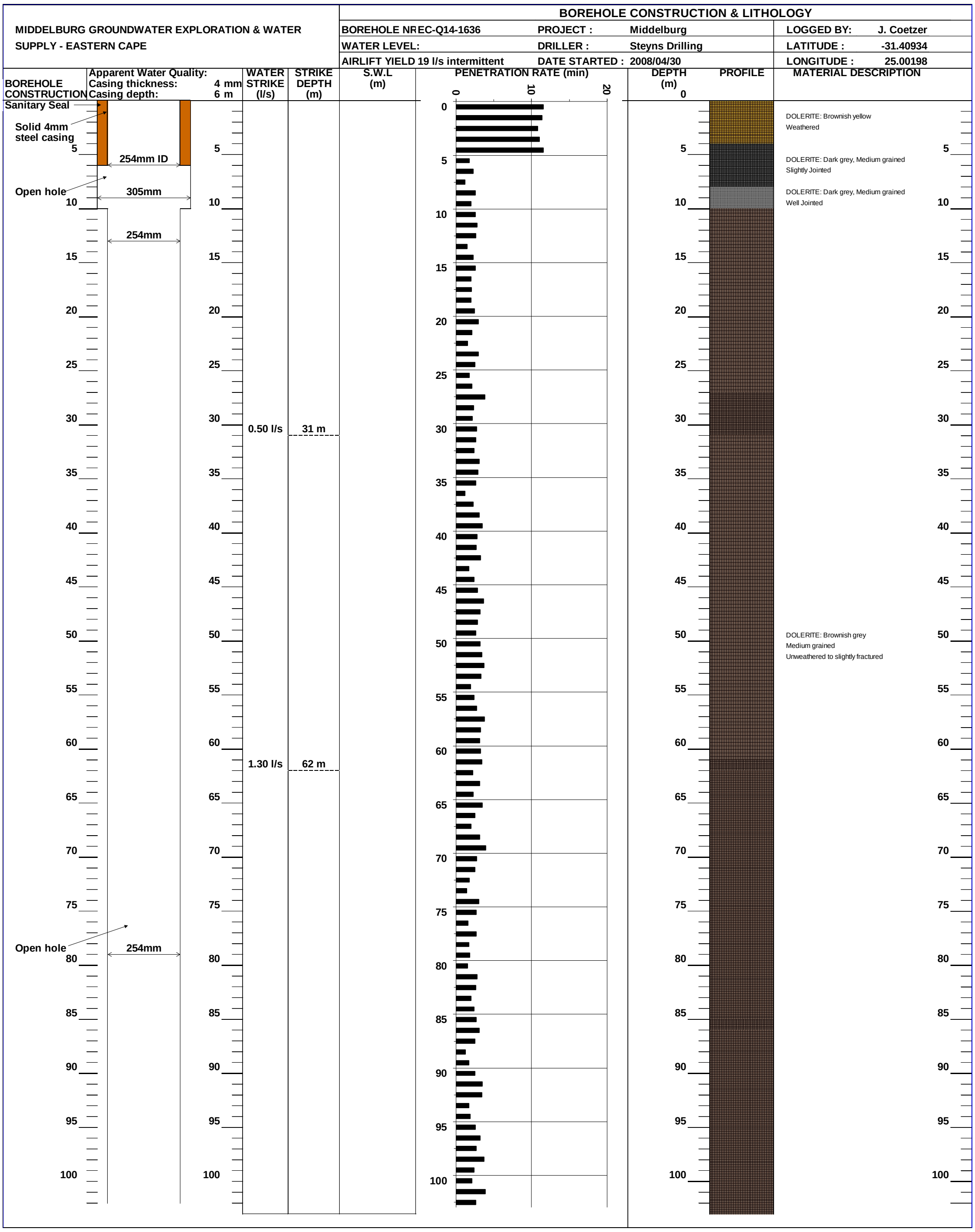


Figure 6-10: Borehole lithology and construction log for EC-Q14-1636: part 1 of 3

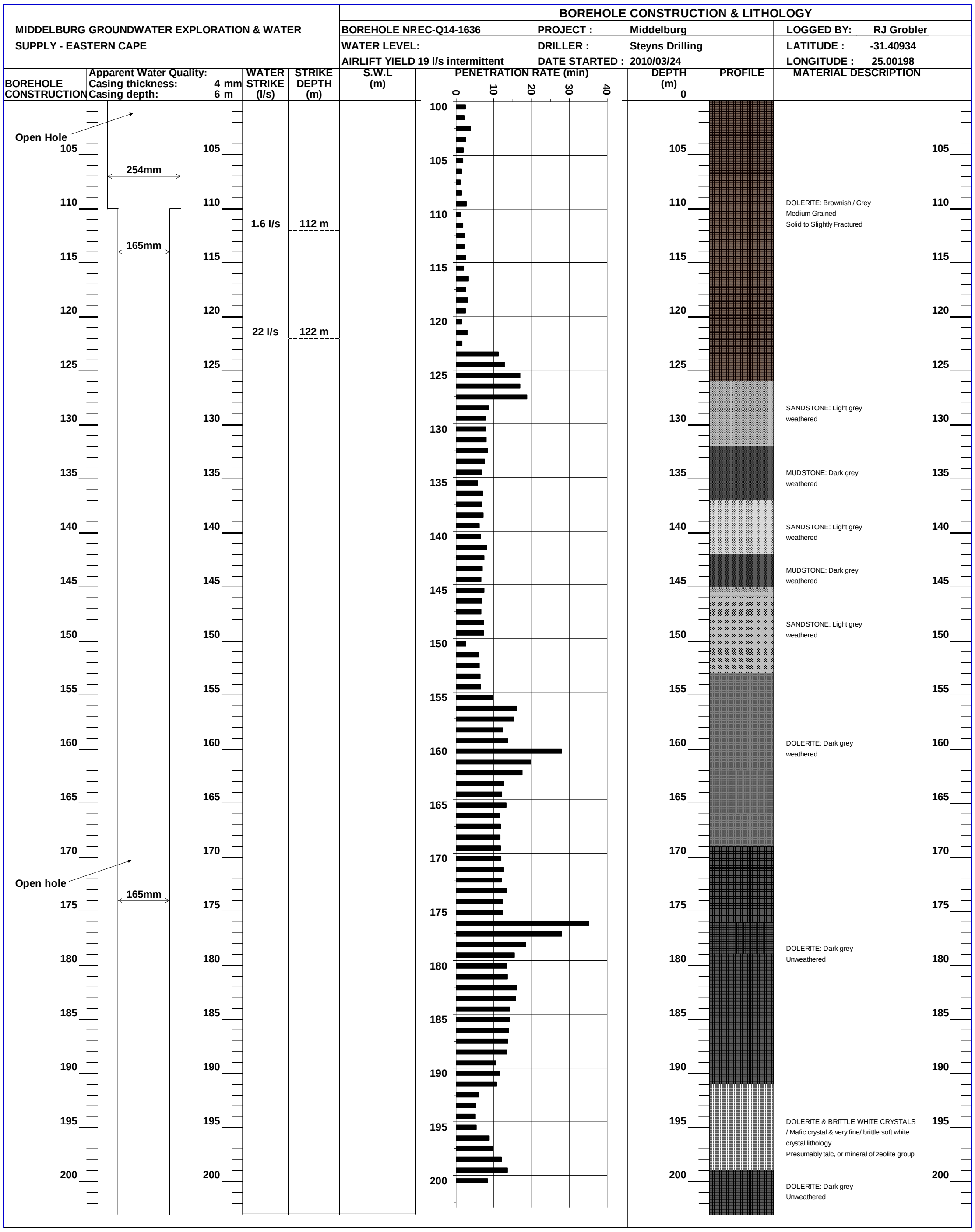


Figure 6-11: Borehole lithology and construction log for EC-Q14-1636: part 2 of 3

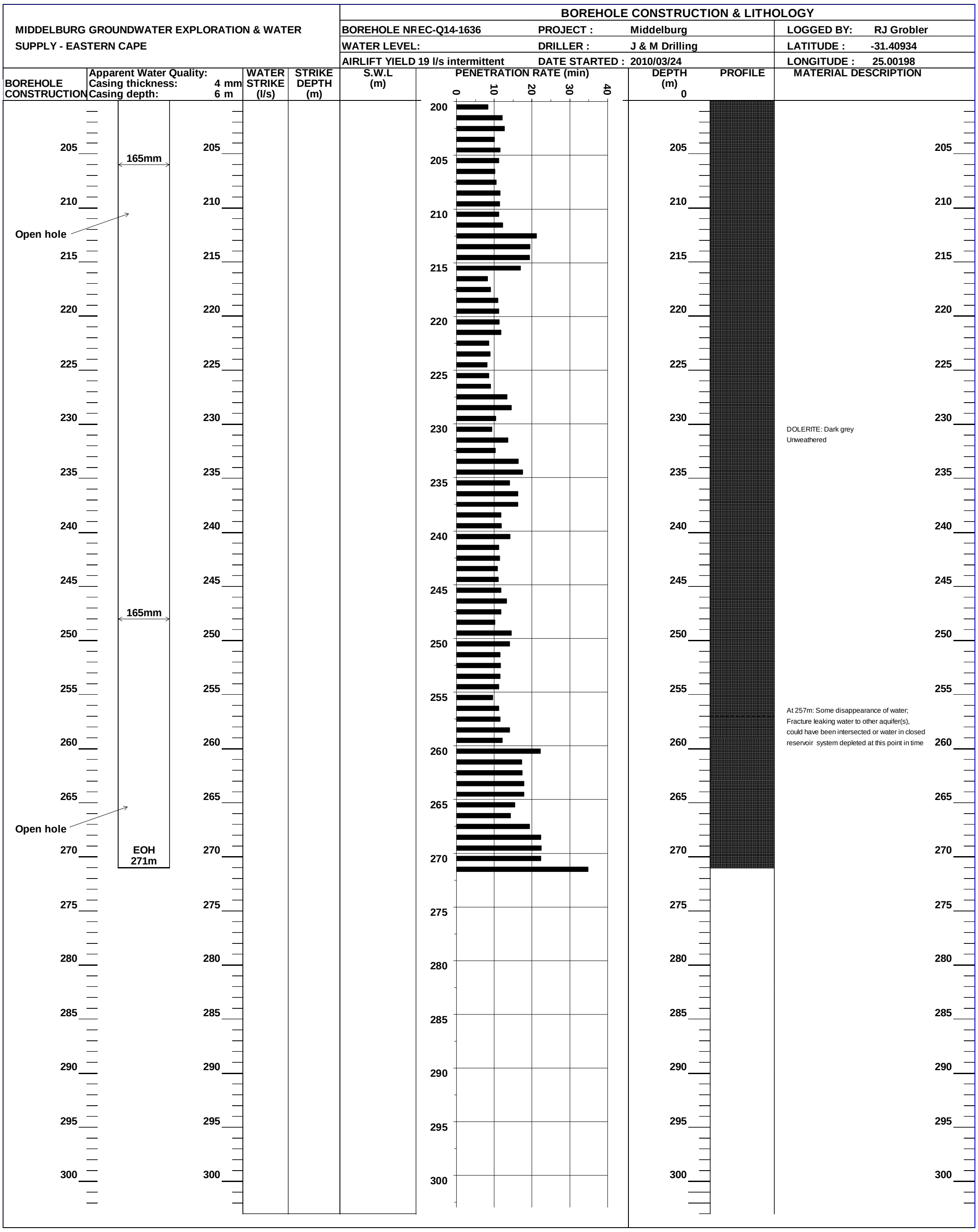


Figure 6-12: Borehole lithology and construction log for EC-Q14-1636: part 3 of 3

EC-Q14-1638

The borehole numbered EC-Q14-1638 was drilled on the Dunblane farm in the Dunblane sub-catchment to a final depth of 228 mbgl and delivered a final airlift yield of 0.8 ℓ/s. A single water bearing fracture was intersected at 14 m (0.5 ℓ/s) on a lithological contact between formations. 254 mm ID solid steel casing was installed from 0 to 6 mbgl into at least 3 mbgl of solid formations to stabilise the borehole. A sanitary seal and concrete collar was installed to prevent the ingress of surface water into the borehole which may lead to groundwater contamination and structural instability of the casing. The borehole was sealed with a 6 mm Allan key lockable borehole cap to prevent vandalism and excessive exposure to the atmosphere until equipping of the borehole could be done.

EC-Q14-1639

The borehole numbered EC-Q14-1639 was drilled on the Dunblane farm in the Dunblane sub-catchment to a final depth of 138 mbgl and delivered a final airlift yield of 1.30 ℓ/s. Water bearing fractures were intersected at 37 m (0.5 ℓ/s) on the lithological contact zones and within joints in dolerite. 254 mm ID solid steel casing was installed from 0 to 6 mbgl into at least 3 mbgl of solid formations to stabilise the borehole. A sanitary seal and concrete collar was installed to prevent the ingress of surface water into the borehole which may lead to groundwater contamination and structural instability of the casing. The borehole was sealed with a 6 mm Allan key lockable borehole cap to prevent vandalism and excessive exposure to the atmosphere until equipping of the borehole could be done.

EC-Q14-1640

The borehole numbered EC-Q14-1640 was drilled on the Dunblane farm in the Dunblane sub-catchment to a final depth of 252 mbgl and delivered a final airlift yield of 1.3 ℓ/s. A single water bearing fracture was intersected at 98 m (1.3 ℓ/s) on a fracture within the dolerite of the Dunblane dyke. 254 mm ID solid steel casing was installed from 0 to 3 mbgl directly into the very stable igneous dolerite of Dunblane dyke to stabilise the borehole. A concrete collar was then installed to prevent the ingress of surface water into the borehole which may lead to groundwater contamination and structural instability of the casing. The borehole was sealed with a 6mm allan key lockable borehole cap to prevent vandalism and excessive exposure to the atmosphere until equipping of the borehole could be done.

EC-Q14-1641

Borehole EC-Q14-1641 was drilled on the Redlands farm in the more distant Lusernvlei sub-catchment, perfectly formed by a large dolerite ring structure. The borehole was drilled to a final depth of 200 mbgl and delivered a final airlift yield of 6.9 ℓ/s. Water bearing fractures were intersected at 3 m (7 ℓ/s), 33 m (0.5 ℓ/s), 84 m (2 ℓ/s) and 92 m (4.4 ℓ/s) where the 3 m strike was within alluvium, the 33 and 84 m within joints in dolerite and the 92 m water strike on the contact between dolerite and the underlying sandstone. 254 mm ID solid steel casing was installed from 0 to 16.5

mbgl into 0.5 m of solid dolerite to stabilise the looser alluvium formation. A sanitary seal and concrete collar was installed to prevent the ingress of surface water into the borehole which may lead to groundwater contamination and structural instability of the casing. The borehole was sealed with a 6 mm Allan key lockable borehole cap to prevent vandalism and excessive exposure to the atmosphere until equipping of the borehole could be done.

<u>EC-Q11-166 (EC-Q14-1652)</u>

Borehole EC-Q11-166 was drilled on the Alfalfa farm in the more distant Lusernvlei sub-catchment, on the downstream side of the large dolerite ring structure. The borehole was drilled to a final depth of 194 mbgl and delivered a final airlift yield of 12.1 ℓ/s. Water bearing fractures were intersected at 19 m (0.2 ℓ/s), 57 m (5.4 ℓ/s), 174 m (2.9 ℓ/s) and 192 m (3.6 ℓ/s) where the water strikes where generally within joints in the dolerite and on lithological contacts between the sedimentary formations. An airlift yield volume of 7 ℓ/s was cased off to target only water from the deeper fractured rock aquifer. 254 mm ID solid steel casing was installed from 0 to 2.5 mbgl to stabilise the highly jointed top section of the dolerite. Solid steel casing with 175 mm ID was also installed from 0 to 24 mbgl to stabilise the rest of the weathered dolerite. A concrete collar was installed to prevent the ingress of surface water into the borehole which may lead to groundwater contamination and structural instability of the casing. The borehole was sealed with a 6 mm Allan key lockable borehole cap to prevent vandalism and excessive exposure to the atmosphere until equipping of the borehole could be done.

<u>EC-Q14-1653</u>

The borehole numbered EC-Q14-1653 was drilled on the Waterkloof farm within the Karmel sub-catchment directly to the northwest of Middelburg. The borehole was drilled to a final depth of 132 mbgl and delivered a final airlift yield of 12.1 ℓ/s. Water bearing fractures were intersected at 34 m (0.5 ℓ/s) and 129 m (11.6 ℓ/s) generally within fractures and joints of the weathered dolerite. 175 mm ID solid steel casing was installed from 0 to 12 mbgl into at least 3 m of solid formations to stabilise the borehole in the looser alluvium formations. A concrete collar was installed to prevent the ingress of surface water into the borehole which may lead to groundwater contamination and structural instability of the casing. The borehole was sealed with a 6 mm Allan key borehole cap to prevent vandalism and excessive exposure to the atmosphere until further equipping of the borehole could be done.

<u>EC-Q14-1654</u>

The borehole numbered EC-Q14-1654 was on the Grootfontein farm in the Dunblane sub-catchment. The borehole was drilled to a final depth of 200 mbgl and delivered a final airlift yield of 14.8 ℓ/s. Water bearing fractures were intersected at 13 m (0.5 ℓ/s) and 78 m (14 ℓ/s) where the shallow strike was on the contact between alluvium and dolerite and the deeper strike was from a large fracture within the siltstone sedimentary formation. 177 mm ID solid steel casing was installed from 0 to 12 mbgl to stabilise the borehole in the looser alluvial formations. A concrete collar was installed to prevent the ingress of surface water into the borehole which may lead to groundwater contamination and structural instability of the casing. The borehole was sealed with a 6 mm Allan key borehole cap to prevent vandalism and excessive exposure to the atmosphere until equipping of the borehole could be done.

<u>EC-Q14-1655</u>

This borehole was also identified as a main production borehole for Middelburg's water supply in The Glen sub-catchment due to the potential it showed during its initial drilling. The borehole was drilled in two stages. Stage 1 was prior to the halt in the project and stage 2 when the project re-activated and completed. It was started on 26 June 2008 and the 1st stage of the borehole's drilling was completed on 4 July 2008. The borehole lithology and construction logs for EC-Q14-1655 are provided in Figure 6-13 to Figure 6-15.

Stage 1

The borehole was started on the 30th of April 2008 and the 1st stage of the borehole's drilling was completed on 26 May 2008. This borehole is situated approximately 30m away from borehole EC-Q14-1634 and thus the effect of the "poort" which drains much of the water from The Glen sub-catchment also applies here. During this stage the borehole was drilled to a depth of 154 mbgl and delivered a final airlift yield of 7 ℓ/s. Water bearing fractures were intersected at 12 m (0.5 ℓ/s), 14 m (1.4 ℓ/s), 40 m (4.4 ℓ/s) and 100 m (2.6 ℓ/s) where the shallower 2 water strikes were in the porous alluvium formation, while the 2 main water strikes were on large fractures found within the sandstone lithological formations.

When drilling in alluvium problems were often encountered when parts of the alluvium formation would collapse onto the drilling hammer while drilling. This causes the drilling hammer to become stuck and could potentially mean the loss of the borehole, drilling hammer and bit. The ODEX technique was applied at this borehole whereby borehole casing rests on top of the drill bit and is taken into the borehole while simultaneously drilling deeper. This ensures that loose sand or boulders cannot fall directly onto the hammer and instead comes to rest against the casing being installed simultaneously while drilling continues.

The borehole was drilled with a 254 mm ODEX drill bit from 0 – 21 m well past the alluvial formation into solid sedimentary formation. The borehole was then drilled with a 165 mm diameter from 21 – 154 m in sandstone/ siltstone Beaufort formations. The initial yield volume steadily increased and at the former mentioned depth, difficulty was also encountered with water pressure and air pressure equalisation. The decision was made to return to the borehole with the water hammer the drilling contractor would acquire as promised.

Stage 2

After the Middelburg project re-activated the drilling of borehole EC-Q14-1655 was resumed on the 5th of March 2010 with the Mincon high capacity hammer installation and the borehole was completed on 23 March 2010. The borehole was drilled to a final depth of 282 mbgl and delivered a constant final airlift yield of 19.0 ℓ/s. Possible fractures were intercepted at 155 m (3 ℓ/s) as well as 176 m (2 ℓ/s) where the 155 m strike was based on a dolerite sandstone contact and the 176 mbgl strike based on a less obvious quartz inclusion in the dolerite. The fact that the borehole airlift yield kept increasing since drilling resumed up to 21.75 ℓ/s made it difficult to distinguish whether deeper strikes had been encountered or not.

The drilling of EC-Q14-1655 was resumed in Stage 2 with the reaming of the borehole at a 203mm drilling diameter from 21 m to 154 m. This was done to allow for the option to case off all alluvial and shallow formation water strikes, in order to be able to drill to depths in excess of 300 m without the water pressure head problem.

From 154 mbgl drilling commenced with the 165 mm diameter newly acquired Mincon high capacity drill bit and hammer and also with the larger air-compressor now on site compared to the compressor used during Stage 1, progress was made with drilling depth. The airlift yield of the borehole started initially at around 10 ℓ/s and increased right through the drilling process. Drilling became complicated at around 240 mbgl when the pressure from the water's hydraulic head became so much that if adding another drilling rod to the drill string took too long, the water could not be lifted from the borehole. The only solution in this case would be to take out all drilling rods, insert one drilling rod at a time and properly blow water from the borehole with each addition. At 270 m it became the only way to make drilling progress and the addition of each drilling rod had to be done very quickly. The cause was that water was coming into the borehole at a very high rate. Slowly the drilling progressed to a final depth of 282 m where the water pressure head could not be lifted anymore. A decision was made that the drilling depth is sufficient based on the geology and that water hammer establishment for Stage 2 on EC-Q14-1636 can commence.

The borehole was then reamed with a 240 mm diameter from 21 m to 38 m. uPVC casing with an ID of 181 mm was installed from 0 to 38 m to stabilise the borehole in the weathered sections of the sandstone and siltstone formations. The uPVC casing was slotted from 18 to 36 m to allow for groundwater flow through at such depths. A concrete collar was installed to prevent the ingress of surface water into the borehole which may lead to groundwater contamination and structural instability of the casing. The borehole was sealed with a 6 mm Allan key borehole cap to prevent vandalism and excessive exposure to the atmosphere until equipping of the borehole could be done.

EC-Q14-1656

The borehole numbered EC-Q14-1656 was drilled as a Water Hammer water supply borehole approximately 25 m from EC-Q14-1636 and was completed on 3 February 2010. The borehole was drilled to a final depth of 63 mbgl and delivered a final blowyield of 10.17 ℓ/s. Water bearing fractures were intersected at 32 m (1.26 ℓ/s); 59 m (1 ℓ/s) and 62 m (8 ℓ/s) generally within joints and fractures found in the dolerite. 254 mm ID solid steel casing was installed from 0 to 2 mbgl directly into solid rock dolerite. A Concrete collar was installed to prevent the ingress of surface water into the borehole which may lead to groundwater contamination and structural instability of the casing. The borehole was welded closed with a steel plate to prevent vandalism and excessive exposure to the atmosphere until use of borehole would commence.

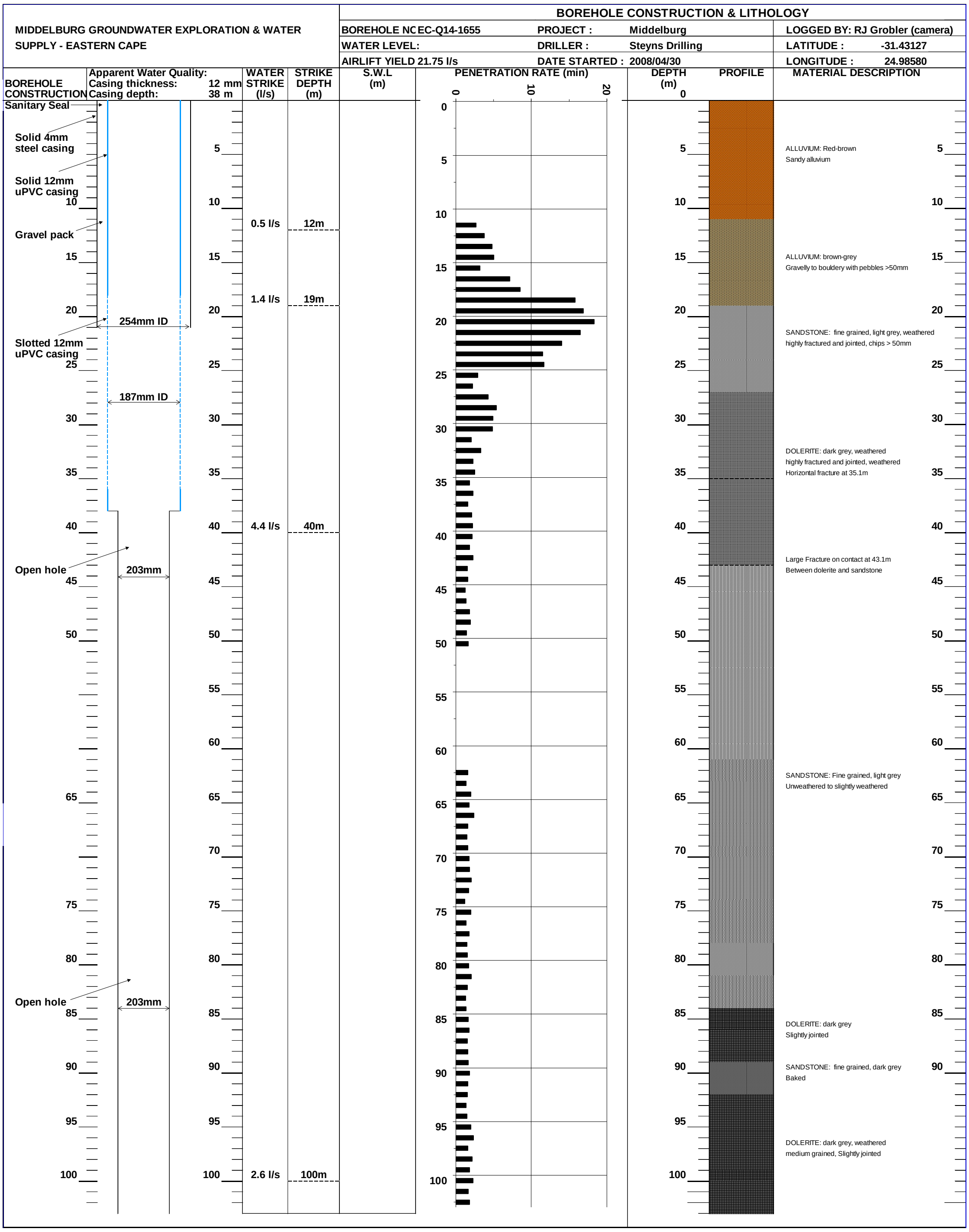


Figure 6-13: Borehole log EC-Q14-1655, Jones Poort, The Glen; log 1 of 3

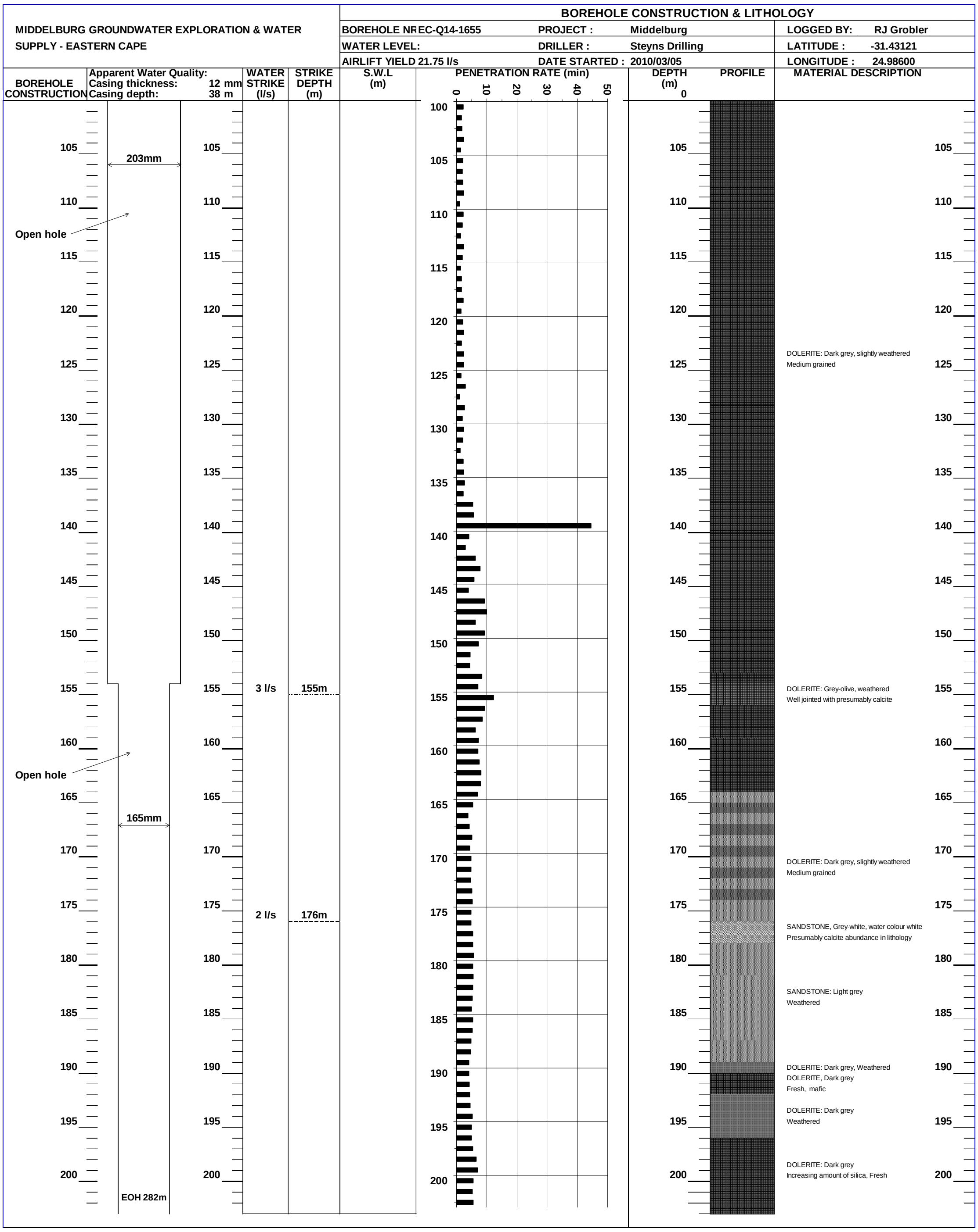


Figure 6-14: Borehole log EC-Q14-1655, Jones Poort, The Glen; log 2 of 3

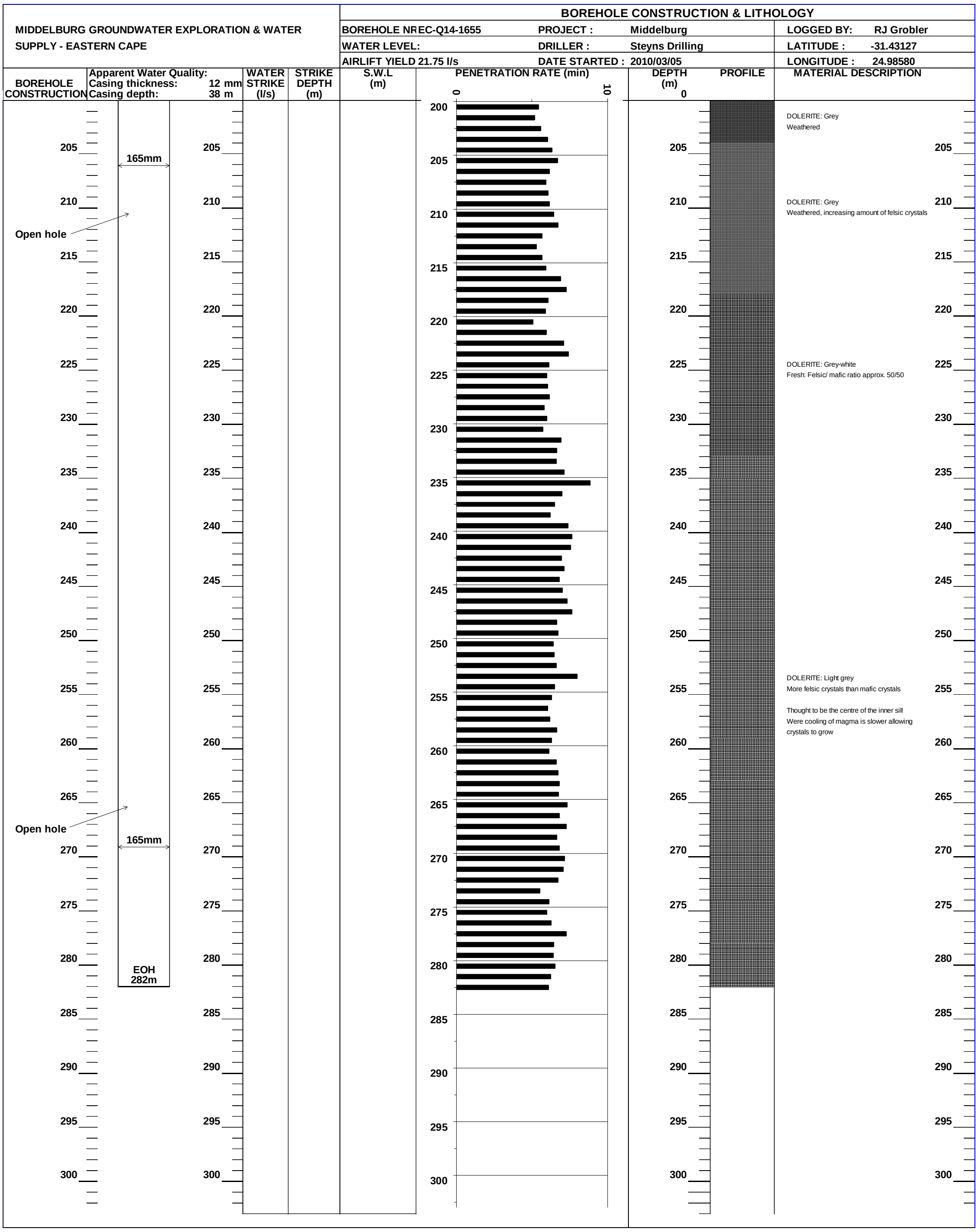


Figure 6-15: Borehole log EC-Q14-1655, Jones Poort, The Glen; log 3 of 3

EC-Q14-1662

The borehole numbered EC-Q14-1662 was drilled on the Grootfontein Agricultural College farm as a deep aquifer monitoring borehole and drilling started on 22 January 2010 and completed on the 24th of January 2010.The borehole was drilled to a final depth of 252 mbgl and delivered a final airlift yield of 2.55 ℓ/s. Water bearing fractures were intersected at 23 m (0.8 ℓ/s) and 25 m (0.5 ℓ/s) on the contact between the alluvium and weathered siltstone and in the weathered siltstone itself. 254 mm ID solid steel casing was installed from 0 to 24 mbgl into solid formations to stabilise the borehole in the looser alluvium formations. A concrete collar was installed to prevent the ingress of surface water into the borehole which may lead to groundwater contamination and structural instability of the casing. The borehole was sealed with a 6 mm Allan key borehole cap to prevent vandalism and excessive exposure to the atmosphere until equipping of the borehole could be done.

6.4 Conclusions on drilling work

Based on the boreholes drilling in the Middelburg study area targeting mostly dolerite structures at depth, the following conclusions were reached.

- Good high yielding boreholes were drilled on the dolerite structures and especially where adjacent fractured or high yielding formations were present.
- Although the goal was to target the dolerite structures at depth, reaching the planned 300 mbgl depths proved difficult due to high water pressure building up. Even where the boreholes reached depths of 200+ mbgl, statistically the most water strikes occurred at shallower depths although it must be recognised that it becomes increasingly difficult to see immediate changes in airlift yield and water strikes at those depths.
- Water pressure from a hydraulic head column forming on top of the drill bit where air needs to blow out, is still the biggest challenge in air-percussion drilling of high yielding boreholes past a depth of approximately 200 – 240 m. Water hammer drilling is seen as a viable alternative, although it did not prove successful in the case of EC-Q14-1655. The problem was thought to be an aquifer reservoir of limited extent and thus no continual flow of water from the outer extents of the aquifer towards the borehole. Also, it is probable that the water supply borehole to the water hammer was directly and closely linked to the production borehole being drilled and thus only recycling of the water with chips would take place, but the drill chips could seriously harm the pump without filter.

- In most instances, shallow water strikes in boreholes could not be sealed off with casing successfully. One exception is the borehole EC-Q14-1634 where the borehole was backfilled and grouted and drilled again. Finally the borehole was still in-situ perforated between 25 – 46 mbgl that again allowed for water from the shallow aquifer to flow in. Time and budget are needed for properly sealed off shallow aquifer sections as well as highly skilled drilling sub-contractors. Time is needed to wait for the grouting to dry and budget is needed for the grouting and casing material. Time was not available during the Middelburg water supply project.
- The ODEX drilling technique was found to be the most effective and far superior technique compared to drill-and-drive when drilling in alluvium especially pebble and boulder size alluvium. ODEX drilling is however significantly more expensive and cannot be used at every opportunity if the constraint in the project is budget. If budget is not the constraint however and time is, ODEX will result in quicker progress through the alluvial section and proper installation of the casing in that section.
- A water supply target area that definitely holds promise and has not been extensively explored yet is the target where a dolerite dyke cuts through the inclined sheet of a dolerite sill- and ring-structure. The stresses associated with the intrusion of the dyke through the already most stressed part of the dolerite sill- and ring-structure yields a high probability of large fracturing being encountered. Even if the dolerite dyke and ring structure solidified into one mass due to intense heat from the dyke intrusion, the adjacent country rock would definitely have a high possibility of extensive fracturing due to the multiple intrusions and thermal jointing. This target area concept has been proven during the study with the borehole EC-Q14-1636 intersecting a very large and high yielding fracture in such a zone, although the aquifer itself was of limited extent. Care should then be taken in selecting such a target in a low lying zone if available, where a large catchment for such a fractured zone exists.

7 AQUIFER TESTING

Aquifer testing was performed by the sub-contractor AB Pumps appointed on 18 January 2008. The Aquifer testing work included pumping tests, down-the-hole camera work and packer testing. A total of 27 pumping tests were performed enabling not only the calculation of sustainable yields for boreholes, but also the wider characterisation of aquifers and their parameters for the different types of aquifers found in Middelburg.

7.1 Methodology

7.1.1 Aquifer testing (Hydraulic tests)

Hydraulic tests (pumping tests) were conducted according to the *Minimum standards and guidelines for groundwater resource development* document of DWA (1997). Generally calibration tests, step tests, constant discharge (CD) tests and recovery tests were performed depending on the individual aquifer conditions at each borehole. Calibration tests were in most cases not performed due to the airlift yield being available at new boreholes. For more information regarding the general procedure of pumping tests the reader is referred to Kruseman and de Ridder (2000) as well as DWA (1997).

7.1.1.1 Theoretical aquifer model (conceptual aquifer model)

The choice of the correct theoretical aquifer model (conceptual aquifer model) related to a type curve (analytical mathematical solution simulating observed drawdown behaviour) is one of the most important choices the analyst has to make to derive aquifer parameters from a hydraulic test correctly (Van Tonder et al, 2001; Kruseman & de Ridder, 2000). The various theoretical aquifer models that partly or almost completely describe the Karoo multi-porous fractured rock aquifer behaviour have been discussed under the theoretical model section in the Literature Study in Chapter 2. The conclusion was that for dual porosity aquifers at late times during the hydraulic tests, the aquifer behaves as one system and shows a pseudo radial flow regime (Kruseman and de Ridder, 2000; Woodford et al., 2002). The implication of this behaviour is that a porous aquifer theoretical model or solution, notably the Theis equation can be used to arrive at a sufficiently accurate estimation of the transmissivity value of the aquifer. This late-time behaviour has also been shown to be true for Karoo fractured rock aquifers by Meier *et al.* (1998) and Van Tonder *et al.*

(2001) consequently developed the Flow Characteristic Method (FCM) based on the Cooper-Jacob approximation of the Theis equation.

During the Middelburg groundwater study and investigation the Flow Characteristic Method (FCM) as well as the Cooper-Jacob approximation of the Theis equation was used to determine the transmissivity (T) values as well as the sustainable yields of boreholes. The storativity (S)/specific yield (S_Y) for the aquifer was determined using AQTESLOLV where accurate observation borehole data from testing were available, e.g. the Neuman (1975) unconfined solution applied for EC-Q14-1655 pumping test.

7.1.1.2 Hydraulic test analysis

While the Theis equation has been shown to be a suitable solution for water level drawdown behaviour at late times during a hydraulic test, the analyst still needs to choose the part of the drawdown curve correctly to fit the log derivative straight line of the Cooper-Jacob approximation. To this end the FCM method developed by Van Tonder *et al.* (2001) has greatly eased the decision of what part of the time-drawdown curve to fit by implementing the Method of Derivative Fitting (MDF) that automatically determines where on the observed time-drawdown curve pseudo radial flow most likely occurred. Using the FCM, no fitting of the curve is necessary and a T- and sustainable yield-value are automatically calculated from observed time-drawdown values. While the FC method has been proven to in most hydraulic test cases make the right curve fitting decision based on the MDF, there is no substitution for an experienced aquifer test analyst and for this reason the Cooper-Jacob approximation of the Theis equation was also used. In some cases the time-drawdown behaviour resembles another aquifer type and the choice of where the straight line is fitted will differ from the choice of the MDF method of the FCM. Both the FCM and Theis solutions were computed in the FC program. For more information regarding the Theis equation and general aquifer test analysis procedure refer to Kruseman & de Ridder (2000).

The following equations are of interest in the aquifer test analysis procedure for the Middelburg groundwater investigation:

Darcy’s law is given by:

$$Q = K\frac{dh}{dl}A$$

Where K is hydraulic conductivity (m/d); dh/dl is the hydraulic gradient and A is the cross sectional area (m^2) through which flow occurs perpendicularly. *Transmissivity* as T is related to hydraulic conductivity through b aquifer thickness (m) in:

$$T = Kb$$

For storativity/storage coefficient values:

$$S_s = \rho g(\alpha + n\beta)$$

where S_s is specific storage, ρ is fluid density, g is acceleration of gravity, α is aquifer compressibility, n is the porosity and β is the fluid compressibility. Storativity S is related to *specific storage* again through *aquifer thickness* b in:

$$S = S_s b$$

The Cooper-Jacob approximation of the Theis equation is of the form:

$$s = 2.3\frac{Q}{4\pi T}\ log\frac{2{,}25Tt_0}{r^2 S}$$

where s is drawdown (m), t_0 is a sufficiently late time during the hydraulic test and r is the distance from the abstraction borehole where the s is measured in the observation borehole or piezometer.

7.2 Assumptions and analytical model limitations

The following assumptions and limitations apply to analytical model solutions used:

- The aquifer is assumed confined;
- The solution assumes the aquifer is infinite in areal extent. It is the analyst's responsibility to explicitly indicate boundaries and factor boundaries into the equation where known boundaries exist.
- The aquifer is homogenous, isotropic and has constant thickness over the area of influence during the test.
- The piezometric surface is horizontal over the area the will be influenced by the test, prior to the start of the pumping test.
- The aquifer is pumped at a constant discharge rate and the discharge borehole fully penetrates the entire thickness of the aquifer.
- Flow to the well is in unsteady state thus drawdown change with time is not negligible, nor is the hydraulic gradient constant with time.

(Kruseman & de Ridder, 2000)

An important limitation to the use of analytical solutions is revealed in calculating the storativity (S) for fractured rock aquifers. An incorrect and unrealistic S value will be obtained for fractured rock aquifers as well as porous aquifers without observation borehole data. This is due to the analytical solutions not being able to take two or more aquifers into consideration at once. Differing vertical flow components typically found in bilinear flow cannot be accounted for in these analytical solutions. The ideal is to use a two or more-layer numerical model for the calculation of S. Even if the S-value looks like it is in the right order of magnitude expected for the aquifer type, there is no mathematical justification, from the analytical solution used, that the S-value is correct. One program developed by Johan Verwey at the IGS addressed this problem called RPTSOLV (Verwey, 1995; Botha *et al.*, 1998). After multiple attempts the outdated program could not be successfully run on Windows 7 for analysis.

7.3 Hydraulic testing results

Due to the large amount of data and results obtained from the pumping tests it is best to represent these results and interpreted aquifer parameters in a summarising table format. The locations of all existing and new boreholes tested are shown in Figure 7-1. The detailed data of each pump test are attached in Appendix D.

7.3.1 Existing boreholes tested

A total of 21 existing boreholes were identified for testing in the various sub-catchments. The goal was to identify possible existing boreholes that could also be tied in for use for Middelburg groundwater supply. Of the 21 boreholes identified, 18 boreholes could be tested. Fifteen constant discharge tests were conducted and three boreholes received only step tests. Table 7-1 provides the basic information for existing boreholes tested, Table 7-2 gives the important pumping test information while Table 7-3 and Table 7-4 display the calculated and estimated aquifer parameters from pump test analysis for these existing boreholes.

7.3.1.1 Selected existing borehole pumping test analysis

EC-Q14-192 was one of the higher yielding existing boreholes tested and shows typical unconfined porous aquifer behaviour. Given that this is an older borehole, it was most probably drilled with a cable tool rig and as such is only drilled up to competent solid rock formation. This implies that the entire fully saturated length of the borehole from water table to the borehole bottom consists of the unconsolidated porous aquifer material and constitutes the aquifer thickness. It is presumed that the bottom part of the borehole consists of a short section of very weathered Beaufort Group sediments that is essentially the same as the rest of the alluvial porous material. The constant discharge (CD) test results graph in Figure 7-2 shows unconfined porous aquifer behaviour with the typical delayed yield response (90 – 1080 min.) as illustrated in Kruseman and de Ridder (2000). The borehole had a static water level of 10.36 mbgl and the pump was installed at 28.0 mbgl with the borehole depth being 29.2 mbgl. The CD test was conducted for 2160 minutes at 14.61 ℓ/s and only 3.5 m drawdown was obtained (20% of available drawdown). It is evident that the CD test rate was too low and therefore the delayed yield effect is not as clearly visible as expected, but still observed. From the pumping test analysis a late transmissivity value of 338.4 m^2/d was obtained with the FC method and a late transmissivity of 227.5 m^2/d with the Cooper-Jacob method. Given the aquifer thickness of 18.84 mbgl, a hydraulic conductivity (K) of 12.06 m/d was calculated. The hydraulic conductivity range for clean sand given by Freeze and Cherry (1979) is 0.86 m/d to 8640 m/d and the K-value obtained is situated approximately in the middle of this range.

The specific yield (S_Y) value of 1,54E-4 obtained is however seen as too small given the type of groundwater reservoir that the porous alluvial aquifer constitutes and a S_Y-value in the order of 1,0E-1 – 1,0E-2 was expected. The result obtained for the S-value could perhaps be attributed to the fact that the Cooper-Jacob confined aquifer method was used instead of a solution for an unconfined aquifer such as the Neuman (1975) curve-fitting method. Kruseman and de Ridder (2000: 101) however states that the early- and late-time drawdown data of an unconfined aquifer conforms to the confined aquifer Theis solution and that the Theis solution can be used to fit the late-time data and obtain the transmissivity value and a fairly realistic specific yield (S_Y). It has however been observed from practical experience that when the constant discharge test is conducted at too low an abstraction rate and reasonable drawdown is not obtained the slope of the Cooper-Jacob straight line fit is too low and the storativity or specific yield obtained is unrealistically low. This concludes that the erroneously low S_Y value obtained is the result of a too low abstraction rate used during the constant discharge test.

Table 7-2 to Table 7-4 summarises the hydraulic testing results and calculated aquifer parameter information for EC-Q14-192 as well as other existing boreholes tested.

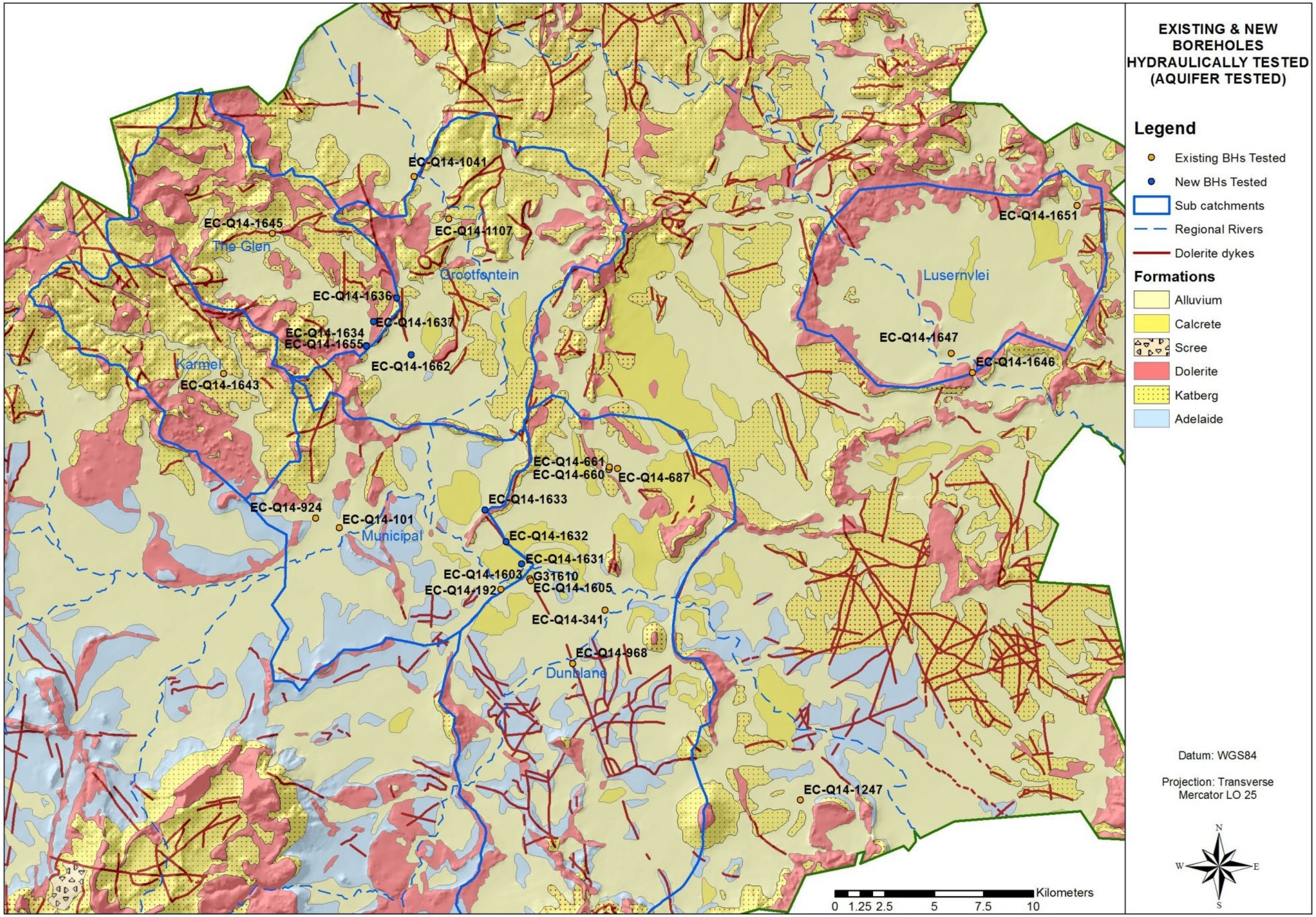


Figure 7-1: **Map of existing and new boreholes that pumping tests were performed on**

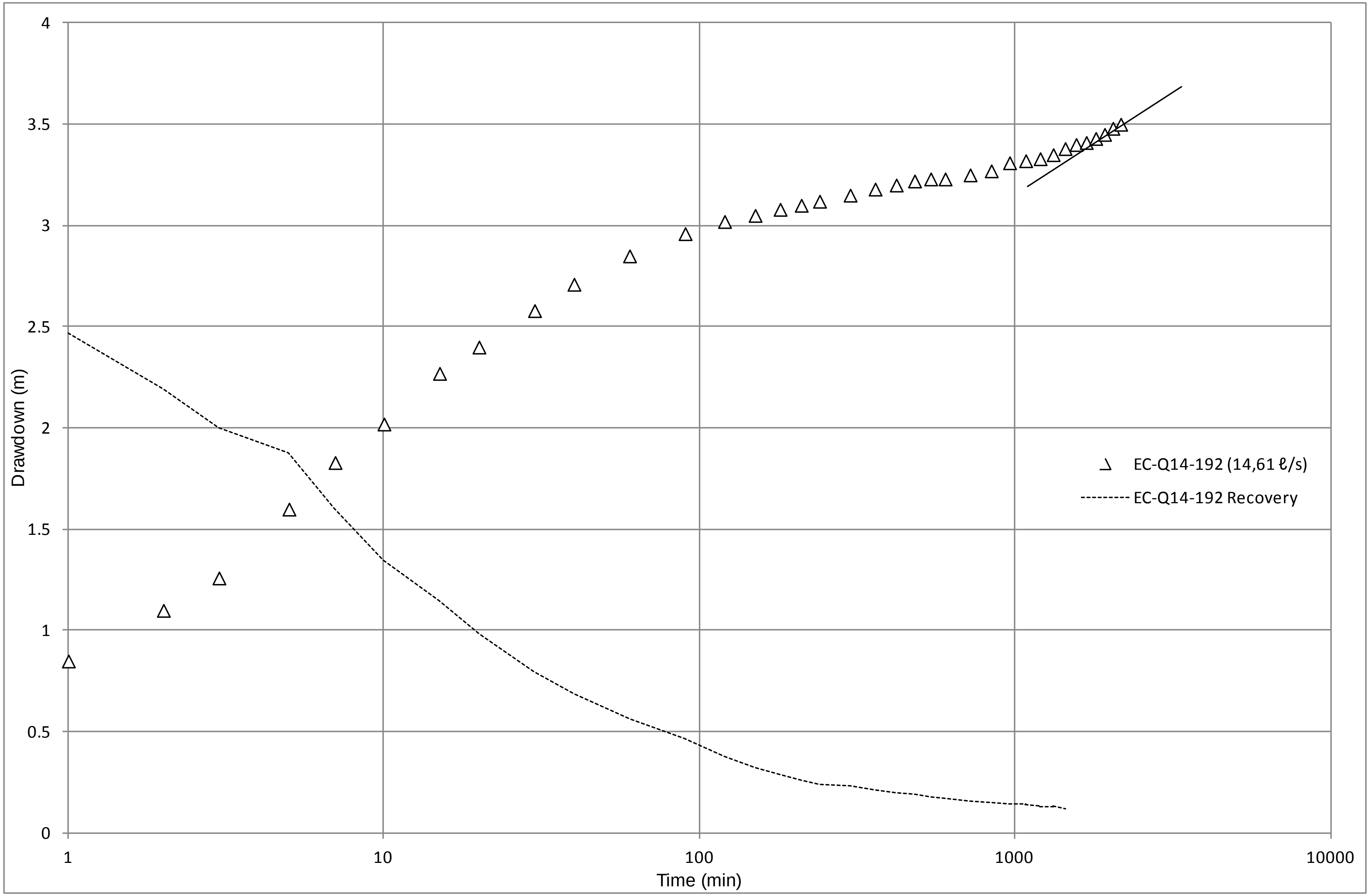


Figure 7-2: Unconfined porous aquifer behaviour with delayed yield in existing borehole EC-Q14-192 constant discharge test

Table 7-1: Basic information of existing boreholes aquifer tested in Middelburg

MIDDELBURG EXISTING BOREHOLES TESTED						
BASIC BOREHOLE INFORMATION						
SUB-CATCHMENT/ DRAINAGE	AREA/ FARM	ALLOCATED BOREHOLE NUMBER	ALTERNATIVE BOREHOLE NUMBER	BOREHOLE STATUS	COORDINATES (WGS84; dd)	
					Latitude	Longitude
					S°	E°
Middelburg Municipal	Vrede	**EC-Q14-924**	BH1	Existing	-31.50968	24.95903
Dunblane	Dunblane	**G31610**	G31610	Existing	-31.53729	25.07269
Dunblane	Dunblane	**EC-Q14-1603**	G31614	Existing	-31.53729	25.07269
Middelburg Municipal	Nuwevlei	**EC-Q14-101**	G31575	Existing	-31.51416	24.97153
Middelburg Municipal	Oranje	**EC-Q14-192**		Existing	-31.54228	25.05748
Dunblane	Buffelsvlei	**EC-Q14-341**	G31581 DWAF Obs. BH	Existing	-31.55157	25.11273
Dunblane	Rosmead	**EC-Q14-660**	BH4	Existing	-31.48762	25.11479
Dunblane	Rosmead	**EC-Q14-661**		Existing	-31.48643	25.11493
Dunblane	Rosmead	**EC-Q14-687**		Existing	-31.48704	25.11950
Middelburg Municipal	Dunblane	**EC-Q14-968**	G31583A	Existing	-31.57601	25.09559
Outside Sub-catchments	Wolwekop	**EC-Q14-1041**		Existing	-31.35404	25.01133
Outside Sub-catchments	Ebenhaezer	**EC-Q14-1107**		Existing	-31.37341	25.02970
Outside Sub-catchments / Dunblane	Dassiesfontein	**EC-Q14-1247**		Existing	-31.63809	25.21684
Karmel	Klipkrantz	**EC-Q14-1643**	EC-Q14-1625	Existing	-31.44394	24.91011
Grootfontein	Padreserwe	**EC-Q14-1644**	EC-Q14-045	Existing	-31.46695	25.01714
The Glen	Groothoek	**EC-Q14-1645**	EC-Q14-1228	Existing	-31.38002	24.93590
Lusernvlei	Redlands	**EC-Q14-1646**	EC-Q14-1646	Existing	-31.44303	25.30775
Lusernvlei	Alfalfa	**EC-Q14-1647**		Existing	-31.43426	25.29641
Karmel	Klip Krands	**EC-Q14-1649**		Existing	-31.46006	24.92580
Lusernvlei	Hartbeesfontein	**EC-Q14-1651**		Existing	-31.36665	25.36313

Table 7-2: Pumping test information of the existing boreholes tested during the Middelburg groundwater investigation

MIDDELBURG EXISTING BOREHOLES TESTED												
AQUIFER TESTING DATA & RESULTS												
ALLOCATED BOREHOLE NUMBER	Date tested	Static water level (mbgl)	Borehole depth (m)	Test Pump depth (mbgl)	Available Drawdown (m)	No. of Steps	Constant Rate Test				Recovery Test	
							Rate (l/s)	Max drawdown (mbgl)	% of Available Drawdown	Duration (min)	%	Duration (min)
EC-Q14-924	4-Sep-2007	10.87	38.52	34.00	23.13	1	-	-	-	-	-	-
G31610	31-Aug-2007	8.44	40.00	34.00	25.56	4	-	-	-	-	-	-
EC-Q14-1603	1-Sep-2007	8.68	40.54	35.15	26.47	5	20.07	18.16	68.61	1320	94.00	480
EC-Q14-101	7-May-2008	9.27	38.80	37.00	27.73	3	8.24	17.89	64.51	1440	92.62	120
EC-Q14-192	13-May-2008	10.36	29.20	28.00	17.64	4	14.61	3.50	19.84	2160	90.86	150
EC-Q14-341	2-May-2008	9.25	71.00	70.00	60.75	4	1.85	11.83	19.47	1440	90.79	420
EC-Q14-660	27-Apr-2008	10.15	23.82	22.00	11.85	4	10.04	3.45	29.11	2880	40.58	1560
EC-Q14-661	8-Jun-2008	14.12	41.30	39.00	24.88	0	-	-	-	-	-	-
EC-Q14-687	9-Jun-2008	14.14	43.27	40.50	26.36	3	0.51	16.51	62.63	1440	92.13	1320
EC-Q14-968	5-May-2008	6.37	65.80	64.00	57.63	3	-	-	-	-	-	-
	11-May-2008	6.05	66.00	64.00	57.95	3	6.84	55.95	96.55	960	92.31	360
EC-Q14-1041	2-Jun-2008	5.79	37.35	35.83	30.04	3	9.77	8.05	26.80	1440	95.65	1
EC-Q14-1107	5-Jun-2008	21.95	73.80	70.35	48.40	4	6.80	14.86	30.70	1440	82.23	1440
EC-Q14-1247	12-Jun-2008	14.62	51.20	49.50	34.88	4	6.24	20.28	58.14	1440	70.76	1440
EC-Q14-1643	16-Jun-2008	6.34	15.08	11.00	4.66	4	0.92	1.51	32.40	1440	90.07	120
EC-Q14-1644	Not tested	3.67	9.00	-	-	-	-	-	-	-	-	-
EC-Q14-1645	30-May-2008	7.07	21.60	18.35	11.28	0	2.00	8.92	P.I	350	67.49	310
EC-Q14-1646	30-May-2008	5.35	45.89	43.50	38.15	4	16.69	28.53	74.78	1440	91.66	840
EC-Q14-1647	28-May-2008	5.94	41.56	40.50	34.56	3	7.20	10.24	29.63	1440	90.04	1
EC-Q14-1649	Farmer refused to pump	-	-	-	-	-	-	-	-	-	-	-
EC-Q14-1651	3-Jun-2008	7.48	45.30	43.50	36.02	0	22.36	4.96	13.77	2160	71.37	2160

Table 7-3: Table 1 of 2 aquifer parameters determined for existing boreholes aquifer tested in Middelburg

MIDDELBURG EXISTING BOREHOLES TESTED													
ALLOCATED BOREHOLE NUMBER	PUMPING TEST ANALYSIS (Duty cycle 24 hours)												
	Main Water Strike (m b Rest WL)	Observation Borehole (dist in m)	FC					Cooper-Jacob					
			Qsust (l/s)	Ave Q sust(l/s)	T early (m^2/d)	T late (m2/d)	Derivative S	Qsust (l/s)	Ave Q sust(l/s)	T late (m2/d)	S (not valid)	Comments
EC-Q14-924	-	-	-	-	-	-		-	-	-	-	No CD test done, only 1 step, very low yielding Borehole
G31610	-	-	-	-	-	-		-	-	-	-	Appears to be good borehole, only step test, good recovery
EC-Q14-1603	max drawdown, 18.16	-	7.41	3.75	69.08	29.69	4.82E-04	8.04	4.18	34.40	3.48E-04	Strong borehole, fractured at depth, good recovery as well
EC-Q14-101	max drawdown, 17.89	-	3.65	1.94	19.94	16.48	2.56E-05	3.50	1.82	18.00	1.90E-05	Perfect dual porosity behaviour, well fractured, good recovery
EC-Q14-192	max drawdown, 3.5	EC-Q14-192A	9.44	6.02	271.53	338.35	4.84E-05	8.20	4.26	227.50	1.54E-04	100% Porous Aquifer, unconsolidated sediments, alluvium, very good recovery
EC-Q14-341	max drawdown, 11.8	-	1.12	0.68	12.29	10.80	2.25E-06	1.07	0.56	10.10	7.97E-07	Fractured rock aquifer, good fracture network & recovery
EC-Q14-660	max drawdown, 3.45	-	2.29	1.08	613.52	36.33	2.20E-03	2.55	1.32	39.90	1.29E-01	U no-flow boundary or closed system reached. Porous aquifer. Borehole not sustainable
EC-Q14-661	-	-	-	-	-	-		-	-	-	-	Only Calibration, Low yielding
EC-Q14-687	12.50	-	0.14	0.07	1.75	0.84	2.62E-05	0.13	0.07	0.70	3.37E-05	Standard Low yielding Karoo formations borehole
EC-Q14-968	-	-	-	-	-	-		-	-	-	-	Only steps done, retested on 11/05/2008 as in summary table
	21.50	G31583B	0.68	0.32	7.85	2.05	1.98E-04	1.79	0.93	7.20	4.41E-05	Good borehole, good recovery. FC not representative of Yield ability

Table 7-4: Table 2 of 2 aquifer parameters determined for existing boreholes aquifer tested in Middelburg

ALLOCATED BOREHOLE NUMBER	PUMPING TEST ANALYSIS (Duty cycle 24 hours)											
			FC					Cooper-Jacob				
	Main Water Strike (m b Rest WL)	Observation Borehole (dist in m)	Qsust (l/s)	Ave Q sust(l/s)	T early (m^2/d)	T late (m2/d)	Derivative S	Qsust (l/s)	Ave Q sust(l/s)	T late (m2/d)	S (not valid)	Comments
EC-Q14-1041	max drawdown, 8.05	-	7.02	4.78	205.30	144.73	2.20E-03	7.80	4.06	216.70	2.26E-08	Very good borehole, Porous aquifer, immediate recovery
EC-Q14-1107	max drawdown, 14.86	-	3.43	1.92	36.80	21.34	2.34E-05	3.46	1.80	21.50	1.87E-05	1 no-flow or parallel no-flow boundary reached, borehole not sustainable
EC-Q14-1247	20.30	-	2.80	1.49	13.14	11.24	3.80E-05	2.57	1.34	11.10	3.92E-05	Good fracture network, recharge boundary reached at late time, recovery slow
EC-Q14-1643	1.51	-	0.53	0.30	39.67	32.89	1.46E-05	0.40	0.21	26.50	1.98E-05	Multiple fractures dewatered, typical Low yielding fractured rock aquifer
EC-Q14-1644	-	-	-	-	-	-		-	-	-	-	Borehole not tested
EC-Q14-1645	P.I	-	-	-	-	-		-	-	-	-	Parallel no-flow boundaries reached, Borehole not sustainable
EC-Q14-1646	26.20	-	6.16	3.12	55.55	15.52	8.44E-04	6.89	3.58	18.30	3.74E-04	High Yielding Karoo fractured rock borehole, 1 no-flow boundary reached
EC-Q14-1647	max drawdown, 10.24	-	4.38	2.67	50.83	49.60	6.46E-06	4.12	2.14	42.30	7.61E-06	Highly fractured & weathered Karoo fractured rock aquifer, Immediate recovery, Excellent Borehole
EC-Q14-1649	-	-	-	-	-	-		-	-	-	-	Farmer refused to pump
EC-Q14-1651	max drawdown, 4.96	-	7.39	3.67	476.84	96.30	2.20E-03	5.60	2.91	63.90	2.15E-02	Porous aquifer - U no-flow boundary or closed system reached, incomplete recovery
	TOTAL		**42.03**	**23.36**				**42.72**	**22.21**			**Unsustainable BHs Not incl.**

7.3.2 New boreholes tested

From the total of 18 new boreholes drilled and 2 existing boreholes rehabilitated, only 10 boreholes where hydraulically tested. This is largely due to the year-long halt in the project and the changing of the scope of the project. Eight constant discharge tests were performed on boreholes newly drilled during the study. Only step tests were performed on the two rehabilitated boreholes. In summary; three 48 hour-; four 24 hour- and one short-lived 2.5 hour-constant discharge tests were performed. Table 7-5 provides the basic information for the new boreholes drilled and tested, Table 7-6 gives the important pumping test information while Table 7-7 and Table 7-8 display the calculated and estimated aquifer parameters from pumping test analysis for the new and rehabilitated boreholes.

Figure 7-3: Fickson from AB Pumps at riser pipe yielding 25 ℓ/s from EC-Q14-1655 during its constant discharge test

Table 7-5: Basic information of new boreholes aquifer tested in Middelburg

MIDDELBURG NEW BOREHOLES DRILLED & TESTED							
BASIC BOREHOLE INFORMATION							
SUB-CATCHMENT/ DRAINAGE	AREA/ FARM	ALLOCATED BOREHOLE NUMBER	ALTERNATIVE BOREHOLE NUMBER	BOREHOLE STATUS	COORDINATES (WGS84; dd)		Airlift yield (l/s)
					Latitude	Longitude	
					S°	E°	
Dunblane	Dunblane	**EC-Q14-1630**		New Borehole	-31.53032	25.06802	10.20
Dunblane	Dunblane	**EC-Q14-1631**		New Borehole	-31.53056	25.06852	>24.7
Middelburg Municipal	Grootfontein	**EC-Q14-1632**		New Borehole	-31.52057	25.06010	>16
Middelburg Municipal	Grootfontein	**EC-Q14-1633**		Monitoring Borehole	-31.50590	25.04889	4.00
Middelburg Municipal	Grootfontein	**EC-Q14-1634**		Monitoring Borehole	-31.43121	24.98600	10.00
Dunblane	Dunblane	**G31594**	G31594	Rehabilitated BH	-31.53831	25.07322	2.90
Dunblane	Rosmead	**EC-Q14-1635**		Monitoring Borehole	-31.48739	25.10955	0.10
The Glen	Grootfontein	**EC-Q14-1636**		New Borehole	-31.40934	25.00198	31.36
The Glen	Grootfontein	**EC-Q14-1637**		New Borehole	-31.42006	24.98976	10.00
Dunblane	Dunblane	**EC-Q14-1638**		New Borehole	-31.54539	25.07747	0.80
Dunblane	Dunblane	**EC-Q14-1639**		New Borehole	-31.55227	25.08233	1.30
Dunblane	Dunblane	**EC-Q14-1640**		New Borehole	-31.54533	25.07756	1.30
Lusernvlei	Redlands	**EC-Q14-1641**		New Borehole	-31.43910	25.30730	6.94
Lusernvlei	Alfalfa	**EC-Q11-166**	EC-Q14-1652	New Borehole	-31.43999	25.29330	12.10
Karmel	Waterkloof-Karmel	**EC-Q14-1653**		New Borehole	-31.48460	24.92575	12.10
Dunblane	Grootfontein	**EC-Q14-1654**		New Borehole	-31.50720	25.06023	14.80
The Glen	Grootfontein	**EC-Q14-1655**		New Borehole	-31.43127	24.98580	21.75
The Glen	Grootfontein	**EC-Q14-1656**		Water hammer supply/ monitoring	-31.40960	25.00199	10.17
Grootfontein	Grootfontein	**EC-Q14-1662**		New Borehole	-31.43534	25.00983	2.55
Grootfontein	Grootfontein	**EC-Q14-1668**	G31587 (Vandoolaeghe)	Existing/ Cleaned	-31.43521	25.00851	0.20
						Minimum	**0.10**
						Maximum	**31.36**
						Mean	**9.66**
						Total (Low yielding airlift yields Excluded)	**189.57**

Table 7-6: Pump testing information of the new boreholes tested during the Middelburg groundwater supply study

MIDDELBURG NEW BOREHOLES DRILLED & TESTED												
AQUIFER TESTING DATA & ANALYSIS												
ALLOCATED BOREHOLE NUMBER	Date tested	Static water level (mbgl)	Borehole depth (m)	Test Pump depth (mbgl)	Available Drawdown (m)	Nr of Steps	Constant Rate Test				Recovery Test	
							Rate (l/s)	Max drawdown (mbgl)	% of Available Drawdown	Duration (min)	%	Duration (min)
EC-Q14-1630	Not tested	-	-	-	-	-	-	-	-	-	-	-
EC-Q14-1631	29-Jan-2008	11.10	126.70	110.00	98.90	4	17.12	39.29	39.73	2880	90.00	540
EC-Q14-1632	8-Feb-2008	9.28	236.00	203.00	193.72	4	15.50	110.45	57.02	1500	90.81	20
EC-Q14-1633	4-Feb-2008	32.10	256.00	203.00	170.90	4	1.52	90.75	53.10	1440	63.00	1440
EC-Q14-1634	12-Feb-2008	10.37	298.00	200.00	189.63	3	11.03	151.07	79.67	150	93.07	360
	14-Feb-2008	10.37	298.00	200.00	189.63	0	8.26	30.89	16.29	2880	65.75	1560
G31594	31-Aug-2007	7.37	27.70	23.00	15.63	1	-	-	-	-	-	-
EC-Q14-1635	Not tested											
EC-Q14-1636	24-Apr-2010	18.05	271.00	100.00	81.95	5	12.68	55.41	67.61	1440	78.65	1020
EC-Q14-1637	5-May-2010	8.46	258	98	89.54	5	20.21	36.04	40.25	2880	90.01	360
EC-Q14-1638	Not tested											
EC-Q14-1639	Not tested											
EC-Q14-1640	Not tested											
EC-Q14-1641	Not tested											
EC-Q14-1652	Not tested											
EC-Q14-1653	Not tested											
EC-Q14-1654	Not tested											
EC-Q14-1655	26-Mar-2010	9.72	282.00	44.00	34.28	5	25.04	5.34	0.16	2880	90.82	150
EC-Q14-1662	5-Feb-2010	18.63	252.00	33.00	14.37	6 steps; P.I.S. = ~**11** l/s	Only steps conducted - need Slots	-	-	-	-	-
EC-Q14-1668	Not tested due to low airlift yield											

Table 7-7: Table 1 of 2 aquifer parameters determined for new boreholes aquifer tested in Middelburg

MIDDELBURG NEW BOREHOLES DRILLED & TESTED												
ALLOCATED BOREHOLE NUMBER	PUMPING TEST ANALYSIS (Duty cycle 24 hours)											
	Main Water Strike (m b Rest WL)	Observation BH (dist in m)	FC					Cooper-Jacob				
			Qsust (l/s)	Ave Q sust(l/s)	T early (m^2/d)	T late (m2/d)	Derivative S	Qsust (l/s)	Ave Q sust(l/s)	T late (m2/d)	S (not valid)	Comments
EC-Q14-1630	-	-	-	-	-	-		-	-	-	-	-
EC-Q14-1631	68.00	-	6.56	3.15	35.11	7.23	8.57E-04	9.36	4.86	12.90	2.75E-04	High Yielding Fractured Karoo rock aquifer, 1 no-flow boundary reached, use Cooper-Jacob(CJ)
EC-Q14-1632	110.00	-	5.78	2.93	11.88	3.78	1.28E-04	7.59	3.95	5.70	2.05E-05	Multiple fractures dewatered, good high yielding fractured rock aquifer, use CJ
EC-Q14-1633	88.00	-	0.90	0.55	1.09	1.18	1.00E-06	0.82	0.42	1.10	9.64E-08	Outer boundary reached, recovery incomplete, borehole not sustainable
EC-Q14-1634	-	-	-	-	-	-		-	-	-	-	CD rate too high, Test to be redone at later stage
	32.36		5.86	3.93	23.02	26.77	1.05E-05	6.31	3.28	34.90	3.06E-09	parallel or U no-flow boundaries reached at depth, very slow recovery of borehole
G31594	-		-	-	-	-		-	-	-	-	Only 3 min step, low yielding
EC-Q14-1635	-	-	-	-	-	-		-	-	-	-	-
EC-Q14-1636	55.41(max drawdown)	EC-Q14-1656	4.21	2.08	17.91	5.15	2.20E-03	4.49	2.33	5.70	2.25E-03	parallel or U no-flow boundaries reached at depth, very slow recovery of borehole.

Table 7-8: Table 2 of 2 aquifer parameters determined for new boreholes aquifer tested in Middelburg

ALLOCATED BOREHOLE NUMBER	PUMPING TEST ANALYSIS (Duty cycle 24 hours)											
	Main Water Strike (m b Rest WL)	Observation BH (dist in m)	FC					Cooper-Jacob				
			Qsust (l/s)	Ave Q sust(l/s)	T early (m^2/d)	T late (m2/d)	Derivative S	Qsust (l/s)	Ave Q sust(l/s)	T late (m2/d)	S (not valid)	Comments
EC-Q14-1637	36.0 (max drawdown)		11.17	6.48	42.26	28.19	1.05E-04	11.02	5.73	27.3	5.59E-05	Good borehole, good recovery of 90% of SWL, dewatering of top 2 m of water level. Recommended 5.5 - 7.5 l/s - Conservative
EC-Q14-1638	-	-	-	-	-	-		-	-	-	-	-
EC-Q14-1639	-	-	-	-	-	-		-	-	-	-	-
EC-Q14-1640	-	-	-	-	-	-		-	-	-	-	-
EC-Q14-1641	-	-	-	-	-	-		-	-	-	-	-
EC-Q14-1652	-	-	-	-	-	-		-	-	-	-	-
EC-Q14-1653	-	-	-	-	-	-		-	-	-	-	-
EC-Q14-1654	-	-	-	-	-	-		-	-	-	-	-
EC-Q14-1655	30 (max drawdown for analysis = 5.34)	135m; 2.4 km EC-Q14-1637	15.33	9.56	382.50	321.20	5.87E-05	15.52	8.07	310.40	1.01E-2	Borehole influenced by recharge boundary. Composite alluvial and highly fractured aquifer. Only 5m AD used for analysis. Conservative
EC-Q14-1662												Perforation of casing required before Constant Discharge Test can be performed
EC-Q14-1668	Not tested due to low airlift yield											
TOTAL			**38.84**	**22.12**				**26.54**	**13.80**			**Unsustainable Boreholes Excl.**

7.3.2.1 Selected new boreholes pumping test analysis

EC-Q14-1631

EC-Q14-1631 was drilled into the Dunblane dyke and entered the dolerite at 20 mbgl. The borehole could only be drilled up to a 127 mbgl due to water pressure and never exited the almost 90 degree vertical dyke. The highest yielding water strikes (7.65 ℓ/s at 34 mbgl; 8.2 ℓ/s at 117 mbgl) were also found in calcified fractures or joints in the dyke itself. The static water level was at 11.10 mbgl. From the constant discharge test conducted on EC-Q14-1631 it is evident that multiple fractures were dewatered during the test (Figure 7-4). The drawdown curve shows clear linear fracture flow at early times during the test (20 – 180 min.) where after a single no-flow boundary (Dunblane dyke) is reached (see Figure 7-4). It is also after the single no-flow boundary is reached that pseudo radial flow is observed, even though it is possible that no outer boundary was reached and that it is only the radial acting flow that is creating the linear behaviour in the drawdown curve. There are however clearly visible fractures dewatered during the pseudo radial flow period and the fact that the drawdown curve returns to the exact slope and trend of the previous linear segment of pseudo radial flow after fracture dewatering supports the hypothesis of a single no-flow boundary reached. The Cooper-Jacob straight line solution was fitted to the EC-Q14-1631 drawdown curve on the pseudo radial flow section as shown in Figure 7-4. The borehole water level showed virtually complete (98%) recovery within 67% of the pumping time (2880 minutes) indicating sustainability of the borehole.

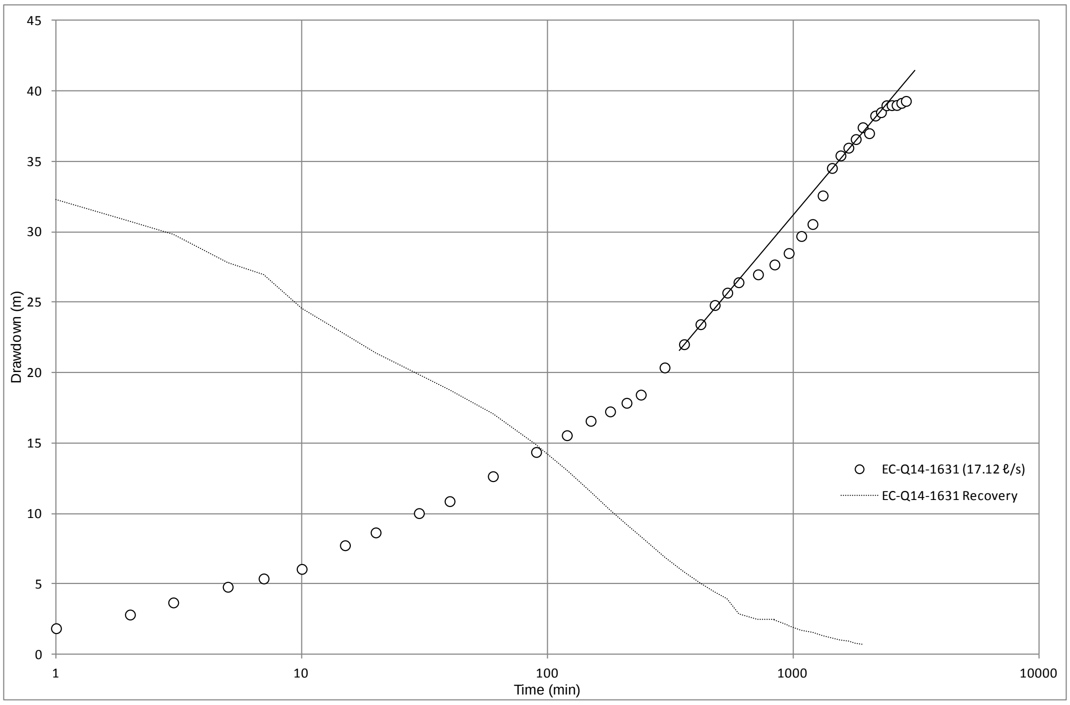


Figure 7-4: EC-Q14-1631 CD test and recovery, line fitted on 1 no-flow boundary

EC-Q14-1636

The EC-Q14-1636 aquifer test from all the aquifer tests conducted presents a unique example of a very high yielding borehole, but with a limited catchment area for recharge to the aquifer or a closed reservoir system (see Figure 7-5 to Figure 7-7).

From the observations of the EC-Q14-1636 pumping test it is probably a case of a limited catchment area rather than a closed reservoir system and it is thought that no outer boundary was reached. This hypothesis is substantiated by the diagnostic plots and drawdown behaviour during the constant discharge test. On the linear-log plot at early time (< 90 min) there is linear fracture flow that later (after 90 min.) doubles in slope to a precisely linear drawdown and one can perhaps deduce that 1 no-flow boundary was reached, namely the dolerite dyke adjacent to EC-Q14-1636. From the log-log plot the water level drawdown however shows a curve very much like that of the pumped borehole in a single plane, vertical fracture- or the confined aquifer-theoretical model as illustrated in Kruseman and de Ridder (2000). There is also no evidence of 2 parallel no-flow boundaries or closed system reached from the log-log plot of the CD test at late time (Van Tonder *et al.*, 2001). The recovery after the constant discharge test is however very slow considering the water level was never drawn down below the main fracture water strike (22 ℓ/s at 122 mbgl) and it is presumed that the aquifer above this main water strike was dewatered to some extent. There is recovery of the water level, even though it is slow so that 79% recovery was reached after 1020 minutes compared to the pumping time of 1440 minutes. This recovery although slow, rules out a closed reservoir system as initially thought, but rather suggests a no-flow boundary somewhere in the system. It is however concluded that the recovery rather shows that the aquifer has been dewatered to a large extent, but there is some groundwater left in some distant parts of the system and a no outer boundary was reached.

EC-Q14-1637 situated 1662 m away and downstream of EC-Q14-1636 was used as an observation borehole during the pumping test of EC-Q14-1636 and showed significant drawdown during the EC-Q14-1636 pumping test. This proves that there is a definite hydraulic connection between the two boreholes and the two boreholes probably share parts of the same fracture network forming an aquifer. EC-Q14-1637 however showed almost no recovery (68 cm in 1440 min.) and it is clear that the upstream aquifer of the ring structure in the vicinity of EC-Q1636 forms and integral part of the aquifer that recharges EC-Q14-1637.

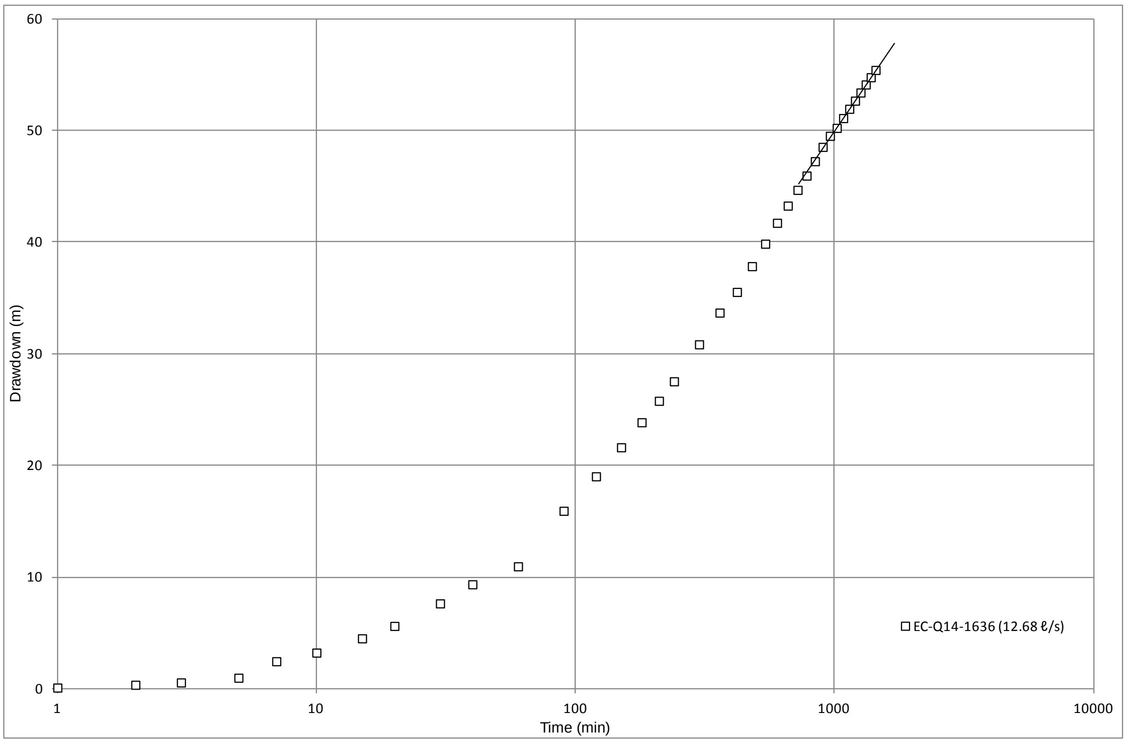


Figure 7-5: Linear-log graph of constant discharge test for EC-Q14-1636 with fitted line at pseudo radial flow

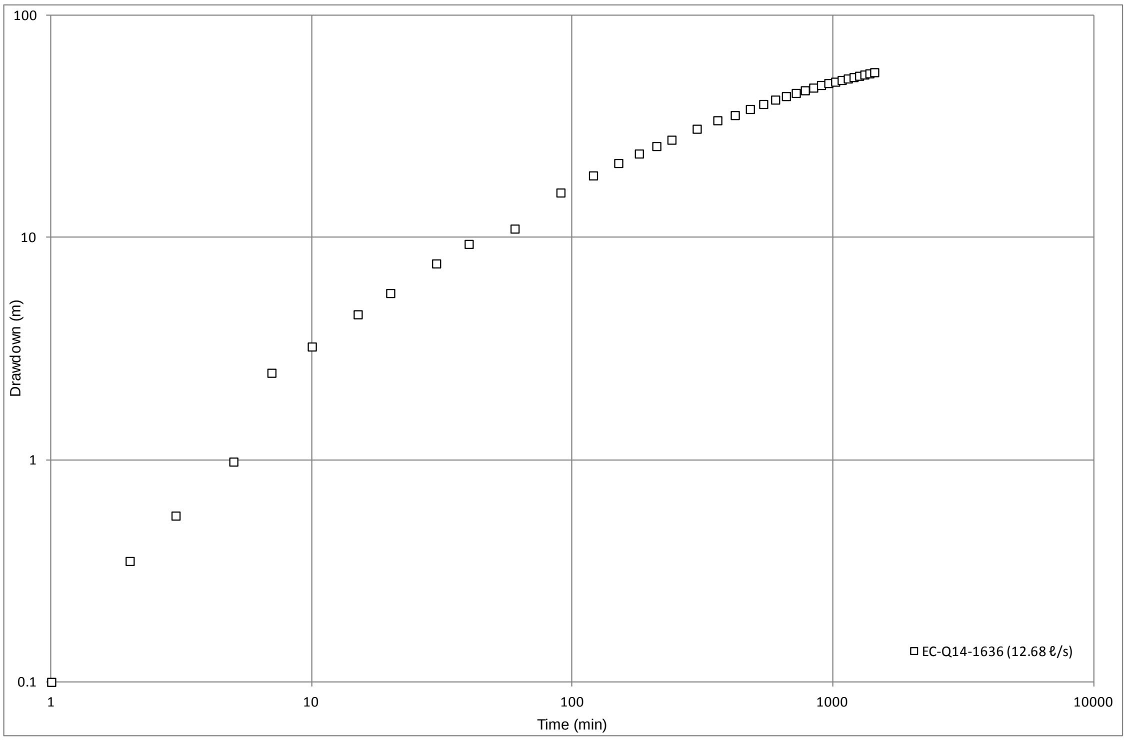


Figure 7-6: Log-log graph of EC-Q14-1636 constant discharge test

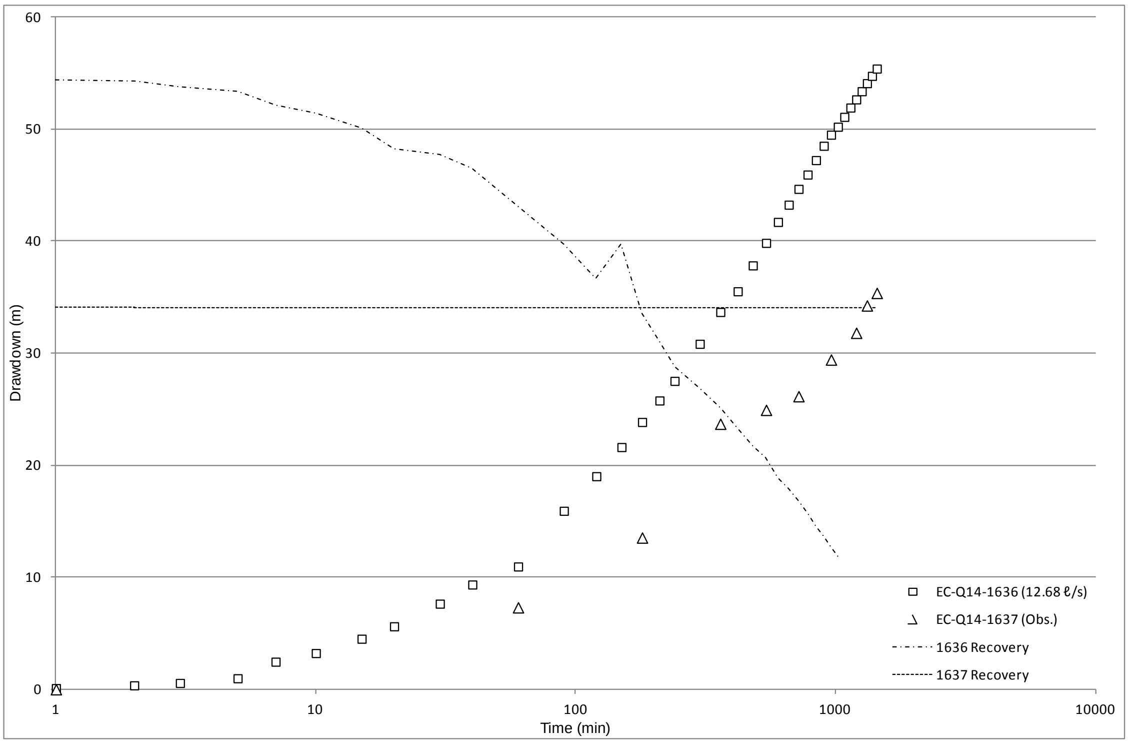


Figure 7-7: Graph showing drawdown and poor recovery in EC-Q14-1636; observation borehole EC-Q14-1637 response during testing of EC-Q14-1636

<u>EC-Q14-1655</u>

EC-Q14-1655 is, based on the constant discharge test and recovery, a main production borehole (Figure 7-8). The constant discharge test was performed at 25 ℓ/s and this yield was also the maximum yield that could be sustained by the largest pump the aquifer testing contractor had available at the time on site. The borehole showed only 5.34 m drawdown after 2880 minutes and the water level recovered 90% within 120 minutes after pumping was stopped.

The largest water strikes were intercepted in the fractured sandstone below the unconfined porous aquifer as well as in the deeper dolerite ring structure and deeper sandstone. Two smaller water strikes were also intercepted in the alluvium, but these were to some extent cased off during ODEX drilling. The large seemingly sustainable yield intercepted by EC-Q14-1655 in this multi-layered aquifer is thought to be supported by a recharge boundary approximately 40 m away that is the main non-perennial drainage of The Glen ring structure exiting through Jones Poort. Also, Jones Poort where EC-Q14-1655 is situated is topographically the lowest point of The Glen ring structure and it is thought that most groundwater would also move through this “poort”/narrow valley into the Grootfontein sub-catchment.

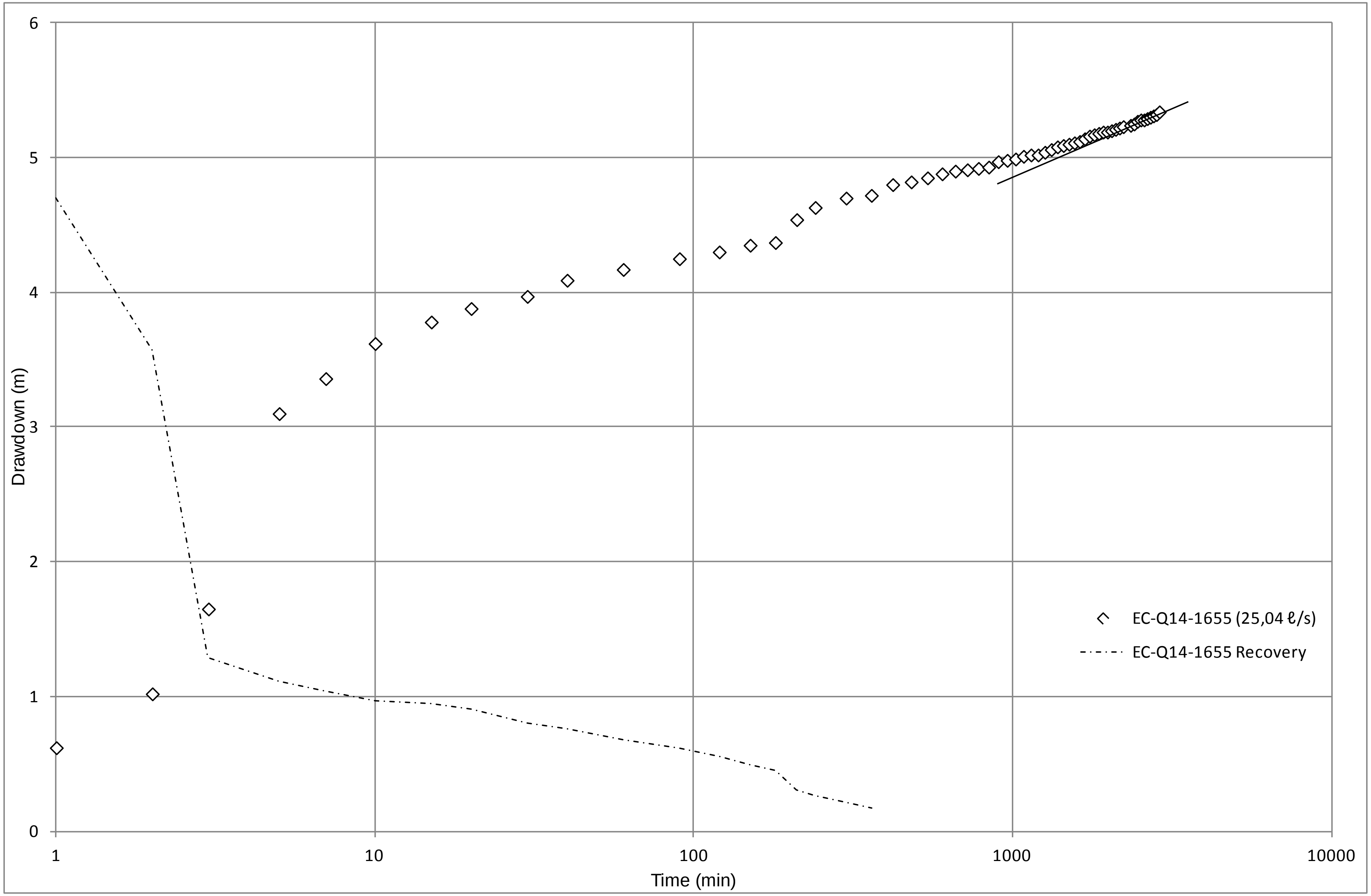


Figure 7-8: Linear-log graph of EC-Q14-1655 constant discharge test at 25 ℓ/s and recovery

7.3.3 Aquifer mechanics and aquifer types

The system of interconnected aquifers and aquitards found in the Middelburg study area are in unity not such a clear cut aquifer type as for example an unconfined or confined aquifer. The type of aquifer found in literature that is most likened to the complete aquifer system penetrated by deeper boreholes drilled during the study, is a leaky aquifer or a multi-layered leaky aquifer system. The individual aquifers that make up this interconnected multi-layered aquifer can however be described.

7.3.3.1 Unconfined porous alluvial aquifer

The unconsolidated sediments or superficial deposits have been described to some extent in the Literature Study Chapter. These alluvial deposits form a major aquifer type in the Middelburg study area and it is these aquifers that are currently the sole source of water supply to Middelburg and surrounding farmers. They are unconfined and can be up to 25 m in thickness (Vandoolaeghe, 1979). The unconfined aquifer primarily consists from top to bottom of:

- An unconsolidated argillaceous sequence of silty or clayey material (1 – 7 m thickness);
- An unconsolidated arenaceous sequence of fine to medium grained sand (3 – 6 m in thickness);
- A sequence of gravels and coarse sand with pebbles (4 – 8 m in thickness);
- In some instances boulder alluvium presumably found in deeper parts of paleo channels (1 – 3 m thickness);
- A very weathered or weathered/ jointed zone of argillaceous or arenaceous Beaufort Group rocks.

The alluvial deposits are relatively widely distributed in the Middelburg study area and have a high transmissivity (T) depending on the aquifer thickness (b), hence dependent on the water table. Thicker alluvial sediments however only occur in isolated old valley areas. Although Vandoolaeghe (1979) conducted an extensive investigation on the Groot Brak River Catchment of Middelburg, his aquifer parameter values were found to be much larger and higher (T up to 1800 m^2/d) than those calculated from results during this investigation. During another AGES groundwater resource evaluation at Rosmead, a very small little railway town approximately 10 km east of Middelburg, the alluvial aquifer was evaluated to have a transmissivity in the order of 138 – 226 m^2/d and a storativity value in the order of 1E-3. The conclusion reached solely based on T- and S-value comparison is that there has definitely been a decline in the water level from 1979 to present. Due to long time use of these aquifers the water table has been drawn down significantly and the result is much lower yielding shallow alluvial aquifer boreholes. Based on the aquifer testing results these aquifers however have a characteristically quick water level recovery after pumping is stopped and are ideal in terms of this aspect. The quick water level recovery also means that these aquifers present excellent opportunities for water level monitoring and aquifer management. The unconfined alluvial aquifers could thus be sustainably managed if other aquifers are also used in conjunction to supply in the full potable water needs of the Middelburg and the water level in the unconfined aquifer is high enough.

7.3.3.2 Semi-confined fractured rock aquifer

Directly below the alluvial aquifer is a very weathered or slightly weathered and jointed fractured rock aquifer consisting of argillaceous or arenaceous Beaufort Group sedimentary rocks. In some cases where there is no alluvium, but there is a dolerite intrusion, this aquifer forms the primary aquifer where it is generally vertically or horizontally fractured in the vicinity of the dolerite intrusion. In areas where there are no dolerite intrusions or alluvium, the Beaufort Group formations would in general not be as weathered or fractured at approximately 25 mbgl and in these cases act as aquicludes or aquitards.

In the vicinity of dolerite intrusions as shown in the camera log of EC-Q14-1655, the semi confined fractured rock aquifers can be extensively fractured up to depths of 50 mbgl. This kind of fracturing presents a very good aquifer almost comparable with the porous aquifer, but more sustainable due to their greater depth. Bedding plane fractures are the dominant type of fractures present, but it is presumed that vertical fractures are also widely distributed. In this case the dual porosity type aquifer and flow behaviour is dominant. These are the aquifers that are referred to as Karoo fractured-rock aquifers in South African literature. Karoo fractured rock aquifers are also associated with dolerite intrusions.

7.3.3.3 Dolerite associated fractured rock aquifer

Aquifers associated with dolerite intrusions are considered the other major type of aquifer found in the Middelburg study area. Large dolerite intrusion structures were also chosen to be targeted at depth as the primary groundwater targets during this study. The specific types of fracturing that form at contact zones and within different dolerite intrusions have been described in detail in Chapter 2’s Literature Study and will not be discussed in detail again. The general aquifer zones created by fracturing associated dolerite intrusions will however be discussed. There are generally 3 types of fracture zones that create aquifers associated with dolerite intrusions.

(1) Contact zone fracturing. This kind of fracturing and aquifer zones it creates at dolerite/ country rock contacts is well known and well studied. These zones are especially prominent as vertical aquifer zones at dolerite dyke and country rock contacts. They are less known or studied at dolerite inclined sheet contacts or feeder dyke contacts, but also form at these interfaces and are equally important (EC-Q14-1636). These vertical contact zones of fracturing often form the vertical conduits for groundwater flow between the upper unconfined aquifer and the lower semi-confined or confined aquifer in the deeper formations of bedding plane-fractured Beaufort Group rocks. Horizontal fracturing found on the contact where a dolerite sill intrudes a bedding plane fracture in the country rock also occurs, but seems to be less prominent or rewarding or is less studied than dyke contact zone fracturing and weathering.

(2) Fracturing within the country rock in the vicinity of dolerite intrusions due to the tectonic stresses imposed during magma intrusion and cooling. Bedding plane fractures up to 176 mbgl were found in the Beaufort Group sedimentary rocks in the vicinity of the dolerite intrusion (EC-Q14-1655). Fractures at around 90mbgl were also clearly visible in the camera log of EC-Q14-1655. A Transgressive fracture can also develop in the vicinity of a dyke, where the fracture transgresses the dyke and extends for tens of metres into the country rock adjacent to the intrusion. Vandoolaeghe (1979) made an observation of such a transgressive fracture associated with the Dunblane dyke extending 90 m away from the dyke into the country rock.

(3) Fracturing within the dolerite intrusion itself as well as the aquifer created by substantial weathering of the intrusion, in some cases the totally decomposed nature of dolerite intrusions especially in thin dykes and valley bottom situations. Fracturing within the dolerite itself was encountered in boreholes EC-Q14-1631, EC-Q14-1632 (Dunblane dyke), EC-Q14-1636 (dyke cutting through inclined sheet), EC-Q14-1637 (weathered minor sill) and EC-Q14-1655 (“poort” at inclined sheet and inner sill) etc.

Good to medium yield groundwater sources can be found associated with dolerite intrusions and the accompanying fracturing they present, both in the host rock and the dolerite itself. The recharge of the aquifer is however dependant on the bilinear flow of groundwater from the host rock to the fractures when abstracted. This recharge or recovery process is slower than that of an alluvial aquifer. The host rock such as sandstone in the area does however represent a good reservoir of groundwater although it often does not reach a 100% recovery until the next good precipitation and recharge event. The dolerite intrusions often cause large fracturing and medium to high sustainable yields can be expected.

In some instances, an ideal aquifer is created when a dolerite intrusion which has caused significant fracturing in the host rock is covered by alluvium and the alluvium gives quick recharge and recovery to the fracture network when abstracted from.

7.3.3.4 Beaufort Group sedimentary formations

Low to medium groundwater yields can be expected from successful boreholes in the un-intruded sedimentary formations of the Beaufort sedimentary formations encountered in Middelburg. Successful boreholes must however intercept a bedding plane fracture or vertical fracture to yield an economically viable volume of water. Unfractured Beaufort Group sedimentary rocks such as those found away from dolerite intrusions can be regarded as aquitards or in some cases aquicludes. The yields of successful boreholes are normally sufficient for the lifelong sustainability of wind pumps and associated yield volumes of 0.1 – 0.3 ℓ/s.

7.4 Packer isolated water quality testing

Packer isolated water quality testing was also performed on borehole EC-Q14-1632 and EC-Q14-1655. The goal of the packer testing was not to determine the aquifer parameters of certain sections or fractures of each borehole, but to obtain the specific water quality associated with the deeper aquifer and fractures. Results of the water qualities obtained from the packer isolated tests are discussed in the Groundwater Chemistry, Chapter 9.

7.5 Conclusions

- EC-Q14-1636 had the largest airlift yield and fracture of all the boreholes, but when the pumping test was performed it was seen that EC-Q14-1636 was drilled into a U no-flow reservoir or closed reservoir. After pumping test analysis it was observed that there is some recovery, although it was slow, thus ruling out a closed reservoir system. The relatively higher elevation of EC-Q14-1636 means that although it has the largest fractures with the highest transmissivity due to the dyke cutting through the dolerite ring structure, the catchment area of the aquifer is limited and recharge to the aquifer would be slow. It was in conclusion hypothesised that based on the pumping test analysis the cone of depression did not reach a no-flow boundary, but the slow recovery was due to almost complete dewatering of the limited catchment aquifer and recharge to the aquifer occurred from distant small parts of the aquifer that still had some water.

- EC-Q14-1637 showed significant drawdown during the pumping test at EC-Q14-1636. Both boreholes are situated within The Glen ring structure and EC-Q14-1636 is situated at a higher elevation on the border inside of the inclined sheet and dyke cutting through it. It must then be concluded that based on the drawdown and poor recovery of EC-Q14-1637, the two boreholes share a common groundwater reservoir and fracture network based on the distance between the boreholes. EC-Q14-1636 cannot yield large volumes for a long time, but it will be evaluated for long term sustainability at lower yields using its monitoring borehole. The aquifer test performed at EC-Q14-1637 later in 2010, showed that this borehole can be sustainable and also has a quick recovery. EC-Q14-1636 should then only be used in emergencies to quickly supply a large volume to the reticulation system while EC-Q14-1637 can be used as a production borehole.

8 NEW MIDDELBURG GROUNDWATER MONITORING NETWORK

After observing the absence of reliable continuous groundwater monitoring data regionally around Middelburg, a new network of groundwater monitoring boreholes was developed by the consulting firm tasked with the groundwater exploration investigation. The monitoring borehole network was developed by selecting hydrogeologically representative existing boreholes as well as new exploration boreholes drilled, that were not selected for water supply purposes. New and existing boreholes were selected to monitor groundwater level fluctuations in both the shallow and the deeper fractured rock aquifer. A total of 14 boreholes were selected and implemented for the groundwater monitoring network.

Boreholes were selected to be representative of each sub-catchment under investigation. The new monitoring borehole network is shown in Figure 8-2.

Figure 8-1: Installation of groundwater monitoring equipment by Mr. R. Haasbroek

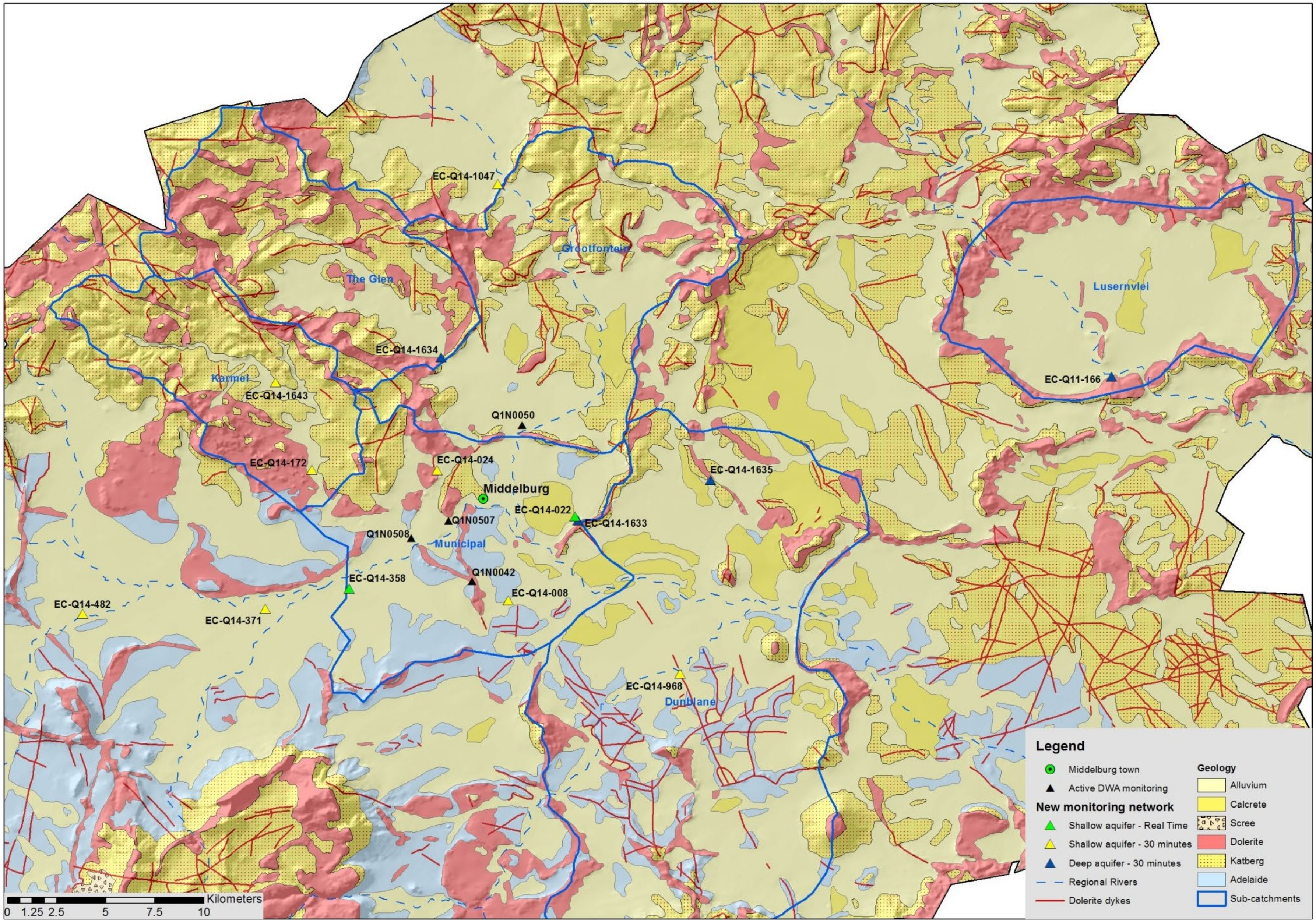


Figure 8-2: Map of new groundwater monitoring borehole network

Table 8-1: New monitoring borehole network summary table

Count	Site ID	Catchment	Farm	Depth (m)	Monitoring Type	Cable Length (m)	Logger type (M5, M10, M30, M60)	Water Level (mbgl)
1	EC-Q14-482	Outside -18.5 km WSW of Middelburg - Q14A	Grootvlei	32	Shallow aquifer - 30 minutes	30	M30	6.60
2	EC-Q14-371	Outside - 11.1 km WSW of Middelburg	Rusoord	56	Shallow aquifer - 30 minutes	10	M10	6.20
3	EC-Q14-008	Middelburg Municipal	Municipality - Vliegveld	34	Shallow aquifer - 30 minutes	10	M10	4.62
4	EC-Q14-024	Middelburg Municipal	Municipality - Uitsig	36	Shallow aquifer - 30 minutes	30	M30	15.09
5	EC-Q14-1634	The Glen	Grootfontein AC - Jones Poort	298	Deep aquifer - 30 minutes	30	M30	6.25
6	EC-Q14-1633	Middelburg Municipal	Grootfontein AC - Rooirandjies	256	Deep aquifer - 30 minutes	60	M30	30.62
7	EC-Q14-172	Karmel	Karmel	38	Shallow aquifer - 30 minutes	30	M30	10.20
8	EC-Q14-1635	Dunblane	Rosmead	120	Deep aquifer - 30 minutes	30	M30	11.45
9	EC-Q11-166	Lusernvlei	Alfalfa	194	Deep aquifer - 30 minutes	30	M30	5.81
10	EC-Q14-968	Dunblane	Greyville	65.66	Shallow aquifer - 30 minutes	30	M30	7.83
11	EC-Q14-1643	Karmel	Ravensbourne	15	Shallow aquifer - 30 minutes	10	M10	6.22
12	EC-Q14-1047	Outside - 15.5 km North of Middelburg	Sherbourne	26.5	Shallow aquifer - 30 minutes	30	M30	5.98
13	EC-Q14-358	Middelburg Municipal	Rusoord	70	Shallow aquifer - Real Time		Siemens	6.32
14	EC-Q14-022	Middelburg Municipal	Municipality - Dunblane	51	Shallow aquifer - Real Time		Siemens	16.23
15	EC-Q14-1597	The Glen	The Glen	9	Not installed - borehole not rehabilitated -possible future monitoring.	-	-	-

8.1 Methodology

Construction of protected borehole caps and concrete collars as well as setting up and installation of Solinst leveloggers in each monitoring borehole was performed during December 2008.

Twelve continuously recording manually downloadable leveloggers were installed in shallow and deep boreholes with two real time battery operated loggers installed in existing shallow aquifer boreholes to monitor the Middelburg Municipal aquifer groundwater level fluctuations.

Details of the each monitoring borehole and leveloggers settings are summarized in Table 8-1.

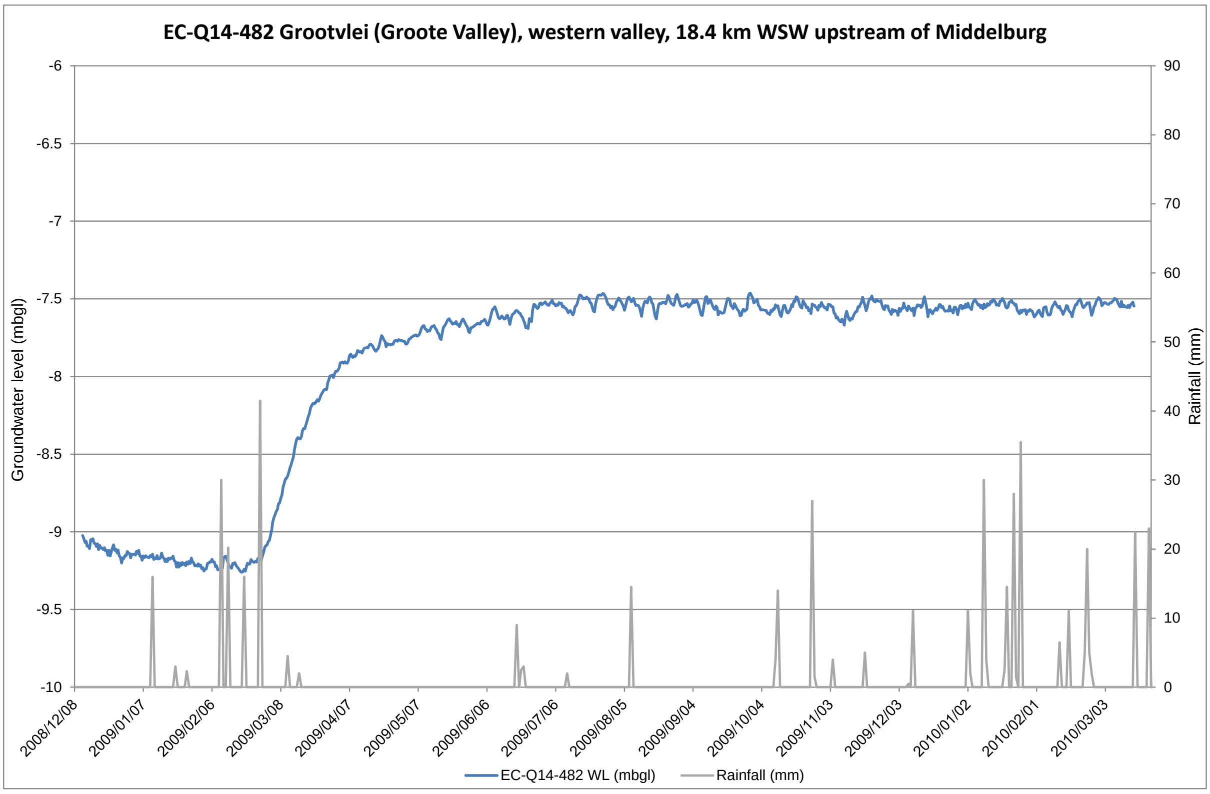
8.2 Results

8.2.1 Monitoring period December 2008 to March 2010

The groundwater level fluctuations are shown for each borehole in Figure 8-3 to Figure 8-9. The duration (± 1 year and 4 months) of groundwater level monitoring from the new production boreholes is too short to conclusively elaborate on aquifer status, but in general groundwater level declines seem to be less than expected.

From most of the graphs for the period December 2008 to March 2010 there is rise in groundwater level. This is expected to also be a result of above average rainfall years 2004, 2006, 2007, 2010, 2011 and 2012. A five year drought occurred between 1999 and 2004, with each of these years having below average rainfall. There is a ±1.5 m rise in EC-Q14-482 groundwater level in the far western valley that directly supplies groundwater to the Middelburg Municipal sub-catchment. The western valley in EC-Q14-482 looks largely unaffected by the Municipal abstraction in the Middelburg Municipal sub-catchment. It is however important that the western valley be protected from extensive further development as has been mentioned by Gordon-Welsh (1964) and Seward (1987), since it is the direct supplier of groundwater to the Middelburg Municipal sub-catchment.

It is also possible that the groundwater supplied (from the western valley) to other municipal boreholes has been cut-off to some extent, by the increasing abstraction from the Zonnebloem boreholes (see Figure 3-3), located next to the Klein-Brak River and in its palaeo channel alluvial deposits. This possibility must still be investigated. New monitoring borehole EC-Q14-968 for the Dunblane sub-catchment also looks to be representative of the abstraction taking place upstream on the western side of the Dunblane dyke.



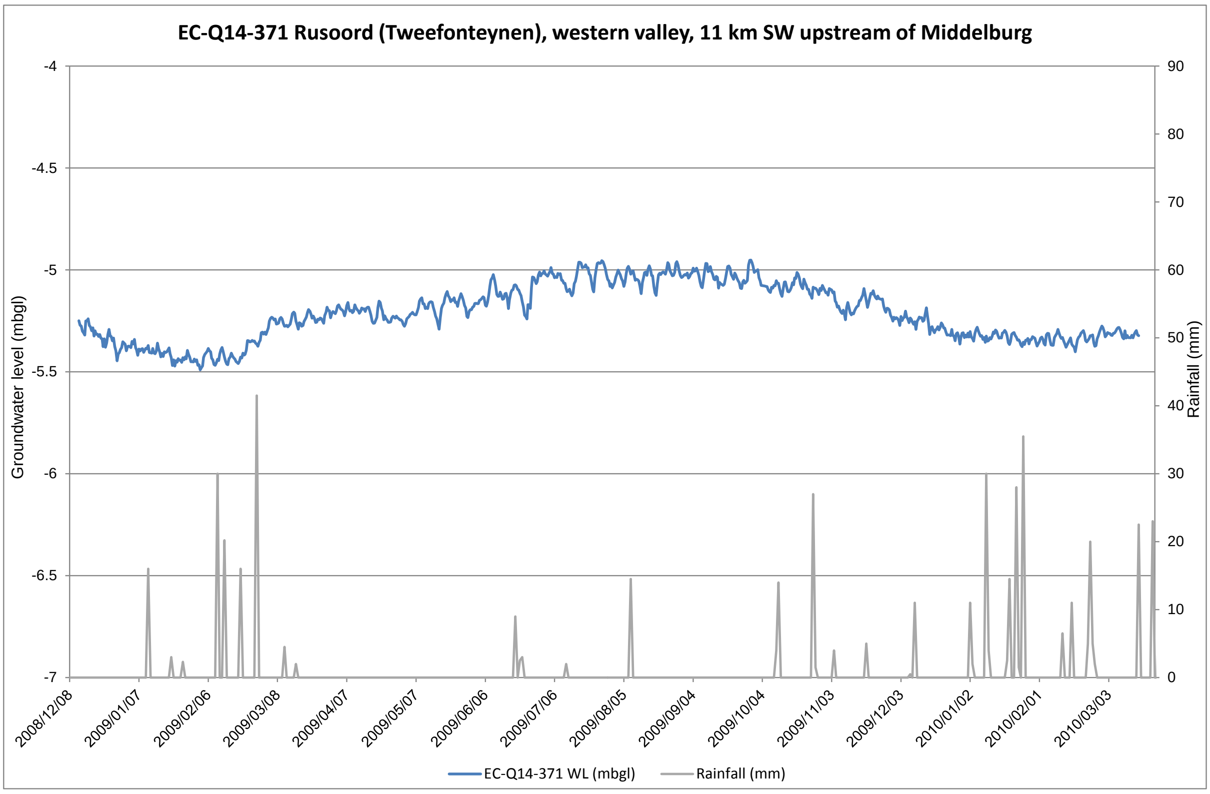
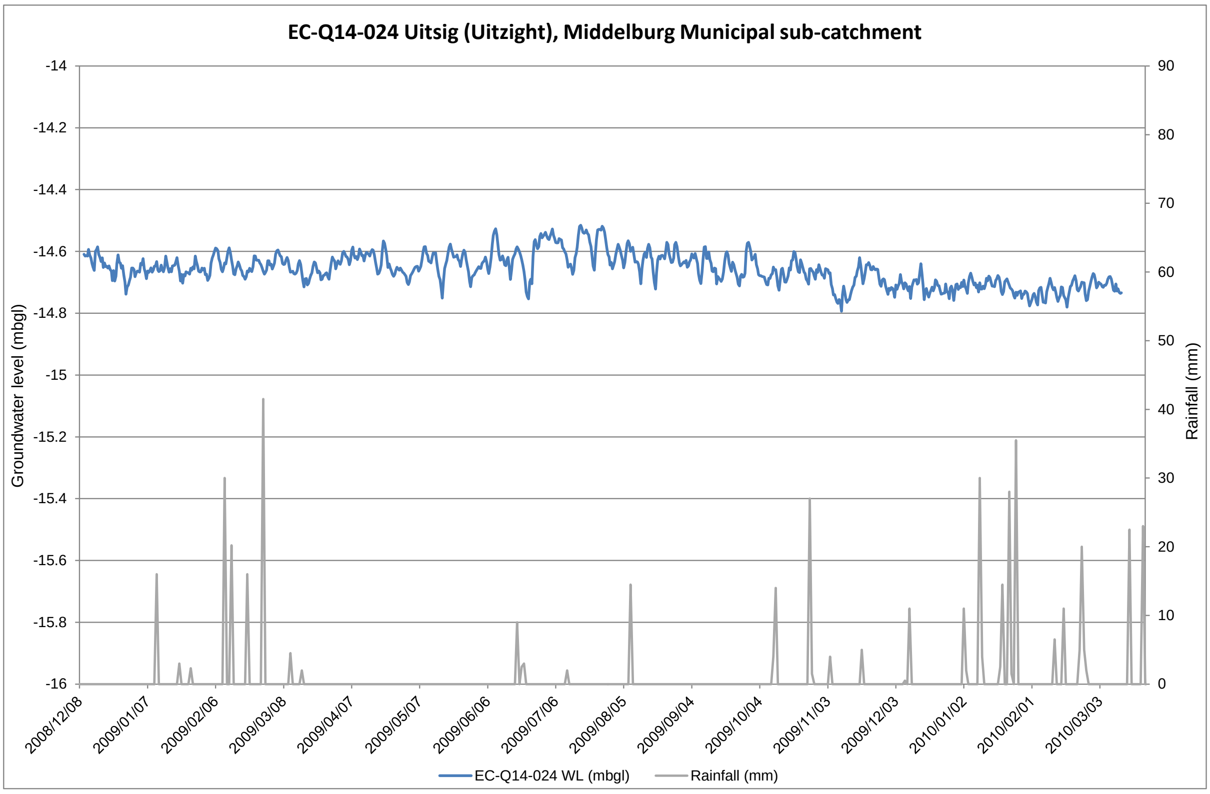


Figure 8-3: EC-Q14-482 and EC-Q14-371 monitoring boreholes in the western valley aquifer



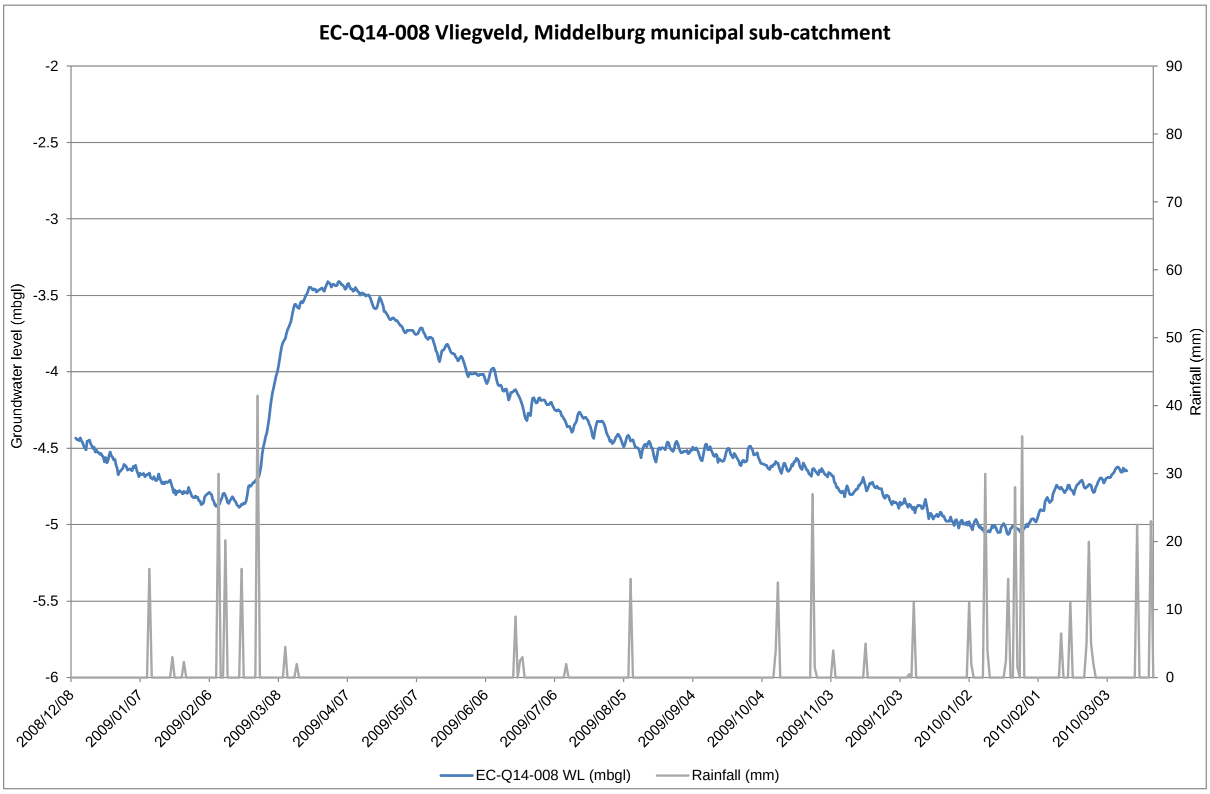


Figure 8-4: Municipal sub-catchment groundwater level fluctuation, new monitoring holes

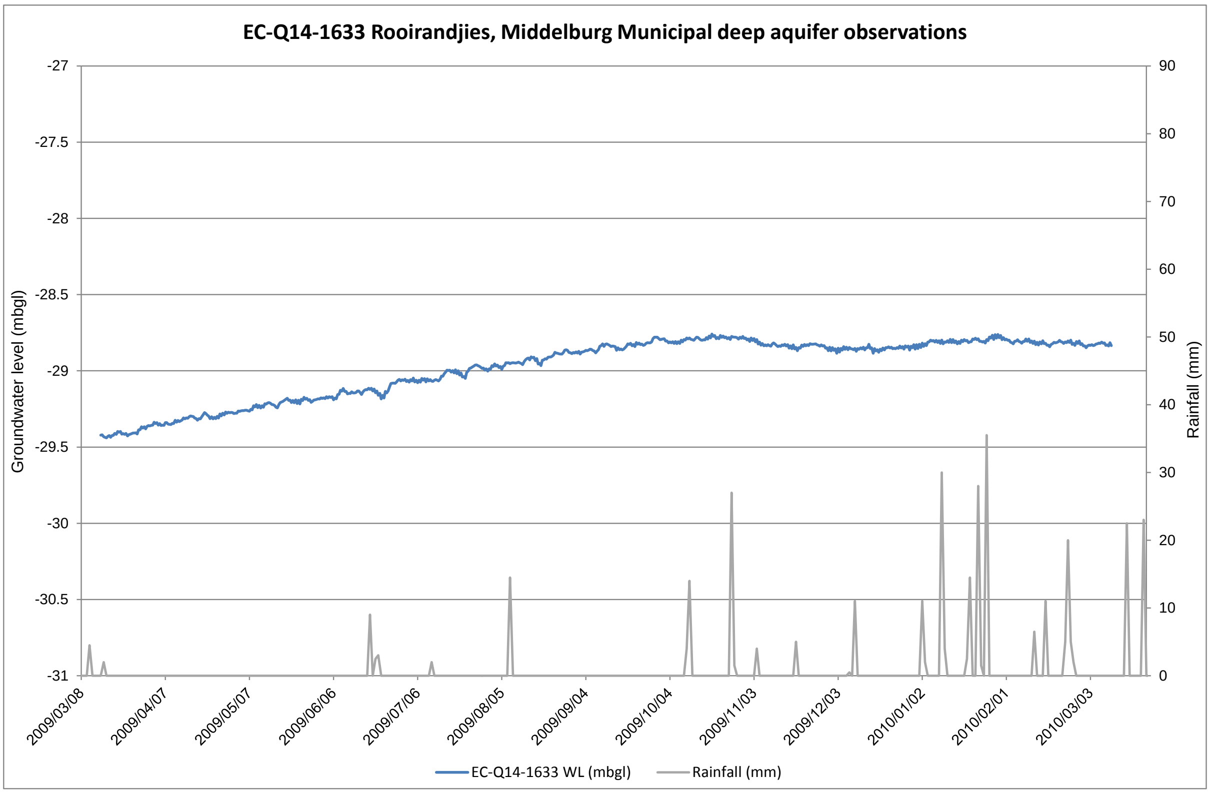
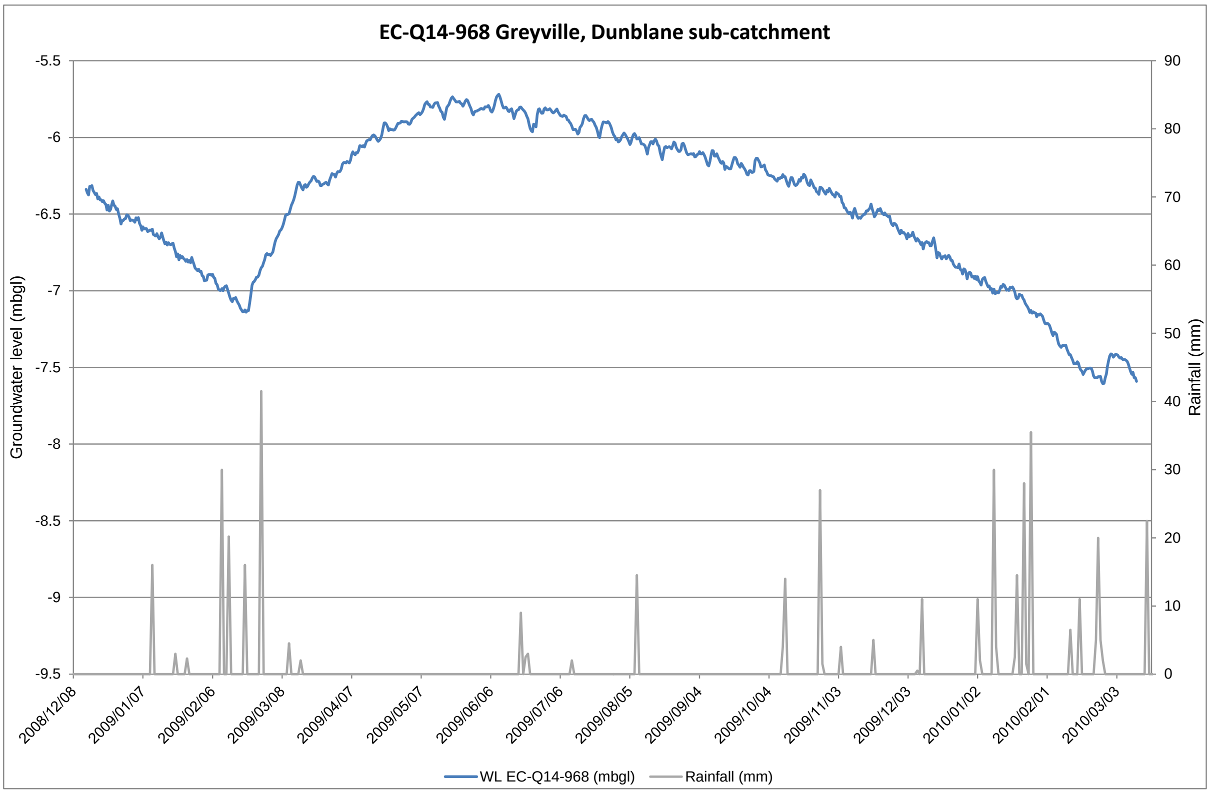


Figure 8-5: Middelburg Municipal deep aquifer monitoring from new exploration borehole



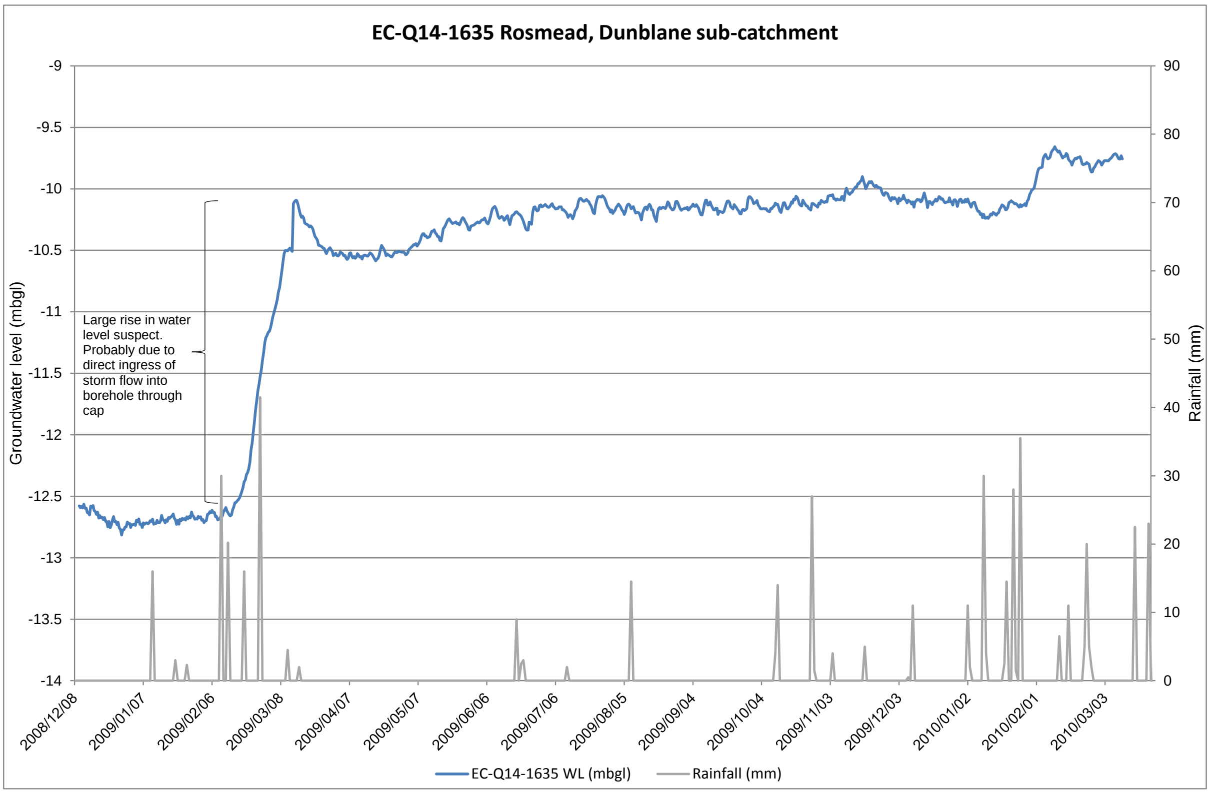
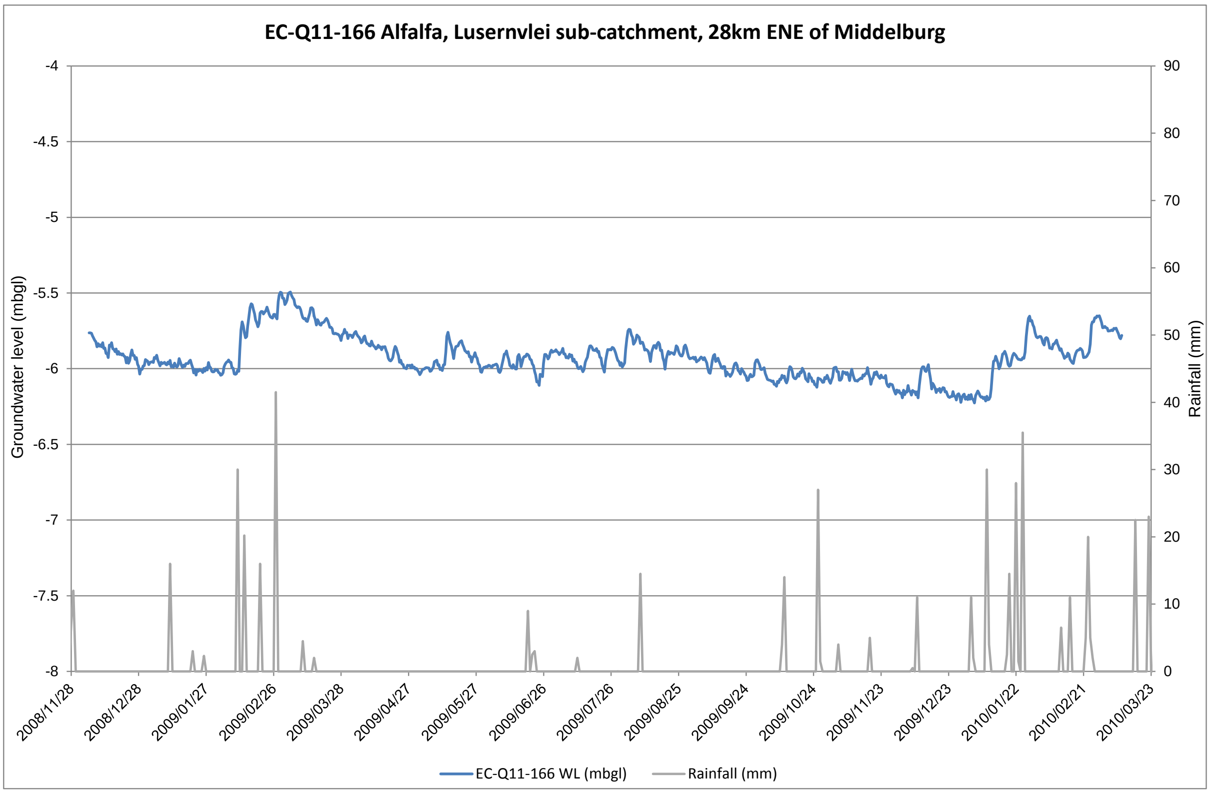


Figure 8-6: Dunblane sub-catchment new groundwater monitoring borehole responses



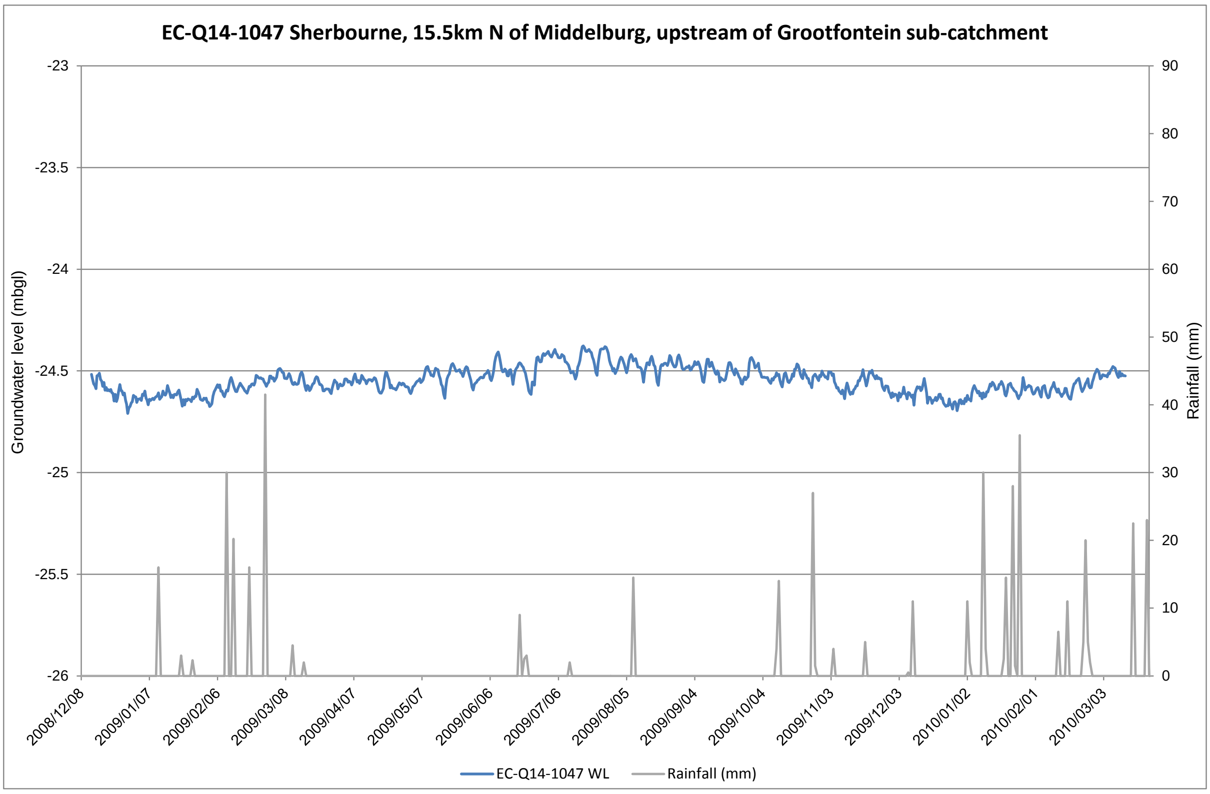


Figure 8-7: More distant monitoring boreholes EC-Q14-172 and EC-Q14-1047 fluctuations

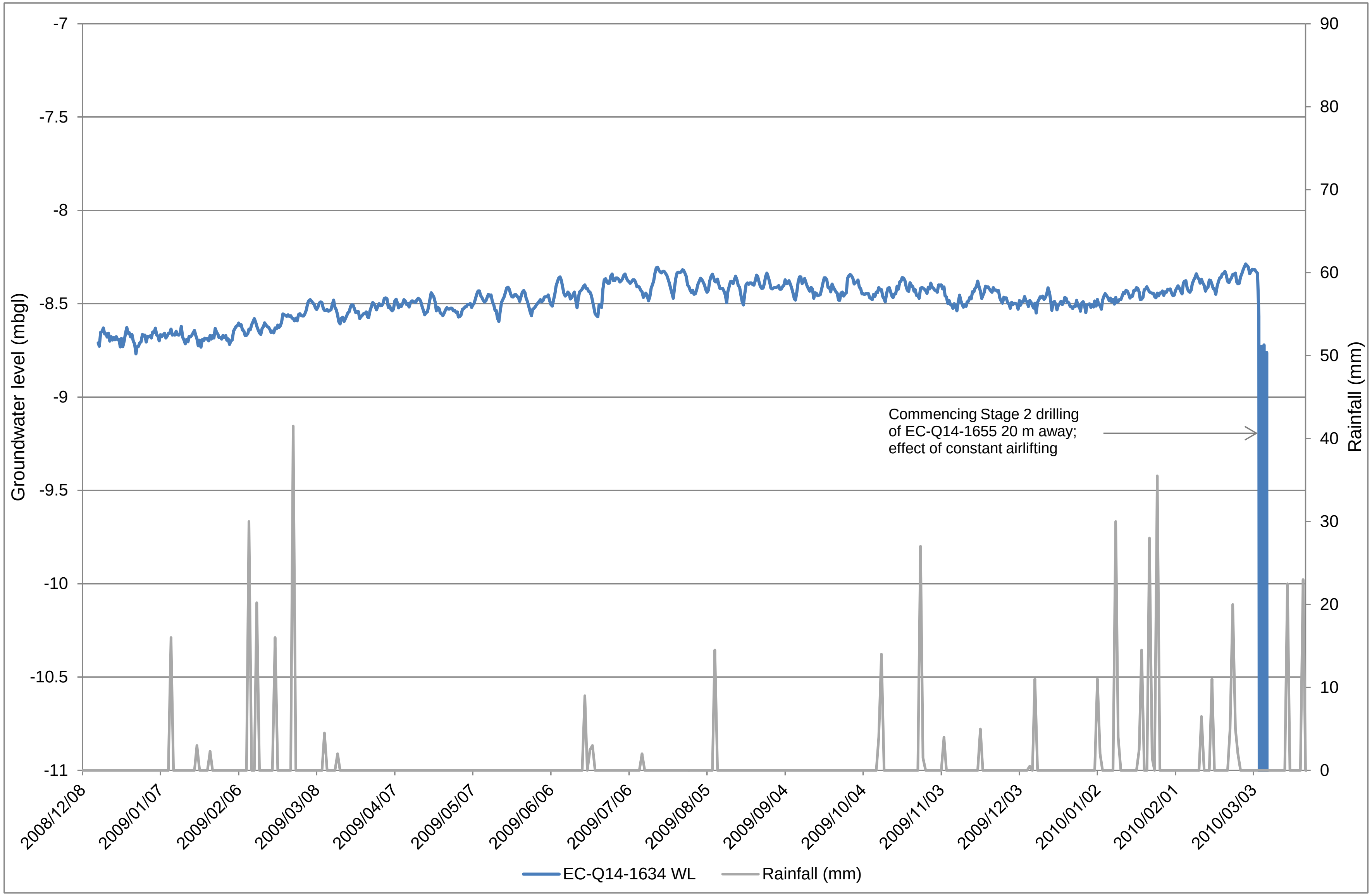
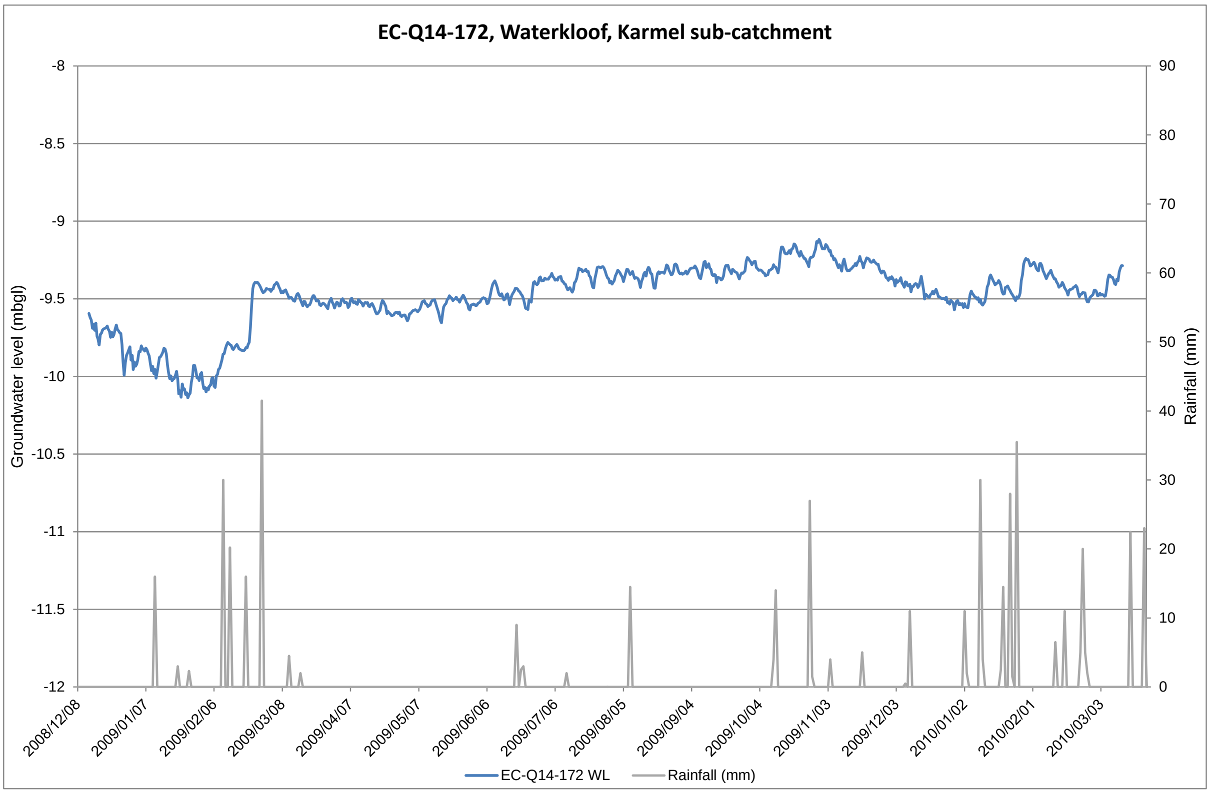


Figure 8-8: Groundwater level from new monitoring borehole EC-Q14-1634 at Jones Poort, The Glen sub-catchment



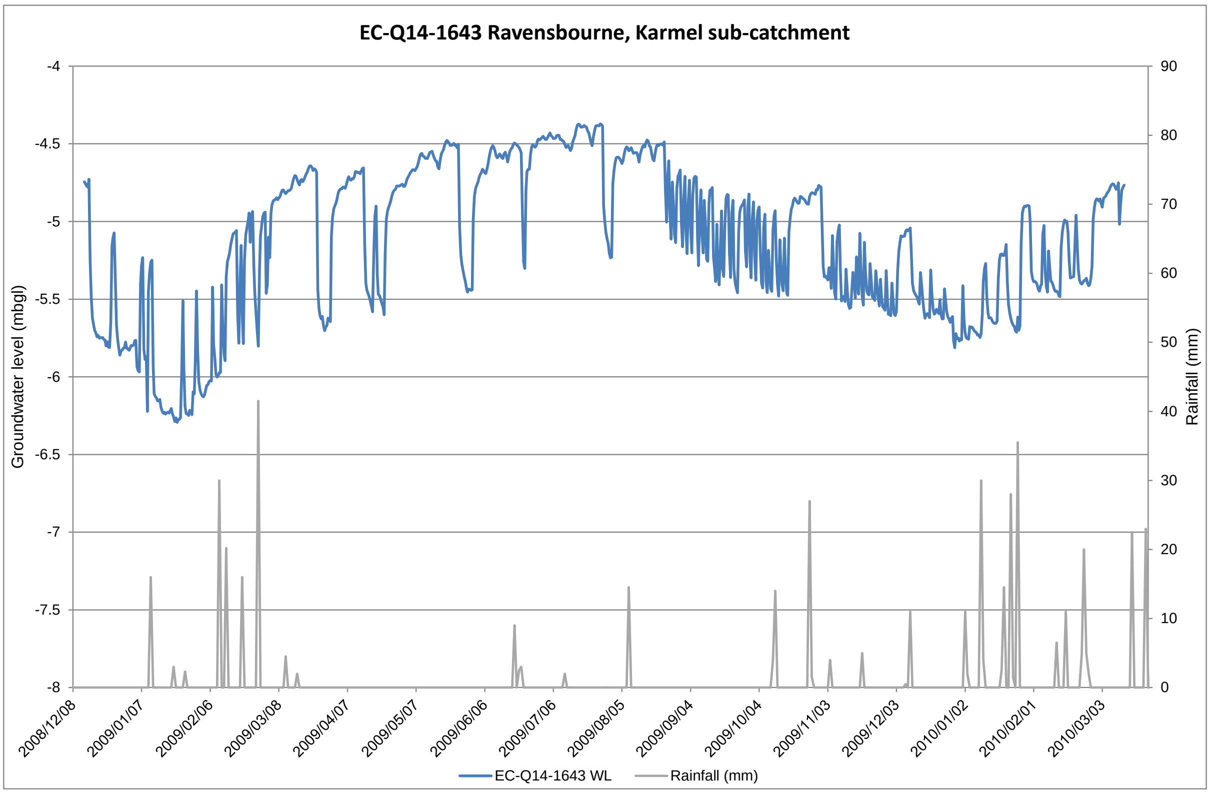


Figure 8-9: Karmel sub-catchment monitored groundwater levels

EC-Q14-1643 is located in close proximity to an abstraction borehole on the farm Ravensbourne, but the overall trend of groundwater level is still visible.

8.2.2 Recovered data: monitoring period July 2010 to March 2013

Sometime after the consulting firm's contract finished the loggers were not visited again for regular download as previously done and consequently the loggers reached their maximum number of readings and also reached the end of their battery life. Figure 8-10 below shows the point where EC-Q14-1634's levelogger battery failed.

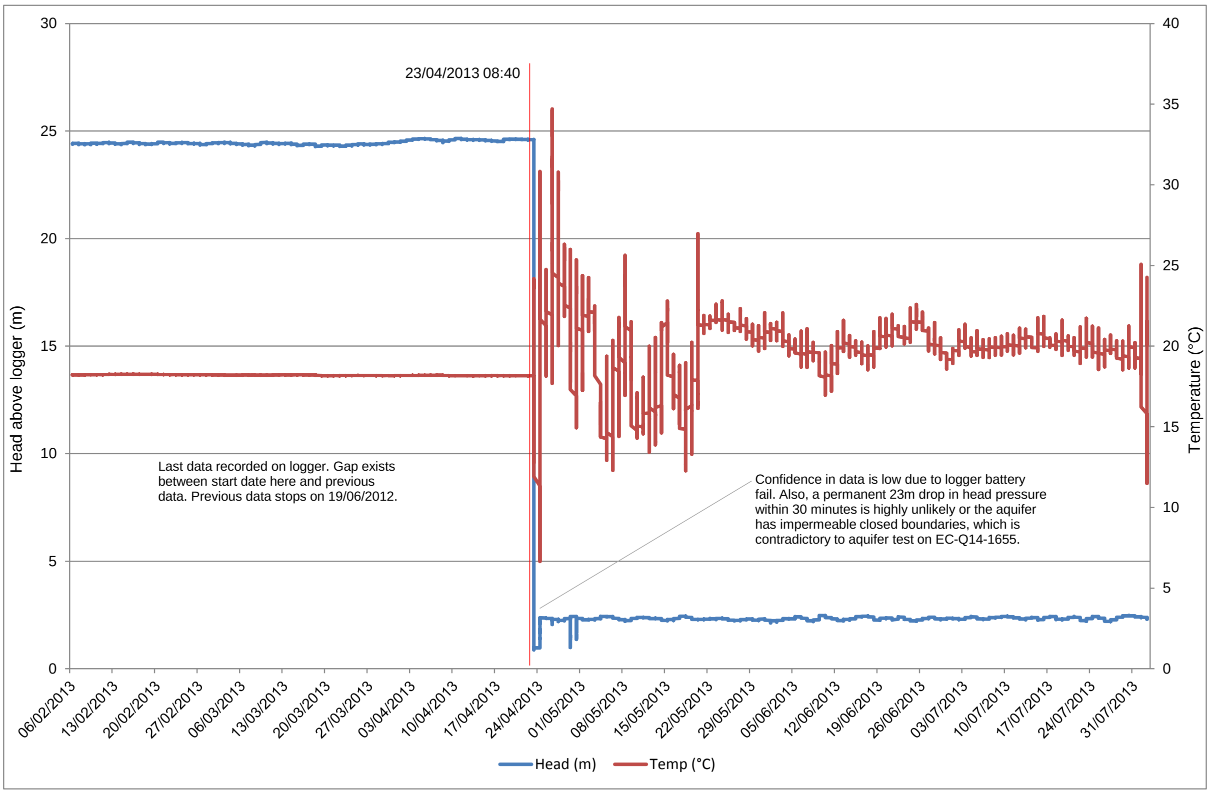


Figure 8-10: Data showing logger battery failure in The Glen sub-catchment

After battery failure some of the loggers were retrieved by DWA and the loggers sent for data recovery. Valuable data was recovered. Data between March 2010 and August 2010 was however scrambled. The recovered data was cleaned and is shown with rainfall for 2 monitoring boreholes in Figure 8-11 and Figure 8-12 below.

The large increase observed in the EC-Q14-1634 groundwater level in Figure 8-11 below is probably due to some dewatering that has taken place due to constant airlifting and drilling of EC-Q14-1655 and recovery of this water removed from the aquifer during drilling and testing. It is also due to the above average rainfall that occurred in the hydrological years 2010/2011 (537 mm) and 2011/2012 (445 mm). It is thought that the aquifer is fully saturated at ±5 mbgl and baseflow to the adjacent main tributary of The Glen sub-catchment occurs to release excess groundwater.

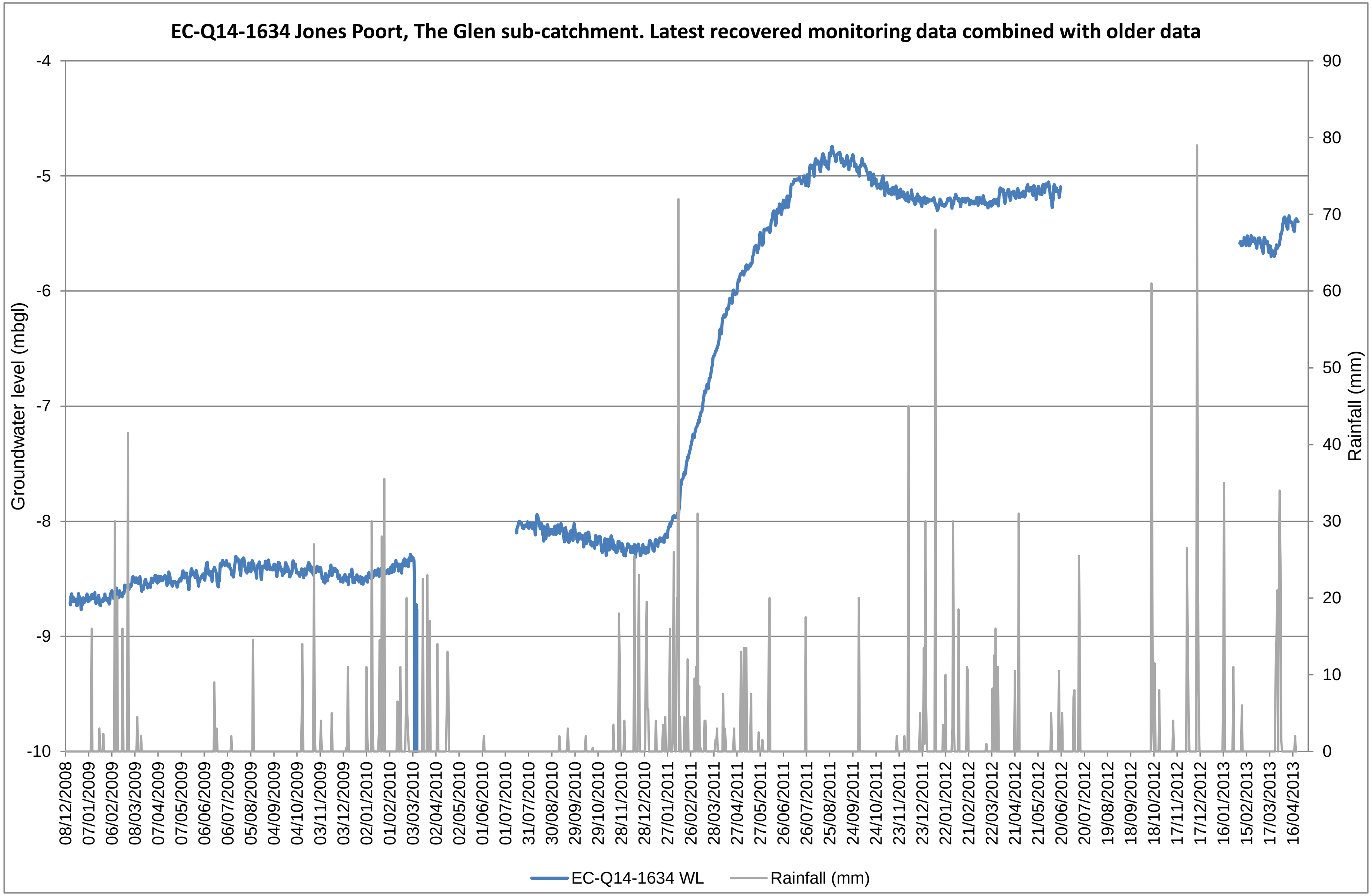


Figure 8-11: **EC-Q14-1634 The Glen sub-catchment recovered data and older data indicating rise in water level due to above MAP rainfall**

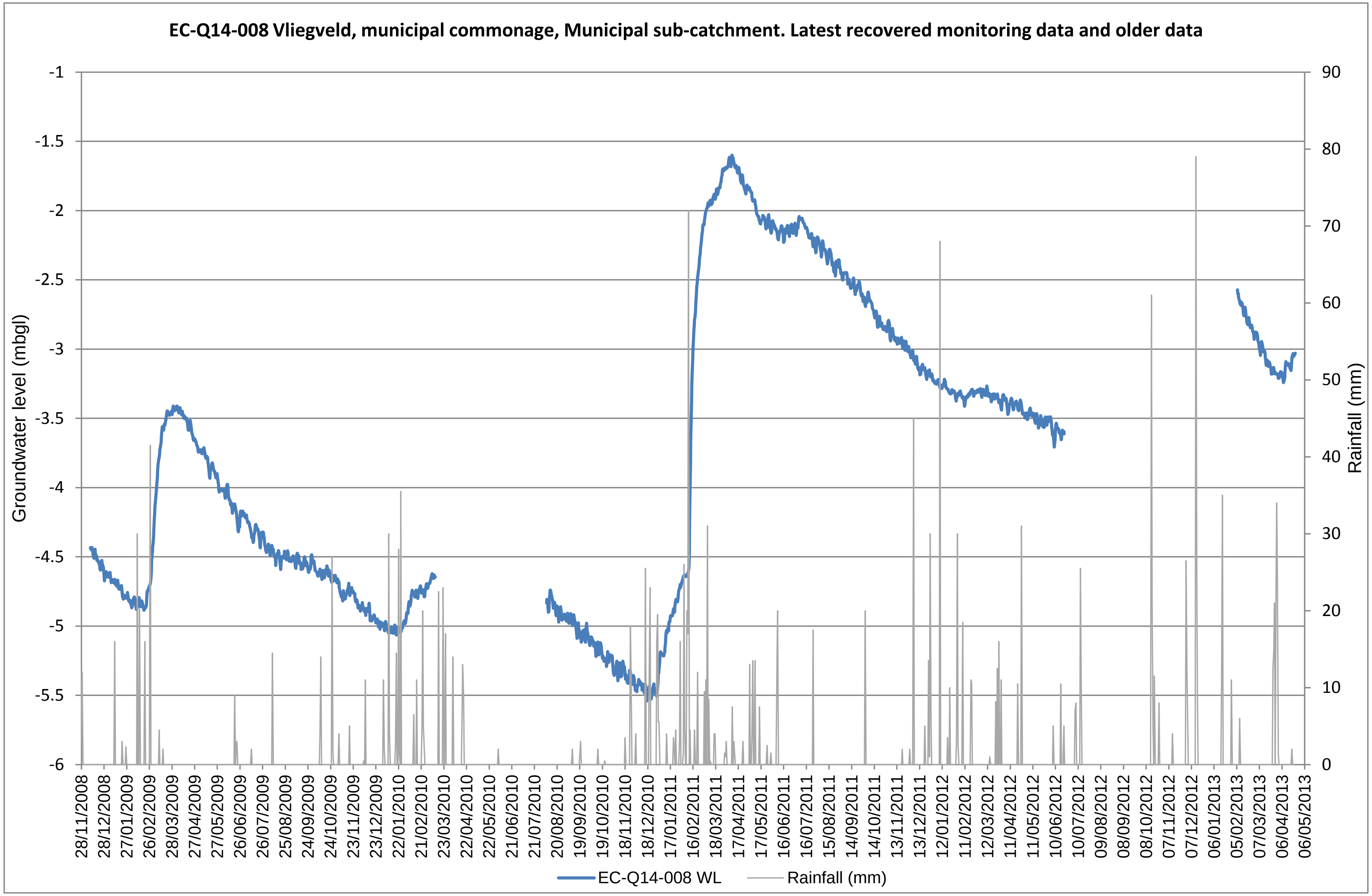


Figure 8-12: EC-Q14-008 Municipal sub-catchment recovered data combined with older data showing abstraction and recharge

8.3 Conclusions

It is of the upmost importance that groundwater level- and abstraction-monitoring be performed and the optimal solution would be that Middelburg Municipality or the local Municipality takes responsibility for this. Continuous monitoring in Middelburg is non-negotiable since groundwater resources supply potable water to a town of ± 50 000 people. The groundwater monitoring network needs to be maintained and data from the monitoring needs to be kept up to date as deliverable for periodic hydrogeological evaluation.

Groundwater monitoring will also create at least 1 job for a responsible person in Middelburg were unemployment is high.

A groundwater monitoring and management plan needs to be compiled for Middelburg. Unfortunately it was out of the financial- and time-scope of this study, but is of critical importance. The first version of this plan was compiled by Dr. J.J.P. Vivier and J.A. Myburgh (Appendix F), but this plan needs to be updated with monitoring information and the monitoring protocol updated. Manual groundwater levels (hydraulic heads) need to be measured at a minimum temporal resolution of 1 month in distant catchment monitoring boreholes to be effectively applied in further refinement of the recharge figures. New selected monitoring boreholes with leveloggers or other electronic loggers installed should have a groundwater level sampling/measurement temporal resolution of at least twice a day, e.g. 12:00 and 00:00.

Even the best and most detailed numerical groundwater model cannot replace measured groundwater level fluctuations in aquifers as the best indicators for informed groundwater management.

The loggers deployed in new groundwater monitoring boreholes have a run time of 4 – 7 years depending on the frequency of readings taken. Over the last 3 years the loggers were not periodically visited and the lithium batteries of the loggers have run flat. DWA have recently removed all the loggers and have installed new loggers in certain strategic boreholes of the new monitoring network.

9 GROUNDWATER CHEMISTRY

9.1 Methodology

9.1.1 Sampling

Three types of samples were collected during this phase of the Middelburg groundwater exploration and supply study. These are groundwater samples taken during or just after drilling, groundwater samples taken close to the end of the constant discharge tests and groundwater samples taken using packer testing.

Groundwater samples taken during or just after drilling were taken by the hydrogeological sub-consultant Japie Coetzer during the J&M drilling phase and by Steyns Drilling themselves during the Steyns Drilling phase. Samples were taken from the V-notch flow during airlift yield and borehole development. Groundwater sampling guidelines as proposed by Weaver *et al.* (2007) were followed when Mr. Coetzer sampled during drilling and a basic level of sampling procedure was followed by the drilling rig manager when he collected samples. This is confirmed when the ion balance error of the borehole EC-Q14-1653 sampled during drilling was found to be 11%.

Samples collected during hydraulic testing were collected by the sub-contractor AB Pumps and groundwater sampling protocol was followed. Water samples were in most cases collected from an open stream of water at the riser pipe or at the outlet nozzle of the mono type pump, close to the end of the constant discharge test. AB Pumps personnel have been instructed in the basic principles of groundwater sampling protocol as described by Weaver *et al.* (2007).

All water quality samples taken during the hydrocensus, drilling and aquifer testing were once-off samples and thus time series water quality data was not available at this stage.

Given the generally marginal to poor water qualities found during Middelburg groundwater sampling as well as observing that the deeper Beaufort Group- and dolerite-groundwaters are influenced by alluvial water due to casing not sealing properly, a decision was made to test the deep aquifer groundwater quality by means of packer isolation. The packers could effectively seal off the direct influence of the top shallow unconfined aquifer and the packers were placed above and below a deep water strike in the form of a fracture zone. Alternatively only one packer was placed at a point above a deep fracture and the rest of the borehole to the bottom was sealed off. A short constant discharge test was performed with the pump intake within the packer zone sealed off, thus abstracting groundwater only from the deep fractured rock aquifer. The groundwater sample was collected close to the end of the constant discharge test using good sampling protocol as described by Weaver *et al.* (2007). For more information regarding the use of packers the reader is referred to Sterrett *et al.* (2008).

All samples were stored in a cooler bag or box and kept as cool as possible until delivered to the accredited laboratory for analysis.

9.1.2 Analysis and classification of results

Samples were submitted to the SANAS accredited Talbot Laboratories to be analysed for physio-chemical parameters, macro elements and limited trace elements related to each sample's water quality. Microbiology was analysed for in limited cases.

The water quality results from samples submitted were interpreted and classified using the Department of Water Affairs (DWA) document entitled *Quality of domestic water supplies, Volume 1: Assessment guide*. The purpose of this document is (1) to provide a guide to assess the suitability of the water for domestic use, given the concentrations of important water quality related constituents and (2) to provide information on treatment options that can be used to improve poor water quality up to a standard where it is again fit for domestic use (DWAF, 1998).

The assessment of the water quality uses a classification system with 5 water quality classes based on concentration ranges per water quality constituent. There are also the different domestic water uses namely Drinking, Food preparation, Bathing and Laundry that each have different water quality ranges per constituent based on the way the water use is influenced by constituent (substance) concentrations.

The water quality of a typical water sample is classified in a two-step process. Firstly the class per constituent is determined for each of the domestic water uses. Secondly the overall water quality class is determined by comparing the classes in the different water uses per substance (constituent). The worst substance class is then determined for each substance and the overall water quality of the sample is determined by comparing worst substance classes. The worst class of the worst substance classes is the overall water quality class.

Table 9-1 shows the water quality classes with their associated health and water use effects as well as colour coding.

Table 9-1: DWA water quality classification system classes and colours (DWAF, 1998)

STRUCTURE OF THE CLASSIFICATION SYSTEM DESCRIBING THE EFFECTS OF THE DIFFERENT CLASSES OF WATER ON THE VARIOUS DOMESTIC USES OF WATER		
CLASS/COLOUR	**DESCRIPTION**	**EFFECTS**
Class 0	Ideal water quality	**Drinking Health:** No effects, suitable for many generations.
		Drinking Aesthetic: Water is pleasing.
		Food preparation: No effects.
		Bathing: No effects.
		Laundry: No effects.
Class 1	Good water quality	**Drinking Health:** Suitable for lifetime use. Rare instances of sub-clinical effects.
		Drinking Aesthetic: Some aesthetic effects may be apparent.
		Food Preparation: Suitable for lifetime use
		Bathing: Minor effects on bathing or on bath fixtures.
		Laundry: Minor effects on laundry or on fixtures.
Class 2	Marginal water quality	**Drinking Health:** May be used without health effects by the majority of individuals of all ages, but may cause effects in some individuals in sensitive groups. Some effects possible after lifetime use.
		Drinking Aesthetic: Poor taste and appearance are noticeable.
		Food preparation: May be used without health or aesthetic effects by the majority of individuals.
		Bathing: Slight effects on bathing or on bath fixtures.
		Laundry: Slight effects on laundry or on fixtures.
Class 3	Poor water quality	**Drinking Health:** Poses a risk of chronic health effects, especially in babies, children and the elderly.
		Drinking Aesthetic: Bad taste and appearance may lead to rejection of the water.
		Food preparation: Poses a risk of chronic health effects, especially in children and the elderly
		Bathing: Significant effects on bathing or on bath fixtures.
		Laundry: Significant effects on laundry or on fixtures.
Class 4	Unacceptable water quality	**Drinking Health:** Severe acute health effects, even with short-term use.
		Drinking Aesthetic: Taste and appearance will lead to rejection of the water.
		Food preparation: Severe acute health effects, even with short-term use.
		Bathing: Serious effects on bathing or on bath fixtures.
		Laundry: Serious effects on laundry or on fixtures.

9.2 Results

9.2.1 Hydrocensus samples groundwater chemistry analysed

A database of existing borehole groundwater chemistries sampled and analysed was compiled. After data cleaning and database compilation, a total of 402 records of analysed groundwater chemistries from existing boreholes were available. These chemistries included all macro elements and a piper diagram was drawn for groundwater characterisation. The Piper diagram is shown in Figure 9-1 and discussed in section 9.3.1.

9.2.2 Groundwater chemistry results from hydraulic testing

Water samples were taken near the end of the hydraulic testing and submitted to Talbot Laboratories to be analysed for physical parameters and macro constituents. Total- and faecal-coliforms were only analysed in a few boreholes as it proved very difficult to get cold samples from Middelburg to the lab within 6 hours. There was also no reason to suspect microbiological problems based on previous microbiology results of existing boreholes. A total of 11 new boreholes and 5 existing boreholes were sampled, analysed and the results classified according to the DWAF quality of domestic water supplies assessment guide of 1998 (DWAF, 1998). One existing borehole (EC-Q14-1603) was sampled with a bailer as it was not sampled during the hydraulic test. Two new boreholes, EC-Q14-1632 and EC-Q14-1636 were sampled with a packer isolation in order to obtain water quality results of the deeper aquifers. The locations of new and existing boreholes sampled at the end of constant discharge tests or with packer isolation and including EC-Q14-1603 are shown in Figure 9-4.

Trace elements were not analysed with sampling during drilling or hydraulic testing. It is however recommended that sampling and lab analysis of microbiology, physical parameters, macro constituents and trace elements be performed for boreholes that will be used in the water supply for Middelburg. Trace elements only have to be monitored bi-annually or annually.

The results of the hydrochemical laboratory analysis are shown in Table 9-2 and Table 9-3 with the concentration of chemical constituents and values of physio-chemical parameters highlighted in the colour according to their DWA Drinking class range. The groundwater types of the boreholes sampled are plotted on the Piper diagram in Figure 9-2 for existing boreholes and in Figure 9-3 for new boreholes.

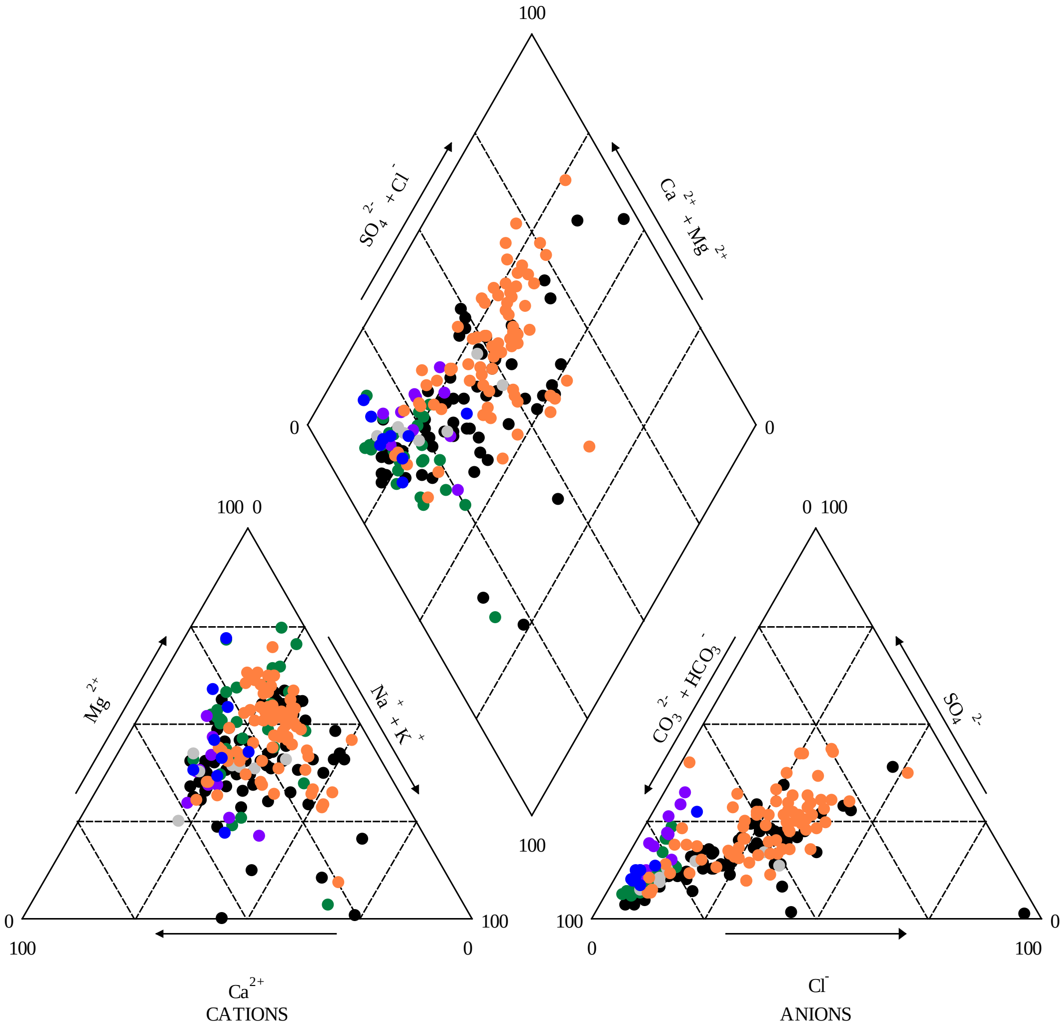


Figure 9-1: Piper diagram of groundwater chemistries of all existing boreholes sampled during hydrocensus (n = 402)

Table 9-2: Table 1 of 2 hydrochemistry results of existing and new boreholes sampled during hydraulic testing and drilling

Abbreviation	Date sampled	Electrical conductivity EC	Total Dissolved Solids TDS	pH Value pH	Turbidity	Calcium Ca^{2+}	Magnesium Mg^{2+}	Sodium Na^{+}	Potassium K^{+}	Cabonate CO_3^{2-}	Bicarbonate HCO_3^{-}	Chloride Cl^{-}	Sulphate SO_4^{2-}	Fluoride F^{-}	Total Hardness $CaCO_3$
Units		mS/m	mg/l		NTU	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
Class 0		<70	<450	5<pH<9,5	<0.1	<80	<70	<100	<25	NA	NA	<100	<200	<0,7	<200
Class 1		70-150	450-1000	4,5-5; 9,5-10	0.1-1	80-150	70-100	100-200	25-50			100-200	200-400	0,7-1,0	200-300
Class 2		150-370	1000-2400	4-4,5; 10-10,5	1-20	150-300	100-200	200-400	50-100			200-600	400-600	1,0-1,5	300-600
Class 3		370-520	2400-3400	3-4; 10,5-11	20-50	>300	200-400	400-1000	100-500			600-1200	600-1000	1,5-3,5	>600
Class 4		>520	>3400	3>pH>11	>50		>400	>1000	>500			>1200	>1000	>3,5	
Existing BHs															
EC-Q14-192	2008/05/16	264	1492	7.6	0.3	92.0	158.0	288.0	2.3	1	661	183	287.0	1.01	880
EC-Q14-924	2007/03/27	87	420	7.8	0.3	60.0	43.0	52.0	1.0	1	318	33	67.7	0.72	327
EC-Q14-968	2008/05/12	89	458	7.2	0.5	50.0	30.0	75.0	1.9	0	374	88	52.0	0.73	249
EC-Q14-1603	2010/03/30	104	488	7	2.7	23.0	20.0	122.0	0.6	0	293	117	33.5	1.86	139
EC-Q14-1651	2007/09/17	48	294	7.4	0.4	37.0	14.0	34.0	1.0	0	196	7	57.6	0.73	150
New BHs															
EC-Q14-1630	2007/09/13	188	1112	7.9	416.0	80.0	106.0	137.0	4.3	1	396	170	216.0	1.05	637
EC-Q14-1631	2008/02/01	85	444	7.8	0.9	27.0	26.0	93.0	1.0	1	293	91	42.4	1.11	174
EC-Q14-1632	2009/12/12	184	1082	7.4	2.2	93.0	130.0	152.0	2.1	1	617	176	185.0	0.67	767
EC-Q14-1633	2008/02/05	37	210	9.6	0.7	7.8	0.1	63.0	1.0	8	44	73	5.6	1.90	20
EC-Q14-1634	2008/02/16	73	412	8.5	0.5	34.0	36.0	45.0	1.1	5	364	28	34.7	0.44	233
EC-Q14-1635	2008/04/30	48	332	8.1	33320.0	25.0	5.9	110.0	12.0	5	945	55	152.0	0.38	86
EC-Q14-1636	2009/12/10	42	292	7.8	0.7	29.0	7.1	49.0	0.3	1	198	13	9.2	0.36	101
EC-Q14-1637	2010/05/13	54	316	6.6	0.4	47.0	16.0	37.0	0.7	0	262	14	17.3	0.48	183
EC-Q14-1653	2008/06/26	67	416	7.3	0.4	70.0	14.0	25.0	1.4	0	173	8	109.0	0.46	233
EC-Q14-1655	2010/05/07	71	430	7.7	0.7	45.0	42.0	44.0	1.1	1	389	22	34.1	0.60	285
EC-Q14-1662	2010/02/05	102	450	7.2	1.4	50.0	44.0	39.0	2.2	0	390	20	21.4	0.47	306

Table 9-3: Table 2 of 2 hydrochemistry results of existing and new boreholes sampled during hydraulic testing and drilling

Abbreviation	Date sampled	Faecal coliforms	Total Coliforms	Nitrate as N NO_3^-	Nitrite as N NO_2^-	Iron *Fe*	Ammonia NH_3	Calcium Hardness $CaCO_3$	Magnesium Hardness $MgCO_3$	Total Alkalinity *Alk.*
Units		CFU/ 100mℓ	CFU/ 100mℓ	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l	mg/l
Class 0		0	0	<6	<6	<0,5	NA	NA	NA	NA
Class 1		0-1	0-10	6-10	6-10	0,5-1,0				
Class 2		1-10	10-100	10-20	10-20	1,0-5,0				
Class 3		10-100	100-1000	20-40	20-40	5,0-10,0				
Class 4		>100	>1000	>40	>40	>10,0				
Existing BHs										
EC-Q14-192	2008/05/16	0	18	7.91	7.91	0.20	0.08	230	650	544
EC-Q14-924	2007/03/22	0	110	0.56	0.56	0.05	0.18	150	177	262
EC-Q14-968	2008/05/12	0	0	0.03	0.03	0.02	0.11	125	124	307
EC-Q14-1603	2010/03/30	0	0	0.28	0.28	0.34	0.31	57	82	240
EC-Q14-1651	2007/09/17	0	0	0.57	0.57	0.05	0.12	92	58	161
New BHs										
EC-Q14-1630	2007/09/13	0	0	9.16	9.16	0.38	0.08	200	437	327
EC-Q14-1631	2008/02/01	0	0	0.38	0.38	0.05	0.12	67	107	242
EC-Q14-1632	2009/12/12	0	0	5.38	5.38	0.08	0.08	232	535	507
EC-Q14-1633	2008/02/05	0	0	0.39	0.39	0.05	0.24	19	0.4	52
EC-Q14-1634	2008/02/16	0	0	0.60	0.60	0.05	0.20	85	148	307
EC-Q14-1635	2008/04/30	0	0	1.48	1.48	2.80	1.00	62	24	784
EC-Q14-1636	2009/12/10	0	0	0.38	0.38	0.04	0.08	72	29	163
EC-Q14-1637	2010/05/13	0	0	1.21	1.21	0.05	0.08	117	66	215
EC-Q14-1653	2008/06/26	0	48	0.68	0.68	0.05	0.15	175	58	142
EC-Q14-1655	2010/05/07	0	8	0.43	0.43	0.03	2.86	112	173	320
EC-Q14-1662	2010/02/05	0	0	4.03	4.03	0.01	0.08	125	181	320

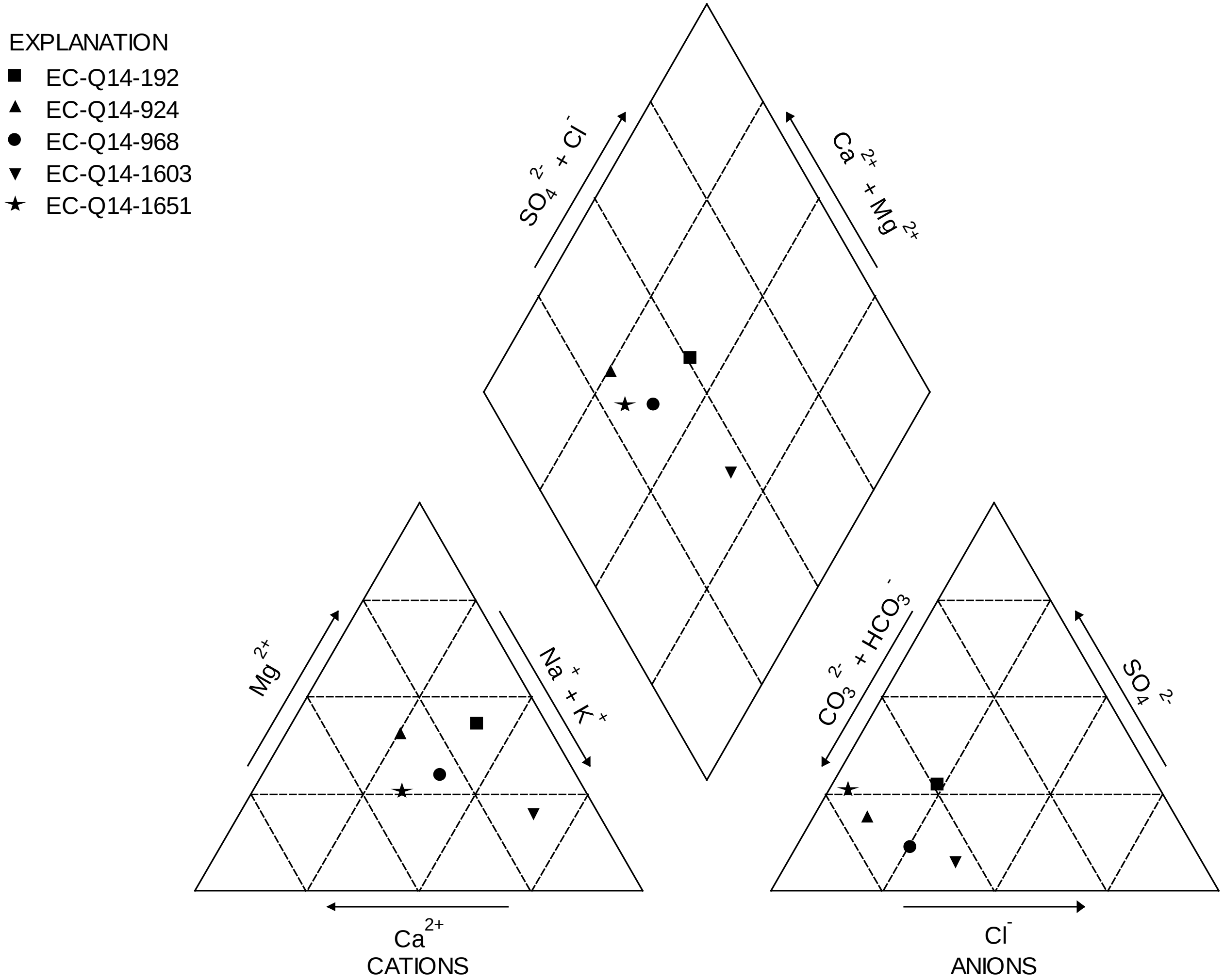


Figure 9-2: **Piper diagram of existing boreholes sampled during hydraulic testing**

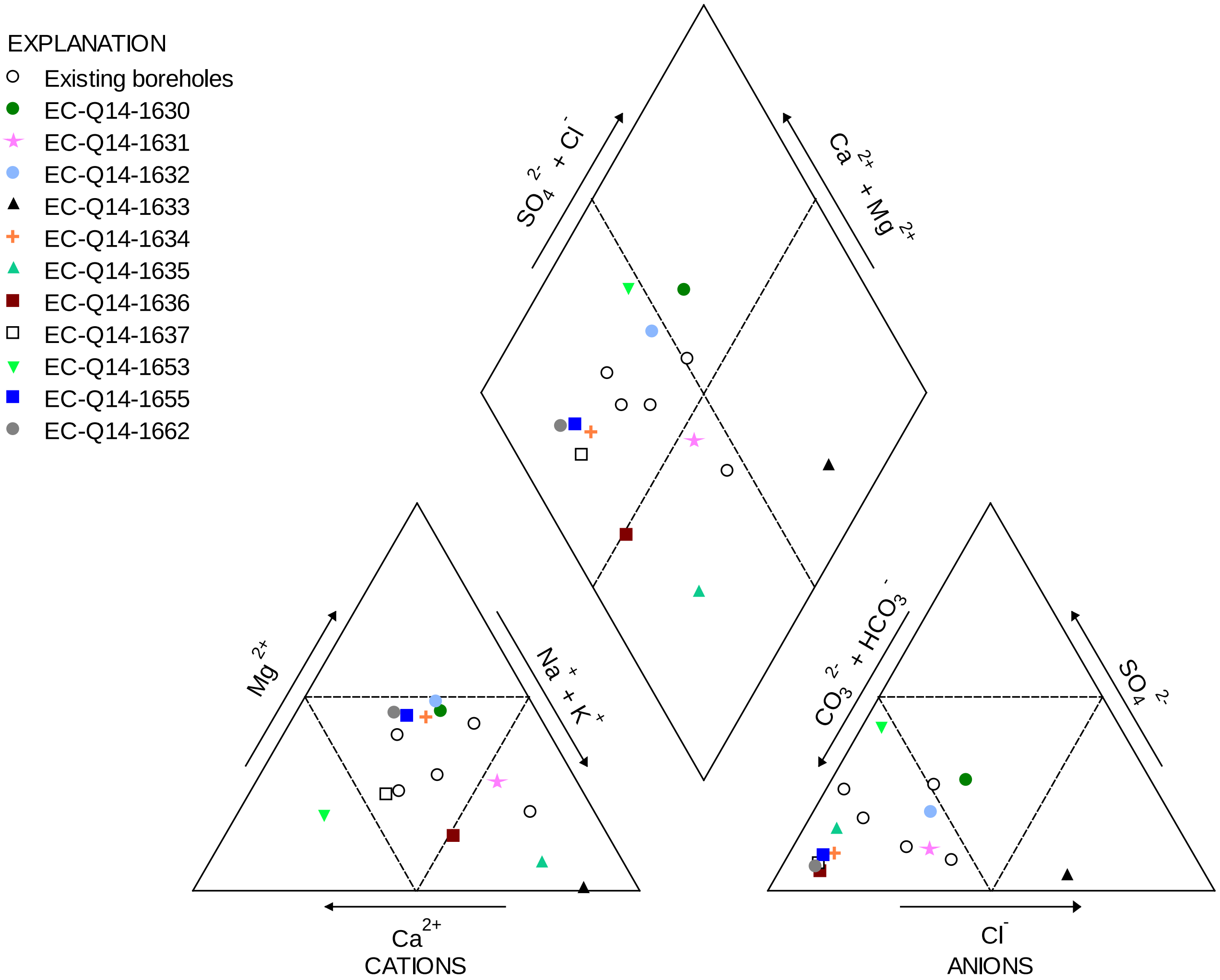


Figure 9-3: Piper diagram of new boreholes drilled during the investigation

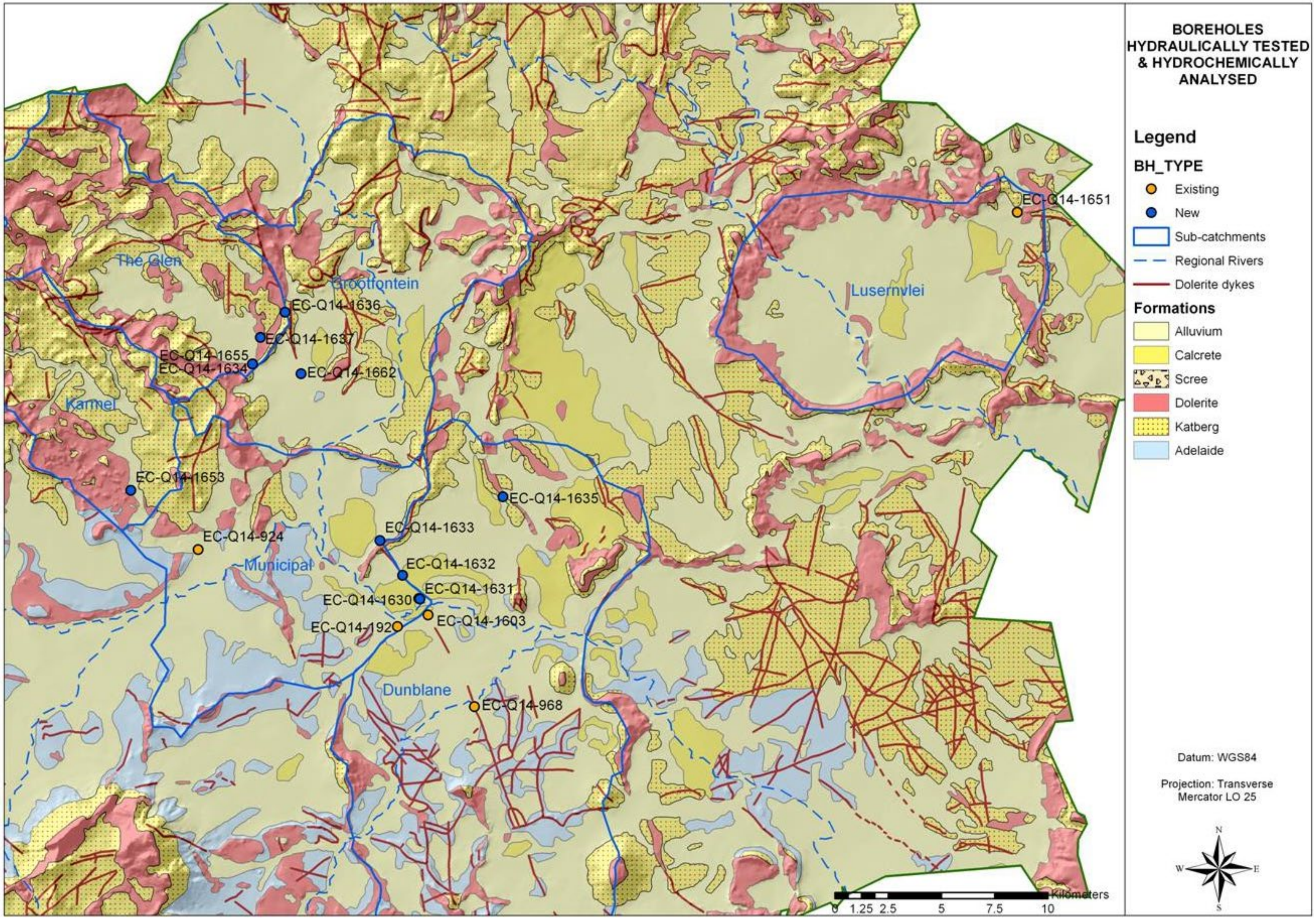


Figure 9-4: Map of new and existing boreholes hydraulically tested and hydrogeochemically interpreted

9.3 Discussion

9.3.1 Groundwater characterisation from hydrocensus samples

Figure 9-1 shows 402 existing borehole groundwater chemistries on a piper trilinear plot. All of the chemistries were sampled during hydrocensus and not during hydraulic testing, however samples were taken where an open stream of water or tank to supply such groundwater was available. All of the groundwaters sampled during the hydrocensus were obtained from shallow boreholes, many of them drilled with a cable tool rig and thus only penetrating the shallow unconfined aquifer. The colours in the piper diagram indicate the different sub-catchments in which the boreholes are located: The Glen (blue), Grootfontein (green), Karmel (purple), Municipal (orange), Dunblane (black) and Lusernvlei sub-catchment (grey). From the resultant piper plot, The Glen-, Karmel- and Grootfontein-sub-catchments all show a dominant Ca^{2+}/Mg^{+} HCO_3^{-} groundwater type that is recently recharged (Cl^{-} values indicate fresh groundwater). The municipal sub-catchment on the other hand shows a range of groundwater facies from Ca^{2+}/Mg^{+} HCO_3^{-} to Ca^{2+}/Mg^{+} SO_4^{2-}/Cl^{-}. The latter groundwater type indicates a more mineralised groundwater in the Municipal sub-catchment than The Glen, Grootfontein or Karmel sub-catchments. The higher mineralisation can be due to slower or no groundwater movement, longer residence time within the catchment, less recharge as well as evaporation considering the shallow nature of groundwater in the vicinity of drainages (see Figure 9-4). Less recharge is expected in the Municipal sub-catchment due to its flat basinal pediplain geomorphological character compared to the more mountainous and recently recharged The Glen, Grootfontein and Karmel sub-catchments. The most likely causes of mineralisation in the Municipal sub-catchment are thought to be evaporation and concentration of dissolved constituents in groundwater as well as slow groundwater movement due to decrease in spill-over of groundwater from upstream sub-catchments.

The Dunblane sub-catchment has a predominantly $Ca^{2+}/Mg^{+}/Na^{2+}$ HCO_3^{-} type groundwater with some zones of less groundwater movement and recharge indicated in the piper diagram as Ca^{2+}/Mg^{+} SO_4^{2-}/Cl^{-} type groundwaters. The Lusernvlei sub-catchment has a predominantly Ca^{2+}/Mg^{+} HCO_3^{-} groundwater character.

9.3.2 Borehole hydrochemical characterisation from hydraulic testing

Existing boreholes

The hydrochemical results of existing boreholes sampled during hydraulic testing are given in Table 9-2 and Table 9-3 and are hydrochemically portrayed in Figure 9-2. The hydrochemical signatures of existing boreholes in Figure 9-2 are also shown in Figure 9-3 to compare shallow existing borehole signatures with new deep borehole signatures.

The existing boreholes as mentioned represent groundwater only from the shallow unconfined alluvial aquifer as well as the thin highly weathered and jointed section of Beaufort Group rocks directly below it. In examining the Piper diagram in Figure 9-2, the existing boreholes have a similar groundwater type with the exception of EC-Q14-192 and EC-Q14-1603.

Spatially both EC-Q14-192 and EC-Q14-1603 are located in relatively close proximity (300-500 m) to the non-perennial Klein-Brak River. Consequently their groundwater sampled during hydraulic testing is expected to be influenced by an underflow aquifer system. Groundwater from both EC-Q14-192 and EC-Q14-1603 is of a Na-HCO_3^- character. Concentrations of salts (Na^+, Cl^-) in these two boreholes are elevated compared to other existing boreholes and are expected to be the result of reactions with the salts that have precipitated in the river bed and banks due to evaporation of shallow groundwater just below the river bed surface. Concentration of the groundwater in this area would also naturally take place due to evaporation of shallow groundwater. EC-Q14-192 groundwater also had anomalously high concentrations of NO_3^- and SO_4^{2-} (Table 9-2 & Table 9-3) compared to other existing boreholes and here the influence of agriculture and fertilisers is strongly considered as source for NO_3^-.

The elevated F^- concentration in EC-Q14-1603 is due to the fact that the borehole was sampled by bailer with no hydraulic test conducted. The fact that a bail sample was taken means that water movement through the local aquifer and borehole was limited compared to the other samples of existing boreholes taken at the end of hydraulic testing. Waters from EC-Q14-1603 has had longer time to react with the surrounding rocks and as such will show pronounced concentrations of chemical constituents due to minerals commonly reacted with or minerals that have longer reaction times. Such minerals include mica (containing F^-) based on the hydrochemistry results of EC-Q14-1603 (Table 9-2).

Although EC-Q14-924, EC-Q14-968 and EC-Q14-1651 are spatially very different and each in a different sub-catchment (Figure 9-4), their groundwater type is similar. This groundwater type has no clearly dominant cation, but anion-wise HCO_3^- is dominant. The groundwater is indicative of the shallow unconfined aquifer. The similar background F^- concentration is thought to be from the mica mineral fragments in the fine sediments found in the upper argillaceous part of the alluvial aquifer.

EC-Q14-1630 and EC-Q14-1632

Highly mineralised waters were intercepted at EC-Q14-1630 and EC-Q14-1632. They are clearly of the same aquifer or fracture network as most of their chemistry values are in a similar range and in fact almost have similar values (Table 9-2). Even the electrical conductivity and total dissolved solids values are very close to each other. Nitrate in these boreholes is also elevated in similar ranges compared to the NO_3^- in other new boreholes. The lithological logs of these boreholes also show a similar lithology: 10-15 m alluvium followed by a succession of Beaufort Group sedimentary layers with very little dolerite intercepted. The hydrohemistry from these boreholes are thought to represent predominantly the influence of the Beaufort Group sedimentary rock aquifers. These waters are also expected to have undergone some groundwater mixing with the Dunblane dolerite dyke and associated fractures close by as well as water from the alluvial aquifer through vertical aquifer leakage to the Beaufort Group fractures below.

The groundwater in EC-Q14-1630 and EC-Q14-1632 is of a Na-HCO_3^- character with Mg as the other major cation and SO_4^{2-} and Cl^- the other major anions. One clear deviation between the two groundwaters sampled is F^-. Here the F^- in EC-Q14-1630 is approximately double that of EC-Q14-1632. The elevated concentrations of EC-Q14-1630 can be explained to some extent by the fact that the groundwater sample was taken during or just after drilling, as is evident from the turbidity value. EC-Q14-1632 was however sampled during a packer test with water collected from the 194 – 236 mbgl section of the borehole after some abstraction time. Boreholes EC-Q14-1630 and EC-Q14-1631 are also spatially at some distance (1.3 km) from EC-Q14-1632 and it could be that there is a slow moving or stagnant groundwater zone in the area of EC-Q14-1630 and EC-Q14-1631.

The highly mineralised water and elevated Cl^- represents an aquifer with little recharge and large residence times found within the Middelburg Municipal sub-catchment (Middelburg ring structure). The elevated Cl^- could also present a quasi-barrier effect given the groundwater direction and the strike of the Dunblane dyke.

<u>Water from EC-Q14-1631 and EC-Q14-1633</u>

Although borehole EC-Q14-1630 and EC-Q14-1631 are very close to each other they do not share a similar groundwater type (Figure 9-4). They do however share an elevated F^- concentration that is associated with the Dunblane dyke at this spatial location and long residence times of groundwater here. EC-Q14-1631 and EC-Q1633 are more similar in groundwater type (Table 9-2). This is due to the fact that both boreholes are drilled into dolerite, more specifically the Dunblane dyke and both boreholes intercepted no Beaufort Group rocks. Borehole EC-Q14-1630 intercepted some alluvium before entering dolerite for the rest of the borehole, while EC-Q14-1633 is dolerite right through.

A deviation however occurs between these two groundwater types when classifying them. As with all the other boreholes, the clearly dominant anion in EC-Q14-1630 is HCO_3^-. The groundwater in EC-Q14-1630 consequently has a Na-HCO_3^- character. The exception in all the other boreholes is EC-Q14-1633, where its major anion is Cl^-, thus its groundwater type is Na-Cl. This is due to the fact that EC-Q14-1633 intercepted no alluvium or sedimentary rock, just dolerite. Based on its airlift yield, groundwater flow through this aquifer is also slower and from the water quality results groundwater movement appears to be only in dolerite. The high F^- has been dealt with in the discussion of major and minor ions in chapter section 9.3.4.

<u>EC-Q14-1634, 1636, 1637, 1655, 1662</u>

The hydrochemistry for all the new boreholes in The Glen sub-catchment and Grootfontein sub-catchment are very similar (Table 9-2). These are boreholes EC-Q14-1634, EC-Q14-1636, EC-Q14-1637, EC-Q14-1655 and EC-Q14-1662. The hydrochemical characterisation in the piper diagram to determine similar and dominant groundwater types, clearly show these boreholes (EC-Q14-1636 to a lesser extent) to be part of the same aquifer or hydrochemical sequence (Figure 9-3). This statement is qualified in their spatial locations with all the above mentioned boreholes in The Glen sub-catchment and downstream Grootfontein sub-catchment (EC-Q14-1662). The boreholes are representative of a high recharge, upper reaches groundwater type of the Middelburg study area. This is evident when the Cl^- values are examined (Table 9-2). Between these boreholes, the highest Cl^- value is 28 mg/ℓ.

EC-Q14-1662 is thought to be located in the main groundwater (and surface water) flow zone of the Grootfontein sub-catchment, the downstream sub-catchment that The Glen sub-catchment flows directly into through Jones Poort, where EC-Q14-1634 and EC-Q14-1655 are located within a radius of 50 m of each other (see Figure 9-4).

Based on the trilinear Piper diagram plot the groundwater is of a Ca-HCO_3 type for boreholes EC-Q14-1634, EC-Q14-1637, EC-Q14-1655 and EC-Q14-1662 (Figure 9-3). Upon closer inspection of the hydrochemistry values the groundwater from boreholes EC-Q14-1637, EC-Q14-1655 and EC-Q14-1662 is seen to be of a Ca-HCO_3 type while the groundwater from boreholes EC-Q14-1634 and EC-Q14-1636 is seen to be of a Na-HCO_3 type. Based on the cation triangle faces in the Piper diagram (Figure 9-3) all these boreholes have no dominant cations with the exception of EC-Q14-1636.

Groundwaters from EC-Q14-1634, EC-Q14-1637, EC-Q14-1655 and EC-Q14-1662 are considered to be of a mixed groundwater type with all of the boreholes encountering alluvium, Beaufort Group rocks as well as dolerite. The dominant types of hydrochemical influences are however considered to be from the Beaufort Group rocks and the high permeability lower sequence of alluvial deposits.

All the boreholes in The Glen and Grootfontein sub-catchments have a distinctly lower SO_4^{2-} concentration, indicating a young and continuously recharged groundwater compared to SO_4^{2-} concentrations of boreholes in the Middelburg ring structure (Municipal sub-catchment).

When comparing hydrochemical signatures on the Piper trilinear plot in Figure 9-3, a marked difference exists between the signature of EC-Q14-1636 and the rest of the boreholes in The Glen and Grootfontein sub-catchments. This is however readily explained when the borehole lithological logs of boreholes in the former mentioned catchments are compared. In boreholes EC-Q14-1634, EC-Q14-1637, EC-Q14-1655 and EC-Q14-1662 multiple types of geology are encountered. In contrast EC-Q14-1636 only encountered dolerite up to the absolute bottom of the borehole, where the drill bit came to rest on a Beaufort Group formation succession at 126 mbgl. Although

EC-Q14-1636 was drilled to a final depth of 271 mbgl during stage 2 of its drilling, the borehole was only drilled to a 126 mbgl at the time of packer isolation sampling.

EC-Q14-1635

EC-Q14-1635 groundwater plots at a different location on the Piper trilinear diagram when compared to the other boreholes (Figure 9-3). EC-Q14-1635 also had the lowest airlift yield (0.1 ℓ/s) of all the boreholes drilled during the Middelburg groundwater study. From the borehole lithological log EC-Q14-1635 was drilled to a final depth of 120 mbgl and intercepted 3 m weathered dolerite material (topsoil) with dolerite talus boulders, 15 m weathered and well jointed dolerite followed by alternating sandstone and siltstone beds. The single water strike was encountered at 15 mbgl within the weathered dolerite above the Beaufort Group sandstone/ siltstone, which is described as baked.

Groundwater from EC-Q14-1635 is of a Na-HCO_3 character. The water has a similar cation ratio and composition to the water of EC-Q14-1633, indicating the effect of groundwater reactions with dolerite. EC-Q14-1635 is however very different in anion composition, with the highest value of HCO_3^- of all the new boreholes drilled. The borehole also has a relatively elevated concentration of SO_4^- compared to that of EC-Q14-1633. The SO_4^-, possibly from pyrite oxidation or interception of ancient gypsum evaporate deposits within the Karoo sedimentary sequence, is thought to originate from the Beaufort Group aquifer below, while the HCO_3^- is from both the Beaufort Group rocks as well as rainwater interaction with the atmosphere, carrying HCO_3^- down into the aquifer. Groundwater flow through EC-Q14-1635 is expected to be slow, but not stagnant, with the groundwater flow under natural conditions being down gradient and towards the alluvial basins. For this reason the Cl^- is not as comparably elevated as the concentrations found in the alluvial groundwater. Based on the Piper trilinear plot the groundwater is anion-wise more comparable with the high recharge zone groundwaters of The Glen and Grootfontein. The iron concentration in EC-Q14-1635 is seen as abnormally high and is attributed to a man-made iron object that could have fallen into the borehole during construction or it is simply the casing that is rusting. Either way the iron-concentration is seen as not indicative of the geology or natural hydrochemistry of the area when other borehole concentrations are examined. Another possibility for the abnormally high Fe concentration is perhaps the weathered dolerite topsoil from the sill which enriches infiltrating rainwater that eventually reaches the groundwater.

EC-Q14-1653

EC-Q14-1653 is the only new borehole drilled in the Karmel sub-catchment, which is a directly upstream sub-catchment of the Municipal sub-catchment (Figure 9-4). Groundwater from EC-Q14-1653 is of a dominant Ca-HCO_3 character (Figure 9-3). The groundwater has a strong Ca^{2+} cation dominated character when compared with the other boreholes that generally are Na^+ cation dominated. The sample from EC-Q14-1653 also has the lowest Cl^- concentration (8 mg/ℓ) indicating a very young and continuously recharged groundwater. In the concentration relationships and ratios between cations and anions, hence the Piper trilinear diagram, groundwater from EC-Q14-1653 compares to the groundwater of EC-Q14-1630 and EC-Q14-1632. One has to be cautious however in interpreting plots on the Piper trilinear diagram, as it does not take individual element and TDS concentration differences into account. The Cl value of EC-Q14-1653 is 8 mg/ℓ for example, while the Cl values of EC-Q14-1630 and EC-Q14-1632 is 170 mg/ℓ and 176 mg/ℓ respectively.

Vandoolaeghe groundwater types

Vandoolaeghe (1979: 44) described two main hydrochemical sequences from his investigation of the shallow unconfined aquifer in the Middelburg area: a high permeability sequence within the sandy-gravelly part of the alluvial aquifer represented by the Ca/ Mg HCO_3 and Na-HCO_3. The Na-HCO_3 water was ascribed to a dynamic underflow system. The second sequence, a low permeability sequence was found to be associated with the alluvial aquifer and specifically its fine grained upper part, i.e. the clayey argillaceous top sequence of the alluvium. This water was found to have a whole sequence from Ca/Mg HCO_3 to Na_2SO_4/NaCl (Vandoolaeghe, 1979). Vandooleaghe (1979) also mentions that this sequence could be accelerated by irrigation. In general highly mineralised waters were thought to be associated with the clayey fine-grained upper part of the alluvial deposits (Vandoolaeghe, 1979).

9.3.3 Major ions

Ca, Mg, Na

High sodium (Na) is expected to be derived from plagioclase feldspars found in abundance in both the Beaufort Group sediments as well as dolerite. Na is also higher due to the fact that Ca and Mg can form carbonate precipitates and are removed from solution, while Na is conservative and does not readily form such precipitates.

HCO_3^- & CO_3^{2-}

Evaporation has played a large role in the groundwater chemistry in Middelburg, especially that of the shallow aquifer. The effect of the evaporative environment created in the alluvial aquifer and fluctuating shallower water levels (1-5 mbgl) during 1979 and earlier times, resulted in the concentration of dissolved chemical constituents derived from the weathering of minerals in contact with groundwater, unless frequently recharged. This concentration, coupled with the upward capillary rise of groundwater, resulted in the precipitation and formation of calcrete in the upper layers of the alluvial aquifer in some places, as is evident from the geological map in Figure 9-4.

Bicarbonate is in general the dominant anion in the groundwater of the Middelburg area, in existing boreholes and new boreholes bicarbonate dominates over CO_3^{2-} as the carbonate form given the circa-neutral pH of the study area. The generally high concentrations of HCO_3^- in most of the groundwater sampled is expected to be the result of infiltrating rainwater being weakly acidic and dissolving some of the calcrete and cemented parts of the alluvial sediments and transporting both Ca^{2+} and HCO_3^- down into the aquifers. There are also some smaller sources of CO_3^- in the mineral cement of the Beaufort Group formations.

Elevated HCO_3^- can also be the result of a still present evaporative environment where Ca^{2+} and HCO_3^- accumulate as water evaporates from the remaining groundwater, thus concentrating dissolved constituents.

SO_4:

Evaporites such as gypsum [$CaSO_4.2H_2O$] as well as anhydrite [$CaSO_4$] could be the cause of the elevated sulphate in the water. The evaporates would probably be associated with mudstones, as the mudstones would have created pans with slow infiltration and therefore when the climate changed from a humid to arid climate, considerable evaporation occurred at these pans forming the evaporite minerals on the mudstones.

Another hypothesis is that the SO_4^{2-} could also be associated with small amounts of pyrite in the mudstone. The pyrites probably formed in a reducing environment prior to lithification. The pyrite in the mudstones and argillaceous sequences were in recent geologic times exposed to oxygen through the water of the shallow unconfined alluvial aquifer as well as drilling. This has started the reaction of oxidation of pyrite, hence forming dissolved SO_4^{2-} in the groundwater exposed to pyrite bearing Beaufort Group argillaceous sediments.

Vandoolaeghe (1979) thought that the SO_4 found in his low permeability upper alluvial sequence could be from the oxidation of pyrite locally present in the argillaceous Beaufort sediments or could simply be associated with the clay deposits in the upper part of the alluvial aquifer. In any case Vandoolaeghe (1979) noticed pyrite in the drilling chips of borehole G31589, located in the highly mineralised zone to the west of the Municipal sub-catchment.

From the deeper boreholes drilled during this study and from the camera log of EC-Q14-1655, the SO_4 is ascribed to the mudstone and argillaceous Beaufort Group sedimentary rocks. The borehole EC-Q14-1655 has a definite smell of H_2S and the presence of the gas was also confirmed by an independent gas chromatography consultant. EC-Q14-1655 has large fractures within the Beaufort Group sedimentary rocks below a 100mbgl and gas bubbles are actually seen on the camera log of EC-Q14-1655, rising from depths well beyond that of the alluvial aquifer.

Chloride (Cl^-)

Both Cl^- and F^- are conservative elements and do not easily form precipitates with other ions. Where present in relatively large concentrations (Table 9-2) they are expected to indicate groundwater that is not recharged frequently or has experienced evaporation.

Chloride is not encountered in the minerals of any of the rocks and unconsolidated deposits in the study area and is considered to be a direct indication of residence time and groundwater recharge.

9.3.4 Minor ions

Fluoride (F^-)

The fluoride (F^-) concentrations that are elevated above the background F^- value are considered to indicate groundwater that has been in contact with dolerite and has been stagnant for some time or has not had much groundwater mixing with the alluvial aquifer water to dilute the F^- concentration. The groundwater of EC-Q14-1633 is a prime example of such water. EC-Q14-1633 intercepted neither alluvium nor sedimentary formations and has its only significant water strikes at 123 mbgl and 157 mbgl in the dolerite. In the case of the elevated concentration of F^- in EC-Q14-1633, it is possible that a fluorite [CaF] vein, associated with hydrothermal activity from the Dunblane dyke cutting through the dolerite ring structure, was intercepted. This borehole is considered a good example of the deep aquifer and its water quality. Biotite is found in dolerite and could be the source of F^- in cases where boreholes in the vicinity of dolerite have larger concentrations of F^-. Larger residence times and stagnant waters are however required for such large concentrations of F^- to form from the biotite in dolerite, unless a fluorite-rich vein or lens was intercepted. Fluoride is found in specific types of dolerite and especially in groundwater within deep fractures in dolerite based on some case studies conducted in the Eastern Cape (pers comm. J. Myburgh, 2012).

The elevated concentrations of F^- in EC-Q14-1630 and EC-Q14-1632 are also interesting. These boreholes have been drilled to intercept fractures associated with the contact zone between the Dunblane dyke and the Beaufort Group country rock as well as in the Dunblane dyke itself. The elevated concentrations of both Cl^- and F^- indicate slow movement of groundwater in this region of the aquifer. The unused shallow existing borehole EC-Q14-1603 that was bail sampled was also drilled to target the Dunblane dyke and its elevated concentration of F^- confirms the weathered dolerite as source of F^- compared with the F- concentrations of other existing boreholes only targeting the alluvial aquifer with no dolerite near. Fluroride is present in existing alluvial boreholes, but in lower concentration than in the immediate vicinity of dolerite intrusions. Conditions of stagnant or slow groundwater movement in the fractured dolerite aquifers are however prerequisites for the concentration of F^- and above background concentrations of F^- to form.

Vandoolaeghe (1979) ascribed the higher concentrations of F^- to the micas in the clay deposits in the fine grained upper part of the alluvial aquifer, but according to Vandoolaeghe (1979) dolerite also cannot be neglected as source for the F^-.

It is concluded that F- can be associated with micas in the low permeability sequence in the upper part of the alluvial aquifer, but is also likely to be present in less frequently recharged, slow moving groundwater in the deep fracture aquifers and in the immediate vicinity of weathered dolerite intrusions.

9.3.5 Deductions from groundwater characterisation

It seems to be obvious that groundwater within the Middelburg ring structure (Middelburg Municipal sub-catchment) is not recharged frequently compared to the groundwater in the other sub-catchments represented here such as The Glen, Karmel and Lusernvlei sub-catchments. This is evident from the concentrations of the conservative anions Cl^- and F^-. Highly mineralised water within the Middelburg ring structure was also noted by Vandoolaeghe (1979). This is most likely due to over-abstraction and lowering of the water level by the Grootfontein Agricultural College in the Grootfontein sub-catchment at the bottom of the sub-catchment as well as continued use of the perrenial Grootfontein weir spring in between the Grootfontein and Middelburg Municipal sub-catchments. Inflow of groundwater from the western catchments into the Middelburg ring structure is also blocked by abstraction by the Middelburg Municipality boreholes in the Western valley aquifer. The two main points of inflow into the Middelburg ring structure namely at the perennial Grootfontein weir spring and the inflow boundary of the western valley aquifer have been effectively closed by continued large scale abstraction. The abstraction has also caused the water level to drop below most of the weathered surface parts of the dolerite ring structures and it is thought that the sub-catchments are now basically isolated dams. Based on the groundwater gradient, groundwater from the Middelburg municipal sub-catchment flows into the Dunblane sub-cathment. Currently the only flow into the Municipal and Dunblane sub-catchments is then from the eastern aquifers.

All the hydrochemical results and interpretations add to the impression that the dolerite ring complex structures are more impermeable deeper below surface than expected, and in effect form large dams within their basins. The shallow dolerite of the ring structures is however seen as much more weathered and permeable as seen in the case of the Dunblane dyke and Jones Poort. These are also areas of the dolerite structures that have been extensively exposed to groundwater flow and thus groundwater has not equilibrated with the adjacent weathered dolerite as much as is expected of the deeper groundwater.

9.4 Water quality classification

Of the 11 new boreholes sampled, 9% classified as DWA Overall Class 1 (good water quality), 46% classified as DWA Overall Class 2 (marginal water quality), 27% classified as DWA Overall Class 3 (poor water quality) and 18% of the new boreholes Classified as DWA Overall Class 4 (unacceptable water quality). The Class 4 classification is due to highly elevated turbidity in boreholes sampled during or just after drilling. The Class 3 classification is predominantly due to elevated levels of total hardness, with elevated concentrations of Mg and F to a lesser extent as shown in Table 9-4. Class 2 classifications are due to various constituents as shown in Table 9-4 although total hardness is by far the reason for most classifications. Total hardness is directly calculated from Ca and Mg concentrations and it typically creates problems with soap not foaming or scaling in geysers and kettles. It is less problematic when the drinking water use is considered.

When the existing boreholes hydraulically tested are considered, three boreholes classified as DWA Overall Class 3, due to elevated levels of total hardness, Mg, total coliforms and F. The two other boreholes classified as DWA Overall Class 2 due to total hardness.

A summary of the new and existing borehole water quality classification per water use is provided in Table 9-4. When the water uses are compared the most important consideration is health in the drinking water use. In providing long term water supply to Middelburg all uses should however be taken into account. The extent to which water will be treated will be based on a balance between acceptability of the water quality for use by Middelburg’s water users and the cost implications of the treatments required for the various elevated constituents.

Based on the outcomes of the hydraulic testing for new and existing boreholes, treatment options for the water quality of boreholes selected for water supply are considered.

Table 9-4: DWA classification of existing and new boreholes

General information			Water Quality Class							
Borehole Number	Date sampled	Sample type	Overall	Drinking		Food preparation	Bathing	Laundry	Problem Constituent(s)
				Health	Aesthetic				
Existing boreholes									
EC-Q14-192	2008/05/16	Hydraulic test	3	3	3	3	3	3	Class 3: T.H., Mg; Class 2: EC, TDS, F, Fe, Na.
EC-Q14-924	2007/03/27	Hydraulic test	3	3	2	3	3	3	Class 3: Total coliforms, T.H.
EC-Q14-968	2008/05/12	Hydraulic test	2	1	1	2	2	2	Class 2: T. H.
EC-Q14-1603	2010/03/30	Bail sample taken 2m below WL	3	3	2	3	1	2	Class 3: F; Class 2: Turbidity, Fe.
EC-Q14-1651	2007/09/17	sampled from pumped stream	2	1	1	1	2	2	Class 2: T. H.
New boreholes									
EC-Q14-1630	2007/09/13	Just after drilling	4	4	4	4	3	3	Class 4: Turbidity; Class 3: T.H., Mg; Class 2: EC, TDS, Ca, F, Fe.
EC-Q14-1631	2008/02/01	Hydraulic test	2	2	1	2	2	2	Class 2: F, T.H.
EC-Q14-1632	2009/12/12	Packer test at 194-236mbgl	3	3	3	3	3	3	Class 3: T.H., Mg; Class 2: EC, TDS, Turbidity, Ca.
EC-Q14-1633	2008/02/05	Hydraulic test	3	3	2	3	2	2	Class 3: F; Class 2: pH, Ca, T. H.
EC-Q14-1634	2008/02/16	Hydraulic test	2	1	1	2	2	2	Class 2: T. H.
EC-Q14-1635	2008/04/30	Sampled during drilling	4	4	4	4	4	4	Class 4: Turbidity; Class 3: Fe.
EC-Q14-1636	2009/12/10	Packer test at 121-126mbgl	1	1	1	1	1	1	
EC-Q14-1637	2010/05/13	Hydraulic test	2	1	1	1	2	2	Class 2: T. H.
EC-Q14-1653	2008/06/26	Just after drilling	2	2	1	2	2	2	Class 2: Total coliforms, T. H.
EC-Q14-1655	2010/05/07	Hydraulic test	2	1	1	2	2	2	Class 2: T. H.
EC-Q14-1662	2010/02/05	Hydraulic test	3	2	2	3	3	3	Class 3: T. H.; Class 2: Turbidity.

9.5 Water treatment options

From the hydraulic testing chapter, boreholes that are recommended for Middelburg water supply supplementation are EC-Q14-1637 and EC-Q14-1655 for a phase A well field development and either new and existing boreholes in Karmel (EC-Q14-1653 for e.g.) or Dunblane (EC-Q14-1631, EC-Q14-1632 and EC-Q14-1603) sub-catchment for phase B well field development.

For these boreholes, treatment options for the constituents identified in the water quality classification section 9.4 are provided in Table 9-5. For a more detail discussion of the various treatment options identified, the reader is referred to the DWA quality of domestic supplies assessment guide (DWAF, 1998).

9.6 Chloride interpolation of new and existing boreholes

From the existing and new borehole water qualities analysed a database of 415 boreholes was compiled. An interpolation of chloride was performed for these 415 spatially distributed boreholes. The kriging interpolation method was used and the results of two software packages namely Surfer 9 and ArcGIS: Geostatistical Analyst were compared. Geostatistical Analyst as a specialist extension of ArcGIS has an analysis wizard that automatically evaluates that data, creates and plots semi-variograms that are then used to optimize the kriging interpolation. The Geostatistical Analyst interpolation results in this case created the best interpolation when accuracy and the combination of smallest cell size and smoothest interpolation are considered. A raster grid of the interpolated chloride values was created with a 252m grid cell resolution. Figure 9-5 presents the interpolation result graphically.

The map in Figure 9-5 creates a very good idea of where high groundwater recharge occurs as well as where highly mineralised groundwater/ low recharge occur. Highest recharge occurs in mountainous regions where rocks outcrop. It is evident that there is correlation between highly mineralised groundwater and the major drainages in the study area, especially in the Municipal sub-catchment. All drainages within the study area are non-perennial and the drainages in the Municipal sub-catchment only flow after large rainfall events or if the Grootfontein Agricultural College stops pumping from the Grootfontein weir spring. Clearly evaporation of groundwater takes place and concentrates dissolved constituents in groundwater. There is also major groundwater abstraction taking place along the drainages in the Municipal sub-catchment.

Table 9-5: Treatment options for problem constituents in recommended boreholes

Problem constituent	Symbol	Units	Problem range	Treatment options (DWAF, 1998)
Microbiology: Total & faecal coliforms		Counts / 100mℓ	standard procedure	Full removal requires disinfection: - chemical disinfection eg. Chlorine - physical disinfection eg. Ultra filtration or UV light Recommend keeping free available chlorine residual 0,2 - 0,5 mg/ℓ to ensure disinfection in distribution system
Calcium	*Ca*	mg/l	93	- chemical precipitation & sedimentation - large volumes - cation exchange softening: replaces Ca with Na - demineralisation techniques such as ion exchange
Electrical conductivity	*EC*	mS/m	184	Energy intensive processes required: - reverse osmosis - electrodialysis - distillation - demineralisation with mixed bed resin ion-exchange Requires high level of operator skill & maintenance; concentrated brine could present disposal problems
Fluoride	*F*	mg/l	1.11-1.86	Difficult to remove from water at low concentrations; Effective removal requires advanced technology: - activated alumina or bone char to absorb fluoride - desalinisation with ion-exchange resins Requires high level of operator skill & maintenance
Iron	*Fe*	mg/l	0.34	If iron is uncomplexed such as in groundwater: - aeration to precipitate Fe from solution Conventional treatments: - coagulation - flocculation - coupled with use of strong oxidant (complexed Fe) & lime if necessary usually effective in removing iron from solution
Magnesium	*Mg*	mg/l	130	- Lime softening & re-carbonation Other techniques include: - ion exchange resins - precipitation of Mg at high pH
Total dissolved solids	*TDS*	mg/l	1082	Energy intensive processes required: - reverse osmosis - electrodialysis - distillation - demineralisation with mixed bed resin ion-exchange Requires high level of operator skill & maintenance; concentrated brine could present disposal problems
Total hardness	*T.H.*	mg/l	174-285	Conventional treatments: - chemical precipitation & sedimentation- large volumes - cation exchange softening - demineralisation techniques eg. mixed bed ion-exchange desalination - other desalination techniques
Turbidity		NTU	2.2-2.7	Excessive turbidity cause problems with water purification, flocculation and filtration Excessive turbidity also causes problems with disinfection Conventional treatment of turbidity includes: - flocculation - settlement - filtration

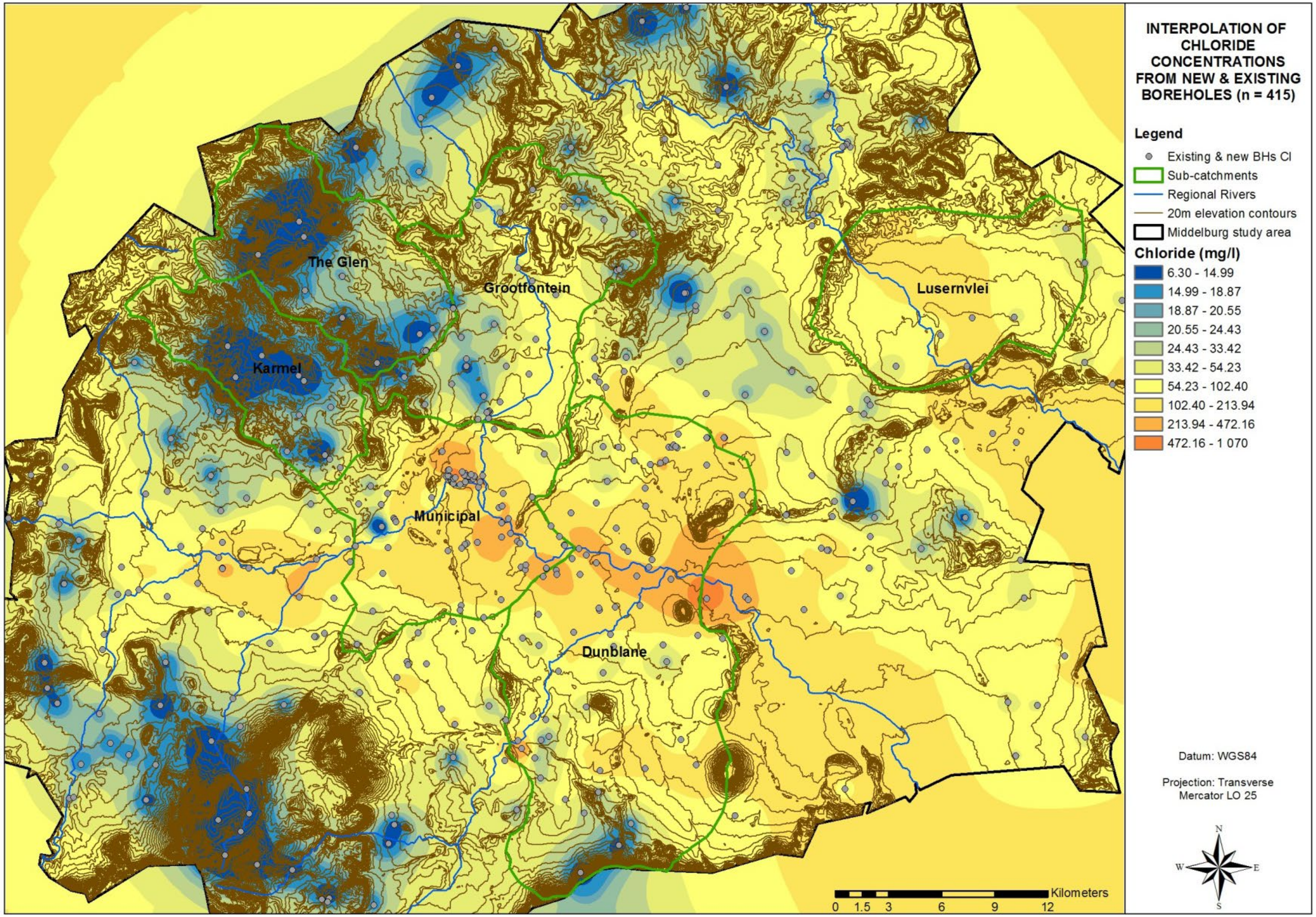


Figure 9-5: Kriging interpolation of all (n=415) chloride values sampled at boreholes, effectively representing a map of recharge

9.7 Conclusions & recommendations from hydrochemistry

- The highly mineralised nature of groundwater in the Middelburg ring structure (Municipal sub-catchment) is thought to be primarily the consequence of no constant flow of groundwater from the Grooftontein weir spring into the directly downstream drainage. The Grootfontein weir spring is located on the watershed between the Grootfontein and Municipal sub-catchments. As soon as the damming of spring water in the weir almost reaches the crest of the weir, two turbine pumps of the Grootfontein Agricultural College are switched on and the spring water is abstracted until the weir water level has dropped to a sufficiently low level. The weir water level rises again due to permanent spring flow and the former mentioned abstraction process is repeated iteratively. This impacts directly on the downstream groundwater, as the natural surface water and groundwater flow regime from one catchment to another is disturbed and changed. It is recommended that a two-step process be followed to improve the groundwater and surface water regime. (1) The Grootfontein weir spring abstraction practice should be reduced or stopped so that the groundwater table and groundwater quality in the Municipal and the Dunblane sub-catchments can recover and (2) Artificial Recharge (Managed Aquifer Recharge) methods should be implemented through for example the emplacing of a coarse sand or gravel section in the river bed just below the Grootfontein weir spring bridge. The river bed bottom at this location should also be modified by removing the thin clayey argillaceous impermeable top layer of the river bed to dramatically improve the infiltration of the spring water. Some form of gabion structure with wire mesh and concrete downstream wall should be constructed to protect this artificial recharge section during rainy season and flooding times.

- The other major groundwater and surface water inflow points into the Municipal sub-catchment from upstream sub-catchments should be investigated. These inflow points are for instance located at Vinkfontein and Onbekendt on the western and south-western boundary of the study area.

- From time spent in Middelburg it was obvious that residents and water users are unhappy with the current water quality. It is not clear whether the water is currently treated. Given the considerable capital expenditure that will be saved by not building a pipeline from the Orange-Fish River scheme, some of this saving could be used to build a proper water treatment plant or upgrade the existing one. This will also create much needed jobs in Middelburg.

- Within the Middelburg study area as a whole, no areas of permanently poor water qualities were observed, for example zone of permanently high fluoride values. This is mainly due to the similar lithologies and hydrogeological settings that are found across the study area. Boreholes with high fluoride for instance coincided with samples that were captured with a bailer, as opposed to samples taken at the end of a constant discharge test. In the latter case, standing water in a borehole was eliminated by groundwater flow from the aquifer. The only current temporary cases of highly mineralised groundwater can be made for the Municipal sub-catchment and catchments downstream from it, for example the Dunblane sub-catchment. The groundwater from these catchments is mineralised and even higher groundwater mineralisation is expected further downstream. The highly mineralised groundwater in the Municipal and Dublane sub-catchments however result in a Class 2 Marginal drinking water quality that is fit for human consumption. The Class 2 water quality is mainly due to Mg and Total hardness concentrations. The reason for the highly mineralised groundwater is thought to be primarily due to freshly recharged groundwater not being able to “spill over” from upstream sub-catchments as discussed in the first conclusion, or groundwater recharged upstream being cut-off by abstraction boreholes. It is thus seen as a temporary problem that can solved or groundwater quality improved by better groundwater abstraction management or artificial recharge enhancement. The mineralised groundwater would definitely be influenced to some extent by the argillaceous upper part of the unconfined aquifer as well as evaporation along drainage channel beds and banks.

10 GROUNDWATER BALANCE

10.1 Introduction

Arguably the most important aspect during a groundwater resource development project is to determine if there is enough groundwater available in the area to meet the planned supply.

10.2 Methodology

The methodology followed for the Middelburg water balance is referred to as the Groundwater Yield Model for the Reserve (GYMR) and was developed by AGES (Pty) Ltd. and Dr. JJP Vivier. The GYMR groundwater flow balance developed for Middelburg was calculated analytically. For a detail overview and development of the GYMR approach the reader is referred to the DWA RDM document entitled *Reserve Determination studies for selected surface water, groundwater, estuaries and wetlands in the Outeniqua catchment: Technical component – Knysna and Swartvlei*. The full GYMR methodology is provided on CD as Appendix E.

In essence, the GYMR approach takes into account groundwater inflows and outflows in the natural order that they would occur during the hydrological cycle. It also accounts for evapotranspiration through two different calculation methods where older methodologies have lacked the incorporation of this loss component.

The flow components incorporated into the equation for the Middelburg GYMR were the following.

$$Q_{RE} + Q_{DS} - Q_{BHN} - Q_{Bh} - Q_{LSF} - Q_{WLD} - Q_{SF} - Q_{ET} - Q_{BF} = \mathrm{S} \cdot \frac{\Delta V}{\Delta t}$$

where:

Q_{RE} = groundwater recharge from rainfall (m^3/a);

Q_{DS} = groundwater inflow from dam seepage (m^3/a);

Q_{BHN} = Basic Human Needs (BHN) for the Reserve (m^3/a);

Q_{Bh} = existing borehole abstraction (m^3/a);

Q_{LSF} = abstraction from boreholes for livestock farming (m^3/a);

Q_{WLD} = groundwater use from groundwater dependent wetlands (m^3/a);

Q_{SF} = spring flow losses (m^3/a);

Q_{ET} = evapotranspiration losses (m^3/a);

Q_{BF} = Groundwater baseflow losses (m^3/a);

ΔV = change in saturated aquifer volume during the time period;

Δt = time period over which the GYMR is performed, in this case per annum (*a*).

The evapotranspiration (Q_{ET}) and baseflow (Q_{BF}) loss components are included in the Middelburg GYMR as standard components, but all of the drainages are dry except during and just after storm flow and large rainfall events. Assurance levels are incorporated in the form of statistics percentile calculations of the available rainfall data, for evaluation of a drought cycle. The 5th percentile of rainfall, approximately half of mean annual precipitation (MAP), is used.

10.3 Existing Middelburg studies: Vandooleaghe (1979) water balance

Vandoolaeghe performed a brief water balance for the Klein-Brak River catchment and selected compartments. The western valley catchment was studied in greatest detail.

Vandoolaeghe (1979) estimated net inflow to the Western valley compartment from the Onbekent compartment at $2x10^5$ m^3/a. Groundwater recharge to the western valley aquifer through mountainous recharge (7% of rainfall) and recharge on the plains (2% of rainfall) amounted to $11x10^6$ m^3/a (Vandoolaeghe, 1979). He noted that slightly less than two-thirds of the catchment is mountainous. According to Vandoolaeghe (1979) total borehole abstraction in the western valley catchment amounted to $-5.5x10^6$ m^3/a. Losses within the compartment through spring flow and evapotranspiration were estimated at $-2.7x10^6$ m^3/a. These sinks and losses accumulate to more than the current borehole abstraction (-7 761 837 m^3/a) calculated during this investigation's water balance. The western valley compartment area was calculated at 605 km^2, approximately 69% of the total sub-catchment area evaluated in this investigation (877 km^2). Total outflow through the semi-permeable Dunblane (Middelburg) dyke was estimated at $-1.5x10^6$ m^3/a.

According to Vandoolaeghe (1979), the unconfined aquifer is divided into a number of compartments by semi-permeable dolerite intrusions. He highlighted the western valley-, Grootfontein- and eastern valley-compartments as being the most important.

Vandoolaeghe estimated recharge at 2% for the plains and 7% for the mountainous areas while he used a 4% recharge from rainfall figure for the Klein-Brak River catchment as a whole.

From extensive drilling and pumping tests, the specific yield of the western valley compartment was calculated at $1.5x10^{-2}$ while the specific yield for the Grootfontein compartment was calculated at $4x10^{-2}$ (Vandoolaeghe, 1979).

10.4 Water demand

10.4.1 Current municipal abstraction

Current municipal abstraction has been reported to be approximately 80 litres per second (ℓ/s) over a 24 hour duty cycle from 15 municipal production boreholes within a 6 km radius of the town (Middelburg municipality, 2007).

Municipal pumping station (abstraction borehole) monthly abstraction volumes are only available from January 2001 to June 2006. From these monthly volumes a maximum annual abstraction of 56 litres per second over a 24 hour duty cycle was recorded for 2001. Although there is a 24 litres per second difference between these two figures, the decision was made to work with the reported estimate of 80 ℓ/s as a conservative approach. This is in line with the precautionary principle.

10.4.2 Current consumption per capita

Based on a previous investigation done by WRP in 2006, the average water consumption for Middelburg and its suburbs Kwanonzame, Lusaka and Midros is 194 litres per capita per day (ℓ/c/d). Middelburg town's per capita usage by itself is very high at approximately 400 ℓ/c/d. The current population estimate is approximately 48 000 people. The current peak water demand is calculated to be approximately 100 ℓ/s.

10.4.3 Water supply phase 1: Immediate drought relief

The town of Middelburg urgently requires 20 ℓ/s for general town water use for immediate drought relief (Inxuba Yethemba, 2007). This phase is currently being addressed with 20 ℓ/s of groundwater supplied from The Glen sub-catchment. After the implementation of the first phase, a second phase of groundwater development will be undertaken and another 20 ℓ/s supplied. This brings the new supplement of groundwater up to a total of 40 ℓ/s above the 80ℓ/s currently supplied.

10.4.4 Future 2024 water demand

The future municipal water demand seasonal peak was calculated by GAST (2006) to be 153 ℓ/s in 2024 based on 300 ℓ/c/d in Middelburg, 120 ℓ/c/d in Kwanonzame, Lusaka, Midros and Rosmead and projected total population of 59 971 people in 2024. The future per capita demands seem rather high, but this future demand is used as a conservative approach.

10.5 Results

10.5.1 Rainfall, assurance levels and groundwater recharge

Middelburg, Eastern Cape is located in an arid region of the country and has a mean annual precipitation (MAP) of 348.1 mm/a (Middleton & Bailey, 2008; SAWS, 2013). The quaternary based rainfall from the WR2005 (Middleton & Bailey, 2008) dataset was used in the GYMR. Where the saturated volume fluctuation (SVF) groundwater recharge method was used, daily rainfall (2008 – 2010) obtained from the Argricultural Research Council (ARC) was initially used from an automatic rainfall station at the Grootfontein Agricultural College near Middelburg. Daily rainfall data from a South African Weather Service (SAWS, 2013) rainfall gauge at the Middelburg correctional services was used to later revise SVF estimates.

10.5.1.1 Rainfall

Quaternary catchment Q14B (Karmel, The Glen, Grootfontein and Middelburg) has a MAP of 345 mm/a calculated during the WR2005 project. The rainfall data spans from 1920 – 2005 to provide 85 hydrological years of rainfall data. Karmel, The Glen, Grootfontein and Middelburg Municipal sub-catchments have a minimum annual precipitation of 150 mm/a, a maximum annual precipitation of 734 mm/a and a standard deviation of 110 mm/a. The 5th percentile (only five MAP values in the dataset fall below this interval) was calculated at 191 mm/a and the 95th percentile calculated to be 526 mm/a (WR2005 data).

Quaternary catchment Q14C (Dunblane sub-catchment) has a MAP of 320 mm/a calculated during the WR2005 project. The rainfall data spans from 1920 – 2005 to provide 85 hydrological years of rainfall data. Karmel, The Dunblane sub-catchment has a minimum annual precipitation of 140 mm/a, a maximum annual precipitation of 680 mm/a and a standard deviation of 102 mm/a. The 5th percentile (only five MAP values in the dataset fall above this interval) was calculated at 177 mm/a and the 95th percentile calculated to be 488 mm/a (WR2005 data).

Quaternary catchment Q11D (Lusernvlei sub-catchment) has a MAP of 314 mm/a calculated during the WR2005 project. The rainfall data spans from 1920 – 2005 to provide 85 hydrological years of rainfall data. The Lusernvlei sub-catchment has a minimum annual precipitation of 128 mm/a, a maximum annual precipitation of 662 mm/a and a standard deviation of 102 mm/a. The 5th percentile (only five MAP values in the dataset fall above this interval) was calculated at 176 mm/a and the 95th percentile calculated to be 478 mm/a (WR2005 data).

10.5.1.2 Assurance levels

As with hydrological investigations and dam construction projects, the GYMR approach uses probability statistics to provide a confidence level to the assurance of water supply and address the inherent uncertainty in the volume of groundwater calculated to be available in a catchment. The assurance levels are implemented through the use of confidence intervals for population percentiles, calculated from the available rainfall data. The 5^{th} percentile of the rainfall within a catchment is used as the annual rainfall, and not the MAP as is normally used in other groundwater balance approaches. The 5^{th} percentile represents a 1 in 20 year drought as drought periods are known to occur in South Africa. For catchment Q14B for instance the MAP is 345mm/a while the 5^{th} percentile is 191 mm/a, 20mm more than half of the MAP. It can be said that the annual rainfall will be 191 mm/a or more 95% of the time, given the available data (population). Hence a lower bound estimated volume of groundwater available is reported and the actual volume can only be more, based on rainfall. If more data becomes available and a more accurate water balance or model is calculated it should theoretically then only report a greater volume of groundwater available. This ensures a more sustainable strategic planning approach and that no surprises are discovered at an advanced stage of the water supply development.

10.5.1.3 Recharge from Cl mass balance method

The chloride mass balance (CMB) groundwater recharge confirmed the estimates Vandoolaeghe (1979) noted of high recharge in the mountainous areas and lower recharge in the floodplains. The CMB method is an effective groundwater recharge estimation method to use in in semi-arid and arid areas if reasonable soil/overburden thickness occurs (Bredenkamp *et al.*, 1995; Wood, 1999). The CMB results found during this investigation from a good spatial borehole distribution (n = 415), support the findings from other semi-arid investigations (). The chloride mass balance equation is defined as:

$$RE = \frac{Cl_{rain}}{Cl_{gw}} \cdot Rf$$

Where RE = groundwater recharge (mm)/time unit, Cl_{rain} = the chloride (Cl) concentration in the rain water, Cl_{gw} = Cl concentration in the groundwater and Rf = rainfall in mm per relevant time unit.

The Glen and Karmel sub-catchments are adjacent mountainous sub-catchments located on the watershed of the Fish to Tsitsikamma and Upper Orange water management areas (WMA). These sub-catchments are created by ring structures and also have alluvial plains at their centres, with groundwater and surface water generally exiting through a single downstream “poort”/valley (assuming little groundwater flow occurs along younger dykes cutting through ring structure compartment boundaries). These sub-catchments are predominantly undeveloped with minimal abstraction, thus if they are large enough, an accurate annual groundwater safe yield can be calculated for them.

The Glen sub-catchment has a dataset of 14 spatially distributed boreholes where chloride was sampled, of which five boreholes were sampled at the end of a constant discharge or abstraction period. All boreholes in the dataset were used during the chloride mass balance calculation and a recharge figure of 6.7% was obtained. Karmel sub-catchment has a dataset of 11 spatially distributed boreholes sampled for chloride and a recharge figure of 7.0% was calculated. Again, all boreholes in the dataset was used.

The Grootfontein sub-catchment has predominantly mountainous or outcropping dolerite boundaries, but also has a large alluvial plain at its centre. It has a dataset of 31 boreholes sampled for chloride. All boreholes in the dataset were used and a chloride mass balance recharge figure of 4.0% was calculated.

In the predominantly fluvial floodplain areas such as the Middelburg Municipal and Dunblane sub-catchments, evaporation of groundwater occurs along drainages and concentrates dissolved salts in the groundwater.

In the Dunblane sub-catchment 8 boreholes with high chloride concentrations located along the non-perennial Klein-Brak- and Oompiespruit Rivers were removed. Two anomalous Cl values were also removed from the dataset.

22 chloride records were removed from the Middelburg Municipal sub-catchment dataset, all of which are situated in the town. Chloride values in the town boreholes are concentrated by abstraction. Even after the highest (>300 mg/ℓ) chloride concentrations in town are removed from the dataset, the Middelburg sub-catchment still has a mean chloride concentration of 149.2 mg/ℓ that amounts to less than 1% recharge (0.68%). The recharge of 0.7% is obviously influenced by evaportranspiration and thus represents an effective recharge. The recharge figure is not regarded as representative for the sub-catchment due to the skewed nature of the chloride method when evaporation and concentrated abstraction is present.

As described in chapter 9, the fact that overflow of groundwater from the Grootfontein sub-catchment does not occur anymore and inflow from the western valley is also limited by abstraction at Zonnebloem 1 & 2, also decreases fresh groundwater entering the Middelburg ring structure and Middelburg municipal sub-catchment through lateral inflow.

The large role of evapotranspiration of groundwater along meandering drainages and the focused abstraction in town becomes apparent as the dissolved salts are concentrated and the Cl values are much higher than the surrounding floodplain or pediplain values.

The Lusernvlei sub-catchment has a dataset of 7 boreholes of which one was removed. It was situated directly on the Rooispruit non-perennial drainage. A CMB recharge of 2.1% was calculated including a borehole where less groundwater circulation and evaporation is apparent (centre of floodplain away from drainage).

The map of interpolated chloride concentrations from sampled boreholes effectively represents groundwater recharge variation across the study area (see Figure 9-5).

10.5.1.4 Recharge from the saturated volume fluctuation (SVF) method

The SVF method was applied to The Glen and Grootfontein sub-catchments for comparative purposes. Application of the SVF method to other catchments was not attempted as they have too many unknown variables to perform SVF recharge estimations with confidence. The SVF equation used is of the form:

$$I - O + RE - Q = \frac{\Delta V}{\Delta t}$$

where:

I = lateral inflow;

O = lateral outflow;

RE = groundwater recharge;

Q = net discharge or abstraction from the groundwater system;

ΔV = change in the saturated volume of the aquifer;

Δt = t_2-t_1 or the time period for which the water balance is calculated.

The results for the SVF recharge calculations are presented in Table 10-1.

The Glen sub-catchment is a good candidate for the SVF method since there is no lateral inflow; it is located on the watershed. The SVF recharge estimate is equal to the effective recharge, meaning all losses have already been accounted for. The estimate obtained is however not regarded as thoroughly verified, since there is only about a year and a half of daily water level measurements available. Approximately one season's water level data was available and it can be seen from limited water level data before the SVF time period used that there was a larger water level change.

10.5.1.5 Woodford trend line recharge estimation method

A method of groundwater recharge estimation developed by Allan Woodford during the DWAF Groundwater Resource Assessment II (GRA II) project, termed the "Woodford trend line" was also used for recharge estimation (DWAF, 2006). The equation is published as:

$$y = 0{,}0001x^2 + 6^{-16x} - 8^{-13}$$

where:

y = groundwater recharge in mm/a;

x = mean annual precipitation in mm/a.

Using a mean annual precipitation (MAP) of 320 mm/a as obtained from the WR2005 dataset for quaternary catchment Q14C, a recharge figure of 3.2% is obtained. The MAP for Q14B from WR2005 is 345 mm/a and a recharge estimate of 3.4% was obtained.

10.5.1.6 Recharge estimates from the Vandoolaeghe (1979) geohydrological investigation

As discussed above, Vandoolaeghe (1979) estimated a recharge from MAP of 7% for the mountainous regions and figure of 2% for the plains in the study area. For the entire Klein-Brak River sub-catchment he used a recharge figure of 4%.

10.5.1.7 Groundwater recharge summary

The groundwater recharge percentage of rainfall for each estimation method is given in Table 10-1. The recharge figures for each sub-catchment were further calibrated during the development of the Groundwater Yield Model for the Reserve.

The SVF method could not be applied to the Dunblane and Municipal sub-catchment due to the large abstraction unknowns. The SVF method was not attempted for Karmel as this sub-catchment's composition and geomorphology is much the same as The Glen. The Lusernvlei sub-catchment balance is regarded as less important due to its distance from Middelburg, therefore no SVF estimate was calculated. The CMB estimate for Lusernvlei is however regarded as an effective recharge estimate due to the inclusion of evapotranspiration affected boreholes.

Table 10-1: Comparison of recharge estimates obtained from different recharge calculations

Sub-catchment	CMB	SVF	Woodford trend line	Vandoolaeghe (1979)	Predominant morphology
The Glen	6.7%	3.3%	3.4%	7.0%	mountainous
Karmel	7.0%	-	3.4%	7.0%	mountainous
Grootfontein	4.0%	2.2%	3.4%	4.0%	floodplain-mountainous
Municipal	0.7%	-	3.4%	2.0%	floodplain
Dunblane	1.3%	-	3.2%	2.0%	floodplain
Lusernvlei	2.1%	-	3.2%	4.0%	floodplain-mountainous

10.5.2 Groundwater volume in storage

The volume of groundwater that is in storage in an aquifer is an important component to the groundwater balance as the storage acts as a buffer during drought years when abstraction is more than groundwater recharge. Without groundwater in storage, well fields and schemes would immediately fail during drought years. The groundwater storage component is the reservoir or dam in the aquifer system.

Based on depth of fracturing and water strikes encountered during Middelburg exploration drilling, a maximum aquifer depth could be determined. From aquifer testing an overall storage coefficient (S) could also be determined for a combination of the shallow alluvial and weathered unconformity aquifer (±1.00E-2) and the much thicker fractured rock aquifer (±1.00E-3) below. For groundwater volume in storage used in the GYMR balance, a storage coefficient (S) of 1.00E-3 was used due to the dominant thickness of the fractured rock aquifer and as a conservative approach.

Table 10-2 below shows the groundwater volumes in storage based static water levels (water tables, hydraulic heads) measured during the hydrocensus and delineated sub-catchments.

A water level management constraint of 25% is also placed on the max aquifer thickness (b) to indicate usable groundwater in storage, to prevent permanent aquifer deformation and to provide a depth guide for engineers for installation of pump cut-out switches.

Table 10-2: Groundwater volume in storage (m^3) for each sub-catchment

Sub-catchment	Surface area (km^2)	Depth to water level (m)	Min depth to water level (m)	Max aquifer depth (m)	Water level management constraint (m)	Aquifer storativity	Groundwater volume in storage (m^3)	Max usable groundwater volume in storage (m^3)
The Glen	108	-11.9	-5.0	-100.0	-36.9	0.0010	5 711 429	3 447 274
Dunblane	286	-10.5	-0.8	-118.0	-40.0	0.0010	18 463 291	11 218 331
Middelburg Municipal	133	-11.2	-1.6	-236.0	-70.2	0.0010	17 980 788	9 153 592
Karmel	82	-11.9	-1.4	-129.0	-44.1	0.0010	5 787 010	3 517 057
Lusernvlei	124	-11.3	-1.4	-192.0	-59.3	0.0010	13 388 804	7 154 049
Grootfontein Compartment	143	-13.8	-1.4	-25.0	-20.1	0.0010	958 033	2 675 638
Total	**877**						**62 289 355**	**37 165 940**

10.5.3 Dams seepage

There are no large surface water bodies present in the Middelburg study area. The only smaller surface water bodies that could represent appreciable groundwater seepage are in the Grootfontein sub-catchment. A seepage area of 500 m^2 has been assigned to the seepage component of the Grootfontein sub-catchment.

10.5.4 Basic human needs (BHN) Reserve

A population figure of 48 000 people was obtained for Middelburg town from the Middelburg local municipality. Population figures were also estimated for the other sub-catchments based on the number of farms as well as the AGES hydrocensus conducted in these catchments. Based on these population figures the Basic Human Needs Reserve allocation was calculated and subtracted from the balance in each catchment. Because groundwater supply to all people in the Middelburg town has already been accounted for in the existing borehole abstraction, the BHN Reserve calculation was scaled down accordingly for the Middelburg sub-catchment.

10.5.5 Current borehole abstraction

Three estimates of groundwater abstraction have been calculated to compare different abstraction scenarios:

1. Potential abstraction based purely on hydrocensus results, reported yields, known equipment mean yields and duty cycle information where available;
2. Estimated abstraction (AGES) based on hydrocensus results, known equipment yields, experience from other groundwater investigations and abstraction realistically possible from a given geological formation;
3. Water level-transmissivity (T) based abstraction through use of the Cooper-Jacob equation.

The first calculated abstraction estimate is probably an over-estimation while the second could be an under estimation. The third abstraction estimate was found to best correlate with water levels and it is the only abstraction estimate that could be calibrated to a directly measured parameter. From the results it is recommended that the yields of large abstraction point sources, such as centrifugal pump borehole installations be verified and field tested. This task should be undertaken for the Dunblane and Municipal sub-catchments.

10.5.6 Reported municipal abstraction

The reported current municipal abstraction and demand has been discussed in the water demand section 10.4. Current reported municipal abstraction of 80 litres per second (ℓ/s) or 2 522 880 m^3 per annum is used in the potential abstraction for the Present Day scenarios. A combined existing, residential and municipal abstraction figure is used in the AGES estimated abstraction Present Day scenarios for the Middelburg Municipal sub-catchment. The AGES abstraction estimate for the Middelburg Municipal sub-catchment was based on the measured monthly municipal abstraction volume of 56 ℓ/s.

10.5.7 Total livestock farms water use

The primary type of farming practiced in the Middelburg study area is livestock farming. The groundwater used for livestock watering has however already been accounted for in the existing abstraction of boreholes surveyed on all farms during the hydrocensus. Livestock watering is primarily supplied from wind pumps and from the concrete dams they supply right next to them.

10.5.8 Total mine usage

There are currently no mines in the study area.

10.5.9 Community groundwater use

Community groundwater use has been addressed in the current/ existing borehole abstraction and has also been further supplemented by the basic human needs (BHN) Reserve allocation in 10.5.4.

10.5.10Wetland water use

Wetland surface area coverage in the study area was derived from 1: 50 000 topographic maps, 1: 10 000 ortho-rectified photos, field work and subsequent Google Earth imagery evaluation. Based on the wetland surface areas, groundwater use was calculated. It was assumed that wetlands were groundwater driven. Total wetlands in the study area were very small in comparison to the total sub-catchment areas due to the arid climate of the Middelburg area and also due to mean groundwater level being 10.78 mbgl.

10.5.11Spring flow

Springs were identified from existing NGDB data, previous geology and geohydrological studies as well as during the comprehensive GRIP hydrocensus. In many cases, flows were estimated and noted during the GRIP hydrocensus survey. Accordingly total springs and flows were used per sub-catchment in the GYMR groundwater flux balance.

The perennial Grootfontein weir spring in the Grootfontein compartment/ sub-catchment is the largest spring in the study area and its yield well defined through discussions with the Grootfontein Agricultural College. The College uses the yield from the spring to irrigate 18 ha of crops with 1500 mm of groundwater per annum. The area/ seepage zone of the Grootfontein weir spring has been dug deeper with TLB in 2009 to better accumulate and channel the groundwater. The spring is created by a dolerite ring structure/ embankment at the most downstream point of the Grootfontein compartment and provides the proof that the Grootfontein compartment/ sub-catchment still has a positive groundwater balance of at least 270 000 m^3/a or 8.6 ℓ/s.

10.5.12Evapotranspiration

As mentioned in the Methodology section, the evapotranspiration (Q_{ET}) loss component is not directly included in the Middelburg GYMR because all of the drainages are dry except during and just after storm flow and large rainfall events. This does however not preclude that evapotranspiration does not occur. The possibility of evapotranspiration losses have however been taken into account by applying effective recharge estimates through the SVF method. The SVF method can be applied in compartments where monthly groundwater level fluctuations, accurate abstraction and monthly rainfall are known.

10.6 Discussion

The analytical Groundwater Yield model for the Reserve (GYMR) flux balance was used to calculate scenarios of available groundwater per sub-catchment through a balance of groundwater sources, sinks and losses (springs). Five groundwater scenarios were simulated. Flow components were also evaluated and considered in sub-scenarios within main scenarios. Sub-scenarios are denoted below by alphabetical numbering. Based on the scenario outcomes management decisions can be made in planning going forward.

The scenarios were:

1. Present day (current) scenario, chloride mass balance (CMB) and saturated volume fluctuation (SVF) recharge estimates applied to the 5th percentile (95% assured) of rainfall. Worst case scenario:
    a. Potential existing abstraction used (based on equipment installed and duty cycles from hydrocensus);
    b. AGES estimated abstraction;
    c. AGES reported GYMR.
2. Present day scenario, CMB and SVF recharge estimates applied to mean annual precipitation (MAP). Best case scenario:
    a. Potential abstraction used;
    b. AGES estimated abstraction.
3. Present day scenario: Comparison of the CMB recharge estimates applied to the 5th percentile (95% assured) of rainfall and the SVF recharge estimates applied to MAP. These sub-scenarios are perceived to be the most realistic estimates of groundwater volumes in the study area achievable within the GYMR balance workflow.
    a. Potential abstraction used. Shown to be an overestimation;
    b. AGES estimated abstraction: Best case scenario, but thought to be an underestimation in three sub-catchments;
    c. SVF and CMB recharge applied to MAP rainfall and use of water level-transmissivity estimated abstraction (best actual present day balance estimate);
    d. ‘Woodford (2006) trend line’ recharge estimates applied to MAP and the use of water level-transmissivity estimated abstraction (best case realistic balance estimate).
4. The Glen Implementation: Immediate drought relief (20 ℓ/s) scenario:
    a. SVF and CMB recharge applied to MAP rainfall and use of water level-transmissivity estimated abstraction;

    b. 'Woodford (2006) trend line' recharge estimates applied to MAP and the use of water level-transmissivity estimated abstraction.

5. Future scenario 155 ℓ/s
    a. SVF and CMB recharge applied to MAP rainfall and use of water level-transmissivity estimated abstraction;
    b. 'Woodford (2006) trend line' recharge estimates applied to MAP and the use of water level-transmissivity estimated abstraction.

<u>Assumptions and analytical model limitations</u>

Storativity (S) is not taken into account in the analytical (deterministic) balance since the groundwater volume in storage over time is not considered. The balance is assessed using annual volumes, and groundwater inflows (sources) are solely represented by groundwater recharge and earthen dam seepage.

Storativity was however considered during the calculation of the water level-transmissivity based abstraction estimates.

In reality, the Middelburg study area groundwater system is in equilibrium (steady-state) or constantly adjusting to reach equilibrium. Groundwater sources (inflows) are counter-balanced by groundwater sinks (outflows); notably borehole abstraction, vegetation water use, spring losses, riparian zone evapotranspiration losses and finally baseflow. All drainages in the study area are non-perennial, thus the groundwater level is below or just below the base of the channels of the drainages. Due to the groundwater level being below the drainage channel base, evapotranspiration from riparian vegetation has been assumed absent as a groundwater loss in the analytical GYMR balances.

10.6.1 Scenario 1: Present day GYMR 95% assured rainfall

Scenario 1 (a) represents the minimum current amount of groundwater available with the potential existing abstraction estimate calculated. The potential abstractions are in the cases of the Dunblane, Middelburg Municipal and Lusernvlei sub-catchments expected to be over-estimated. Scenario 1 (a) thus gives a drought year and worst case abstraction estimate.

Table 10-3: Scenario 1(a) present day 95% assured rainfall with potential existing abstraction

Catchment	The Glen	Dunblane	Municipal	Karmel	Lusernvlei	Grootfontein Compartment
Surface Area (km^2)	108	286	133	82	124	143
MAP (mm/a) WR2005 Data	345.0	320.0	345.0	345.0	316.0	345.0
MAE (mm/a) SA WR2005 Data	1 850	1 850	1 850	1 850	1 800	1 850
MAR (%) WR2005	3.78%	3.26%	3.78%	3.78%	2.53%	3.78%
MAR (m^3/a) WR2005	1 409 298	2 986 291	1 739 095	1 073 937	988 204	1 866 769
Recharge Chloride Mass Balance (CMB) method (%)	6.7%	2.0%	2.0%	7.0%	2.1%	4.0%
Recharge Saturated Volume Fluctuation (SVF) method (% of MAP)	3.3%	2.0%	2.0%	3.3%	2.0%	2.2%
Rainfall 95% assured WR2005 (mm/a)	190.5	176.7	190.5	190.5	175.9	190.5
CMB Recharge 95% assured rainfall (m^3/a)	1 372 633	1 011 316	507 916	1 102 742	460 385	1 101 311
SVF Recharge 95% assured rainfall (m^3/a)	683 543	1 002 511	503 493	520 885	488 661	613 087
Total dam seepage (m^3/a)	0	0	0	0	0	50
Basic Human Needs for Reserve [l/p/p/d] (m^3/a)	-5475	-10950	-13 334	-5475	-5475	-5475
Number of abstraction boreholes	21	111	123	20	40	53
Potential existing borehole abstraction (m3/a)	-168 345	-2 938 118	-1 959 752	-293 037	-944 605	-764 297
Number of Municipal abstraction boreholes	0	0	15	0	0	0
Reported Municipal abstraction (m3/a)	0	0	-2 522 880	0	0	0
Wetlands (groundwater driven) (km^2)	3	2	1	2	1	3
Wetland water use (m3/a)	-750	-500	-250	-500	-250	-750
No of springs	4	3	2	0	1	2
Spring flow (m3/a)	-11 826	-9 461	0	0	-6 623	-270 000
Total inflow CMB 95% assured (m3/a)	1 372 633	1 011 316	507 916	1 102 742	460 385	1 101 361
Total inflow SVF 95% assured (m3/a)	683 543	1 002 511	503 493	520 885	488 661	613 137
Total outflow before losses (sinks) m3/a	-186 396	-2 959 028	-4 496 216	-299 012	-956 953	-1 040 522
Time (y) to reach groundwater storage management constraint	NA	4.65	3.59	NA	9.45	NA
Net balance (baseflow) - CMB recharge (m^3/a)	1 186 238	-1 947 712	-3 988 300	803 730	-496 568	60 840
Net balance (baseflow) - SVF recharge (m^3/a)	497 148	-1 956 518	-3 992 722	221 873	-468 292	-427 385
Potential stress status CMB (total outflow / total inflow)	14%	293%	885%	27%	208%	94%
95% assured CMB balance (ℓ / s)	37.62	-61.76	-126.47	25.49	-15.75	1.93
95% assured SVF balance (ℓ / s)	15.76	-62.04	-126.61	7.04	-14.85	-13.55

Table 10-3 shows scenario 1 (a) with all participating balance flux components. The components mean annual evaporation (MAE), mean annual runoff (MAR) WR2005, total dam seepage, basic human needs (BHN), wetlands (groundwater driven) and springs will remain the same for all other scenarios and will be excluded from further table presentation to simplify the GYMR balance.

The SVF based recharge estimate shown in Table 10-3 cannot be regarded as accurate when used in conjunction with the 5th percentile of rainfall (95% assured rainfall), since the SVF method uses actual daily rainfall and abstraction data and not the 5th percentile of either one of these. The SVF recharge percentage must be used in conjunction with the MAP of the recorded rainfall data to obtain an annual volume of groundwater recharge. The SVF method provides an effective recharge estimate, meaning evapotranspiration has already been taken into account. It is only shown here to provide some insight into the sensitivity of the recharge percentage used.

As the minimum amount of groundwater available has been determined, and the groundwater balance further refined and evaluated, the SVF recharge estimates applied to MAP rainfall are adopted, taking into consideration other estimates where the SVF method could not be calculated (Dunblane, Middelburg, Lusernvlei) due to abstraction uncertainties.

The first scenario for Lusernvlei is not regarded as accurate as there is still a spring present in the valley of the sub-catchment that is being used for irrigation. Thus the abstraction cannot be more than the groundwater recharge; otherwise the spring would be dry.

It can be seen that in the cases of Dunblane, Middelburg Municipal and Lusernvlei sub-catchments, outflow (sinks) from the system grossly outweighs inflow into the system due to the potential abstraction calculated from hydrocensus data. There are a number of very large point source abstraction rates reported during hydrocensus that skew the balance. These need to be field tested and verified practically by measuring the actual abstraction.

Another possibility that could perhaps explain the very high annual potential abstraction rates is if irrigation and agricultural abstraction only took place during the planting season. The GRIP hydrocensus information sheet only requires daily and weekly duty cycles, but does not enquire whether irrigation is year round or only seasonally. If the assumption is made that irrigation and agricultural abstraction took place only during planting season, then it would essentially half the annual abstraction for Dunblane and Lusernvlei.

Table 10-4: Scenario 1 (b): Present day 95% assured rainfall & AGES estimated abstraction

Sub-catchment	Surface Area (km²)	Recharge chloride mass balance (CMB) method (% of rainfall)	Rainfall 95% assured WR2005 (mm/a)	CMB Recharge 95% assured rainfall (m³/a)	AGES estimated borehole abstraction (m³/a)	Total inflow 95% assured (m³/a)	Total outflow (sinks) m³/a	Time (y) to reach GMC	Net balance (baseflow) (m³/a)	Potential stress status CMB (total outflow / total inflow)	Net balance (ℓ/sec)
The Glen	108	6.7%	190.5	1 372 633	-44 150	1 372 633	-62 201	NA	1 310 432	5%	41.55
Dunblane	286	2.0%	176.7	1 011 316	-898 305	1 011 316	-919 216	NA	92 101	91%	2.92
Middelburg Municipal	133	2.0%	190.5	507 916	-2 115 936	507 916	-2 129 520	6.82	-1 621 604	419%	-51.42
Karmel	82	7.0%	190.5	1 102 742	-64 266	1 102 742	-70 241	NA	1 032 501	6%	32.74
Lusernvlei	124	2.1%	175.9	460 385	-411 516	460 385	-423 863	NA	36 522	92%	1.16
Grootfontein Compartment	143	4.0%	190.5	1 101 311	-657 352	1 101 361	-933 577	NA	167 784	85%	5.32
Total	**877**			**5 556 304**	**-4 191 525**	**5 556 354**	**-4 538 618**		**1 017 735**		

Table 10-5: Scenario 1 (c): AGES reported GYMR balance to DWA

Sub-catchment	Surface area (km²)	Recharge chloride mass balance (CMB) method (% of rainfall)	Rainfall 95% assured (mm/a)	CMB Recharge 95% assured rainfall (m3/a)	AGES estimate existing abstraction (m³/a)	Total livestock farm usage (m³/a)	Total inflow 95% assured (m³/a)	Total outflow (sinks) m³/a	Time (y) to reach GMC	Net balance (baseflow) (m³/a)	Potential stress status CMB (total outflow / total inflow)	Net balance (ℓ/sec)
The Glen	108	5.00%	158.6	856 278	-44 150	0	856 278	-59 836	NA	796 442	7%	25.3
Dunblane	286	3.00%	158.6	1 360 531	-898 305	-15768	1 360 531	-925 523	NA	435 008	68%	13.8
Middelburg Municipal	133	3.00%	158.6	632 694	-2 115 936	-15768	632 694	-2 145 254	6.46	-1 512 560	339%	-48.0
Karmel	82	4.81%	158.6	627 725	-64 266	-15768	627 725	-95 470	NA	532 255	15%	16.9
Lusernvlei	124	5.00%	158.6	979 224	-411 516	-15768	979 224	-433 009	NA	546 215	44%	17.3
Grootfontein Compartment	143	5.00%	158.6	1 133 776	-657 352	0	1 133 826	-933 577	NA	200 248	82%	6.3
Total	**876**		**143**	**1 133 776**	**-4 191 525**	**-63072**	**5 590 277**	**-4 592 669**		**997 608**		

The biggest difference between scenario 1 (a) vs. scenario 1 (b) and (c) is the different calculated estimates for existing borehole abstraction. Both abstraction estimates (Potential and AGES) are based on evaluating yield per borehole based on pumping equipment installed, duty cycles and the status of the borehole. The potential abstraction is however based more solidly on the hydrocensus data, while the AGES estimate has been revised based on field experience. There is a high confidence in the potential abstraction estimates of Grootfontein compartment, The Glen and Karmel sub-catchments, while large abstraction uncertainties exist around Dunblane, Municipal and Lusernvlei sub-catchments. The AGES estimates are expected to be closer to reality in the latter mentioned sub-catchments.

The AGES estimated abstraction also combined the abstraction from residential boreholes, farm boreholes and municipal boreholes into one abstraction figure for the Middelburg Municipal sub-catchment. This figure has been split into existing borehole abstraction (residential and agriculture) and municipal abstraction for the potential abstraction estimate. The municipal abstraction is based on a figure reported by the municipality of ±80 litres (ℓ) per second, whilst actual monthly municipal abstraction volumes show less (maximum of 56 ℓ/s in 2001).

Recharge percentages for scenario 1 (c) (AGES GYMR to DWA) are based on the chloride mass balance (CMB) recharges calculated, but are also estimated based on existing Karoo knowledge. These estimates are in close agreement with the "Woodford trend line" recharge estimates of 3.2% and 3.4%. The Woodford (2006) estimates are however based on a national scale rainfall-recharge relationship and do not take local topography or geology into account. The CMB estimates for the mountainous sub-catchments (The Glen, Karmel, Grootfontein) are thus seen to be higher than the Woodford (2006) estimate and this also correlates well with the recharge estimates of Vandoolaeghe (1979).

The 95% assured rainfall and mountainous catchment CMB recharge estimates (5%) in scenario 1 (c) are regarded as conservative and the combination of CMB recharge and 95% assured rainfall in 1 (b) is regarded as more accurate.

Scenario 1 (c) 95% assured rainfall also differs from scenario 1 (a) and (b) 95% assured rainfall. Scenarios 1 (a) and (b) rainfall is based on the WR2005 monthly rainfall data available per quaternary catchment, whilst 1 (c) rainfall is based on historic WRIMS rainfall station specific data.

10.6.2 Scenario 2: Present day GYMR with MAP rainfall, both recharge estimates

The minimum amount of groundwater available has now been determined using the 5th percentile of rainfall, and the MAP based amount of groundwater available can be evaluated in Scenario 2.

Scenario 2 (a): Present Day GYMR with MAP rainfall and Potential existing abstraction is shown in Table 10-6 (CMB recharge) and Table 10-7 (SVF recharge). Similar scenarios, but with AGES estimated abstraction are shown in Table 10-8 and Table 10-9.

MAP rainfall combined with SVF recharge in Table 10-7 is regarded as an accurate estimate of the volume of groundwater recharged annually for planning purposes. The recharge percentages for Middelburg Municipal-, Dunblane- and Lusernvlei-sub-catchments were however calculated from the CMB method although they appear in the SVF recharge column. No SVF recharge estimates could be calculated for the 3 former mentioned catchments. Karmel sub-catchment is very similar in hydrogeology to The Glen sub-catchment and thus, the SVF recharge % calculated for The Glen was applied to Karmel. This (3.3%) is a conservative recharge estimate for the mountainous sub-catchments.

The Potential abstraction figures for Dunblane, Middelburg Municipal and Lusernvlei sub-catchments are as previously mentioned thought to be over-estimated, although they are thoroughly based on hydrocensus data.

The AGES estimated abstraction in Table 10-8 and Table 10-9 could be too low, hence actual abstraction is expected to fall somewhere in between the Potential abstraction and AGES estimated abstraction. Only field verification of the handful of high volume abstraction point sources will ensure higher confidence in the balance and refine the abstraction estimates.

The CMB recharge estimates for the mountainous sub-catchments (The Glen and Karmel) applied to the MAP are regarded as too high for planning purposes. The CMB recharge estimates obtained could however be accurate as the boreholes used were spatially distributed across The Glen and Karmel sub-catchments, chloride values were predominantly consistent and both catchments have a similar recharge figure. This figure also agrees very well with the recharge figure Vandoolaeghe (1979) used for mountainous areas in his Middelburg water supply investigation. The MAP rainfall and CMB recharge combination (Table 10-6 and Table 10-8) can then be regarded as an upper bound scenario.

Table 10-6: Scenario 2 (a): Present day MAP rainfall with CMB recharge and Potential existing abstraction

Sub-catchment	Surface Area (km²)	MAP WR2005 (mm/a)	Recharge chloride mass balance (CMB) method (%)	CMB Recharge MAP rainfall (m³/a)	Potential existing borehole abstraction (m³/a)	Reported Municipal abstraction (m³/a)	Total inflow MAP CMB (m³/a)	Total outflow (sinks) m³/a	Time (y) to reach GMC	Net balance (baseflow) - CMB recharge (m³/a)	Potential stress status CMB (total outflow / total inflow)	Net balance (ℓ / s)
The Glen	108	345.0	6.7%	2 486 384	-168 345	0	2 486 384	-186 396	NA	2 299 988	7%	72.9
Dunblane	286	320.0	2.0%	1 831 896	-2 938 118	0	1 831 896	-2 959 028	3.85	-1 127 133	162%	-35.7
Middelburg Municipal	133	345.0	2.0%	920 037	-1 959 752	-2 522 880	920 037	-4 496 216	3.32	-3 576 179	489%	-113.4
Karmel	82	345.0	7.0%	1 997 504	-293 037	0	1 997 504	-299 012	NA	1 698 492	15%	53.9
Lusernvlei	124	316.0	2.1%	826 960	-944 605	0	826 960	-956 953	7.51	-129 993	116%	-4.1
Grootfontein Compartment	143	345.0	4.0%	1 994 912	-764 297	0	1 994 962	-1 040 522	NA	954 441	52%	30.3
Total	**877**				**-7 068 153**	**-2 522 880**	**10 057 744**	**-9 938 126**		**119 617**		**3.8**

Table 10-7: Scenario 2 (a): Present day MAP rainfall with SVF recharge estimates and Potential existing abstraction

Sub-catchment	Surface Area (km²)	MAP WR2005 (mm/a)	Recharge saturated volume fluctuation (SVF) method (%)	SVF Recharge MAP rainfall (m³/a)	Potential existing borehole abstraction (m³/a)	Reported Municipal abstraction (m³/a)	Total inflow MAP SVF (m³/a)	Total outflow (sinks) m³/a	Time (y) to reach GMC	Net balance (baseflow) - SVF recharge (m³/a)	Potential stress status SVF (total outflow / total inflow)	Net balance (ℓ / s)
The Glen	108	345.0	3.3%	1 238 169	-168 345	0	1 238 169	-186 396	NA	1 051 773	15%	33.4
Dunblane	286	320.0	2.0%	1 815 946	-2 938 118	0	1 815 946	-2 959 028	3.85	-1 143 083	163%	-36.2
Middelburg Municipal	133	345.0	2.0%	912 026	-1 959 752	-2 522 880	912 026	-4 496 216	3.32	-3 584 189	493%	-113.7
Karmel	82	345.0	3.3%	943 531	-293 037	0	943 531	-299 012	NA	644 518	32%	20.4
Lusernvlei	124	316.0	2.0%	773 767	-944 605	0	773 767	-956 953	7.51	-183 186	124%	-5.8
Grootfontein Compartment	143	345.0	2.2%	1 110 544	-764 297	0	1 110 594	-1 040 522	NA	70 072	94%	2.2
Total	**877**				**-7 068 153**	**-2 522 880**	**6 794 032**	**-9 938 126**		**-3 144 095**		**-99.7**

Table 10-8: Scenario 2 (b): Present day MAP rainfall with CMB recharge and AGES estimated abstraction

Catchment	Surface Area (Km^2)	MAP WR2005 (mm/a)	Recharge chloride mass balance (CMB) method (%)	CMB Recharge MAP rainfall (m^3/a)	AGES estimated borehole abstraction (m^3/a)	Total inflow MAP CMB (m^3/a)	Total outflow (sinks) m^3/a	Time (y) to reach GMC	Net balance (baseflow) - CMB recharge (m^3/a)	Potential stress status CMB (total outflow / total inflow)	Net balance (ℓ / s)
The Glen	108	345.0	6.7%	2 486 384	-44 150	2 486 384	-62 201	NA	2 424 183	3%	76.9
Dunblane	286	320.0	2.0%	1 831 896	-898 305	1 831 896	-919 216	NA	912 680	50%	28.9
Middelburg Municipal	133	345.0	2.0%	920 037	-2 115 936	920 037	-2 129 520	5.90	-1 209 483	231%	-38.4
Karmel	82	345.0	7.0%	1 997 504	-64 266	1 997 504	-70 241	NA	1 927 263	4%	61.1
Lusernvlei	124	316.0	2.1%	826 960	-411 516	826 960	-423 863	NA	403 097	51%	12.8
Grootfontein Compartment	143	345.0	4.0%	1 994 912	-657 352	1 994 962	-933 577	NA	1 061 385	47%	33.7
Total	**877**				**-4 191 525**	**10 057 744**	**-4 538 618**		**5 519 125**		**175.0**

Table 10-9: Scenario 2 (b): Present day MAP rainfall with SVF recharge and AGES estimated abstraction

Sub-catchment	Surface Area (km^2)	MAP WR2005 (mm/a)	Recharge saturated volume fluctuation (SVF) method (%)	SVF Recharge MAP rainfall (m^3/a)	AGES estimated borehole abstraction (m^3/a)	Total inflow MAP SVF (m^3/a)	Total outflow (sinks) m^3/a	Time (y) to reach GMC	Net balance (baseflow) - SVF recharge (m^3/a)	Potential stress status SVF (total outflow / total inflow)	Net balance (ℓ / s)
The Glen	108	345.0	3.3%	1 238 169	-44 150	1 238 169	-62 201	NA	1 175 967	3%	37.3
Dunblane	286	320.0	2.0%	1 815 946	-898 305	1 815 946	-919 216	NA	896 730	50%	28.4
Middelburg Municipal	133	345.0	2.0%	912 026	-2 115 936	912 026	-2 129 520	5.90	-1 217 494	231%	-38.6
Karmel	82	345.0	3.3%	943 531	-64 266	943 531	-70 241	NA	873 290	4%	27.7
Lusernvlei	124	316.0	2.0%	773 767	-411 516	773 767	-423 863	NA	349 904	51%	11.1
Grootfontein Compartment	143	345.0	2.2%	1 110 544	-657 352	1 110 594	-933 577	NA	177 017	47%	5.6
Total	**877**				**-4 191 525**	**6 794 032**	**-4 538 618**		**2 255 413**	45%	**71.5**

10.6.3 Scenario 3: Present day, comparison of 95% assured rainfall & CMB recharge vs. MAP rainfall & SVF recharge

In Table 10-10 a recharge volume comparison is made between the CMB recharge figures applied to 95% assured rainfall and the SVF recharge figures applied to the MAP rainfall.

As shown by the recharge volumes calculated in Table 10-10, there seems to be a good correlation between the CMB estimates applied to the 5^{th} percentile of rainfall and the SVF recharge estimates applied to the MAP rainfall in the mountainous catchments. Whether this is coincidence or not is uncertain, but the cause is expected to be the 5^{th} percentile of rainfall accounting for some possible losses while the CMB method is not an effective recharge estimate and the SVF is. The CMB method lies somewhere in between an effective recharge estimation method and a recharge estimation method that does not take evapotranspiration into account (Bredenkamp *et al.*, 1995).

As the minimum amount of groundwater available has been determined, and the groundwater balance further refined and evaluated, the SVF recharge estimates applied to MAP rainfall are adopted, taking into consideration CMB estimates where the SVF method could not be calculated (Dunblane, Middelburg, Lusernvlei) due to abstraction uncertainties. The SVF method is preferred here, because it is based on measurable evidence of volume change in a catchment, through groundwater levels and rainfall.

The SVF recharge estimates (updated with CMB estimates where SVF unavailable) adopted (e.g. Table 10-11 and Table 10-12) are best of knowledge estimates for the GYMR water balances, are Middelburg specific and are also conservative for planning purposes. It is expected that all SVF recharge estimates could be higher, up to 1.0% higher in the case of Dunblane, Middelburg Municipal and Lusernvlei.

Table 10-11 (Scenario 3a) and Table 10-12 (Scenario 3b) present a good comparison between the GYMR groundwater balance outcomes with Potential abstraction and with AGES estimated abstraction used. Evident from this comparison is the large difference and uncertainty associated with abstraction. This difference equates to ± 65 ℓ/s in the case of the Dunblane sub-catchment and ± 75 ℓ/s in the case of the Municipal sub-catchment. It is recommended that this abstraction uncertainty range be reduced by field verification of several very large point source abstractions reported.

Table 10-10: Scenario 3 (a): Present day comparison of 95% assured rainfall & CMB recharge vs. MAP & SVF recharge, both with Potential abstraction volumes

Sub-catchment	The Glen	Dunblane	Middelburg Municipal	Karmel	Lusernvlei	Grootfontein Compartment
Surface Area (km^2)	108	286	133	82	124	143
MAP WR2005 (mm/a)	345.0	320.0	345.0	345.0	316.0	345.0
Rainfall 95% assured (mm/a)	190.5	176.7	190.5	190.5	175.9	190.5
Recharge Chloride Mass Balance (CMB) method (%)	6.7%	2.0%	2.0%	7.0%	2.1%	4.0%
Recharge Saturated Volume Fluctuation (SVF) method (%)	3.3%	2.0%	2.0%	3.3%	2.0%	2.2%
CMB Recharge 95% assured rainfall (m^3/a)	1 372 633	1 011 316	507 916	1 102 742	460 385	1 101 311
SVF Recharge MAP rainfall (m^3/a)	1 238 169	1 815 946	912 026	943 531	773 767	1 110 544
Total dam seepage (m^3/a)	0.00	0.00	0.00	0.00	0.00	50.00
Basic Human Needs for Reserve [l/p/p/d] (m^3/a)	-5475	-10950	-13 334	-5475	-5475	-5475
Number of abstraction boreholes	21	111	123	20	40	53
Potential existing borehole abstraction (m^3/a)	-168 345	-2 938 118	-1 959 752	-293 037	-944 605	-764 297
Number of Municipal abstraction boreholes	0	0	15	0	0	0
Reported Municipal abstraction (m^3/a)	0	0	-2 522 880	0	0	0
Wetlands groundwater driven (km^2)	3	2	1	2	1	3
Wetland water use (m^3/a)	-750	-500	-250	-500	-250	-750
No of springs	4	3	2	0	1	2
Spring flow (m^3/a)	-11 826	-9 461	0	0	-6 623	-270 000
Total inflow 95% CMB (m^3/a)	1 372 633	1 011 316	507 916	1 102 742	460 385	1 101 361
Total inflow MAP SVF (m^3/a)	1 238 169	1 815 946	912 026	943 531	773 767	1 110 594
Total outflow (sinks) m^3/a	-186 396	-2 959 028	-4 496 216	-299 012	-956 953	-1 040 522
Time (y) to reach GMC	NA	16.15	5.02	NA	73.09	NA
Net balance (baseflow) - CMB recharge (m^3/a)	1 186 238	-1 947 712	-3 988 300	803 730	-496 568	60 840
Net balance (baseflow) - SVF recharge (m^3/a)	1 051 773	-1 143 083	-3 584 189	644 518	-183 186	70 072
CMB Potential stress status (total outflow / total inflow)	14%	293%	885%	27%	208%	94%
SVF Potential stress status (total outflow / total inflow)	15%	163%	493%	32%	124%	94%
95%assure CMB balance (ℓ/ s)	37.6	-61.8	-126.5	25.5	-15.7	1.9
SVF MAP balance (ℓ / s)	33.4	-36.2	-113.7	20.4	-5.8	2.2

Table 10-11: Scenario 3 (a): Present day MAP rainfall with SVF recharge estimates and Potential abstraction

Sub-catchment	Surface Area (km2)	MAP WR2005 (mm/a)	Recharge Saturated Volume Fluctuation (SVF) method (% of MAP)	SVF Recharge MAP rainfall (m3/a)	Potential existing borehole abstraction (m3/a)	Reported Municipal abstraction (m3/a)	Total inflow MAP SVF (m3/a)	Total outflow (sinks) m3/a	Time (y) to reach GMC	Net balance (baseflow) - SVF recharge (m3/a)	Potential stress status CMB (total outflow / total inflow)	SVF Net Balance (ℓ / s)
The Glen	108	345.0	3.3%	1 238 169	-168 345	0	1 238 169	-186 396	NA	1 051 773	14%	33.35
Dunblane	286	320.0	2.0%	1 815 946	-2 938 118	0	1 815 946	-2 959 028	16.15	-1 143 083	293%	-36.25
Middelburg Municipal	133	345.0	2.0%	912 026	-1 959 752	-2 522 880	912 026	-4 496 216	5.02	-3 584 189	885%	-113.65
Karmel	82	345.0	3.3%	943 531	-293 037	0	943 531	-299 012	NA	644 518	27%	20.44
Lusernvlei	124	316.0	2.0%	773 767	-944 605	0	773 767	-956 953	73.09	-183 186	208%	-5.81
Grootfontein Compartment	143	345.0	2.2%	1 110 544	-764 297	0	1 110 594	-1 040 522	NA	70 072	94%	2.22
Total	**877**				**-7 068 153**	**-2 522 880**	**6 794 032**	**-9 938 126**		**3 144 095**		**-99.70**

Table 10-12: Scenario 3 (b): Present day MAP rainfall with SVF recharge estimates and AGES estimated abstraction

Sub-catchment	Surface Area (km2)	MAP WR2005 (mm/a)	Recharge Saturated Volume Fluctuation (SVF) method (% of MAP)	SVF Recharge MAP rainfall (m3/a)	AGES estimated borehole abstraction (m3/a)	Total inflow MAP SVF (m3/a)	Total outflow (sinks) m3/a	Time (y) to reach GMC	Net balance (baseflow) - SVF recharge (m3/a)	Potential stress status CMB (total outflow / total inflow)	SVF Net Balance (ℓ / s)
The Glen	108	345.0	3.3%	1 238 169	-44 150	1 238 169	-62 201	NA	1 175 967	5%	37.29
Dunblane	286	320.0	2.0%	1 815 946	-898 305	1 815 946	-919 216	NA	896 730	91%	28.44
Middelburg Municipal	133	345.0	2.0%	912 026	-2 115 936	912 026	-2 129 520	14.77	-1 217 494	419%	-38.61
Karmel	82	345.0	3.3%	943 531	-64 266	943 531	-70 241	NA	873 290	6%	27.69
Lusernvlei	124	316.0	2.0%	773 767	-411 516	773 767	-423 863	NA	349 904	92%	11.10
Grootfontein Compartment	143	345.0	2.2%	1 110 544	-657 352	1 110 594	-933 577	NA	177 017	85%	5.61
Total	**877**				**-4 191 525**	**6 794 032**	**-4 538 618**		**-2 255 413**		**71.52**

10.6.3.1 Abstraction estimated through groundwater levels & aquifer parameters

Although beyond the scope of the GYMR groundwater balance calculations, a third attempt at quantifying groundwater abstraction in problematic sub-catchments (Middelburg Municipal, Dunblane, Lusernvlei) was made, due to the large abstraction uncertainties involved. Since a number of hydraulic tests were performed on existing and new boreholes, good aquifer parameter data are available for the study area aquifers as well as many water levels from the hydrocensus.

It is not feasible or economically viable to field test the abstraction rate of each existing borehole in a catchment and abstraction verification field tests are normally not done. Given the information as mentioned above one can however determine a maximum sustainable yield from a borehole based on the aquifer parameters that correlates with the groundwater levels measured during the hydraulic tests and hydrocensus. The Cooper-Jacob approximation of the Theis equation was used for its simplicity and since the value of the well function, *W(u)* in the Theis equation becomes negligible after approximately one hour of pumping (Kruseman & de Ridder, 2000; Bear, 1979). Kruseman and de Ridder (2000) also state that early and late-time drawdown data from unconfined aquifers can be analysed with the Theis equation-based methods under suitable conditions. The Cooper-Jacob approximation can be defined as follows:

$$s = \frac{2{,}3Q}{4\pi T} log \frac{2{,}25Tt}{r^2 S}$$

where:

s = drawdown below static water level in metres (m);

Q = abstraction rate of the pumped well in m^3/d;

T = transmissivity in m^2/d where $T = K.b$;

K = hydraulic conductivity in m/d;

b = aquifer thickness in m;

r = distance of piezometer (observations) from pumped well in m;

t = time in days (d) since pumping started;

S = storativity or storage coefficient, dimensionless.

And abstraction, Q can be derived by rearranging the equation to:

$$Q = \frac{s\ .\ 4\pi T}{[2{,}3\log(2{,}25Tt/r^2 S)]}$$

Only large abstraction boreholes were re-evaluated, due to their sensitivity on the total abstraction figure per sub-catchment. Abstraction of the three problematic sub-catchments namely Middelburg Municipal, Dunblane and Lusernvlei was reviewed. The results obtained are more in line with what the available time-series and other water levels (hydraulic heads) are indicating. The water levels are also the best measurable benchmark to which existing abstraction can be calibrated. In this sense, the water level-transmissivity abstraction estimation method is similar to the calibration of simulated hydraulic heads with measured hydraulic heads in a numerical model.

The results of Scenario 3 (c) show that water level-transmissivity based abstraction is lower than the Potential abstraction estimate in all three sub-catchments. The water level-transmissivity estimated abstraction in the Dunblane sub-catchment was calculated to be -1 675 372 m^3/a while the Potential abstraction was -2 938 118 m^3/a, a ±1 263 000 m^3/a difference. The differences in the Municipal and Lusernvlei sub-catchments were less pronounced, with a difference of approximately 416 000 m^3/a and 151 000 m^3/a respectively. In the case of Lusernvlei, Scenario 3 (c) is closer to field observations since there is still a flowing perennial spring in the catchment, thus the groundwater balance must be positive. The final available groundwater volume (ℓ/s) for Dunblane in Table 10-14 also makes more sense when the available time series water level data is evaluated in Figure 10-1. 2009 was a below average rainfall year (233.5 mm) hence a more favourable (increasing) water level trend would be expected for 2010 (426 mm) and 2011 (524.9 mm) for example.

Table 10-13: Comparison of the three abstraction estimates

Sub-catchment	SVF Recharge MAP rainfall (m^3/a)	AGES estimated borehole abstraction (m^3/a)	Potential existing borehole abstraction (m^3/a)	Water level-transmissivity based abstraction est. (m^3/a)
Dunblane	1 815 946	-898 305	-2 938 118	-1 675 372
Middelburg Municipal	912 026	-2 115 936	-4 482 632 (-1 959 752)	-4 067 013 (-1 544 133)
Lusernvlei	773 767	-411 516	-944 605	-793 774

Although there is a contradiction in what the historically recorded municipal abstraction is (maximum 56 ℓ/s), and the reported current municipal abstraction (80 ℓ/s), the 80 ℓ/s is used in the Middelburg Municipal sub-catchment due to the current peak demand being 100 ℓ/s.

The water level-transmissivity based abstraction figures could certainly still be out by some measure, but they are the best conservative estimates currently possible within the feasible water balance workflow for planning purposes. Better abstraction estimates could well be obtained through numerical modelling. The water level-transmissivity based abstraction estimates were used in the scenarios that follow.

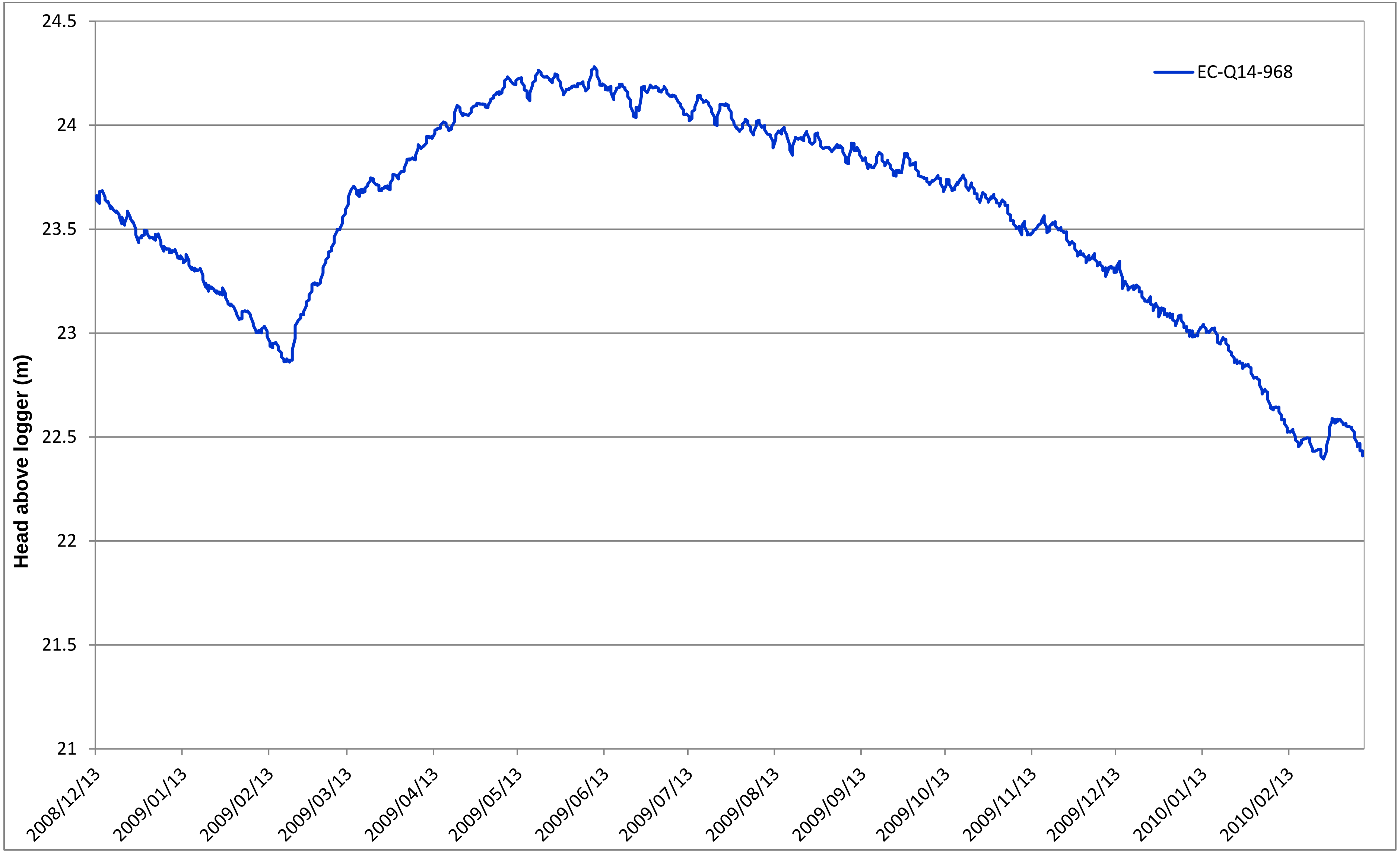


Figure 10-1: Time series water level data of borehole EC-Q14-968 on Greyville farm in the middle of the Dunblane sub-catchment

Table 10-14: Scenario 3 (c): Present day scenario with SVF-MAP recharge and water level-transmissivity estimated abstraction

Sub-catchment	Surface Area (km2)	MAP WR2005 (mm/a)	Recharge Saturated Volume Fluctuation (SVF) method (% of MAP)	SVF Recharge MAP rainfall (m3/a)	Cooper & Jacob - water level borehole abstraction (m3/a)	Reported Municipal abstraction (m3/a)	Total inflow MAP SVF (m3/a)	Total outflow (sinks) m3/a	Time (y) to reach GMC	Net balance (baseflow) - SVF recharge (m3/a)	Potential stress status (total outflow / total inflow)	Net Balance (ℓ / s)
The Glen	108	345.0	3.3%	1 238 169	-168 345	0	1 238 169	-186 396	NA	1 051 773	15%	33.4
Dunblane	286	320.0	2.0%	1 815 946	-1 675 372	0	1 815 946	-1 696 283	NA	119 663	93%	3.8
Middelburg Municipal	133	345.0	2.0%	912 026	-1 544 133	-2 522 880	912 026	-4 080 597	5.67	-3 168 570	447%	-100.5
Karmel	82	345.0	3.3%	943 531	-293 037	0	943 531	-299 012	NA	644 518	32%	20.4
Lusernvlei	124	316.0	2.0%	773 767	-793 774	0	773 767	-806 121	413.81	-32 355	104%	-1.0
Grootfontein Compartment	143	345.0	2.2%	1 110 544	-764 297	0	1 110 594	-1 040 522	NA	70 072	94%	2.2
Total	**877**			**6 793 982**	**-5 238 957**	**-2 522 880**	**6 794 032**	**-8 108 930**		**-1 314 898**		**-41.7**

10.6.3.2 Recharge sensitivity analysis: Comparison of SVF conservative recharge and Woodford trend line regional recharge estimates

The Woodford trend line recharge method (regional recharge) provides a much higher recharge estimate to the Dunblane and Middelburg Municipal sub-catchments than the SVF estimates; approximately 1.4% higher. The results of the Present day GYMR using the "Woodford trend line" recharge with MAP are shown in Table 10-15 as Scenario 3 (d).

If a single recharge figure had to be given for the whole study area, these figures are also highly probable, because a mean is obtained between the higher recharge found in the mountainous areas (± 7%) and the lower recharge found in the alluvial plains (± 2%). Vandoolaeghe (1979) used a single recharge estimate of 4% for the whole Klein-Brak River catchment, based on ± one-third of the catchment dominated by plains and ± two-thirds of the catchment dominated by outcropping dolerite complex sill, ring and dyke structures.

To illustrate the sensitivity of the recharge parameter and surface area, a rounded recharge figure of 0.5% of MAP rainfall is applied to the Dunblane and Middelburg Municipal sub-catchments. An increase in recharge of 0.5% in the Dunblane sub-catchment equates to an additional 458 000 m^3/a (14.5 ℓ/s) and in the Middelburg Municipal sub-catchment it equates to an additional 230 000 m^3/a (7.3 ℓ/s).

Due to the catchment specific evaluation in the GYMR water balance, the SVF recharge applied to MAP rainfall is however more accurate for each sub-catchment. This statement cannot be made when lateral inflow from adjacent sub-catchments is considered or the study area in totality evaluated.

The GYMR balances calculated for the above two scenarios, namely Scenario 3 (c) and Scenario 3 (d) are shown graphically in Figure 10-2 and Figure 10-3 respectively.

Table 10-15: Present day scenario with Woodford trend line estimated recharge and water level-transmissivity estimated abstraction

Sub-catchment	Surface Area (km2)	MAP WR2005 (mm/a)	Recharge Woodford trend line method (%)	Woodford Recharge MAP rainfall (m3/a)	Water level-transmissivity based borehole abstraction (m3/a)	Reported Municipal abstraction (m3/a)	Total inflow MAP Woodford (m3/a)	Total outflow (sinks) m3/a	Time (y) to reach GMC	Net balance (baseflow) - recharge (m3/a)	Potential stress status (total outflow / total inflow)	Net Balance (ℓ / s)
The Glen	108	345.0	3.4%	1 286 097	-168 345	0	1 286 097	-186 396	NA	1 099 701	14%	34.9
Dunblane	286	320.0	3.2%	2 931 033	-1 675 372	0	2 931 033	-1 696 283	NA	1 234 750	58%	39.2
Middelburg Municipal	133	345.0	3.4%	1 587 064	-1 544 133	-2 522 880	1 587 064	-4 080 597	7.21	-2 493 533	257%	-79.1
Karmel	82	345.0	3.4%	980 054	-293 037	0	980 054	-299 012	NA	681 042	31%	21.6
Lusernvlei	124	316.0	3.2%	1 248 901	-793 774	0	1 248 901	-806 122	NA	442 779	65%	14.0
Grootfontein Compartment	143	345.0	3.4%	1 703 576	-764 297	0	1 703 626	-1 040 522	NA	663 104	61%	21.0
Total	**877**				**-7 068 153**	**-2 522 880**	**6 794 032**	**-9 938 126**		**1 627 843**		**51.6**

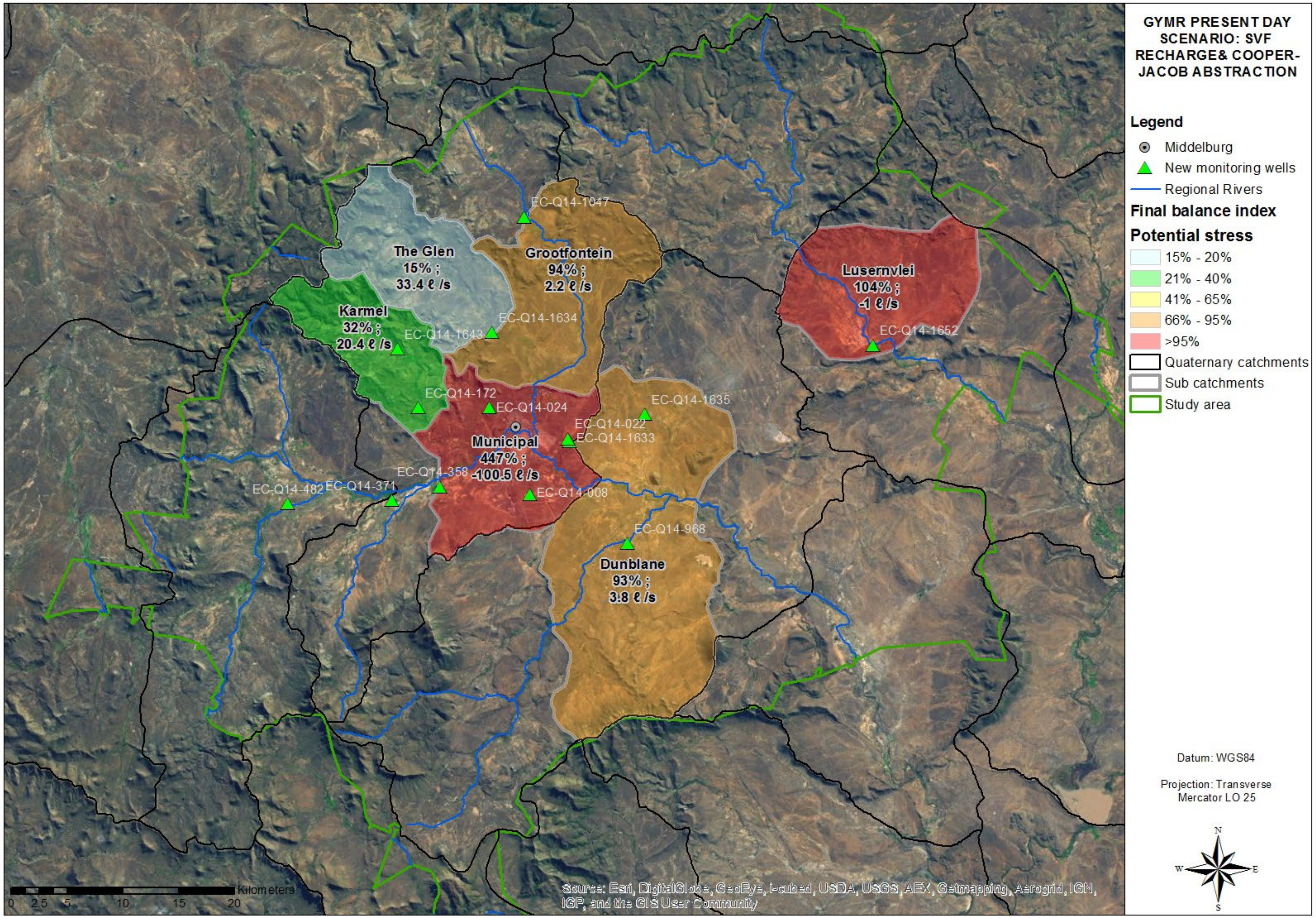


Figure 10-2: Map showing stress index of Present day scenario with SVF recharge and water level-Cooper & Jacob abstraction

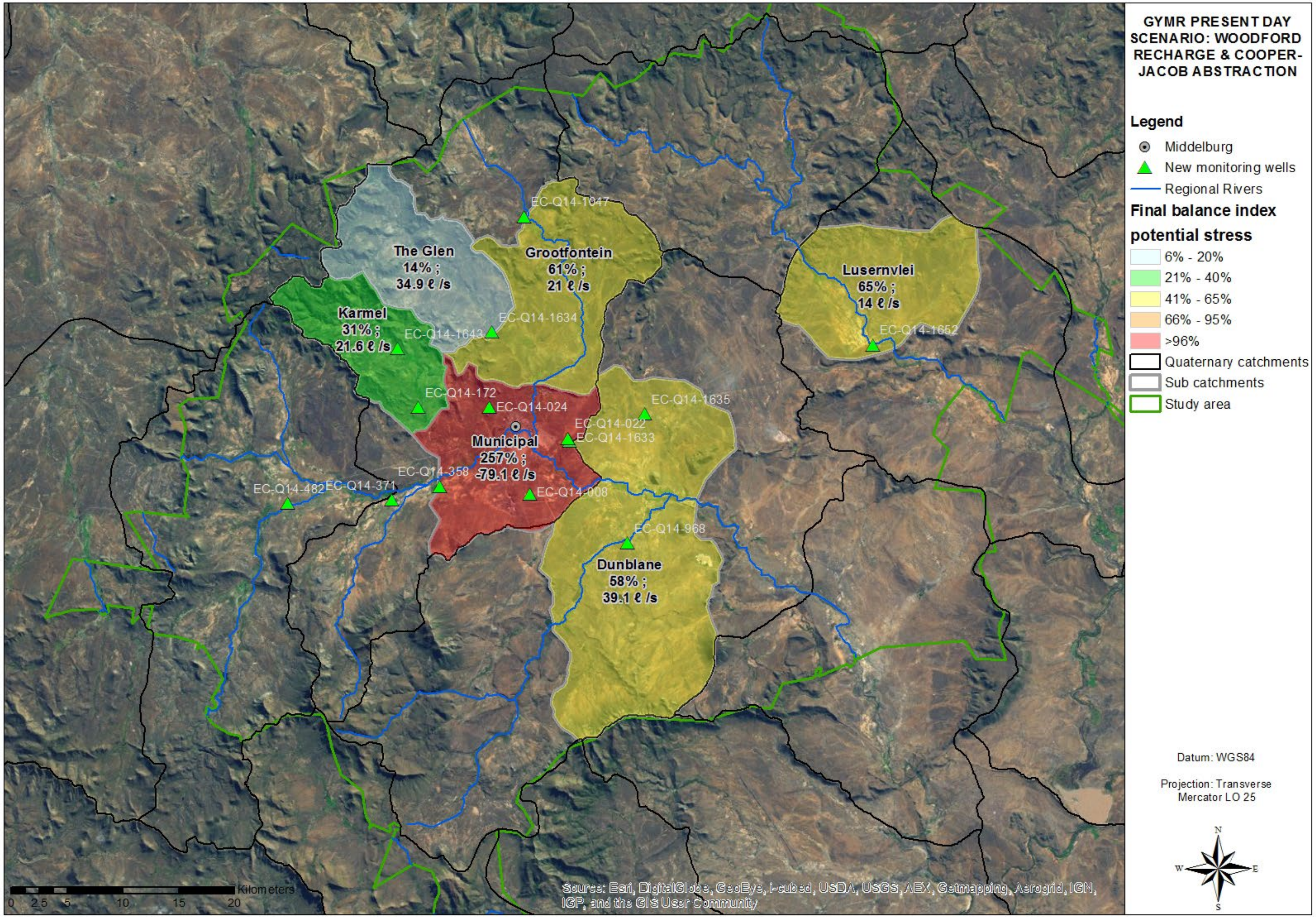


Figure 10-3: Map showing stress index of Present day scenario with Woodford recharge and water level-Cooper & Jacob abstraction

10.6.4 Scenario 4: Present day, the Glen implementation 20 ℓ/s drought relief

From the scenarios shown in Table 10-11 to Table 10-15 for currently available groundwater, it can be seen that there is more than sufficient groundwater in The Glen sub-catchment to supplement municipal demand with the first 20 ℓ/s. This is based on conservative, but proven SVF recharge estimates.

Table 10-16 and Table 10-17 show the implementation of the 20 ℓ/s immediate drought relief demand from The Glen sub-catchment. As can be seen there is still approximately 420 000 m^3/a (13.3+ ℓ/s) of water available in The Glen for future development.

For the next phase of groundwater implementation (20 ℓ/s), Karmel sub-catchment looks to be the most suitable for groundwater development as well as having the advantage of gravity fed water reticulation, hence no booster pumps (incl. electricity costs) required.

10.6.5 Scenario 5: Future 2024 scenario

A total demand of 153.3 ℓ/s has been calculated by GAST (2006) in their 2024 projection. 80 ℓ/s is already supplied from current municipal abstraction. With The Glen immediate relief of 20 ℓ/s in the first phase being implemented and the next phase 20 ℓ/s, the total water served is at 120 ℓ/s and the remaining groundwater to be implemented is 33.3 ℓ/s.

For the future scenario, further development of The Glen sub-catchment has been simulated totalling 33.35 ℓ/s from it. The second phase development of 20 ℓ/s in Karmel has been implemented and 20 ℓ/s from the Dunblane sub-catchments has been simulated.

The projected total future demand cannot be met in the SVF recharge scenario without looking to other sub-catchments (see Table 10-18). Based on the Woodford recharge, the future demand can however be supplied, if an additional sub-catchment is evaluated and approximately 22 ℓ/s obtained from it (see Table 10-19).

In all practicality, it is foreseen that groundwater balances/ budgets will need to be calculated for adjacent mountainous sub-catchments and lateral inflows/ outflows included to provide more assurance that the projected demand for Middelburg can be supplied from groundwater.

Table 10-16: Scenario 4: Present day, The Glen implementation for immediate drought relief, SVF recharge and water level-Cooper & Jacob abstraction

Sub-catchment	Surface Area (km2)	MAP WR2005 (mm/a)	Recharge Saturated Volume Fluctuation (SVF) method (% of MAP)	SVF Recharge MAP rainfall (m3/a)	Cooper & Jacob - water level borehole abstraction (m3/a)	Municipal abstraction (m3/a)	Total inflow MAP SVF (m3/a)	Total outflow (sinks) m3/a	Time (y) to reach GMC	Net balance (baseflow) - SVF recharge (m3/a)	Potential stress status CMB (total outflow / total inflow)	SVF Net Balance (ℓ / s)
The Glen	108	345.0	3.3%	1 238 169	-168 345	-630 720	1 238 169	-817 116	NA	421 053	66%	13.35
Dunblane	286	320.0	2.0%	1 815 946	-1 675 372	0	1 815 946	-1 696 283	NA	119 663	93%	3.79
Middelburg Municipal	133	345.0	2.0%	912 026	-1 544 133	-2 522 880	912 026	-4 080 597	5.67	-3 168 570	447%	-100.47
Karmel	82	345.0	3.3%	943 531	-293 037	0	943 531	-299 012	NA	644 518	32%	20.44
Lusernvlei	124	316.0	2.0%	773 767	-793 774	0	773 767	-806 121	413.81	-32 355	104%	-1.03
Grootfontein Compartment	143	345.0	2.2%	1 110 544	-764 297	0	1 110 594	-1 040 522	NA	70 072	94%	2.22
Total	**877**				**-5 238 957**	**-3 153 600**	**6 794 032**	**-8 739 650**		**3 144 095**		**-61.70**

Table 10-17: Scenario 4: Present day, The Glen implementation for immediate drought relief, Woodford recharge and water level-Cooper & Jacob abstraction

Sub-catchment	Surface Area (km2)	MAP WR2005 (mm/a)	Recharge Woodford trend line method (% of MAP)	Woodford Recharge MAP rainfall (m3/a)	Cooper & Jacob - water level borehole abstraction (m3/a)	Municipal abstraction (m3/a)	Total inflow MAP Woodford (m3/a)	Total outflow (sinks) m3/a	Time (y) to reach GMC	Net balance (baseflow) - recharge (m3/a)	Potential stress status (total outflow / total inflow)	Net Balance (ℓ / s)
The Glen	108	345.0	3.4%	1 286 097	-168 345	-630 720	1 286 097	-817 116	NA	468 981	64%	14.87
Dunblane	286	320.0	3.2%	2 931 033	-1 675 372	0	2 931 033	-1 696 283	NA	1 234 750	58%	39.15
Middelburg Municipal	133	345.0	3.4%	1 587 064	-1 544 133	-2 522 880	1 587 064	-4 080 597	7.21	-2 493 533	257%	-79.07
Karmel	82	345.0	3.4%	980 054	-293 037	0	980 054	-299 012	NA	681 042	31%	21.60
Lusernvlei	124	316.0	3.2%	1 248 901	-793 774	0	1 248 901	-806 121	NA	442 779	65%	14.04
Grootfontein Compartment	143	345.0	3.4%	1 703 576	-764 297	0	1 703 626	-1 040 522	NA	663 105	61%	21.03
Total	**877**				**-5 238 957**	**-3 153 600**	**9 736 775**	**-8 739 650**		**997 124**		**31.62**

Table 10-18 Scenario 5 (a): Future 2024 scenario: SVF recharge and 153 ℓ/s municipal abstraction implemented

Sub-catchment	Surface Area (km2)	MAP WR2005 (mm/a)	Recharge Saturated Volume Fluctuation (SVF) method (% of MAP)	SVF Recharge MAP rainfall (m3/a)	Cooper & Jacob - water level borehole abstraction (m3/a)	Municipal abstraction (m3/a)	Total inflow MAP SVF (m3/a)	Total outflow (sinks) m3/a	Time (y) to reach GMC	Net balance (baseflow) - SVF recharge (m3/a)	Potential stress status CMB (total outflow / total inflow)	SVF Net Balance (ℓ / s)
The Glen	108	345.0	3.3%	1 238 169	-168 345	-1 051 725	1 238 169	-1 238 121	NA	48	100%	0.00
Dunblane	286	320.0	2.0%	1 815 946	-1 675 372	-630 720	1 815 946	-2 327 003	36.13	-511 057	128%	-16.21
Middelburg Municipal	133	345.0	2.0%	912 026	-1 544 133	-2 522 880	912 026	-4 080 597	5.67	-3 168 570	447%	-100.47
Karmel	82	345.0	3.3%	943 531	-293 037	-630 720	943 531	-929 732	NA	13 798	99%	0.44
Lusernvlei	124	316.0	2.0%	773 767	-793 774	0	773 767	-806 121	413.81	-32 355	104%	-1.03
Grootfontein Compartment	143	345.0	2.2%	1 110 544	-764 297	0	1 110 594	-1 040 522	NA	70 072	94%	2.22
Total	**877**				**-5 238 957**	**-4 836 045**	**6 794 032**	**-10 422 095**		**-3 628 063**		**-115.05**

Table 10-19 Scenario 5 (b): Future 2024 scenario: Woodford recharge and 153 ℓ/s municipal abstraction implemented

Sub-catchment	Surface Area (km2)	MAP WR2005 (mm/a)	Recharge Woodford trend line method (%)	Woodford recharge MAP rainfall (m3/a)	Cooper & Jacob - water level borehole abstraction (m3/a)	Municipal abstraction (m3/a)	Total inflow MAP Woodford (m3/a)	Total outflow (sinks) m3/a	Time (y) to reach GMC	Net balance (baseflow) - Woodford recharge (m3/a)	Potential stress status (total outflow / total inflow)	Net Balance (ℓ / s)
The Glen	108	345.0	3.3%	1 286 097	-168 345	-1 051 725	1 286 097	-1 238 121	NA	47 976	96%	1.52
Dunblane	286	320.0	2.0%	2 931 033	-1 675 372	-630 720	2 931 033	-2 327 003	NA	604 030	79%	19.15
Middelburg Municipal	133	345.0	2.0%	1 587 064	-1 544 133	-2 522 880	1 587 064	-4 080 597	7.21	-2 493 533	257%	-79.07
Karmel	82	345.0	3.3%	980 054	-293 037	-630 720	980 054	-929 732	NA	50 322	95%	1.60
Lusernvlei	124	316.0	2.0%	1 248 901	-793 774	0	1 248 901	-806 121	NA	442 779	65%	14.04
Grootfontein Compartment	143	345.0	2.2%	1 703 576	-764 297	0	1 703 626	-1 040 522	NA	663 105	61%	21.03
Total	**877**				**-5 238 957**	**-4 836 045**	**9 736 775**	**-10 422 095**		**-685 321**		**-21.73**

10.7 Conclusions

Recharge is the major inflow component in a groundwater balance equation and various recharge estimation methods were used according to the lumped parameter approach proposed by Brendenkamp *et al.* (1995). The two final most realistic recharge scenarios were the saturated volume fluctuation (SVF) recharge based scenario (conservative scenario) and the Woodford trend line (2006) recharge based scenario (best case realistic scenario), applied to mean annual precipitation (MAP). The conservative SVF recharge estimates calculated for The Glen and Grootfontein sub-catchments are based on water level data. These recharge estimates are of higher confidence since they are based on observed volume fluctuations in compartments and measured rainfall. There is a scarcity of data for the application of such volume fluctuation based recharge methods in the Municipal, Dunblane and Lusernvlei sub-catchments and a recommendation of groundwater level monitoring and abstraction verification is put forward in this regard.

There is high confidence in the MAP rainfall and SVF recharge groundwater balances of the Grootfontein, The Glen and Karmel sub-catchments. Abstraction in these catchments is adequately determined and bounded. There is lower confidence in the groundwater balances for Middelburg Municipal, Dunblane and Lusernvlei sub-catchments. This is largely due to abstraction uncertainties.

While the mountainous sub-catchments all have positive groundwater balances, the Dunblane, Middelburg Municipal and Lusernvlei sub-catchments have marginal to negative groundwater balances. From these results it can be seen that while groundwater balances have been calculated per sub-catchment, they cannot be regarded as isolated and lateral inflow from a number of adjacent mountainous catchments occur. Balances were not calculated for these largely undeveloped mountainous sub-catchments and their distances from Middelburg make them a low priority for evaluation. The groundwater system is integrated and the entire catchment is much larger. It can be expected that a groundwater balance for the larger catchment will be positive.

Large uncertainties exist for several agricultural high volume abstraction point sources (used in Potential abstraction scenarios) and actual abstraction should be verified for these point sources. One example of abstraction uncertainty is noted where the borehole abstraction of EC-Q14-924 was reported to be high yielding during hydrocensus. Accordingly, the borehole was aquifer tested by AB Pumps as possible future water supply borehole. During the step tests however, the water level quickly reached pump inlet during the 0.4 ℓ/s step and recovered slowly thereafter. Borehole collapse from test pump installation cannot be ruled out, but is unlikely and this is just one example of high volume abstraction. Licensing and regulation of agricultural groundwater will also need to be addressed, as discussed below, if the future water supply for Middelburg is to be based on groundwater.

Using higher confidence, but conservative SVF recharge estimates applied to MAP rainfall, the Present day balance figures using water level-transmissivity based abstraction are:

- The Glen: +1.05 x10^6 m^3/a;
- Dunblane: +1.20 x10^6 m^3/a;
- Middelburg Municipal: -3.17 x10^6 m^3/a;
- Karmel: +0.65 x10^6 m^3/a;
- Lusernvlei: -0.03 x10^6 m^3/a;
- Grootfontein: +0.07 x10^6 m^3/a;

-1.32 x10^6 m^3/a (-41.7 ℓ/s)

For similar abstraction volumes, but using regional scale Woodford (2006) trend line recharge estimates applied to MAP rainfall, the Present day scenario balance figures are:

- The Glen: +1.10 x10^6 m^3/a;
- Dunblane: +1.24 x10^6 m^3/a;
- Middelburg Municipal: -2.49 x10^6 m^3/a;
- Karmel: +0.68 x10^6 m^3/a;
- Lusernvlei: +0.44 x10^6 m^3/a;
- Grootfontein: +0.66 x10^6 m^3/a;

+1.63 x10^6 m^3/a (51.6 ℓ/s)

The only way to be certain if the groundwater balance (Dunblane) is actually positive or negative is to look at current (2008-2013) time series groundwater level data. Groundwater level monitoring is critical in the Middelburg area and is the key to good management and decision making. The analysis of water level change over time coupled with a better knowledge of agricultural abstraction around Middelburg will provide continually improving management of the aquifers as well as determining accurate recharge estimates using the SVF water balance method.

In many cases a choice was made to use the MAP with SVF recharge instead of 95% assured rainfall (5th percentile) as the MAP is based on long time series information. The 95% assured GYMR is used to present a conservative estimate of the minimum amount of groundwater available. Technically there should be more groundwater available, 95% of the time. With this Middelburg study, a scaled-up more detail balance is calculated and the luxury of working with the 5th percentile of rainfall is no longer available, since there is little surplus groundwater in some sub-catchments, if any. If a realistic estimate of abstraction is used and not its 5th percentile, actual rainfall data must also be used. If for example the Dunblane sub-catchment balance is based on the 5th percentile of rainfall and SVF recharge, the overall result will be negative and groundwater supply from Dunblane will fail. The SVF method must be applied to MAP as it is calculated from real time series rainfall and not its 5th percentile.

The marginal groundwater balance with which the Middelburg study area is left will require diligent groundwater monitoring and management. Large abstraction point sources can be identified and field tested to determine their accurate abstraction volumes. Duty cycles and seasonality of abstraction should be verified. Water use licenses and volumes to these predominantly irrigation-type uses should be carefully calculated and considered.

Middelburg has easily accessible, high yielding and good storage (S ± 0.01) shallow aquifers, but the concentrated abstraction in the Middelburg and Dunblane sub-catchments has created over-exploitation in these areas. The structure of the alluvial plain aquifers is such that a top layer of argillaceous sediments is preventing rainfall infiltration and percolation through to the groundwater table. Recharge is a sensitive parameter in the groundwater balance and by for instance raising the recharge in the Dunblane sub-catchment from 2% to 3% an additional 915 000 m^3/a of groundwater becomes available. One solution to meeting future water supply needs with groundwater in Middelburg is by artificial recharge or managed aquifer recharge, thereby increasing the natural recharge.

After a choice was made in using MAP rainfall applied to SVF recharge, three possible abstraction scenarios were compared in scenario 3. The abstraction scenarios compared were the Potential existing abstraction, AGES estimated abstraction and water level-transmissivity based abstraction. There are large differences between these possible abstractions, reflecting the large amount of uncertainty associated with abstraction in the Dunblane, Municipal and Lusernvlei sub-catchments. Within the most realistic SVF recharge and water level-transmissivity abstraction scenario, the current reported municipal abstraction of 80 ℓ/s cannot be supplied from the combined sub-catchments evaluated. Raising the recharge by just 1% in problematic sub-catchments (Woodford recharge scenario), would change again the water balance outcome to a positive one. Within the Woodford recharge scenario there is adequate groundwater available, and an additional 20 ℓ/s would be required for the future (2024) total municipal abstraction of 153 ℓ/s scenario.

10.8 Recommendations

A recommendation is made to identify very high abstraction point sources and to field verify their abstraction rates. Identification is easily done from the hydrocensus data. It is also important to verify duty cycles and seasonality of these abstraction point sources. The actual abstraction can be field verified with the bucket and stopwatch method or by v-notch if the yield is too large for the container at hand. An accurate flow meter can also be coupled to simply measure the flow. These very high abstraction point sources create what seems to be an unrealistically large Potential annual abstraction in the Dunblane, Middelburg Municipal and Lusernvlei sub-catchments. It is recommended that these abstraction rates and their seasonality be verified if DWA is to proceed with choosing groundwater as the source for town water supply. The water level-transmissivity calculated abstraction rates however provide the maximum amount of groundwater abstraction possible from a borehole, are much lower than the Potential abstraction estimates and are of higher confidence.

Groundwater level monitoring is critical in the Middelburg area and is the key to good management and decision making. It is a necessity for municipal water supply from aquifers. The analysis of water level change over time coupled with a better knowledge of agricultural abstraction around Middelburg will provide continually improving management of the aquifers as well as determining accurate recharge estimates using the SVF or similar water balance recharge methods.

Further work is needed to refine recharge estimates, since at least one of the major components in the groundwater balance equation must be known with high confidence. If one is known, the other is effectively known through water level change analysis. The SVF recharge estimation method is especially promising as it is based on proven change in the groundwater volume of a compartment.

Given the large uncertainty of abstraction and the otherwise good amount of point water levels available, a numerical groundwater model is the most efficient solution for the problem of solving for the abstraction (Q) uncertainties, if groundwater recharge is known.

Licensing and regulation of agricultural groundwater will need to be addressed if the future water supply for Middelburg is to be based on groundwater. Water use licensing should be targeted at high volume point source abstractions as identified from the hydrocensus data and if those abstractions are confirmed to be very large through field verification. From the natural vegetation and climate in the Karoo, it should be obvious that intensive groundwater based brute force intensive irrigation schemes are not sustainable in this environment.

Great scope for artificial recharge or managed aquifer recharge is seen in the study area. Middelburg has easily accessible high yielding and good storage (S ± 0.01) shallow aquifers, The structure of the alluvial plain aquifers is however such that a top layer of argillaceous sediments is preventing rainfall to quickly infiltrate and percolate through to the groundwater table. Recharge is a very sensitive parameter in the groundwater balance and by for instance raising the recharge in the Dunblane sub-catchment from 2% to 3% an additional 915 000 m^3 per annum of groundwater becomes available. One solution to meeting future water supply future needs in Middelburg with groundwater is by artificial recharge or managed aquifer recharge, increasing the natural recharge.

None or very little surface water monitoring data is available in the Middelburg study area that could have assisted in calculating accurate estimates of groundwater recharge in many of the sub-catchments from which water is supplied to Middelburg.

To correctly determine the amount of groundwater available at a chosen assurance of supply, stochastic simulation of the groundwater flow balance needs to performed. It was outside the time constraints and scope of this study to construct a stochastic model, but it is recommended for obtaining a groundwater firm yield at a specified level of assurance. This model can also be iteratively updated as aquifer parameters such as recharge are refined.

11 SUSTAINABILITY VALIDATION: NUMERICAL MODELLING

11.1 Introduction

The water balances performed in Chapter 10 have shown that there is probably a fine balance in the system between sustainable abstraction and operating at a deficit groundwater balance. A more accurate assessment of the system as a whole is required that can be calibrated by some site measurement that is known to be accurate. A numerical model fits this purpose since we can now evaluate the water balance (budget), incorporate the hydrogeology (providing more confidence) and determine how well the model represents reality (hydraulic head calibration). When recharge is estimated for a water balance for instance, there is no way to determine how possible such a recharge figure actually is in the system without a numerical model. It is for these reasons that a numerical model can provide more confidence in determining whether current and future groundwater abstraction will be sustainable in the long term water supply to Middelburg.

11.2 Objectives of numerical modelling

The following objectives were defined for the numerical model:

1. Determine hydraulic head change over time and plot;
2. Determine recharge and mean hydrogeological parameters across the study area through model calibration;
3. Compare the numerical model water budget (rate & period budget) results to the GYMR water balance results per sub-catchment.

11.3 Methodology

The general methodology followed for development of the Middelburg numerical model is based on the ASTM standard D5447: Application of a groundwater flow model to a site-specific problem (ASTM, 2010). Please refer to D5447 for detail on this standard workflow.

Some of the best practices used by AGES (Pty) Ltd. were used during numerical modelling.

The numerical groundwater flow modelling (computer) code used for this study was FEFLOW 6.1. For more information on this numerical modelling code, it's advantages and mathematical overview, the reader is referred to http://www.feflow.info/

Numerical model calibration was performed by using ASTM standard D5981: Calibrating a groundwater flow model application, as a guideline (ASTM, 2008).

Additional references that were consulted are provided in the references of Chapter 13.

11.4 Conceptual model and data

A conceptual model is a simplified representation of our understanding of a real world system. A conceptual model is defined by the ASTM D5447 standard as: "An interpretation or working description of the characteristics and dynamics of the physical hydrogeologic system." (ASTM, 2010). A conceptual model is also used to reduce the geological complexities that exist in reality in order to acceptably represent the groundwater system with a system of mathematical constructs and equations, and find an approximate solution to the flow problem (Spitz and Moreno, 1996).

Conceptual models have already been constructed by the author for the Middelburg groundwater Exploration investigation for DWA and these conceptual models are also presented here (Figure 11-4 and Figure 11-5).

11.4.1 Aquifer system framework

The geological- and hydrogeological-units in the study area have been extensively described in the Literature study chapter and only important aspects of the dynamics of the groundwater system are discussed here.

There are essentially two main hydraulic units in the study area. Their interconnection has not been conclusively proven and provides an open end to future research, but from all site observations and indirect evidence, these hydraulic units are considered connected.

Eight hydraulic zones are defined in the numerical model, but these can be grouped into the two main hydraulic units based on their hydraulic parameters.

The first hydraulic unit is a system of shallow aquifers of predominantly unconsolidated fluvial sediments. Alluvium constitutes most of the shallow aquifer system (calcrete a minor part) and is found in valleys surrounded by mountains, palaeo channels and pediplains. The alluvium of the shallow aquifer systems are the main storage units and also the most transmissive, thus form the best aquifers. Model results suggest that there are unknown boundaries in the alluvium, calcrete and weathered river channel zones that were not charted on the geology map. The first hydraulic unit groups the following aquifers together:

- Alluvium;
- Calcrete;
- 50m buffer zone for weathered river channel along main rivers in the study area.

The second hydraulic unit is the fractured hard rock aquifer system underlying the first hydraulic unit (shallow aquifer) and outcropping at some locations (50% of model domain), consisting of sedimentary rocks and intrusive igneous rocks. Groundwater flow in this system is predominantly associated with the contact aureoles (baked zones) between sedimentary country rock and dolerite ring- and sill-structures as well as dolerite dykes. Fractures and thermal joints are often found in the dolerite. Groundwater is also transmitted in these deeper aquifers via bedding plane fractures in the sedimentary rocks of the Katberg Formation and Adelaide Subgroup. Bedding plane fractures are not continuous in the study area, thus groundwater flow in purely sedimentary rocks will at some locations be very slow due to the low hydraulic conductivity of the rock matrix. The upper 10 – 20 m of outcropping Beaufort Group/dolerite intrusions are more weathered and fractured and have a higher hydraulic conductivity than the fresh rock at greater depth.

Only the shallow depth groundwater flow is represented in the numerical model. The zone of weathered and fractured rock associated with the unconformity between alluvium and underlying Beaufort Group/ dolerite rock is assumed to be part of the shallow aquifer in the numerical groundwater flow model.

11.4.2 Groundwater flow system

Based on extensive hydraulic head measurements, groundwater follows topography very well (see Figure 11-3). This is indicative of an unconfined aquifer system based on existing boreholes where water level measurements were taken.

Besides following topography, groundwater flow is controlled to a large extent by the order of magnitude difference between the hydraulic conductivity of the unconsolidated sediments hydraulic unit and the fractured hard rock hydraulic unit.

Alluvium thickness varies within its mapped zones and is thicker in valley areas, palaeo channels and depressions. It then happens that where two relatively deep (±20 m) alluvial reservoirs were connected by a thin (±5 m) strip of shallow alluvium, they can become isolated due to the lowering of the groundwater level by abstraction within one of the alluvial reservoirs. The alluvial reservoir is now of limited extent and volume and, although it has almost ideal hydraulic parameters, abstraction from it is bound to fail unless recharge exceeds abstraction in or around it.

This concept can be extended to the complex dolerite ring and sill structures that dominate the landscape and control the geomorphology of the study area. The alluvial sediments fill the valley (deeper alluvium) and pediplain (shallower alluvium) areas inside the ring structures. The upper 10 m of the dolerite ring is weathered and has a higher hydraulic conductivity, especially at its lowest topographical point where groundwater exits. Again, if the groundwater level is lowered below this upper part of weathered dolerite, due to abstraction, groundwater flow from one catchment to another is slowed due to increasingly fresher rock (decreasing hydraulic conductivity) and finally ring structure catchments become isolated. It is now a simple finite reservoir calculation and if abstraction exceeds recharge, groundwater supply within this isolated compartment will fail.

Groundwater can however regionally follow the more conductive baked zones along dolerite dykes and flow in this case is not limited by the basins that the dolerite ring structures create.

By targeting deep fracture zones on the dolerite ring and sill structures as well as the Dunblane dyke, the sustainability of supply from the borehole is increased as well as its resilience to drought. It also makes sense to target the Dunblane dyke due to the regional groundwater flow potential it has (see Figure 11-5). Assuming that the shallow and deep aquifer systems are connected, deep aquifer abstraction does not solve the problem of over-abstraction in a single dolerite ring compartment and abstraction needs to be better managed, balanced and spread out.

Conceptual models are presented in Figure 11-2, Figure 11-4 and Figure 11-5 to provide some visual description of groundwater flow dynamics and hydrogeology within the Middelburg study area. Figure 11-4 gives an example of the geological complexity and sub-structures that can be encountered within a dolerite sill- and ring-complex structure. The cross-section A-B (Figure 11-2) was drawn through the Grootfontein weir spring (EC-Q14-059) at the downstream point of the Grootfontein compartment. Figure 11-1 is a map for the cross-section A-B and Figure 11-6 shows where the cross sections for the other two conceptual models are.

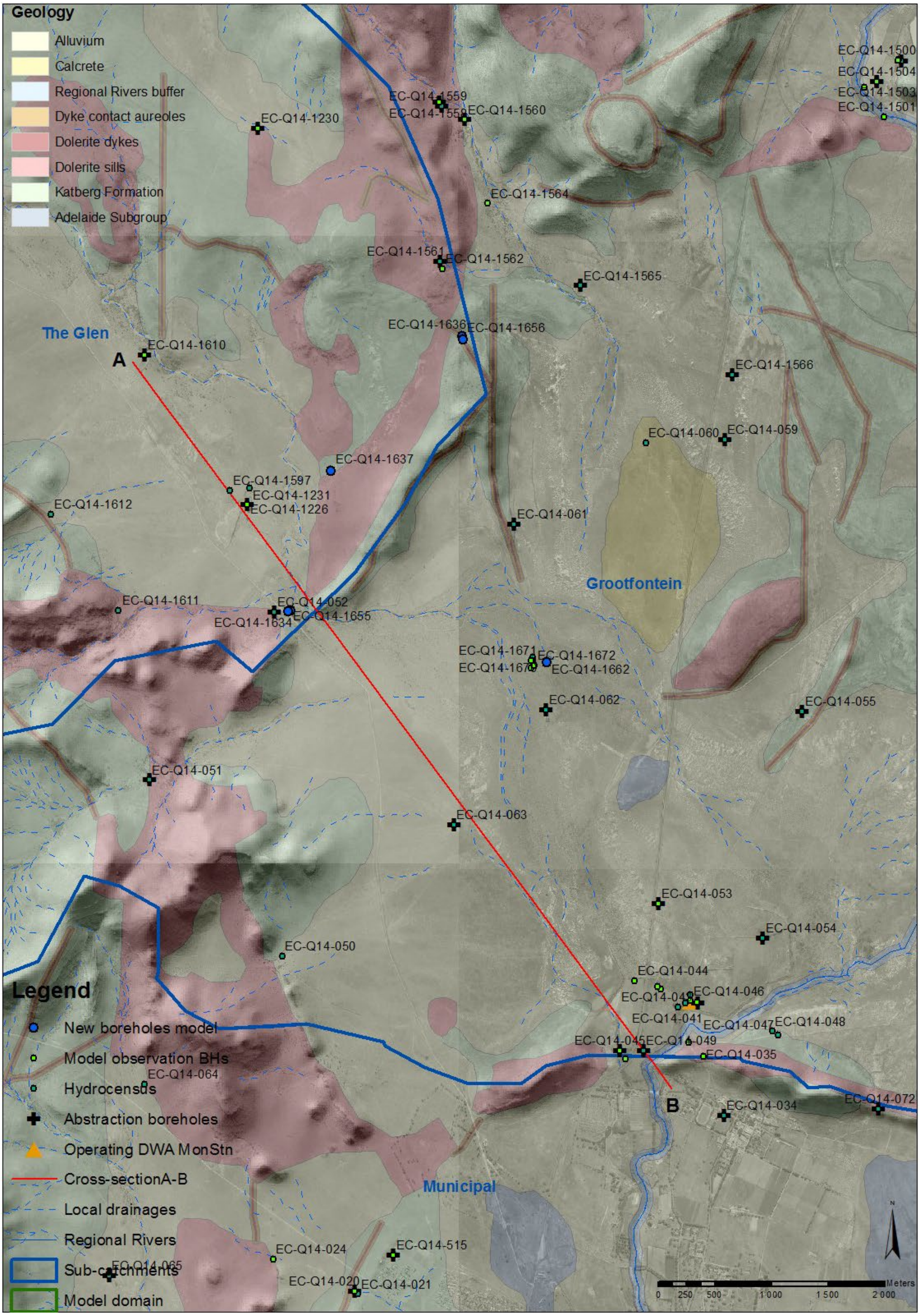


Figure 11-1: Map for cross-section A-B for conceptual model

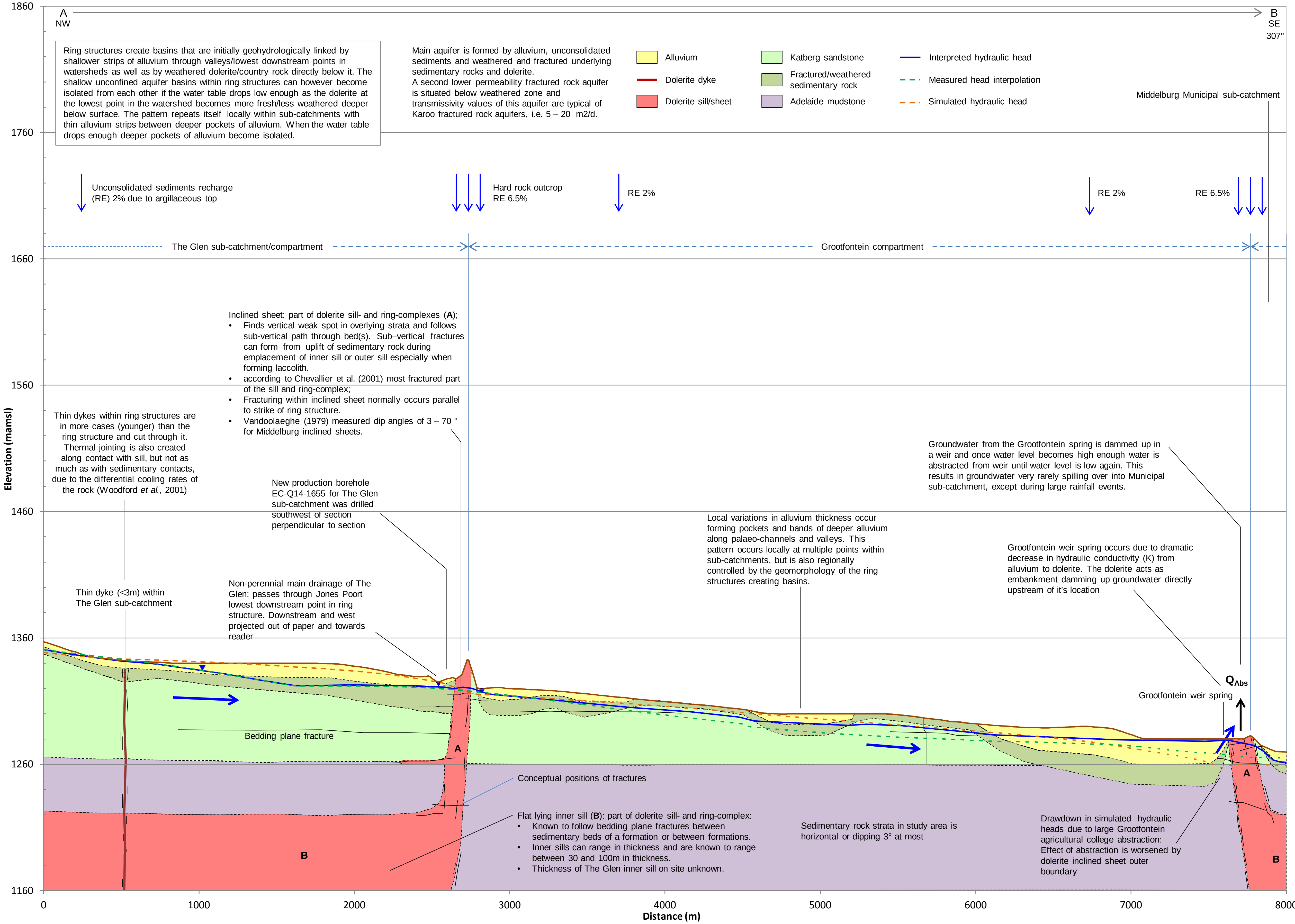


Figure 11-2: NW – SE section conceptual model through The Glen sub-catchment, Grootfontein compartment and small part of the Municipal sub-catchment

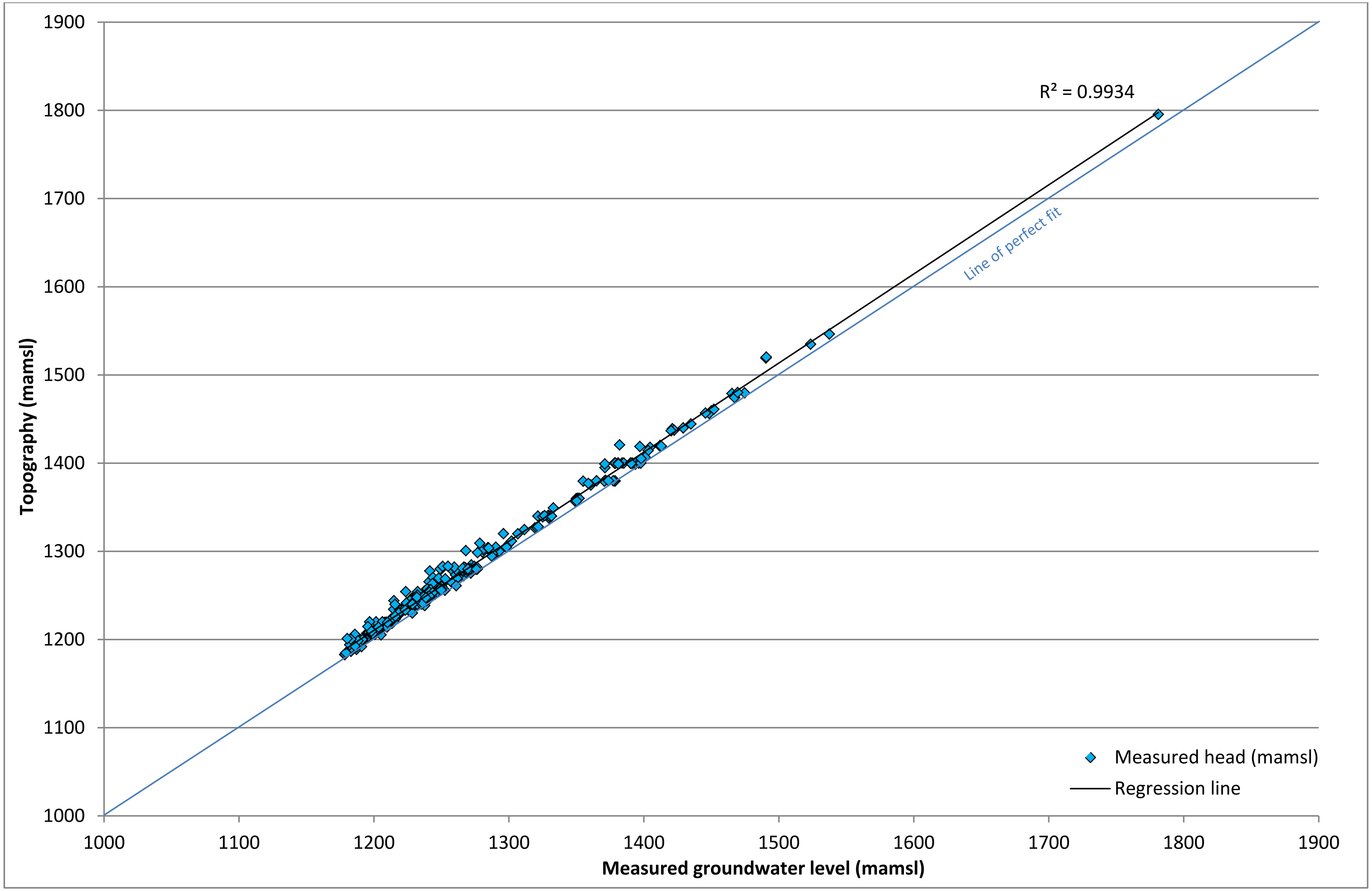


Figure 11-3: Measured groundwater levels vs. topography graph and correlation (n = 378)

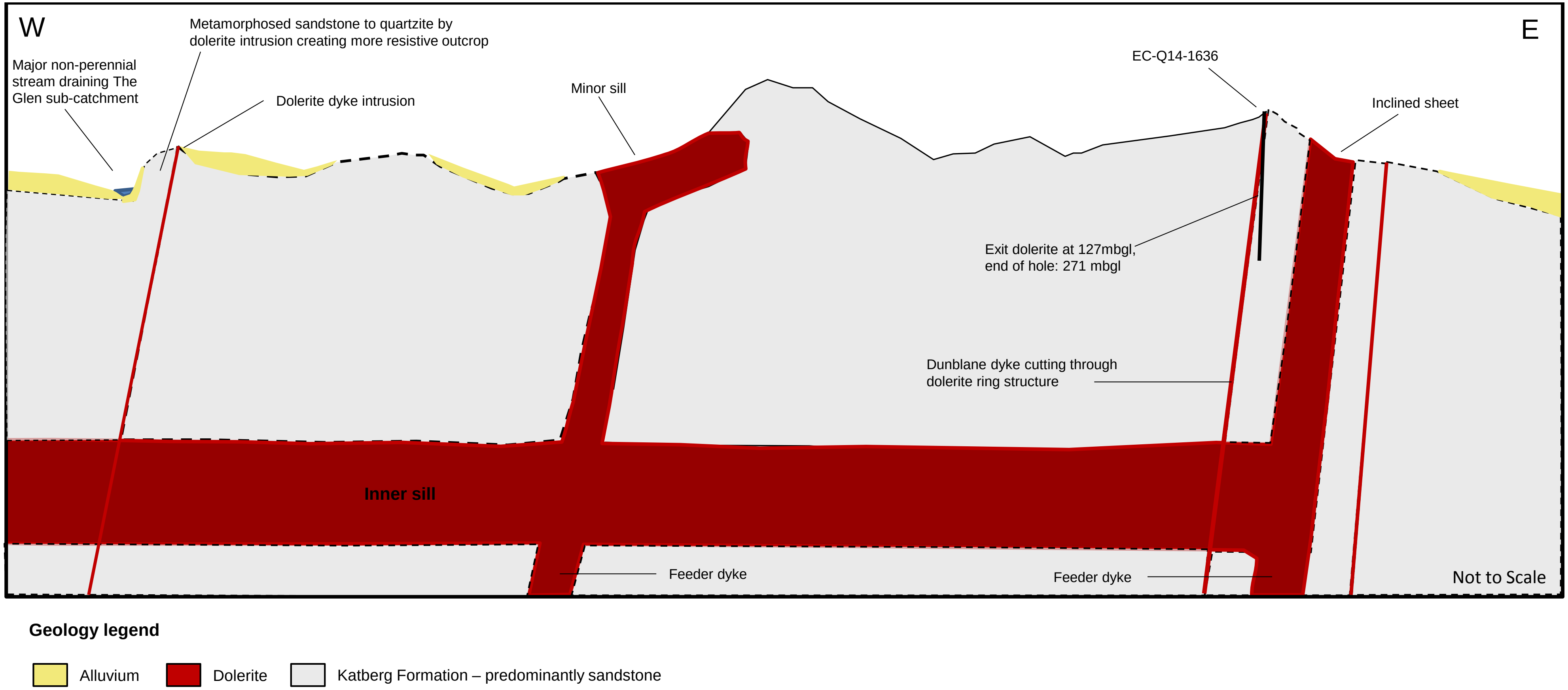


Figure 11-4: Conceptual model and cross section E – W through The Glen sub-catchment and borehole EC-Q14-1636

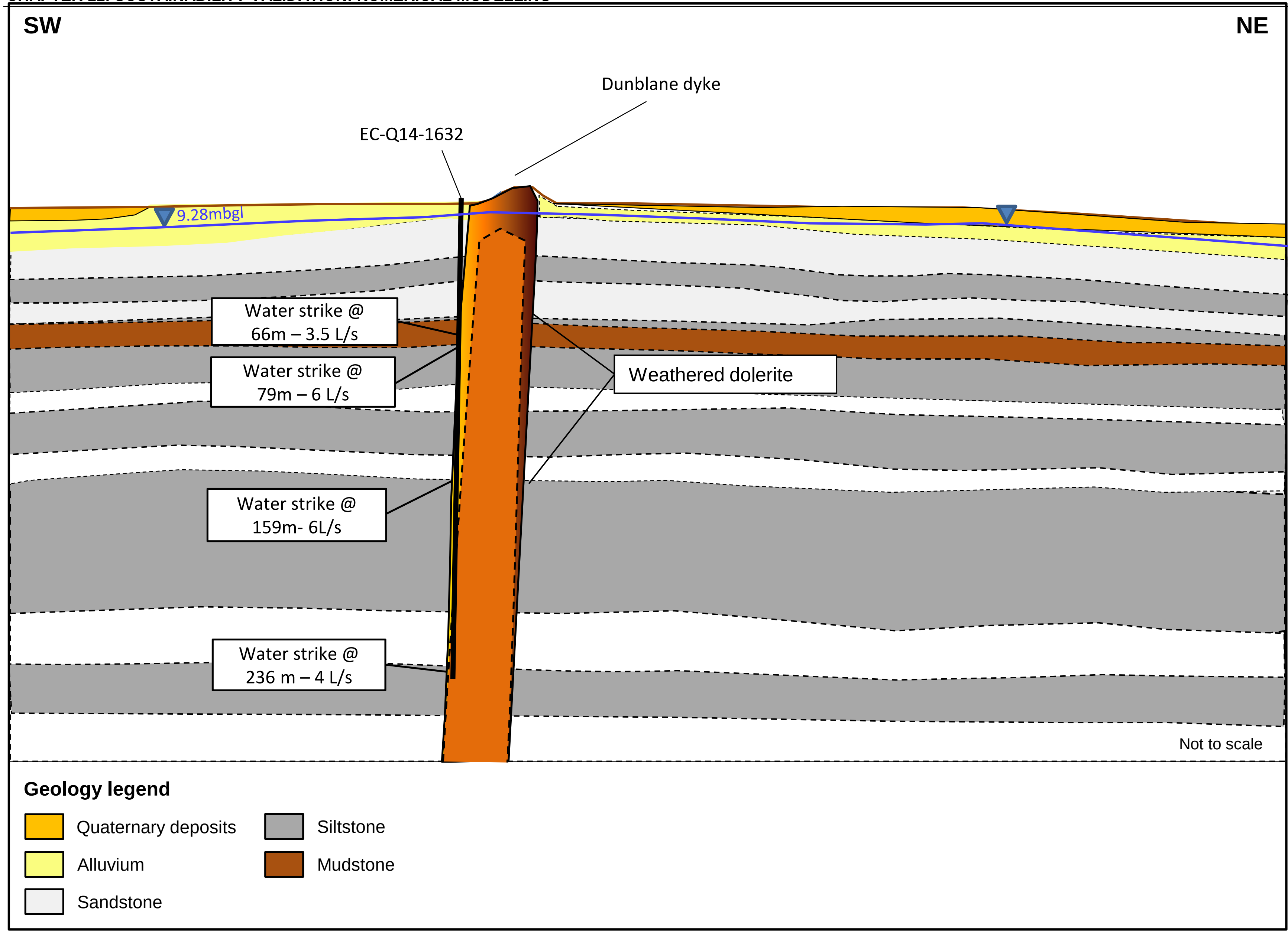


Figure 11-5: Conceptual model and cross section perpendicular to Dunblane dyke at EC-Q14-1632

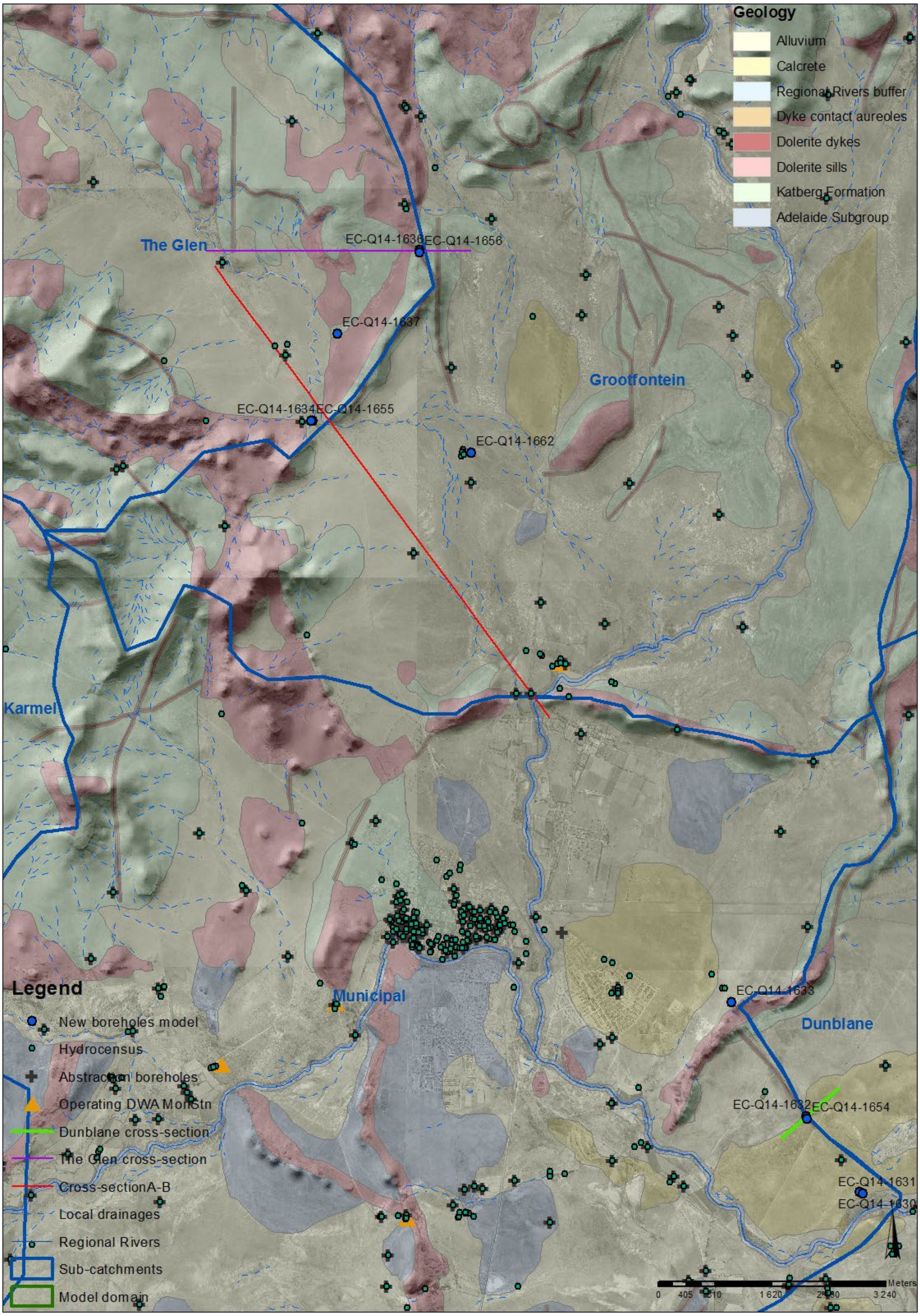


Figure 11-6: Map showing location of all cross-sections for conceptual models

11.4.3 Hydrological and hydrogeological boundaries

The sub-catchments used in the study thus far are purely hydrology based boundaries and were re-evaluated. Groundwater compartments were delineated based on quaternary catchment boundaries, sub-catchment boundaries and a close look at the geological map, aerial photos and satellite images was taken to identify likely hydrogeological boundaries. Such boundaries are typically formed by dolerite ring and sill structures clearly visible from the aerial photos and in most cases noted on the geological map. The prominence and freshness of the dolerite on the aerial photos provide an indication whether the ring and sill structures are likely to form semi-impermeable groundwater flow boundaries.

After a number of groundwater compartments were delineated, the model domain boundary was selected so that all of the important sub-catchments evaluated in the water balance Chapter 10 are included. Due to the updated groundwater compartment approach, the Dunblane sub-catchment boundary has changed and is now smaller than the original Dunblane sub-catchment. All existing municipal boreholes were included with a generous radial buffer distance from the model domain boundary. Considerations for the model domain also included the distance of new production boreholes from the boundary. A radial distance of ±8 km was maintained between new boreholes and the model domain boundary.

11.4.4 Model domain

The model domain covers an area of 788 km^2, is 36.7 km in length (N – S) and 35.7 km in width (W - E). The hydrogeological boundaries and final model domain are shown in Figure 11-7.

11.4.5 Hydraulic properties

From aquifer testing the hydraulic properties of the different lithologies were summarised in Table 11-1 for model construction. The final geometry features used in the model supermesh construction are displayed in Figure 11-8.

Table 11-1: Hydraulic parameters used to determine initial transmissivity and specific yield

Allocated borehole number	Sub-catchment	Alluvium T (m2/d)	Calcrete T (m2/d)	Weathered Zone Rivers T (m2/d)	Dyke Contacts T (m2/d)	Dykes T (m2/d)	Fractured/ baked contact	Dolerite sills T(m2/d)	Fractured Beaufort (m2/d)	Katberg T (m2/d)	Adelaide T(m2/d)	SWL	Depth (m)	D (m)	K (m/d)	S	Aquifer testing and general comments
EC-Q14-1603	Dunblane				29.69				29.69			8.68	40.54	31.86	0.93		Strong borehole, fractured at depth, good recovery as well
EC-Q14-101	Middelburg Municipal						18.00					9.27	38.80	29.53	0.61		Fractured rock aquifer, drilled on contact between Adelaide and dolerite sill, baked zone
EC-Q14-192	Middelburg Municipal	271.53	271.53									10.36	29.20	18.84	14.41		100% Porous Aquifer, unconsolidated sediments, alluvium, very good recovery
EC-Q14-341	Dunblane			10.80								9.25	71.00				Combination of weathered unconformity and unconsolidated aquifer
EC-Q14-660	Dunblane											10.15	23.82	13.67			U no-flow boundary or closed system reached. Borehole not sustainable
EC-Q14-661	Dunblane											14.12	41.30	27.18			Only Calibration, Low yielding
EC-Q14-687	Dunblane									0.84	0.84	14.14	43.27	29.13	0.03		Single bedding plane fracture type yield, Karoo sedimentary rock
EC-Q14-968					7.20	7.20						6.05	66.00				Dunblane dyke contact, T could be 2.1<T>7.8 m2/d
EC-Q14-1041	Outside Sub-catchments	216.70										5.79	37.35	31.56	6.87		Excellent borehole, Porous aquifer, immediate recovery
EC-Q14-1107	Outside Sub-catchments			21.50			21.50					21.95	73.80				Weathered fractured unconformity, receiving some recharge from alluvium-leaky aquifer, bounded
EC-Q14-1247	Outside Sub-catchments / Dunblane						11.10		11.10			14.62	51.20				Fractured rock aquifer. More probably only sedimentary rock
EC-Q14-1643	Karmel	32.89	32.89	32.89								6.34	15.08	4.66	7.06		Alluvium, weathered Katberg, SWL= 6.34, Depth = 15m, K = 7.1 m/d
EC-Q14-1645	The Glen											7.07	21.60	14.53			Parallel no-flow boundaries reached, Borehole not sustainable
EC-Q14-1646	Lusernvlei						18.30		18.30			5.35	45.89	40.54	0.45		On contact between dolerite ring and Katberg, in Lusernvlei poort
EC-Q14-1647	Lusernvlei	49.60		49.60								5.94	41.56	35.62	1.39		Combination of alluvial aquifer and weathered/fractured unconformity aquifer
EC-Q14-1651	Lusernvlei	476.84		96.30								7.48	45.30	37.82	12.61	2.15E-02	T not representative of a specific aquifer since it is combination of aquifers, incomplete recovery
EC-Q14-1631	Dunblane				12.90	12.90						11.10	126.70				Fractured rock, 1-no flow boundary Dunblane-transgressive fracture shows deviation from boundary, good recovery, leaky
EC-Q14-1632	Middelburg Municipal				5.70	5.70						9.28	236.00			1.00E-03	Fractured rock aquifer. Mulitple fractures dewatered. 20min recovery. Leaky aquifer
EC-Q14-1633	Middelburg Municipal							1.10				32.10	256.00				Rooirantjies. Drilled in dolerite ring. Incomplete recovery. Actual SWL closer to 30.62m
EC-Q14-1634	Middelburg Municipal											10.37	298.00				Paralell or U no-flow boundary reached.
G31594	Dunblane											7.37	27.70	20.33			Only 3 min step, low yielding
EC-Q14-1635	Dunblane											11.45	120				Dolerite sill, not tested
EC-Q14-1636	The Glen				5.70		5.70		5.70							2.25E-03	Single large dolerite ring/dyke contact. Limited extent aquifer.
EC-Q14-1637	The Glen						27.30		27.30			8.46	258.00	66.54	0.41		Fractured rock aquifer/ weathered Beaufort. Contact between dolerite inner sill and Katberg. Main water strike 61 mbgl = 6.5 l/s.
EC-Q14-1655	The Glen	321.20										6.15	156	33.85	9.49		Composite alluvial and highly fractured and weathered Katberg sandstone unconformity
EC-Q14-1662	Grootfontein											18.63	252.00	6.37			Not tested, In-situ performations not completed.
	Minimum	32.9	32.9	10.8	5.7	5.7	5.7	1.1	5.7	0.8	0.8	5.4	15.1	4.66	0.03	0.00	
	Maximum	476.8	271.5	96.3	29.7	12.9	27.3	1.1	29.7	0.8	0.8	32.1	298.0	66.54	14.41	0.02	
	Mean	228.1	152.2	42.2	12.2	8.6	17.0	1.1	18.4	0.8	0.8	10.9	96.6	27.63	4.93	0.01	

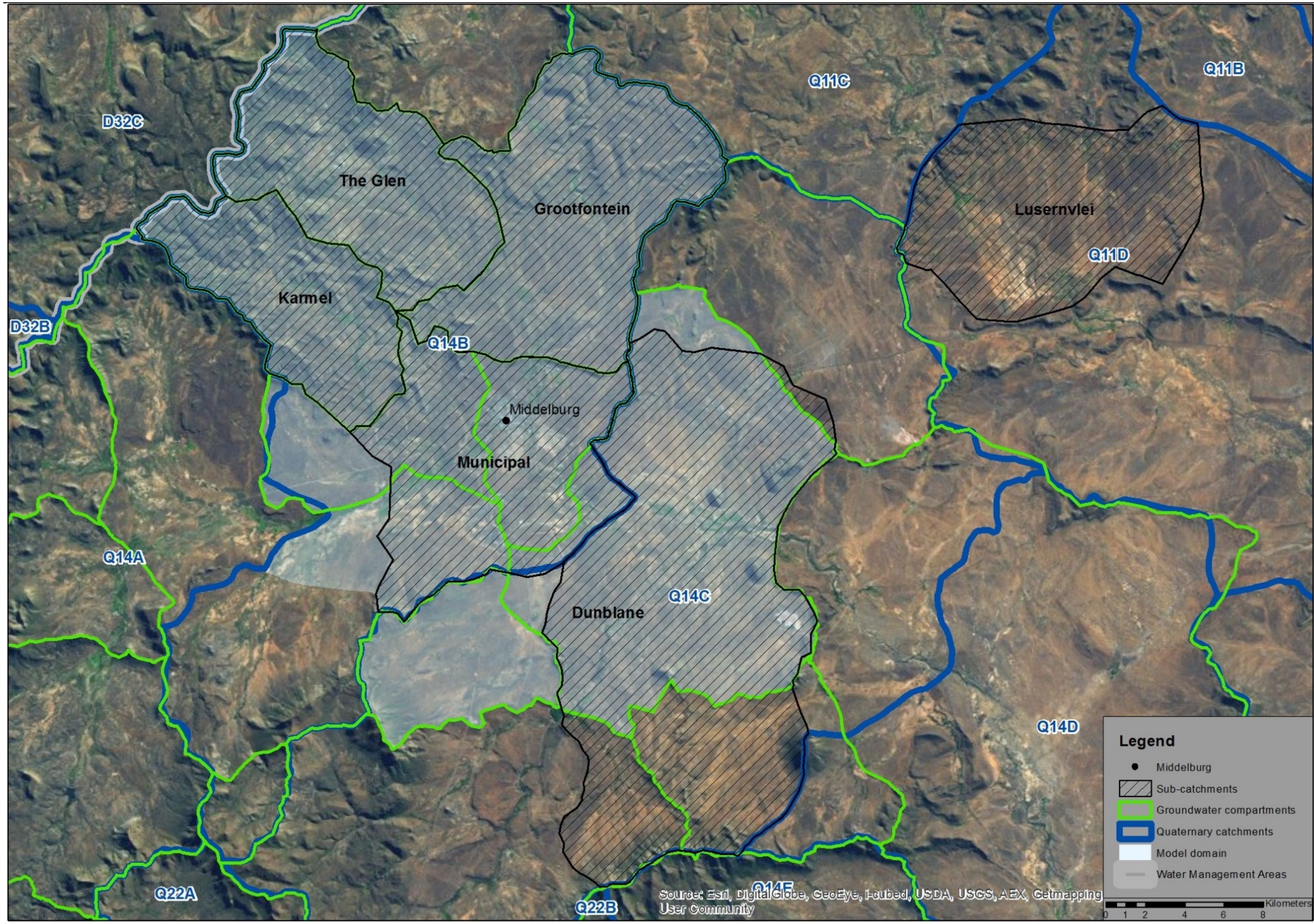


Figure 11-7: Middelburg study area hydrogeological boundaries and model domain

11.4.6 Rainfall records

A 100 year patched rainfall record was created for the purposes of probability statistics and uncertainty analysis of the assurance of supply from groundwater. As noted, the WR2005 monthly rainfall for Q14B was used as this quaternary catchment covers most of the model domain, with a MAP of 345.1mm/a. The WR2005 rainfall covers a time period of 85 years from 1920 to 2005 in hydrological years and is considered to be the most accurate rainfall dataset since it has been validated by Dr Pitman for the WR2005 study. A 100 year rainfall record is however required for the evaluation of 1 in 20 year drought cycles occurring and to evaluate the 95% assurance of groundwater supply.

Rainfall data from the WRIMS/WRMF database was used to patch data prior to 1920 and South African Weather Service (SAWS) data was used to patch WR2005 data post September 2005 up to September 2012. Spurious rainfall data exists prior to October 1916 for the study area, thus the 100 year patched rainfall record was extended into as recent as reasonable SAWS data, September 2012.

Data from WRIMS/WRMF rainfall stations for the area was evaluated and the WR2005 rainfall data was patched with WRIMS data from rainfall station 0144900 AW from the hydrological year 1911/1912 to 1919/1920.

11.4.7 Sources and sinks

Recharge from rainfall is the main source of groundwater addition. There are very little surface water bodies in the study area, so as seen from the groundwater balance in Chapter 10; dam seepage contributes a negligible amount of groundwater to the model domain as a whole. Groundwater recharge analysis was performed for the GYMR water balances and a summary table of recharge estimates calculated and obtained is provided in Table 11-2.

Table 11-2: Recharge estimation method results for sub-catchments and geomorphology

Sub-catchment	CMB	SVF	Woodford trend line	Vandoolaeghe (1979)	Predominant morphology
The Glen	6.7%	3.3%	3.4%	7.0%	mountainous
Karmel	7.0%	-	3.4%	7.0%	mountainous
Grootfontein	4.0%	2.2%	3.4%	4.0%	floodplain-mountainous
Municipal	0.7%	-	3.4%	2.0%	floodplain
Dunblane	1.3%	-	3.2%	2.0%	floodplain
Lusernvlei	2.1%	-	3.2%	4.0%	floodplain-mountainous

Existing borehole abstractions are the main sinks in the system. Other sinks in the system are springs and evapotranspiration. There is only one significant spring in the study area, the Grootfontein weir spring as has been discussed in previous chapters. This spring has a yield of approximately 740 m^3/d (±8.6 ℓ/s). Since the weir of this spring is used as point for continuous irrigation abstraction by the Grootfontein Agricultural College, this spring was simulated as a well in the numerical model and not a Dirichlet boundary condition. Similarly other low yielding springs were simulated as wells in the model.

There is little baseflow if any in the study area due to abstraction and evapotranspiration, keeping the groundwater level below the base of the drainage channels.

11.4.8 Water balance (water budget)

Detailed GYMR groundwater flow balances have been calculated in Chapter 10: Water balance. The more simplified initial water balance used for numerical modelling purposes is presented in Table 11-3.

Table 11-3: Initial model water balance steady state

Component	**Inflow (m^3/d)**	**Outflow (m^3/d)**	**Balance (m^3/d)**
Recharge from rainfall	19100.1	0.0	19100
Dam seepage	0.1	0.0	19100
Existing abstraction (springs included)	0.0	-18655.7	445
Evapotranspiration losses	0.0	0.0	445
Baseflow	0.0	0.0	445
Total	**19100.2**	**-18655.7**	**445**
Balance Error (%)			2.3%

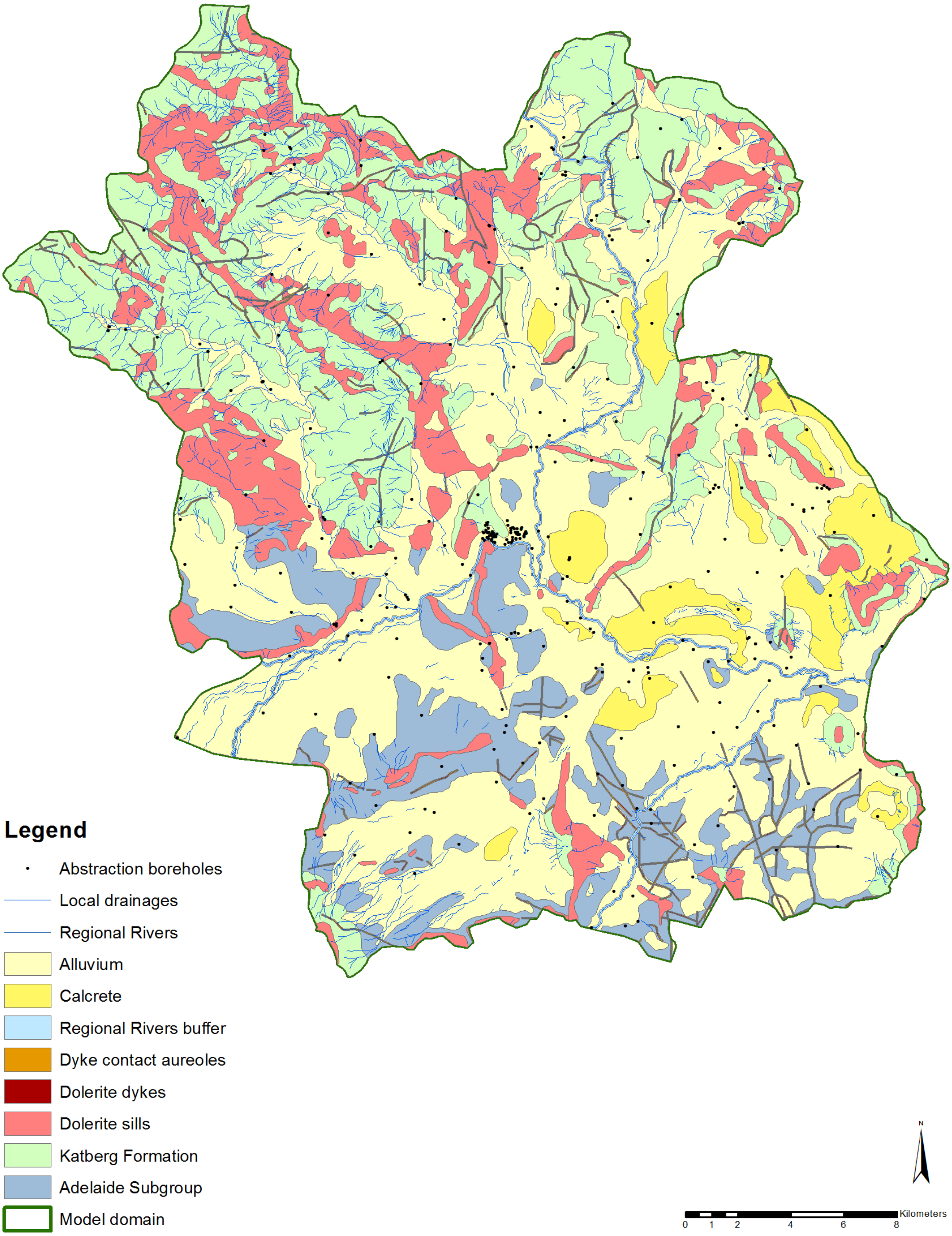


Figure 11-8: All the features used in the FEFLOW Supermesh construction

11.5 Groundwater flow model construction

11.5.1 Finite element mesh construction (model grid)

A two dimensional (2D) model was constructed as it was beyond the scope and resources of this study to construct a three dimensional model. Given that the numerical model is primarily constructed to evaluate the GYMR water balance results and validate the sustainability of groundwater abstraction, a three dimensional would perhaps be excessive.

The FEFLOW finite element (FE) mesh was created by first manually constructing a FEFLOW Supermesh framework from map data. The following map data was used:

- Vector data from the 1: 250 000 geological map (see Figure 11-8);
- Rivers and drainages vector data;
- Regional Rivers were buffered 50 m each side to create weathered zone along rivers often found in reality;
- Dolerite dykes were buffered 10 m on each side, giving them a 20 m thickness. A smaller buffer would create too many small elements that could cause model oscillations;
- Dyke contact zones were created by buffering 20 m on each side of the newly built dykes;
- Existing abstraction boreholes and new exploration boreholes drilled (359 boreholes).

The finite element approach allow nodes to be exactly placed on vertices of rivers, dykes or geological boundaries for instance, allowing perfect FE mesh definition of features if desired. The Supermesh polygons were digitised on the above mentioned map data as far as possible and practical, while angles < 30° were avoided during Supermesh construction. A total of 3117 Supermesh polygons were ‘stitched together’ in the model domain for finite element mesh generation. Existing abstraction boreholes and new exploration boreholes were directly imported as supermesh points.

For finite element mesh generation, the Triangle FE mesh generation algorithm by Jonathan Shewchuk from the University of California at Berkeley was used (Shewchuk, 1996). The finite element mesh was generated with the least number of elements possible given the supermesh framework. After a single smoothing of the generated FE mesh with nodes not located on vector boundaries or points, an acceptable quality FE mesh was obtained with obtuse angled triangles: 0.0% > 120°; 8.6% > 90° and Delaunay violating triangles at 1.3%. The FE mesh has a total of 364 041 elements and 183 014 nodes and no interior holes.

No additional refinement was performed as the finite element mesh was evaluated to be adequately discretised with even transitions between larger and smaller elements. The final FE mesh is presented in Figure 11-9 below and the geological units, structures, rivers and boreholes the FE mesh discretisation was based upon are shown in Figure 11-10.

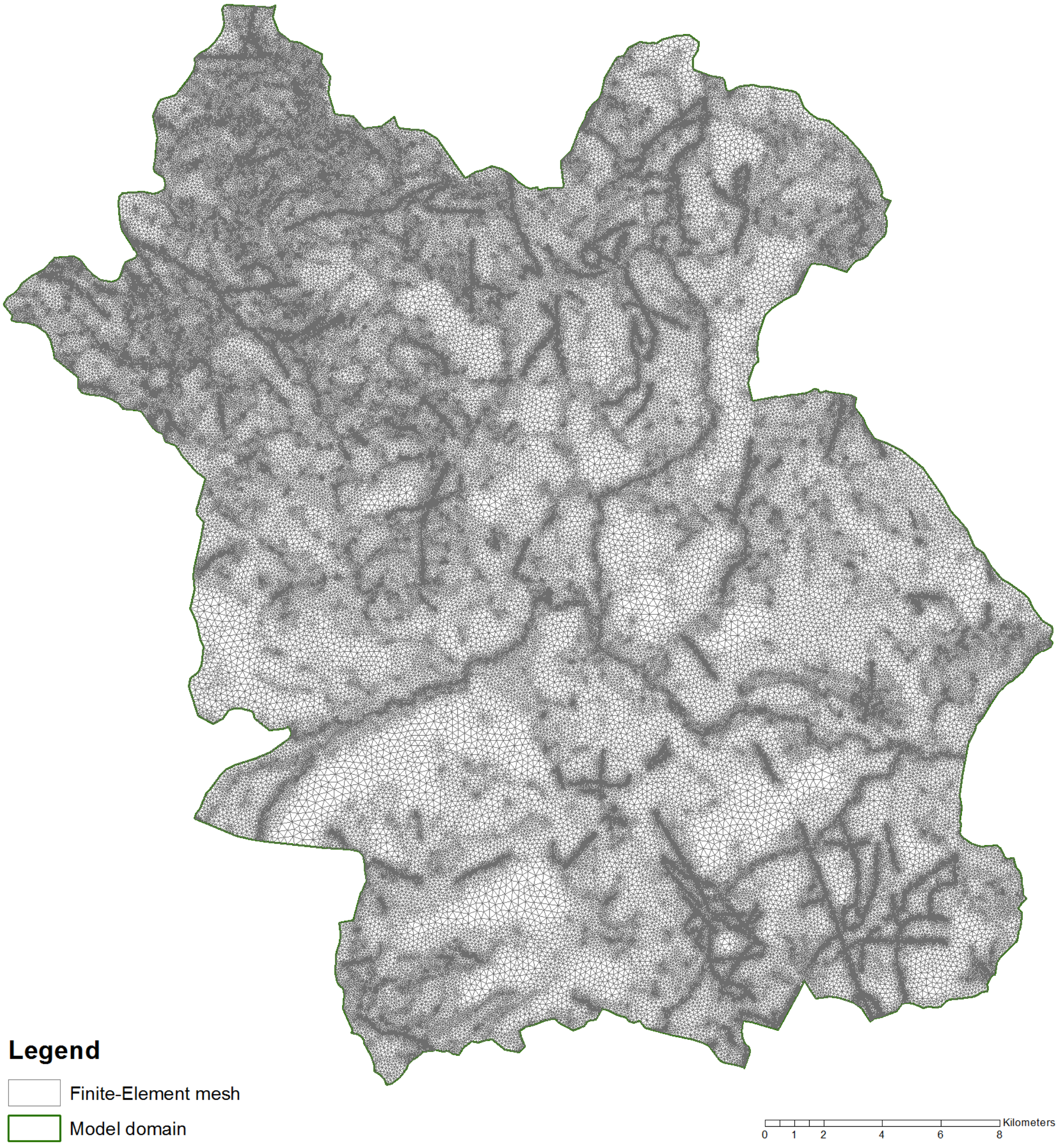


Figure 11-9: FEFLOW finite element mesh

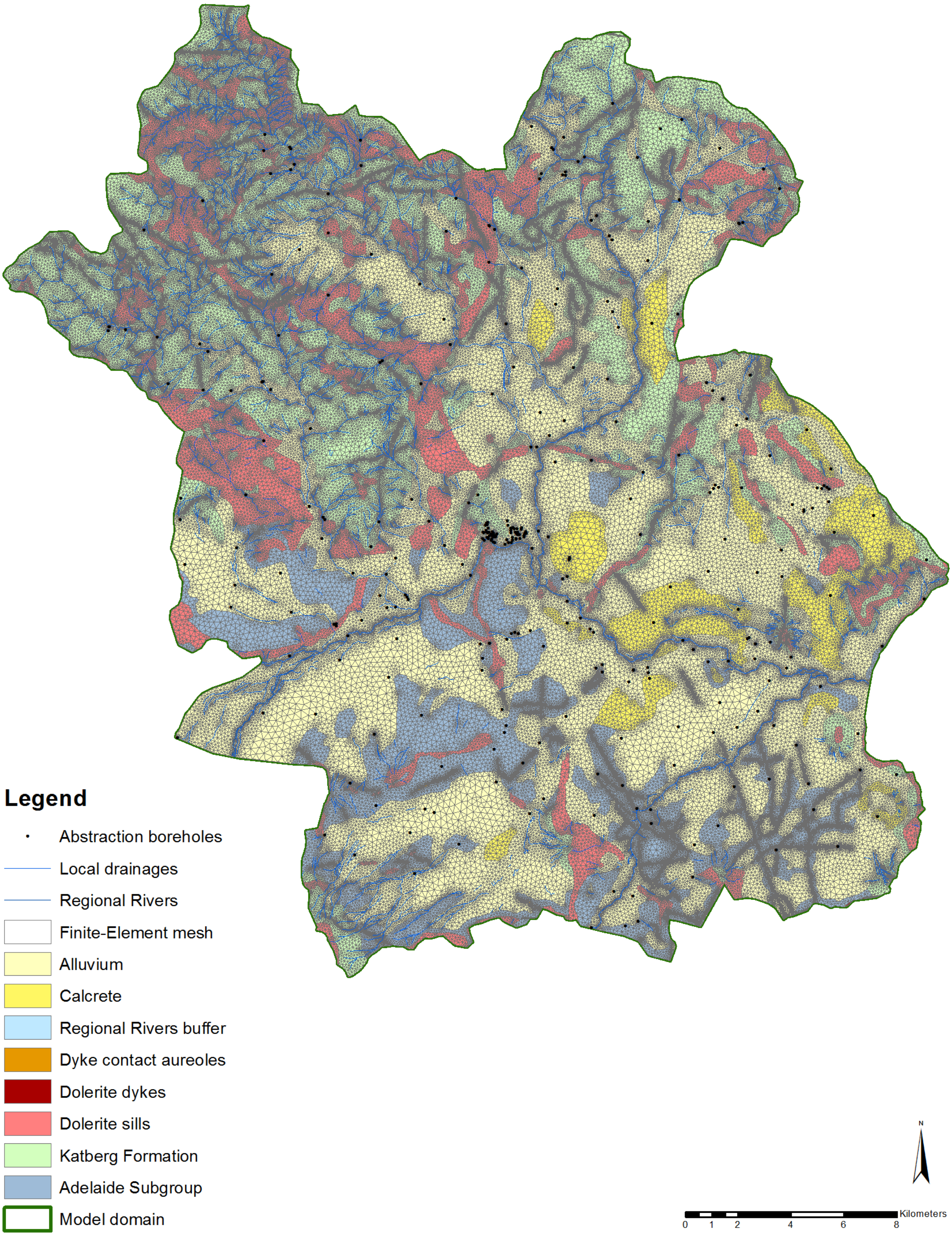


Figure 11-10: Geology, rivers and abstraction boreholes included in FE mesh (Table 11-4)

11.5.2 Temporal dimensionality and discretisation

The numerical model was first calibrated in steady state. The transient model was simulated in days with time-steps in data based on calendar time. Automatic time-step control was used with an initial time step length of 0.001 days, a growth factor of 5 between subsequent time-steps and a maximum time-step length of 30 days. The total simulation time for the transient 100 year simulations was 36 525 days.

11.5.3 Hydraulic parameters

The hydraulic parameters used for the initial steady state calibration are summarised in Table 11-4. Parameters such as mean aquifer thickness and hydraulic conductivity are not required, but shown for interest sake. Transmissivity (T) and specific yield (S) are applicable since only the shallow aquifer is simulated and a 2D model has been constructed. The different hydraulic zones as described in Table 11-4 are shown in Figure 11-10.

Table 11-4: Initial steady state hydraulic parameters

	Lithology	Thickness (m)	Recharge (% MAP)	Transmissivity (m^2/d)	Kx,y (m/d)	Kz (m/d)	Specific yield
1	Alluvium	32	1.98%	244.1	7.7E+00	7.72E-01	1.00E-02
2	Calcrete	32	1.98%	152.2	4.8E+00	4.81E-01	1.00E-02
3	Weathered zone regional rivers	32	1.98%	42.2	1.3E+00	1.33E-01	1.00E-02
4	Dyke contact/ baked zones	32	3.32%	12.2	3.9E-01	3.86E-02	2.25E-03
5	Dykes	32	3.32%	6.5	2.0E-01	2.04E-02	1.00E-03
6	Dolerite sills	32	3.32%	1.1	3.5E-02	3.48E-03	1.00E-03
7	Katberg sandstone/mudstone	32	3.32%	0.8	2.7E-02	2.66E-03	1.00E-03
8	Adelaide mudstone/ sandstone	32	3.32%	0.8	2.7E-02	2.66E-03	1.00E-03

11.5.4 Boundary conditions

By default the model domain boundary is impermeable in FEFLOW. Most of the study area model domain boundary has been digitized on watersheds so an impermeable model domain boundary condition was accepted.

A Dirichlet (First type) boundary condition was placed on all nodes following drainages and larger rivers. All drainages in the study area are non-perennial and as such the Dirichlet boundary conditions are suitably applied. A raster digital terrain model (DTM) with 25 m grid spacing from the National Geospatial Information (NGI) was used to interpolate elevations along drainages. If hydraulic head rises above these elevations at drainages, the excess groundwater will be removed from the model, which is similar to baseflow in nature.

Abstraction boreholes were included in the model as Well boundary conditions (BCs).

11.5.5 Selection of calibration targets (initial conditions)

Boreholes surveyed during the hydrocensus where groundwater levels were measured were plotted in GIS and the model domain polygon used to clip all water level boreholes within the model domain. The selected observation borehole dataset was checked for erroneous water level records. A total of 378 observation boreholes with water levels were obtained for the model domain. The observation boreholes also have a good spatial distribution. All observation boreholes used are within the shallow aquifer or are influenced by the shallow aquifer. The observation boreholes used in the numerical model are shown in Figure 11-11.

11.6 Calibration

11.6.1 Residual analysis

The numerical flow model was simulated in steady state during which calibration was performed by comparing simulated hydraulic heads to measured hydraulic heads and adjusting hydraulic parameters until an acceptable regression fit was obtained between measured and simulated heads. Differences between measured and simulated heads called errors or residuals were calculated, as well as absolute errors (AE). The mean absolute error (MAE) and normalised root mean square error (NRMSE) of all 378 observation boreholes was used as a general guide to calibration improvement, when new hydraulic parameter combinations were applied.

While it is acceptable to remove 10% of outlier observation boreholes due to their spuriously large errors, none of the observation boreholes were removed. At least two outlier boreholes have been identified in the dataset namely EC-Q14-1663 (residual of +205.7 m) and EC-Q14-822 (residual of +118.3 m).

Approximately 44 different calibration runs were performed with different parameter value combinations. A trial-and-error (manual) method of calibration was used where a single or multiple parameter values are varied to observe improvement gained in residual analysis.

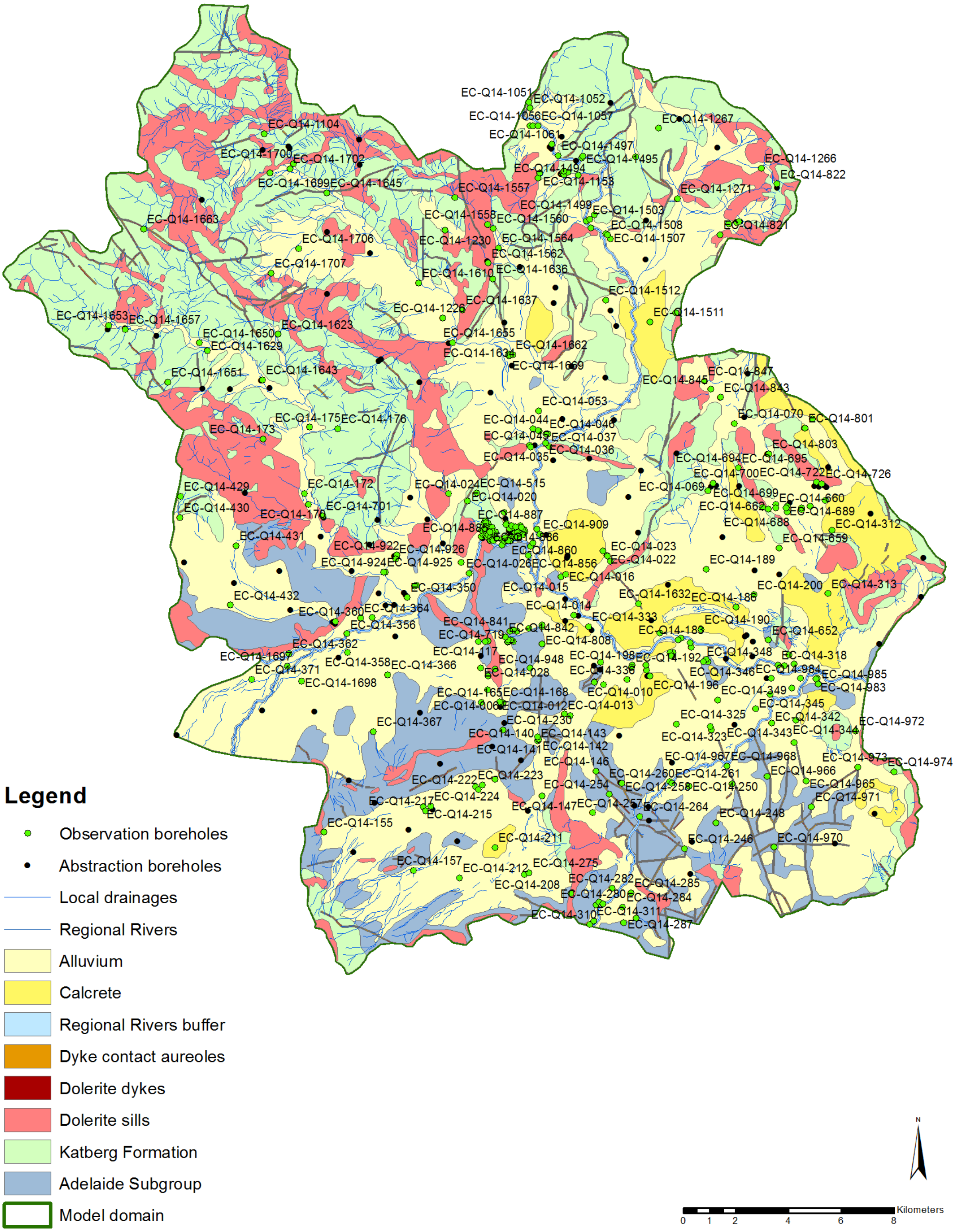


Figure 11-11: Model observation boreholes (N = 378)

The hydraulic parameters used for initial model calibration are presented in Table 11-4. The mean absolute error (MAE) and normalised root mean square error (NRMSE) using initial hydraulic parameters were 64.17 m and 13% respectively. A large improvement in mean absolute error was obtained between calibration 7 and calibration 8, when recharge on hard rock outcrop was increased from 3.32% to 6.0% of MAP. This resulted in a mean absolute error improvement from 50.65 m to 14.97 m, a 35.68 m mean reduction in difference between measured- and simulated-heads.

After calibration 8, a continuous improvement of ± 0.5 m was gained each time the recharge across either unconsolidated- or hard rock-hydraulic units was increased, indicating that recharge for either of the two main hydraulic units could be higher than that of the final model calibration. A decision was made to keep to what is known to be realistic and in this case conservative recharge values, with the final goal of sustainable groundwater supply in mind.

Calibration results are presented graphically in Figure 11-12 through Figure 11-17 to show the degree of fit of simulated heads to measured hydraulic heads and indicate where larger differences in calibration occur. Hydraulic parameters of the final calibration accepted for transient model simulation are presented in Table 11-5.

Table 11-5: Final steady state calibrated hydraulic parameters

	Lithology	Recharge (%)	Recharge (m/d)	Transmissivity (m^2/d)	Specific yield
1	Alluvium	2.00%	1.89E-05	60.0	1.00E-02
2	Calcrete	2.00%	1.89E-05	60.0	1.00E-02
3	Weathered zone regional rivers	2.00%	1.89E-05	60.0	1.00E-02
4	Dyke contact/ baked zones	6.50%	6.14E-05	12.2	2.25E-03
5	Dykes	6.50%	6.14E-05	6.5	1.00E-03
6	Dolerite sills	6.50%	6.14E-05	5.0	1.00E-03
7	Katberg sandstone/mudstone	6.50%	6.14E-05	5.0	1.00E-03
8	Adelaide mudstone/ sandstone	6.50%	6.14E-05	5.0	1.00E-03

The hydraulic conductivity based on numerical model calibration is expected to be ±3 m/d for the combined porous and weathered unconformity hydraulic unit and ±0.2 m/d for the weathered shallow hard rock hydraulic unit.

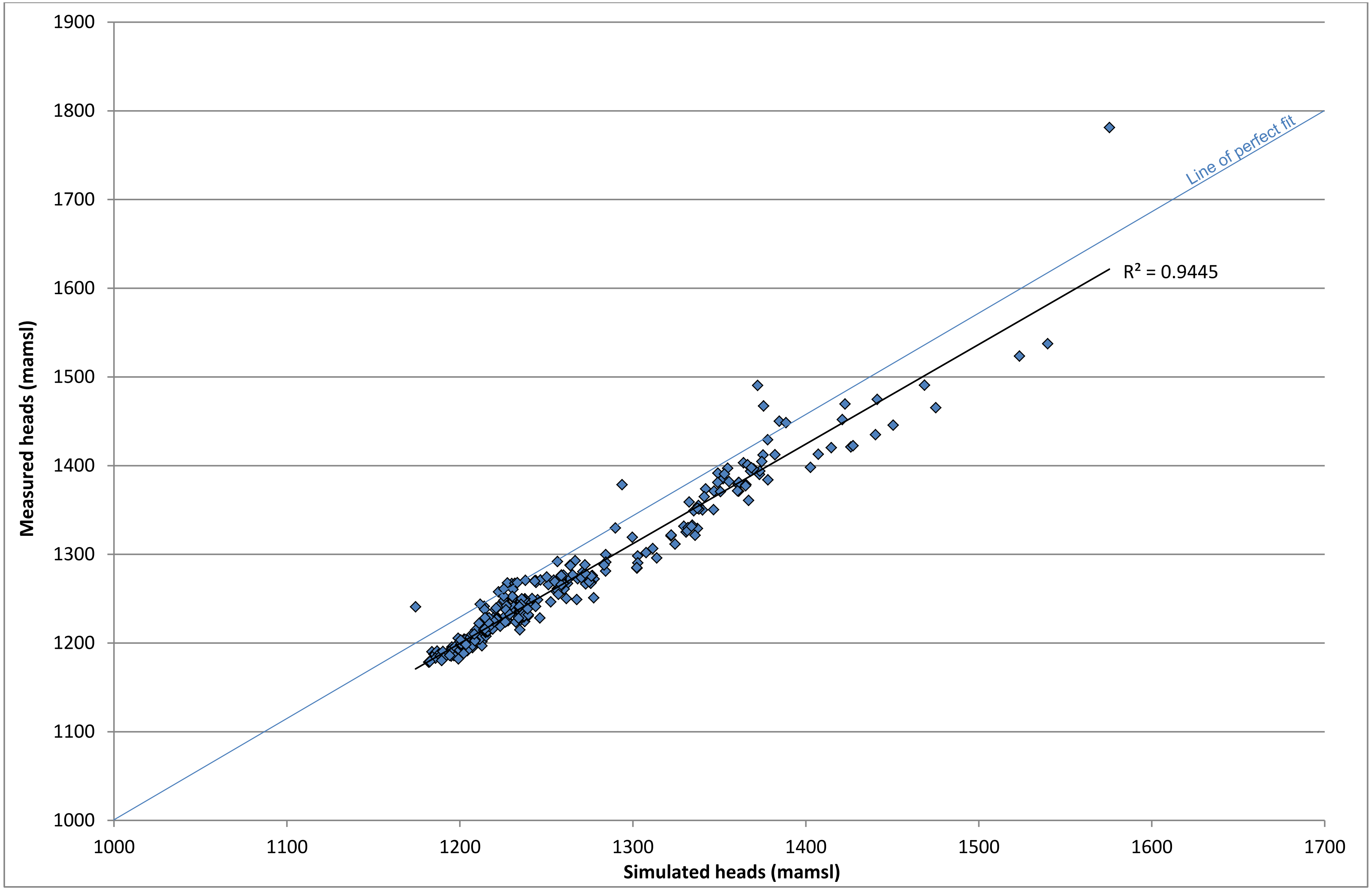


Figure 11-12: Scatter plot of calibrated steady state measured vs. simulated hydraulic heads

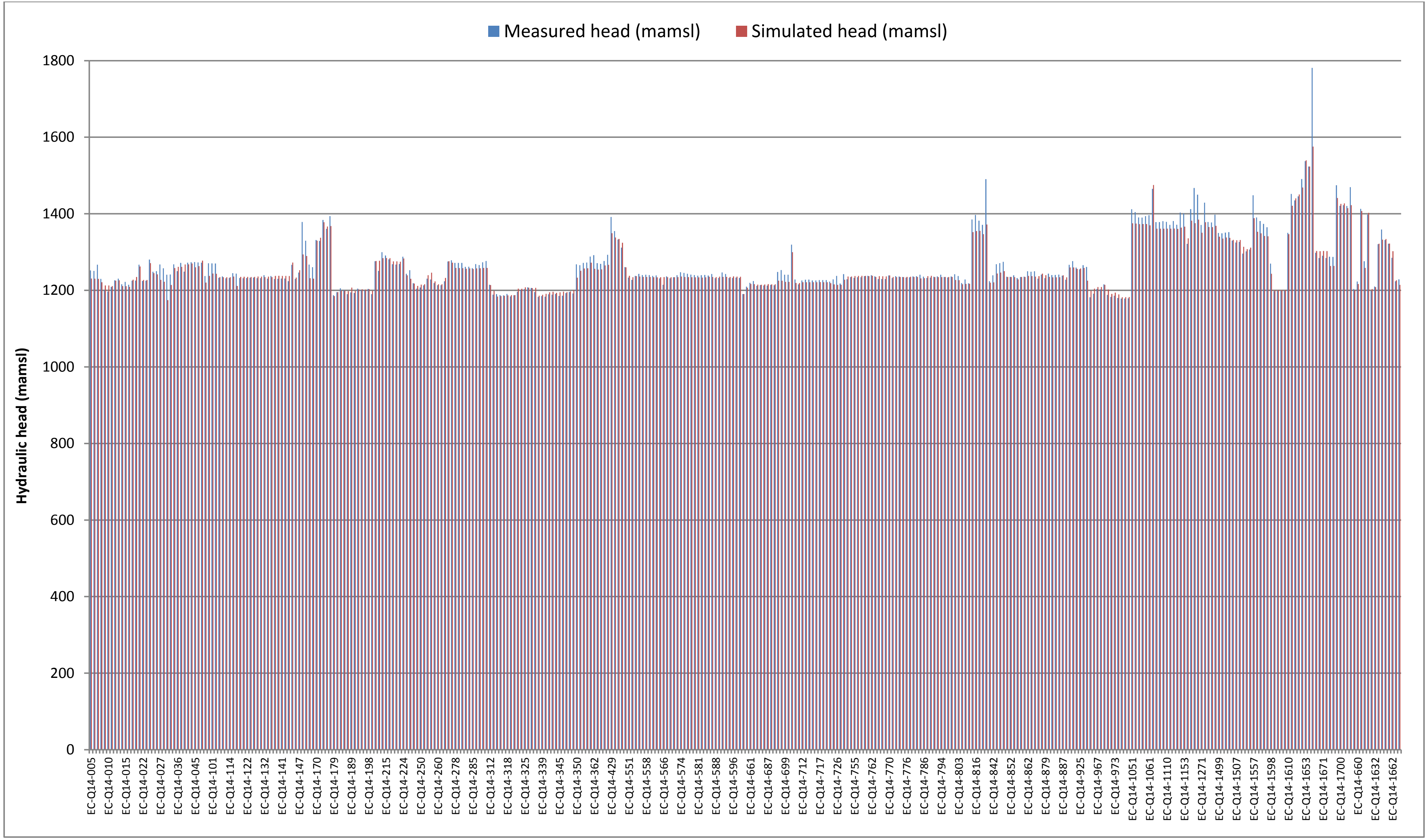


Figure 11-13: Bar chart of calibrated steady state measured vs. simulated hydraulic heads

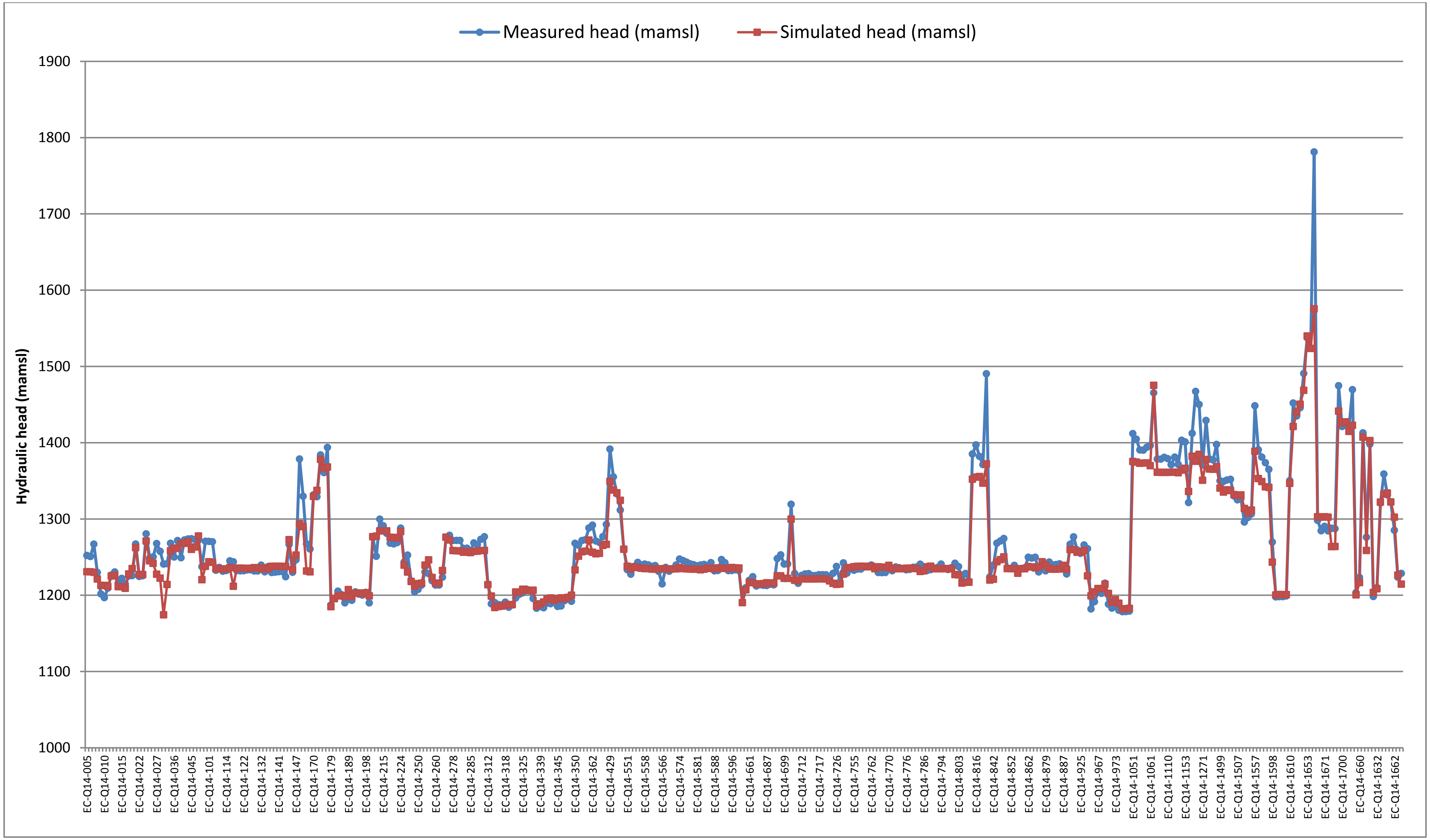


Figure 11-14: Line graph of calibrated steady state measured vs. simulated hydraulic heads

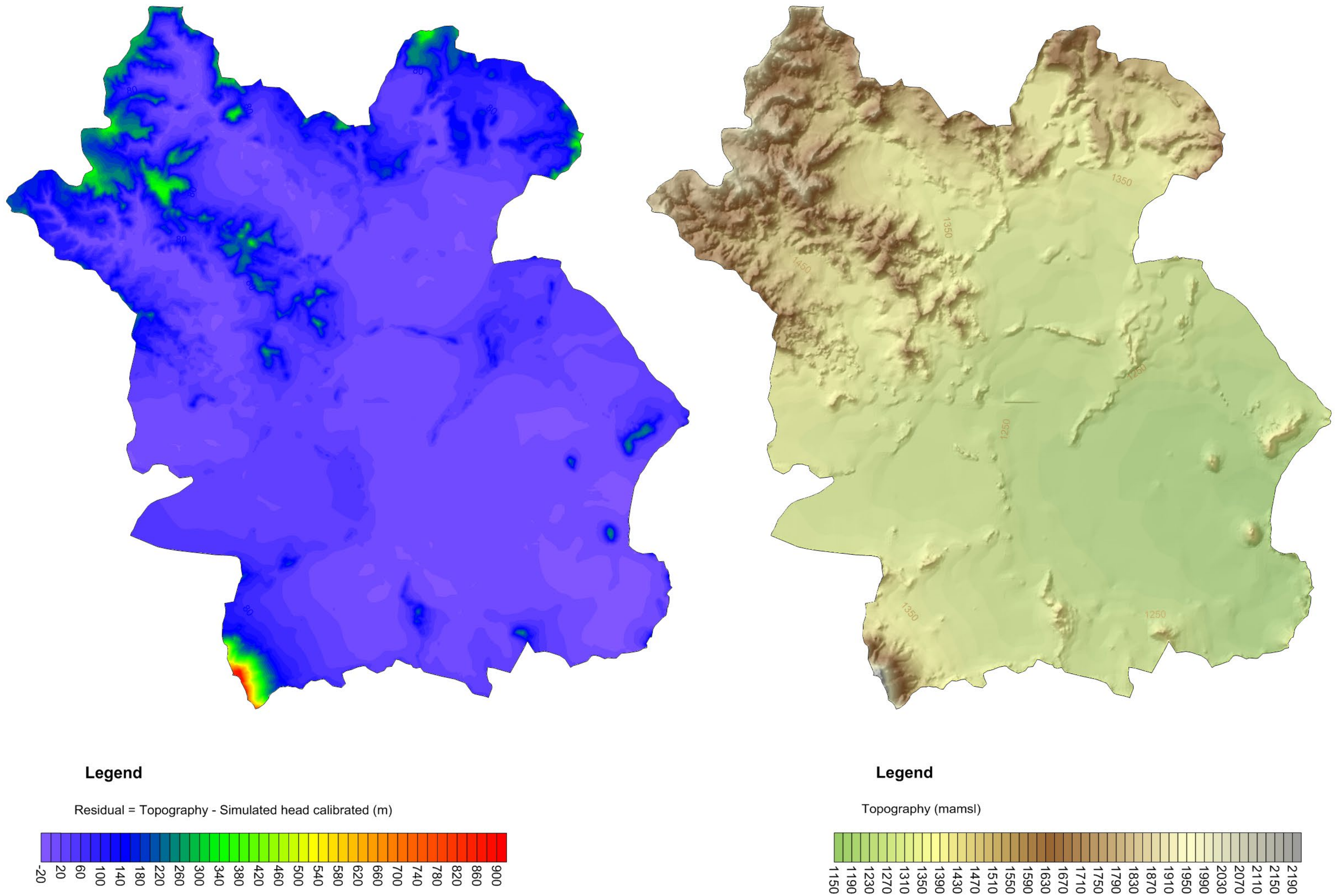


Figure 11-15: Residuals analysis: residual distribution compared to topography

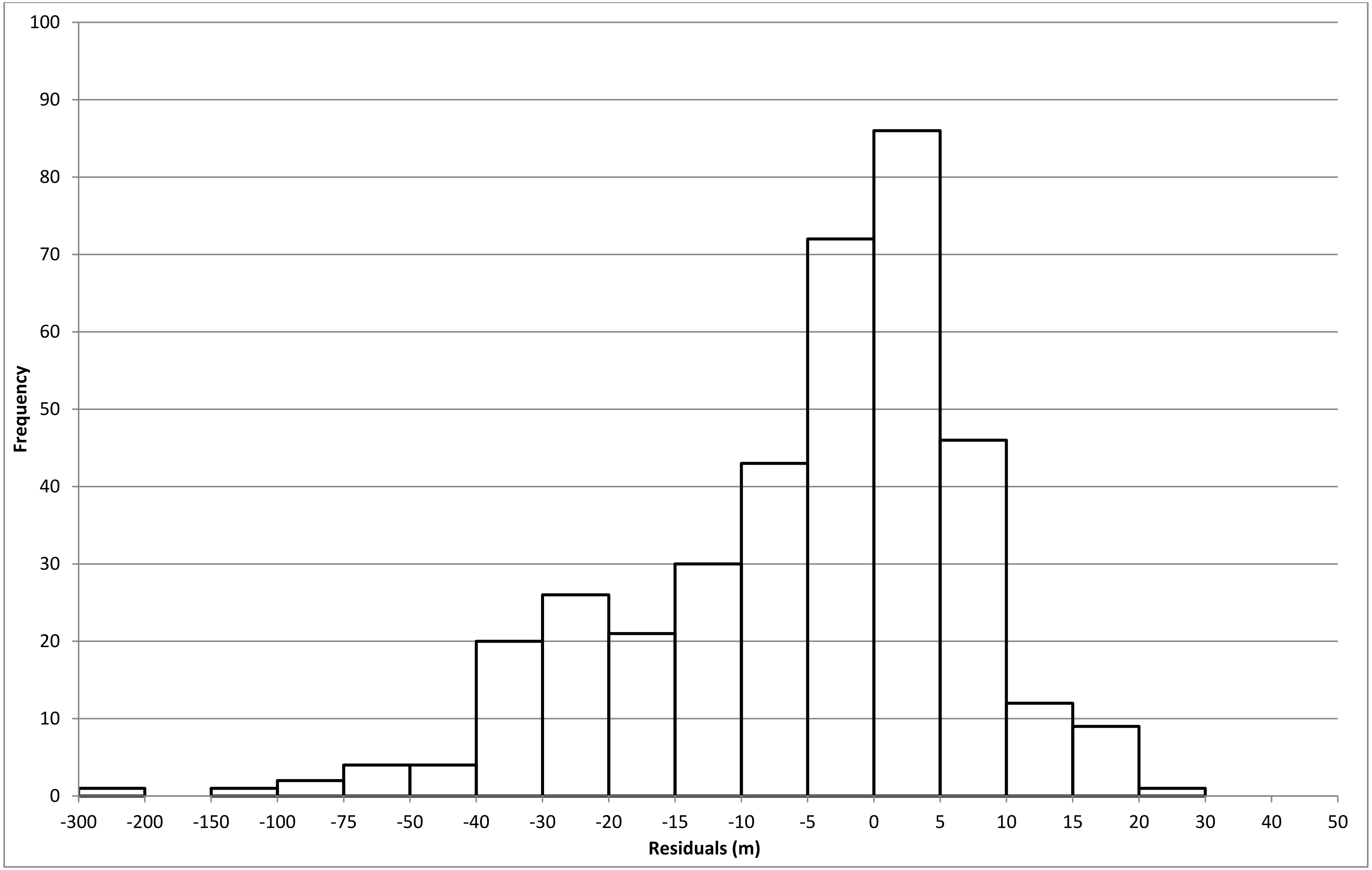


Figure 11-16: Histogram of hydraulic head residuals from final steady state calibration, skewed distribution due to conservative approach

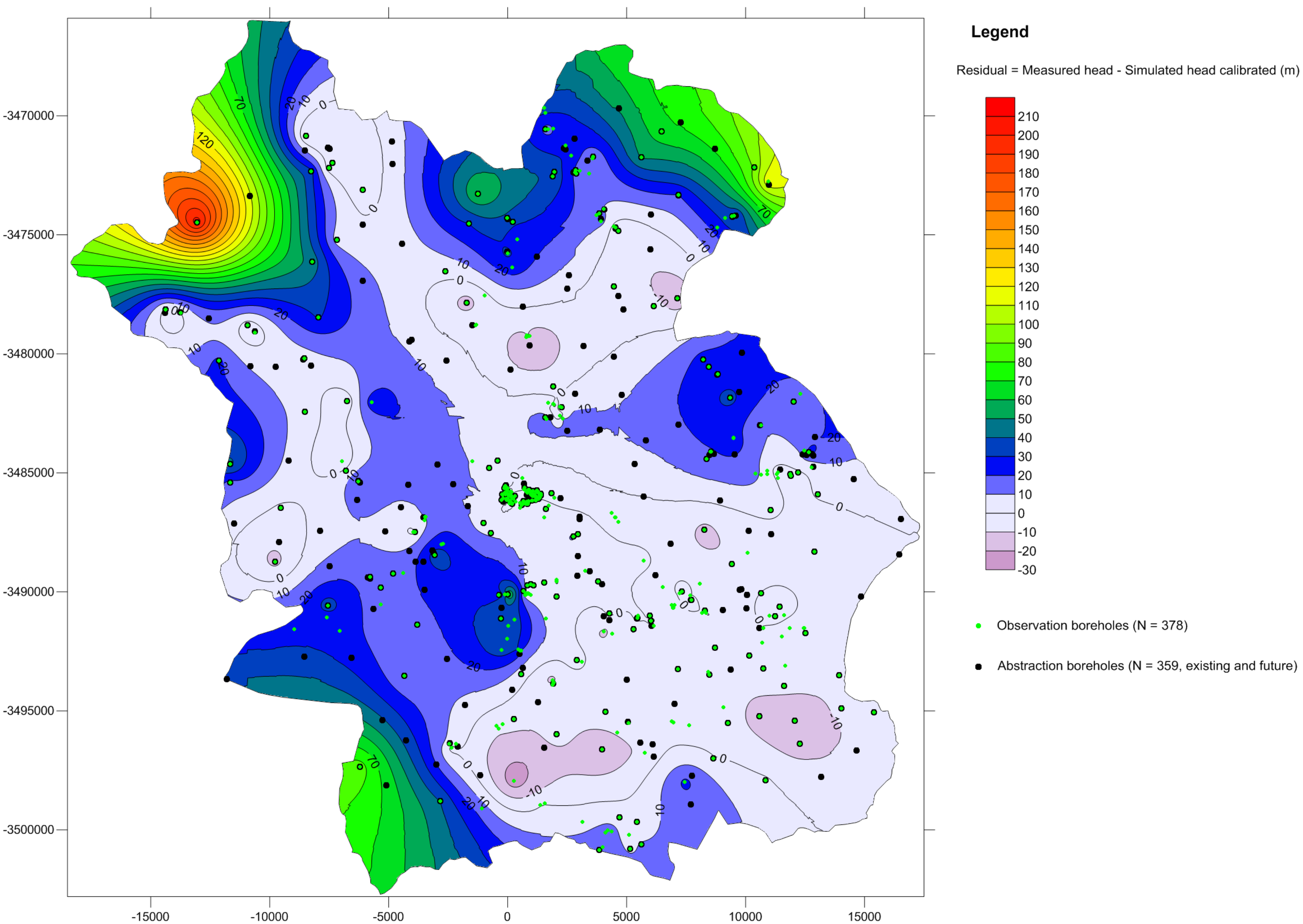


Figure 11-17: Map of interpolated steady state model residuals (N = 378)

11.6.2 Sensitivity analysis

A sensitivity analysis was conducted for aquifer parameters in the steady state model. A single parameter was varied for one of the two major hydraulic units, while the other aquifer parameters were kept constant. The transmissivity of the dolerite dykes and dyke contact/baked zones were not varied and recorded as it was observed that changes to these transmissivities do not affect the calibration results significantly.

Each aquifer parameter was varied within a realistic range for the given parameter.

The realistic range of recharge percentages for the outcropping hard rock geology is expected to range between 3.2% and 7% with a maximum expected recharge of 8%. Figure 11-18 illustrates the results from the manual sensitivity analysis on outcropping hard rock geology recharge. The sensitivity analysis was conducted up to 18% (although unrealistic) simply to illustrate an important concept identified during the sensitivity analysis. The Dirichlet boundary conditions (BC) assigned to almost all local 1: 50 000 mapped drainage lines are removing all excess groundwater from the model to such an extent that hard rock recharge can be made unrealistically high and the model will still calibrate well. The Dirichlet BCs on drainages are too efficient at removing groundwater from the model especially in the mountainous areas, where hard rock geologies dominate. This hampers finding an accurate upper bound limit for the hard rock recharge.

For the unconsolidated sediments and weathered river channel zone as the other hydraulic unit, recharge sensitivity analysis started with a lower bound recharge percentage of MAP of 0.68% obtained from the chloride mass balance (CMB) method for the Municipal sub-catchment. This estimate is rather low, but was nonetheless obtained through empirical methods and thus can be included in the range of possible recharge values (see Figure 11-19). It is expected that some evaporation occurs at the non-perennial drainages especially in the Municipal and Dunblane sub-catchments, but it is difficult to prove.

For the purposes of the unconfined hydraulic unit calibration, analytical hydraulic test verification was performed with AQTESOLV using an unconfined aquifer model for selected hydraulic tests such as EC-Q14-1655. EC-Q14-1655 has the highest transmissivity (T) of all boreholes hydraulically tested. Based on previous evaluations using a confined (more conservative) aquifer model and Cooper-Jacob and FCM methods, a T of 321 m^2/d was obtained.

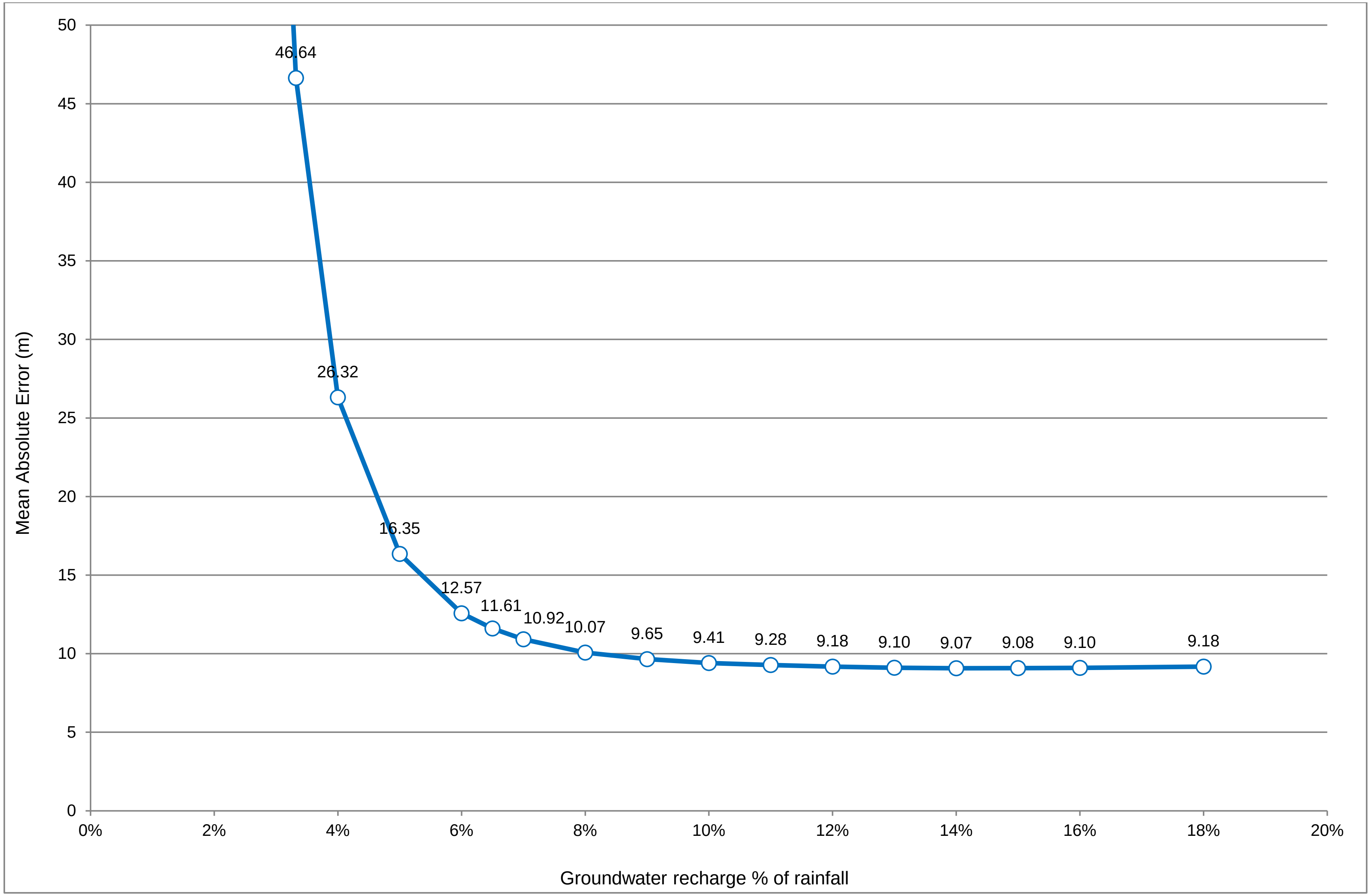


Figure 11-18: Sensitivity analysis for groundwater recharge on fractured hard rock formations that outcrop

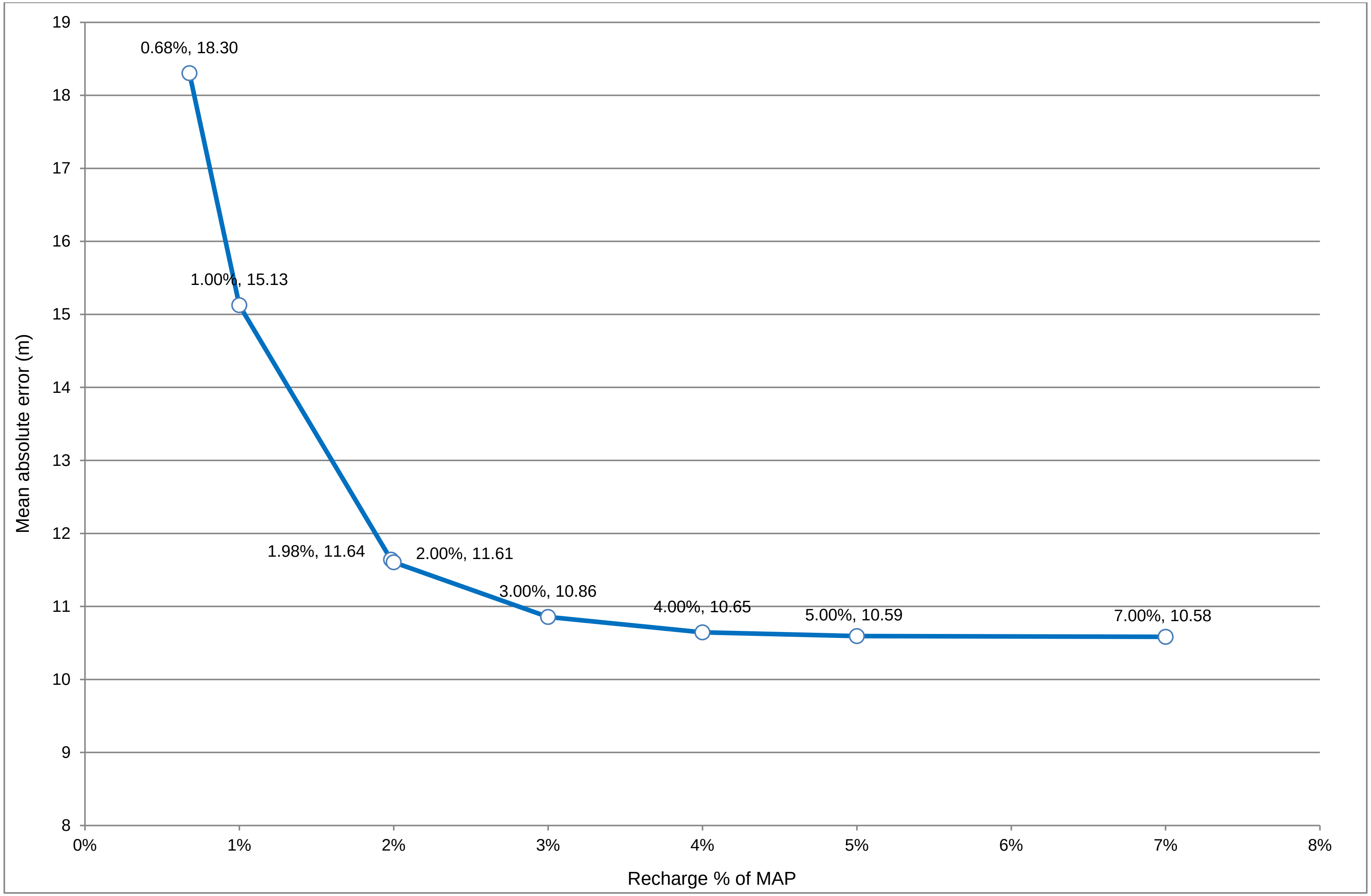


Figure 11-19: Groundwater recharge sensitivity analysis for alluvium, calcrete and weathered river channel (grouped unconsolidated)

Using the Tartakovsky-Neuman (2007) solution for unconfined aquifers, a T-value of 473.5 m^2/d was obtained and using observation borehole EC-Q14-052, a specific yield (S_y) of 0.017. Thus the sensitivity analysis for the unconsolidated sediments/weathered river channel zone was performed within the range of 20 – 473.5 m^2/d. Interesting to note is that Vandoolaeghe (1979) obtained transmissivities in the range of 200 – 1800 m^2/d (and more) for the highly conductive alluvium/calcrete/weathered zone, but one has to keep in mind that the saturated thickness in 1979 was greater (±6 m thicker; groundwater level 3 – 6 mbgl). If the greater aquifer thickness is taken into account unconsolidated sediment transmissivities obtained during this study's hydraulic testing are in line with those of Vandoolaeghe (1979).

Sensitivity analysis for both hard rock- and shallow aquifer/unconfined-transmissivities are shown in Figure 11-20 and Figure 11-21.

Even with a much lower recharge of 3.32% for hard rock outcrop geologies (12035 m^3/d) and 1.98% for superficial deposits (7051 m^3/d), if no drainages are available to remove groundwater from the model (which was thought to be the case), groundwater is still in net excess and hydraulic heads build up in the model domain (abstraction: -18656 m^3/d).

- This means that there are semi-impermeable aquifer boundaries unmapped on the geology map that causes compartmentalisation (could include very shallow or unconnected parts of alluvium as well as dykes, typical of boundaries). Compartmentalisation through dolerite ring- and sill-structures can create isolated catchments with net deficit balances, such as the Middelburg Municipal sub-catchment.
- Hydraulic head in some sub-catchments is much lower due to internal aquifer boundaries. In this case a small section of lower hydraulic conductivity rock controls flow and concentrated abstraction draws down the hydraulic head (groundwater level) locally.

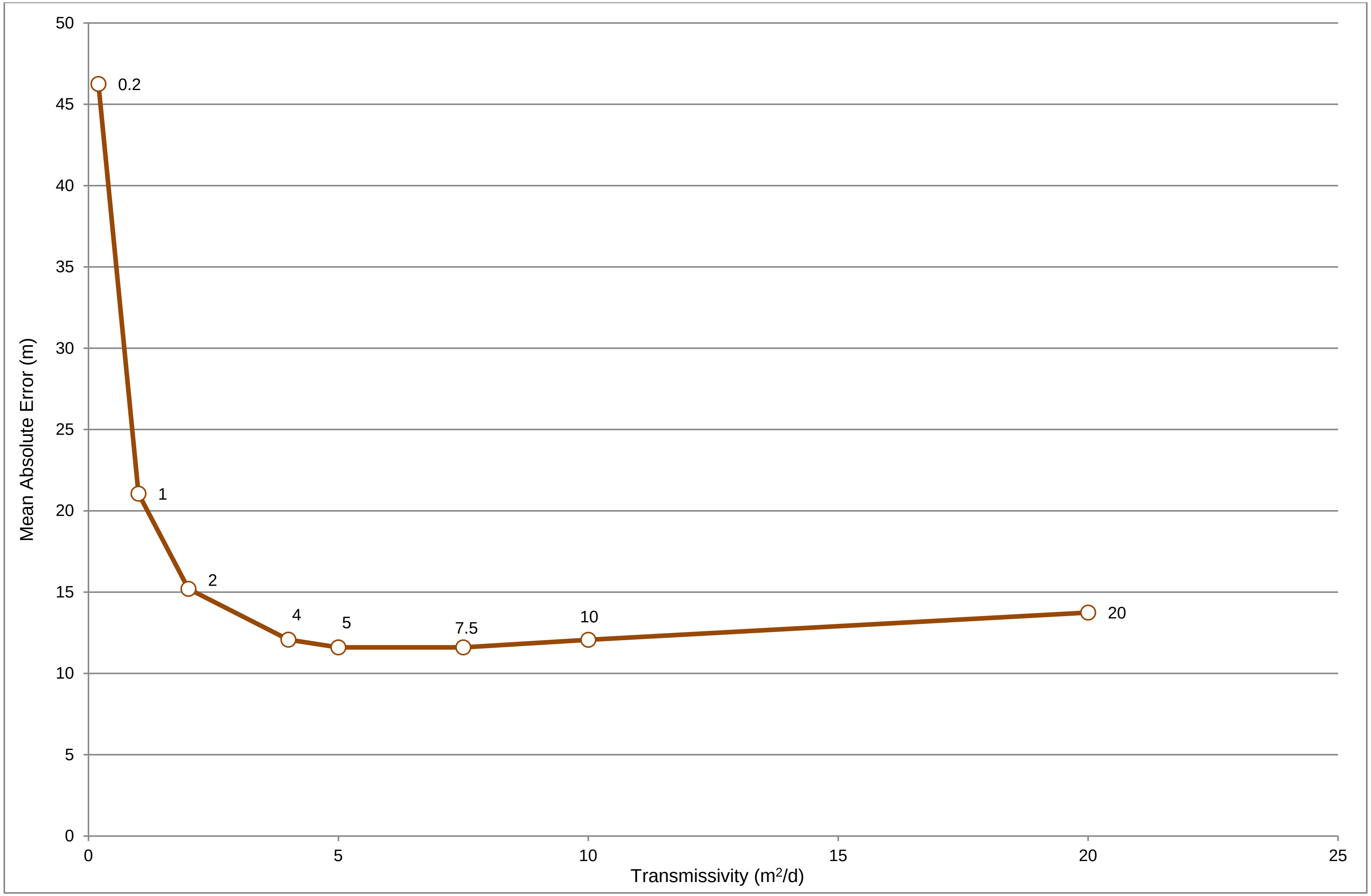


Figure 11-20: Sensitivity analysis for transmissivty (T) of fractured hard rock geology types

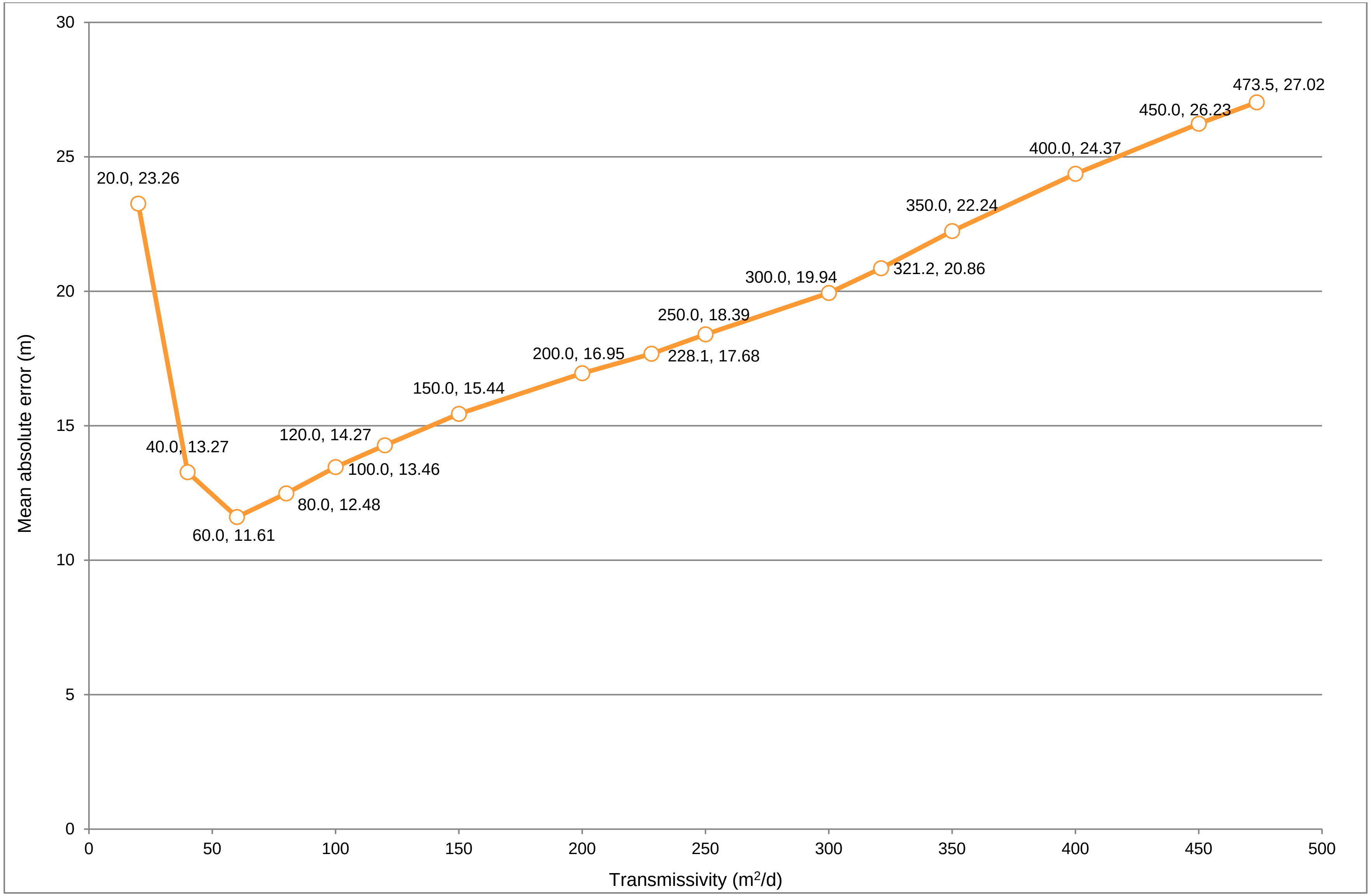


Figure 11-21: Sensitivity analysis for transmissivty (T) of alluvium, calcrete and weathered river channel zone

11.6.3 Model validation

A steady-state calibration comparing a single set of measured hydraulic heads to simulated hydraulic heads does not guarantee that the simulated head change over time will match the actual head change over time. For instance, the simulated hydraulic head could be rising while the hydraulic head is in reality declining.

Also, a number of different combinations of parameters could provide the same calibration result. This modelling calibration problem is what is known as the non-uniqueness problem. Non-uniqueness can however be significantly reduced if a fit of simulated hydraulic heads to measured hydraulic heads is performed for more than one point in time, ideally a time series. This type of calibration is called history matching, model validation or model verification. It also typically provides a higher degree of confidence in the numerical modelling results.

From Chapter 3: Historic groundwater levels and Abstraction there are currently four DWA monitoring boreholes with actively recording water level loggers. Data from these boreholes, although only concentrated around the Municipal sub-catchment, could be used for history matching, especially the later data.

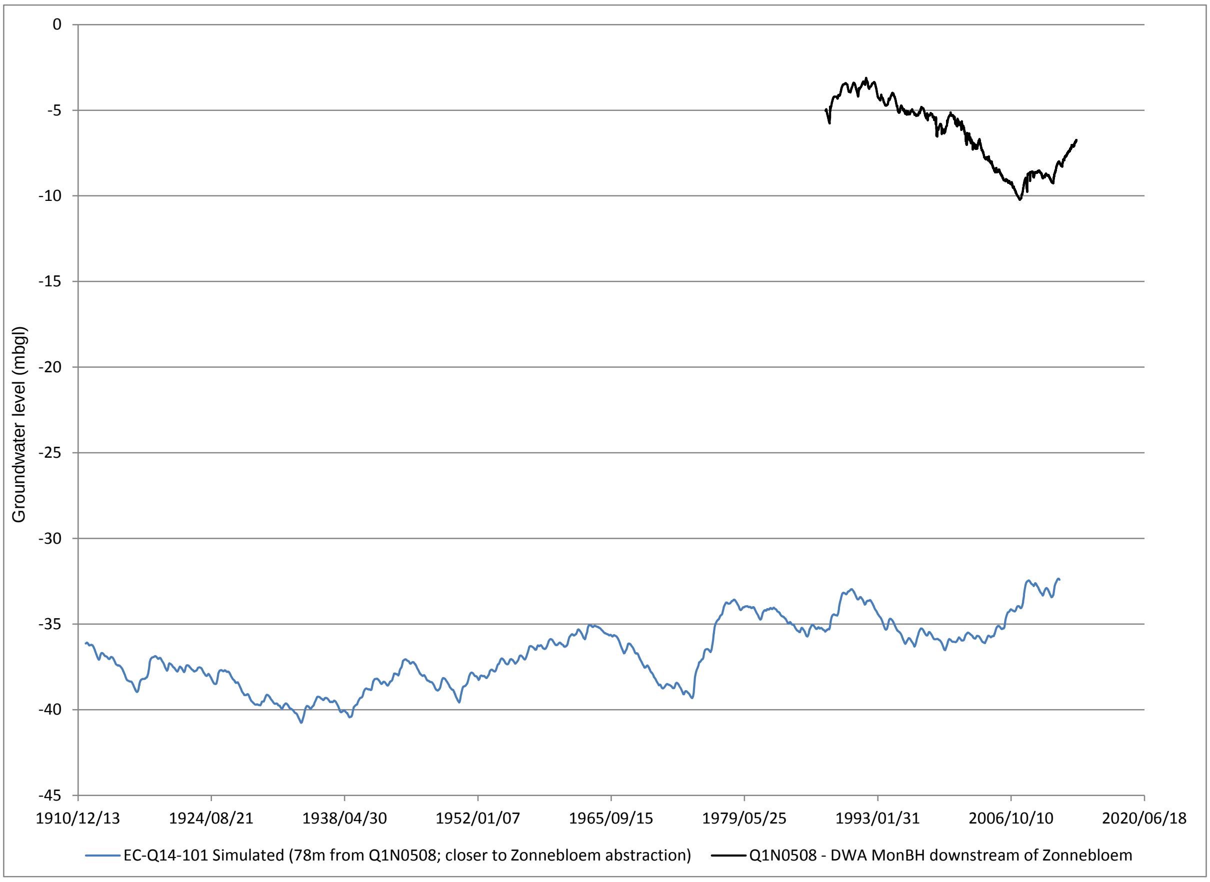


Figure 11-22: Simulated water level EC-Q14-101 compared to monitoring borehole Q1N0508

The initial concern and reason for deciding to perform history matching for the Middelburg groundwater flow model, is illustrated in Figure 11-22 above. Clearly, either the DWA groundwater level recorder is faulty (not likely as they are visited quite regularly) or there is something wrong with the model hydraulic parameters or setup. Figure 11-23 also illustrates this trend.

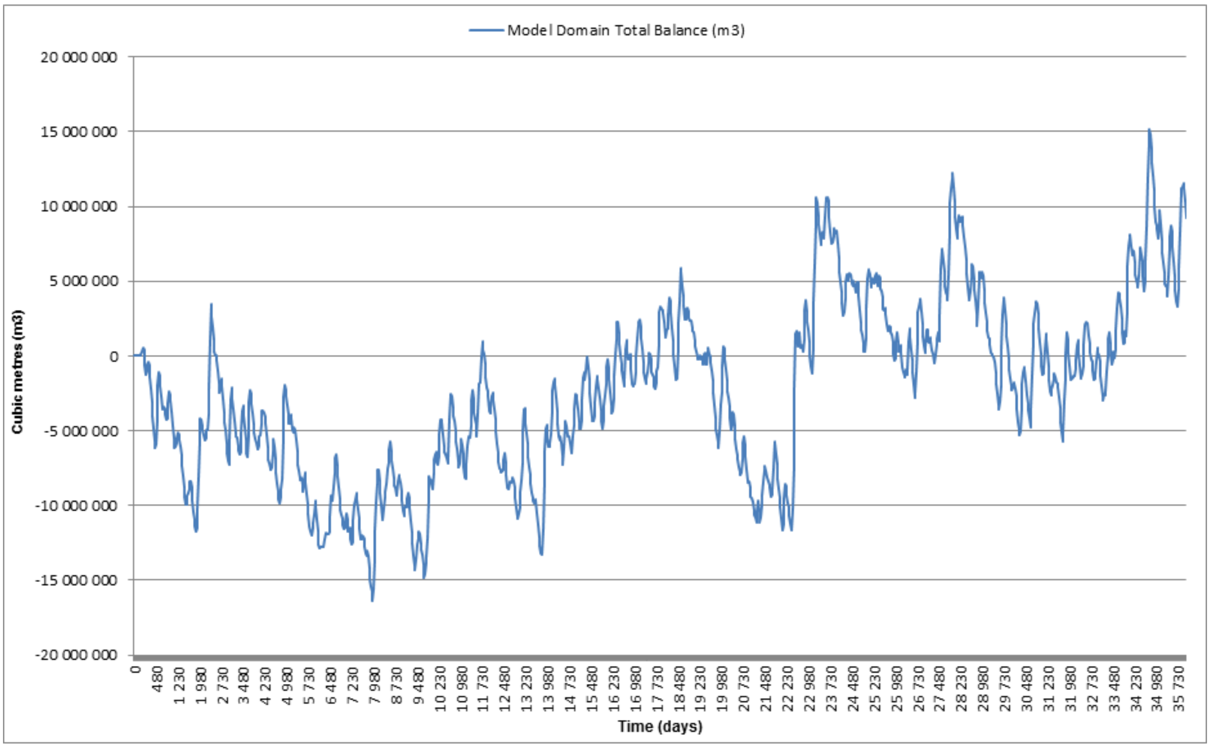


Figure 11-23: Total model domain storage of 100 year simulation without time series abstraction

What could be the cause of a rising groundwater level?

Rainfall analysis was performed for the 100 year patched rainfall sequence, comparing the patched rainfall to various other sources of rainfall records applicable to the Middelburg area. Figure 11-24 shows the 100 year patched rainfall sequence used in the numerical model compared to the 85 years' worth of WR2005 data also used in the patched rainfall sequence. Figure 11-24 also shows a comparison of the 100 year patched rainfall sequence and archive rainfall data from two rainfall stations in Middelburg from the water resource modelling framework (WRMF/WRIMS) database as well as recent SAWS data.

After rainfall analysis has been performed it is seen that there is a slight increasing trend of rainfall over the 100 years and this explains the increasing hydraulic head and model domain storage increase. The rainfall increase however does not explain the measured water table declines around Middelburg.

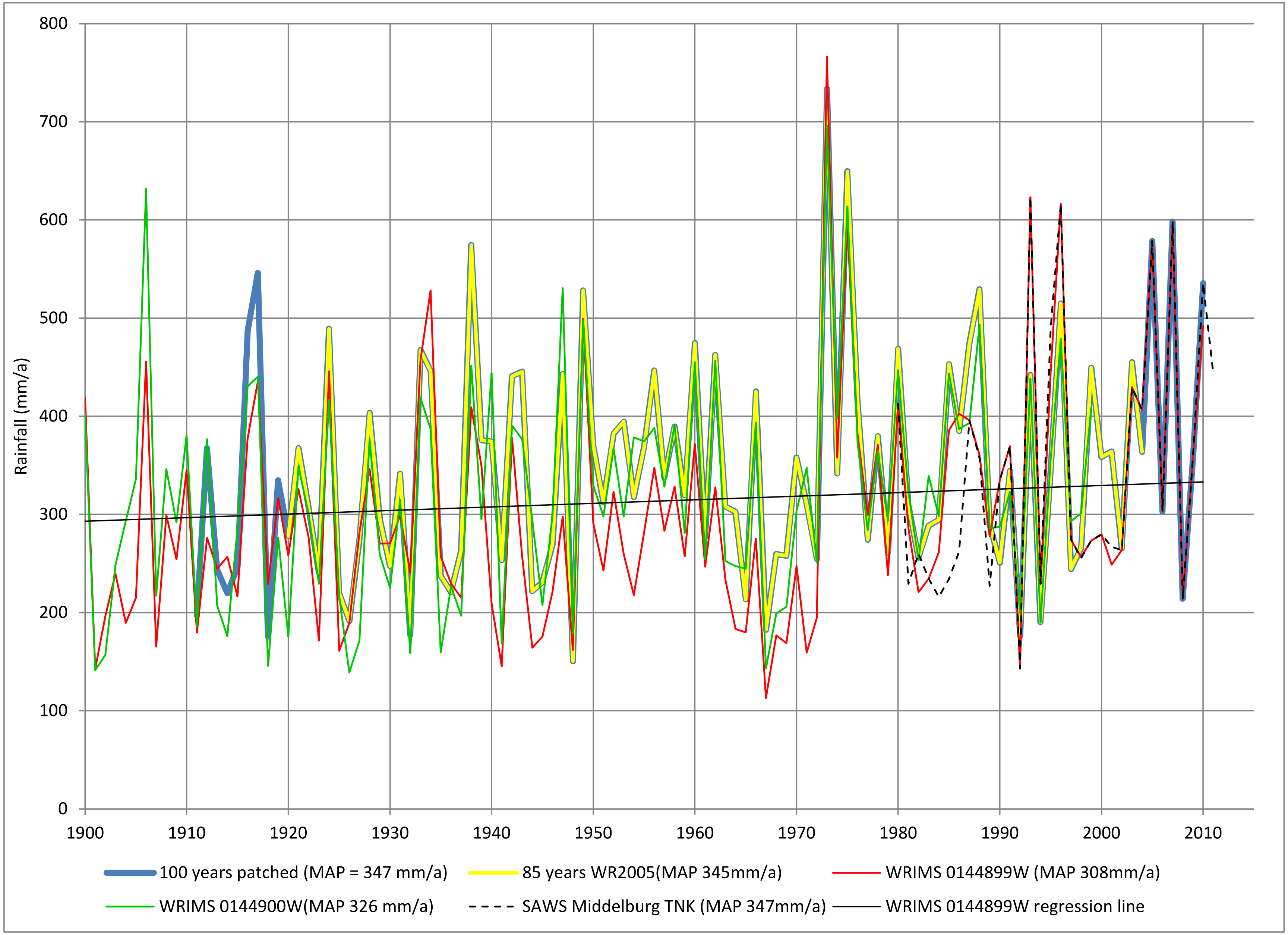


Figure 11-24: Rainfall analysis: comparison of patched rainfall sequence to various other rainfall datasets

11.6.3.1 History matching

Recalling that the steady state calibration is based on current hydraulic head and abstraction conditions, the final hydraulic heads in steady state have been equilibrated to municipal abstraction. Municipal borehole abstraction did not take place since the 1st of October 1911, the simulation date when the transient model starts, but only started during the 1950s. Thus, the current hydraulic head decline observed in the field could still be the result of the hydraulic heads trying to reach equilibrium with the municipal abstractions implemented. It is also known that since 2001, the municipal borehole pumps are switched on and off based on demand and as some borehole supplies fail and recover. Some ideas of when different municipal abstraction boreholes (stations) were first implemented are available from older reports (van Graan, 1946; Gordon-Welsh, 1964; De Bruin, 1975; Vandoolaeghe, 1979; Seward, 1987). Municipal abstraction figures in m^3/month are also available for the period 2001 – 2006. Based on this information time-series municipal abstraction files were created and implemented in the transient model. The steady state model was also recalibrated without the municipal borehole abstractions to provide initial heads for the new transient state model at 01/10/1911. The idea is that the simulated heads will now more closely mimic the hydraulic head decline for recent dates after the municipal abstraction boreholes activate at their respective implementation dates. The results of the first three calibration simulations with time-series municipal abstraction are shown in Figure 11-25.

Figure 11-25: Recharge adjustment effect during history matching and Q1N0508 comparison

In Figure 11-25 above, the simulated hydraulic head trend is now at least starting to look like the measured hydraulic head trend in that both trends are increasing and declining at roughly the same time. The amount of drawdown in the simulated heads is however much more than that of the measured head indicating that the actual aquifer system (and aquifer parameters) is better than the one being simulated.

Solely adjusting recharge does not provide a perfect match of the measured hydraulic head although the general trend of the simulated hydraulic head fluctuation is more similar than the first transient model (Figure 11-22), that had a generally increasing hydraulic head. Transmissivity (T) affects the angle of steepness within the hydraulic head drawdown- and recovery-phases while storativity (S) affects the amplitude of hydraulic head fluctuations. T or S is expected to be higher in reality or they probably both are. One has to keep in mind that there are spatial variations in aquifer parameters especially T and recognising that T = K.b, there is probably a greater aquifer thickness (b) in the region of Q1N0508 in the actual system than is simulated by using a T value of 60 m^2/d. This is proven by tested aquifer parameters in the initial aquifer parameters table in Table 11-4.

The following possible reasons are expected to be the cause of a non-perfect match of measured and simulated hydraulic heads in Figure 11-25:

- Initial municipal abstraction rates were not as high as those simulated.
- Both T and S of the actual aquifer system in the locality of Q1N0508 and EC-Q14-101 are higher. Their values were reduced and one universal alluvium T value for instance used for regional parameter assignment and better calibration.
- In the actual groundwater system, more groundwater enters from adjacent sub-catchments and compartments that were not included in the model domain.

The purpose of the model is however not to be perfectly calibrated both locally and regionally; both in steady- and in transient-state. The model was constructed to provide a tool that can be used to estimate (with more confidence) whether Middelburg and identified sub-catchments have sufficient groundwater now and for future developments in the medium- (5 – 10 years) and long-term (20+ years; less confidence).

Simulated heads in Figure 11-25 above are representative of simulation results for transient models with hard rock outcrop recharge figures of 4%, 5% and 6% as it was initially thought recharge was too high based on the increasing heads in the first transient state model.

Obviously one observation point (EC-Q14-101) 541 m from the Zonnebloem municipal abstraction boreholes does not provide an overall picture of the Municipal sub-catchment and as such, observation boreholes were hand selected per sub-catchment/compartment based on their distance from abstraction, hydrogeological relevance and if they otherwise are one of the four DWA monitoring boreholes.

Running the numerical model for 100 years 1911 – 2011 with time-series municipal abstraction and recharge on hard rock geologies at 6.5% (alluvium and other unconsolidated sediments with clayey top layer = 2%) the following representative hydraulic heads per sub-catchment result.

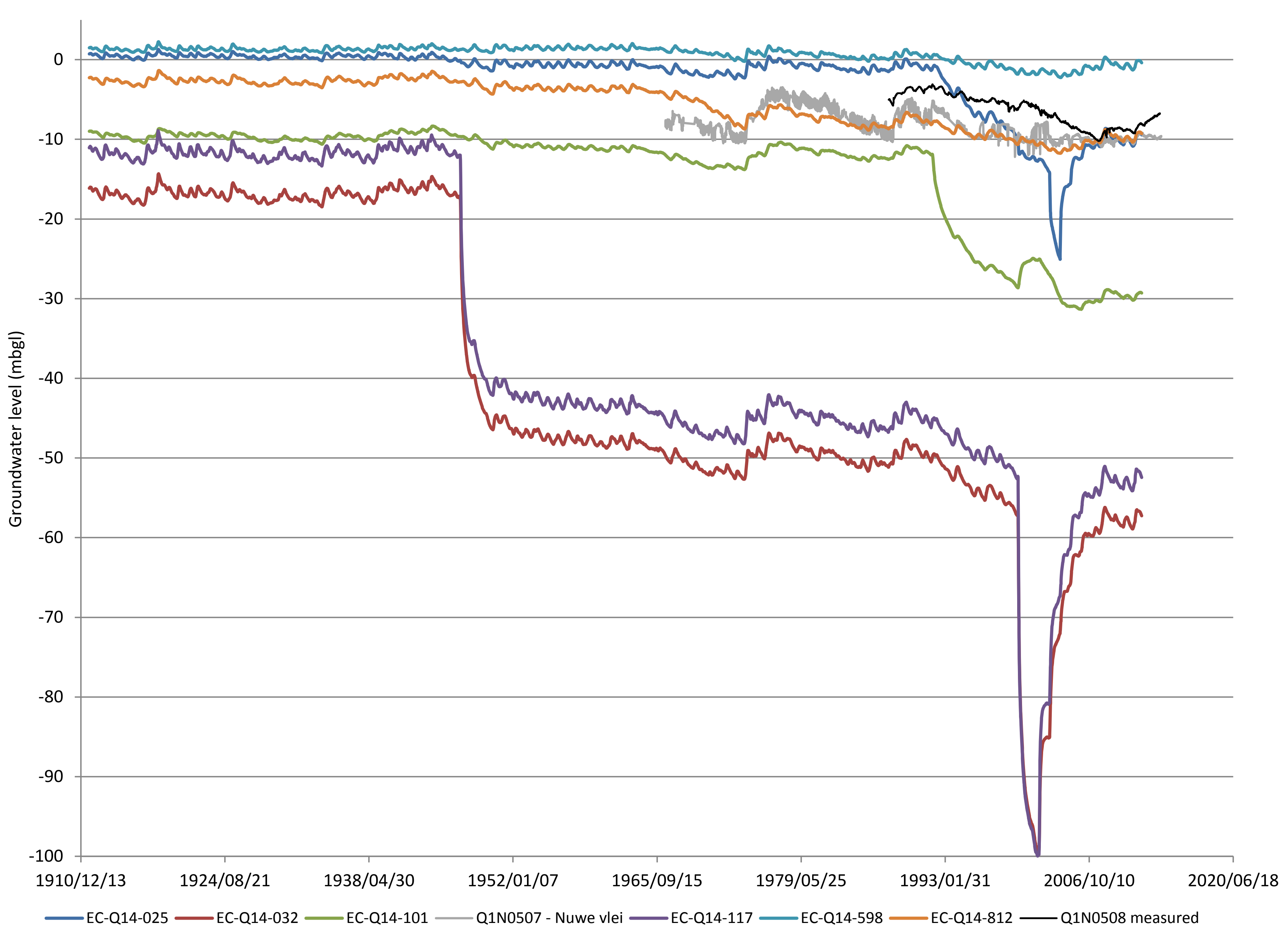


Figure 11-26: Selected groundwater levels for Municipal sub-catchment; different distances from municipal abstraction

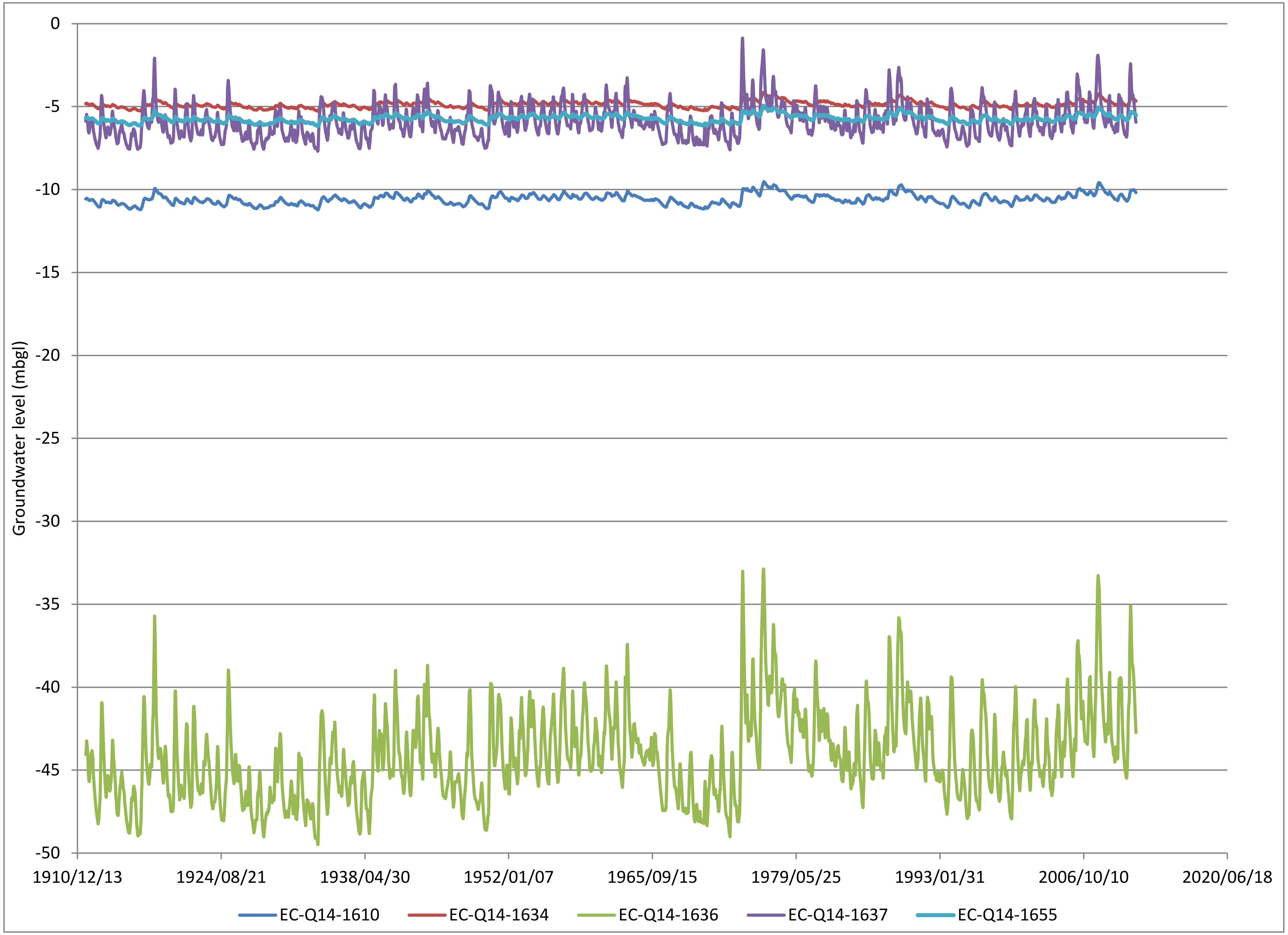


Figure 11-27: Selected groundwater levels for The Glen sub-catchment/compartment; no impact from current abstraction

As illustrated by Figure 11-26, the declining trends of simulated hydraulic head (groundwater level) in the Municipal sub-catchment are now more in line with those expected in reality based on measured head data and concentrated municipal abstraction. Although simulated heads do not exactly match their measured head counterparts based on proximity, overall similar trends in the Municipal sub-catchment are observed. Local variations in transmissivity (T)/aquifer thickness (b), simulated vs. actual abstraction and the effect of outer boundaries in the geology become apparent in Figure 11-26. Simulated heads that show a good correlation to DWA measured heads apparently have no relation due to distal location. Comparing EC-Q14-568 and EC-Q14-812 in the sub-catchment with Q1N0508 (614 m from Zonnebloem municipal abstraction), an even better match is observed although EC-Q14-598 (4.3 km) and EC-Q14-812 (5 km) are much further away from Q1N0508 than EC-Q14-101 (78 m). Another good history match is found between Q1N0507 and EC-Q14-812, but EC-Q14-812 is located on the other side of the non-perennial Klein-brak River and is 3.9 km away. Q1N0507 is located in the close vicinity of the Nuwevlei municipal abstraction borehole while EC-Q14-812 does not have close proximity abstraction.

Another important observation from Figure 11-26 is that a 2D model is used for simulations and as such, its hydraulic head can be drawn down as far as necessary to create a steep enough hydraulic gradient to stabilise hydraulic heads. I.e. the 2D model has infinite aquifer thickness. The mean aquifer thickness of the shallow unconfined aquifer is 22 m in reality. Abstraction boreholes in the region of Matjieskloof and Nuwevlei (compare EC-Q14-031, EC-Q14-117 & EC-Q14-101 in Figure 11-26) are examples of boreholes that are expected to fail due to limited aquifer thickness in reality. From reports they do fail, however they recover very quickly as well.

The shape of the drawdown curve for Q1N0508 (Zonnebloem proximity) is expected to be the result of an aquifer storage depletion problem. This is the reason why the curve gets steeper as time goes on. It can very well also be the result of a constant increase in abstraction rate, as proven by the abstraction figures available from 2001 to 2006.

The over-abstraction is however spatially limited to the Municipal sub-catchment and to a small extent the bottom of the Grootfontein compartment as shown in Figure 11-27 to Figure 11-30. The Glen sub-catchment has no declining groundwater level problem nor does Karmel (Figure 11-27, Figure 11-28).The Dunblane sub-catchment shows some influence of municipal abstraction from the upstream Municipal sub-catchment, but recovered from the initial implementation of the municipal abstraction boreholes.

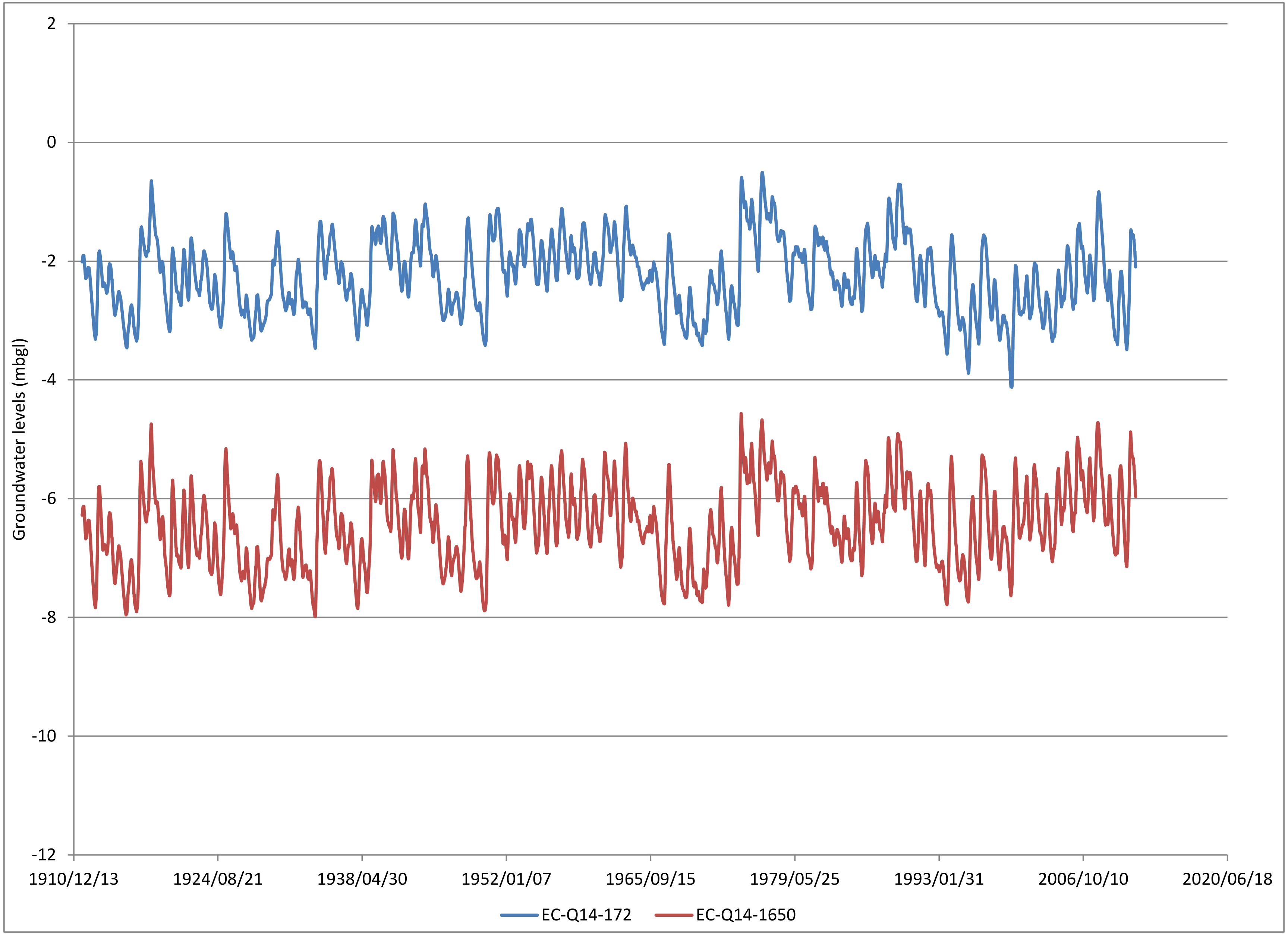


Figure 11-28: Representative groundwater levels in the Karmel sub-catchment upstream of Municipal sub-catchment; no problems

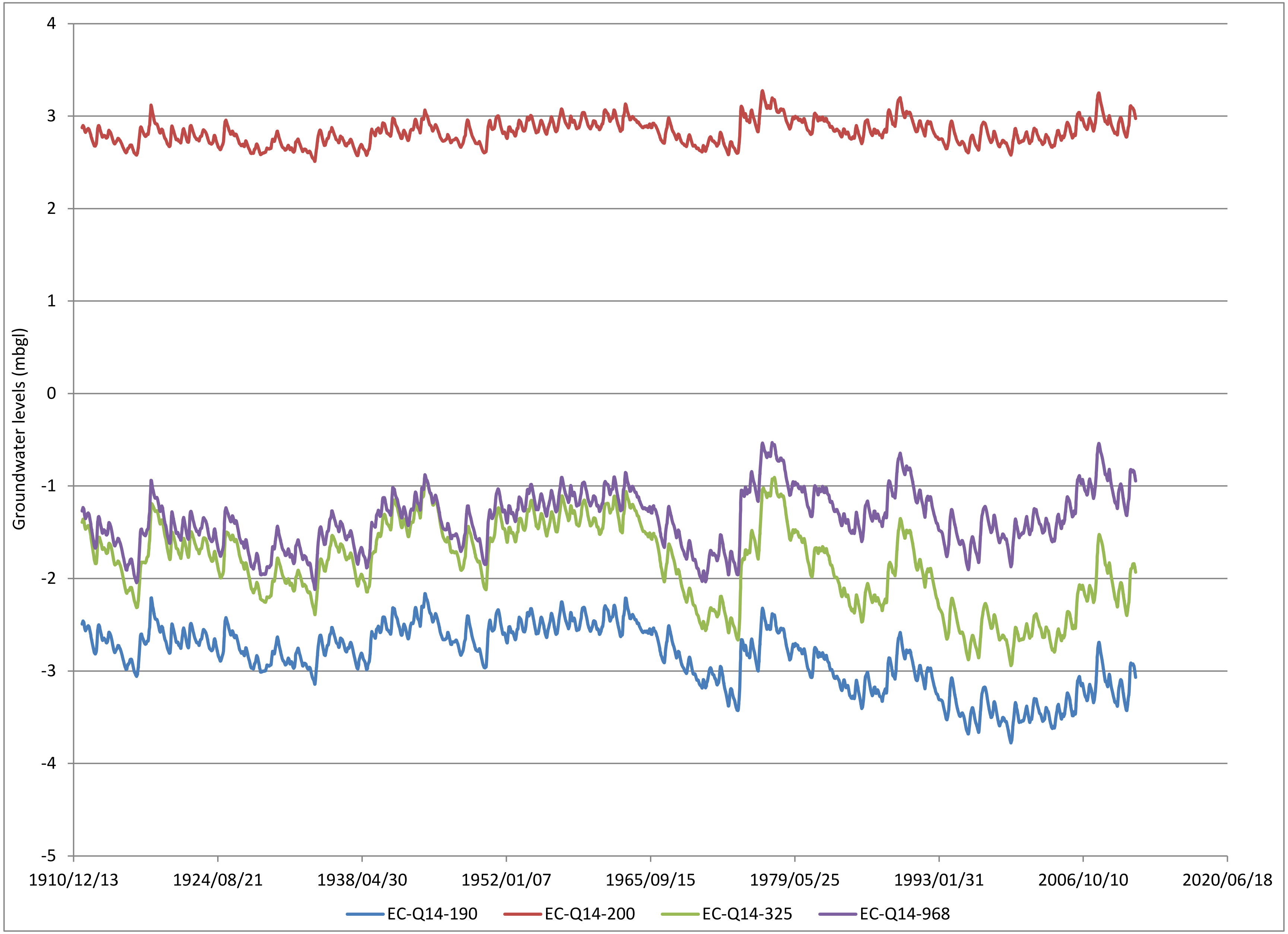


Figure 11-29: Representative groundwater levels in Dunblane sub-catchment: some effects of adjacent municipal sub-catchment abstraction

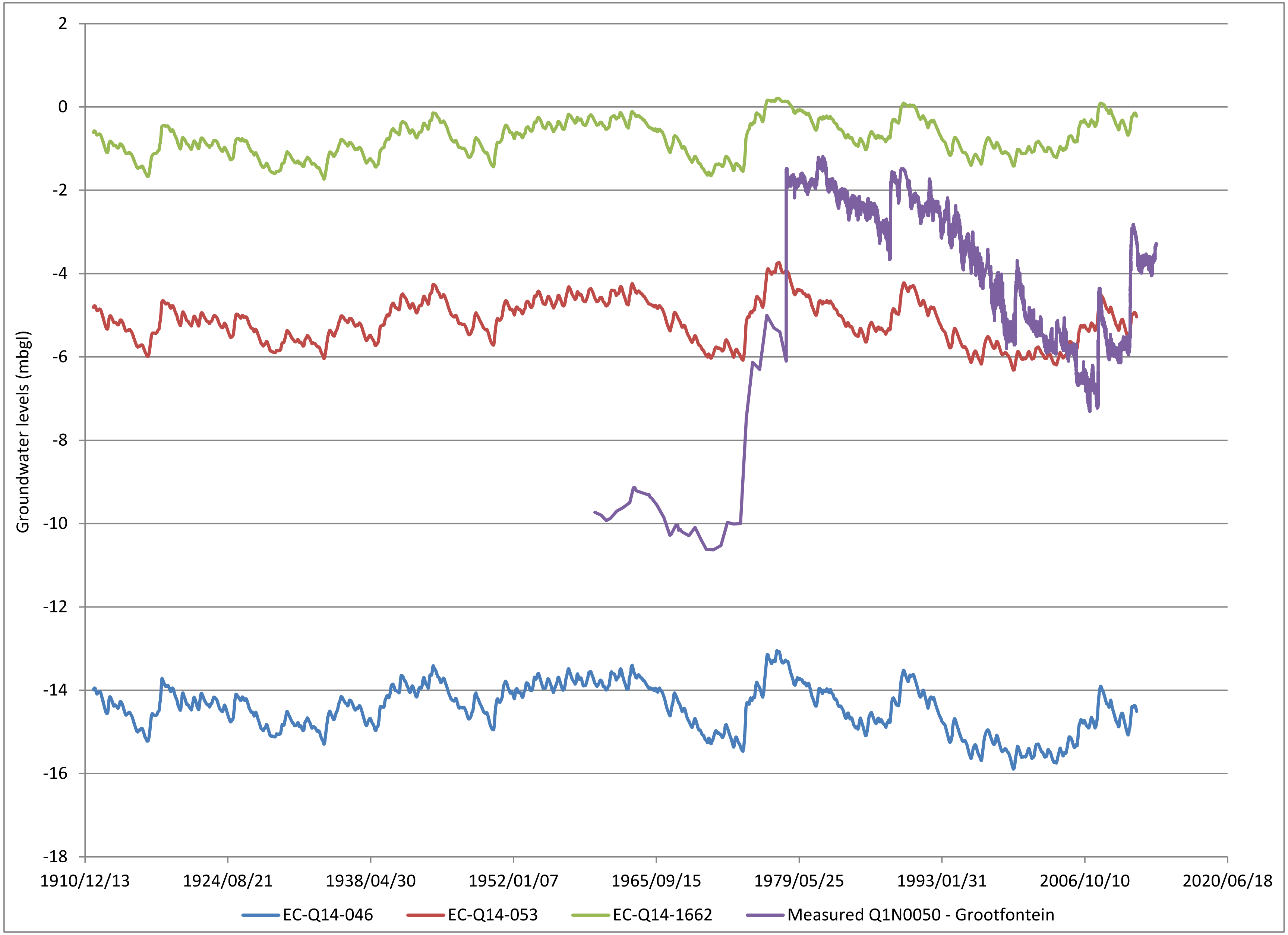


Figure 11-30: Representative groundwater levels for Grootfontein catchment and history match DWA monitoring hole Q1N0050

In Figure 11-30 above EC-Q14-046 = Q1N0050 DWA monitoring borehole. The measured and simulated head trends are more or less the same, except that there is a faster decline and increase in the Q1N0050 measured head, than in the EC-Q14-046 simulated head. There seems to be a smaller groundwater reservoir present in reality than the one simulated, most probably due to less aquifer thickness in reality. Evident from this graph is the difference in depth (EC-Q14-046 simulated vs. Q1N0050 measured) of the groundwater level (pressure head) indicating that there is either an error with the collar elevation in the model (easily possible as raster elevation from NGI 20 m DTM was used) or measured data; or Grootfontein sub-catchment recharge, transmissivity and storativity are higher.

11.6.3.2 Model validation conclusions

Simulated heads from the new transient state model (with time series abstraction) are better correlated to the four DWA measured (time series) heads than the first transient state model. The first transient state model showed negative correlation to the measured time series heads, since the first transient state model had no time series abstraction and had initial heads from a steady state calibration that included municipal abstraction. From simulated and measured head comparison graphs it is evident that locally aquifer parameters could be better calibrated, especially T. Calibration also shows that recharge on outcropping hard rock geologies could be higher than 6.5%. The decision was made to work with more conservative figures i.e. there should be more groundwater available if estimates are wrong. Given the purpose of the numerical model, the aim is not to obtain a perfect calibration both in steady- and transient-states. The aim is for the model to be calibrated well enough to be used as a tool to estimate with confidence whether enough groundwater is available or not and make forecasts on how much groundwater is available. Besides this primary purpose of the model, it would seem ill advised to try and history match aquifer parameters locally based on abstraction rates that are for the early time of the simulation time highly uncertain or unknown and estimated. It is also recommended that the model in future be upgraded from 2D to 3D to better represent the shallow aquifer geometry before further history matching is attempted. Historic time series abstraction rates for municipal boreholes can also be better refined and constrained during such model development.

Concentrated municipal abstraction in the Middelburg Municipal sub-catchment caused steady hydraulic head decline and some abstraction boreholes to fail locally, but outside the Municipal sub-catchment hydraulic head has not declined to such an extent. This is evidenced by representative model hydraulic heads in other sub-catchments and known borehole installation types from the hydrocensus. Regionally hydraulic heads (groundwater levels) have declined by ± 5 m (1977 - 2008) through time as farmers and the Grootfontein Agricultural College (GAC) implemented new abstraction boreholes for irrigation/stock watering use (Seward, 1987). The regional decline is an iterative process whereby each time a new abstraction borehole is implemented the pressure head lowers to reach a new equilibrium between inflow and outflow. A seemingly continuous slow groundwater level decline is observed since the system is never given enough time to equilibrate to each new abstraction imposed. Small fluctuations in groundwater levels are due to time series rainfall fluctuations.

In conclusion two main reasons are hypothesised for decline of groundwater levels in Middelburg:

1. Each time a new abstraction borehole is implemented the local or regional groundwater level is drawn down until a new equilibrium is reached. An equilibrium/quasi steady-state cannot be reached if new abstraction boreholes are implemented regularly, abstraction rates increased regularly or pumps switched on and off intermittently.
2. The more important consideration to take cognisance of is that when the hydraulic head drops, the aquifer thickness and transmissivity is reduced locally in the region of municipal abstraction boreholes, in the Municipal sub-catchment. This reduces the yield of the boreholes. The trend of the drawdown curve for Q1N0508 (Zonnebloem proximity) and the length of time during which measurements were taken leads to believe that there is also an aquifer storage depletion problem locally. It is hypothesised that the reason for the hydraulic head trend becoming steeper and steeper, is that as shallow zones of alluvium are dewatered and deeper zones isolated, the rate of storage depletion is also accelerated, if the same volumes are abstracted from the boreholes.

Since the simulated heads match the general trend of declining hydraulic head as well as recent rise with above average rainfall events as seen on 2005/2006, 2007/2008, and 2010/2011, we now have confidence that the model is sufficiently constructed and calibrated to represent the actual groundwater flow system and we can move on to running transient state scenarios for aquifer management decisions.

11.7 Scenario modelling (ASTM terminology: Predictive simulations)

After successful calibration of the steady state groundwater flow model, transient simulations could be run, each one evaluating a different abstraction or recharge scenario. The following scenarios were simulated:

- Scenario 1: Present day abstraction with transient state simulation 100 years into the future. Patched 100 year monthly rainfall sequence used.
- Scenario 2: The Glen new boreholes implementation and current abstraction: Transient state simulation 100 years into the future. Patched 100 year monthly rainfall sequence used.

11.7.1 Scenario 1: Present day existing abstraction, transient 100 year rainfall

The purpose of this scenario was to evaluate whether current abstraction is sustainable, since there had been reports that water levels are declining and that some boreholes have dried up. The scenario could also indicate overexploitation hot spots where better groundwater management is required.

The final hydraulic heads from the history matching transient simulation from 1911 – 2011 were used as initial- and reference-heads, since the steady state heads assume current abstraction has taken place for eternity, while it has not. After 100 years of simulation time in Scenario 1, hydraulic heads are still adjusting to the imposed abstraction, but decline has slowed down and in some places increases occur (see figures). A mean decrease of -0.89 m, maximum decrease of -6.20 m (EC-Q14-1104) and maximum increase of 0.20 m (EC-Q14-1663) was calculated for the dataset of 378 observation boreholes. The dataset had a standard deviation (σ) of 1.00 m. Scenario results are graphically portrayed in selected representative observation borehole time series graphs per sub-catchment in Figure 11-32 to Figure 11-36. Results are further spatially portrayed in the hydraulic head map in Figure 11-31 and interpolated residuals map in Figure 11-37.

Groundwater levels measured during the hydrocensus and the mean depth of the shallow aquifer (± 22 m) show that the aquifer has not been depleted yet or that it is partially depleted during the summer time, but is recharged again from late summer rains or has a recharge lag effect.

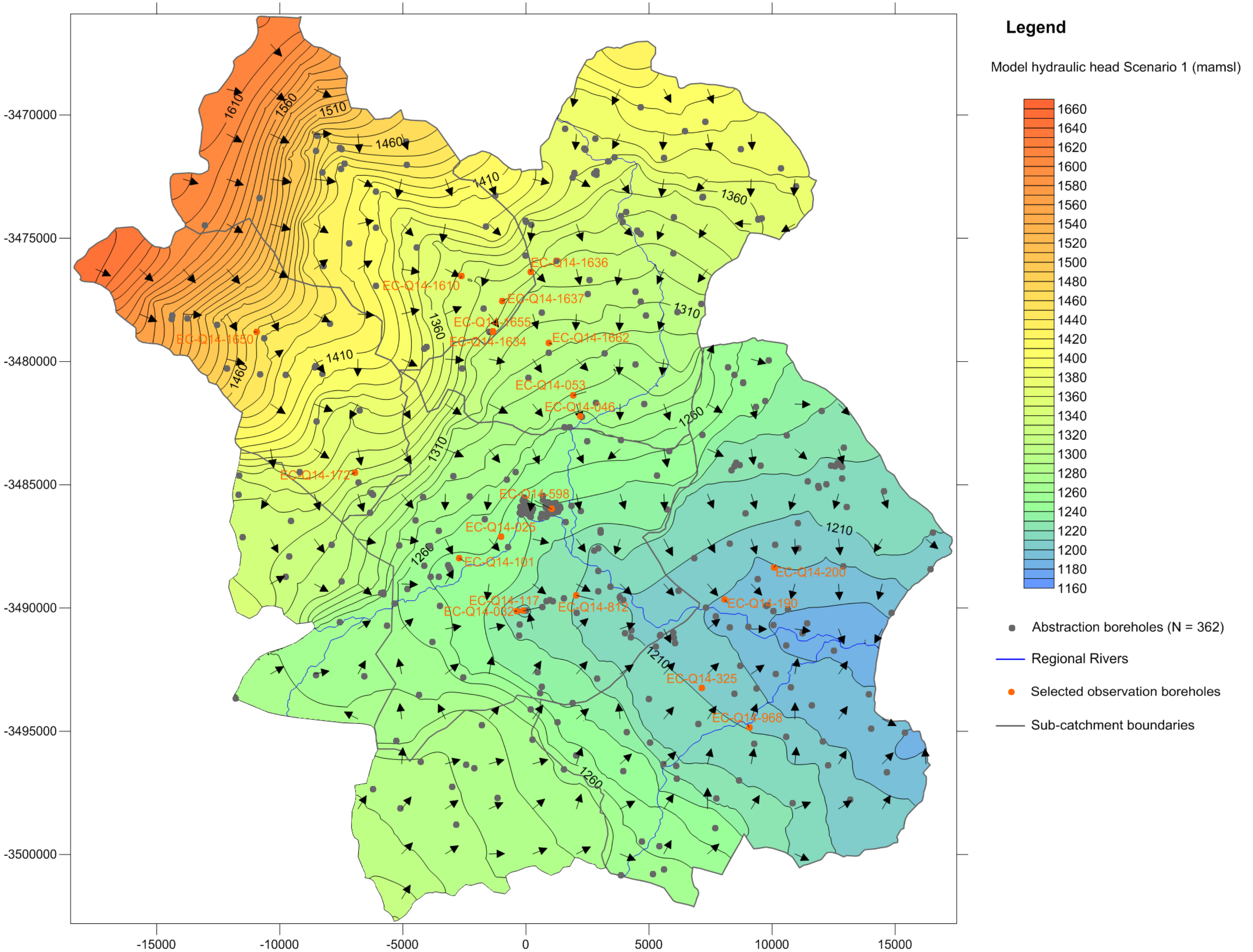


Figure 11-31: Scenario 1 simulated hydraulic head distribution and location of selected boreholes for graphs

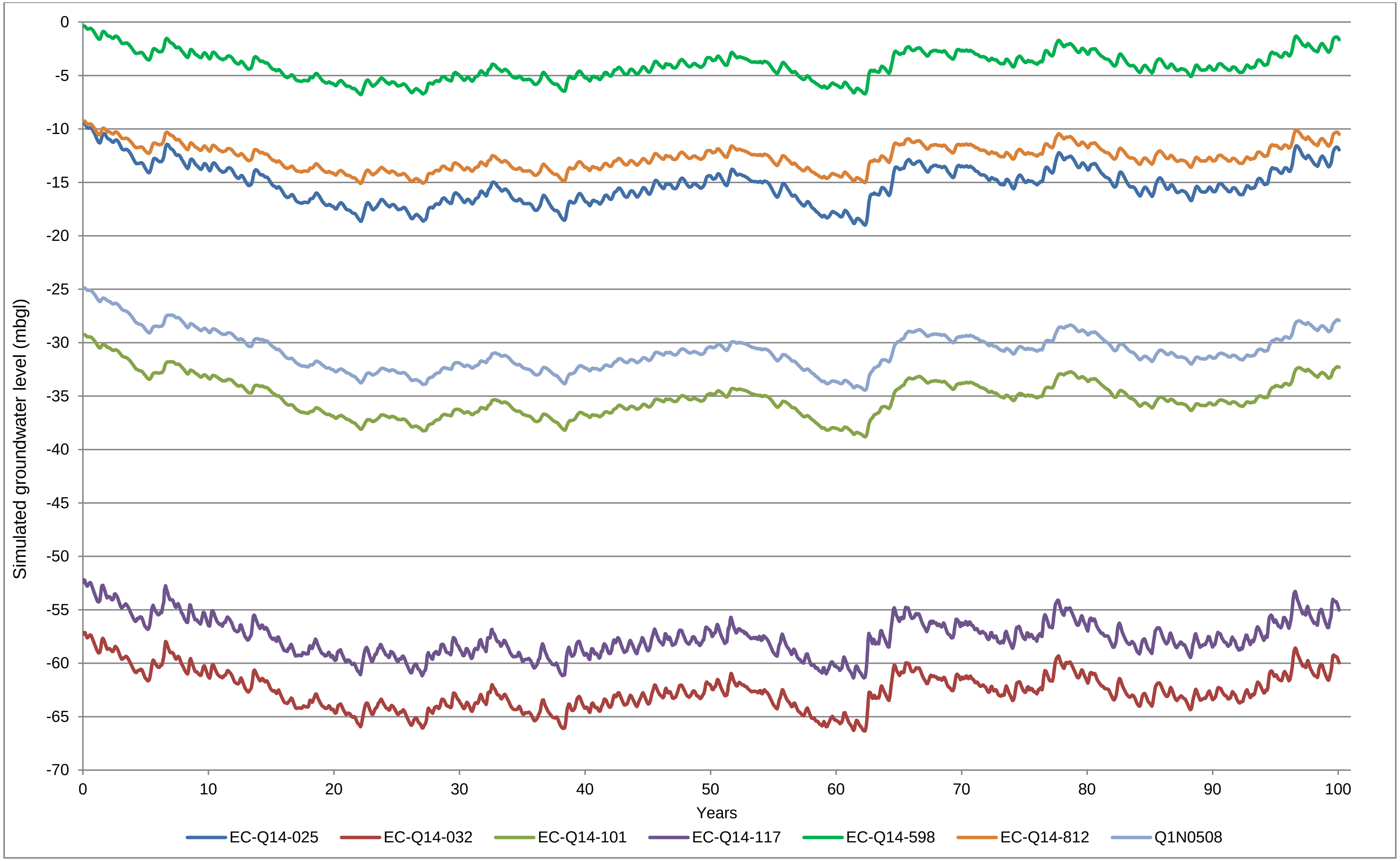


Figure 11-32: Scenario 1 transient 100 year simulated heads (mbgl) for the Middelburg Municipal sub-catchment

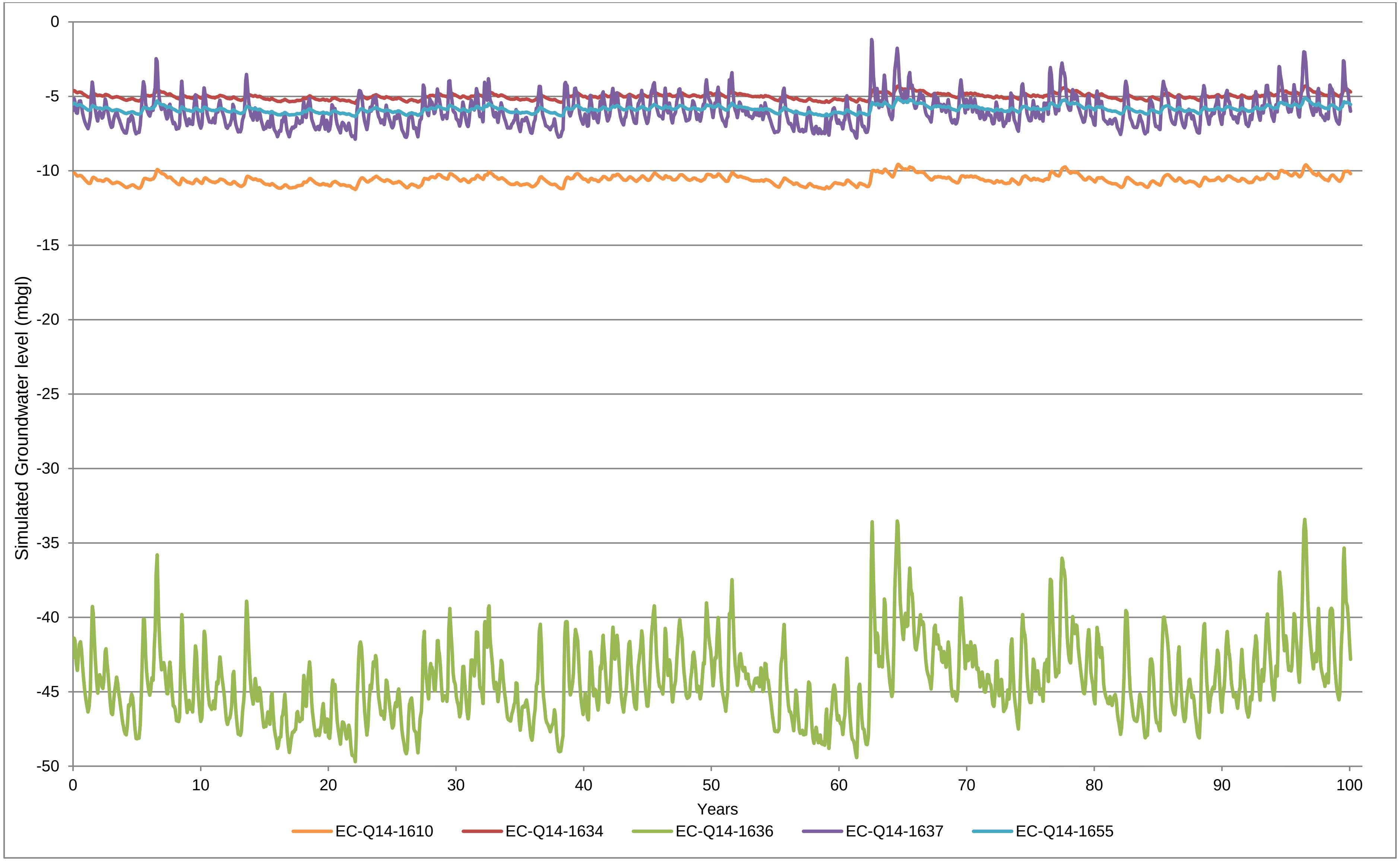


Figure 11-33: Scenario 1 transient 100 year simulated heads (mbgl) for The Glen sub-catchment/compartment

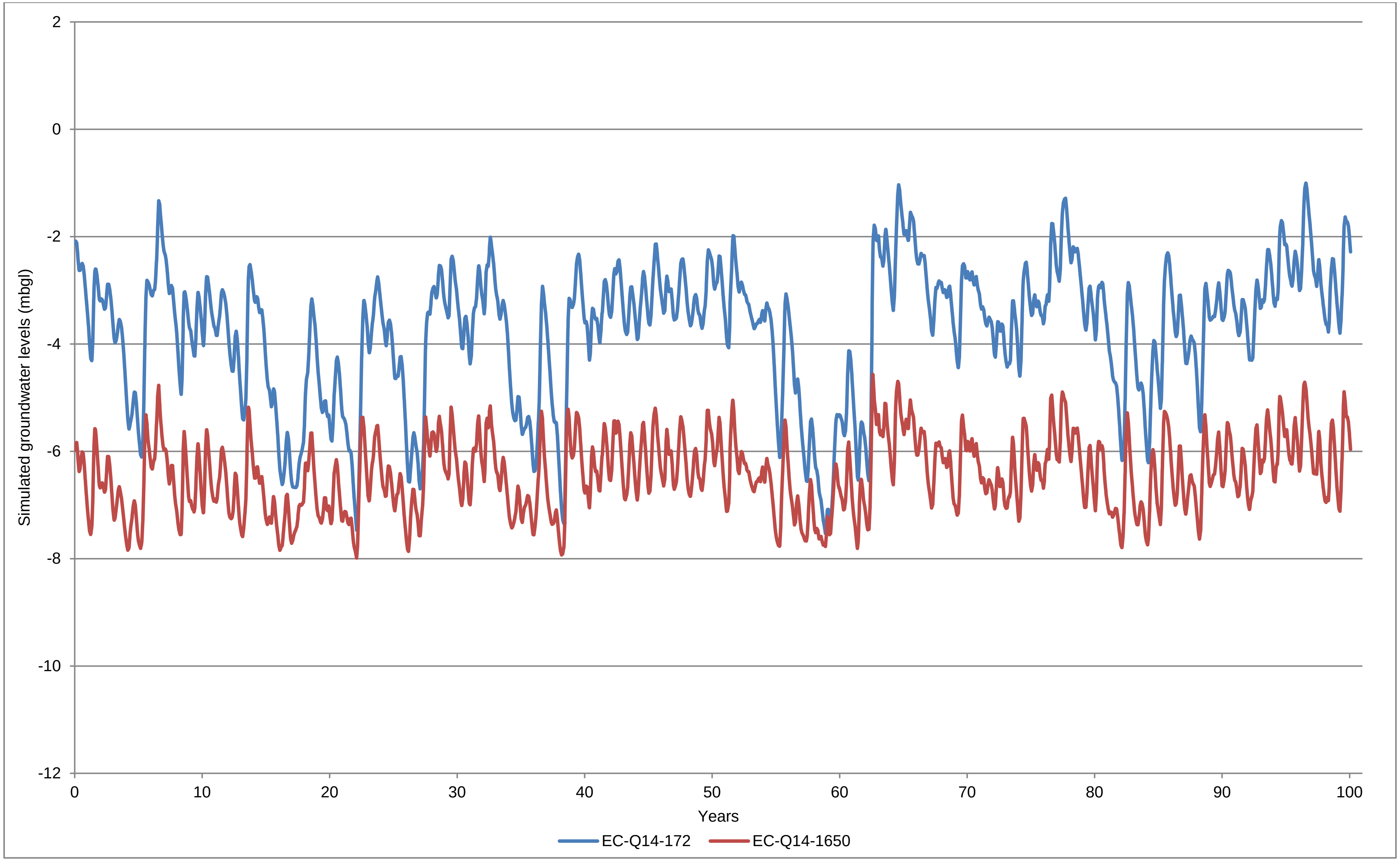


Figure 11-34: Scenario 1 transient 100 year simulated hydraulic heads (mbgl) for the Karmel sub-catchment

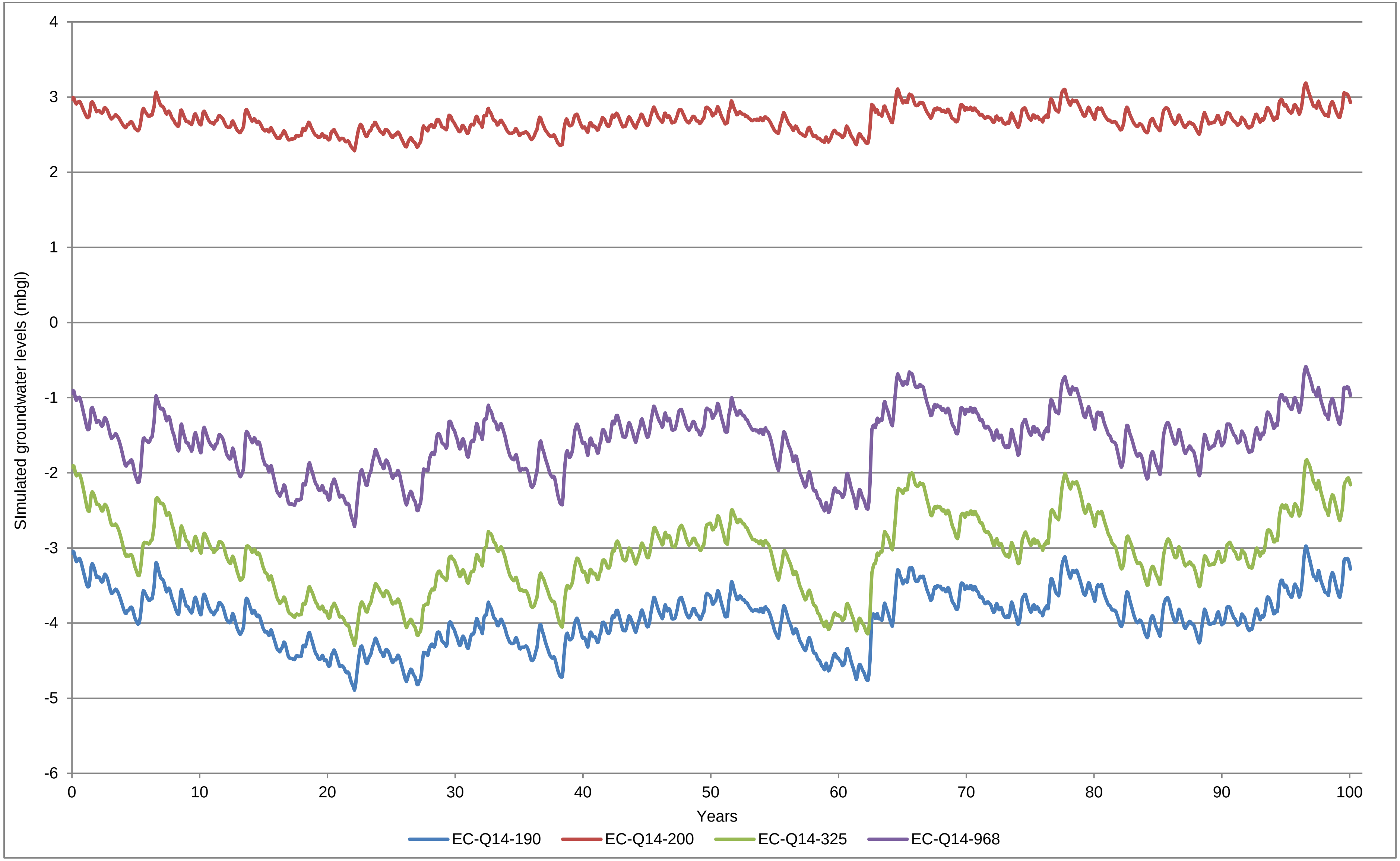


Figure 11-35: Scenario 1 transient 100 year simulated hydraulic heads (mbgl) for the Dunblane sub-catchment

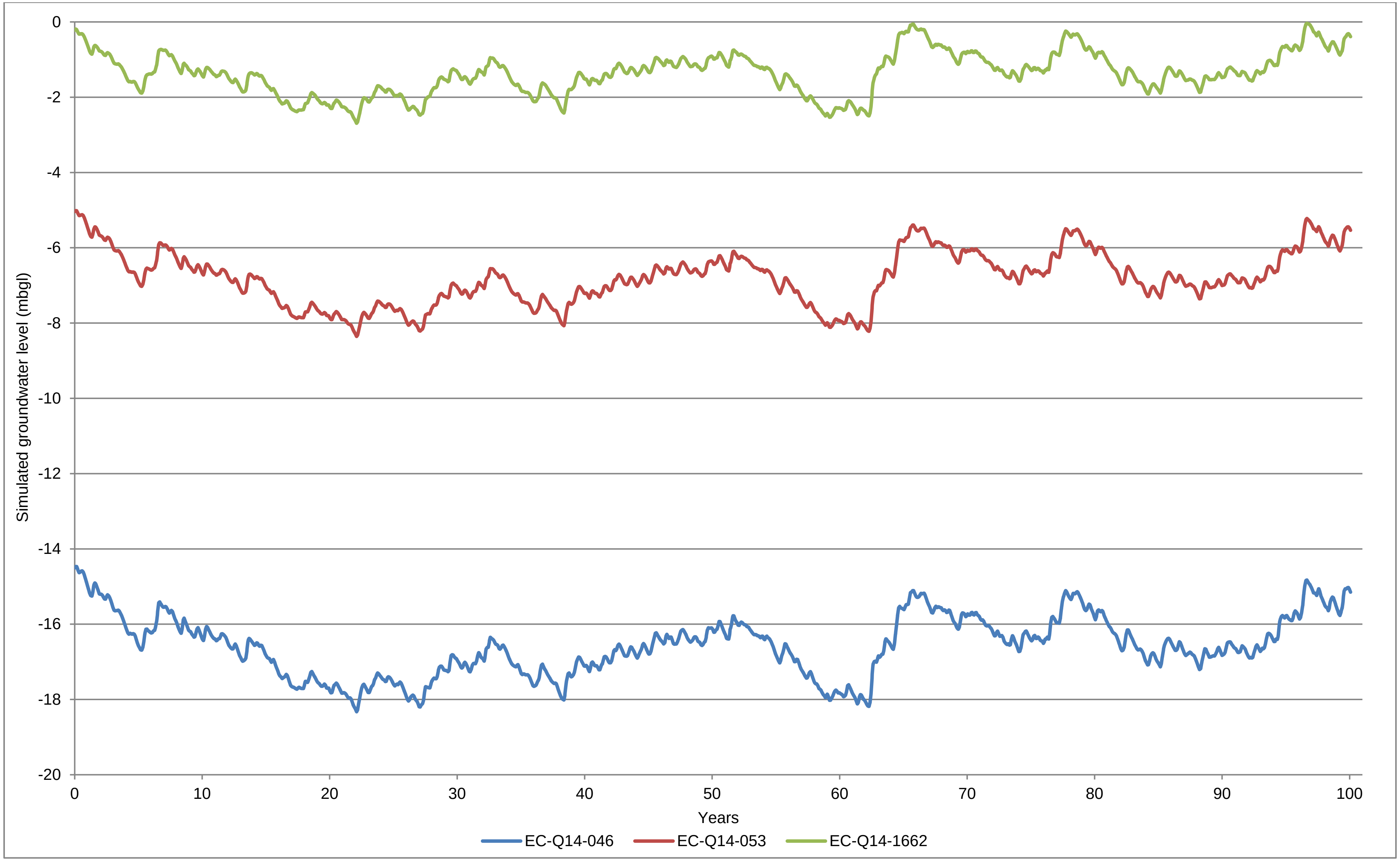


Figure 11-36: Scenario 1 transient 100 year simulated hydraulic heads (mbgl) for the Grootfontein compartment

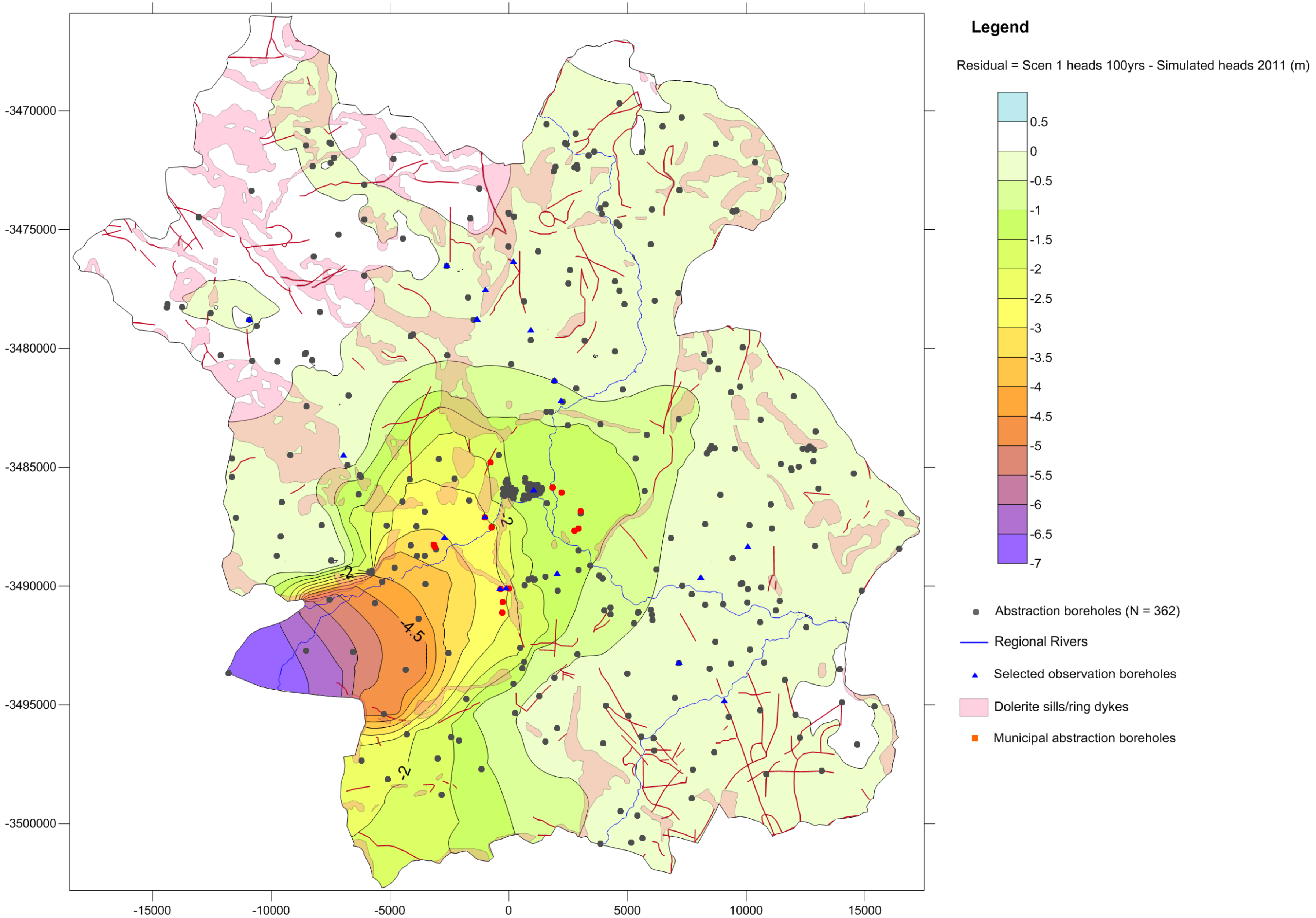


Figure 11-37: Scenario 1 FE node hydraulic head residuals interpolated, note range of residuals

Figure 11-37 illustrates a very telling simulation of the impacts that have been reported and that are expected in the future if municipal abstraction is allowed to continue as currently practiced. It also provides some idea of how the hydraulic head gradient is influenced by sharp contrasts in the T- and S-values of the different geologies. The map also emphasises that the western valley (Klein-Brak River inflow and alluvium) should be monitored as has been mentioned in older Middelburg DWA reports (Seward, 1987).

It must be stated however that the western model domain boundary where most drawdown is shown (Figure 11-37) should actually be an inflow boundary. It is currently an impermeable boundary. There is a large catchment to the west of the model domain, but lateral inflow from this catchment is unknown. Its water balance is however known to be positive. It in turn is fed by four smaller sub-catchments adjacent to it, all of them having watershed boundaries (See Figure 11-7). These sub-catchments were not included in the numerical model domain due to expected numerical computational difficulties. It can however be seen that by adding these sub-catchments to the total available groundwater resources, the hydraulic head decline would not be as much as simulated.

The water budget results from the time steps of the transient state 100 year monthly rainfall with existing abstraction were compared to the GYMR water balances. Some integration and averaging of water budget results had to be done for comparison with the GYMR water balances. Water balances (budgets) were compared per sub-catchment as included in the model domain. The mean water budget results for the entire model domain are shown in Table 11-6 for boundary conditions (BCs), sources/sinks and total balance.

Table 11-6: Model domain mean water budget results for scenario 1

Budget domain	Dirichlet-BCs (baseflow + losses)		Wells		Distributed Sources/ Sinks		Total Balance
	In	Out	In	Out	In	Out	In (+) / Out (-)
Model domain [ℓ/s]	0.0	-158.7	0.0	-219.1	376.6	0.0	-1.1
Model domain [m^3/d]	0	-13 710	0	-18 928	32 538	0	-99
Model domain [m^3/a]	**0**	**-4 935 519**	**0**	**-6 813 983**	**11 713 768**	**0**	**-35 734**

The sub-catchments compared were, The Glen, Karmel, Grootfontein, Dunblane and the Middelburg Municipal sub-catchment. The Dunblane compartment in the model is based on a groundwater compartment and as such is smaller than the Dunblane sub-catchment in the GYMR groundwater balance. None the less, their outflow/inflow percentages could be compared. The numerical model water budgets are slightly more simple and do not differentiate between all the different components used in the GYMR. The GYMR takes the

BHN Reserve into account which is not an active component in groundwater dynamics, but rather a posterior calculation. The GYMR water balance and its components were converted to the FEFLOW water budget table format for comparison. The FEFLOW model results per sub-catchment are shown in white in Table 11-7 and the GYMR water balance results are shown in grey. The Total balance column in Table 11-7 would lead us to quickly preclude that the system has an overall deficit, but the Dirichlet boundary conditions (BCs) are essentially evapotranspiration losses and baseflow and the volumes taken out of the model by the Dirichlet BCs, are more than enough to cover all Well BC abstraction. The volumes in the Dirichlet BCs show that there is excess groundwater from recharge in the model domain, hence the hydraulic head rises to the topographic points where the Dirichlet BCs were assigned on drainages, and the excess groundwater is removed from the system.

Table 11-7: Water budget results from numerical model for sub-catchments, scenario 1

Budget domain	Dirichlet-BCs (baseflow+losses)		Well BCs [+springs]		Distributed Sources/ Sinks		Total Balance	Excess / Deficit Volume
	In	Out	In	Out	In	Out	In (+) / Out (-)	In (+) / Out (-)
	m^3/a	m^3/a	m^3/a	m^3/a	m^3/a	m^3/a	m^3/a	m^3/a
Municipal sub-catchment Model	**0**	**-30**	**0**	**-3 213 458**	**1 743 355**	**0**	**-1 470 133**	**-1 470 104**
Municipal sub-catchment GYMR	**0**	**0**	**0**	**-3 211 260**	**920 404**	**-13 584**	**-2 304 440**	**-2 304 440**
The Glen sub-catchment Model	**0**	**-1 601 747**	**0**	**-181 083**	**2 134 531**	**0**	**351 701**	**1 953 448**
THe Glen sub-catchment GYMR	**0**	**-2 300 980**	**0**	**-180 171**	**2 487 376**	**-6 225**	**0**	**2 300 980**
Karmel sub-catchment Model	**0**	**-743 866**	**0**	**-293 238**	**1 719 927**	**0**	**682 823**	**1 426 689**
Karmel sub-catchment GYMR	**0**	**-1 699 289**	**0**	**-293 037**	**1 998 301**	**-5 975**	**0**	**1 699 289**
Dunblane Model compartment	**0**	**-1 773 132**	**0**	**-1 656 028**	**2 560 063**	**0**	**-869 096**	**904 035**
Dunblane sub-catchment GYMR	**0**	**-279 517**	**0**	**-1 684 833**	**1 975 800**	**-11 450**	**0**	**279 517**
Grootfontein compartment Model	**0**	**-703 093**	**0**	**-1 036 583**	**2 156 648**	**0**	**416 972**	**1 120 065**
Grootfontein compartment GYMR	**0**	**-955 236**	**0**	**-1 034 297**	**1 995 758**	**-6 225**	**0**	**955 236**
							TOTAL	**3 934 134**
								2 930 583

The following deductions are made from Scenario 1 numerical modelling results:

- A total excess groundwater volume of approximately 3.93 million m^3/a (±125 ℓ/s) can be calculated just from the water budgets of the evaluated sub-catchments.
- The total model domain excess groundwater volume is 4.90 million m^3/a (±155 ℓ/s).

- The groundwater system is an interrelated system of sub-catchments and these sub-catchments do not operate in an isolated manner yet. The hydraulic heads in the Municipal sub-catchment would not have been calibrated as well as they were, if the compartments or sub-catchments were isolated.
- There is in general more groundwater available within sub-catchments according to numerical model results than there is with the GYMR water balance calculations. It is attributed to the more refined application of recharge applied to geology in the numerical model as compared to a single recharge figure given per sub-catchment in the GYMR water balance.

11.7.2 Scenario 2: The Glen implementation, transient 100 year simulation

Implementation of new production boreholes drilled in The Glen sub-catchment, in addition to existing abstraction, were evaluated with a 100 year transient simulation. New production boreholes namely, EC-Q14-1636, EC-Q14-1637 and EC-Q14-1655 were evaluated analytically for sustainable abstraction. EC-Q14-1636 was drilled into an aquifer with limited extent, high hydraulic conductivity, but slow recovery. EC-Q14-1636 does however have an adjacent monitoring borehole EC-Q14-1656, that will be monitored, while EC-Q14-1636 is abstracted from at a low 2 ℓ/s rate. The goal will be to see whether recovery can match this abstraction rate or whether EC-Q14-1636 is located at too high an elevation on the ring structure. The additional rates of abstraction for the 3 new boreholes to be implemented are:

- EC-Q14-1636 - 2.0 ℓ/s over 24 hour duty cycle, main water strike – 122 mbgl;
- EC-Q14-1637 - 7.5 ℓ/s over 24 hour duty cycle, main water strike – 61 mbgl;
- EC-Q14-1655 - 12.5 ℓ/s over a 24 hour duty cycle, main water strike – 40 mbgl.

This adds up to a total additional abstraction from the study area of 693 792 m^3/a (22 ℓ/s) that based on the Scenario 1 water budget in Table 11-7, The Glen sub-catchment can easily sustain (Dirichlet BCs).

Results from Scenario 2 model simulation show that the implementation of the new production boreholes will be sustainable based on hydraulic head fluctuations over time (Figure 11-38 to Figure 11-45) and the model domain water budget (Table 11-8). A mean decrease in hydraulic head of -2.4 m was obtained at model observation boreholes, with a maximum decrease of -75.3 m and a maximum increase of 0.17 m after 100 years of simulation (history matching heads 2011 used as initial- and reference-heads).

Residuals from Figure 11-44 and Figure 11-45 must be put into context: A transmissivity of 27.3 m^2/d was calculated from hydraulic test analysis of the 48 hour constant discharge test conducted on EC-Q14-1637, while the model transmissivity assigned in the region of this borehole is 5 m^2/d (Katberg Formation). This is where model limitations are apparent since the 1: 250 000 geology incorporated into the model does not represent the actual site hydrogeology encountered at EC-Q14-1637. Detail aquifer heterogeneity that cannot possibly be built into the model across the model domain is a clear model limitation. However, mean hydraulic parameters used across the model domain provide a good overall convergence of simulated and measured hydraulic heads. Groundwater flow will clearly be faster at some locations than others, but physical boundaries create a mean upper bound transmissivity of ±50 m^2/d and lower bound of ±5 m^2/d.

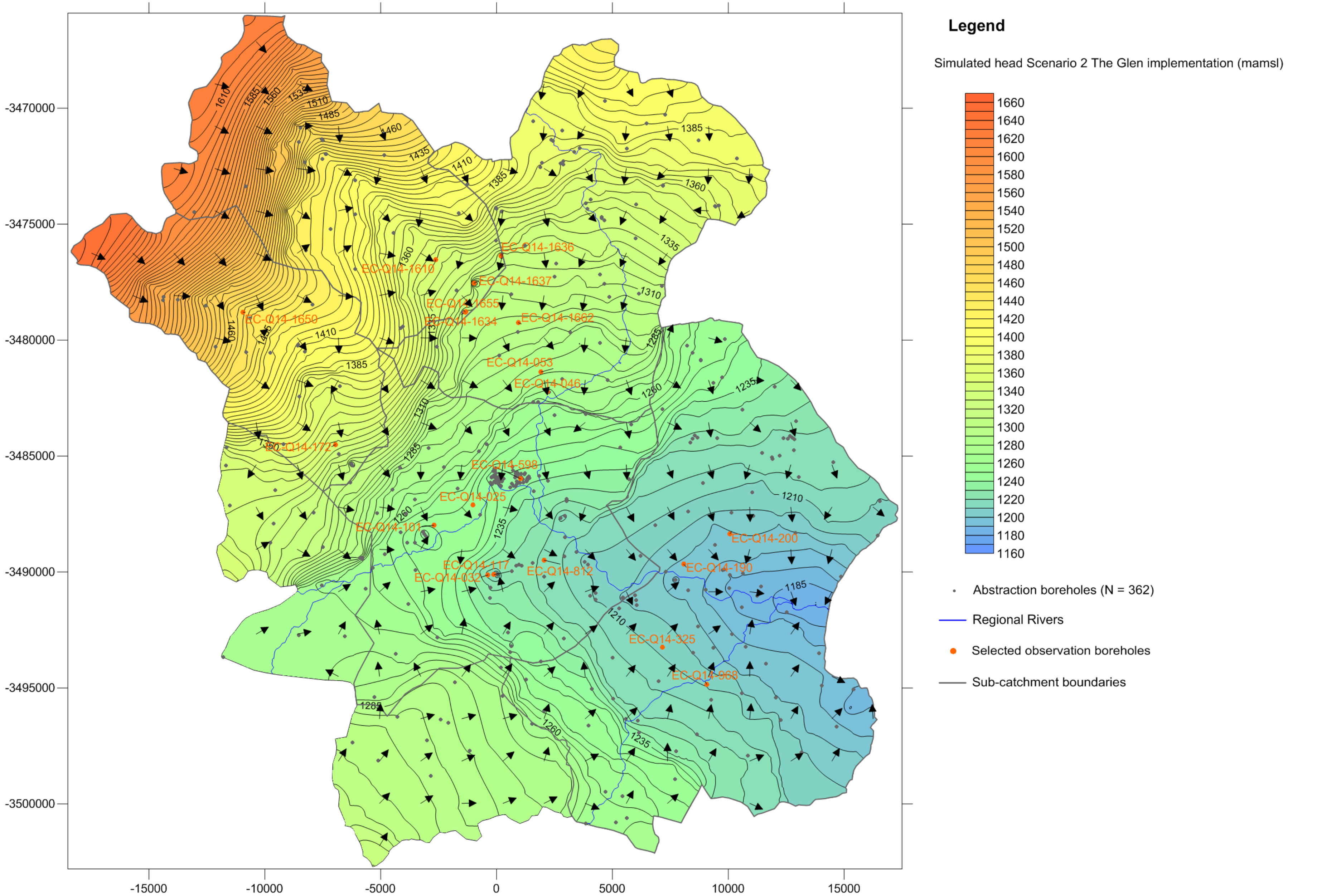


Figure 11-38: Scenario 2 simulated hydraulic head distribution for The Glen sub-catchment new boreholes implementation

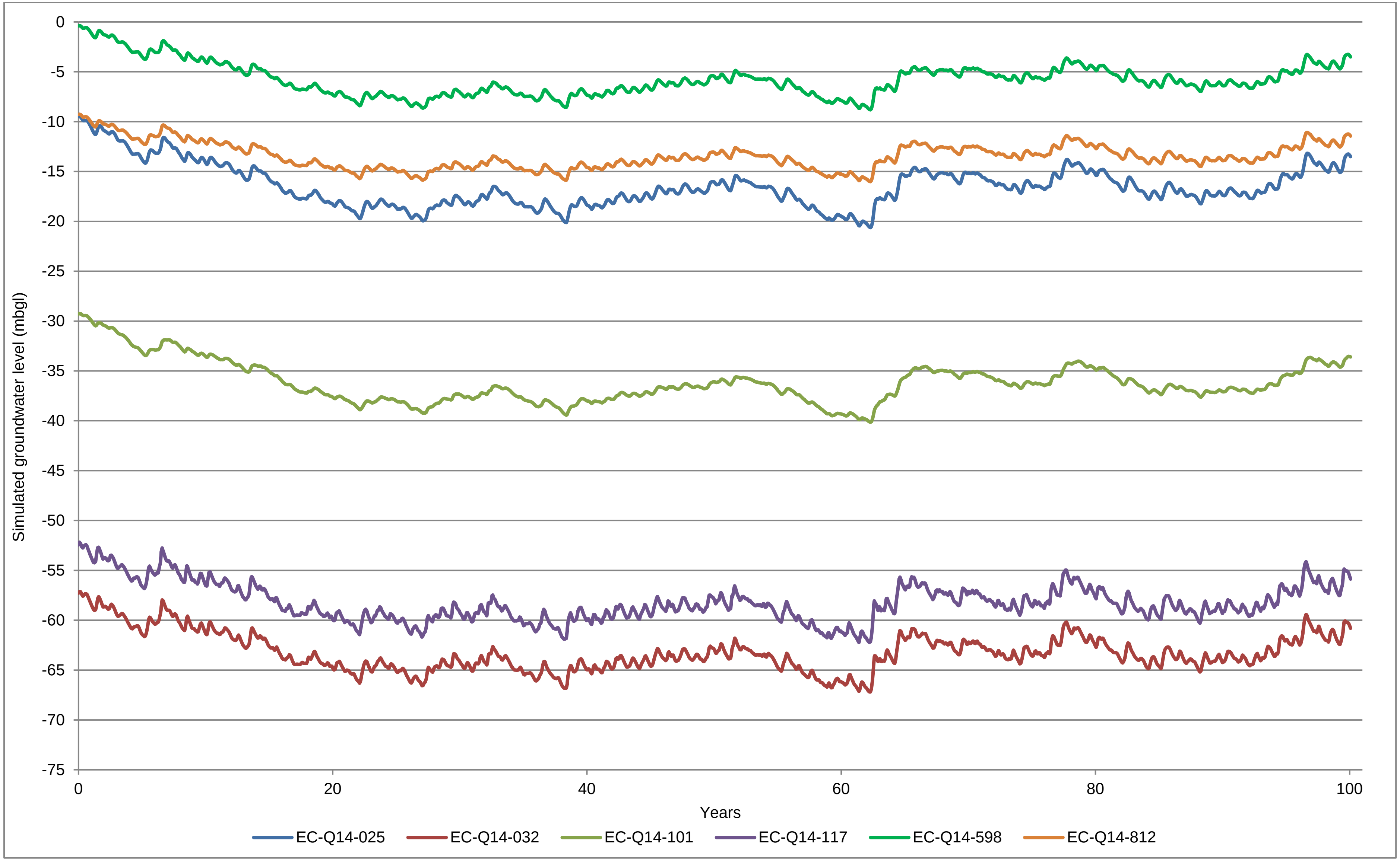


Figure 11-39: Selected Municipal sub-catchment simulated hydraulic heads for Scenario 2 implementation of The Glen boreholes

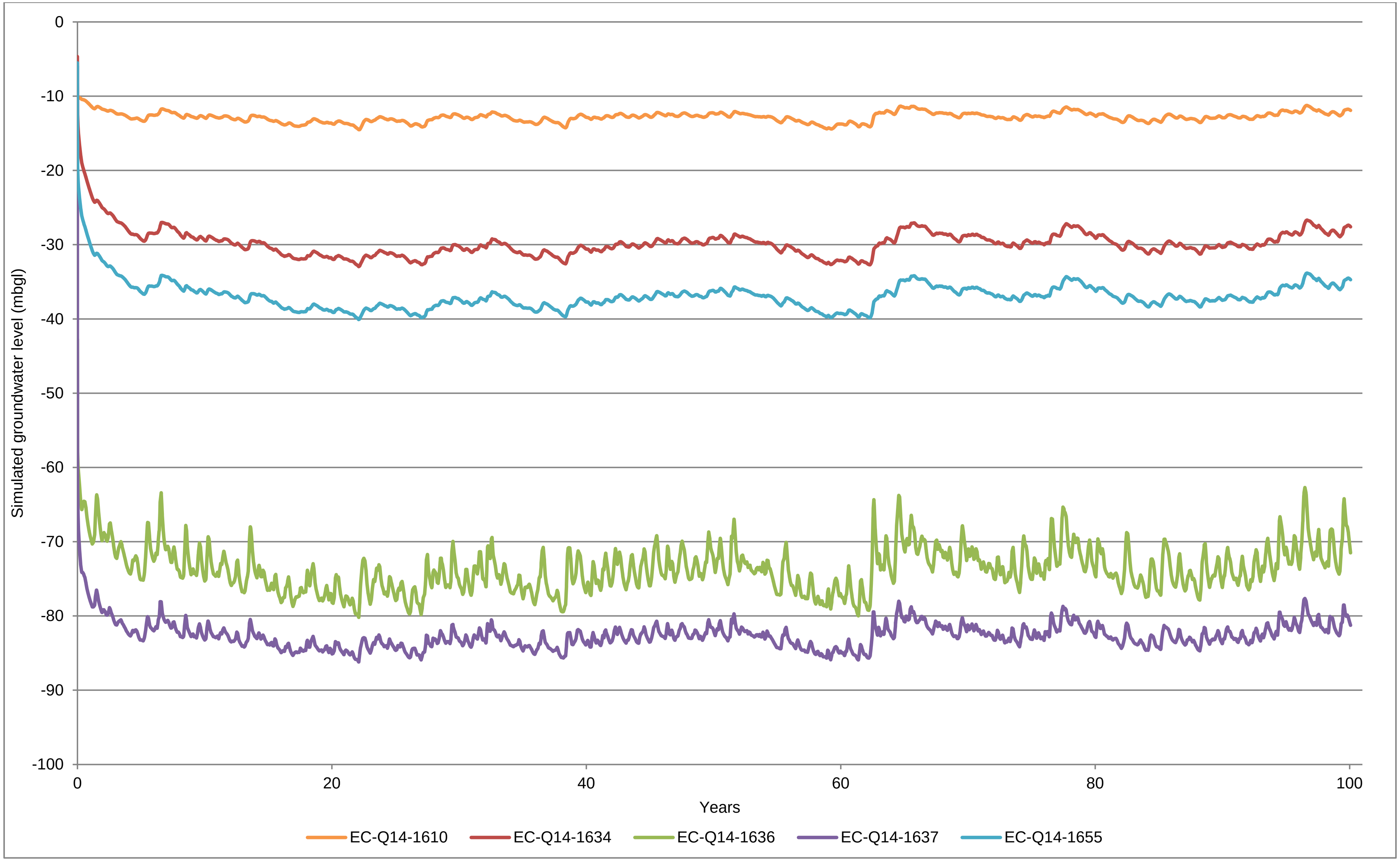


Figure 11-40: Selected simulated hydraulic heads from The Glen sub-catchment for Scenario 2 implementation of The Glen new boreholes

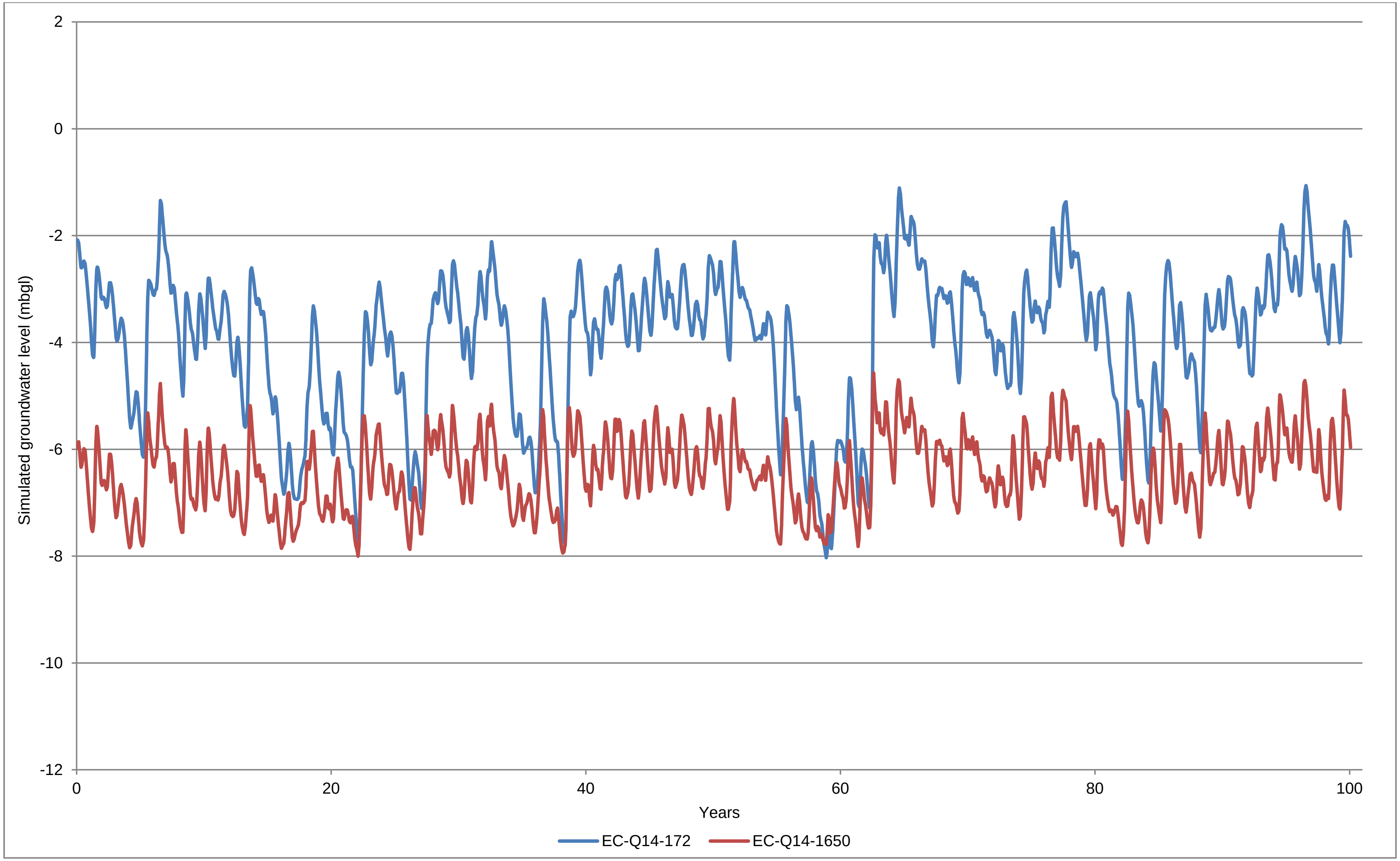


Figure 11-41: Selected Karmel sub-catchment simulated hydraulic heads for Scenario 2 implementation of The Glen boreholes

Figure 11-42: Selected Dunblane sub-catchment simulated hydraulic heads for Scenario 2 implementation of The Glen boreholes

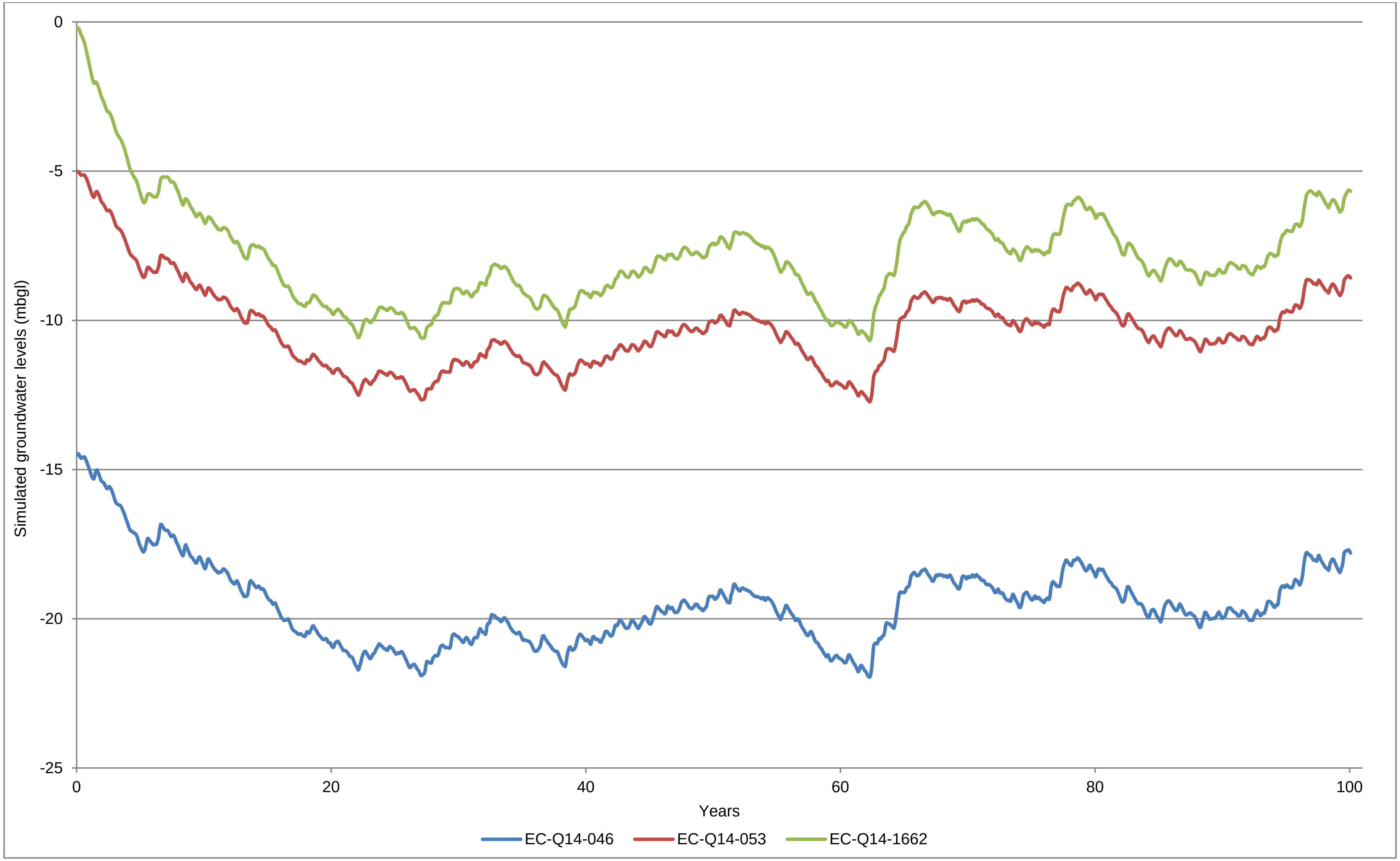


Figure 11-43: Selected Grootfontein compartment simulated hydraulic heads for Scenario 2 implementation of The Glen boreholes

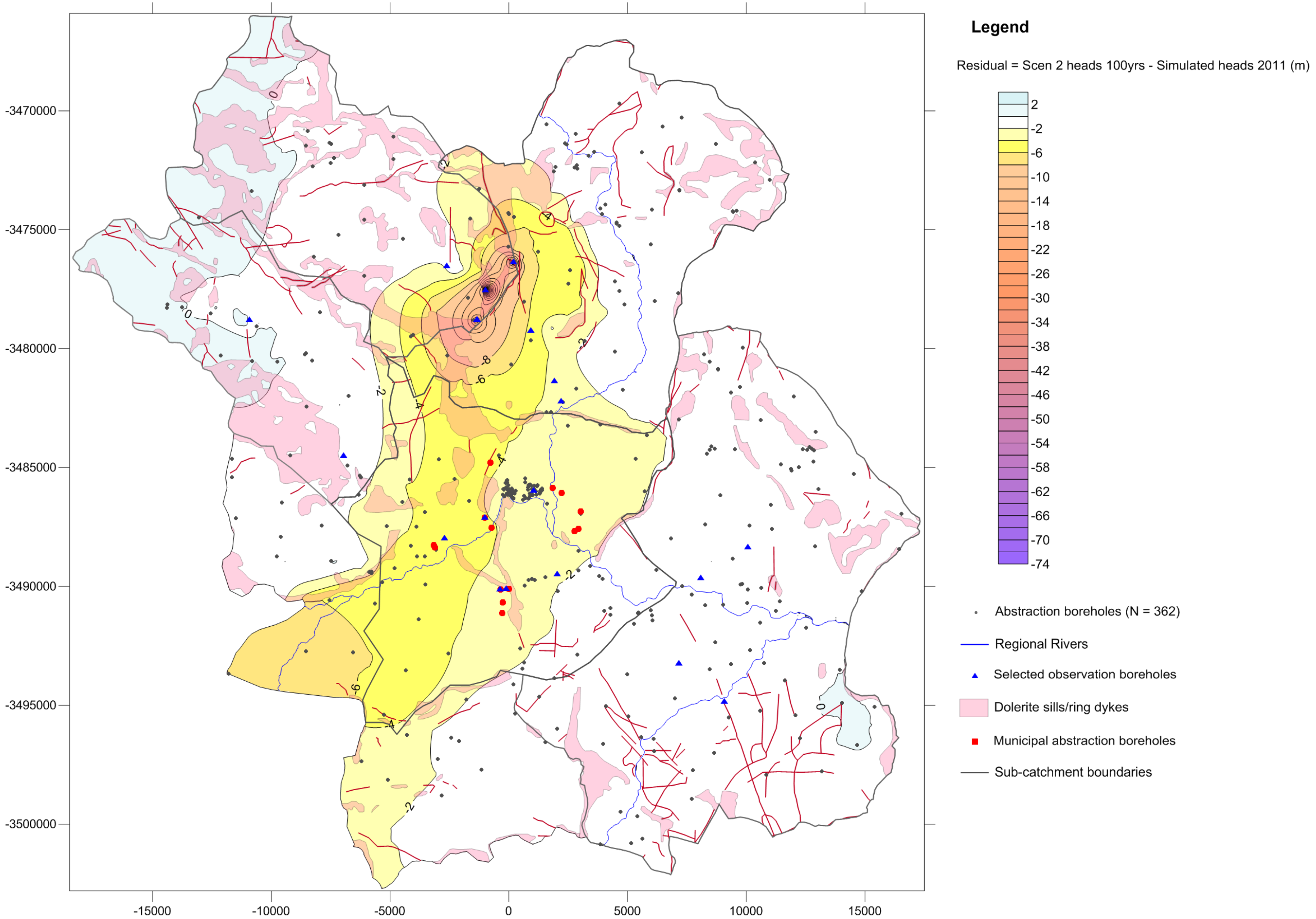


Figure 11-44: Scenario 2 hydraulic heads minus history match final heads 2011: residuals/difference

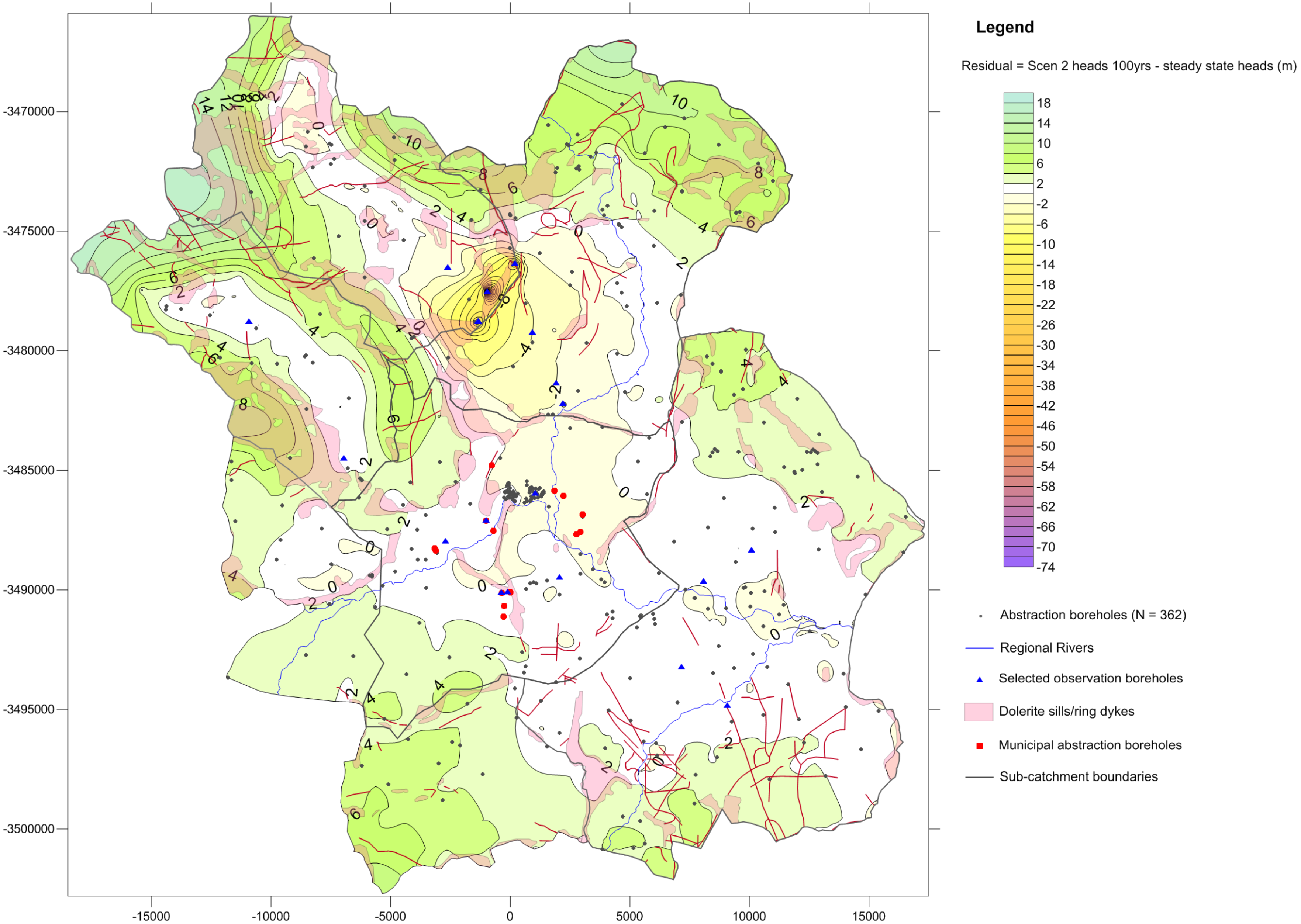


Figure 11-45: Scenario 2 simulated heads minus calibrated steady state heads: residual/difference

Figure 11-44 above shows interpolated residuals of scenario 2 simulated heads minus history matching final simulated heads 2011. Figure 11-45 in turn shows interpolated residuals of scenario 2 simulated heads minus calibrated steady state heads. The residuals from Figure 11-45 show that even after 100 years of simulation with The Glen production boreholes implemented, many areas still have positive residuals. In these mountainous hard rock (low T) areas there is still an appreciable amount of drawdown that has to occur before the model reaches the calibrated steady state. This is due to the slow nature of groundwater flow in low permeability formations. The large drawdowns and steep hydraulic gradients at The Glen production boreholes are expected to be a result of geological outer boundaries in close proximity to the production boreholes (e.g. EC-Q14-1655) and primarily due to the EC-Q14-1637 production borehole located in apparently low hydraulic conductivity formation according to geology map. EC-Q14-1637 is not located in such low hydraulic conductivity geology as discussed above.

EC-Q14-1636, EC-Q14-1637, EC-Q14-1655 had drawdowns of 28.8 m (-71.5 mbgl), 75.3 m (-81.3 mbgl) and 29.2 m (-34.7 mbgl) respectively. All other boreholes had a drawdown of less than 11 m and a mean drawdown of 1.97 m. As mentioned EC-Q14-1637 drawdown is expected to be less in reality.

Model water budget results were evaluated for the model domain and sub-catchments of interest for comparison with GYMR water balance results. After integration and averaging of the monthly sources and sinks the water budget results for the model domain are provided in Table 11-8.

Table 11-8: Scenario 2 model domain mean water budget results

Budget domain	Dirichlet-BCs		Wells		Distributed Sources / Sinks		Total Balance	Excess / Deficit Groundwater
	In	Out	In	Out	In	Out	In (+) / Out (-)	In (+) / Out (-)
Model domain [ℓ/s]	0.0	-137.6	0.0	-241.4	376.6	0.0	-2.4	135.2
Model domain [m^3/d]	0	-11 891	0	-20 856	32 538	0	-209	11 682
Model domain [m^3/a]	**0**	**-4 280 615**	**0**	**-7 508 251**	**11 713 768**	**0**	**-75 098**	**4 205 517**

The model water budgets for the catchments/compartments of interest are compared with the GYMR results in Table 11-9. The GYMR calculations for Scenario 3 were based on mean annual precipitation (MAP). The graph in Figure 11-46 shows how the volume of groundwater in the model domain for scenario 2 and scenario 1 change over time.

Table 11-9: Comparison of Scenario 3 model water budget results and GYMR water balance

Budget domain	Dirichlet-BCs (Baseflow+losses)		Well BCs [+springs]		Distributed Sources/ Sinks		Total Balance	Excess / Deficit Volume
	In	Out	In	Out	In	Out	In (+) / Out (-)	In (+) / Out (-)
	m³/a	m³/a	m³/a	m³/a	m³/a	m³/a	m³/a	m³/a
Municipal sub-catchment Model	**0**	**-17**	**0**	**-3 213 458**	**1 743 355**	**0**	**-1 470 121**	**-1 470 104**
Municipal sub-catchment GYMR	**0**	**0**	**0**	**-3 211 260**	**920 404**	**-13 584**	**-2 304 440**	**-2 304 440**
The Glen sub-catchment Model	**0**	**-1 217 764**	**0**	**-875 350**	**2 134 531**	**0**	**41 417**	**1 259 181**
The Glen sub-catchment GYMR	**0**	**-1 607 188**	**0**	**-873 963**	**2 487 376**	**-6 225**	**0**	**1 607 188**
Karmel sub-catchment Model	**0**	**-727 999**	**0**	**-293 238**	**1 719 927**	**0**	**698 689**	**1 426 689**
Karmel sub-catchment GYMR	**0**	**-1 699 289**	**0**	**-293 037**	**1 998 301**	**-5 975**	**0**	**1 699 289**
Dunblane Model compartment	**0**	**-1 748 161**	**0**	**-1 656 028**	**2 560 063**	**0**	**-844 125**	**904 035**
Dunblane sub-catchment GYMR	**0**	**-279 517**	**0**	**-1 684 833**	**1 975 800**	**-11 450**	**0**	**279 517**
Grootfontein compartment Model	**0**	**-479 331**	**0**	**-1 036 583**	**2 156 648**	**0**	**640 734**	**1 120 065**
Grootfontein compartment GYMR	**0**	**-955 236**	**0**	**-1 034 297**	**1 995 758**	**-6 225**	**0**	**955 236**
							TOTAL	**3 239 867**
								2 236 791

Also interesting to note from Figure 11-45 is that neither Karmel nor Dunblane sub-catchments are affected by drawdown from the current abstraction and The Glen implemented production boreholes over the 100 year simulation. Both sub-catchments have excess groundwater with Karmel having the largest potential (Table 11-9). It is recommended that an evaluation of the shallow unconfined- and deeper semi-confined fractured rock aquifers be performed to estimate Karmel shallow and deep aquifer storage. A hydraulic (pumping) test should be performed for EC-Q14-1653 with observation boreholes.

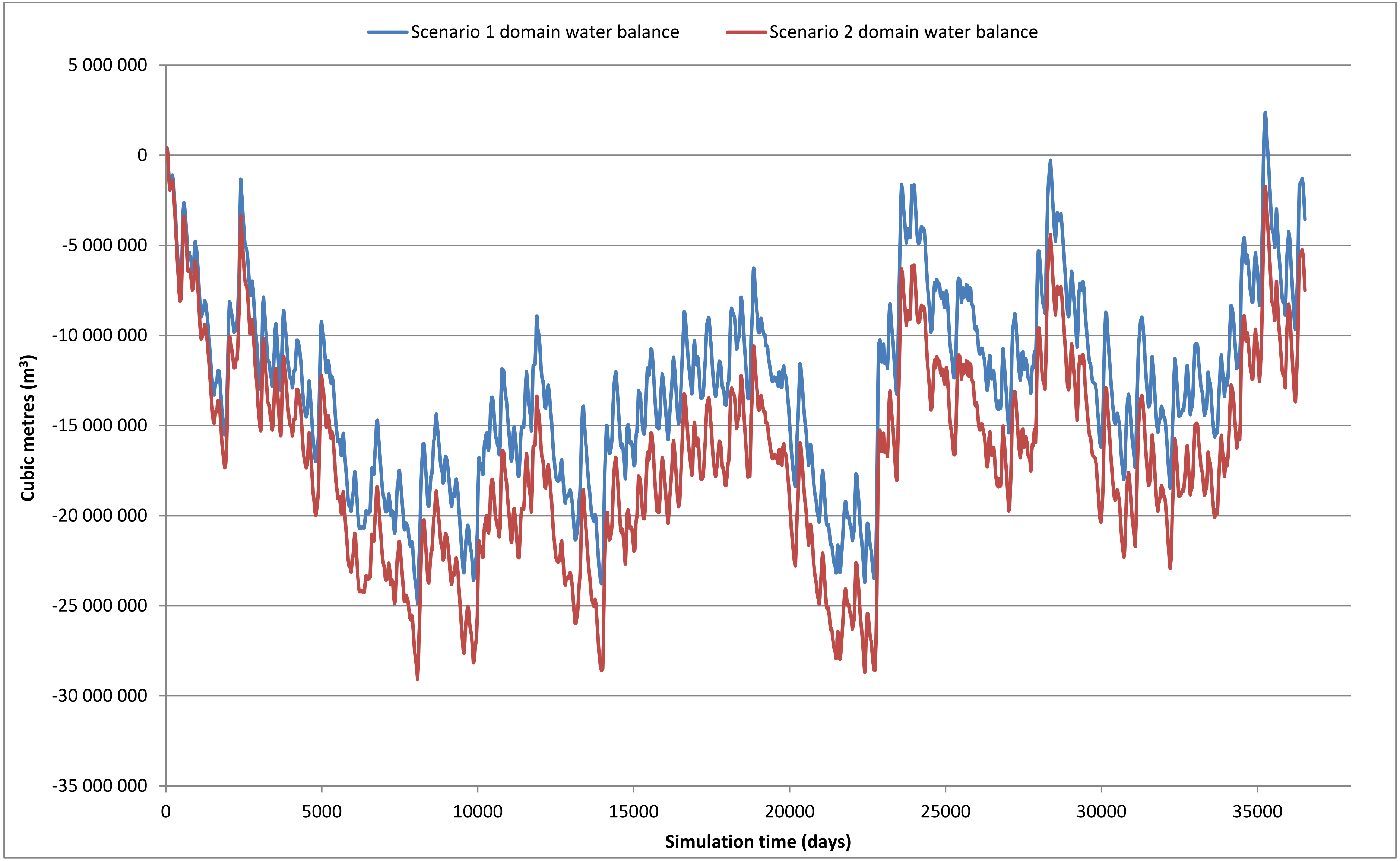


Figure 11-46: Model domain groundwater volume fluctuations over time

11.8 Conclusions

Scenario 1 results from the numerical model show that current abstraction is sustainable based on the calibrated hydraulic parameters. It is recommended that abstraction be reduced at zones of concentrated abstraction (Municipal sub-catchment) and increased/implemented at aquifers further away (abstraction must be spread out).

To achieve calibration with a single recharge figure for outcropping hard geology types, a higher than expected recharge figure was used (6.5%). A recharge figure of 3.32% was obtained with the saturated volume fluctuation (SVF) method for The Glen sub-catchment. The SVF method however determines the mean effective recharge for a catchment, hence included the alluvium recharge and other losses in the calculation. The calibrated recharge figure of 6.5% is however very well correlated with chloride mass balance (CMB) figures obtained for The Glen (6.7%) and Karmel (7.0%) sub-catchments. Vandoolaeghe (1979) also estimated a recharge percentage of MAP of 7.0% for mountainous areas. When model validation is considered, the historic water level trends show a decline while model results show a stable and even increasing groundwater level under actual rainfall conditions, with significant Dirichlet BCs (evaporation losses + baseflow) removing excess groundwater from the system.

It is thought that the declining water levels and boreholes drying up were experienced during a major drought cycle. The drought cycle is confirmed by rainfall figures during the hydrological years of 2002, 2006 and 2008 having annual rainfall's of 265.5 mm/a, 303 mm/a and 214 mm/a respectively. The MAP is 347.2 mm/a for the 100 year patched rainfall record.

Scenario 1 results indicate that either recharge on the outcropping hard rock geology in the model is too high, abstraction is too low or perhaps the predominantly winter time groundwater levels measured do not represent the summer conditions when more abstraction takes place and some boreholes reportedly dry up. It could also be a case of a missing 3D component in limited storage aquifers that we know is the case for the shallow alluvial aquifers. In any case, the groundwater levels measured during the hydrocensus and the mean depth of the shallow aquifer (± 32 m) show that the aquifer has not been depleted or that it is partially depleted during the summer time, but is recharged again from late summer rains or from the recharge lag effect.

Scenario 2 simulation results show that abstraction from new production boreholes at The Glen in addition to current abstraction is sustainable with actual rainfall over time. Significant drawdown of -74.9 m is seen in EC-Q14-1637; however hydraulic test analysis shows otherwise, thus actual geology differs from mapped geology used in the model.

The impact of abstraction in one sub-catchment can be seen in other sub-catchments as well as evidenced in the sub-catchment/compartment water budgets between Scenario 1 and 2.

There is a fair correlation between results from the GYMR water balance and numerical model for catchments/compartments of interest. The differences between final excess/deficit volumes for GYMR and numerical model range between -347 532 m^3/a and 624 518 m^3/a with a root mean square error of ± 391 242 m^3/a (12.4 ℓ/s). This results in a normalised root mean square error (NRMSE) of 37% between the two methods over the volume range. The large difference between the GYMR and numerical model for the Municipal sub-catchment was excluded from statistics. This large difference is attributed to the fact that a single low (2%) recharge figure is used in the GYMR while a much higher recharge figure results for the numerical model due to differentiated geology and recharge figures of both 6.5% and 2% used. The Dunblane sub-catchment and model domain catchment size also differ. Use of recharge per geology (and surface area), hence more than one recharge per sub-catchment can be included in detail GYMR groundwater balances. The great advantage of the numerical model, as mentioned in the Introduction, is the fact that it can be calibrated to actual field conditions and in so doing achieves better accuracy of hydraulic parameters and results. This is true only if the problem of non-uniqueness has been solved by model validation or thorough sensitivity analysis.

11.8.1 Assumptions and model limitations

It is assumed that available municipal abstraction volumes (latest 2005) are in line with the current municipal abstraction volumes.

It is assumed that the 1: 250 000 scale geology used in the model is representative of study area hydrogeology, while EC-Q14-1637 has shown that locally it is not.

Most hydrocensus groundwater levels (measured hydraulic heads) were measured from 24 January 2007 to 17 September 2007. Groundwater levels were mostly measured during late summer to winter months. The implication is that groundwater levels could be different (lower) during the peak summer months when there is more abstraction. It is assumed that the groundwater levels measured are representative of the groundwater system.

The 2D model does not take the multi-layered nature of the aquifers in Middelburg into account and uses a mean transmissivity and storage coefficient for each of the 2D mapped geological (hydraulic) zones.

11.9 Recommendations

It is recommended that once new production boreholes in The Glen are implemented, abstraction from existing municipal boreholes should be lessened where possible. There is gross over-abstraction within the Municipal sub-catchment that is causing boreholes within and around it to fail. Abstraction rates should be decreased at single sources and spread out more, so that the same volume of groundwater is still abstracted, but less from each point source. The first steps towards better aquifer management has been taken by the drilling and equipping of new groundwater monitoring boreholes as well as the establishment of production boreholes in The Glen sub-catchment (Grobler, 2010). A pipeline and balancing reservoir have also been completed and implemented for The Glen sub-catchment and linked to the town’s water supply infrastructure (completed November 2012).

A recommendation is made of running another calibration with the automatic parameter fitting program to evaluate whether lower recharge figures are obtained. If not abstraction could be higher than estimated.

It is recommended that the numerical model be extended to three dimensions (3D) to incorporate the discontinuity of the shallow aquifer base as well as simulating the groundwater dynamics between the shallow and the deep aquifer.

It is recommended that an updated and accurate (WGS84 Datum) isopach map of the thickness distribution of the alluvium and unconfined aquifers be compiled. Vandoolaeghe (1979) completed an isopach map of the unconfined aquifers, but it was found to be spatially warped and difficult to rectify, even after georeferencing. An interpolation of the aquifer thickness can be performed with existing borehole logs and information available and spatial distribution can be determined from currently available satellite imagery and ortho-rectified aerial photos. The isopach map can be used to construct a much more accurate 3D numerical model that will calculate volumes of available groundwater with a high degree of confidence. Currently a 2D model is employed and as such aquifer parameters are averaged vertically for different geological formations.

12 CONCLUSIONS, RECOMMENDATIONS & FUTURE PROSPECTS

The full groundwater resource development cycle has now been completed and documented, including some additional evaluations. From the different groundwater resource development tasks performed, the main conclusions and recommendations are provided here in summary.

12.1 Conclusions

Based on the GYMR water balance, numerical modelling results and 2 – 5 years of new monitoring data, current municipal abstraction is sustainable, but should be more spatially distributed. The numerical model domain has a total abstraction (-6.814×10^{6} m^3/a) to recharge (11.714×10^{6} m^3/a) ratio of 58%, with excess groundwater removed from the system through evapotranspiration, baseflow and other losses. Over-abstraction and concentrated abstraction occurs within the Municipal sub-catchment. The shallow aquifer in the Municipal sub-catchment fails during drought periods due to concentrated abstraction and limited aquifer thickness/storage.

High yielding boreholes were drilled on the dolerite structures and especially where adjacent fractured or high yielding formations were present.

The rationale behind drilling deeper exploration boreholes for municipal abstraction is to create a drought resilient water source. It must however be proven that the shallow and deep aquifers are acceptably recharged again during normal and above average rainfall events through prolonged groundwater monitoring.

Although the goal was to target the dolerite structures at depth, reaching the planned 300m depths proved difficult due to high water pressure building up. Even where the boreholes reached depths of 200+ m, statistically the most water strikes occurred at shallower depths although it must be recognised that it becomes increasingly difficult to see immediate changes in airlift yield and water strikes at those depths given water from existing strikes.

The highly mineralised nature of groundwater in the Middelburg ring structure (Municipal sub-catchment) is thought to be primarily the consequence of no constant flow of groundwater from the Grooftontein weir spring into the directly downstream drainage. The Grootfontein weir spring is located on the watershed between the Grootfontein and Municipal sub-catchments. As soon as the damming of spring water in the weir almost reaches the crest of the weir, two turbine pumps of the Grootfontein Agricultural College are switched on and the spring water is abstracted until the weir water level has dropped to a sufficiently low level. The weir water level rises again due to permanent spring flow and the former mentioned abstraction process is repeated iteratively. This impacts directly on the downstream groundwater, as the natural surface water and groundwater flow regime from one catchment to another is disturbed and changed. It is recommended that a two-step process be followed to improve the groundwater and surface water regime. (1) The Grootfontein weir spring abstraction practice should be reduced or stopped so that the groundwater table and groundwater quality in the Municipal- and Dunblane-sub-catchments can recover and (2) Managed Aquifer Recharge (artificial recharge) methods should be implemented through for example the emplacing of a coarse sand or gravel section in the river bed just below the Grootfontein weir spring bridge. The river bed bottom at this location should also be modified by removing the thin clayey argillaceous impermeable top layer of the river bed to dramatically improve the infiltration of the spring water. Some form of gabion structure with wire mesh and concrete downstream wall should be constructed to protect this artificial recharge section during rainy season and flooding times.

There is high confidence in the MAP rainfall and SVF recharge groundwater balances of the Grootfontein, The Glen and Karmel sub-catchments. Abstraction in these catchments is adequately determined and bounded. There is lower confidence in the groundwater balances for Middelburg Municipal, Dunblane and Lusernvlei sub-catchments. This is largely due to abstraction uncertainties.

While the mountainous sub-catchments all have positive groundwater balances, the Dunblane, Middelburg Municipal and Lusernvlei sub-catchments have marginal to negative groundwater balances. From these results it can be seen that while groundwater balances have been calculated for each sub-catchment, they cannot be regarded as isolated and lateral inflow from a number of adjacent mountainous catchments occur. Balances were not calculated for these largely undeveloped mountainous sub-catchments, but their distances from Middelburg make them a low priority for evaluation. The groundwater system is integrated and the entire catchment is much larger. It can be expected that a groundwater balance for the larger catchment will be positive.

The only way to be certain if the groundwater balance (Dunblane) is actually positive or negative is to look at current (2008-2013) time series groundwater level data. Groundwater level monitoring is critical in the Middelburg area and is the key to good management and decision making. The analysis of water level change over time coupled with a better knowledge of agricultural abstraction around Middelburg will provide continually improving management of the aquifers as well as determining accurate recharge estimates using the SVF water balance method.

In many cases a choice was made to use the MAP with SVF recharge instead of 95% assured rainfall (5^{th} percentile) as the MAP is based on long time series information. The 95% assured GYMR is used to present a conservative estimate of the minimum amount of groundwater available. Technically there should be more groundwater available, 95% of the time. With this Middelburg study, a scaled-up more detail balance is calculated and the luxury of working with the 5^{th} percentile of rainfall is no longer available, since there is little surplus groundwater in some sub-catchments, if any. If a realistic estimate of abstraction is used and not its 5^{th} percentile, real rainfall data must also be used. If for example the Dunblane sub-catchment balance is based on the 5^{th} percentile of rainfall and SVF recharge, the overall result will be negative and groundwater supply from Dunblane will fail. The SVF method must be applied to MAP as it is calculated from real time series rainfall and not its 5^{th} percentile.

Middelburg has easily accessible high yielding and good storage (S ± 0.01) shallow aquifers, but the concentrated abstraction in the Middelburg and Dunblane sub-catchments have created over-exploitation in these areas. The structure of the alluvial plain aquifers is such that a top layer of argillaceous sediments is preventing rainfall infiltration and percolation through to the groundwater table. Recharge is a sensitive parameter in the groundwater balance and by for instance raising the recharge in the Dunblane sub-catchment from 2% to 3% an additional 915 000 m^3/a of groundwater becomes available. One solution to meeting future water supply needs with groundwater in Middelburg is by artificial recharge or managed aquifer recharge, thereby increasing the natural recharge.

After a choice was made in using MAP rainfall applied to SVF recharge, three possible abstraction scenarios were compared in GYMR scenario 3. The abstraction scenarios compared were the Potential existing abstraction, AGES estimated abstraction and water level-transmissivity based abstraction. There are large differences between these possible abstractions, reflecting the large amount of uncertainty associated with abstraction in the Dunblane, Municipal and Lusernvlei sub-catchments. Within the most realistic SVF recharge and water level-transmissivity abstraction scenario, the current reported municipal abstraction of 80 ℓ/s cannot be supplied from the combined sub-catchments evaluated. Raising the recharge by just 1% in problematic sub-catchments (Woodford recharge scenario), would change again the water balance outcome to a positive one. Within the

Woodford recharge scenario there is adequate groundwater available, and an additional 20 ℓ/s would be required for the future (2024) total municipal abstraction of 153 ℓ/s scenario.

12.2 Recommendations

Groundwater level- and abstraction-monitoring are critical in the Middelburg area and are the key to good management and decision making. It is a necessity for municipal water supply from aquifers. The analysis of water level change over time coupled with a better knowledge of agricultural abstraction around Middelburg will provide continually improving management of the aquifers as well as determining accurate recharge estimates using the SVF or similar water balance recharge methods.

A groundwater monitoring and management plan needs to be compiled for Middelburg. Unfortunately it was beyond the time-frame of this study, but is of critical importance. The first version of a plan was compiled by Dr. J.J.P. Vivier and J.A. Myburgh (Appendix E), but this plan needs to be updated with new monitoring information and the monitoring protocol updated. Water quality monitoring also needs to be included. If manual groundwater levels (hydraulic heads) need to be measured, it should be done at a minimum temporal resolution of 1 month in distant catchment monitoring boreholes to be effectively applied in further refinement of the recharge figures (e.g. SVF method). New selected monitoring boreholes with leveloggers or other electronic loggers installed should have a groundwater level sampling/measurement temporal resolution of at least twice a day, e.g. 12:00 and 00:00.

Licensing and regulation of agricultural groundwater will need to be addressed if the future water supply for Middelburg is to be based on groundwater. Water use licensing should be targeted at high volume point source abstractions as identified from the hydrocensus data and if those abstractions are confirmed to be very large through field verification. From the natural vegetation and climate in the Karoo, it should be obvious that groundwater based brute force intensive irrigation schemes are not sustainable in this environment.

It is recommended that an updated and accurate (WGS84 ellipsoid) isopach map of the thickness distribution of the alluvium and unconfined aquifers be compiled. Vandoolaeghe (1979) completed an isopach map of the unconfined aquifers, but it was found to be spatially warped and difficult to rectify even after georeferencing. An interpolation of the aquifer thickness is possible with existing borehole logs and information available and spatial distribution can be determined from currently available satellite imagery and ortho-rectified aerial photos. The isopach map can be used to construct a more accurate 3D numerical model that will calculate volumes of available groundwater with a high degree of confidence.

Currently a 2D model is employed and as such transmissivity (T) and storativity (S) are averaged vertically for different geological formations. Better constraining the shallow aquifer geometry and thickness distribution will directly result in better management of the resource.

Based on successful development of The Glen sub-catchment where little existing abstraction takes place and a large-, but conservative, positive-groundwater balance occurs; further groundwater resource development should take place regionally (away from municipal shallow aquifer) and target more than one aquifer. Ideally a combination of alluvium and underlying weathered/fractured Beaufort formations or dolerite contact zone. For example, the Karmel sub-catchment holds promise as well as the Dunblane sub-catchment, east of the Dunblane dyke. An evaluation of the Karmel sub-catchment's aquifer storage will need to be performed before the next development takes place there. Dunblane sub-catchment's groundwater levels will need to be monitored, it's recharge range be better constrained and large point source abstraction volumes better defined.

Great scope for artificial recharge or managed aquifer recharge is seen in the study area. Middelburg has easily accessible high yielding and good storage (S ± 0.01) shallow aquifers, The structure of the alluvial plain aquifers is however such that a top layer (first 2 – 5 m from surface) of argillaceous sediments is preventing rainfall to quickly infiltrate and percolate through to the groundwater table. Recharge is a very sensitive parameter in the groundwater balance and by for instance raising the recharge in the Dunblane sub-catchment from 2% to 3% an additional 915 000 m^3 per annum of groundwater becomes available. One solution to meeting future water supply future needs in Middelburg with groundwater is by artificial recharge or managed aquifer recharge, increasing the natural recharge.

There is probably a fine balance between recharge and abstraction in the studied Middelburg catchments currently and it is thought that balance or quasi steady-state water level is maintained by means of an interplay between abstraction and evaporation/baseflow. An increase in abstraction results in a decrease in evaporation or baseflow, but the total sinks in the system have not really increased as significantly as expected compared to recharge.

To accurately determine storativity (S) additional observation boreholes must be included in future hydraulic (pumping) tests besides the measurements at the abstraction borehole. The link between the shallow and deep aquifer was not conclusively evaluated. One requires a borehole that is drilled into only the deeper fractured rock aquifer (or has sealed-off shallow aquifer section) and some shallow aquifer boreholes in the vicinity. The prime example of a deep aquifer only borehole is EC-Q14-1633. It has however been constructed as a monitoring borehole.

There is a generally negative perception amongst Middelburg residents regarding tap/municipal water and its quality. This is largely due to elevated magnesium/total hardness and lime scaling. It should perhaps be considered to construct/upgrade a central water treatment plant to treat the water prior to reticulation to houses for potable water use. It has been ascertained that part of the problem is that there is such a shortage in supply, that abstracted groundwater must go directly from the reservoirs to town reticulation.

Water losses throughout the town's reticulation network were measured in 2006 by WRP consultants and real losses were estimated to amount to 351 000 m^3/a or ±8 ℓ/s (WRP, 2006). The executive summary notes that most of the infrastructure required urgent maintenance and upgrading and that further deterioration of specific components may lead to water losses (WRP, 2006). Based on observations in town water losses should be monitored and knowledge about it kept up to date.

12.3 Future Prospects: Artificial Recharge

Artificial recharge or Managed Aquifer Recharge is a technique that has been gaining more and more popularity in recent years. Often highly permeable aquifers such as unconsolidated sediments are present in areas, but one of the critical aquifer parameters influencing the groundwater balance is limiting further development of the aquifer. Examples of such aquifer parameters are recharge (RE), storativity (S) or aquifer thickness (b). While it is difficult to change S or aquifer thickness, recharge can be enhanced artificially. Artificial recharge has been practiced for centuries and uses generally simple engineering solutions to enhance recharge to aquifers (Gale, 2005:10).

In the case of Middelburg, recharge from rainfall directly on the alluvium is a limiting aquifer parameter due to an argillaceous horizon of silty material in the top 2 – 5 m of the alluvium near surface. Middelburg has otherwise porous alluvial deposits that range in thickness from 5 to 25 m and a highly weathered and fractured rock zone below it, approximately 10 m in thickness. The thin alluvium thickness is not ideal, with the thicker deposits being around 20 – 22 m from surface to the start of the weathered, fractured rock zone below it. The highly weathered, fractured-rock zone in combination with the alluvium however presents a fair thickness (±32 m) and if regularly and efficiently recharged, it could assist to significantly reduce or eliminate the water supply shortage that is experienced.

Alluvium is one of the favoured artificial recharge geologies since it is highly transmissive and also normally has a larger specific yield (Gale, 2005: 8).
Only a brief evaluation of the possibility for artificial recharge in the Middelburg study area is presented here and there are more options and locations for implementing artificial recharge based on the good shallow aquifers Middelburg has.

Two types of artificial recharge methods are in the cases looked at, seen as promising: (1) in-channel modifications and (2) dry land farming (Gale, 2005:13).

Just below Jones Poort (see Figure 12-1) after the main drainage of The Glen sub-catchment has passed over the dolerite ring structure, the drainage channel has been deeply incised into the alluvium due to storm water runoff velocities. Through the years the storm water has continued to cut into the alluvium further and further downstream. One or a few gabion structures with boulders and wire mesh can be constructed across the drainage channel to dam up the storm water and slow it down. Wire mesh with boulder/pebble aprons are important along the sides and bottom of the channel as well as a suitable length upstream and downstream of the Gabion leaky dam wall.

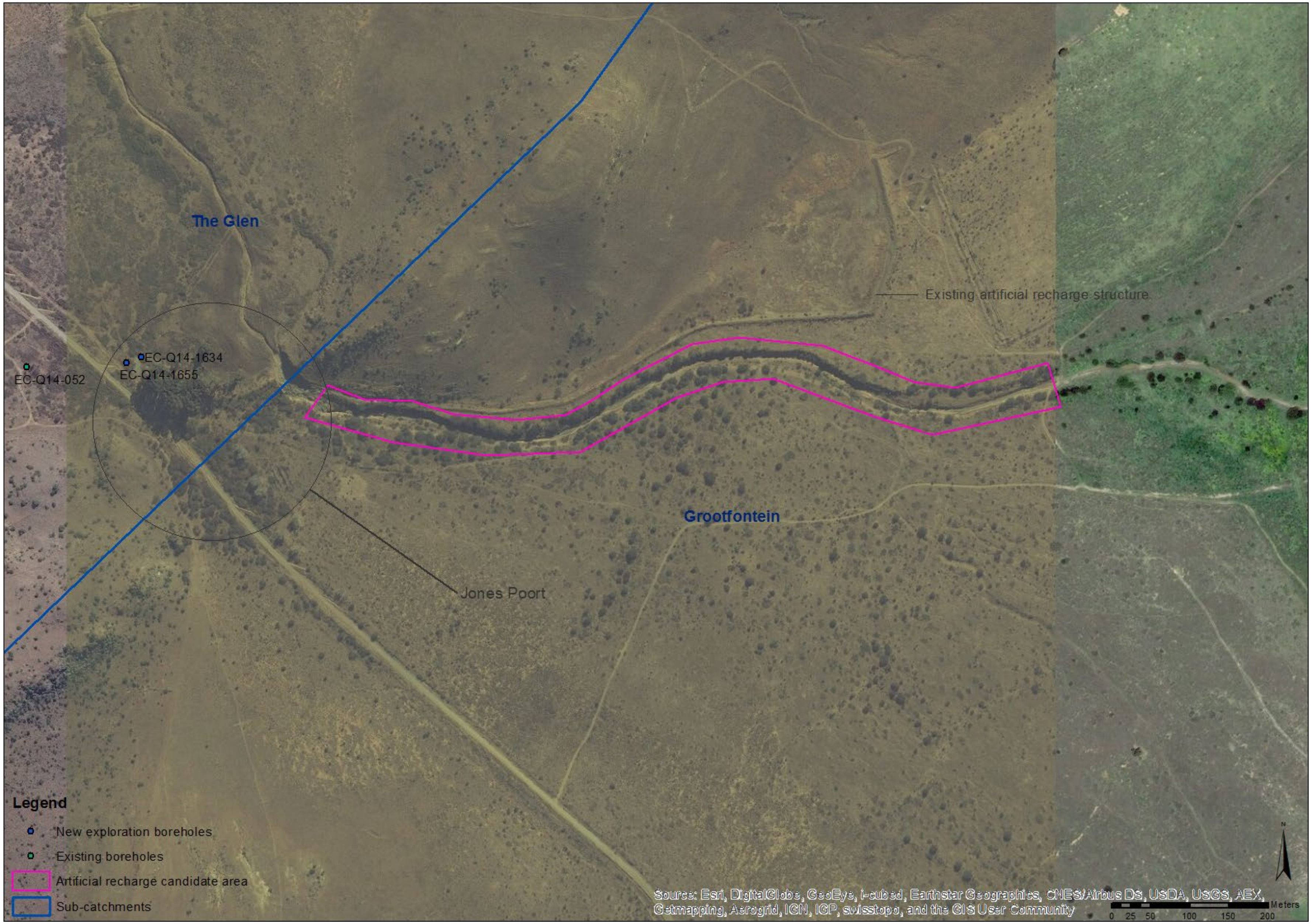


Figure 12-1: Artificial recharge candidate area for in-channel gabion structure and sand dam in Grootfontein sub-catchment

Since the drainage channel has cut through the argillaceous top layers of the alluvium into coarse grained material, drainage into the alluvium at this depth would be comparably quick. A better alternative might be a concrete spillway or weir structure constructed across the drainage channel. A percolation pond behind a check dam type of construction is envisioned here with at least two such structures in the channel in the Grootfontein sub-catchment. As the area behind the concrete wall fills up with sand the wall can be raised incrementally until the dam crest/spillway height is only slightly below the normal surface topography. The sanded up area provides standing time for the storm water to infiltrate into the adjacent banks as well as the aquifer directly below it. The goal is to simultaneously rehabilitate the erosion channels in the alluvium and reduce baseflow, evapotranspiration (from the adjacent alluvium) and runoff that will in any case be lost further downstream.

There is actually an in-channel modification structure unintentionally enhancing groundwater recharge already present in one of the drainages in the Middelburg study area. The structure is located in The Glen sub-catchment some distance upstream of Jones Poort in the main drainage of the sub-catchment. The structure is a combination of a concrete spillway or weir and a sand dam. Unfortunately it has been observed that the porous sand that has accumulated behind the weir wall is being excavated and hauled away by truck to be sold for building or other purposes. This destroys the efficiency of the water being filtered and retained by the sand dam for slower infiltration into the aquifer below. There are more opportunities in The Glen sub-catchment for these types of artificial recharge structures.

It is thought that artificial recharge was historically practiced by the Grootfontein Agricultural College (GAC) as observed in the aerial photos in Figure 12-1. Unfortunately very slow infiltration rates due to the argillaceous top material of the shallow aquifer causes rainwater to stand for days without infiltrating as has been observed by the author in the Grootfontein sub-catchment. From field observations and aerial images it seems that the practice of dry land farming and field bunding has been abandoned by the GAC. In any case, efficient artificial recharge methods can be developed and tailored for the study area.

Another example of where artificial recharge could work well and is critically needed is in the Middelburg Municipal sub-catchment, just behind the Grootfontein weir spring concrete spillway. This example has been mentioned in the conclusions & recommendations of Groundwater chemistry Chapter 9, but is repeated here for completeness. Artificial Recharge (Managed Aquifer Recharge) methods can be implemented through for example the emplacing of a coarse sand or gravel section in the river bed just below the Grootfontein weir spring bridge. The river bed bottom at this location should also be modified by removing the thin clayey argillaceous impermeable top layer of the river bed to dramatically improve the infiltration of the spring water. Some form of gabion structure with wire mesh and concrete downstream wall should be constructed to protect this artificial recharge section during rainy season and flooding times.

There are many other potential locations for artificial recharge downstream of the suggested site, but they become less important the further downstream from municipal abstraction boreholes they get.

The opportunity for artificial recharge in Middelburg and first ideas of how it could be implemented are directly associated with catchment rehabilitation, like preventing erosion of the alluvium that create incised drainage channels and enhance evaporation, baseflow and runoff.

If artificial recharge schemes are to be implemented, care must be taken to not contaminate the aquifers with highly mineralised runoff due to agricultural fertilizers, other contaminants or cause biofouling due to direct injection of contaminated, oxygenated groundwater into the aquifer (Tredoux, 2010). Water use licenses are a requirement for any planned artificial recharge schemes.

Informed responsible management and protection of the natural resources available remain the key to sustainability.

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SUMMARY

The Karoo town of Middelburg in the Eastern Cape Province is solely dependent on groundwater for water supply, as no large surface water bodies are present in the town's vicinity. Previously (1987) water supply from existing municipal production boreholes was adequate to supply the town, but town growth has now resulted in a water supply shortage. The shallow aquifer with alluvial character currently used as sole source is under severe stress and water levels are declining steadily. Piping water from the Orange-Fish River scheme was considered, but this option was shown to be very expensive (±R180 million). Instead, regional and deep groundwater potential was investigated. Deep exploration borehole drilling to around 300 mbgl was used as discussed in Woodford *et al.* (2002).

A detailed GRIP hydrocensus and groundwater sampling was conducted across the study area. A total of 1695 geosites were surveyed. Of 414 boreholes sampled, the water quality of 16% were good, 45% were marginal, 30% were poor and 9% were dangerous. Six sub-catchments were delineated based on hydrogeological principles and groundwater potential. For each sub-catchment a minimum groundwater balance was calculated, based on a 95% assurance level. The Glen, Dunblane, Karmel and Grootfontein sub-catchments were targeted for groundwater exploration based on their favourable groundwater balances.

Geophysical surveys comprised magnetic, electromagnetic and electrical resistivity profiling to determine the orientation of dolerite intrusions. Drilling targets were mainly deep fracturing associated with dolerite ring structures and dyke intrusions. The 18 new boreholes drilled using rotary air-percussion and water-hammer drilling techniques delivered an accumulated airlift yield in excess of 187 ℓ/s with the deepest strike at 236 mbgl. Aquifer tests were conducted and aquifer parameters were calculated using the constant discharge test data and applying the Cooper-Jacob-, FC- and derivative-equations. A total of 26 pumping tests were performed on selected new and existing boreholes. An accumulated sustainable yield was calculated to be approximately 80 ℓ/s.

Detail analytical water balances were calculated for the sub-catchments to estimate the amount of groundwater available in each one. Different recharge and abstraction methods were used and compared through analytical balance scenarios. A higher confidence conservative scenario using the saturated volume fluctuation recharge method and a water level-transmissivity based abstraction estimate per sub-catchment showed abstraction:recharge ratios of: The Glen, 15% (33 ℓ/s); Karmel, 32% (20 ℓ/s); Middelburg Municipal, 447% (-100 ℓ/s); Dunblane, 93% (4 ℓ/s); Lusernvlei, 104% (-1 ℓ/s) and

Grootfontein compartment, 94% (2 ℓ/s). The chloride mass balance recharge provided even higher values of recharge in the order of 6.7% of MAP for mountainous sub-catchments like The Glen and Karmel, which is in line with Vandoolaeghe's (1979) mountainous catchment recharge.

Numerical modelling was performed to determine whether the estimated recharge-based volumes available and abstraction thereof is feasible given hydraulic parameters. A good ($R^2 = 0.94$) snapshot data calibration was obtained, but history matching (transient calibration) was required to get correlation in hydraulic head trends using time series municipal abstraction. The Present day numerical scenario even with inclusion of the new production boreholes in The Glen showed more favourable balances that the analytical balances: The Glen, 41% (40 ℓ/s); Karmel, 17% (45 ℓ/s); Middelburg Municipal, 184% (-47 ℓ/s); Dunblane, 65% (29 ℓ/s); Lusernvlei, 104% (-1 ℓ/s) and Grootfontein compartment, 48% (36 ℓ/s).

The 2 – 5 years of water level information from the new monitoring network developed are also not as negative as expected, however longer groundwater level fluctuation data is required to make conclusive statements. There was also a drought from 1997 – 2002/2003.

Current municipal abstraction is sustainable, but should be more spatially distributed. The shallow Middelburg aquifer has excellent hydrogeological properties, except for aquifer thickness. Production boreholes were historically developed in too close proximity to each other, resulting in the local aquifer being stressed beyond its capacity. The key during new groundwater resource development is a wider borehole distribution and monitoring network and the exploration and development of deeper boreholes associated with fracturing within and adjacent to dolerite ring structures. Results predict a connection between the shallow and deep aquifers. The optimised use of shallow aquifers, combined with monitoring and the use of newly developed deep regional boreholes will ensure a more sustainable groundwater supply to Middelburg. Opportunities for artificial recharge are also seen in the Middelburg study area.

OPSOMMING

Middelburg is ‘n tipiese Karoo dorpie van omtrent 50 000 mense in die Oos Kaap Provinsie en is totaal afhanklik van grondwater as watervoorsieningsbron. Daar is ook geen oppervlak water voorsienings damme in die nabyheid nie. Voorheen (1987) was die munisipale grondwater bronne genoegsaam om die dorp te voorsien, maar dorps uitbreiding en bevolkingsgroei het nou water tekorte tot gevolg. Die vlak akwifeer (water draer) met alluviale karakter is onder druk en watervlakke sak stelselmatig. ‘n Pyplyn van die Oranje-Vis skema was ondersoek en oorweeg, maar die opsie was as te duur bevind (±R180 miljoen, kapitale uitgawe). In pleks hiervan is regionale en diep grondwater potential ondersoek. Diep eksplorasie boorwerk met dieptes tot 300 m onder grondvlak was gedoen soos bespreek deur Woodford *et al.* (2002).

‘n Omvattende GRIP hidrosensus en grondwater monster opname was gedoen regoor die studie area. 1695 “Geosites” se besondhede was verkry. Van die 414 boorgate waar water monsters geneem is, was die water kwaliteit van 16% goed, 45% was redelik, 30% was swak en 9% het gevaarlike water kwaliteit gehad volgens die Department van Waterwese se standaarde. Ses sub-opvang gebiede was gedelinieer gebaseer op geohidrologiese beginsels en grondwater potensiaal. ‘n Minimum water balans (95% sekerheid) was bereken vir elk en daar was gevind dat The Glen, Dunblane, Karmel en Grootfontein sub-opvang gebiede gunstige grondwater balanse het.

Geofisiese ondersoeke was in hierdie opvang gebiede van staple gestuur en het magnetiese-, elektromagnetiese- en weerstands-werk behels, hoofsaaklik om die orientasie van die doleriet indringings te bepaal. Diep frakture geassosieer met doleriet ring strukture en gange was die hoof teikens vir geofisika. 18 Nuwe boorgate is geboor met lugdrukboor tegniek asook water hammer tegniek. ‘n Totale blaas lewering van 187 ℓ/s is verkry met die diepste water draende breuk op 236 m onder grondvlak. Pomp toetse was gedoen en die akwifeer parameters met die FC (Flow Charateristic)-, Cooper-Jacob en afgeleide vergelykings bereken. 26 Pomp toetse was gedoen op bestaande en nuwe gate in die studie area. In totaal is ‘n teoreties volhoubare lewering van omtrent 80 ℓ/s bereken.

Noukeurige water balanse vir elke sub-opvang gebied is vervolgens bereken om te bepaal hoeveel grondwater beskikbaar is in elke sub-opvang gebied. Verskillende water draer aanvulling- en ontrekking-berekeningsmetodes is gebruik om as verskillende uitkomste (scenarios) vergelyk te word. ‘n Meer waarskynlike dog meer konservatiewe uitkoms wat die versadigde volume fluktuasie (SVF) aanvullings metode gebruik het die volgende ontrekking:aanvulling resultate gehad: The Glen, 15% (33 ℓ/s); Karmel, 32% (20 ℓ/s); Middelburg Municipal, 447% (-100 ℓ/s); Dunblane, 93% (4 ℓ/s); Lusernvlei, 104% (-1 ℓ/s) en Grootfontein kompartement, 94% (2 ℓ/s). Die chloried massa balans aanvullings metode het selfs hoër aanvullings waardes gehad van 6.7% vir die bergagtige opvang gebiede en dit strook goed met die aanvullings persentasies van reënval wat verkry is deur Vandoolaeghe (1979) vir die bergagtige dele van die studie area.

Numeriese modellering was uitgevoer om te bepaal of die volumes wat blyk beskikbaar te wees, moontlik is vir aanvulling van die akwifere en ontrekking daarvan gebaseer op hidroliese vloei parameters. ‘n Goeie (R^2 = 0.94) kalibrasie was verkry vir een tydstip data, maar dit was nodig om tydreeks passing te doen van die gemete en gesimuleerde hidroliese drukvlakke ten einde die trant van werklike drukvlakke realisties te simuleer. ‘n Uitkoms met huidige ontrekking asook nuwe munisipale ontrekking in The Glen sub-obvanggebied het meer gunstige grondwater balanse gebaseer op die numeriese model tot gevolg gehad: The Glen, 41% (40 ℓ/s); Karmel, 17% (45 ℓ/s); Middelburg Municipal, 184% (-47 ℓ/s); Dunblane, 65% (29 ℓ/s); Lusernvlei, 104% (-1 ℓ/s) and Grootfontein compartment, 48% (36 ℓ/s).

Die 2 – 5 jaar grondwater moniterings data wys ook dat die grondwater situasie nie so sleg is as wat vermoed was nie, alhoewel langer tydreeks watervlakke data nodig is om hoë sekerheid uitsprake te maak. Daar was ook ‘n droogte vanaf 1997 tot 2002/2003 wat die stelsel geknou het.

Huidige munisipale ontrekkings syfers is volhoubaar, maar moet ruimtelik meer versprei word. Die vlak alluviale akwifeer van Middelburg het goeie hidroliese eienskappe, behalwe ‘n beperkende akwifeer dikte. Munisipale produksie gate was in die verlede te naby aan mekaar geboor en dit het tot gevolg gehad dat daar van die plaaslike vlak akwifeer meer onttrek was, as wat dit kon lewer. Toekomstige boorgate vir munisipale grondwater ontwikkeling moet verder uit mekaar gespasieer wees en moet ‘n grondwater moniterings netwerk insluit. Die eksplorasie en water voorsienings boorwerk moet fokus om dieper fracture geassosieer met dolerite strukture en gange ook te teiken. Die studie se resultate voorspel dat daar ‘n moontlike skakeling tussen die vlak en die diep akwifeer is. Die ge-optimiseerde gebruik van die vlak alluviale akwifere gekoppel met monitering en die gebruik van nuut ontwikkelde diep regionale boorgate sal ‘n meer volhoubare watervoorsiening vir Middelburg bied. Daar is ‘n paar geleenthede vir akwifeer aanvulling doelbewustelik verhoog ook beskikbaar in die Middelburg studie area.

1 APPENDIX A: MUNICIPAL BOREHOLE ABSTRACTION

SITE ID	EC-Q14-019	Midros 2	EC-Q14-866	EC-Q14-016	EC-Q14-015	EC-Q14-031	EC-Q14-030	EC-Q14-029	EC-Q14-028	EC-Q14-033	EC-Q14-026	EC-Q14-025	EC-Q14-020	EC-Q14-104	EC-Q14-103	
DATE	**MIDROS 1**	**MIDROS 2**	**MIDROS 4**	**MIDROS 6**	**MIDROS 7**	**M/KLOOF 1**	**M/KLOOF 2**	**M/KLOOF 6**	**M/KLOOF7**	**M/ KLOOF 9**	**O/VLEI**	**N/VLEI**	**UITSIG**	**Z/BLOEM 1**	**Z/BLOEM 2**	**TOTAL**
J-01	10144	4837	1917	10722	12883	36503	9091	34895	16180	421175	0	29379	2700	11594	6495	**608 515**
F-01	9505	4938	0	4454	11404	2586	1688	27771	8701	48261	0	34163	4300	26370	15294	**199 435**
M-01	8843	4268	0	5361	12481	5583	2925	21094	8186	35169	0	32343	807	26287	17342	**180 689**
A-01	9344	9499	0	4587	15294	35558	19409	1906	0	10915	0	6409	0	13659	7524	**134 104**
M-01	7978	0	1532	5678	11336	29834	15914	4716	8093	8661	0	0	0	24136	10882	**128 760**
J-01	152	0	568	0	0	30950	4771	3566	0	18328	0	0	0	26552	2401	**87 288**
J-01	1445	656	801	0	0	9753	14143	15843	0	12608	0	0	13801	33590	20006	**122 646**
A-01	8096	4117	800	0	0	37238	13520	3381	0	0	4531	0	0	10434	6803	**88 920**
S-01	2448	5339	91	0	0	34859	15371	17654	0	10441	14860	0	0	0	0	**101 063**
O-01	0	4868	1593	5807	11350	33582	17498	18491	1556	23861	180	0	0	0	0	**118 786**
N-01	0	5125	1069	6689	13317	30062	19164	17506	2154	23884	959	2719	0	0	0	**122 648**
D-01	348	4911	1110	2916	8208	28771	14792	28779	3164	25350	0	468	0	0	0	**118 817**
TOTAL	**58 303**	**48 558**	**9 481**	**46 214**	**96 273**	**315 279**	**148 286**	**195 602**	**48 034**	**638 653**	**20 530**	**105 481**	**21 608**	**172 622**	**86 747**	**2 011 671**
MONTH	**MIDROS 1**	**MIDROS 2**	**MIDROS4**	**MIDROS 6**	**MIDROS 7**	**M/KLOOF 1**	**M/KLOOF 2**	**M/KLOOF 6**	**M/KLOOF7**	**M/ KLOOF 9**	**O/VLEI**	**N/VLEI**	**UITSIG**	**Z/BLOEM 1**	**Z/BLOEM 2**	**TOTAL**
J-02	3677	4903	901	8124	15038	5596	17999	32381	20286	25042	7484	15246	9639	22558	12608	**201 482**
F-02	5670	5106	3675	7940	14949	0	18051	33671	18674	222615	0	0	0	18905	12191	**361 447**
M-02	4677	4419	1503	5772	13088	0	15252	28663	19974	17474	0	0	0	10259	8020	**129 101**
A-02	5773	4220	178	7325	15462	0	20786	31501	0	19935	0	0	0	21605	10937	**137 722**
M-02	5421	5043	0	6826	14164	0	19492	24215	0	22110	0	0	0	19952	3634	**120 857**
J-02	3882	2241	0	6547	13088	0	17896	3624	0	5766	0	0	0	34200	2145	**89 389**
J-02	0	0	0	8206	13215	0	22842	7318	2764	18468	0	0	0	43172	0	**115 985**
A-02	0	0	0	7022	14580	0	18247	13202	4204	19501	0	0	0	11235	7644	**95 635**
S-02	0	0	0	7310	16469	0	20017	16775	4836	19806	0	0	0	19122	14990	**119 325**
O-02	3048	1909	0	7998	16454	0	18071	33644	17543	6676	4927	35189	1592	24227	16902	**188 180**
N-02	4155	3541	0	2807	17717	0	20229	25455	2106	30770	15620	30172	4614	18978	14476	**190 640**
D-02	0	0	0	0	17959	0	19288	9605	4393	22121	16017	32810	5958	13987	9692	**151 830**
TOTAL	**36 303**	**31 382**	**6 257**	**75 877**	**182 183**	**5 596**	**228 170**	**260 054**	**94 780**	**430 284**	**44 048**	**113 417**	**21 803**	**258 200**	**113 239**	**1 901 593**
MONTH	**MIDROS 1**	**MIDROS 2**	**MIDROS4**	**MIDROS 6**	**MIDROS 7**	**M/KLOOF 1**	**M/KLOOF 2**	**M/KLOOF 6**	**M/KLOOF7**	**M/KLOOF 9**	**O/VLEI**	**N/VLEI**	**UITSIG**	**Z/BLOEM 1**	**Z/BLOEM 2**	**TOTAL**
J-03	111	13	0	26635	23114	9190	24384	18844	7344	34583	20622	43251	3989	31353	27305	**270 738**
F-03	0	0	0	10485	8400	0	11324	6213	50	18651	5715	22772	3547	3477	12240	**102 874**
M-03	0	0	0	5992	14797	0	13493	9387	8832	11433	6297	24142	2596	122223	8510	**227 702**
A-03	0	0	0	0	17968	0	22835	10714	0	30750	14974	39967	4369	7680	3596	**152 853**
M-03	0	0	0	0	13468	0	16485	8250	1430	23902	4933	26527	3351	1430	5867	**105 643**
J-03	0	0	0	0	0	0	20095	14523	0	30227	0	18466	497	2220	1860	**87 888**
J-03	0	0	0	0	9028	0	5021	14946	4140	21948	896	36453	139	8525	8866	**109 962**
A-03	0	0	0	0	17373	0	0	9243	0	25843	8364	30526	0	12811	10162	**114 322**
S-03	0	0	0	13640	16221	235	0	11139	4468	29101	0	24552	858	23296	17606	**141 116**
O-03	3992	0	0	24200	14863	4011	1001	13216	1584	28598	0	25029	6847	19240	15227	**157 808**
N-03	5659	0	0	25560	15182	9819	14300	7869	6586	24045	298	24852	2261	22454	16752	**175 637**
D-03	5930	0	0	25366	15958	0	17860	11441	13613	25967	0	12195	3997	24704	21366	**178 397**
TOTAL	**15 692**	**13**	**0**	**131 878**	**166 372**	**23 255**	**146 798**	**135 785**	**48 047**	**305 048**	**62 099**	**328 732**	**32 451**	**279 413**	**149 357**	**1 824 940**
MONTH	**MIDROS 1**	**MIDROS 2**	**MIDROS4**	**MIDROS 6**	**MIDROS 7**	**M/KLOOF 1**	**M/KLOOF 2**	**M/KLOOF 6**	**M/KLOOF7**	**M/KLOOF 9**	**O/VLEI**	**N/VLEI**	**UITSIG**	**Z/BLOEM 1**	**Z/BLOEM 2**	**TOTAL**
J-04	0	0	0	24766	15031	0	9570	13596	23731	16528	0	20692	4368	24833		**153 115**
F-04	10612	0	0	20679	14061	0	9647	9403	17342	1777	0	0	4177	21917	19291	**128 906**
M-04	803	0	0	19713	12134	0	9852	0	0	23936	0	14600	3663	17252	13517	**115 470**
A-04	0	0	0	22601	10064	0	10520	0	5587	30868	0	919	3211	20835	15858	**120 463**
M-04	0	0	0	22637	14435	12055	10220	0	12175	21235	0	0	3060	21561	17999	**135 377**
J-04	0	0	0	24181	0	1	10644	0	19740	19029	0	0	0	20033	20624	**114 252**
J-04	0	0	0	24181	0	0	10313	0	19302	22405	0	0	0	24700	19358	**120 259**
A-04	0	0	0	25999	8096	0	10980	0	16165	26217	0	0	0	26650	23408	**137 515**
S-04	0	0	0	30223	0	0	10326	684	14794	27295	2886	9374	0	26727	23721	**146 030**
O-04	0	0	0	15237	40	5863	9595	2240	12413	27312	14999	0	0	26313	19565	**133 577**
N-04	0	0	0	23662	150	11961	9298	670	19554	24651	15967	14410	6879	25610	23823	**176 635**
D-04	0	0	0	21066	3070	10793	9285	1207	19430	26068	10526	18155	22506	24704	21326	**188 136**
TOTAL	**11415**	**0**	**0**	**274945**	**77081**	**40673**	**120250**	**27800**	**180233**	**267321**	**44378**	**78150**	**47864**	**281135**	**218490**	**1 669 735**
MONTH	**MIDROS 1**	**MIDROS 2**	**MIDROS4**	**MIDROS 6**	**MIDROS 7**	**M/KLOOF 1**	**M/KLOOF 2**	**M/KLOOF 6**	**M/KLOOF7**	**M/KLOOF 9**	**O/VLEI**	**N/VLEI**	**UITSIG**	**Z/BLOEM 1**	**Z/BLOEM 2**	**TOTAL**
J-05	0	0	0	24374	4740	743	9858	8257	29443	27261	1393	0	4200	22554	25389	**158 212**
F-05	0	0	0	23978	11531	1126	9620	7442	23623	21079	9467	7056	0	25699	24501	**165 122**
M-05	3956	0	0	21127	9801	1	9122	756	23214	24125	0	0	0	21099	14251	**127 452**
A-05	5411	0	0	22336	12198	1017	10308	992	9868	18236	0	0	0	24008	25300	**129 674**
M-05	0	0	0	20485	11117	0	10043	574	5268	18555	0	0	0	21769	23895	**111 706**
J-05	5561	0	0	22348	11519	2	11480	4	1657	32727	0	0	0	21508	21091	**127 897**
J-05	4021	0	0	21122	11210	0	9795	7016	5496	4508	0	0	0	15561	25778	**104 507**
A-05	0	0	0	27392	14843	0	11084	0	22168	17583	0	0	0	26419	22267	**141 756**
S-05	0	0	0	19693	11596	0	10539	0	23339	23030	6670	0	0	22327	25752	**142 946**
O-05	0	0	0	23087	10545	9243	9513	2514	18309	18309	27964	0	0	25683	25535	**170 702**
N-05	0	0	0	22934	12932	7408	10776	1451	12750	12750	477	0	0	24237	25964	**131 679**
D-05	0	0	0	23865	12555	0	6994	206	18136	18136	15796	5671	5728	22742	25645	**155 474**
TOTAL	**18 949**	**0**	**0**	**272 741**	**134 587**	**19 540**	**119 132**	**29 212**	**193 271**	**236 299**	**61 767**	**12 727**	**9 928**	**273 606**	**285 368**	**1 667 127**
MONTH	**MIDROS 1**	**MIDROS 2**	**MIDROS4**	**MIDROS 6**	**MIDROS 7**	**M/KLOOF 1**	**M/KLOOF 2**	**M/KLOOF 6**	**M/KLOOF7**	**M/KLOOF 9**	**O/VLEI**	**N/VLEI**	**UITSIG**	**Z/BLOEM 1**	**Z/BLOEM 2**	**TOTAL**
J-06	0	0	0	16066	7587	0	4372	16464	9304	18539	7173	2803	1	17757	15596	**115 662**
F-06	0	0	0	27294	12882	0	0	1238	20367	40912	0	0	1988	28821	33507	**167 009**
M-06	0	0	0	18452	10594	0	0	0	10019	994	4619	0	1975	29385	20019	**96 057**
A-06	0	0	0	19920	12979	0	0	6245	13688	32015	0	0	1981	17718	25969	**130 515**
M-06	0	0	0	6000	14592	0	0	0	11202	30878	0	0	1920	25887	24906	**115 385**
J-06	0	0	0	0	12057	0	0	0	14863	32539	0	0	7041	31066	26599	**124 165**
J-06																
A-06																
S-06																
O-06																
N-06																
D-06																
TOTAL																

2 APPENDIX B: GEOPHYSICS

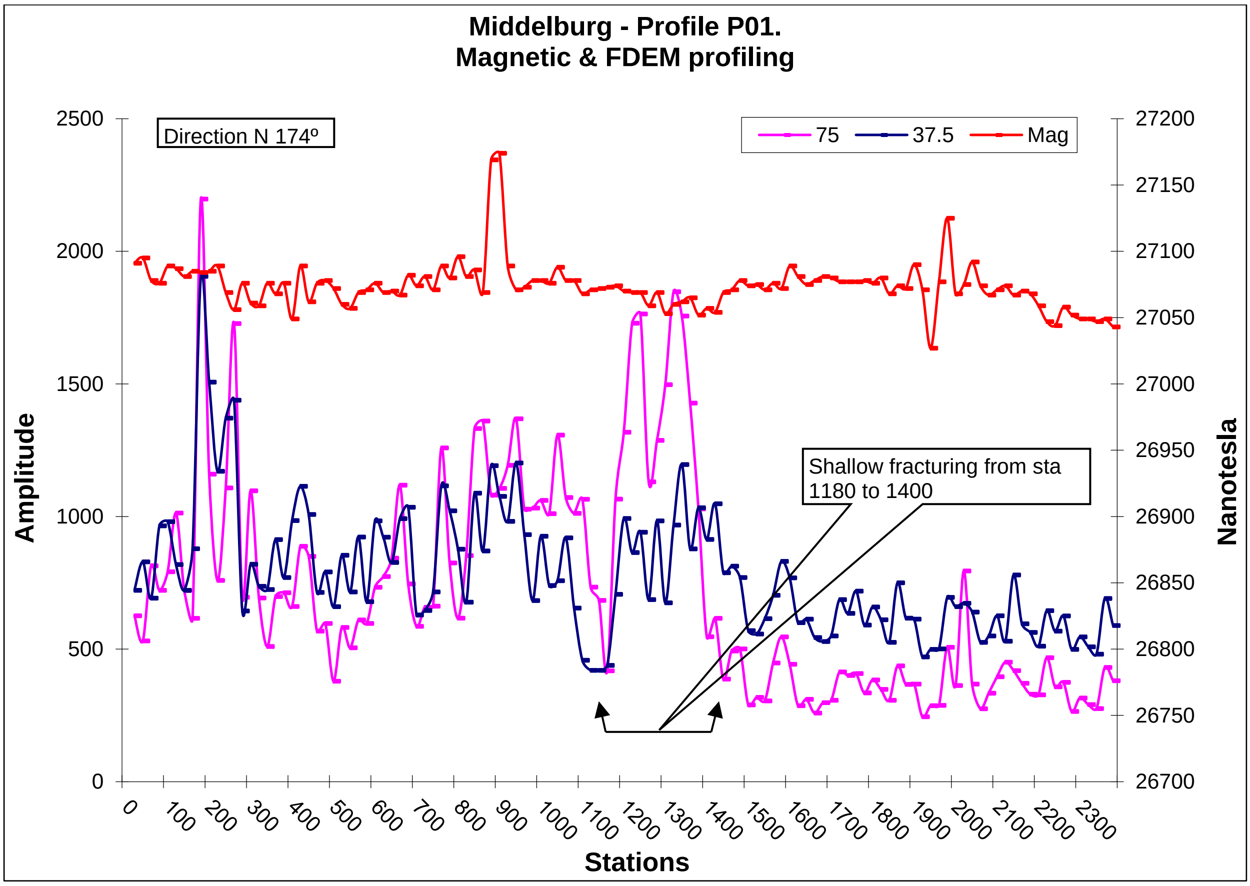

Figure 2-1 Profile P01 on Lusernvlei farm in Lusernvlei sub-catchment (Coetzer, 2008)

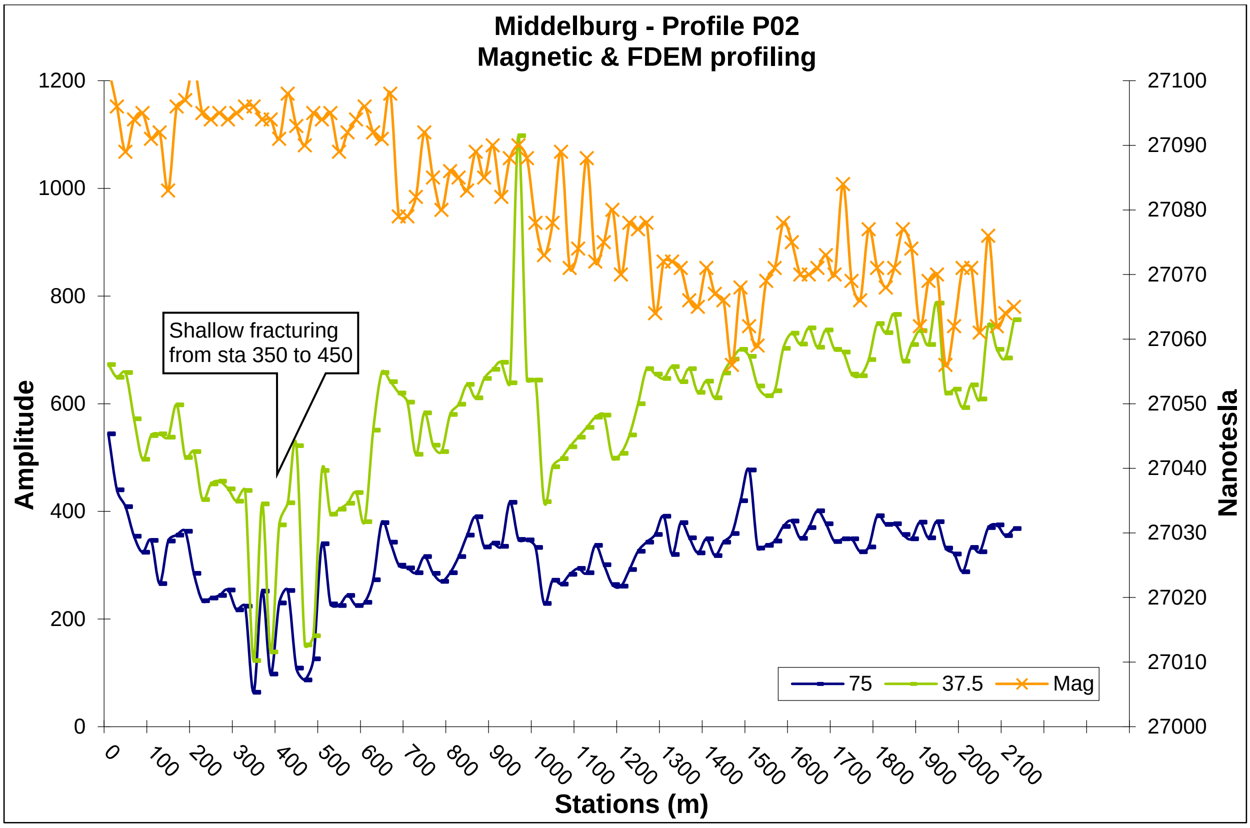

Figure 2-2 Profile P02 on Lusernvlei farm in Lusernvlei sub-catchment (Coetzer, 2008)

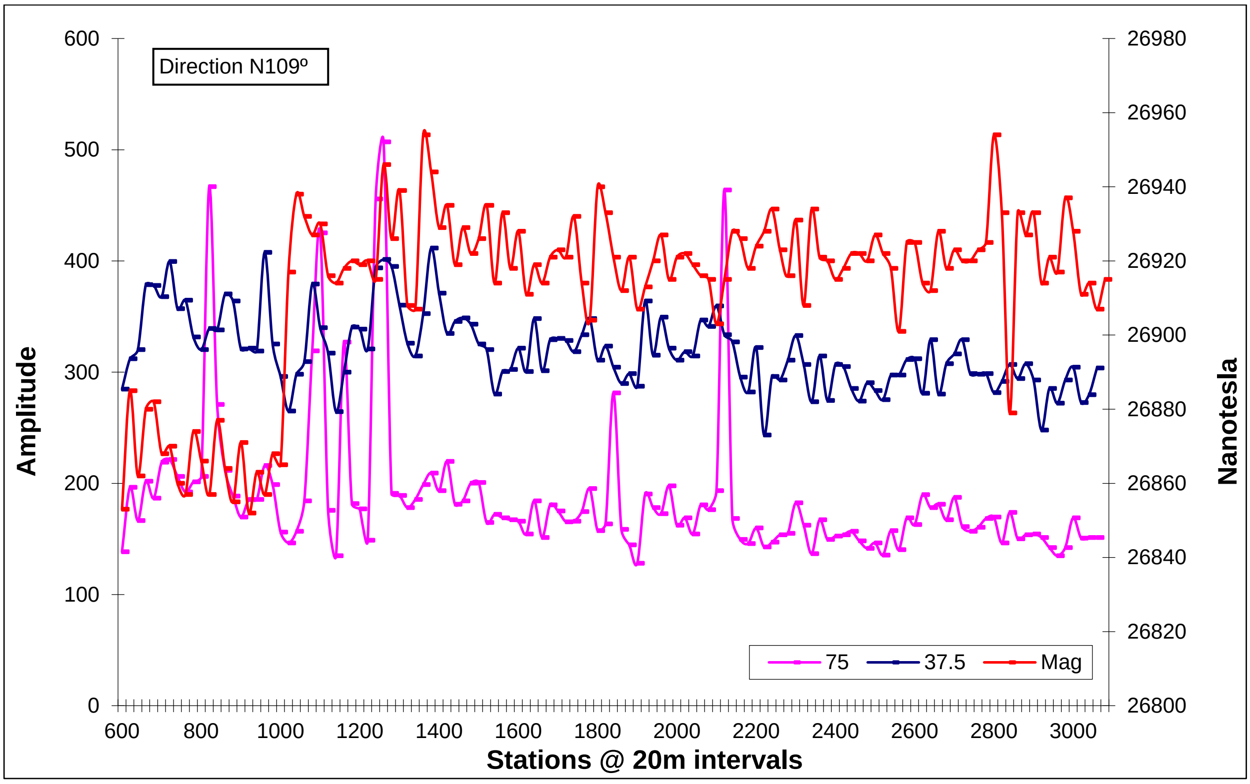

Figure 2-3 Profile P03 on the farm Platberg

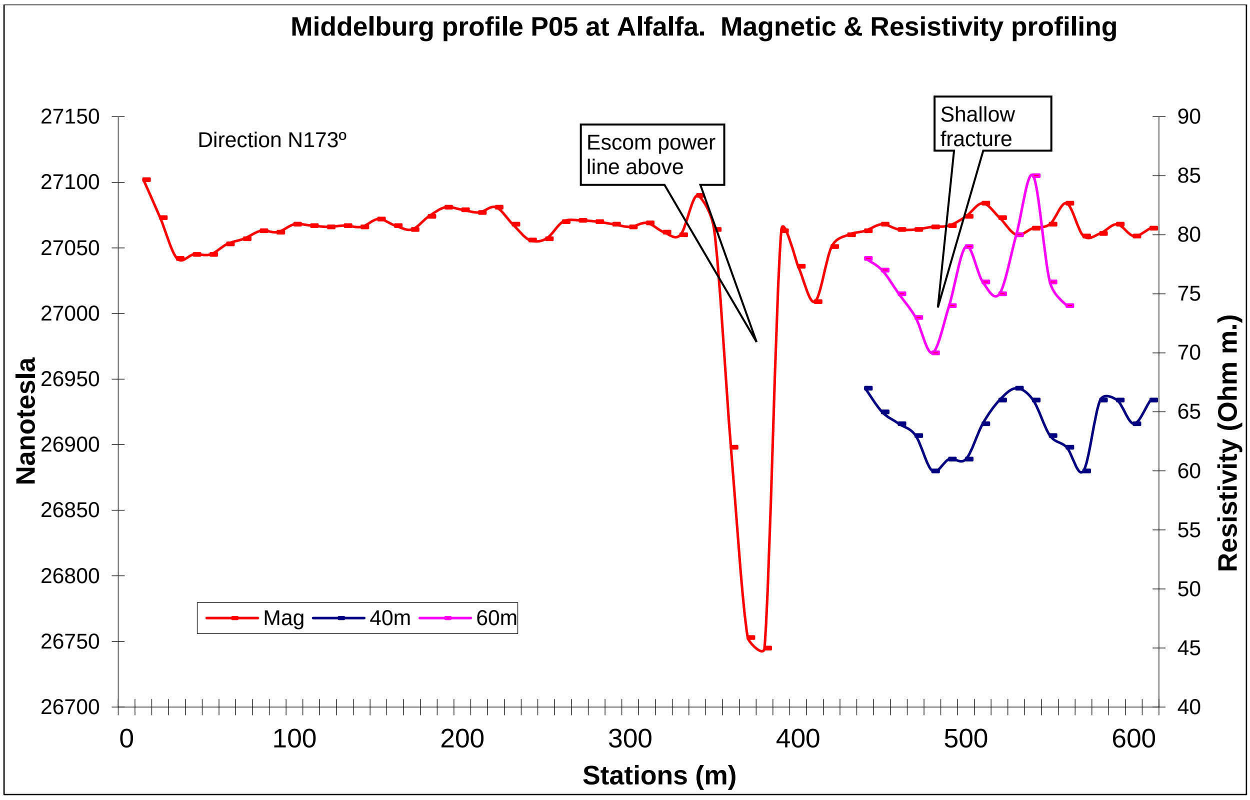

Figure 2-4 Profile P05 on Alfalfa farm in the Lusernvlei sub-catchment (Coetzer, 2008)

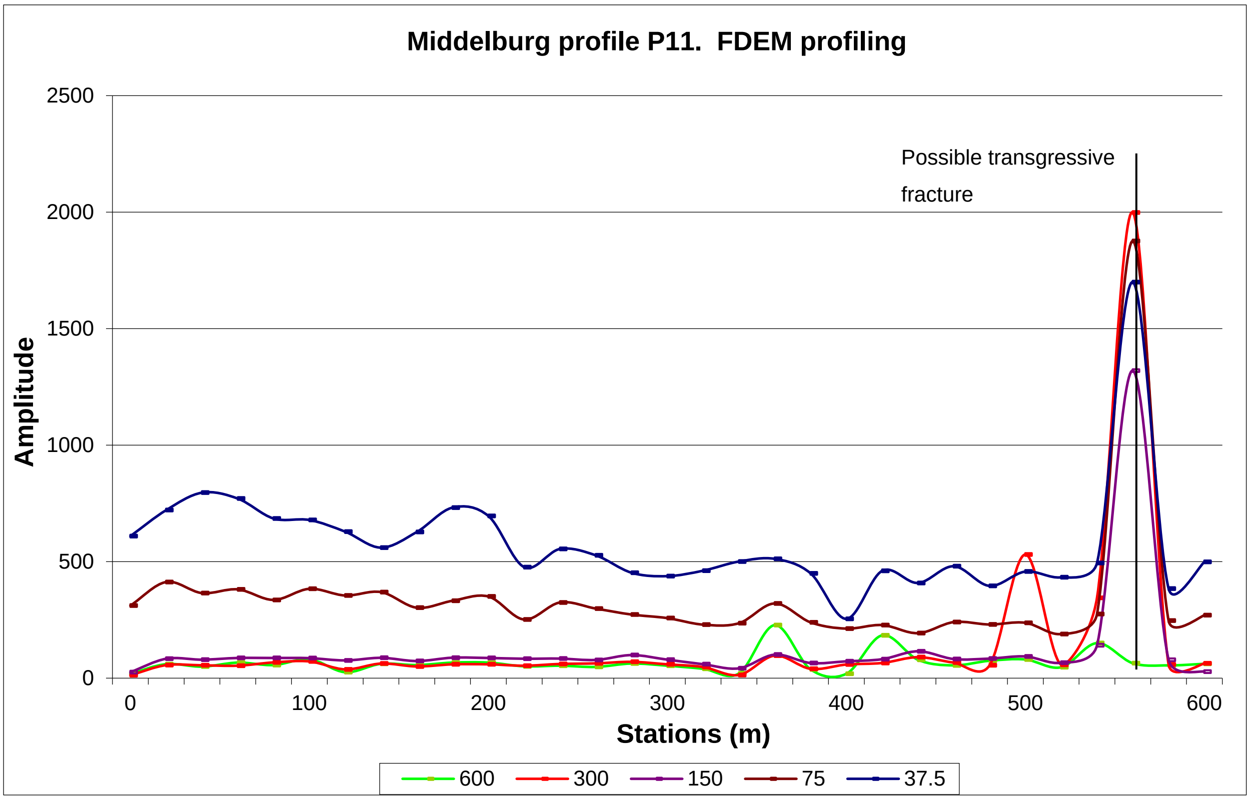

Figure 2-5 P11 parallel to Dunblane dyke to identify zones of most fracturing next to dyke

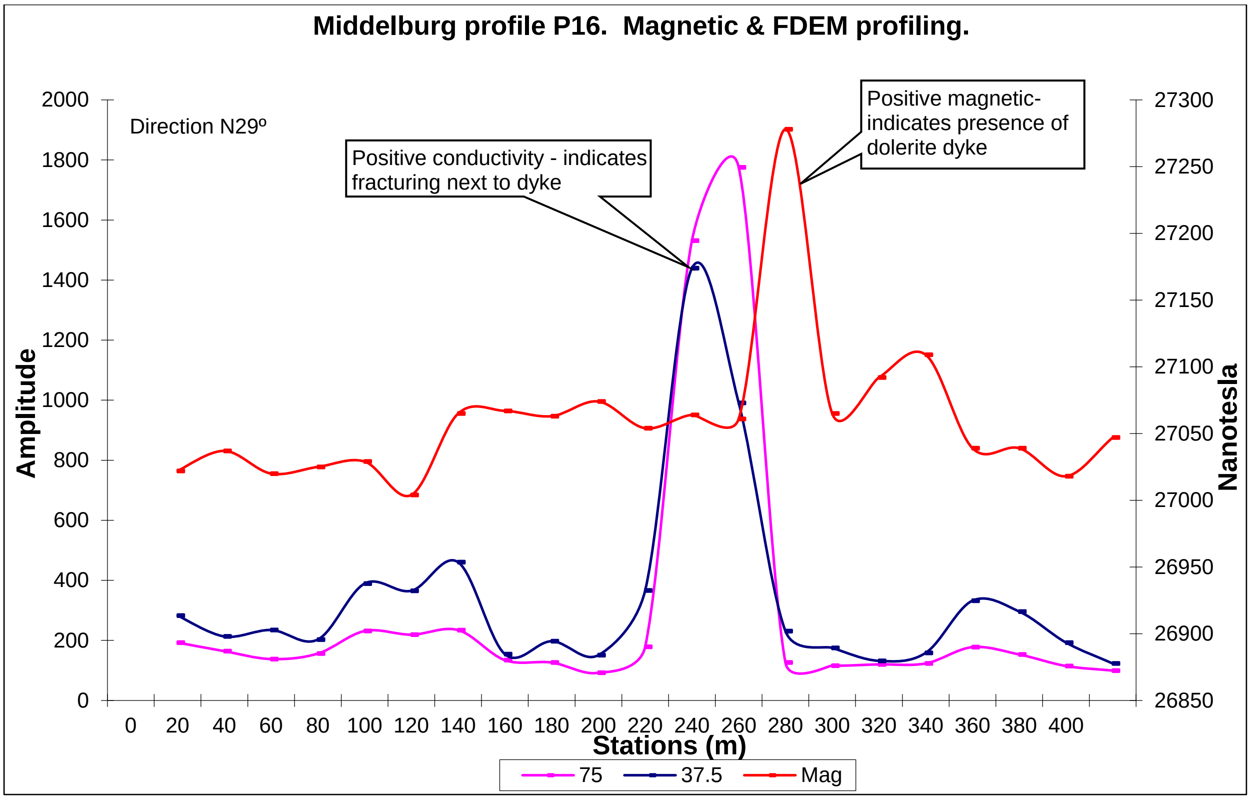

Figure 2-6 Profile P16 surveyed to detect strike and geometry of Dunblane dyke under alluvium in Municipal sub-catchment (Coetzer, 2008)

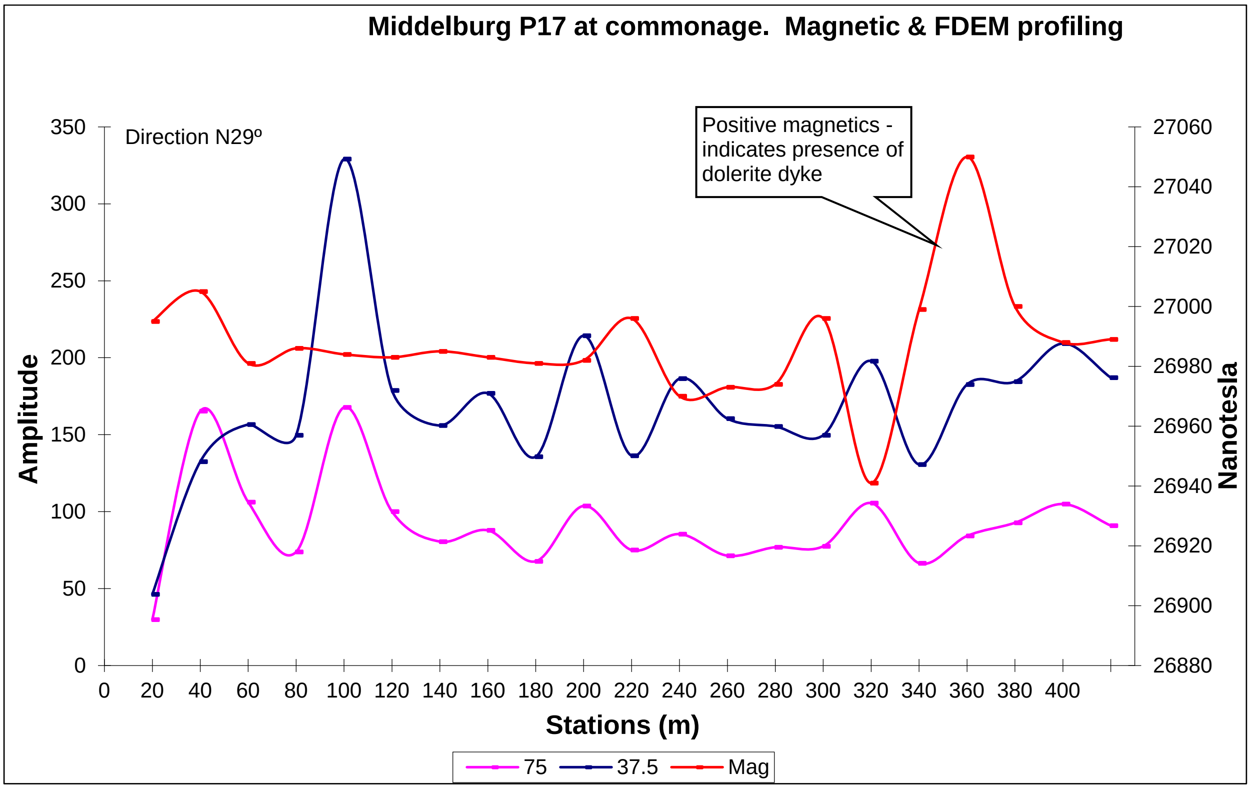

Figure 2-7 Profile P17 at Middelburg allotment area to determine orientation of Dunblane dyke (Coetzer, 2008)

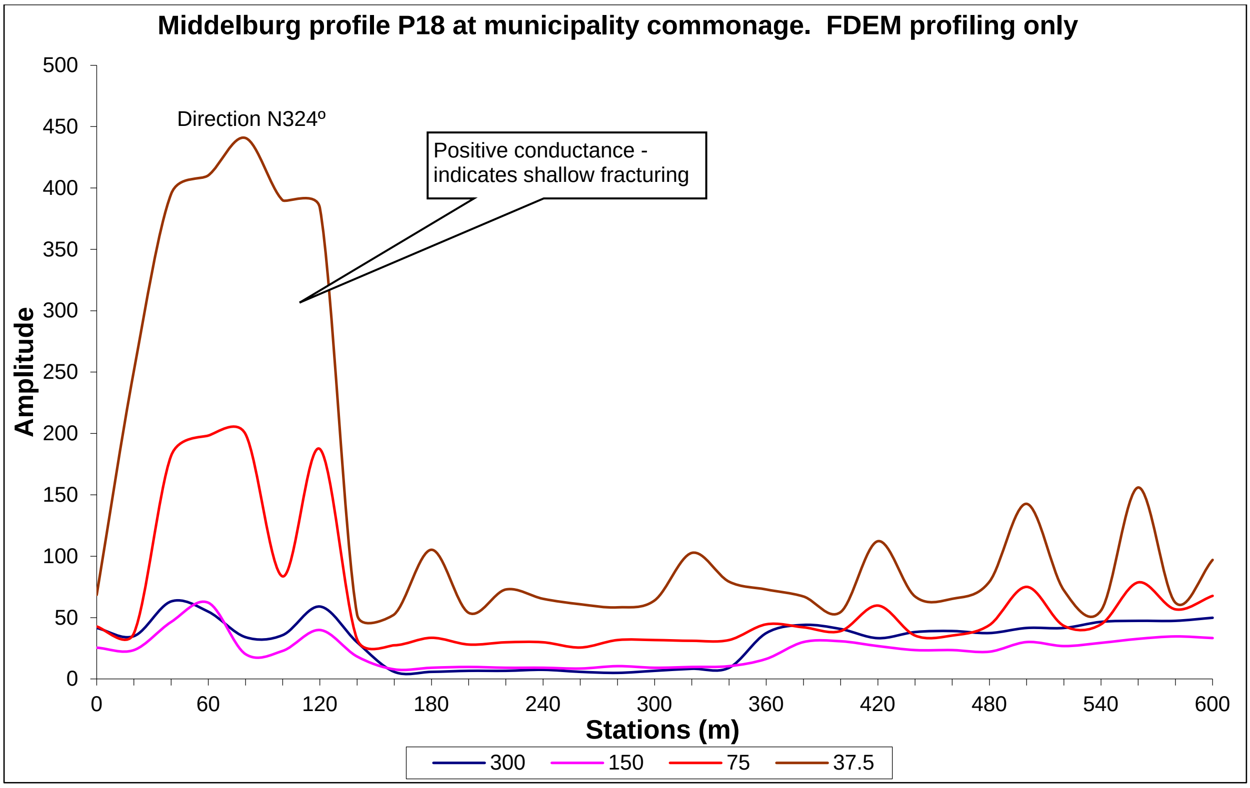

Figure 2-8 Profile P18 on Municipal allotment area in the Municipal sub-catchment (Coetzer, 2008)

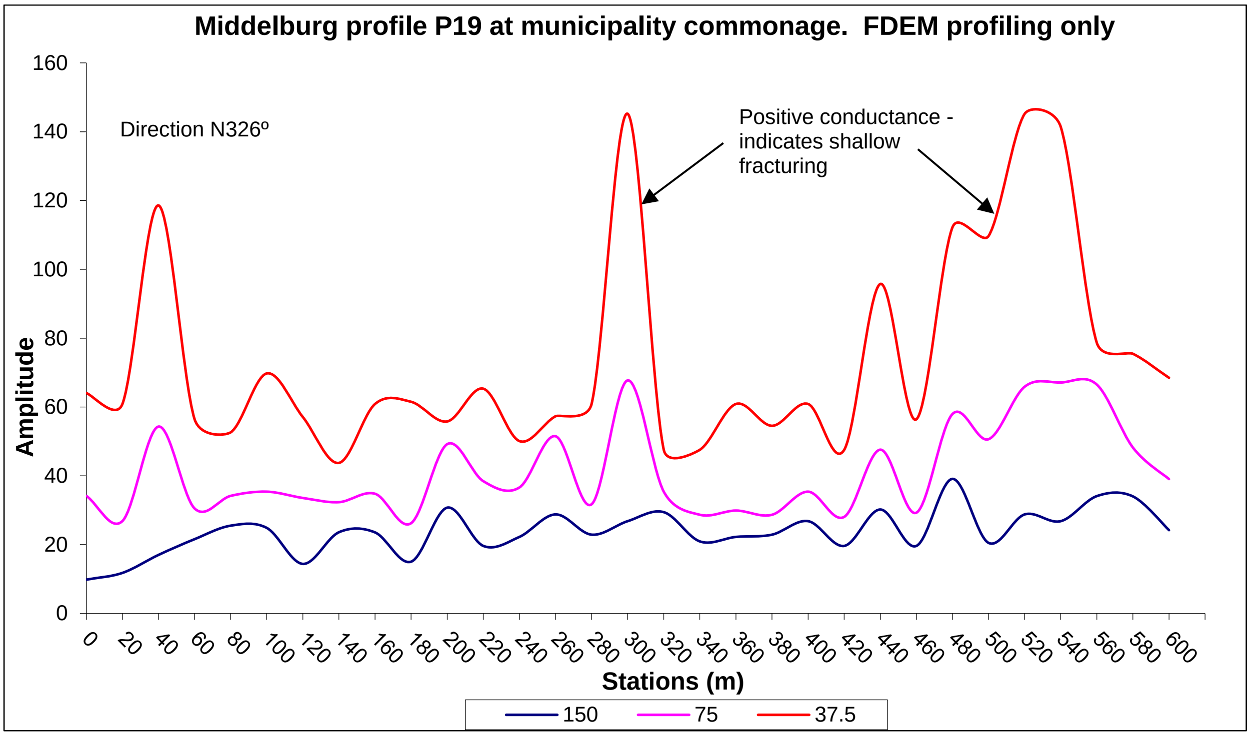

Figure 2-9 Profile P19 to investigate extension and strike of the Dunblane dyke in area (Coetzer, 2008)

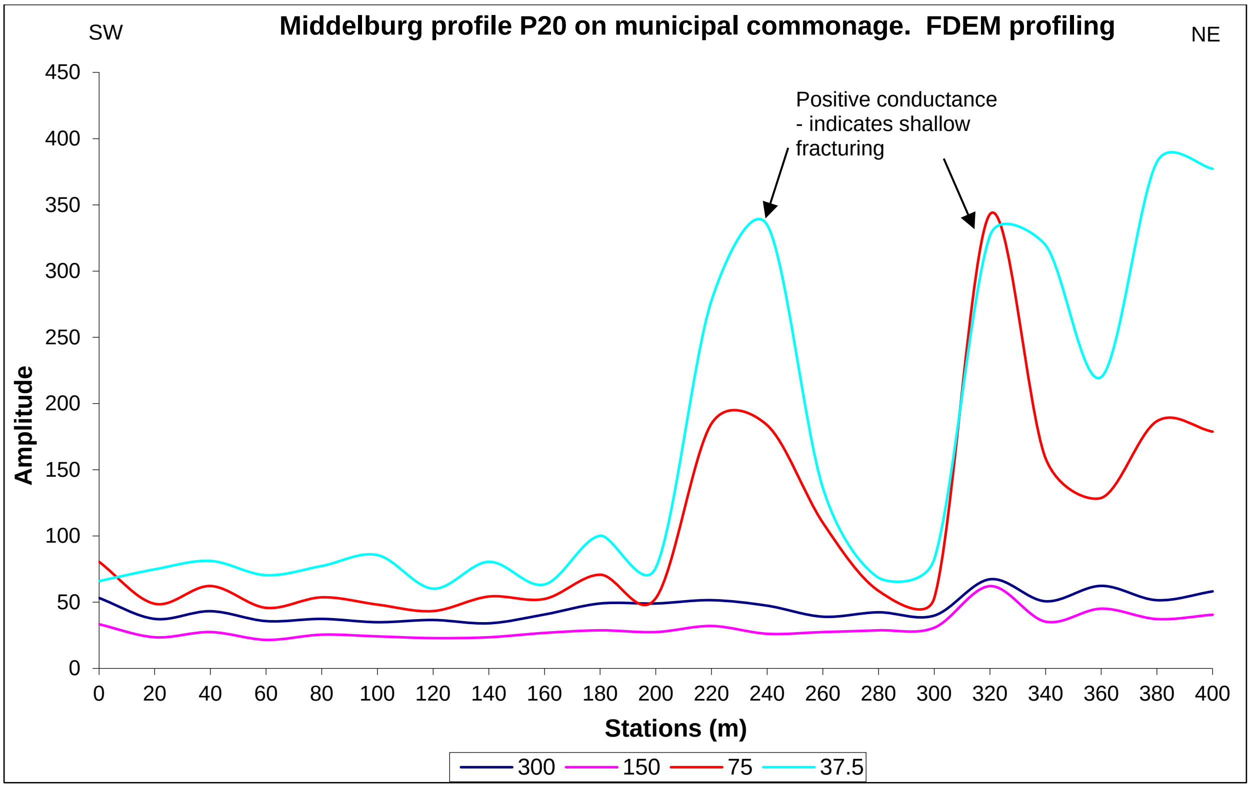

Figure 2-10 **Profile P20 on Municipal allotment area in Municipal sub-catchment (Coetzer, 2008)**

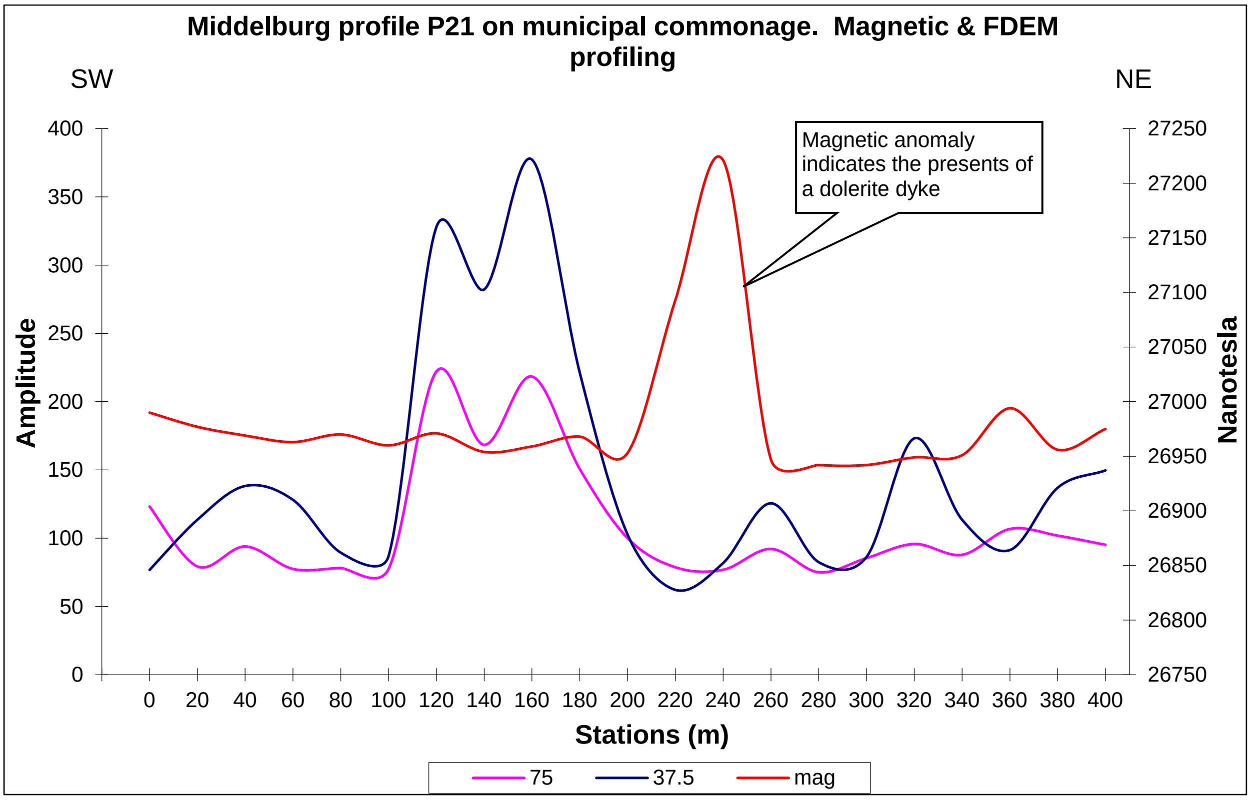

Figure 2-11 **Profile P21 on Municipal allotment area in the municipal sub-catchment (Coetzer, 2008)**

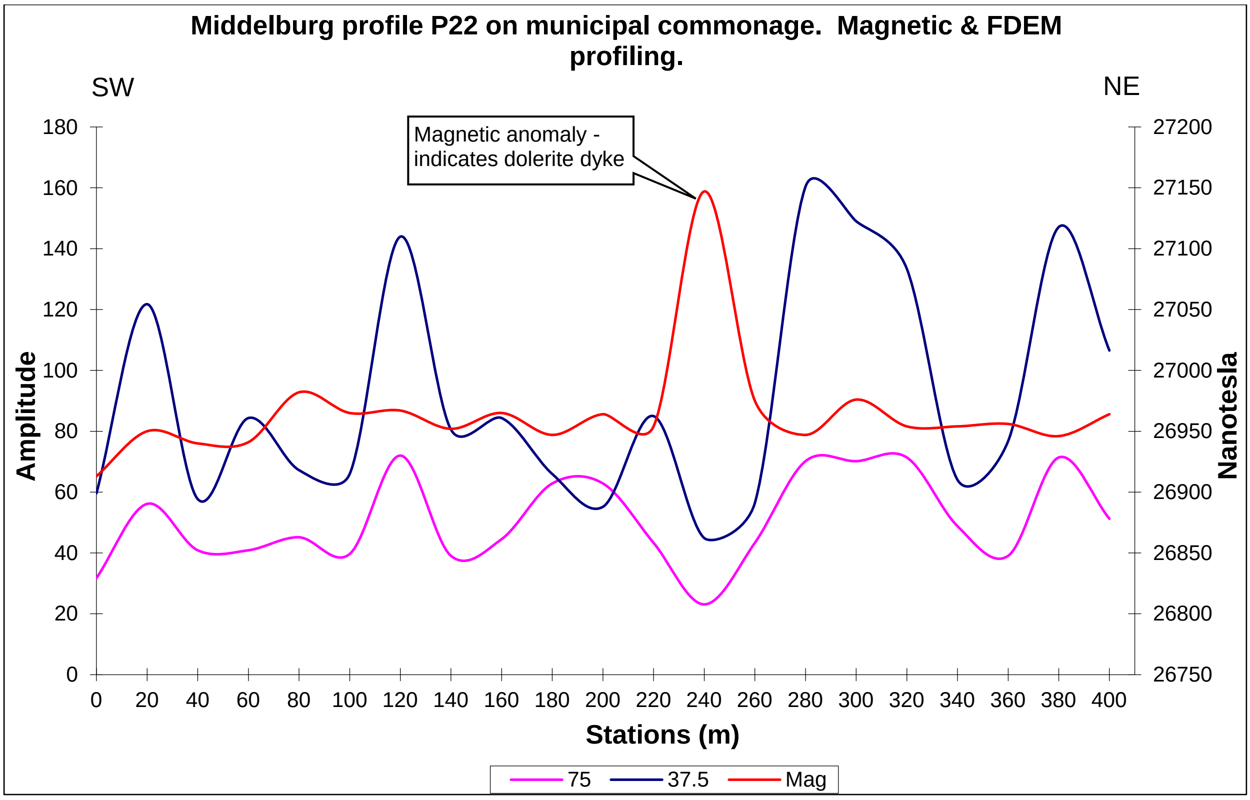

Figure 2-12 Profile P22 on Municipal allotment area in the municipal sub-catchment (Coetzer, 2008)

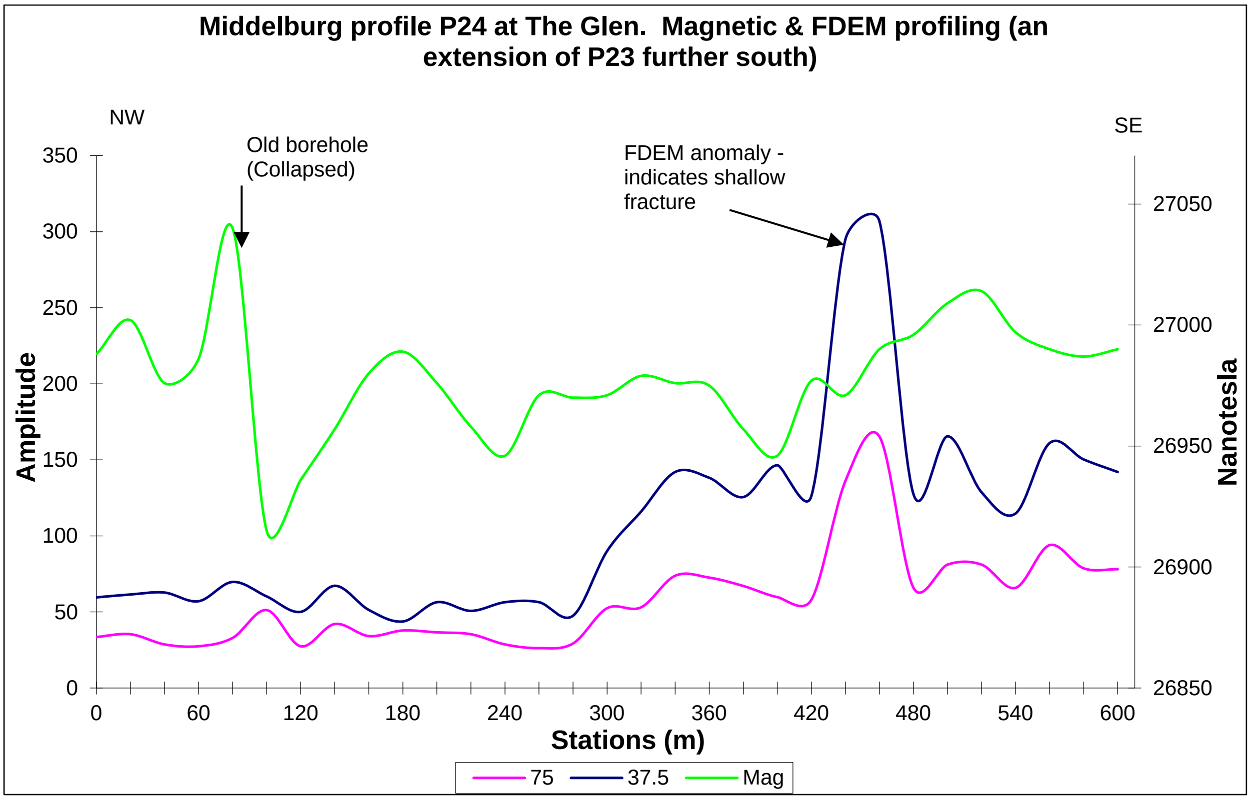

Figure 2-13 Profile P23 an extension of P23 further south through Jones poort, The Glen (Coetzer, 2008)

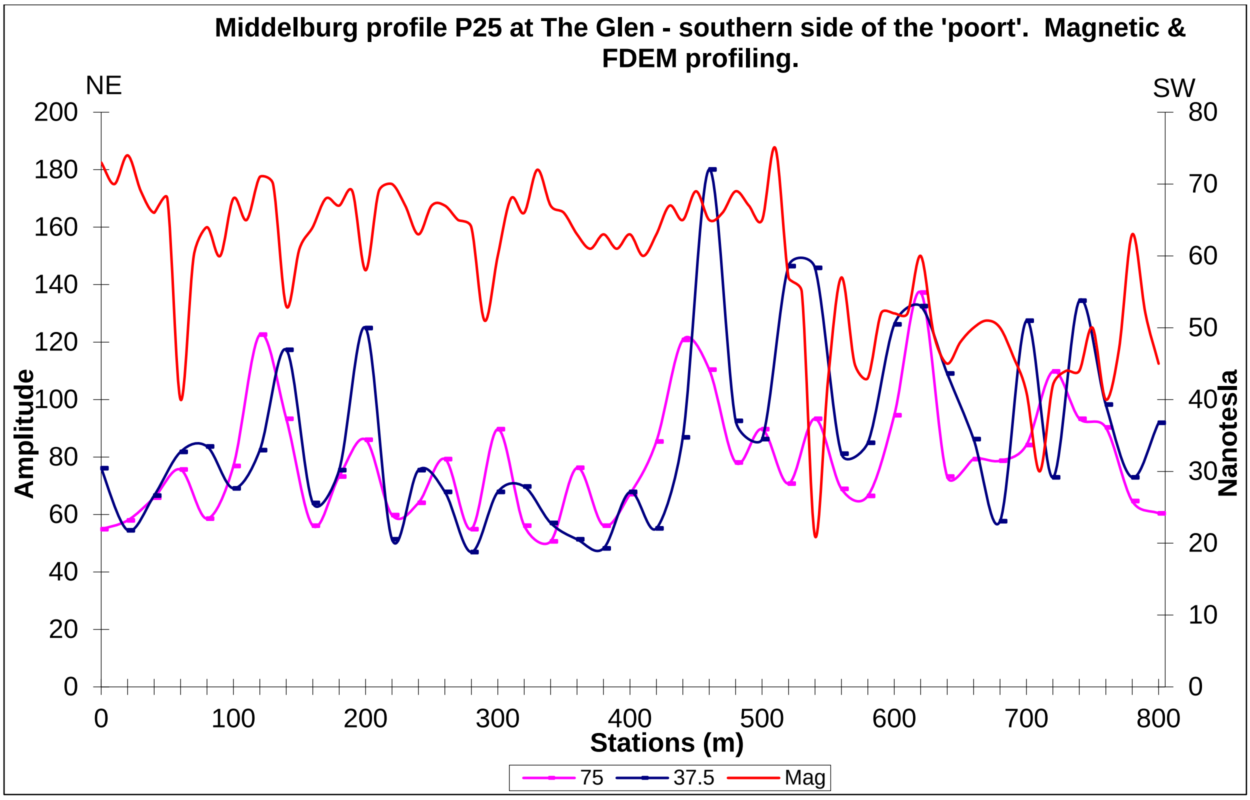

Figure 2-14 Profile P25 NE-SW just south of Jones poort, The Glen (Coetzer, 2008)

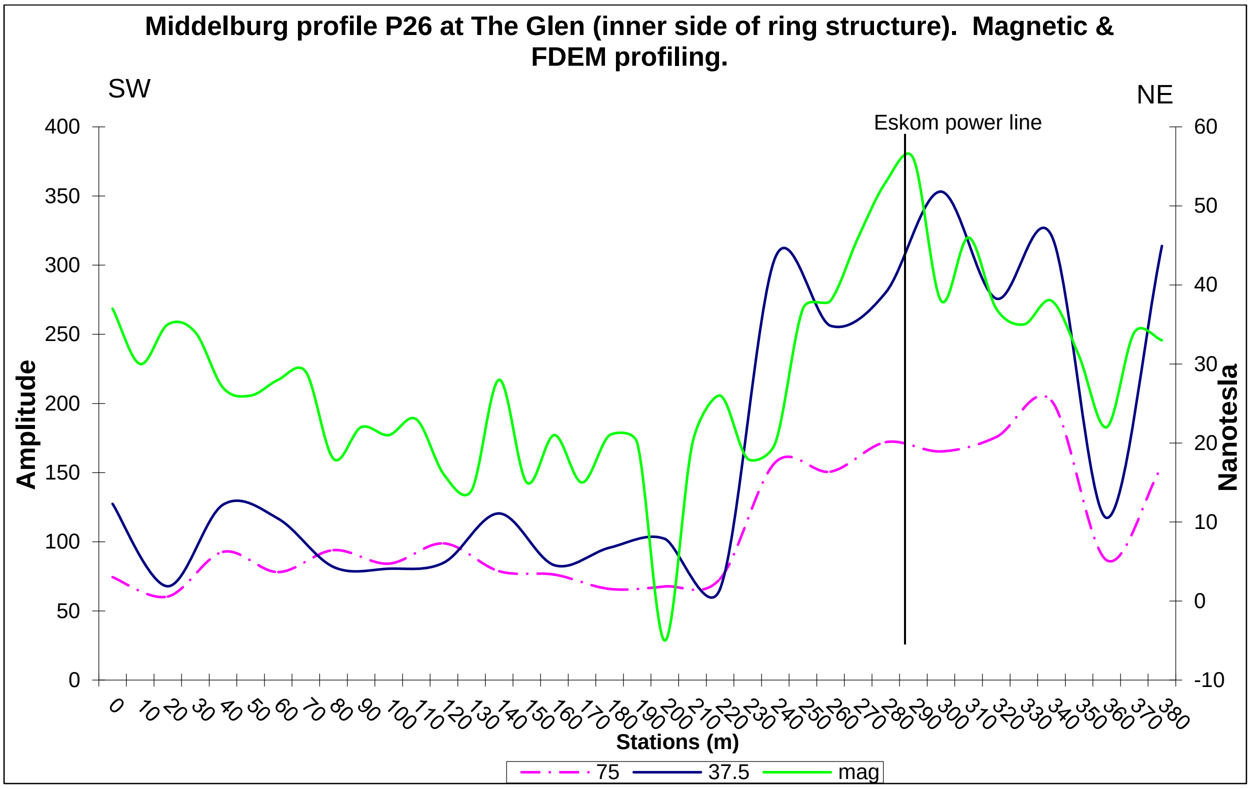

Figure 2-15 Profile P26 on the Glen farm on inner side of ring structure (Coetzer, 2008)

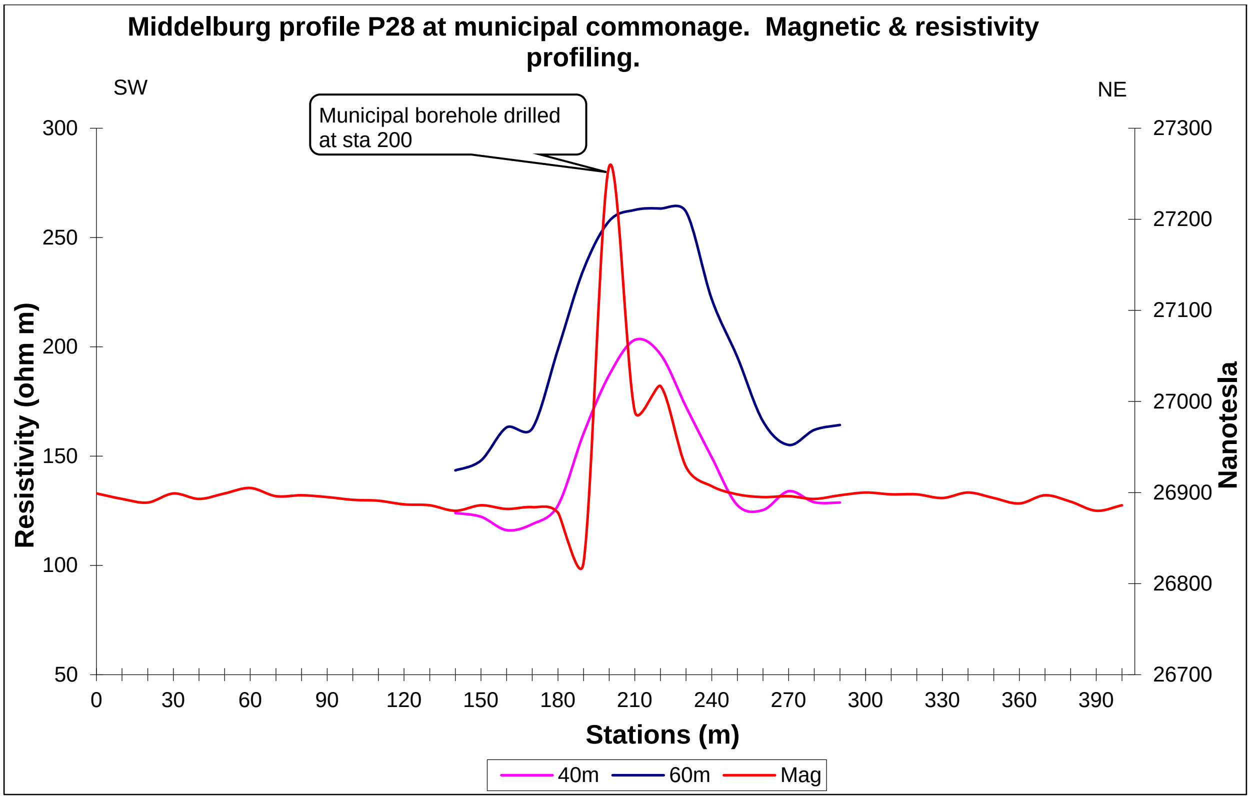

Figure 2-16 Profile P28 for verification of existing municipal borehole information (Coetzer, 2008)

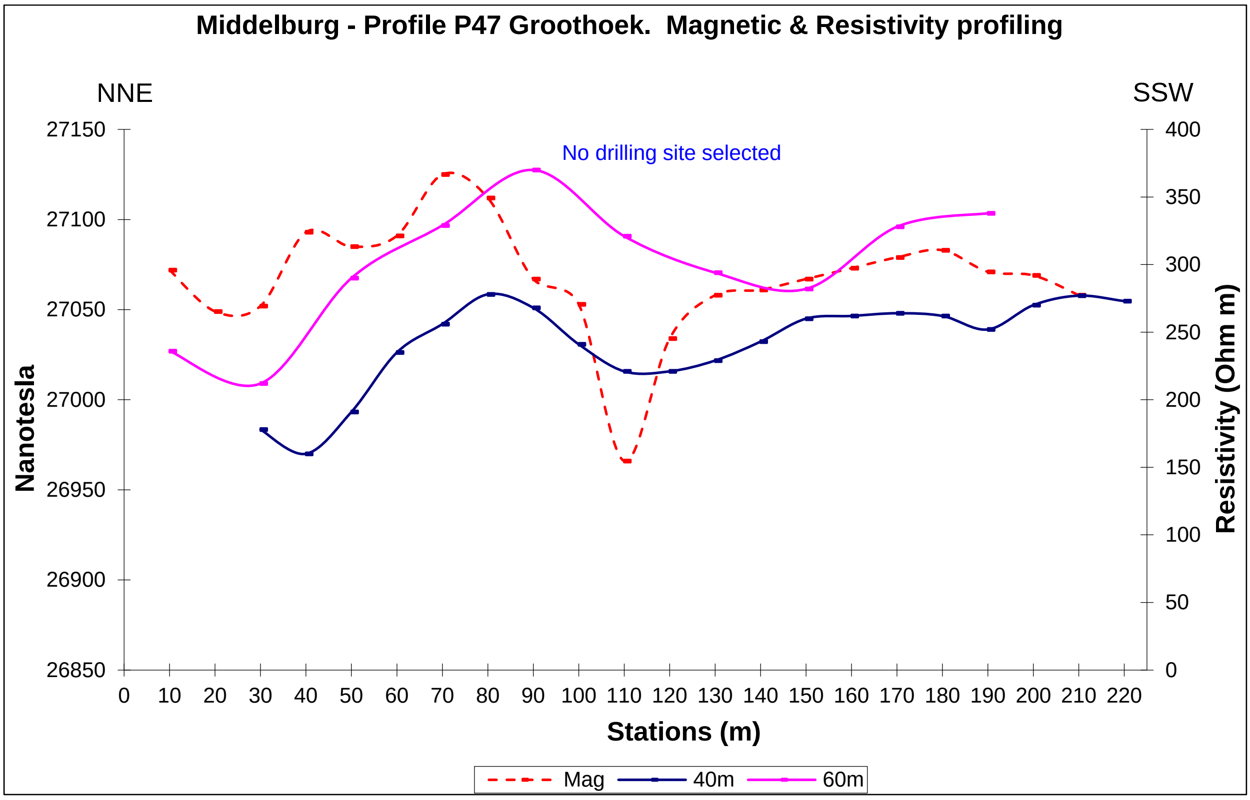

Figure 2-17 Profile P47 on Groothoek farm in The Glen sub-catchment (Coetzer, 2008)

3 APPENDIX C: EXPLORATION BOREHOLE LOGS

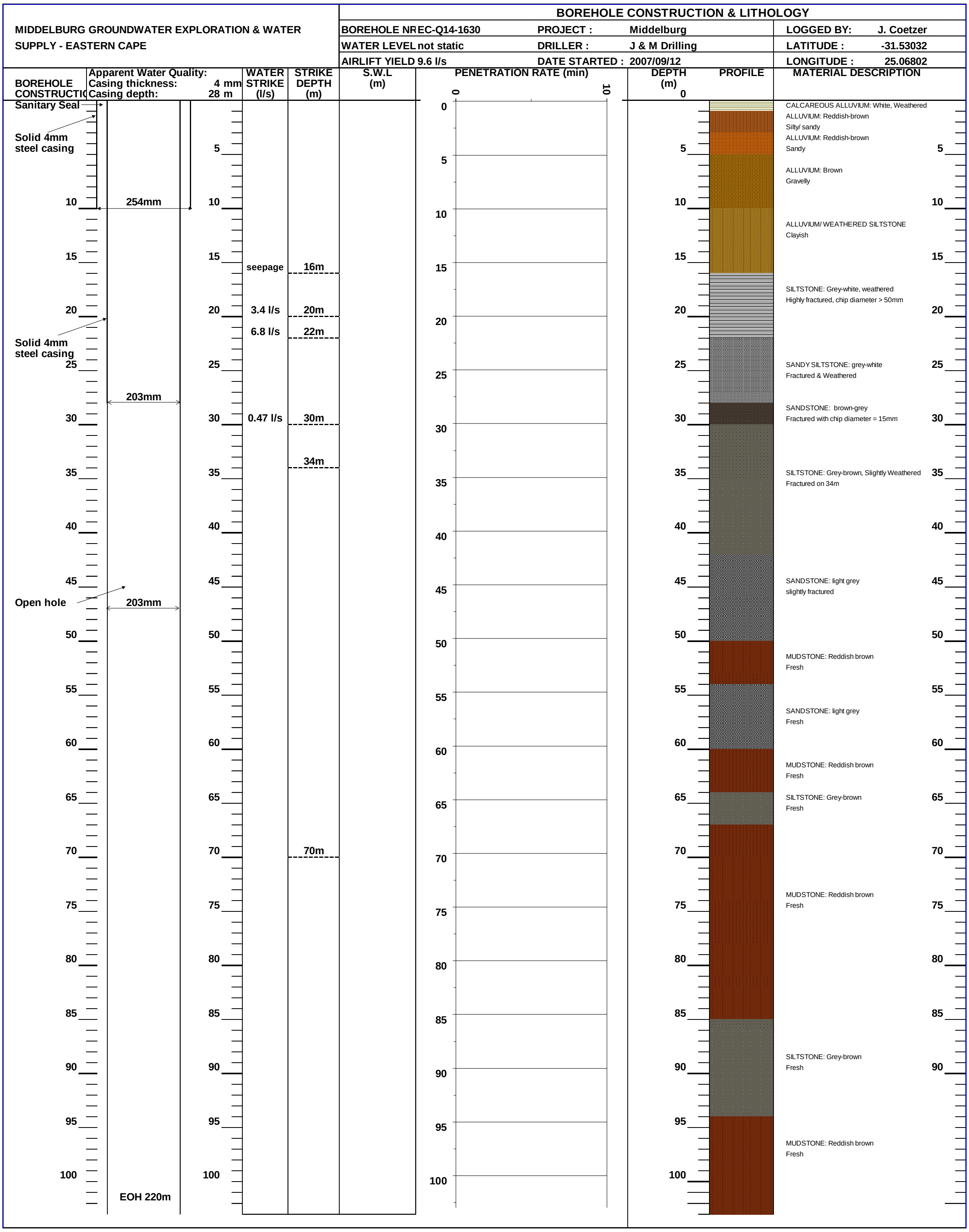

Figure 3-1: Borehole log EC-Q14-1630 part 1 of 2

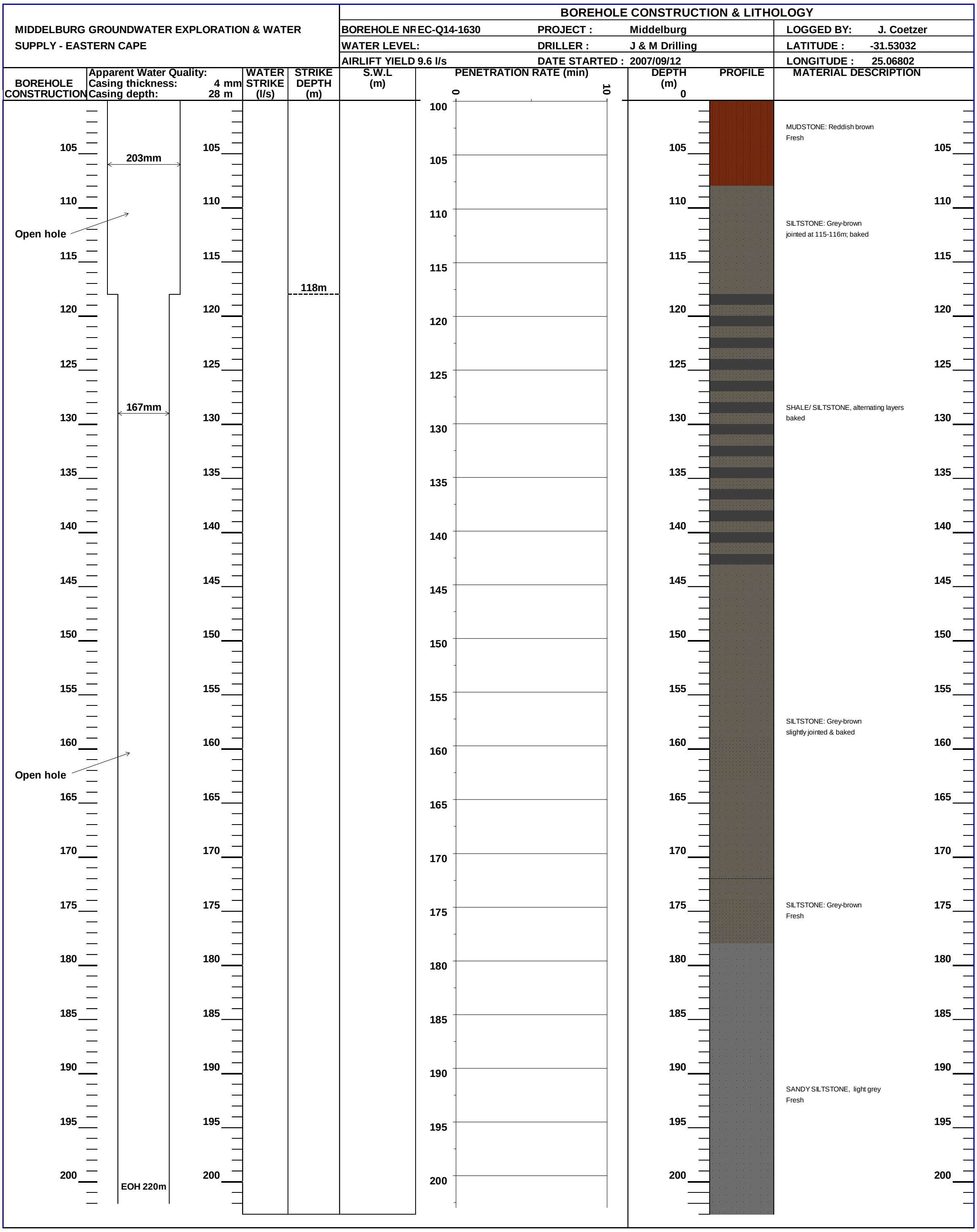

Figure 3-2: Borehole log EC-Q14-1630 part 2 of 3

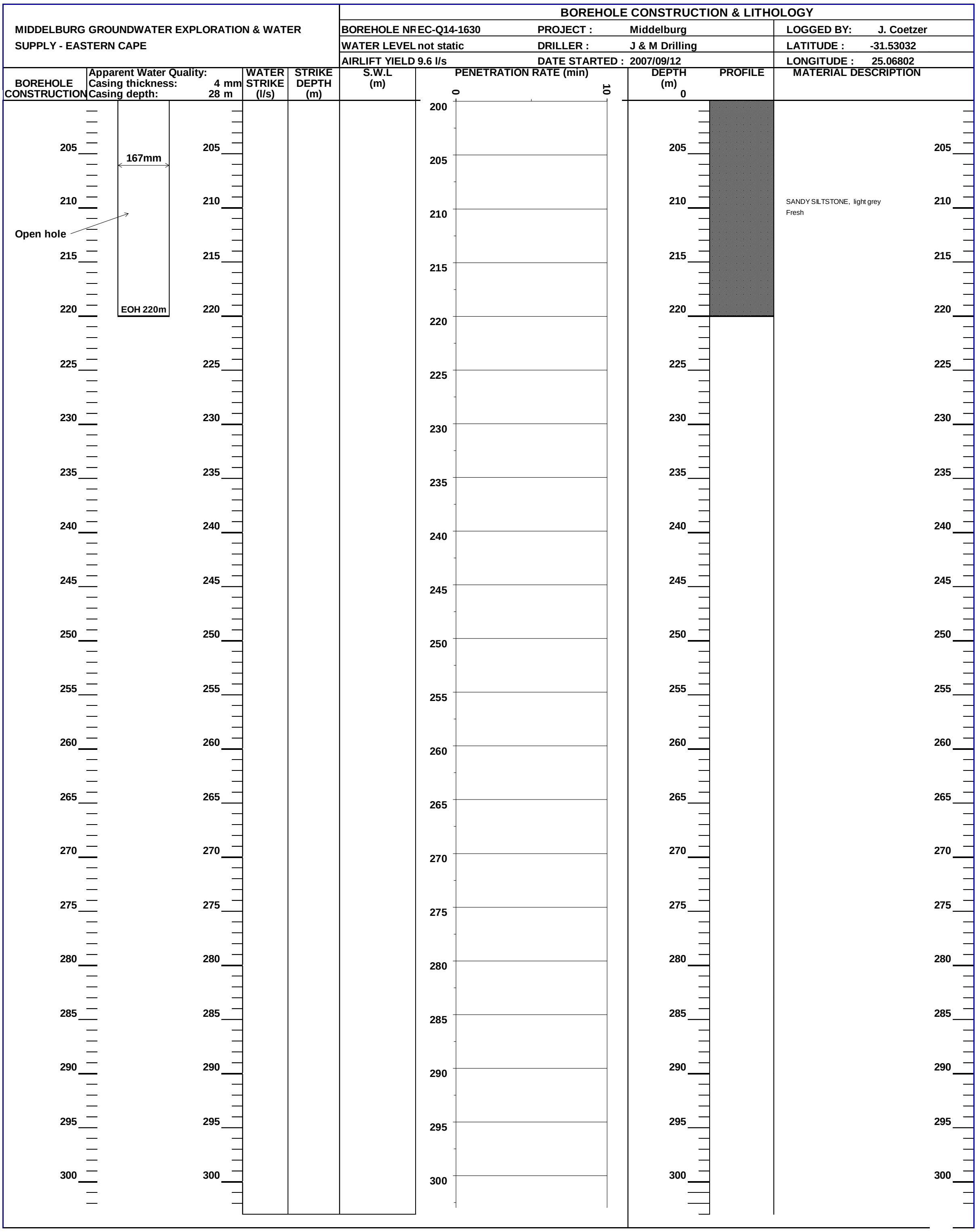

Figure 3-3: Borehole log EC-Q14-1630 part 3 of 3

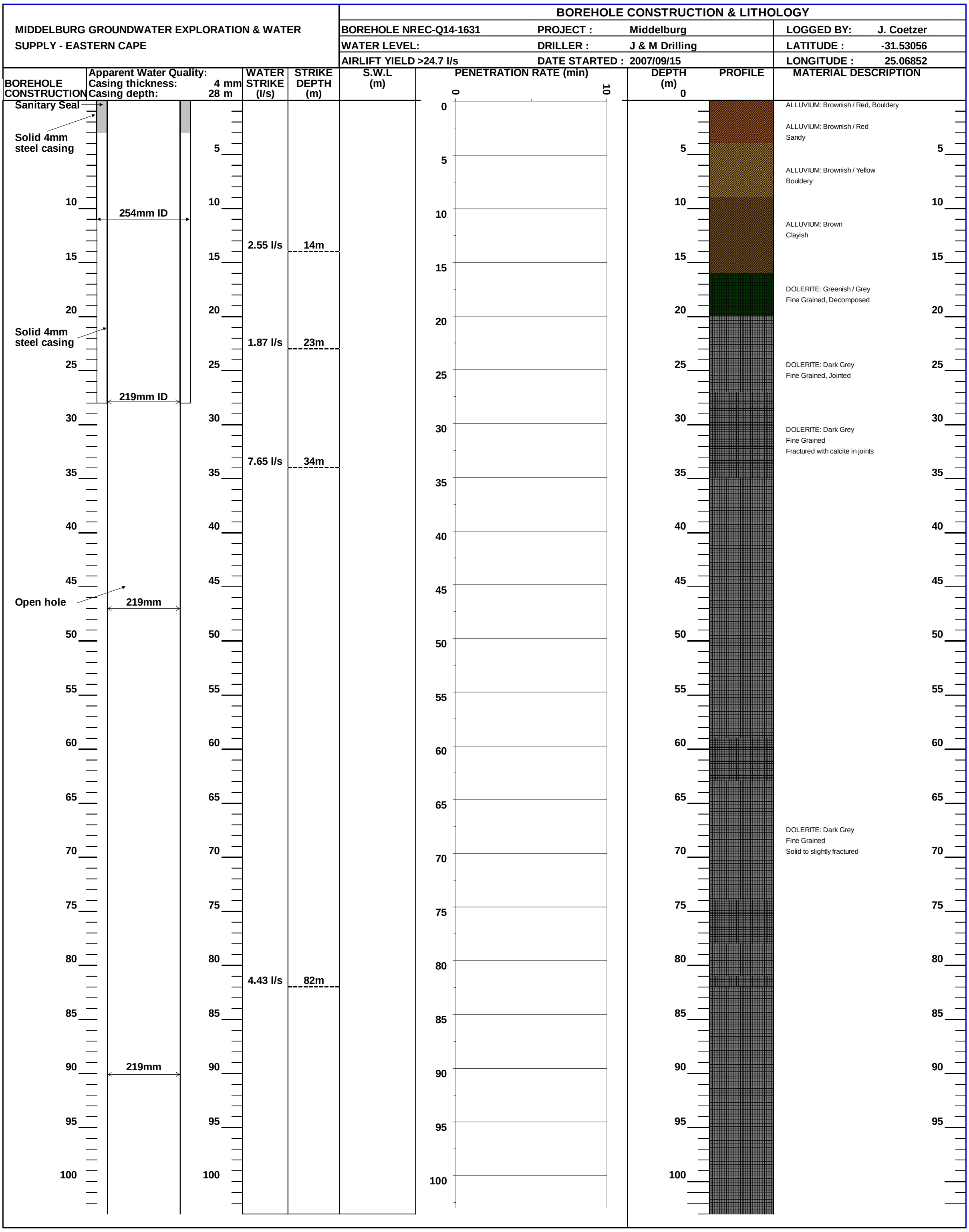

Figure 3-4: Borehole log EC-Q-14-1631 part 1 of 2

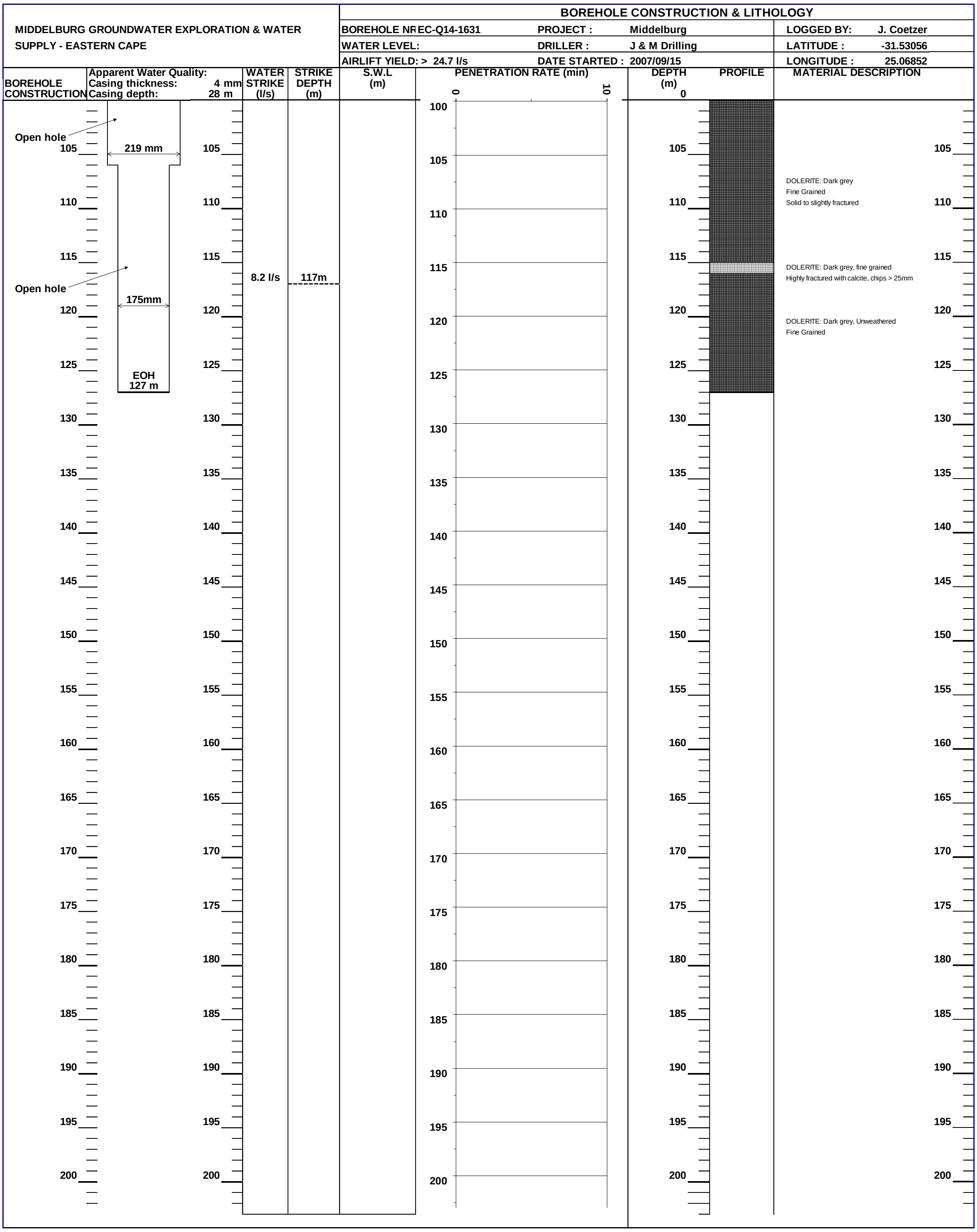

Figure 3-5: Borehole log EC-Q14-1631 part 2 of 2

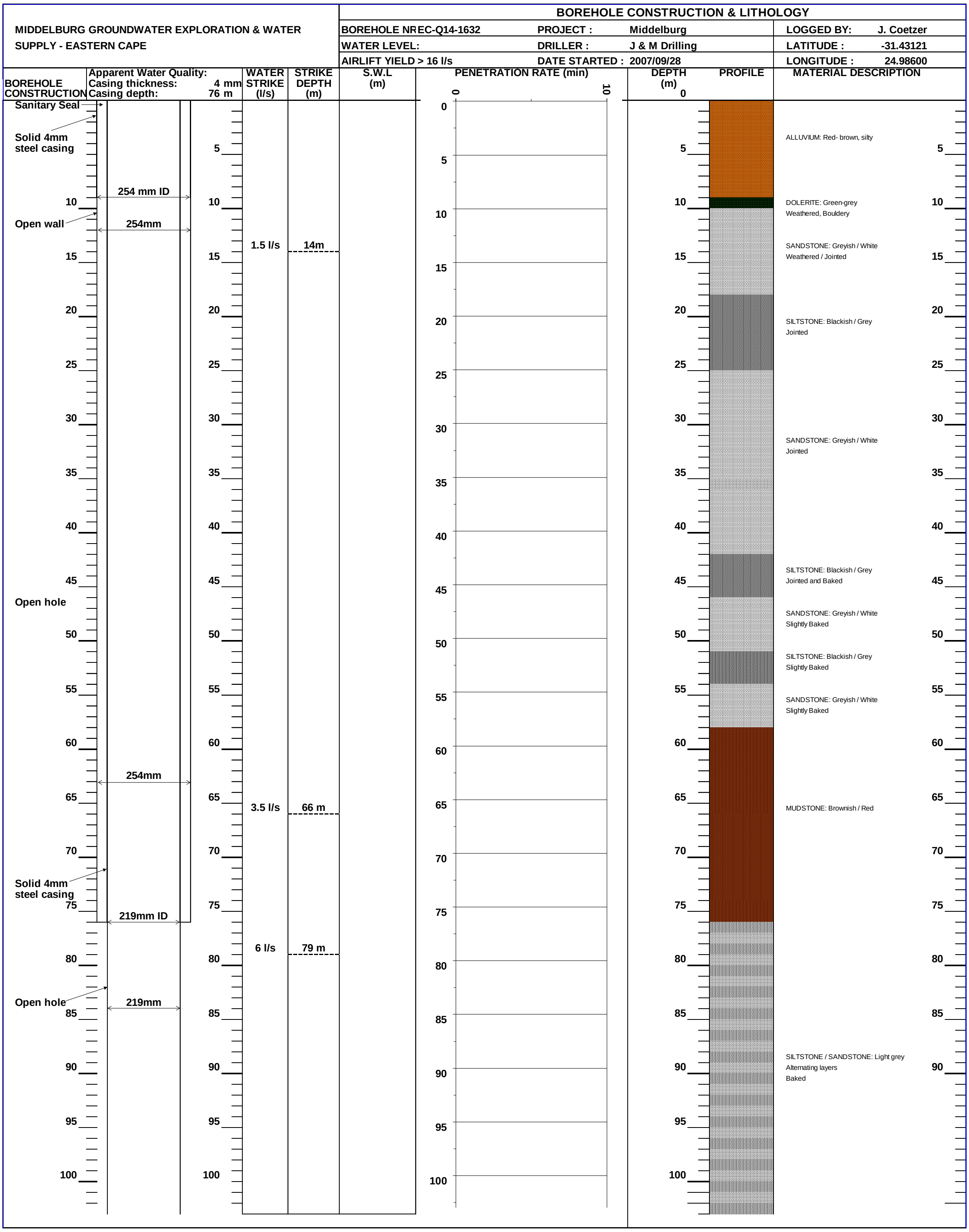

Figure 3-6: Borehole log EC-Q14-1632 part 1 of 3

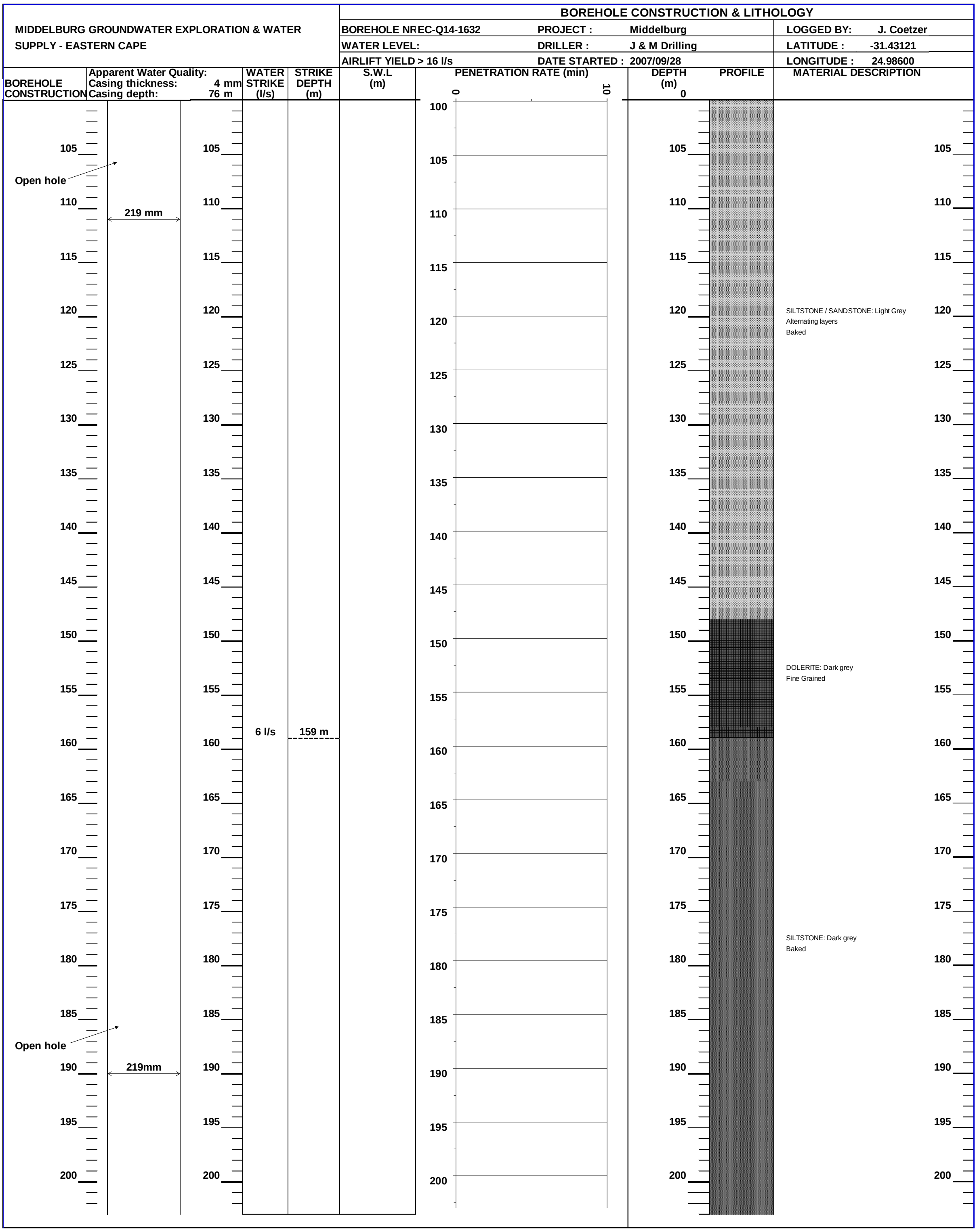

Figure 3-7: Borehole log EC-Q14-1632 part 2 of 3

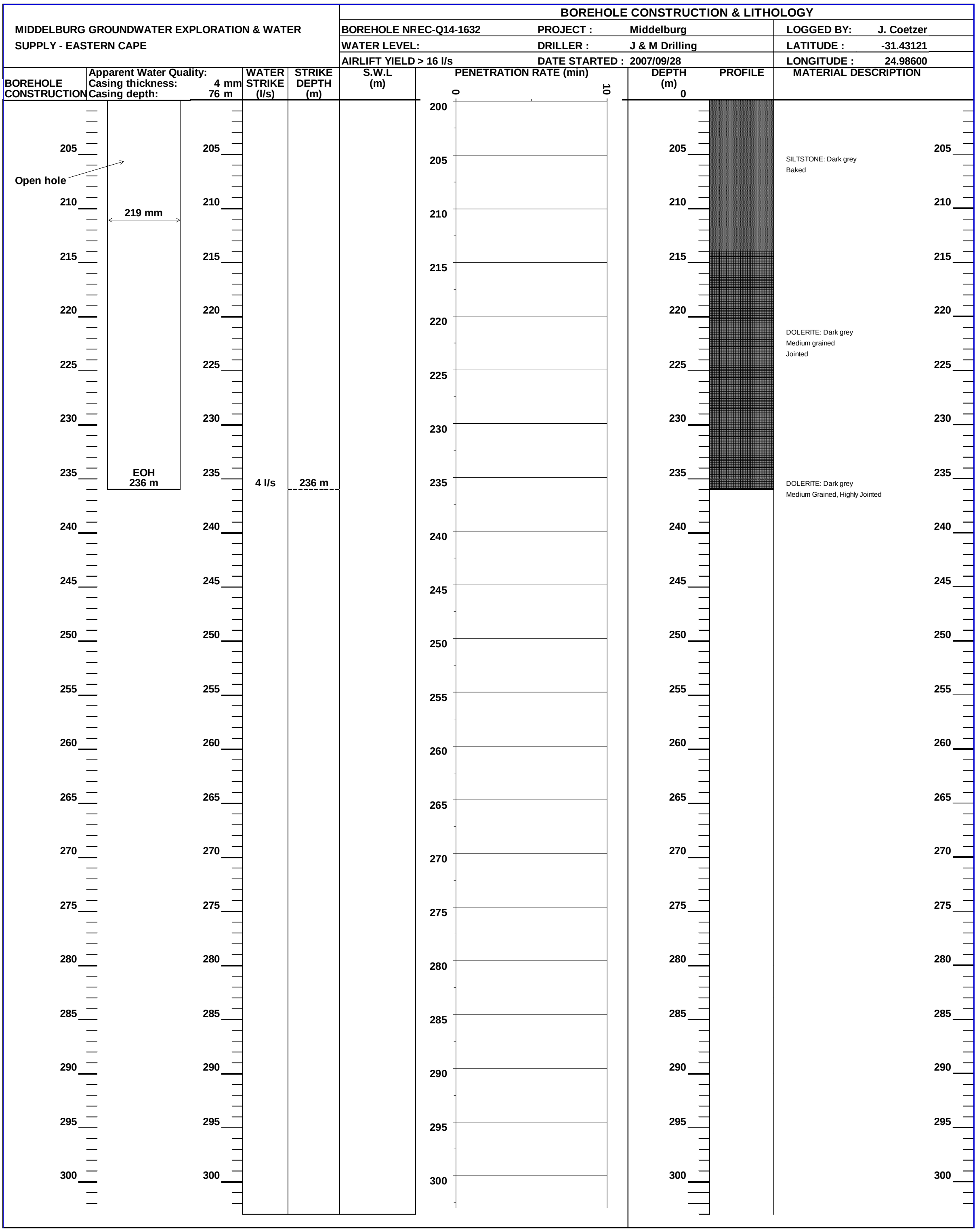

Figure 3-8: Borehole log EC-Q14-1632 part 3 of 3

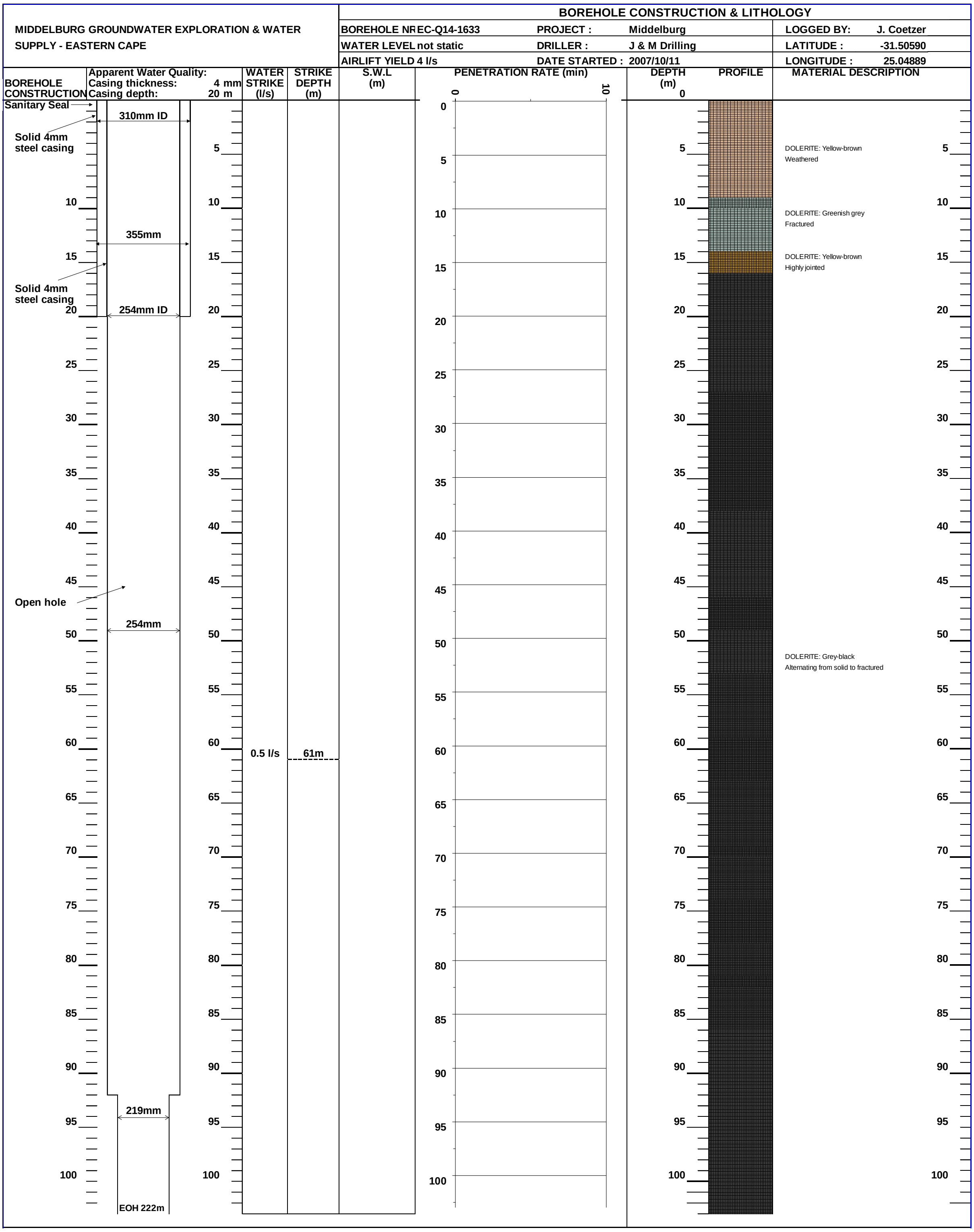

Figure 3-9: Borehole log EC-Q14-1633 part 1 of 3

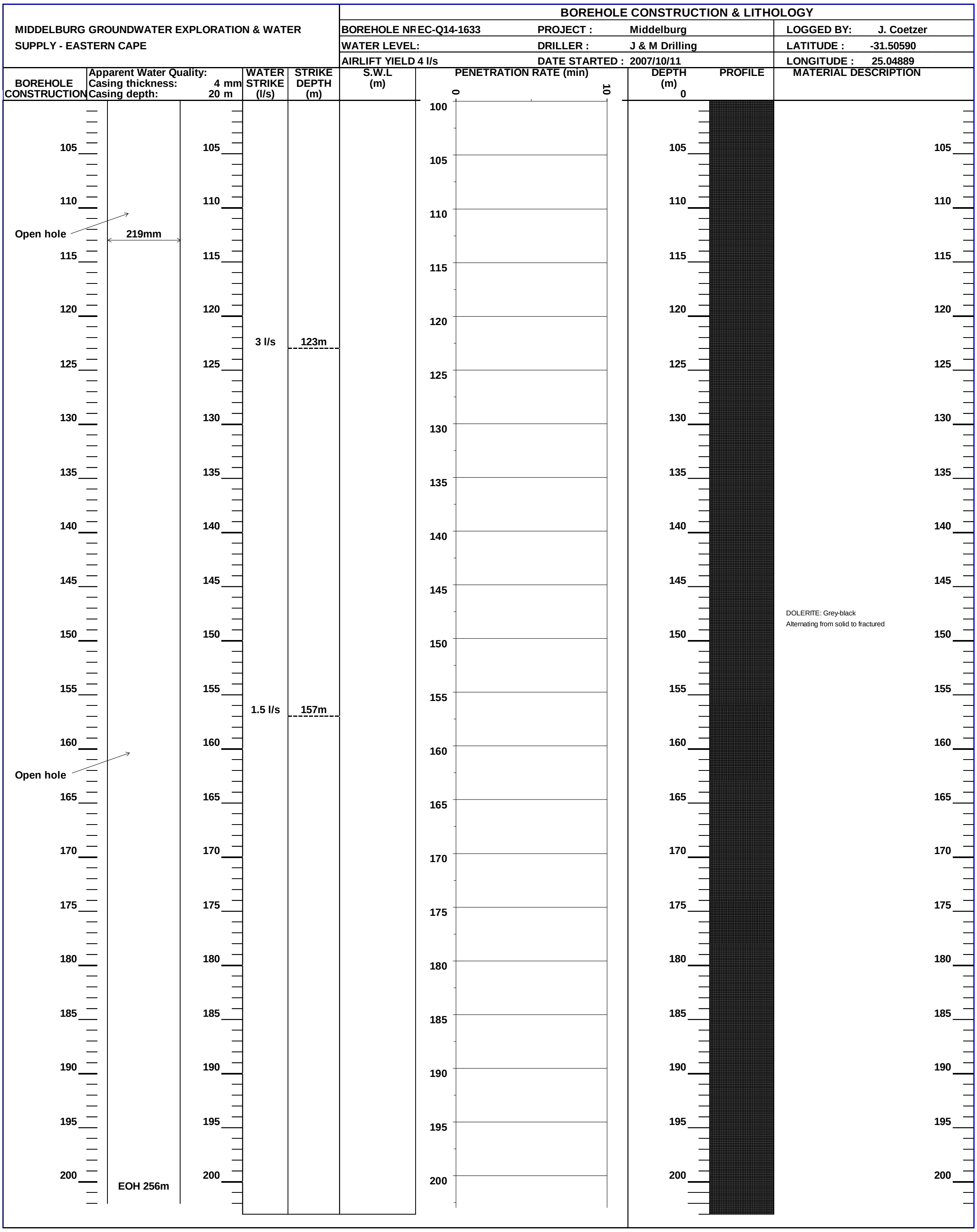

Figure 3-10: Borehole log EC-Q14-1633 part 2 of 3

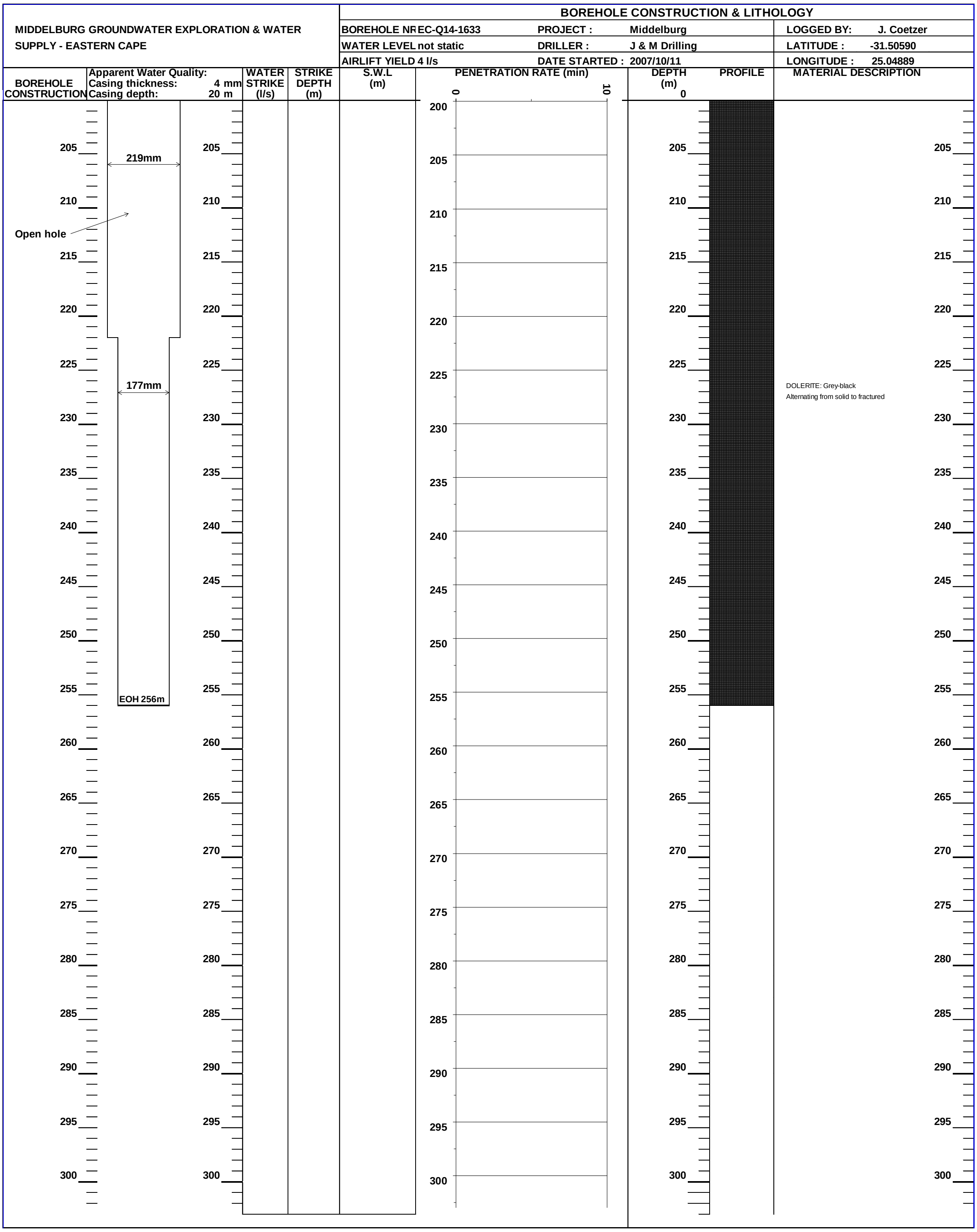

Figure 3-11: Borehole log EC-Q14-1633 part 3 of 3

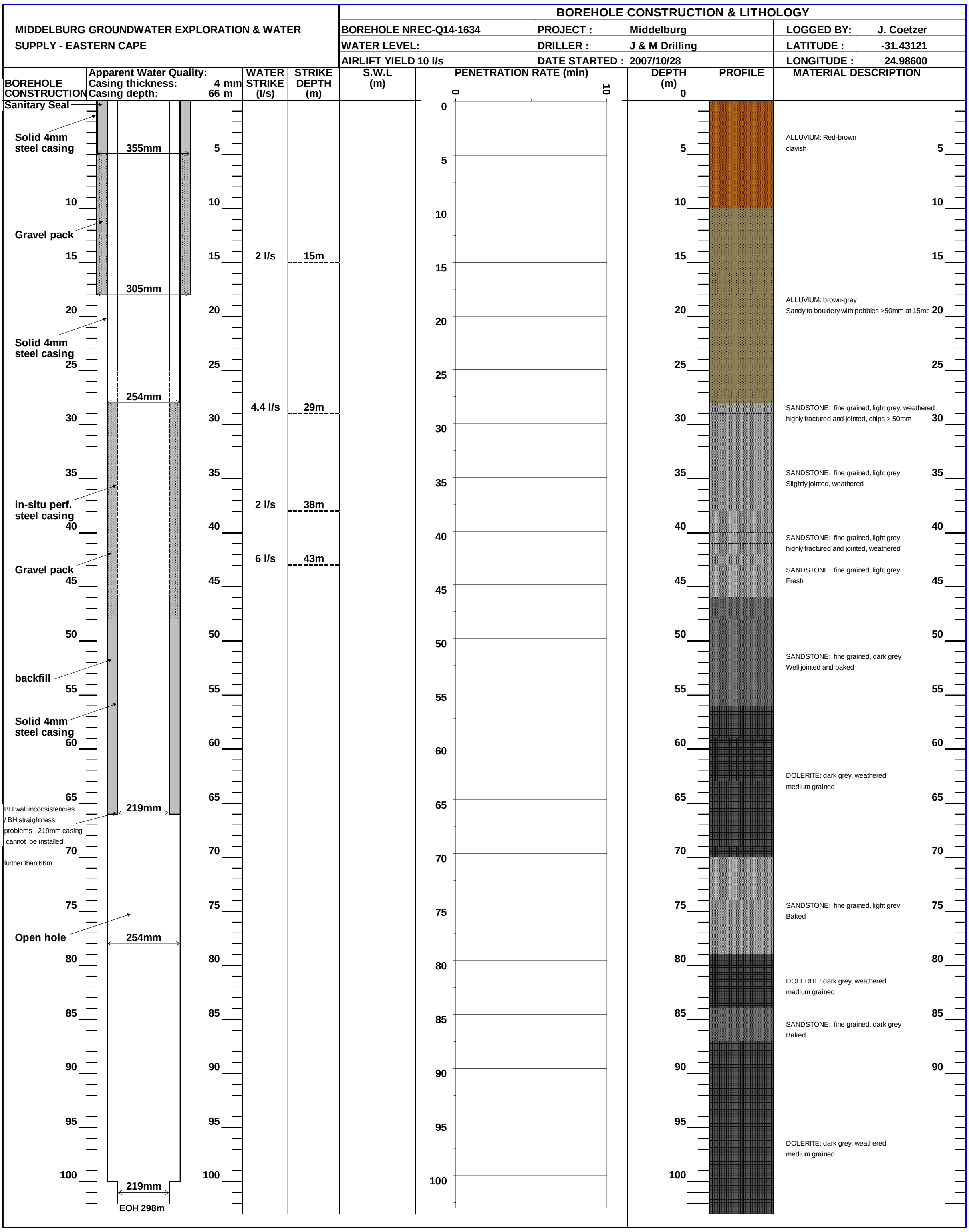

Figure 3-12: Borehole log EC-Q14-1634 part 1 of 3

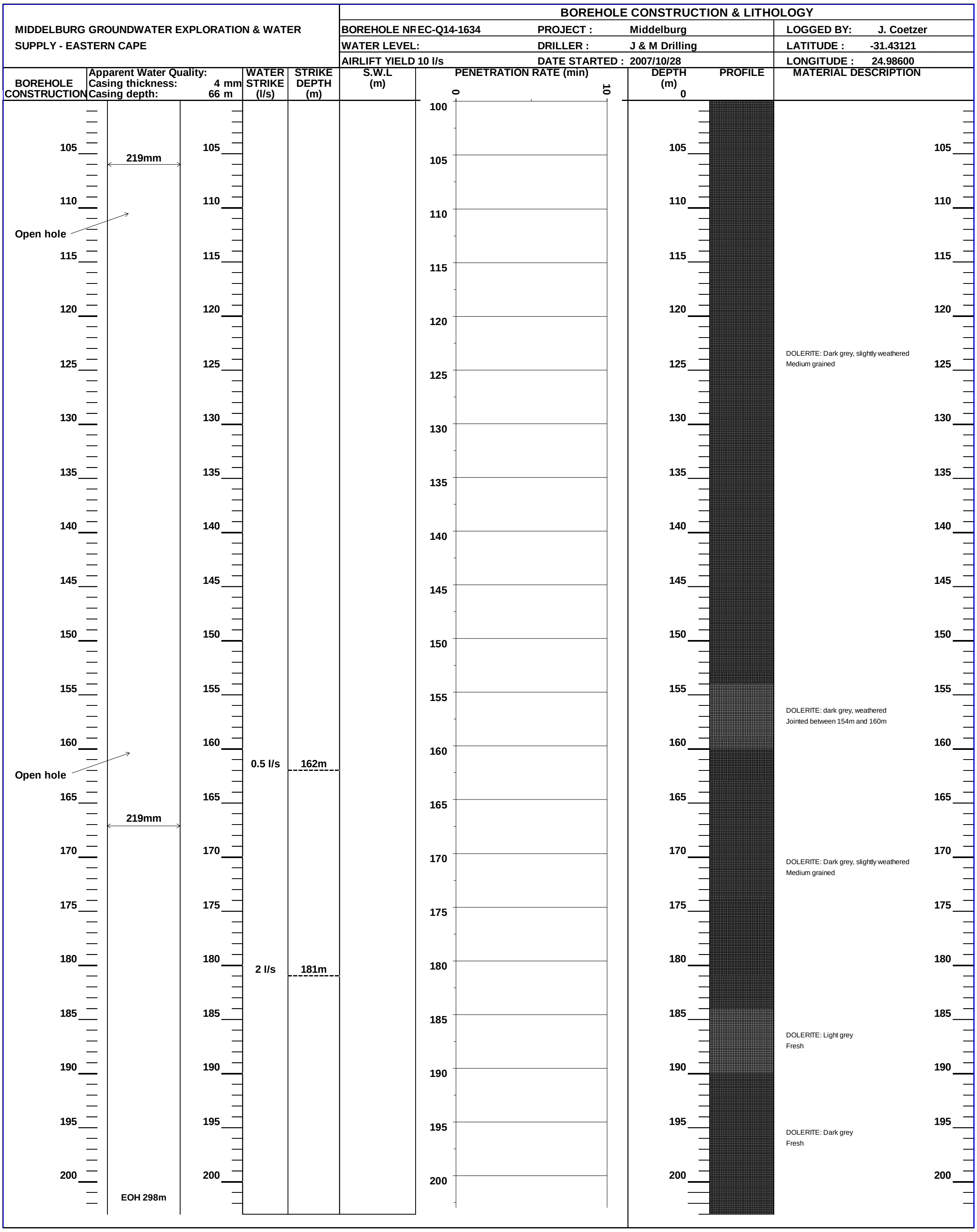

Figure 3-13: Borehole EC-Q14-1634 part 2 of 3

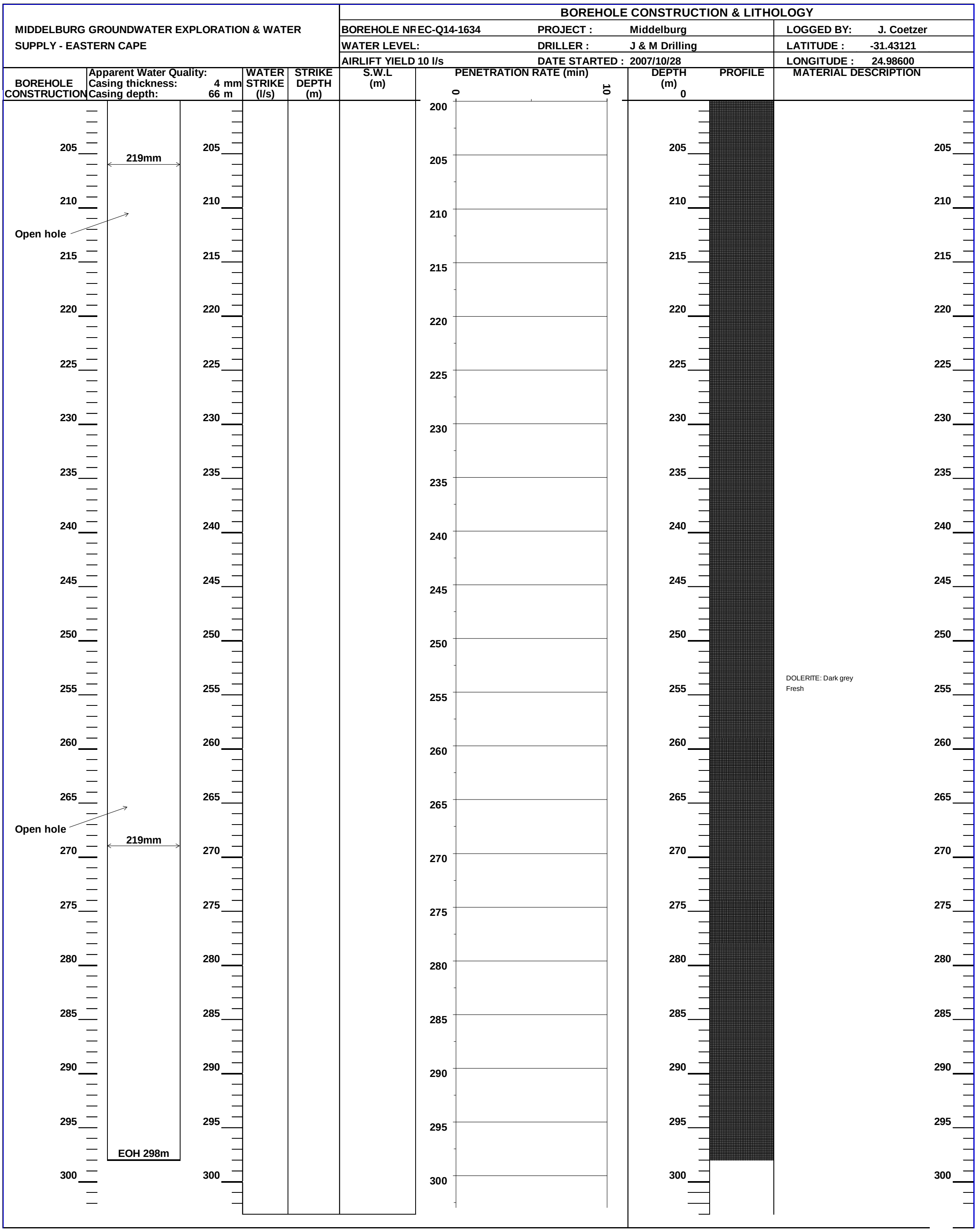

Figure 3-14: Borehole logs EC-Q14-1634 part 3 of 3

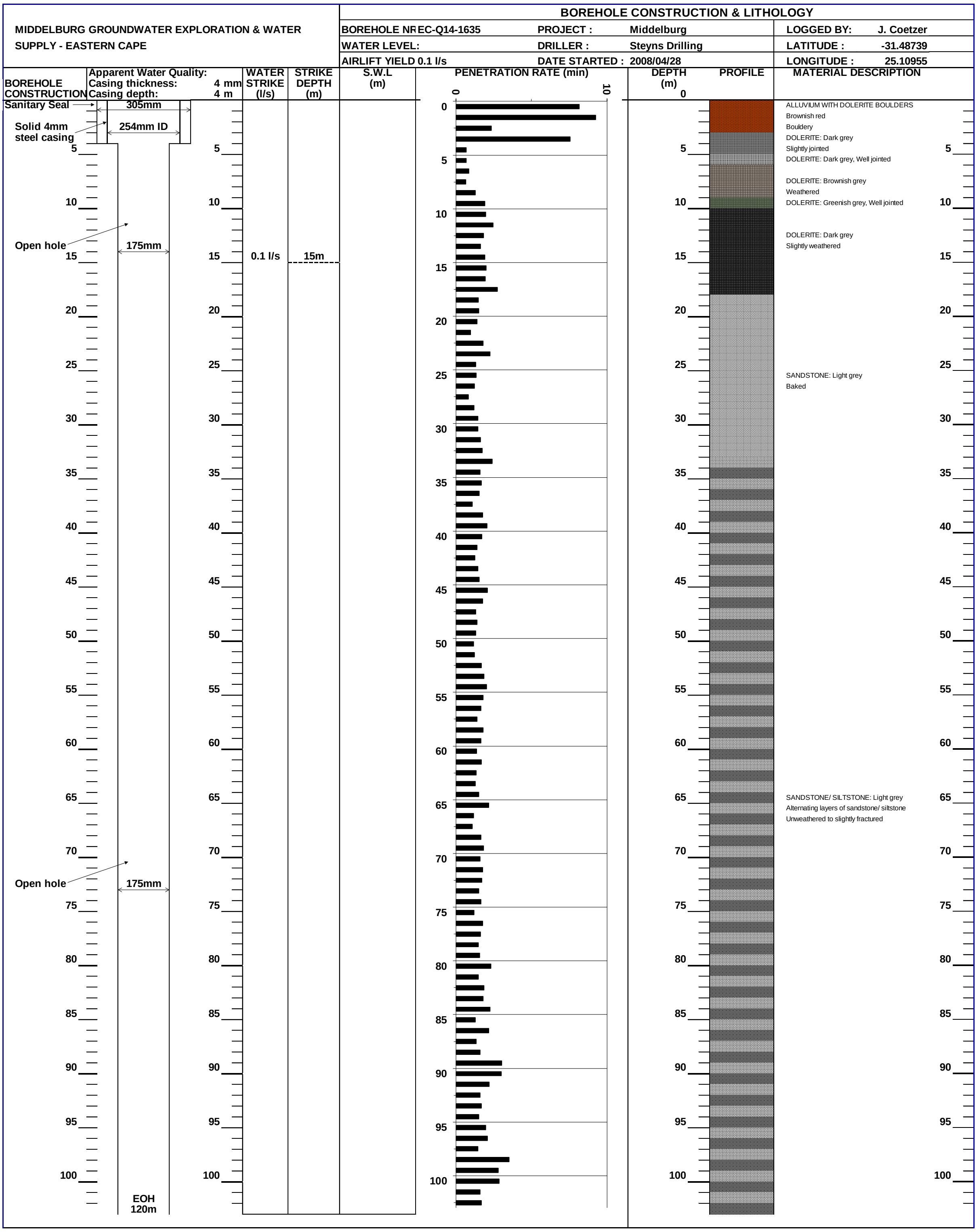

Figure 3-15: Borehole log EC-Q14-1635 part 1 of 2

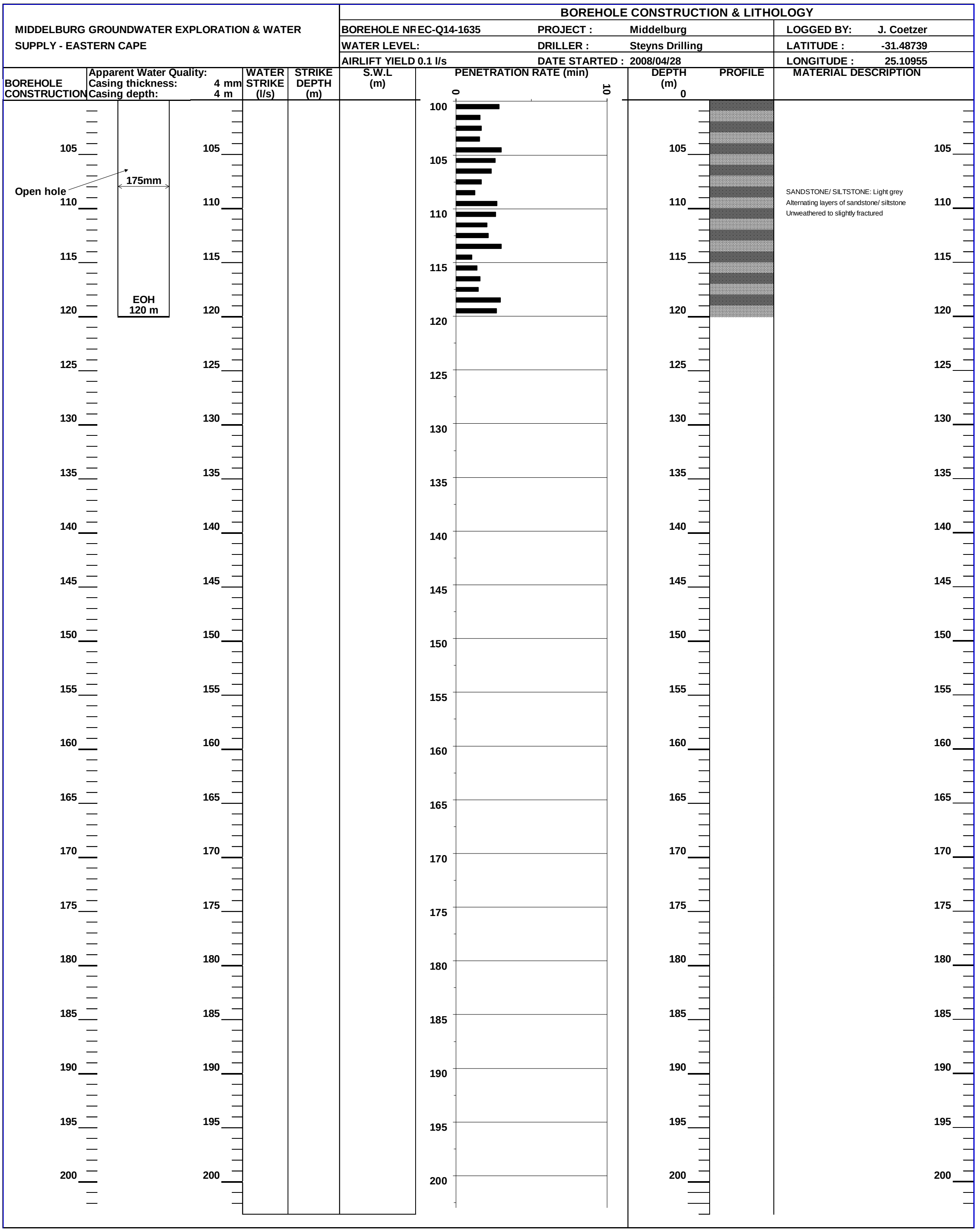

Figure 3-16: Borehole log EC-Q14-1635 part 2 of 2

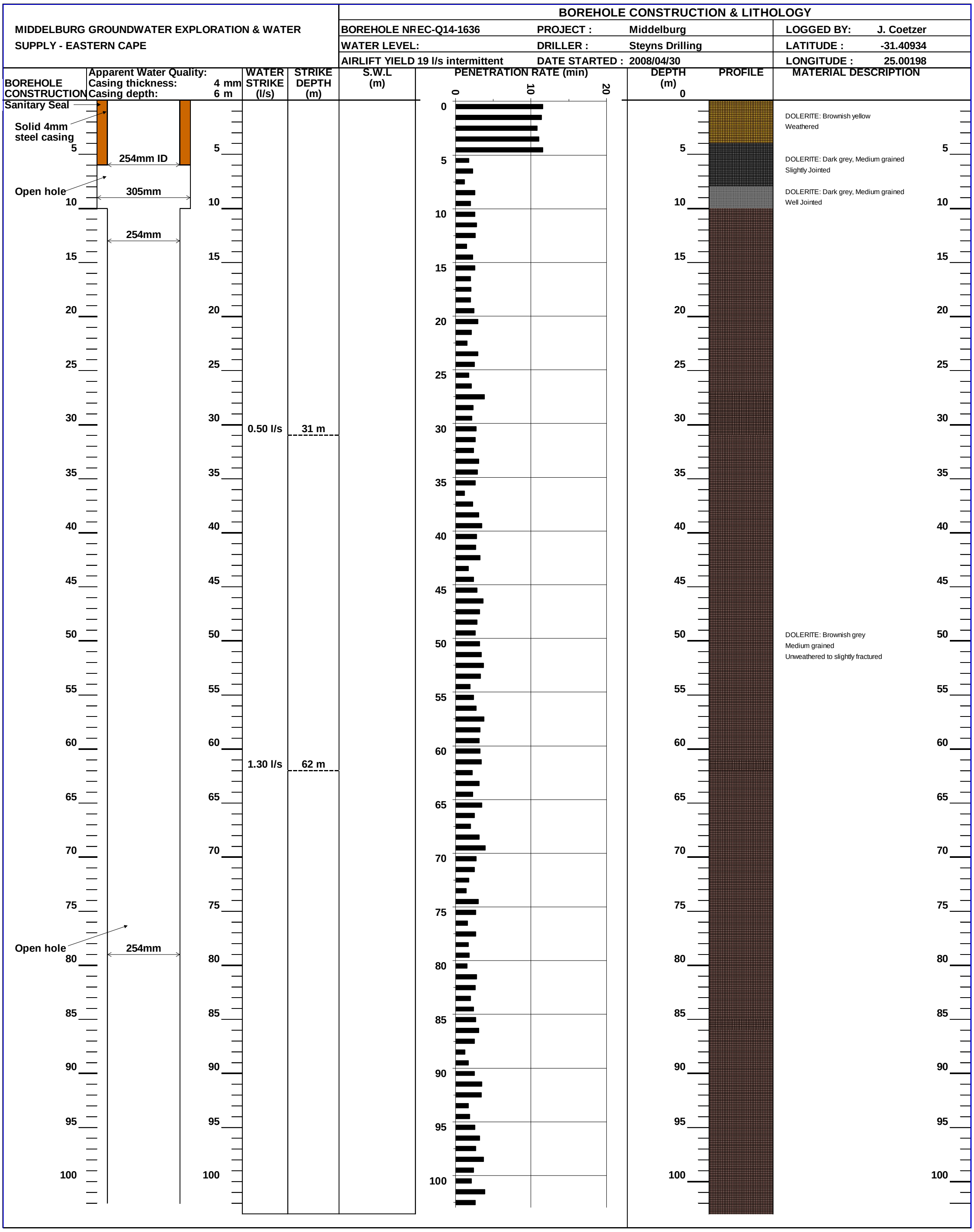

Figure 3-17: Borehole EC-Q14-1636 part 1 of 3

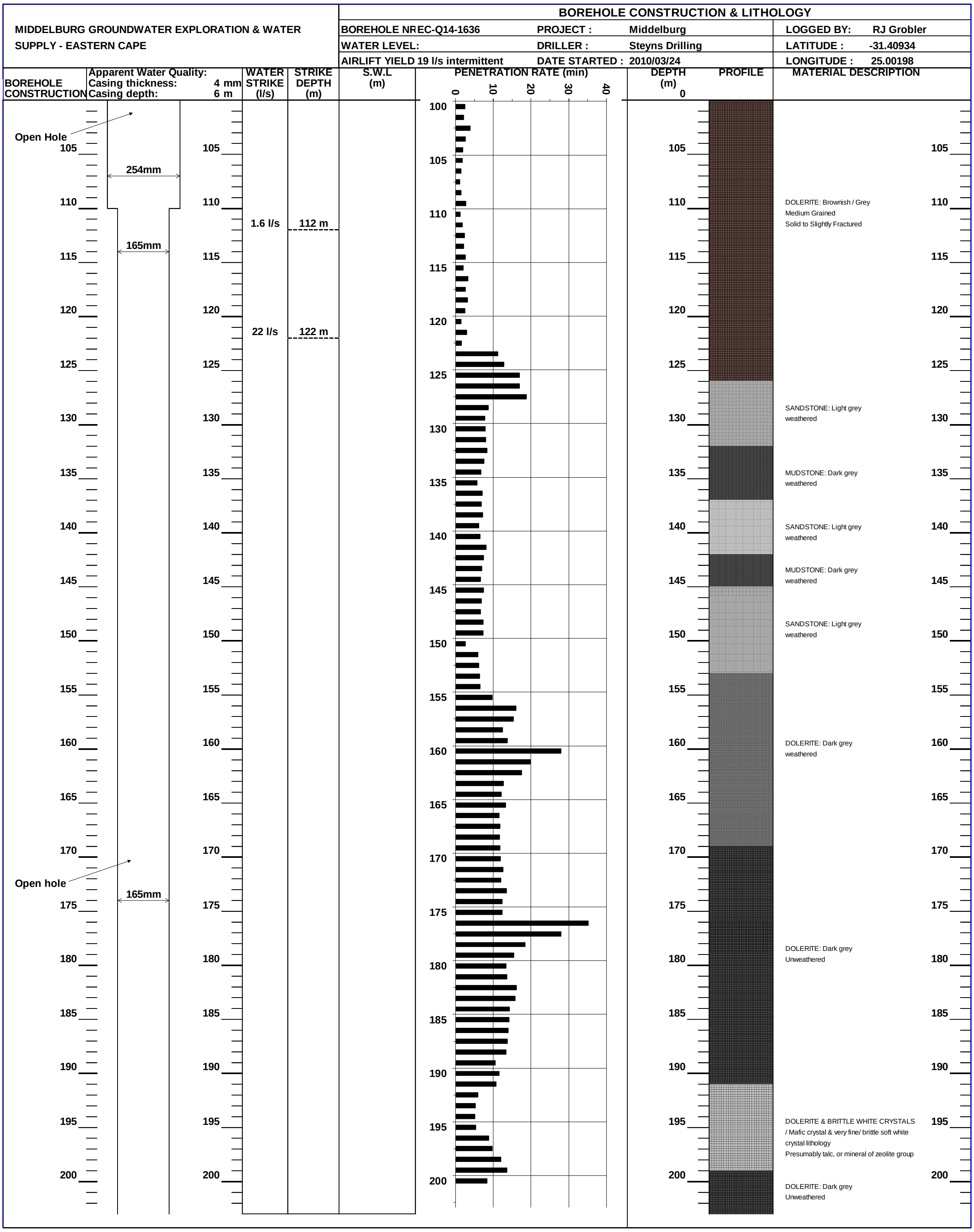

Figure 3-18: Borehole EC-Q14-1636 part 2 of 3

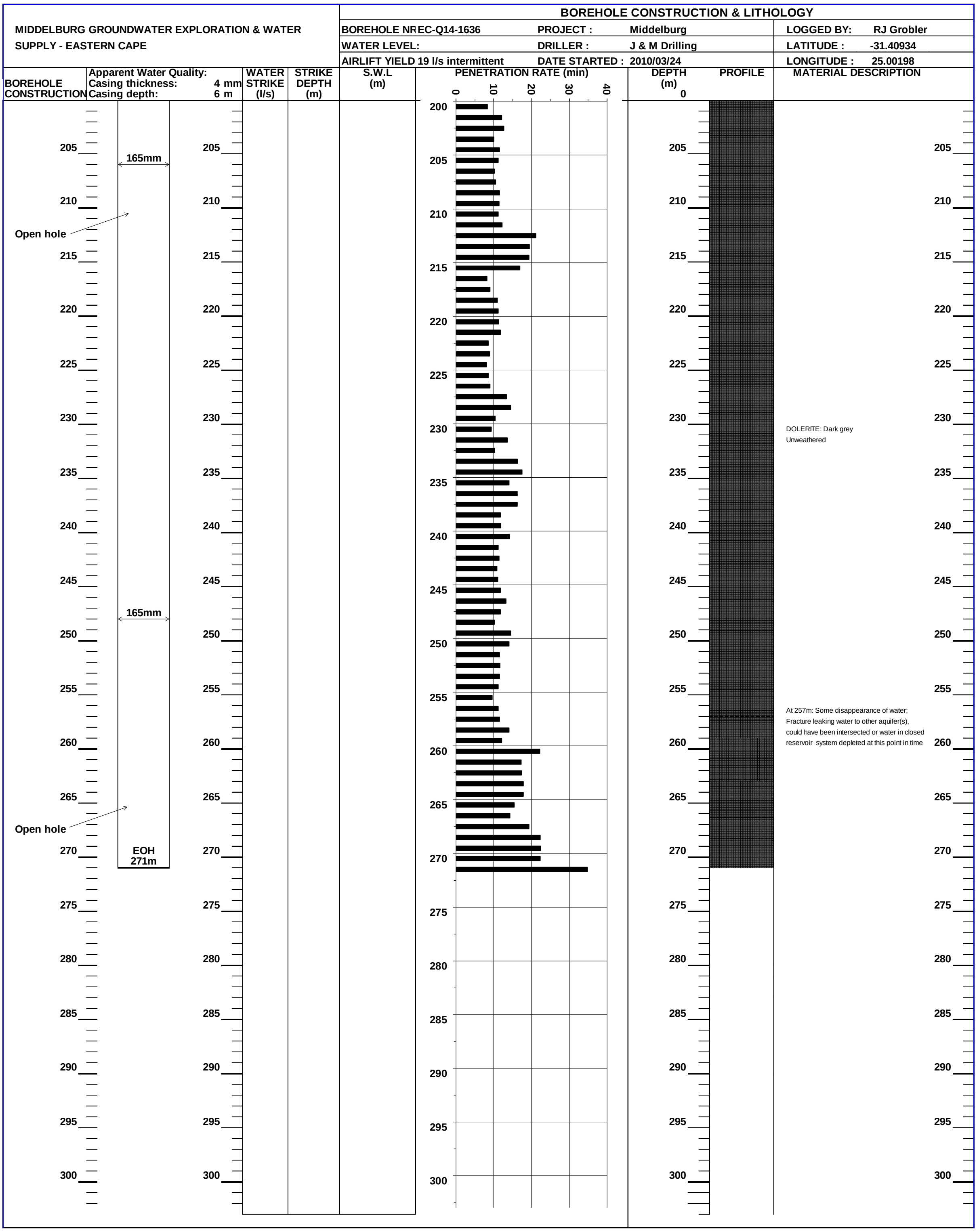

Figure 3-19: Borehole EC-Q14-1636 part 3 of 3

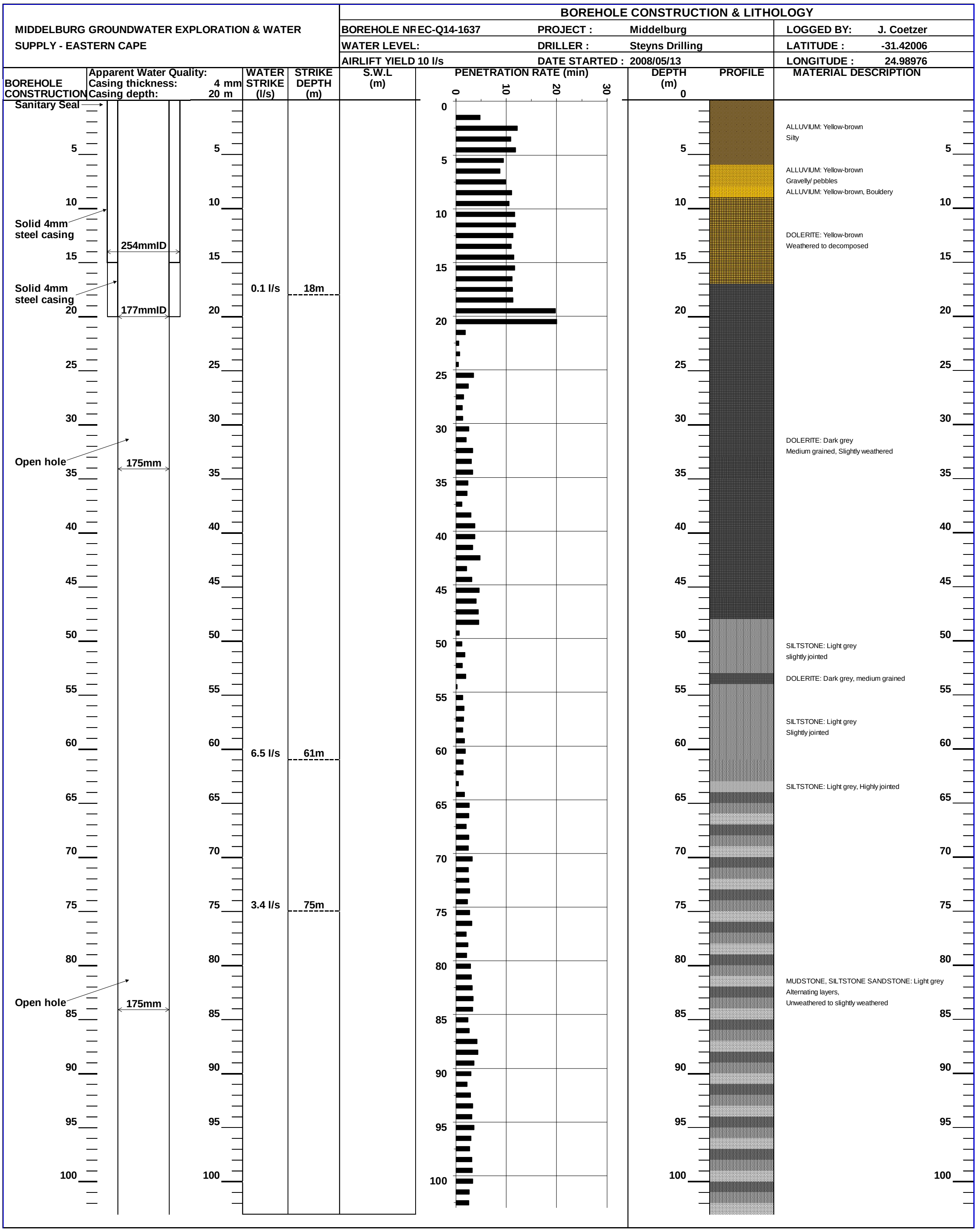

Figure 3-20: Borehole log EC-Q14-1637, The Glen part 1 of 3

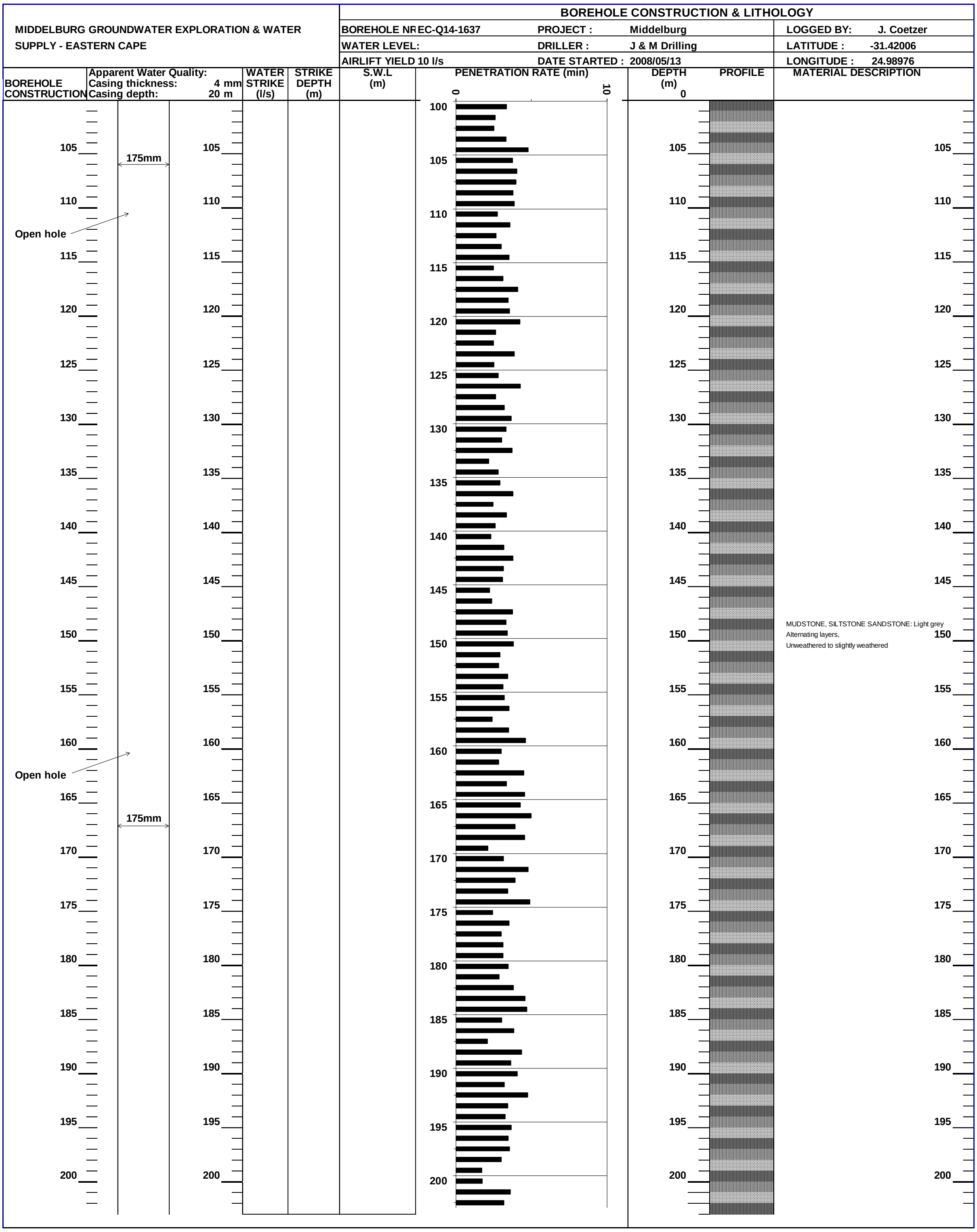

Figure 3-21: Borehole log EC-Q14-1637 part 2 of 3

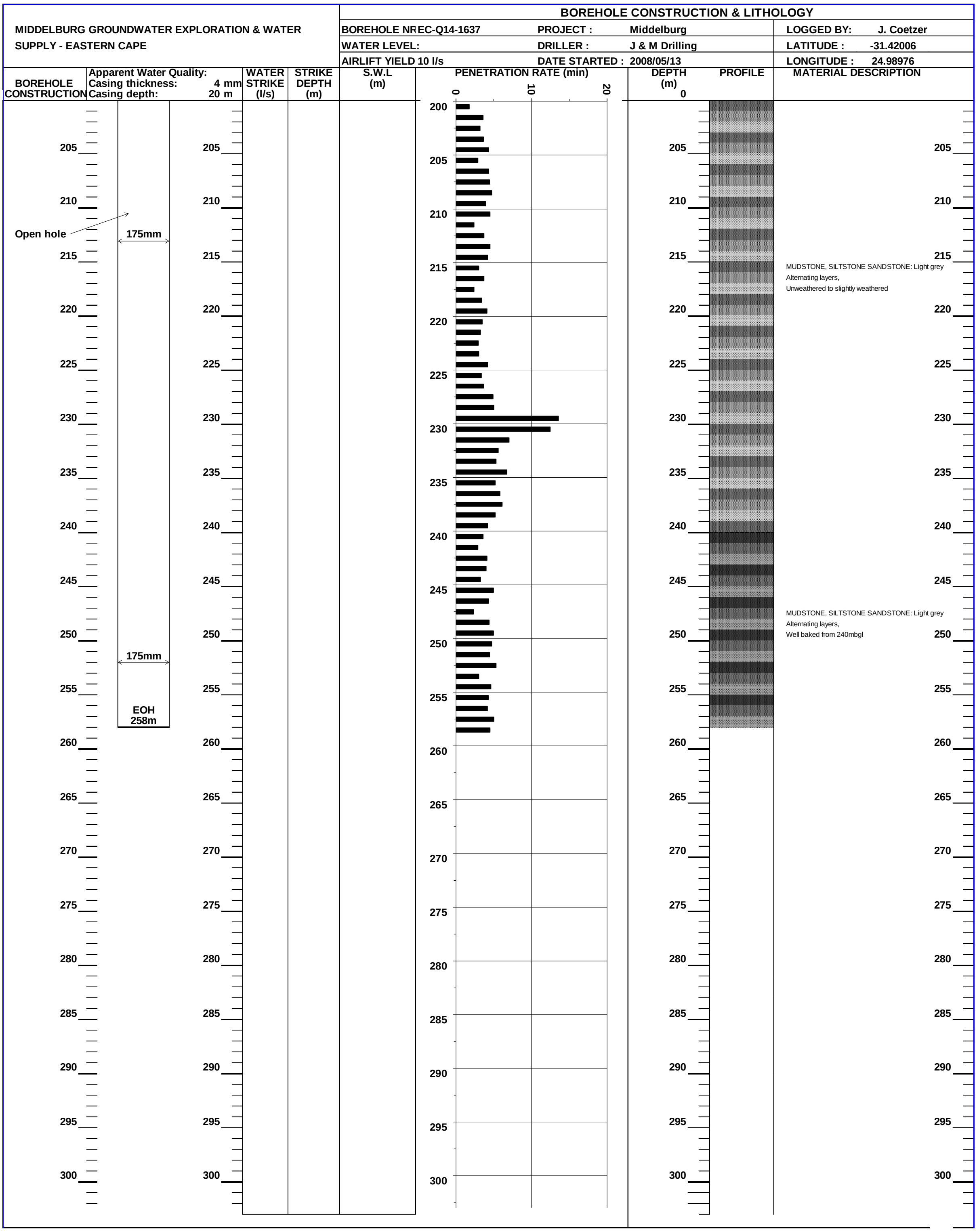

Figure 3-22: Borehole log EC-Q14-1637 part 3 of 3

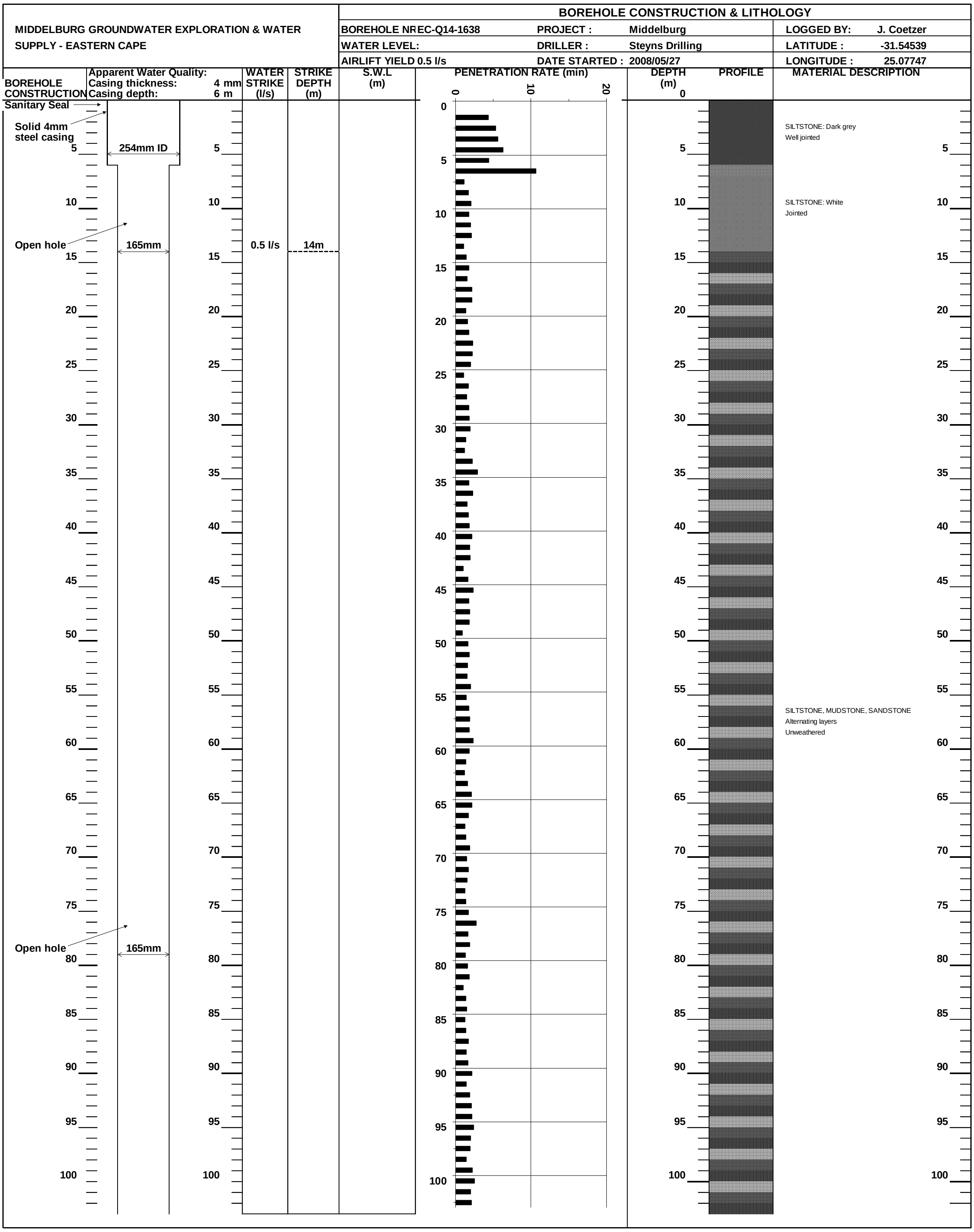

Figure 3-23: Borehole log EC-Q14-1638 part 1 of 3

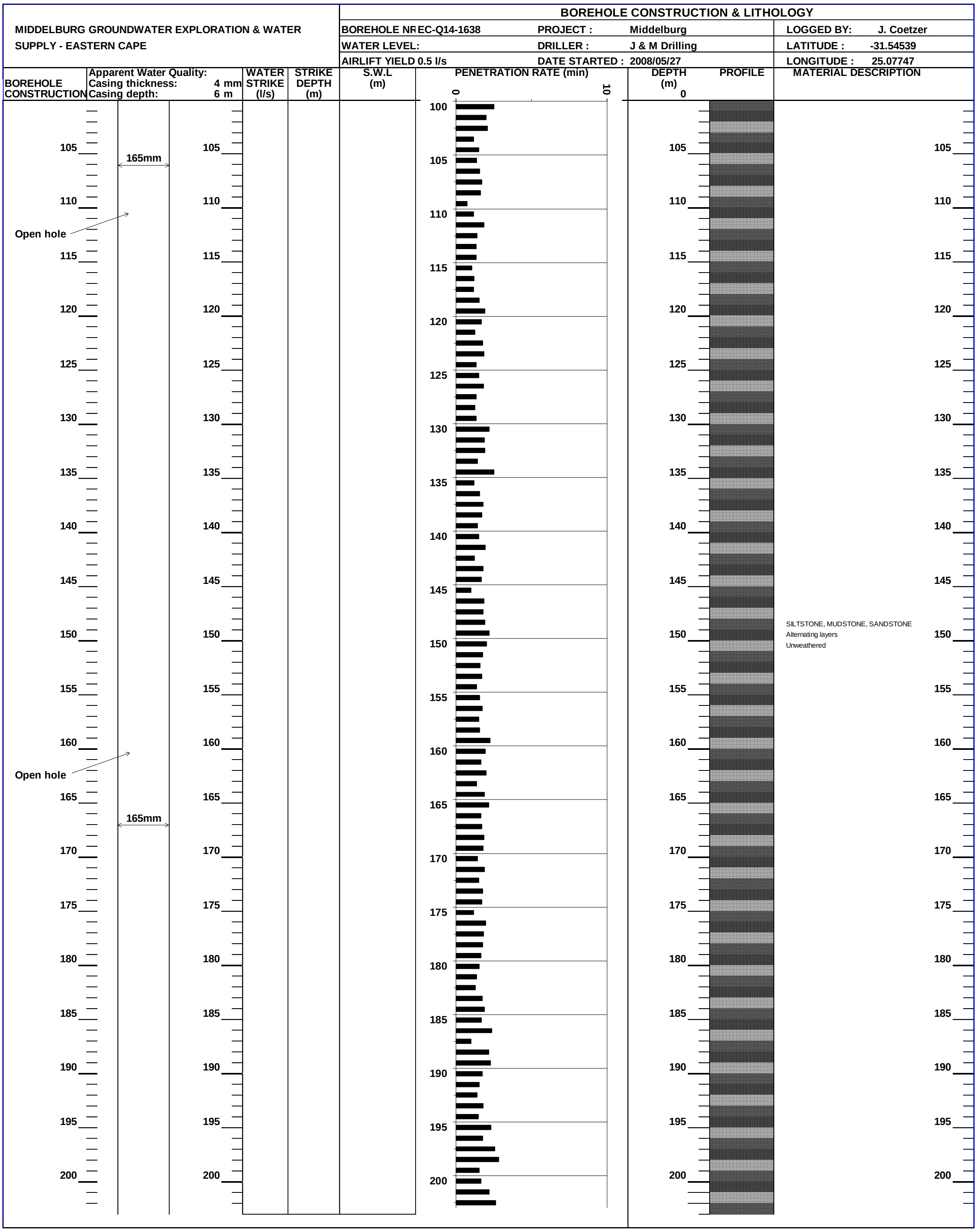

Figure 3-24: Borehole log EC-Q14-1638 part 2 of 3

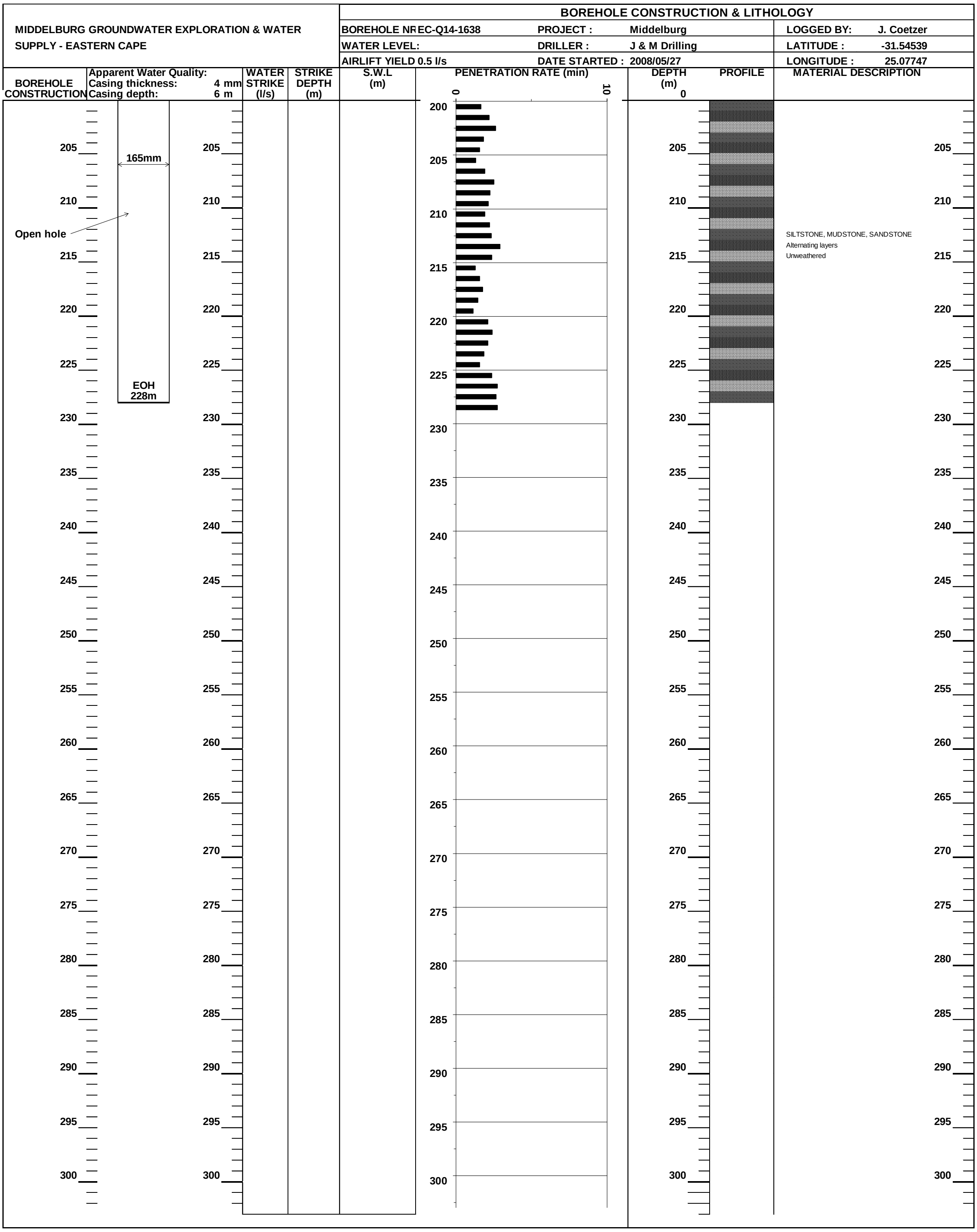

Figure 3-25: Borehole log EC-Q14-1638 part 3 of 3

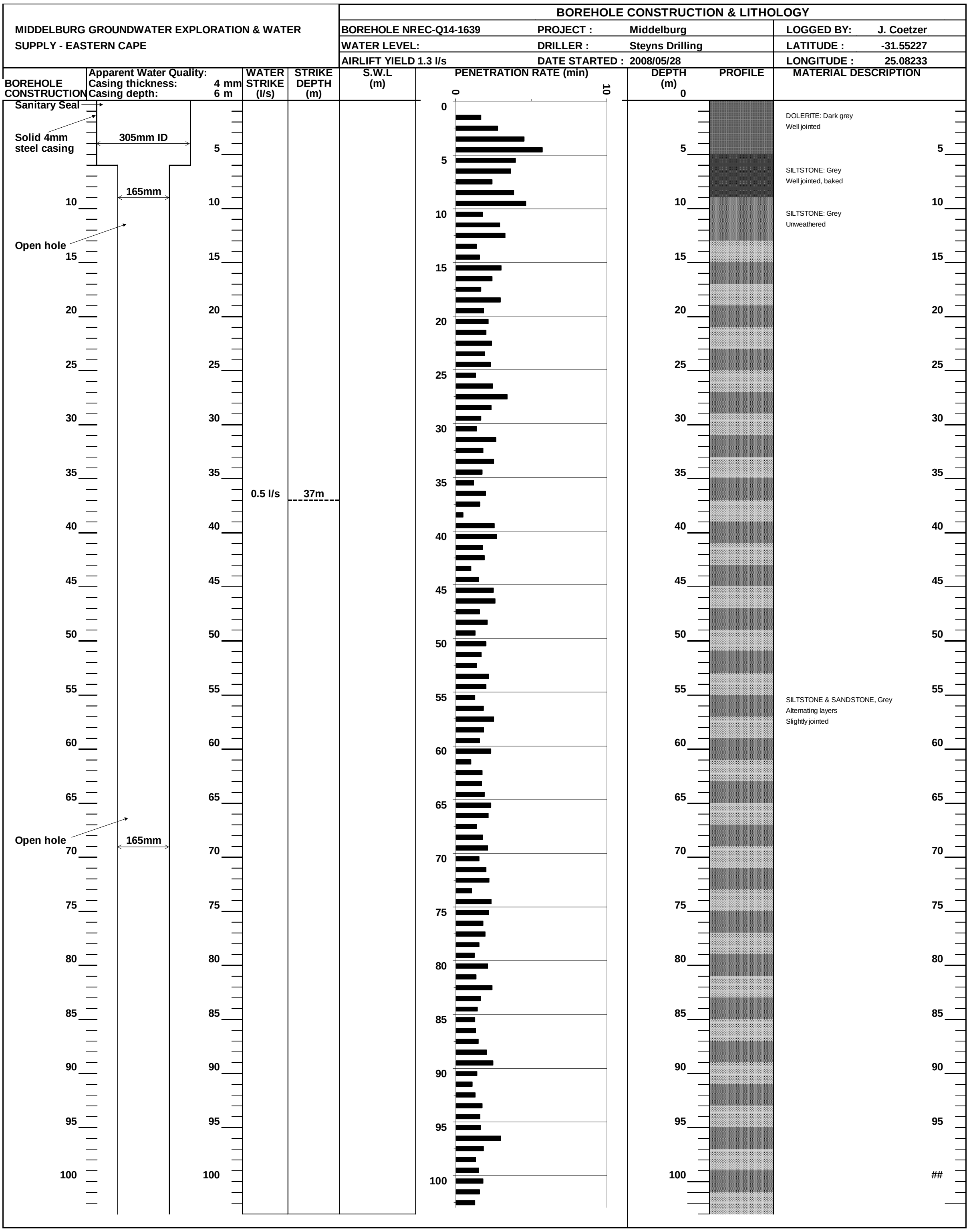

Figure 3-26: Borehole log EC-Q14-1639 part 1 of 2

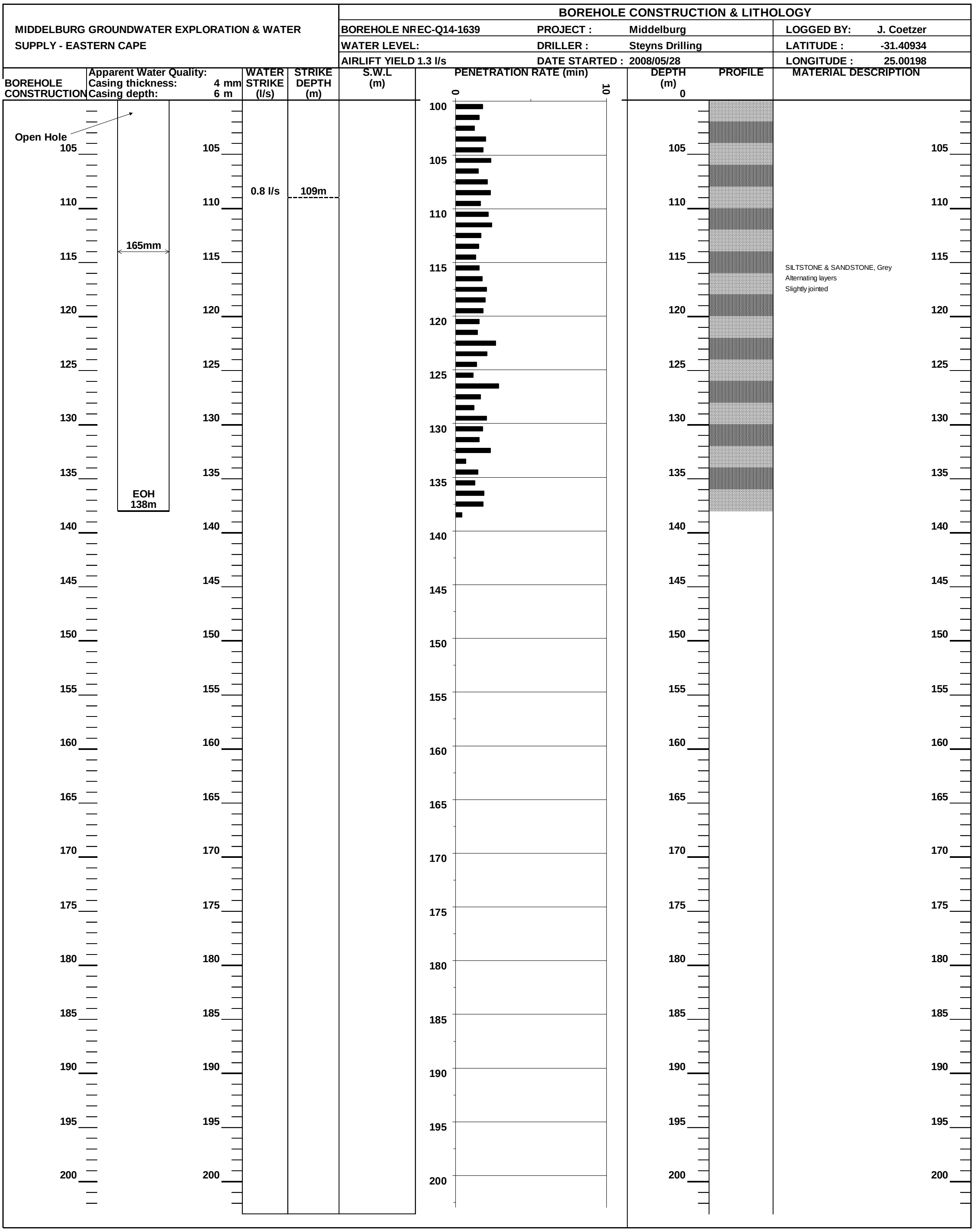

Figure 3-27: Borehole log EC-Q14-1640 part 2 of 2

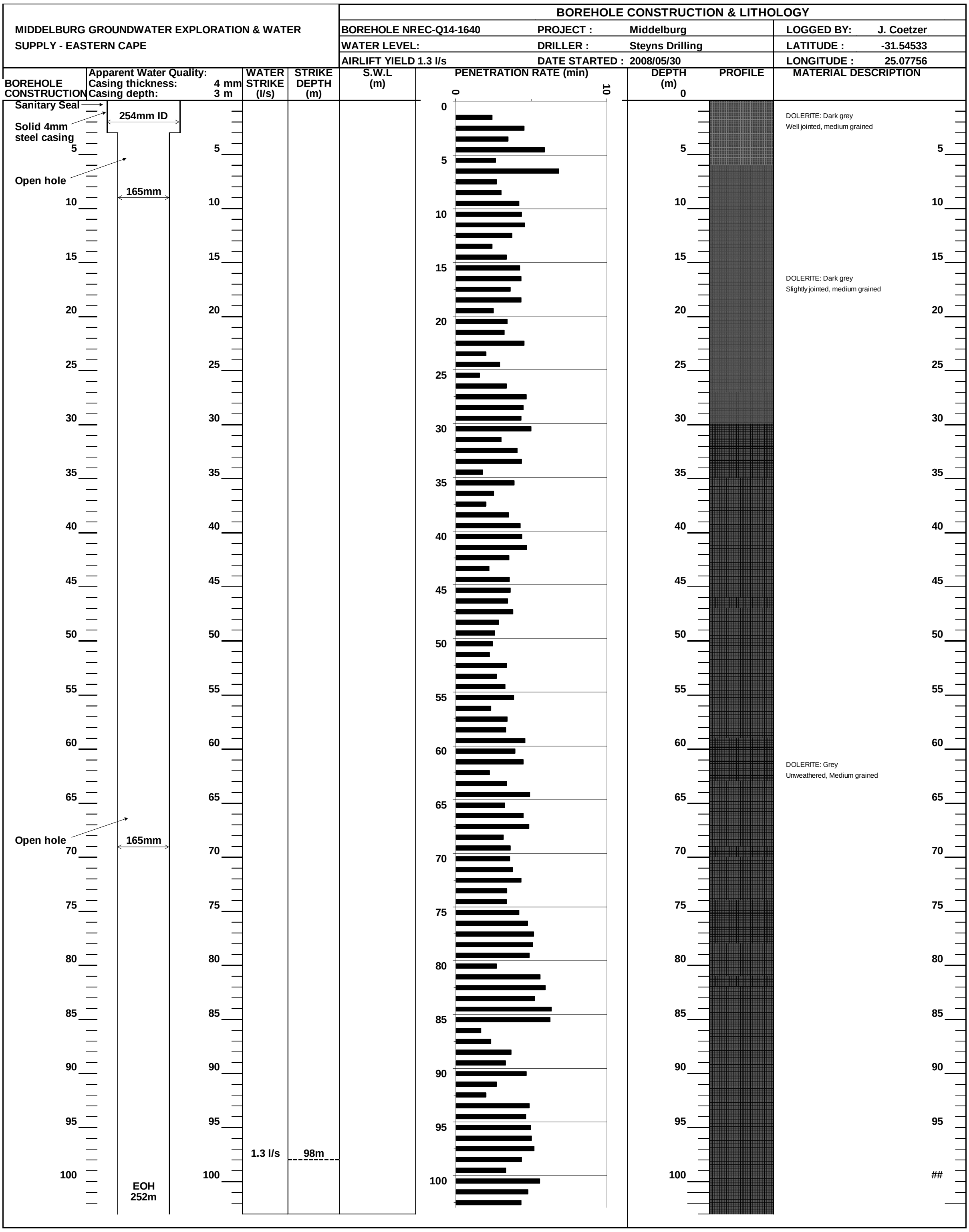

Figure 3-28: Borehole log EC-Q14-1640 part 1 of 3

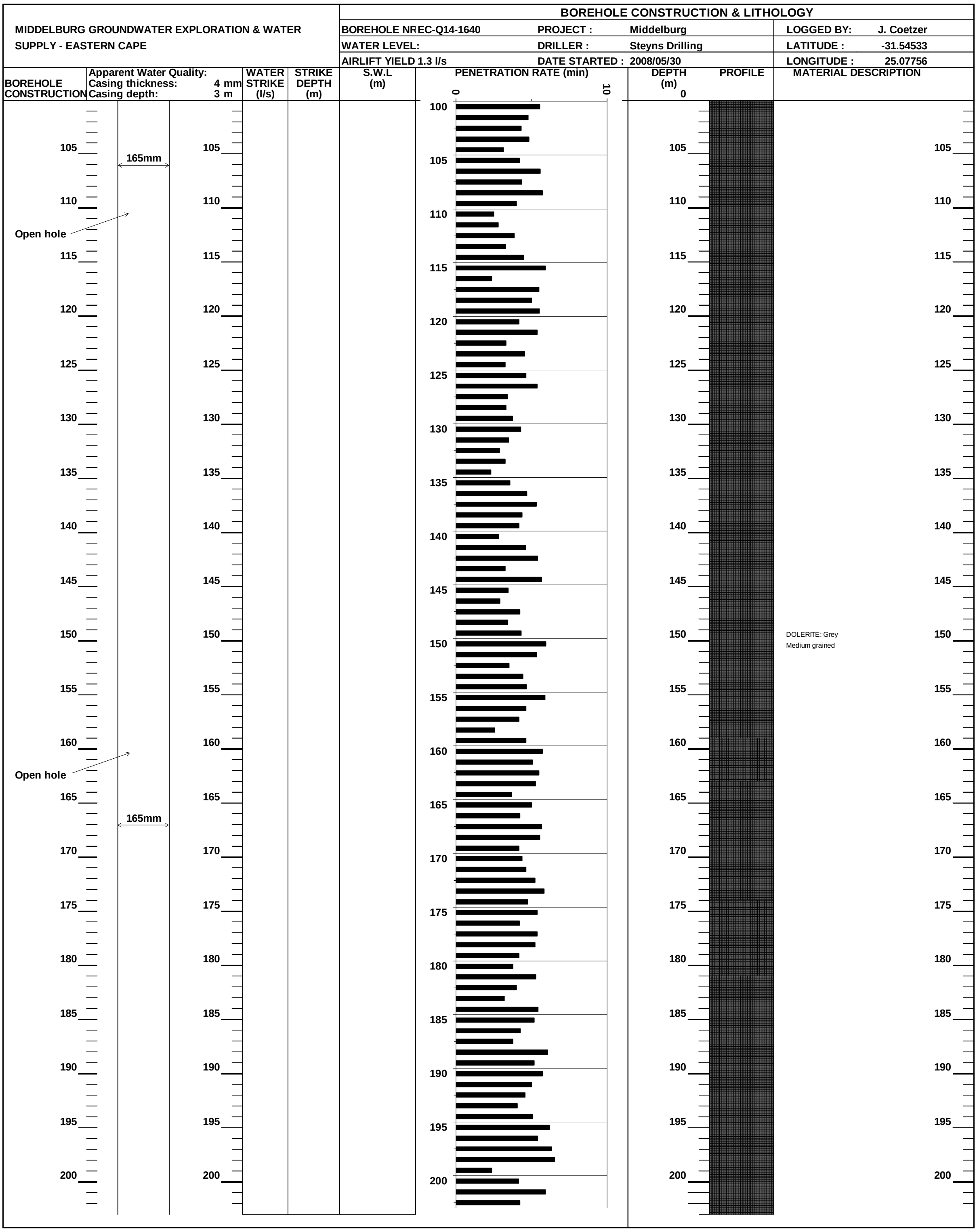

Figure 3-29: Borehole log EC-Q14-1640 part 2 of 3

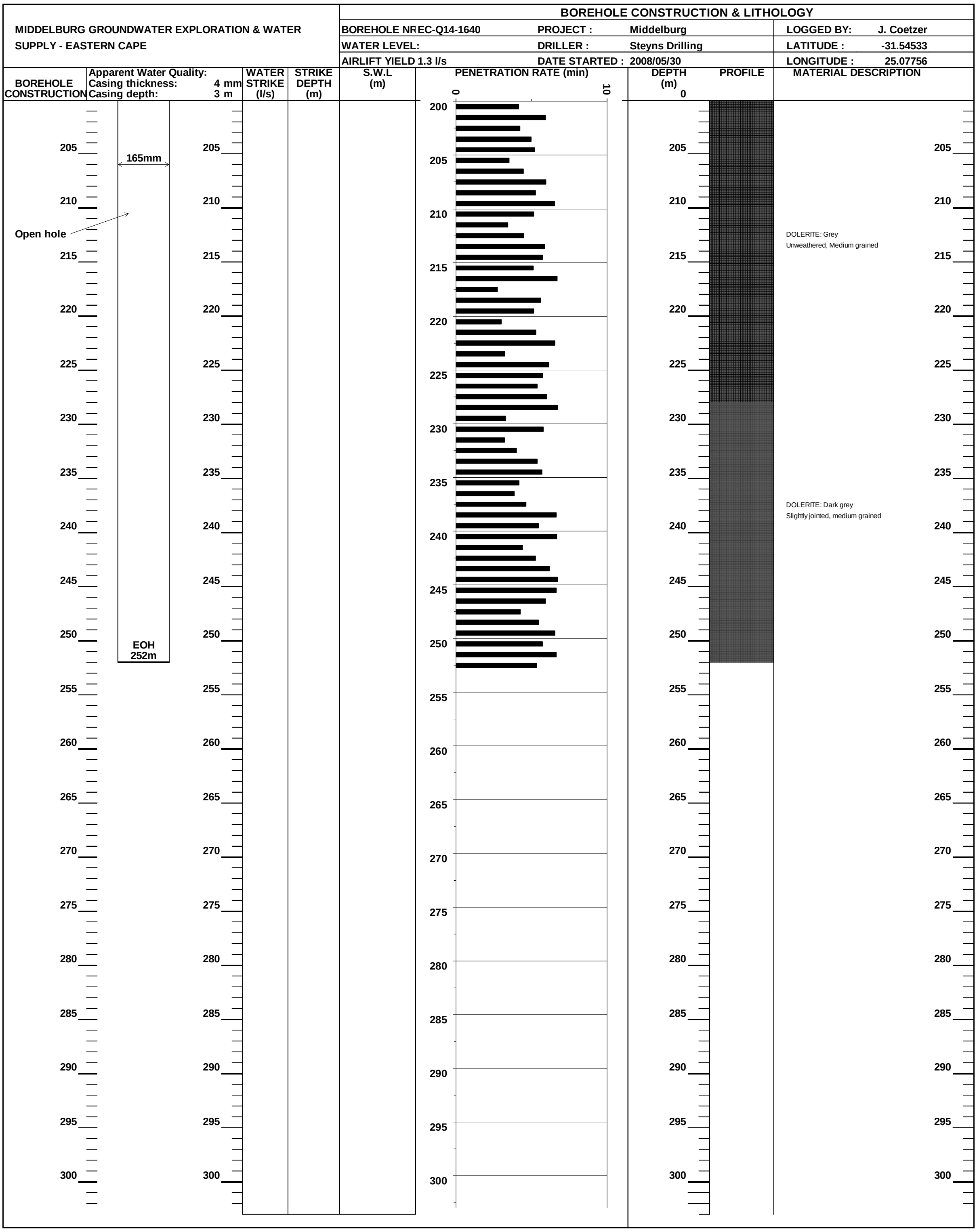

Figure 3-30: Borehole log EC-Q14-1640 part 3 of 3

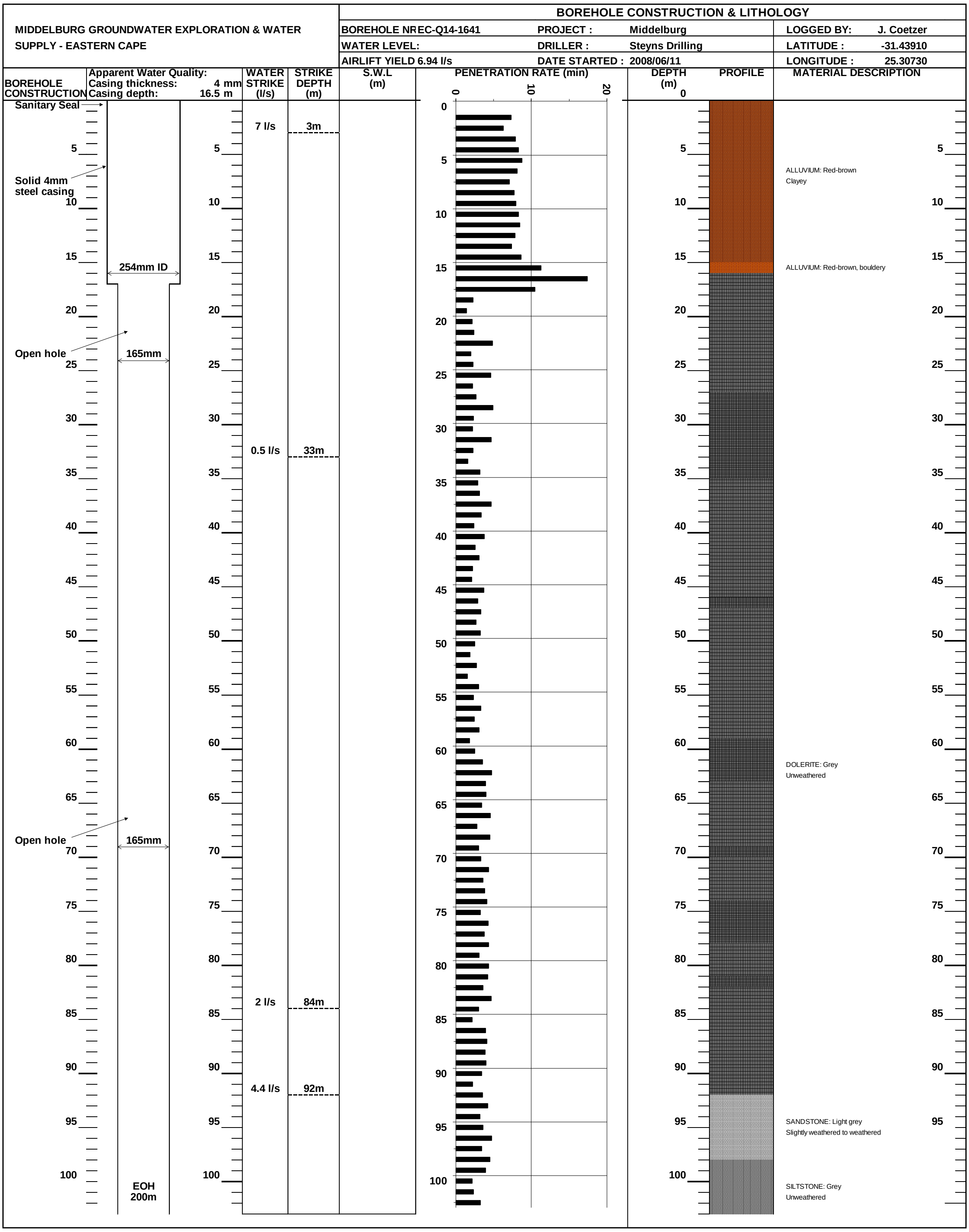

Figure 3-31: Borehole log EC-Q14-1641 part 1 of 2

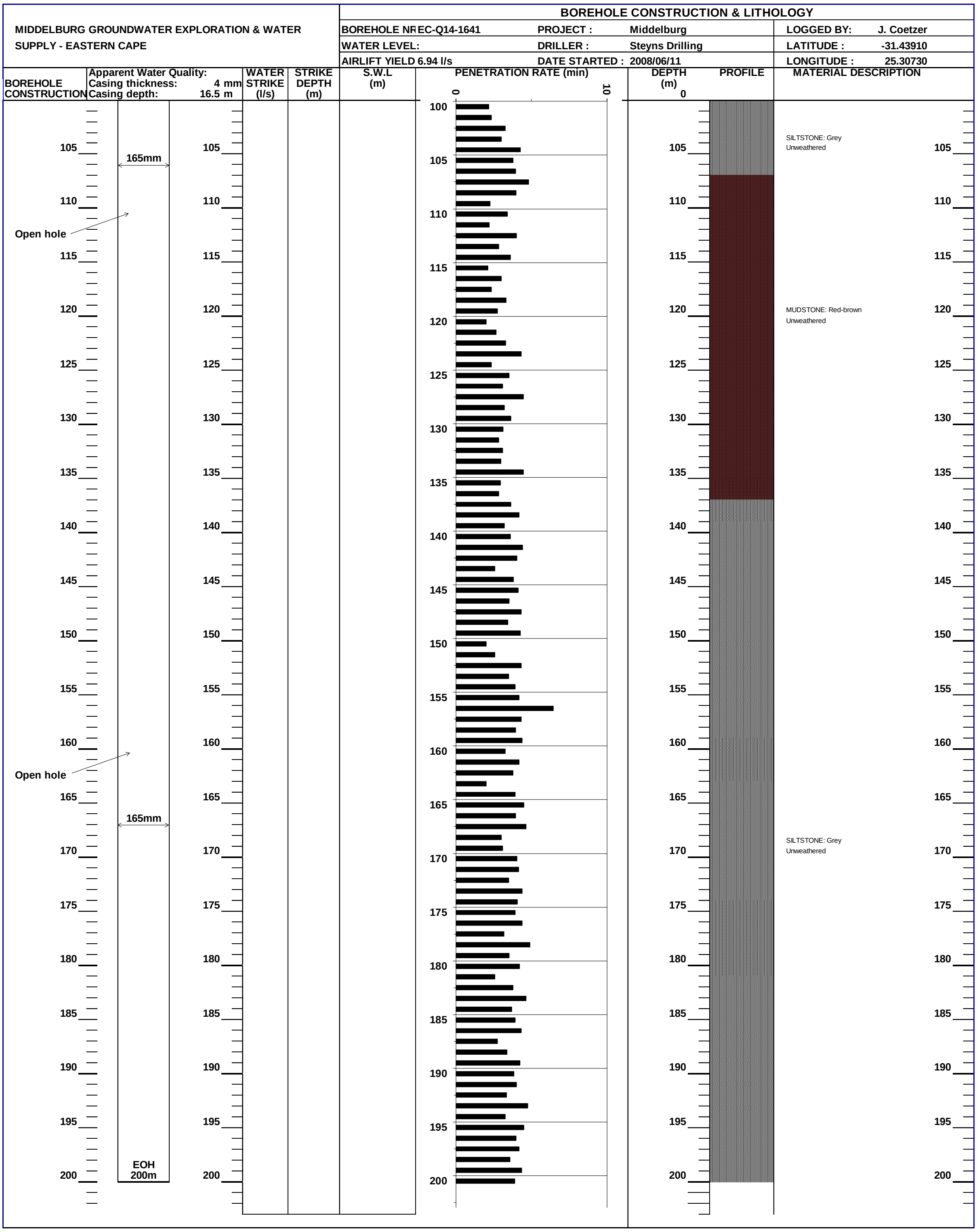

Figure 3-32: Borehole log EC-Q14-1641 part 2 of 2

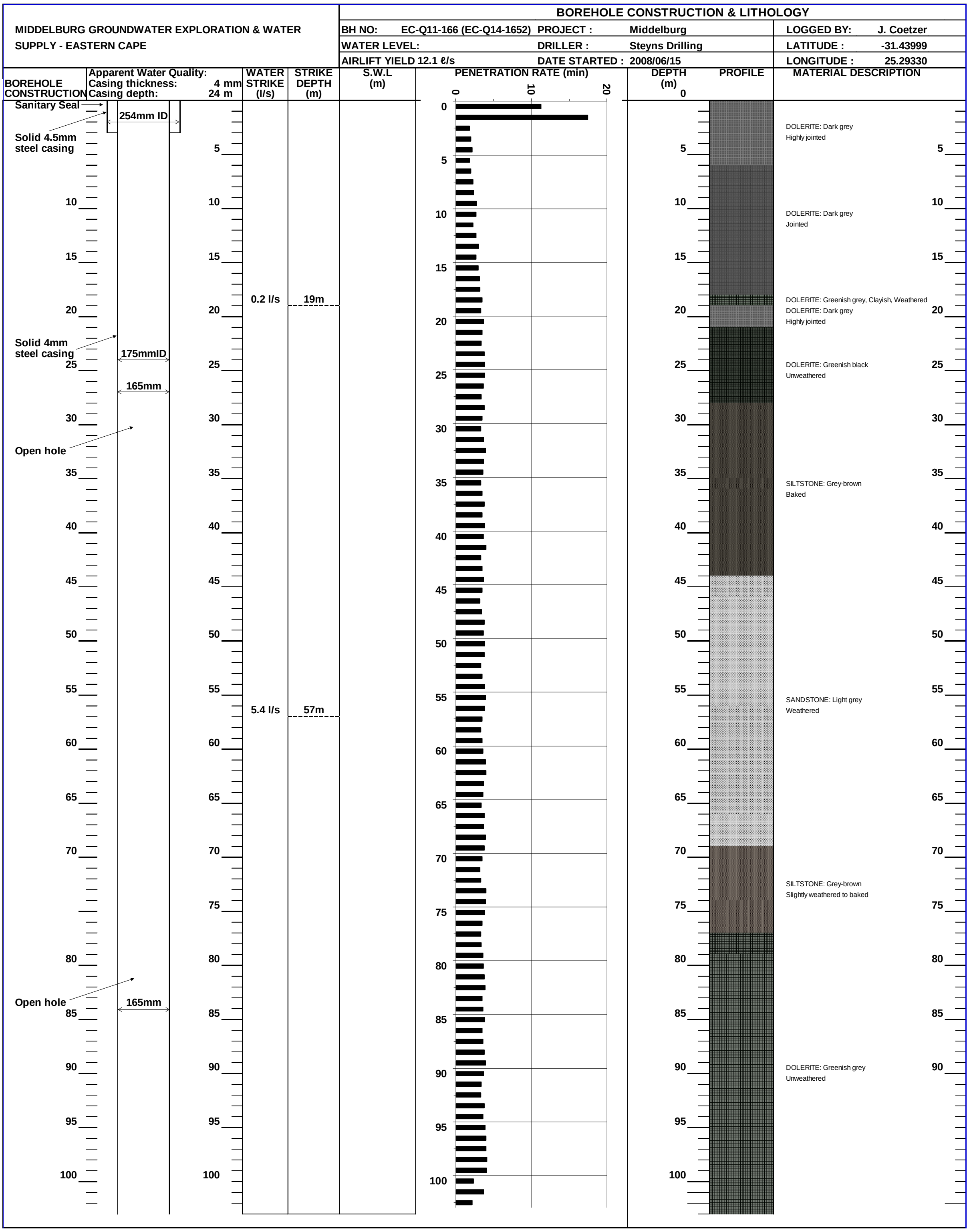

Figure 3-33: Borehole log EC-Q11-166 Alfalfa, Lusernvlei; log 1 of 2

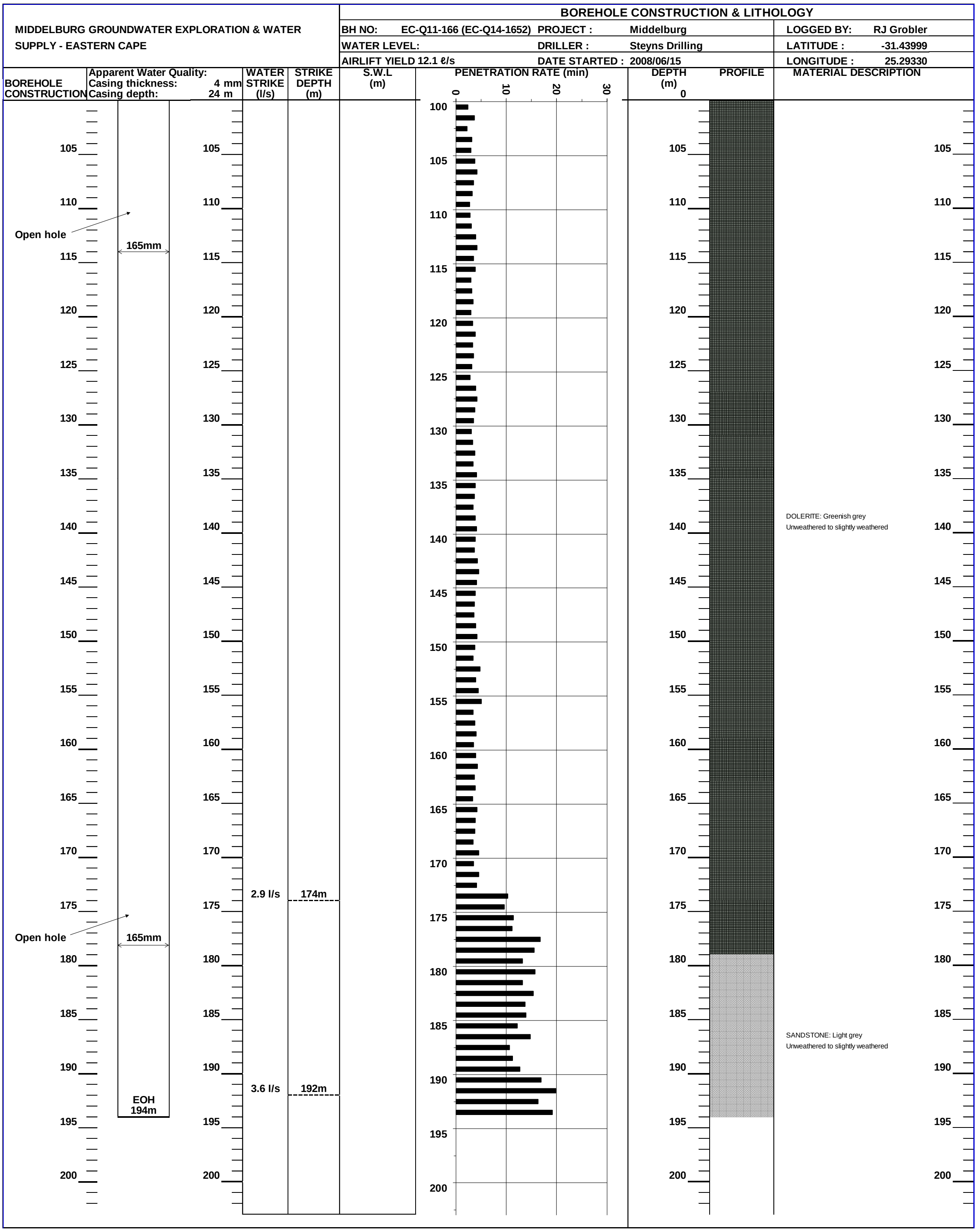

Figure 3-34: Borehole log EC-Q11-166 Alfalfa, Lusernvlei; log 2 of 2

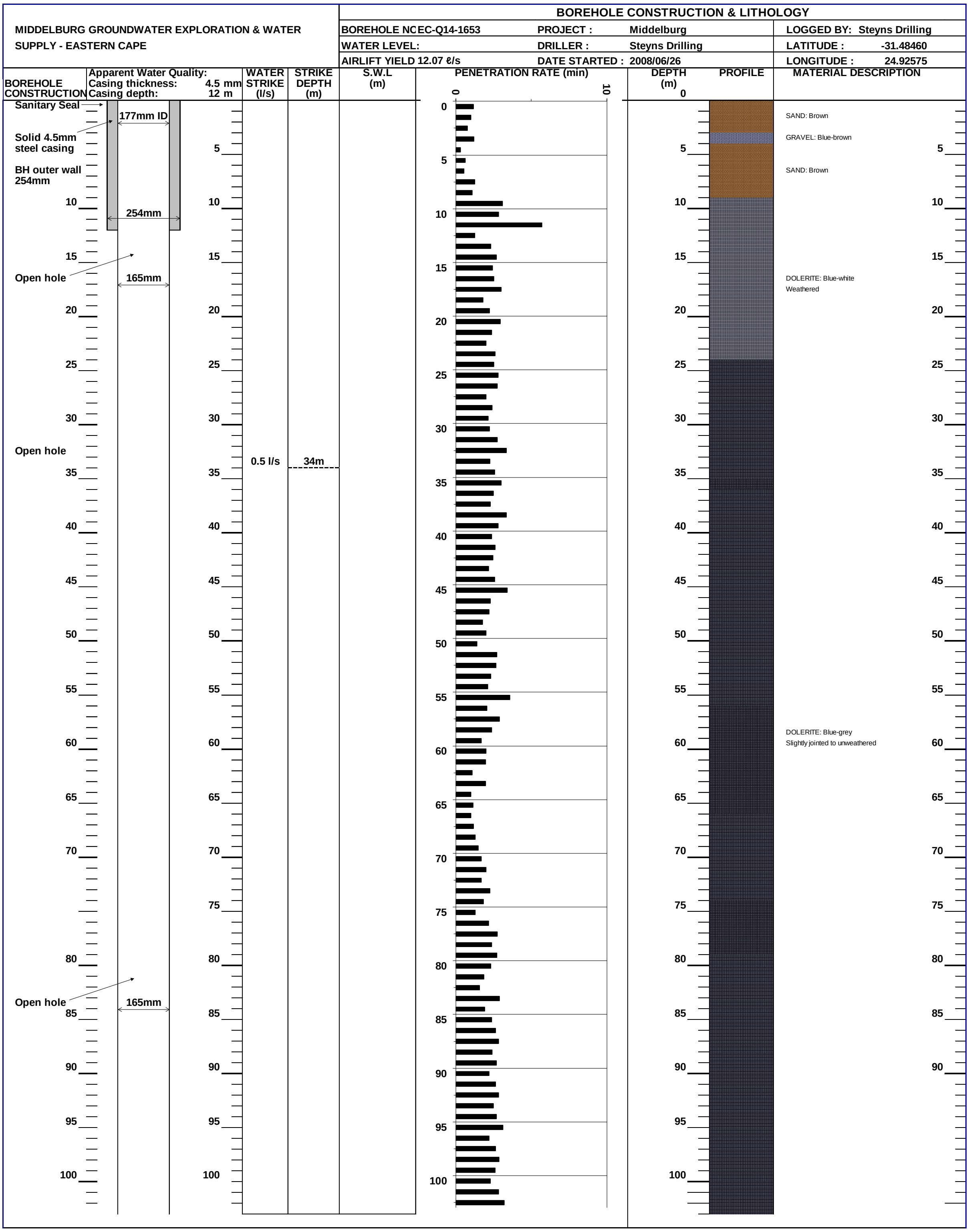

Figure 3-35: Borehole log EC-Q14-1653 part 1 of 2

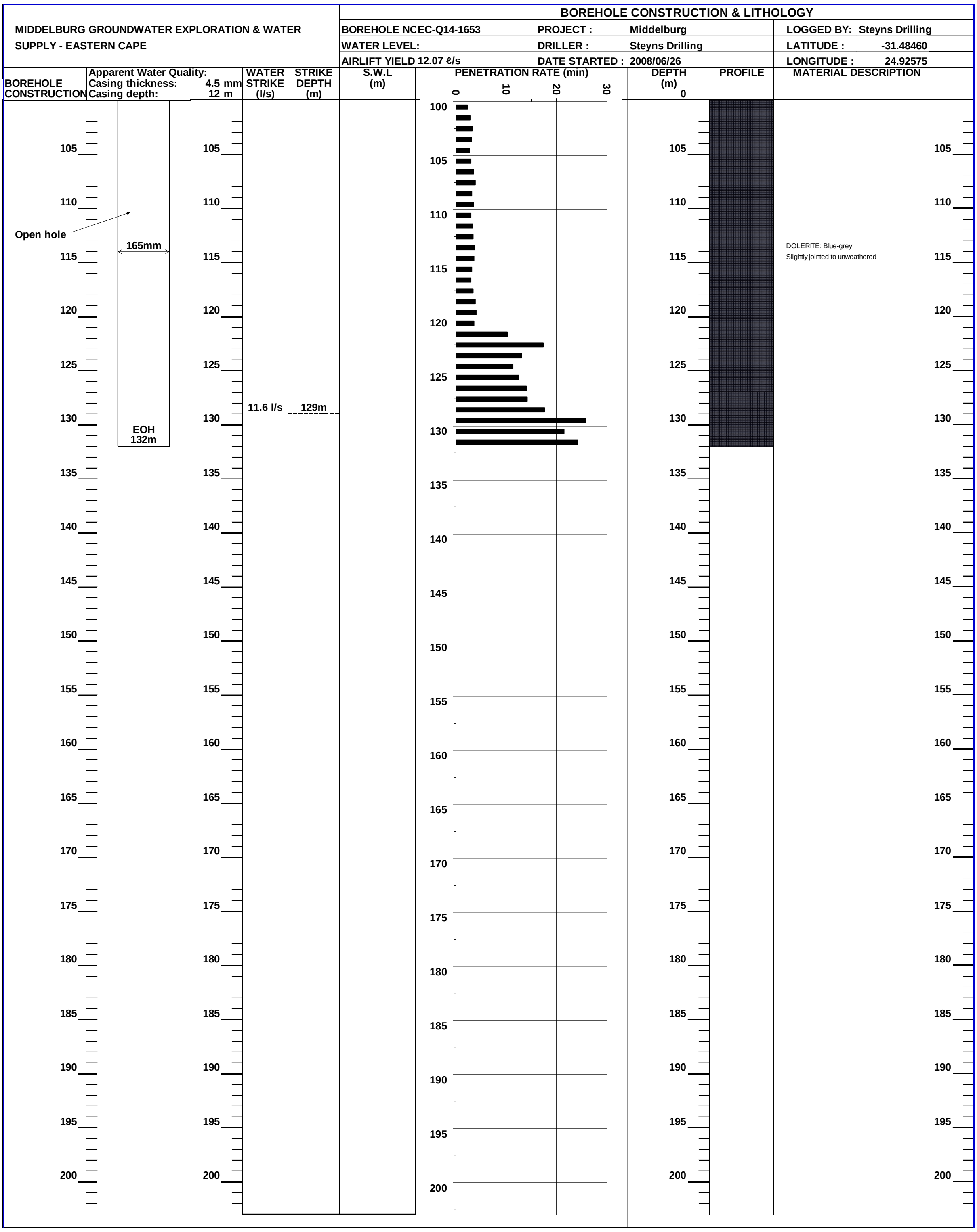

Figure 3-36: Borehole log EC-Q14-1653 part 2 of 2

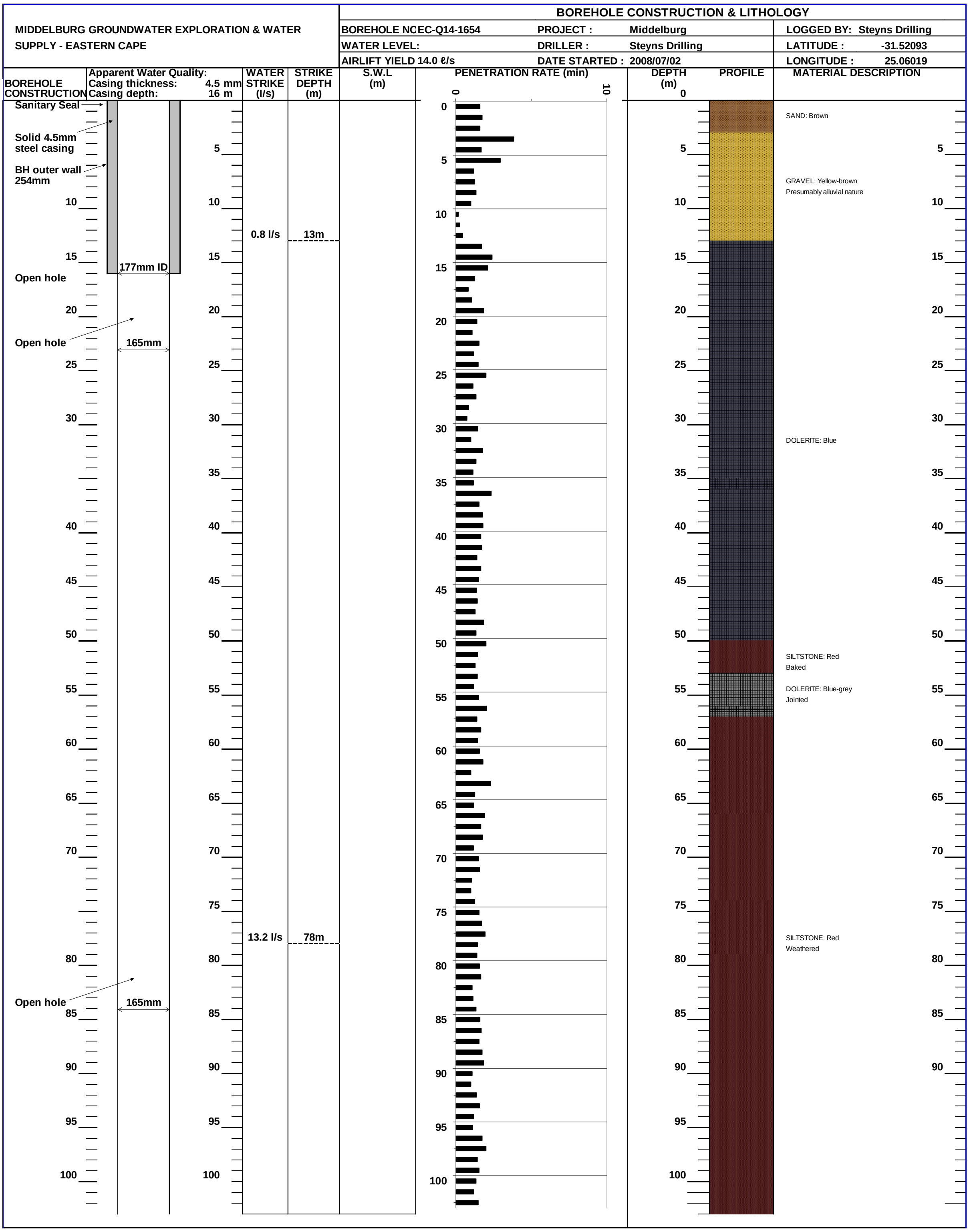

Figure 3-37: Borehole log EC-Q14-1654 part 1 of 2

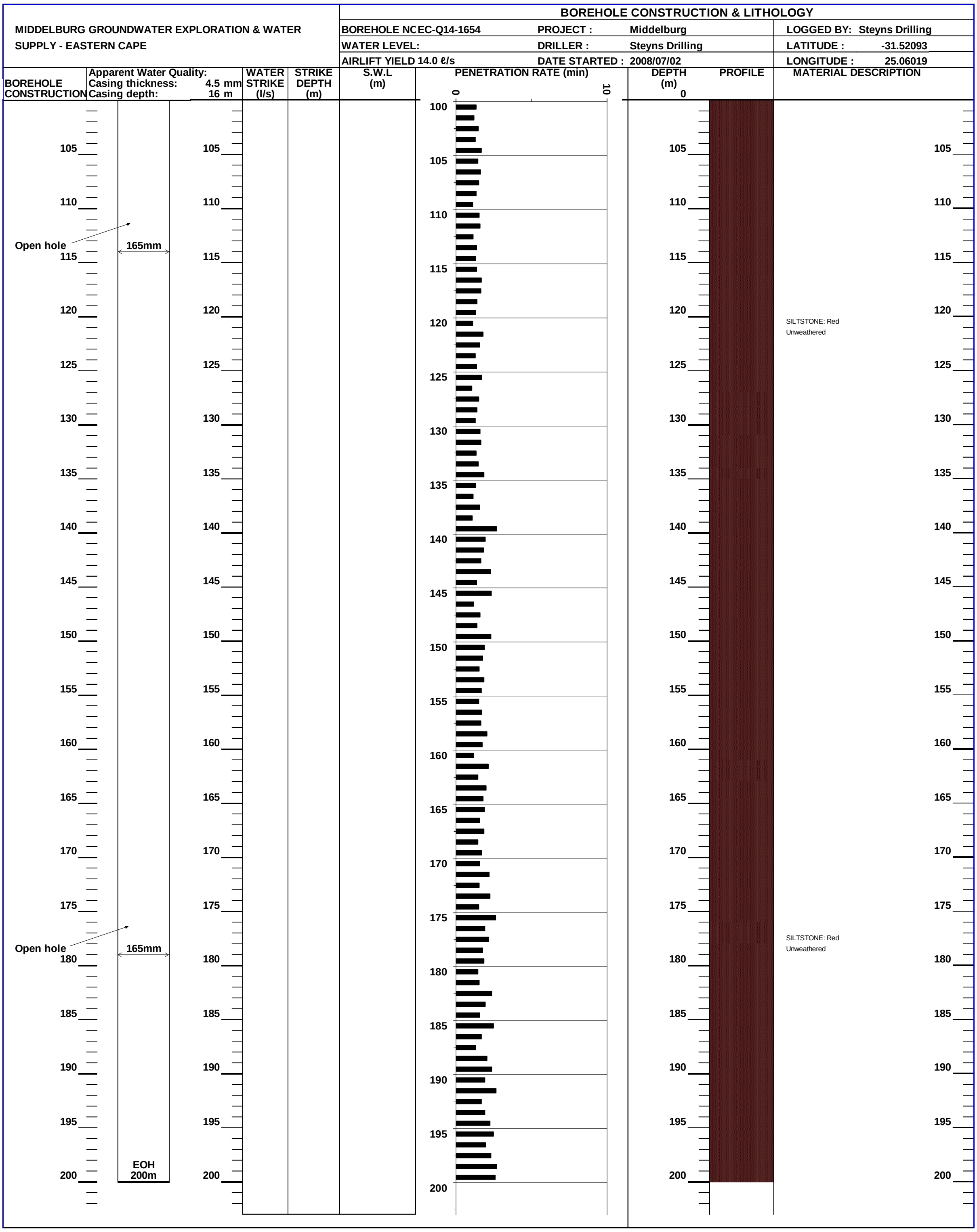

Figure 3-38: Borehole log EC-Q14-1654 part 2 of 2

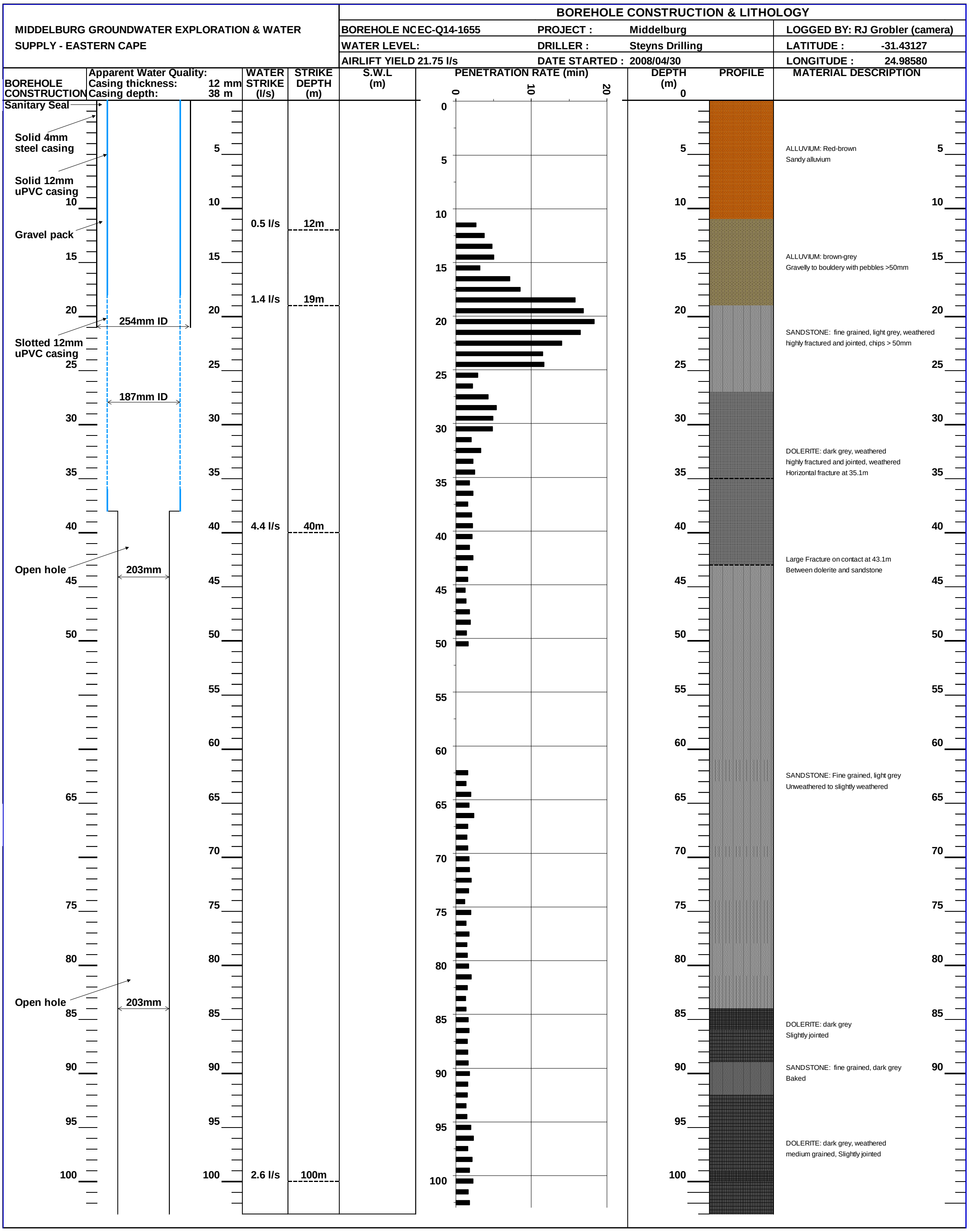

Figure 3-39: Borehole log EC-Q14-1655, Jones Poort, The Glen; log 1 of 3

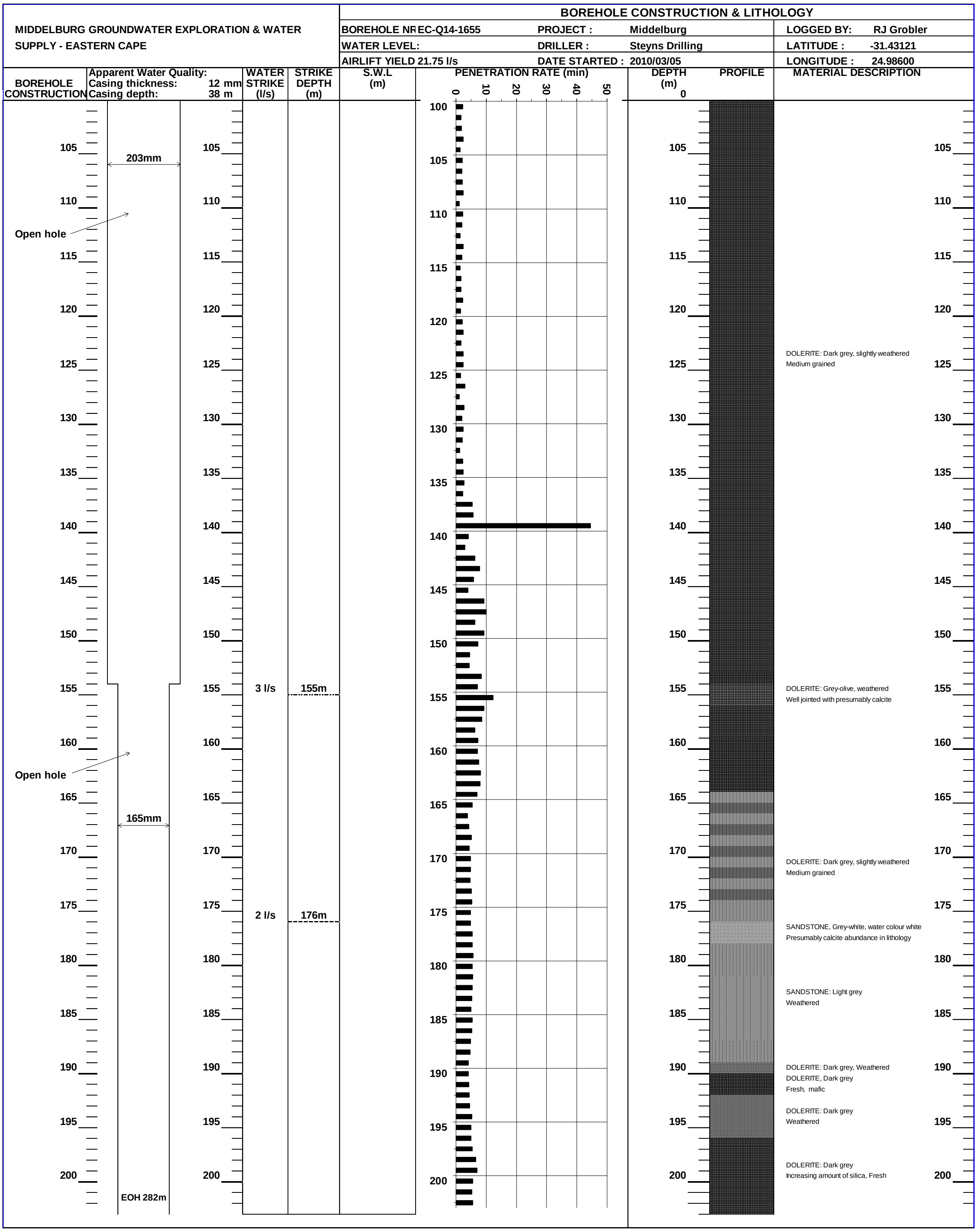

Figure 3-40: Borehole log EC-Q14-1655, Jones Poort, The Glen; log 2 of 3

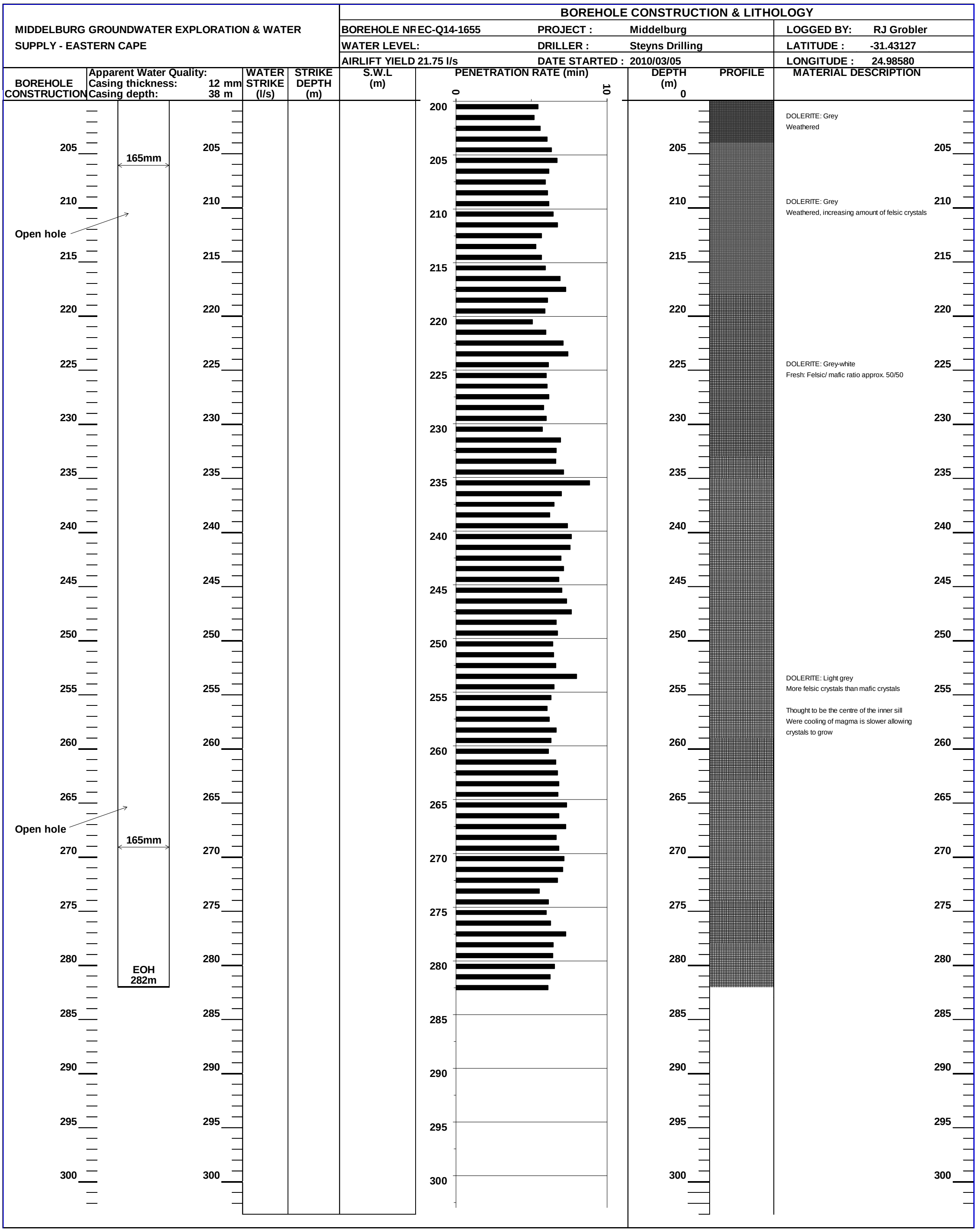

Figure 3-41: Borehole log EC-Q14-1655, Jones Poort, The Glen; log 3 of 3

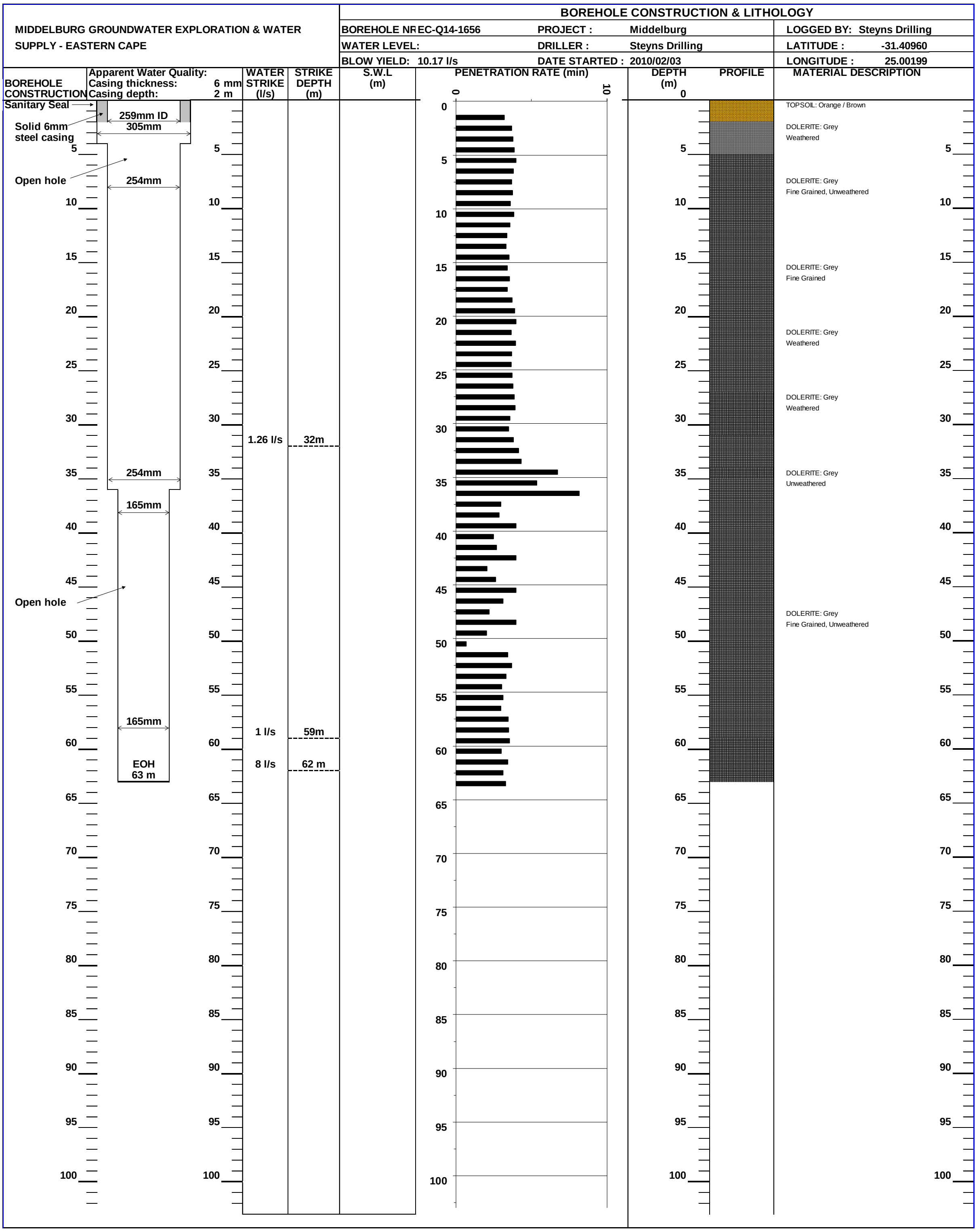

Figure 3-42: Borehole log EC-Q14-1656, EC-Q14-1636 water hammer supply hole

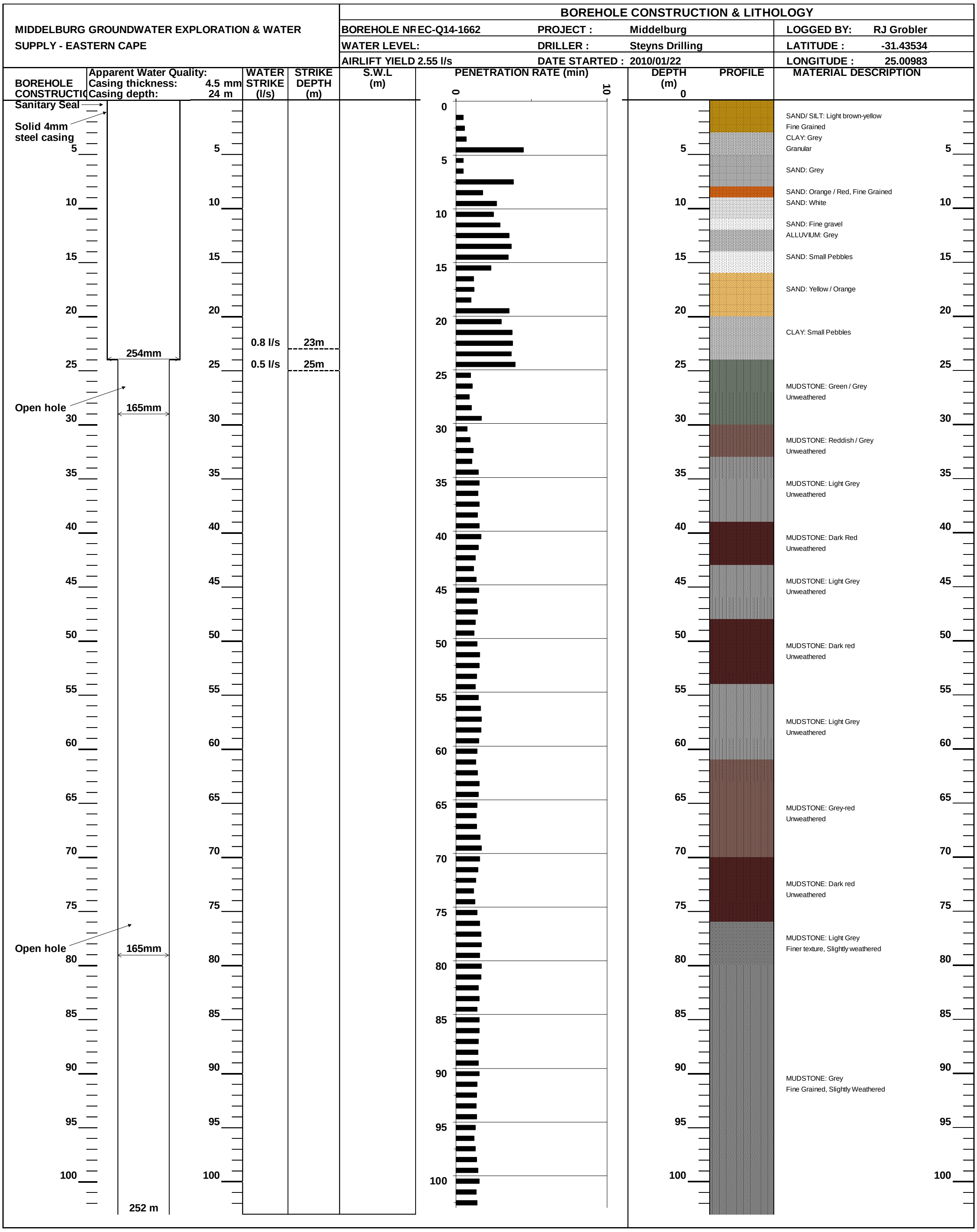

Figure 3-43: Borehole log EC-Q14-1662, Grootfontein sub-catchment; log 1 of 3

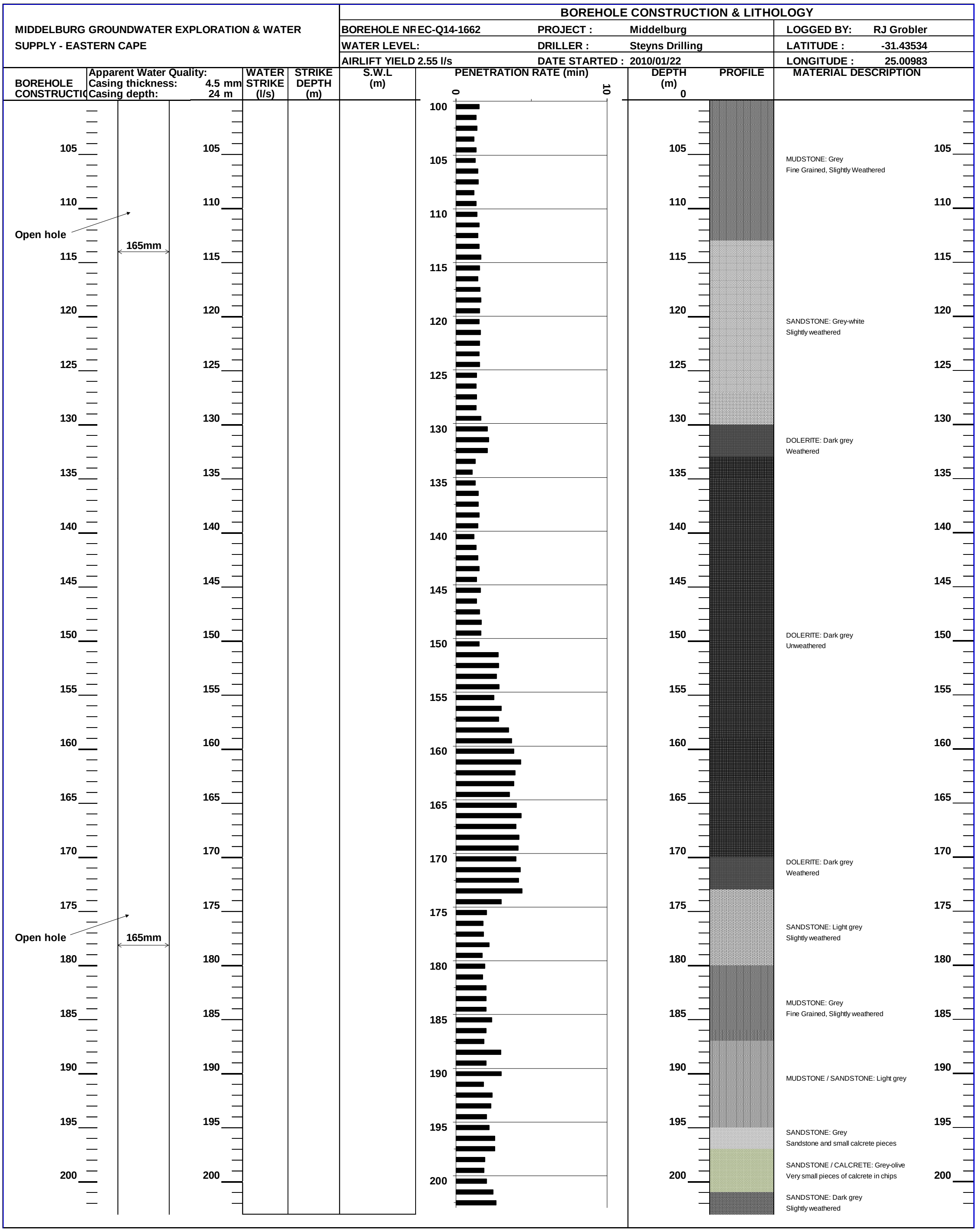

Figure 3-44: Borehole log EC-Q14-1662, Grootfontein sub-catchment; log 2 of 3

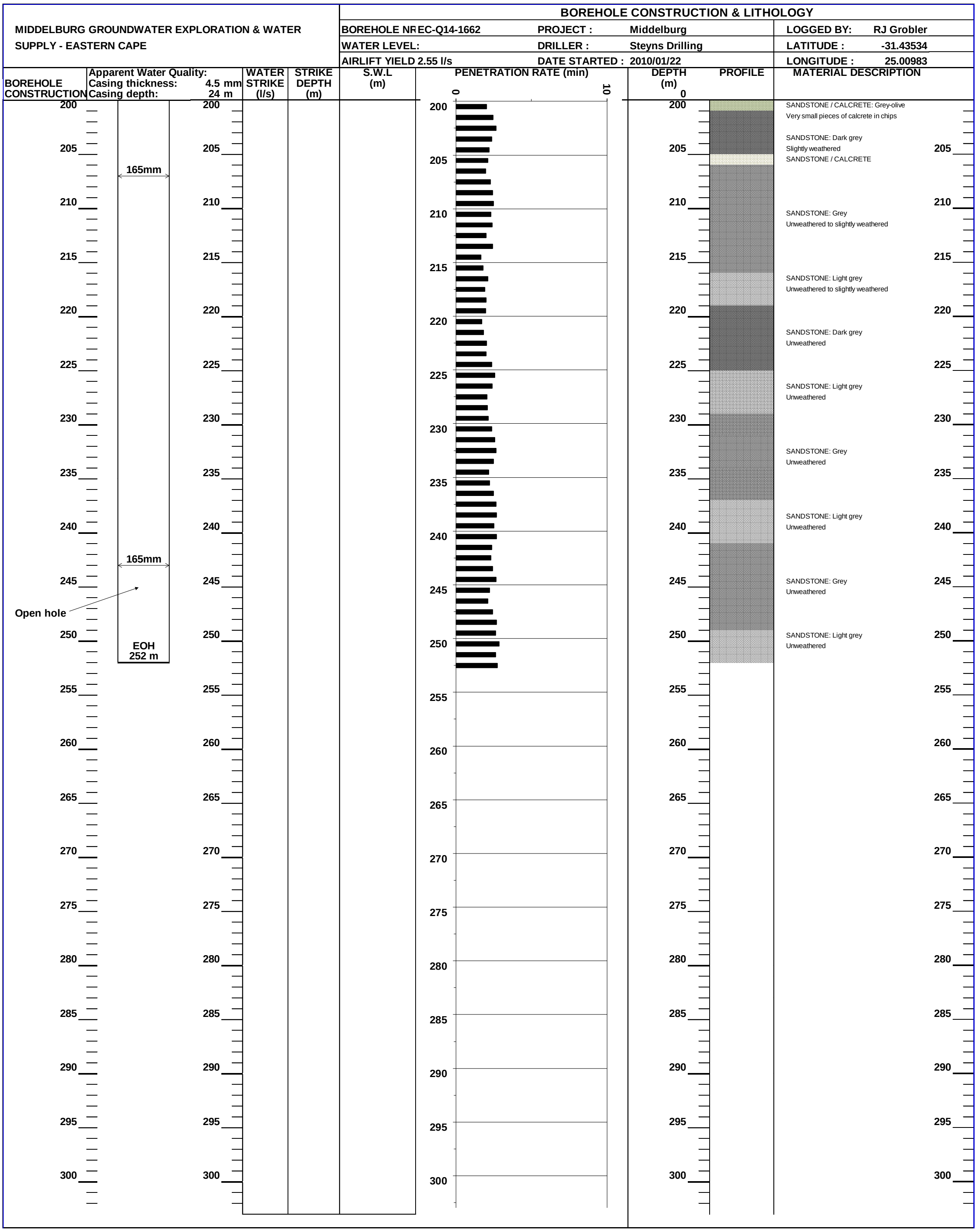

Figure 3-45: Borehole log EC-Q14-1662, Grootfontein sub-catchment; log 3 of 3

4 APPENDIX D: HYDRAULIC (PUMPING) TESTS

4.1 Existing boreholes

STEPPED DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	EC-Q14-101(G31575)		PROJECT:	GWSE - Middelburg Grootfontein Aquifer	
ALTERNATIVE NO. :	0		SITE NAME:	Nuwelei	
ALTERNATIVE NO. :	0		CLIENT:	Department of Water Affairs and Forestry	
BOREHOLE DEPTH (mbdl):	38.80	CASING DEPTH (mbdl):	0.00	PUMP TYPE USED:	P150
DEPTH OF PUMP (mbdl):	37.00	CASING HEIGHT (magl):	0.20	OPERATOR:	0
PUMP INLET DIAMETER (mm):	160.000	CASING ID (mm):	0.000	CONTRACTOR:	AB Pumps
STATIC WATER LEVEL (mbdl):	9.27	DATUM LEVEL (magl):	0.41		

DISCHARGE RATE 1			Time	*Recovery 1*	*DISCHARGE RATE 2*			Time	*Recovery 2*	*DISCHARGE RATE 3*			Time	*Recovery 3*
DATE:	07-May-08		(min)	(m)	DATE:	07-May-08		(min)	(m)	DATE:	07-May-08		(min)	(m)
TIME:	1:50 PM		1		TIME:	14:50		1		TIME:	15:50		1	
Time	Drawdown	Yield	2		Time	Drawdown	Yield	2		Time	Drawdown	Yield	2	
(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3	
1	0.80		5		1	5.13		5		1	10.21		5	
2	1.11		7		2	5.49		7		2	10.30		7	
3	1.33		10		3	6.06	4.830	10		3	10.66		10	
5	1.74		15		5	6.67	4.530	15		5	11.83	9.160	15	
7	2.23	2.180	20		7	7.02		20		7	12.45		20	
10	2.58		30		10	7.35		30		10	13.23		30	
15	3.08		40		15	7.84		40		15	14.27	9.150	40	
20	3.43		50		20	8.22	4.520	50		20	15.17		50	
30	3.90	2.200	60		30	8.81		60		30	16.28		60	
40	4.32		70		40	9.19		70		40	16.96	9.160	70	
50	4.50		80		50	9.46	4.850	80		50	17.85		80	
60	4.72		90		60	9.71	4.530	90		60			90	
70			100		70			100		70			100	
80			110		80			110		80			110	
90			120		90			120		90			120	
100			150		100			150		100			150	
110			180		110			180		110			180	
120			210		120			210		120			210	
Average yield:		2.19	(l/s)		Average yield:		4.652			Average yield:		9.1566667		

DISCHARGE RATE 4			Time	*Recovery 4*	*DISCHARGE RATE 5*			Time	*Recovery 5*	*DISCHARGE RATE 6*			Time	*Recovery*
DATE:	07-May-08		(min)	(m)	DATE:	07-May-08		(min)	(m)	DATE:	07-May-08		(min)	(m)
TIME:			1		TIME:			1		TIME:			1	12.97
Time	Drawdown	Yield	2		Time	Drawdown	.	2		Time	Drawdown	Yield	2	12.38
(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3	11.99
1			5		1			5		1			5	10.81
2			7		2			7		2			7	9.68
3			10		3			10		3			10	9.30
5			15		5			15		5			15	8.28
7			20		7			20		7			20	6.28
10			30		10			30		10			30	4.98
15			40		15			40		15			40	4.08
20			50		20			50		20			50	3.29
30			60		30			60		30			60	2.69
40			70		40			70		40			70	2.26
50			80		50			80		50			80	2.23
60			90		60			90		60			90	1.50
70			100		70			100		70			100	1.28
80			110		80			110		80			110	1.15
90			120		90			120		90			120	1.01
100			150		100			150		100			150	0.7
110			180		110			180		110			180	0.54
120			210		120			210		120			210	
Average yield:		#DIV/0!						240		150			240	
COMMENTS:								300		180			300	
								360		210			360	

CONSTANT DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	EC-Q14-101(G31575)	PROJECT:	GWSE - Middelburg Grootfontein Aquifer	CLIENT:	DWA
ALTERNATIVE NO. :	0	SITE NAME:	Nuwelei		
DEPTH OF PUMP (mbdl):	37.00	PUMP TYPE USED:	P150	OPERATOR:	0
INLET DIAMETER (mm):	160	EXISTING EQUIPMENT:	0	CONTRACTOR:	AB Pumps

TEST STARTED	DATE:	2008/05/10	TEST COMPLETED	DATE:		TOTAL TIME - PUMPED (min):		TOTAL TEST TIME (min):	
	TIME:	1:50 PM		TIME:		TOTAL TIME-RECOVERY(min):		AVERAGE YIELD (l/s):	8.24

DISCHARGE BOREHOLE		*OBSERVATION BOREHOLE 1*		*OBSERVATION BOREHOLE 2*		*OBSERVATION BOREHOLE 3*	
CASING HEIGHT (magl):	0.20	No. :		No. :		No. :	
CASING DEPTH (mbdl):	0.00	DATUM LEVEL (magl):		DATUM LEVEL (magl):		DATUM LEVEL (magl):	
CASING ID (mm):	0.00	CASING DEPTH (mbdl):		CASING DEPTH (mbdl):		CASING DEPTH (mbdl):	
BOREHOLE DEPTH (mbdl):	38.80	BOREHOLE DEPTH :		BOREHOLE DEPTH :		BOREHOLE DEPTH :	
WATER LEVEL (mbdl):	9.27	WATER LEVEL:		WATER LEVEL:		WATER LEVEL:	
DATUM LEVEL (magl):	0.41	DISTANCE (m):		DISTANCE (m):		DISTANCE (m):	

Time (min)	Drawdown (m)	Yield (l/s)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)
1	1.54		15.99	1			1			1		
2	2.49		14.91	2			2			2		
3	3.38		14.08	3			3			3		
5	4.41		13.07	5			5			5		
7	5.31		11.98	7			7			7		
10	5.92	8.20	11.19	10			10			10		
15	7.32		9.72	15			15			15		
20	7.96		9.05	20			20			20		
30	9.02	8.23	7.10	30			30			30		
40	9.60		5.58	40			40			40		
60	11.20		3.61	60			60			60		
90	12.64	8.22	2.12	90			90			90		
120	13.65		1.32	120			120			120		
150	14.34	8.20	0.95	150			150			150		
180	14.92		0.73	180			180			180		
210	15.42		0.58	210			210			210		
240	15.76	8.23	0.49	240			240			240		
300	16.10		0.35	300			300			300		
360	16.38			360			360			360		
420	16.72	8.20		420			420			420		
480	16.86			480			480			480		
540	16.95			540			540			540		
600	17.05	8.23		600			600			600		
720	17.24			720			720			720		
840	17.37			840			840			840		
960	17.40	8.42		960			960			960		
1080	17.51			1080			1080			1080		
1200	17.68			1200			1200			1200		
1320	17.75	8.20		1320			1320			1320		
1440	17.89			1440			1440			1440		
1080				1800			1800			1800		
1140				2280			2280			2280		
1200				2880			2880			2880		
1260												
1320												
1380												
1440												

STEPPED DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	G31583A	PROJECT:	GWSE - Middelburg Grootfontein Aquifer
ALTERNATIVE NO. :	0	SITE NAME:	0
ALTERNATIVE NO. :	0	CLIENT:	DWA

BOREHOLE DEPTH (mbdl):	66.06	CASING DEPTH (mbdl):	0.00	PUMP TYPE USED:	BP105
DEPTH OF PUMP (mbdl):	64.00	CASING HEIGHT (magl):	0.24	OPERATOR:	0
PUMP INLET DIAMETER (mm):	170.000	CASING ID (mm):	0.000	CONTRACTOR:	AB Pumps
STATIC WATER LEVEL (mbdl):	6.05	DATUM LEVEL (magl):	0.20		

DISCHARGE RATE 1			Time	Recovery 1	DISCHARGE RATE 2			Time	Recovery 2	DISCHARGE RATE 3			Time	Recovery 3
DATE:	11-May-08		(min)	(m)	DATE:	11-May-08		(min)	(m)	DATE:	11-May-08		(min)	(m)
TIME:	8:00 AM		1		TIME:	09:00		1		TIME:	10:00		1	
Time	Drawdown	Yield	2		Time	Drawdown	Yield	2		Time	Drawdown	Yield	2	
(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3	
1	0.98		5		1	6.58		5		1	16.18	9.280	5	
2	1.23		7		2	7.05	5.580	7		2	16.80		7	
3	1.46		10		3	7.54		10		3	17.28	10.210	10	
5	1.72	3.320	15		5	8.62	6.150	15		5	20.96		15	
7	2.01		20		7	9.40		20		7	22.42	10.280	20	
10	2.18	3.330	30		10	10.17	6.150	30		10	23.97		30	
15	2.55		40		15	11.50		40		15	25.94	10.230	40	
20	2.87	3.320	50		20	12.23	6.170	50		20	26.86		50	
30	3.52		60		30	13.51		60		30	35.92	10.220	60	
40	4.04	3.310	70		40	14.30	6.160	70		40	47.03		70	
50	4.44		80		50	14.42		80		50	57.92	10.230	80	
60	4.88	3.320	90		60	14.54	6.150	90		51	57.92	9.040	90	
70			100		70			100		52	57.92	8.930	100	
80			110		80			110		53	57.90	8.580	110	
90			120		90			120		90			120	
100			150		100			150		100			150	
110			180		110			180		110			180	
120			210		120			210		120			210	
	Average yield:	3.32	(l/s)			Average yield:	6.06				Average yield:	9.6666667		

DISCHARGE RATE 4			Time	Recovery 4	DISCHARGE RATE 5			Time	Recovery 5	DISCHARGE RATE 6			Time	Recovery
DATE:	11-May-08		(min)	(m)	DATE:	11-May-08		(min)	(m)	DATE:	11-May-08		(min)	(m)
TIME:			1		TIME:			1		TIME:			1	29.74
Time	Drawdown	Yield	2		Time	Drawdown	.	2		Time	Drawdown	Yield	2	25.20
(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3	22.19
1			5		1			5		1			5	21.27
2			7		2			7		2			7	20.13
3			10		3			10		3			10	19.01
5			15		5			15		5			15	17.57
7			20		7			20		7			20	16.33
10			30		10			30		10			30	14.41
15			40		15			40		15			40	12.74
20			50		20			50		20			50	11.25
30			60		30			60		30			60	9.92
40			70		40			70		40			70	8.75
50			80		50			80		50			80	7.67
60			90		60			90		60			90	6.79
70			100		70			100		70			100	6.01
80			110		80			110		80			110	5.24
90			120		90			120		90			120	4.75
100			150		100			150		100			150	3.3
110			180		110			180		110			180	2.38
120			210		120			210		120			210	
	Average yield:	#DIV/0!						240		150			240	
COMMENTS:								300		180			300	
								360		210			360	
								420		240			420	

CONSTANT DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	G31583A	PROJECT:	GWSE - Middelburg Grootfontein Aquifer	CLIENT:	DWA
ALTERNATIVE NO. :	0	SITE NAME:	0		
DEPTH OF PUMP (mbdl):	64.00	PUMP TYPE USED:	BP105	OPERATOR:	0
INLET DIAMETER (mm):	170	EXISTING EQUIPMENT:	0	CONTRACTOR:	AB Pumps

TEST STARTED	DATE:	2008/05/11	TEST COMPLETED	DATE:		TOTAL TIME - PUMPED (min):		TOTAL TEST TIME (min):	
	TIME:	2:30 PM		TIME:		TOTAL TIME-RECOVERY(min):		AVERAGE YIELD (l/s):	6.76

DISCHARGE BOREHOLE		OBSERVATION BOREHOLE 1		OBSERVATION BOREHOLE 2		OBSERVATION BOREHOLE 3	
CASING HEIGHT (magl):	0.24	No. :	G31583B	No. :		No. :	
CASING DEPTH (mbdl):	0.00	DATUM LEVEL (magl):		DATUM LEVEL (magl):		DATUM LEVEL (magl):	
CASING ID (mm):	0.00	CASING DEPTH (mbdl):		CASING DEPTH (mbdl):		CASING DEPTH (mbdl):	
BOREHOLE DEPTH (mbdl):	66.06	BOREHOLE DEPTH :		BOREHOLE DEPTH :		BOREHOLE DEPTH :	
WATER LEVEL (mbdl):	6.05	WATER LEVEL:		WATER LEVEL:		WATER LEVEL:	
DATUM LEVEL (magl):	0.20	DISTANCE (m):		DISTANCE (m):		DISTANCE (m):	

Time (min)	Drawdown (m)	Yield (l/s)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)
1	0.78		27.57	1			1			1		
2	2.27		23.93	2			2			2		
3	4.15		22.94	3			3			3		
5	6.13	6.85	22.62	5			5			5		
7	7.45		22.52	7			7			7		
10	9.02	6.84	22.22	10	5.92	20.43	10			10		
15	11.04		21.68	15			15			15		
20	11.96	6.85	22.29	20			20			20		
30	14.42		20.58	30	11.75	19.14	30			30		
40	16.27	6.85	19.79	40	13.90	18.46	40			40		
60	18.76		18.52	60	16.39	17.45	60			60		
90	21.51	6.83	16.80	90	18.90	16.29	90			90		
120	22.78		14.55	120	20.59	13.80	120			120		
150	22.88	6.83	12.86	150	20.70	12.46	150			150		
180	25.55		11.37	180	21.03	10.52	180			180		
210	33.28	6.84	10.10	210	21.25	9.83	210			210		
240	35.15		8.77	240	21.23	8.60	240			240		
300	38.01	6.85	6.40	300	21.20	6.32	300			300		
360	41.43		4.30	360	21.15	4.28	360			360		
420	46.29	6.85	2.65	420	21.13	2.64	420			420		
480	49.62		1.38	480	21.11	1.43	480			480		
540	51.68	6.85	0.55	540	21.08	0.58	540			540		
600	52.30		0.17	600	21.05	0.20	600			600		
720	53.88	6.84	0.00	720	21.01	0.00	720			720		
840	54.38			840			840			840		
960	55.95	5.88		960			960			960		
840				1080			1080			1080		
900				1200			1200			1200		
960				1320			1320			1320		
1020				1440			1440			1440		
1080				1800			1800			1800		
1140				2280			2280			2280		
1200				2880			2880			2880		
1260												
1320												
1380												
1440												

STEPPED DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	G31610	PROJECT:	GWSE - Middelburg Grootfontein Aquifer
ALTERNATIVE NO. :	0	SITE NAME:	Danblane Farm
ALTERNATIVE NO. :	0	CLIENT:	DWA

BOREHOLE DEPTH (mbdl):	40.00	CASING DEPTH (mbdl):	0.00	PUMP TYPE USED:	GW1304
DEPTH OF PUMP (mbdl):	34.00	CASING HEIGHT (magl):	0.20	OPERATOR:	Isaac
PUMP INLET DIAMETER (mm):	160.000	CASING ID (mm):	0.000	CONTRACTOR:	AB Pumps
STATIC WATER LEVEL (mbdl):	8.44	DATUM LEVEL (magl):	0.34		

DISCHARGE RATE 1			Time	Recovery 1	DISCHARGE RATE 2			Time	Recovery 2	DISCHARGE RATE 3			Time	Recovery 3
DATE:	31-Aug-07		(min)	(m)	DATE:	31-Aug-07		(min)	(m)	DATE:	31-Aug-07		(min)	(m)
TIME:	3:20 PM		1		TIME:	4:20 PM		1		TIME:	5:20 PM		1	
Time	Drawdown	Yield	2		Time	Drawdown	Yield	2		Time	Drawdown	Yield	2	
(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3	
1	0.02		5		1	0.48		5		1	1.02		5	
2	0.05		7		2	0.52	2.61	7		2	1.05		7	
3	0.08		10		3	0.56	3.04	10		3	1.11		10	
5	0.10	1.03	15		5	0.59		15		5	1.13	5.51	15	
7	0.10	1.52	20		7	0.62	3.06	20		7	1.17		20	
10	0.15		30		10	0.66		30		10	1.28	5.50	30	
15	0.23	1.50	40		15	0.70	3.08	40		15	1.39		40	
20	0.27		50		20	0.76		50		20	1.48	5.54	50	
30	0.33	1.52	60		30	0.83	3.05	60		30	1.58	5.55	60	
40	0.37		70		40	0.89	3.06	70		40	1.72	5.51	70	
50	0.40	1.50	80		50	0.93	3.10	80		50	1.79	5.54	80	
60	0.44		90		60	1.00	3.08	90		60	1.84	5.59	90	
70			100		70			100		70			100	
80			110		80			110		80			110	
90			120		90			120		90			120	
100			150		100			150		100			150	
110			180		110			180		110			180	
120			210		120			210		120			210	
	Average yield:	1.414	(l/s)			Average yield:	3.01				Average yield:	5.5342857		

DISCHARGE RATE 4			Time	Recovery 4	DISCHARGE RATE 5			Time	Recovery 5	DISCHARGE RATE 6			Time	Recovery
DATE:	31-Aug-07		(min)	(m)	DATE:	31-Aug-07		(min)	(m)	DATE:	31-Aug-07		(min)	(m)
TIME:	6:20 PM		1		TIME:			1		TIME:			1	1.70
Time	Drawdown	Yield	2		Time	Drawdown	.	2		Time	Drawdown	Yield	2	1.67
(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3	1.56
1	1.97		5		1			5		1			5	1.43
2	2.08		7		2			7		2			7	1.34
3	2.15	7.80	10		3			10		3			10	1.29
5	2.19		15		5			15		5			15	1.17
7	2.23	7.87	20		7			20		7			20	1.07
10	2.27	7.84	30		10			30		10			30	0.96
15	2.33	7.89	40		15			40		15			40	0.89
20	2.38	7.90	50		20			50		20			50	0.81
30	2.44	7.89	60		30			60		30			60	0.75
40	2.46	7.91	70		40			70		40			70	0.69
50	2.47	7.88	80		50			80		50			80	0.62
60	2.53		90		60			90		60			90	0.59
70			100		70			100		70			100	0.54
80			110		80			110		80			110	0.50
90			120		90			120		90			120	0.47
100			150		100			150		100			150	0.44
110			180		110			180		110			180	0.29
120			210		120			210		120			210	0.22
	Average yield:	7.8725						240		150			244	0.14
COMMENTS:								300		180			300	
								360		210			360	
								420		240			420	

STEPPED DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	G31614	PROJECT:	GWSD - Middelburg Grootfontein Aquifer
ALTERNATIVE NO. :	0	SITE NAME:	Danblane Farm
ALTERNATIVE NO. :	0	CLIENT:	Department of Water Affairs

BOREHOLE DEPTH (mbdl):	40.54	CASING DEPTH (mbdl):	0.00	PUMP TYPE USED:	GW9002
DEPTH OF PUMP (mbdl):	35.15	CASING HEIGHT (magl):	0.12	OPERATOR:	Muyanalo
PUMP INLET DIAMETER (mm):	160.000	CASING ID (mm):	0.000	CONTRACTOR:	AB Pumps
STATIC WATER LEVEL (mbdl):	8.68	DATUM LEVEL (magl):	0.37		

DISCHARGE RATE 1			Time	Recovery 1	DISCHARGE RATE 2			Time	Recovery 2	DISCHARGE RATE 3			Time	Recovery 3
DATE:	01-Sep-07		(min)	(m)	DATE:	01-Sep-07		(min)	(m)	DATE:	01-Sep-07		(min)	(m)
TIME:	10:50 AM		1		TIME:	11:50		1		TIME:	12:50		1	
Time	Drawdown	Yield	2		Time	Drawdown	Yield	2		Time	Drawdown	Yield	2	
(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3	
1	0.17		5		1	0.84		5		1	2.15		5	
2	0.20		7		2	0.87		7		2	2.23		7	
3	0.26		10		3	0.90	3.530	10		3	2.37	6.560	10	
5	0.29		15		5	0.87		15		5	2.43	7.140	15	
7	0.32	2.010	20		7	1.03		20		7	2.54	7.140	20	
10	0.35	2.050	30		10	1.08	3.500	30		10	2.63	7.110	30	
15	0.39	2.030	40		15	1.16	3.580	40		15	2.82	7.150	40	
20	0.42	2.000	50		20	1.22	3.550	50		20	2.91	7.130	50	
30	0.49	2.020	60		30	1.33	3.510	60		30	3.06	7.100	60	
40	0.53	2.010	70		40	1.42	3.530	70		40	3.19	7.120	70	
50	0.57	2.070	80		50	1.50	3.500	80		50	3.31	7.140	80	
60	0.63	2.050	90		60	1.59	3.540	90		60	3.43	7.110	90	
70			100		70			100		70			100	
80			110		80			110		80			110	
90			120		90			120		90			120	
100			150		100			150		100			150	
110			180		110			180		110			180	
120			210		120			210		120			210	
	Average yield:	2.03	(l/s)			Average yield:	3.53				Average yield:	7.07		

DISCHARGE RATE 4			Time	Recovery 4	DISCHARGE RATE 5			Time	Recovery 5	DISCHARGE RATE 6			Time	Recovery
DATE:	01-Sep-07		(min)	(m)	DATE:	01-Sep-07		(min)	(m)	DATE:	01-Sep-07		(min)	(m)
TIME:	13:50		1		TIME:	14:50		1		TIME:			1	10.64
Time	Drawdown	Yield	2		Time	Drawdown	Yield	2		Time	Drawdown	Yield	2	9.15
(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3	8.30
1	4.40		5		1	7.86		5		1			5	7.38
2	4.58		7		2	7.90		7		2			7	6.79
3	4.67	10.96	10		3	7.98	18.40	10		3			10	6.28
5	4.80	12.01	15		5	8.94	25.28	15		5			15	5.64
7	4.91		20		7	9.93		20		7			20	5.29
10	5.00	12.08	30		10	10.37	25.26	30		10			30	4.68
15	5.13	12.05	40		15	10.85	25.23	40		15			40	4.17
20	5.29	12.07	50		20	11.23		50		20			50	3.75
30	5.48	12.03	60		30	11.73	25.24	60		30			60	3.52
40	5.70	12.00	70		40	12.22	25.21	70		40			70	3.24
50	5.82	12.04	80		50	12.51	25.26	80		50			80	2.87
60	6.07	12.01	90		60	13.13		90		60			90	2.74
70			100		70			100		70			100	2.54
80			110		80			110		80			110	2.40
90			120		90			120		90			120	2.24
100			150		100			150		100			150	1.89
110			180		110			180		110			180	1.66
120			210		120			210		120			210	1.44
	Average yield:	11.916667				Average yield:	24.268571	240		150			240	1.29
COMMENTS:								300		180			300	1.18
								360		210			360	
								420		240			420	

CONSTANT DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	G31614	PROJECT:	GWSD - Middelburg Grootfontein Aquifer	CLIENT:	Department of Water Affairs
ALTERNATIVE NO. :	0	SITE NAME:	Danblane Farm		
DEPTH OF PUMP (mbdl):	35.15	PUMP TYPE USED:	GW9002	OPERATOR:	Muyanalo
INLET DIAMETER (mm):	160	EXISTING EQUIPMENT:	0	CONTRACTOR:	AB Pumps

TEST STARTED	DATE:	2-Sep-07	TEST COMPLETED	DATE:	4-Sep-07	TOTAL TIME - PUMPED (min):	1320	TOTAL TEST TIME (min):	2640
	TIME:	8:00 AM		TIME:	12:00 AM	TOTAL TIME-RECOVERY(min):	1320	AVERAGE YIELD (l/s):	19.97

DISCHARGE BOREHOLE		*OBSERVATION BOREHOLE 1*		*OBSERVATION BOREHOLE 2*		*OBSERVATION BOREHOLE 3*	
CASING HEIGHT (magl):	0.12	No. :		No. :		No. :	
CASING DEPTH (mbdl):	0.00	DATUM LEVEL (magl):		DATUM LEVEL (magl):		DATUM LEVEL (magl):	
CASING ID (mm):	0.00	CASING DEPTH (mbdl):		CASING DEPTH (mbdl):		CASING DEPTH (mbdl):	
BOREHOLE DEPTH (mbdl):	40.54	BOREHOLE DEPTH :		BOREHOLE DEPTH :		BOREHOLE DEPTH :	
WATER LEVEL (mbdl):	8.68	WATER LEVEL:		WATER LEVEL:		WATER LEVEL:	
DATUM LEVEL (magl):	0.37	DISTANCE (m):		DISTANCE (m):		DISTANCE (m):	

Time (min)	Drawdown (m)	Yield (l/s)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)
1	0.79		13.79	1			1			1		
2	1.92		13.18	2			2			2		
3	2.94	17.61	12.91	3			3			3		
5	3.81	20.06	12.44	5			5			5		
7	4.55		12.01	7			7			7		
10	4.86	20.09	11.65	10			10			10		
15	5.35	20.07	11.12	15			15			15		
20	5.72	20.04	10.96	20			20			20		
30	6.25	20.06	9.87	30			30			30		
40	6.66	20.01	9.16	40			40			40		
60	7.48	20.03	7.94	60			60			60		
90	8.47	20.00	6.50	90			90			90		
120	9.34	20.05	5.31	120			120			120		
150	10.15	20.08	4.33	150			150			150		
180	10.76	20.06	3.47	180			180			180		
210	11.34	20.04	2.90	210			210			210		
240	11.75	20.07	2.44	240			240			240		
300	12.49	20.09	1.85	300			300			300		
360	13.02	20.02	1.49	360			360			360		
420	14.03	20.08	1.27	420			420			420		
480	14.62	20.05	1.09	480			480			480		
540	15.08	20.10	0.96	540			540			540		
600	15.61	20.07	0.85	600			600			600		
720	16.24	20.01	0.72	720			720			720		
840	17.04	20.06	0.60	840			840			840		
960	17.53	20.40	0.51	960			960			960		
1080	17.85	20.08	0.43	1080			1080			1080		
1200	18.09	20.03	0.38	1200			1200			1200		
1320	18.16	20.00	0.33	1320			1320			1320		
1320				1440			1440			1440		
1080				1800			1800			1800		
1140				2280			2280			2280		
1200				2880			2880			2880		
1260												
1320												
1380												
1440												

STEPPED DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	EC-Q14-192			PROJECT:	Middelburg Grootfontein Aquifer
ALTERNATIVE NO. :	0			SITE NAME:	0
ALTERNATIVE NO. :	0			CLIENT:	Department of Water Affairs and Forestry
BOREHOLE DEPTH (mbdl):	29.20	CASING DEPTH (mbdl):	0.00	PUMP TYPE USED:	BP105
DEPTH OF PUMP (mbdl):	28.00	CASING HEIGHT (magl):	0.27	OPERATOR:	0
PUMP INLET DIAMETER (mm):	160.000	CASING ID (mm):	0.000	CONTRACTOR:	AB Pumps
STATIC WATER LEVEL (mbdl):	10.36	DATUM LEVEL (magl):	0.15		

DISCHARGE RATE 1			Time	Recovery 1	DISCHARGE RATE 2			Time	Recovery 2	DISCHARGE RATE 3			Time	Recovery 3
DATE:	14-May-08		(min)	(m)	DATE:	14-May-08		(min)	(m)	DATE:	14-May-08		(min)	(m)
TIME:	9:40 AM		1		TIME:	10:40		1		TIME:	11:40		1	
Time	Drawdown	Yield	2		Time	Drawdown	Yield	2		Time	Drawdown	Yield	2	
(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3	
1	0.24		5		1	0.63		5		1	1.32		5	
2	0.27	3.030	7		2	0.69	5.890	7		2	1.39	11.940	7	
3	0.30		10		3	0.77		10		3	1.48		10	
5	0.33	3.030	15		5	0.82	6.400	15		5	1.67	12.060	15	
7	0.36		20		7	0.85		20		7	1.74		20	
10	0.36	3.040	30		10	0.89	6.420	30		10	1.83	12.050	30	
15	0.38		40		15	0.94		40		15	1.94		40	
20	0.39	3.020	50		20	0.98	6.410	50		20	2.01	12.050	50	
30	0.40		60		30	1.02		60		30	2.09		60	
40	0.40	3.010	70		40	1.04	6.400	70		40	2.14	12.040	70	
50	0.41		80		50	1.04		80		50	2.19		80	
60	0.41	3.020	90		60	1.05	6.410	90		60	2.24	12.040	90	
70			100		70			100		70			100	
80			110		80			110		80			110	
90			120		90			120		90			120	
100			150		100			150		100			150	
110			180		110			180		110			180	
120			210		120			210		120			210	
	Average yield:	3.025	(l/s)			Average yield:	6.3216667				Average yield:	12.03		

DISCHARGE RATE 4			Time	Recovery 4	DISCHARGE RATE 5			Time	Recovery 5	DISCHARGE RATE 6			Time	Recovery
DATE:	14-May-08		(min)	(m)	DATE:	14-May-08		(min)	(m)	DATE:	14-May-08		(min)	(m)
TIME:	12:40		1		TIME:			1		TIME:			1	3.82
Time	Drawdown	Yield	2		Time	Drawdown	.	2		Time	Drawdown	Yield	2	3.10
(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3	2.65
1	3.15		5		1			5		1			5	2.25
2	3.34	24.10	7		2			7		2			7	1.87
3	3.58		10		3			10		3			10	1.50
5	3.93	24.10	15		5			15		5			15	1.07
7	4.09		20		7			20		7			20	0.85
10	4.29	24.12	30		10			30		10			30	0.60
15	4.67		40		15			40		15			40	0.44
20	4.93	24.11	50		20			50		20			50	0.32
30	5.17		60		30			60		30			60	0.26
40	5.44	24.11	70		40			70		40			70	0.22
50	5.64		80		50			80		50			80	0.20
60	5.83	24.10	90		60			90		60			90	0.17
70			100		70			100		70			100	0.14
80			110		80			110		80			110	0.13
90			120		90			120		90			120	0.12
100			150		100			150		100			150	0.11
110			180		110			180		110			180	0.1
120			210		120			210		120			210	
	Average yield:	24.106667						240		150			240	
COMMENTS:								300		180			300	
								360		210			360	
								420		240			420	

CONSTANT DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	EC-Q14-192	PROJECT:	Middelburg Grootfontein Aquifer	CLIENT:	DWA
ALTERNATIVE NO. :	0	SITE NAME:	0		
DEPTH OF PUMP (mbdl):	28.00	PUMP TYPE USED:	BP105	OPERATOR:	0
INLET DIAMETER (mm):	160	EXISTING EQUIPMENT:	0	CONTRACTOR:	AB Pumps

TEST STARTED	DATE: 2008/05/14	TEST COMPLETED	DATE:	TOTAL TIME - PUMPED (min):		TOTAL TEST TIME (min):	
	TIME: 5:00 PM		TIME:	TOTAL TIME-RECOVERY(min):		AVERAGE YIELD (l/s):	14.61

DISCHARGE BOREHOLE		OBSERVATION BOREHOLE 1		OBSERVATION BOREHOLE 2		OBSERVATION BOREHOLE 3	
CASING HEIGHT (magl):	0.27	No. :	EC-Q14-192A	No. :		No. :	
CASING DEPTH (mbdl):	0.00	DATUM LEVEL (magl):		DATUM LEVEL (magl):		DATUM LEVEL (magl):	
CASING ID (mm):	0.00	CASING DEPTH (mbdl):		CASING DEPTH (mbdl):		CASING DEPTH (mbdl):	
BOREHOLE DEPTH (mbdl):	29.20	BOREHOLE DEPTH :		BOREHOLE DEPTH :		BOREHOLE DEPTH :	
WATER LEVEL (mbdl):	10.36	WATER LEVEL:		WATER LEVEL:		WATER LEVEL:	
DATUM LEVEL (magl):	0.15	DISTANCE (m):		DISTANCE (m):		DISTANCE (m):	

Time (min)	Drawdown (m)	Yield (l/s)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)
1	0.85		2.47	1			1			1		
2	1.10		2.19	2			2			2		
3	1.26	14.51	2.00	3			3			3		
5	1.60		1.88	5			5			5		
7	1.83	14.62	1.60	7			7			7		
10	2.02		1.35	10	0.29	0.79	10			10		
15	2.27	14.60	1.15	15	0.34	0.79	15			15		
20	2.40		0.98	20	0.40	0.70	20			20		
30	2.58	14.62	0.80	30	0.53	0.56	30			30		
40	2.71		0.69	40	0.68	0.50	40			40		
60	2.85	14.61	0.56	60	0.80	0.43	60			60		
90	2.96		0.47	90	0.82	0.36	90			90		
120	3.02	14.63	0.38	120	0.82	0.30	120			120		
150	3.05		0.32	150	0.81	0.25	150			150		
180	3.08	14.62	0.29	180	0.81	0.21	180			180		
210	3.10		0.26	210	0.80	0.19	210			210		
240	3.12	14.64	0.24	240	0.79	0.17	240			240		
300	3.15		0.23	300	0.79	0.13	300			300		
360	3.18	14.64	0.21	360	0.79	0.11	360			360		
420	3.20		0.20	420	0.79	0.09	420			420		
480	3.22	14.63	0.19	480	0.79	0.06	480			480		
540	3.23		0.18	540	0.79	0.04	540			540		
600	3.23	14.62	0.17	600	0.79	0.02	600			600		
720	3.25		0.16	720	0.79	0.00	720			720		
840	3.27	14.60	0.15	840	0.79		840			840		
960	3.31		0.14	960	0.79		960			960		
1080	3.32	14.62	0.14	1080	0.79		1080			1080		
1200	3.33		0.13	1200	0.79		1200			1200		
1320	3.35	14.60	0.13	1320	0.79		1320			1320		
1440	3.38		0.12	1440	0.79		1440			1440		
1560	3.40	14.63		1800			1800			1800		
1680	3.41			2280			2280			2280		
1800	3.43	14.62		2880			2880			2880		
1920	3.45											
2040	3.48	14.62										
2160	3.50											
1440												

STEPPED DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	EC-Q14-341(G31581)	PROJECT:	GWSE - Middelburg Grootfontein Aquifer
ALTERNATIVE NO. :	0	SITE NAME:	Bufferspoort
ALTERNATIVE NO. :	0	CLIENT:	DWA

BOREHOLE DEPTH (mbdl):	71.00	CASING DEPTH (mbdl):	0.00	PUMP TYPE USED:	P150
DEPTH OF PUMP (mbdl):	70.00	CASING HEIGHT (magl):	0.30	OPERATOR:	0
PUMP INLET DIAMETER (mm):	165.000	CASING ID (mm):	0.000	CONTRACTOR:	AB Pumps
STATIC WATER LEVEL (mbdl):	9.25	DATUM LEVEL (magl):	0.32		

DISCHARGE RATE 1			Time	Recovery 1	DISCHARGE RATE 2			Time	Recovery 2	DISCHARGE RATE 3			Time	Recovery 3
DATE:	03-May-08		(min)	(m)	DATE:	03-May-08		(min)	(m)	DATE:	03-May-08		(min)	(m)
TIME:	6:00 AM		1		TIME:	07:00		1		TIME:	08:00		1	
Time	Drawdown	Yield	2		Time	Drawdown	Yield	2		Time	Drawdown	Yield	2	
(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3	
1	1.60		5		1	6.24		5		1	9.30		5	
2	2.44		7		2	6.69		7		2	10.12		7	
3	2.80	0.750	10		3	7.02	1.550	10		3	10.82		10	
5	3.26		15		5	7.15		15		5	13.24	3.050	15	
7	3.50	0.740	20		7	7.20	1.540	20		7	15.47		20	
10	3.82		30		10	7.26		30		10	18.23	3.040	30	
15	4.10	0.750	40		15	7.32	1.550	40		15	21.55		40	
20	4.33		50		20	7.49		50		20	24.17	3.050	50	
30	4.60	0.740	60		30	7.72	1.540	60		30	25.93		60	
40	4.86		70		40	7.90		70		40	27.47	3.040	70	
50	5.06	0.750	80		50	8.20	1.550	80		50	29.97		80	
60	5.18		90		60	8.21		90		60	32.51	3.050	90	
70			100		70			100		70			100	
80			110		80			110		80			110	
90			120		90			120		90			120	
100			150		100			150		100			150	
110			180		110			180		110			180	
120			210		120			210		120			210	
	Average yield:	0.746	(l/s)			Average yield:	1.546				Average yield:	3.046		

DISCHARGE RATE 4			Time	Recovery 4	DISCHARGE RATE 5			Time	Recovery 5	DISCHARGE RATE 6			Time	Recovery
DATE:	03-May-08		(min)	(m)	DATE:	03-May-08		(min)	(m)	DATE:	03-May-08		(min)	(m)
TIME:	09:00		1		TIME:			1		TIME:			1	50.14
Time	Drawdown	Yield	2		Time	Drawdown	Yield	2		Time	Drawdown	Yield	2	43.09
(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3	34.53
1	37.37		5		1			5		1			5	23.78
2	39.48		7		2			7		2			7	11.81
3	42.21		10		3			10		3			10	5.07
5	44.50	4.35	15		5			15		5			15	4.30
7	47.31	5.05	20		7			20		7			20	3.70
10	51.02		30		10			30		10			30	2.87
15	51.85		40		15			40		15			40	2.43
20	51.85	2.86	50		20			50		20			50	2.16
21	51.85	2.80	60		30			60		30			60	2.01
22	51.85	2.60	70		40			70		40			70	1.82
50			80		50			80		50			80	1.67
60			90		60			90		60			90	1.53
70			100		70			100		70			100	1.45
80			110		80			110		80			110	1.34
90			120		90			120		90			120	1.23
100			150		100			150		100			150	1.16
110			180		110			180		110			180	0.9
120			210		120			210		120			210	
	Average yield:	3.532						240		150			240	
COMMENTS:								300		180			300	
								360		210			360	
								420		240			420	

CONSTANT DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	EC-Q14-341(G31581)	**PROJECT:**	GWSE - Middelburg Grootfontein Aquifer	**CLIENT:**	DWA
ALTERNATIVE NO. :	0	**SITE NAME:**	Bufferspoort		
DEPTH OF PUMP (mbdl):	70.00	**PUMP TYPE USED:**	P150	**OPERATOR:**	0
INLET DIAMETER (mm):	165	**EXISTING EQUIPMENT:**	0	**CONTRACTOR:**	AB Pumps

TEST STARTED	**DATE:**	2008/05/03	**TEST COMPLETED**	**DATE:**		**TOTAL TIME - PUMPED (min):**		**TOTAL TEST TIME (min):**	
	TIME:	12:30 PM		**TIME:**		**TOTAL TIME-RECOVERY(min):**		**AVERAGE YIELD (l/s):**	1.85

DISCHARGE BOREHOLE		*OBSERVATION BOREHOLE 1*		*OBSERVATION BOREHOLE 2*		*OBSERVATION BOREHOLE 3*	
CASING HEIGHT (magl):	0.30	**No. :**		**No. :**		**No. :**	
CASING DEPTH (mbdl):	0.00	**DATUM LEVEL (magl):**		**DATUM LEVEL (magl):**		**DATUM LEVEL (magl):**	
CASING ID (mm):	0.00	**CASING DEPTH (mbdl):**		**CASING DEPTH (mbdl):**		**CASING DEPTH (mbdl):**	
BOREHOLE DEPTH (mbdl):	71.00	**BOREHOLE DEPTH :**		**BOREHOLE DEPTH :**		**BOREHOLE DEPTH :**	
WATER LEVEL (mbdl):	9.25	**WATER LEVEL:**		**WATER LEVEL:**		**WATER LEVEL:**	
DATUM LEVEL (magl):	0.32	**DISTANCE (m):**		**DISTANCE (m):**		**DISTANCE (m):**	

Time (min)	Drawdown (m)	Yield (l/s)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)
1	2.48		9.30	**1**			**1**			**1**		
2	3.65		7.57	**2**			**2**			**2**		
3	4.25		6.51	**3**			**3**			**3**		
5	5.78	1.88	5.31	**5**			**5**			**5**		
7	6.76		4.77	**7**			**7**			**7**		
10	7.64	1.84	4.39	**10**			**10**			**10**		
15	8.31		4.03	**15**			**15**			**15**		
20	8.81	1.85	3.81	**20**			**20**			**20**		
30	8.86		3.52	**30**			**30**			**30**		
40	8.94	1.84	3.25	**40**			**40**			**40**		
60	9.08		2.99	**60**			**60**			**60**		
90	9.35	1.84	2.59	**90**			**90**			**90**		
120	9.50		2.25	**120**			**120**			**120**		
150	9.70	1.85	2.10	**150**			**150**			**150**		
180	9.89		1.87	**180**			**180**			**180**		
210	10.01	1.83	1.76	**210**			**210**			**210**		
240	10.16		1.61	**240**			**240**			**240**		
300	10.32	1.84	1.40	**300**			**300**			**300**		
360	10.45		1.21	**360**			**360**			**360**		
420	10.64	1.83	1.09	**420**			**420**			**420**		
480	10.86		0.93	**480**			**480**			**480**		
540	10.93	1.85	0.81	**540**			**540**			**540**		
600	11.10		0.70	**600**			**600**			**600**		
720	11.26	1.87	0.58	**720**			**720**			**720**		
840	11.42		0.32	**840**			**840**			**840**		
960	11.54	1.84	0.26	**960**			**960**			**960**		
1080	11.62			**1080**			**1080**			**1080**		
1200	11.69	1.84		**1200**			**1200**			**1200**		
1320	11.76			**1320**			**1320**			**1320**		
1440	11.83			**1440**			**1440**			**1440**		
1080				**1800**			**1800**			**1800**		
1140				**2280**			**2280**			**2280**		
1200				**2880**			**2880**			**2880**		
1260												
1320												
1380												
1440												

STEPPED DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	EC-Q14-660			PROJECT:	GWSE - Middelburg Grootfontein Aquifer
ALTERNATIVE NO. :	0			SITE NAME:	Rosmead
ALTERNATIVE NO. :	0			CLIENT:	DWA
BOREHOLE DEPTH (mbdl):	23.82	CASING DEPTH (mbdl):	0.00	PUMP TYPE USED:	P150
DEPTH OF PUMP (mbdl):	22.00	CASING HEIGHT (magl):	0.19	OPERATOR:	0
PUMP INLET DIAMETER (mm):	160.000	CASING ID (mm):	0.000	CONTRACTOR:	AB Pumps
STATIC WATER LEVEL (mbdl):	10.15	DATUM LEVEL (magl):	0.54		

DISCHARGE RATE 1			Time	Recovery 1	DISCHARGE RATE 2			Time	Recovery 2	DISCHARGE RATE 3			Time	Recovery 3
DATE:	28-Apr-08		(min)	(m)	DATE:	28-Apr-08		(min)	(m)	DATE:	28-Apr-08		(min)	(m)
TIME:	12:30 PM		1		TIME:	13:30		1		TIME:	14:30		1	
Time	Drawdown	Yield	2		Time	Drawdown	Yield	2		Time	Drawdown	Yield	2	
(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3	
1	0.22		5		1	0.34		5		1	0.85		5	
2	0.24		7		2	0.34		7		2	0.88		7	
3	0.25		10		3	0.37	4.030	10		3	0.90	8.040	10	
5	0.25		15		5	0.37		15		5	0.90		15	
7	0.25	2.010	20		7	0.37	4.020	20		7	0.90	8.030	20	
10	0.25		30		10	0.37		30		10	0.91		30	
15	0.25	2.020	40		15	0.37	4.030	40		15	0.93	8.040	40	
20	0.25		50		20	0.39		50		20	0.93		50	
30	0.25	2.010	60		30	0.39	4.020	60		30	0.94	8.030	60	
40	0.25		70		40	0.40		70		40	0.96		70	
50	0.25	2.010	80		50	0.41	4.020	80		50	0.99	8.040	80	
60	0.25		90		60	0.41		90		60	0.99		90	
70			100		70			100		70			100	
80			110		80			110		80			110	
90			120		90			120		90			120	
100			150		100			150		100			150	
110			180		110			180		110			180	
120			210		120			210		120			210	
	Average yield:	2.0125	(l/s)			Average yield:	4.024				Average yield:	8.036		

DISCHARGE RATE 4			Time	Recovery 4	DISCHARGE RATE 5			Time	Recovery 5	DISCHARGE RATE 6			Time	Recovery
DATE:	28-Apr-08		(min)	(m)	DATE:	28-Apr-08		(min)	(m)	DATE:	28-Apr-08		(min)	(m)
TIME:	15:30		1		TIME:			1		TIME:			1	0.44
Time	Drawdown	Yield	2		Time	Drawdown	Yield	2		Time	Drawdown	Yield	2	0.36
(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3	0.34
1	1.11		5		1			5		1			5	0.33
2	1.11	14.01	7		2			7		2			7	0.32
3	1.11		10		3			10		3			10	0.31
5	1.11	14.02	15		5			15		5			15	0.30
7	1.12		20		7			20		7			20	0.29
10	1.13	14.01	30		10			30		10			30	0.29
15	1.13		40		15			40		15			40	0.28
20	1.13	14.02	50		20			50		20			50	0.27
30	1.17		60		30			60		30			60	0.26
40	1.17	14.01	70		40			70		40			70	0.26
50	1.19		80		50			80		50			80	0.25
60	1.20		90		60			90		60			90	0.25
70			100		70			100		70			100	0.25
80			110		80			110		80			110	0.24
90			120		90			120		90			120	0.24
100			150		100			150		100			150	0.24
110			180		110			180		110			180	0.23
120			210		120			210		120			210	
	Average yield:	14.014						240		150			240	
COMMENTS:								300		180			300	
								360		210			360	
								420		240			420	

CONSTANT DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	EC-Q14-660	PROJECT:	GWSE - Middelburg Grootfontein Aquifer	CLIENT:	DWA
ALTERNATIVE NO. :	0	SITE NAME:	Rosmead		
DEPTH OF PUMP (mbdl):	22.00	PUMP TYPE USED:	P150	OPERATOR:	0
INLET DIAMETER (mm):	160	EXISTING EQUIPMENT:	0	CONTRACTOR:	AB Pumps

TEST	DATE:	2008/04/29	TEST	DATE:		TOTAL TIME - PUMPED (min):		TOTAL TEST TIME (min):	
STARTED	TIME:	7:00 AM	COMPLETED	TIME:		TOTAL TIME-RECOVERY(min):		AVERAGE YIELD (l/s):	10.04

DISCHARGE BOREHOLE		*OBSERVATION BOREHOLE 1*		*OBSERVATION BOREHOLE 2*		*OBSERVATION BOREHOLE 3*	
CASING HEIGHT (magl):	0.19	No. :		No. :		No. :	
CASING DEPTH (mbdl):	0.00	DATUM LEVEL (magl):		DATUM LEVEL (magl):		DATUM LEVEL (magl):	
CASING ID (mm):	0.00	CASING DEPTH (mbdl):		CASING DEPTH (mbdl):		CASING DEPTH (mbdl):	
BOREHOLE DEPTH (mbdl):	23.82	BOREHOLE DEPTH :		BOREHOLE DEPTH :		BOREHOLE DEPTH :	
WATER LEVEL (mbdl):	10.15	WATER LEVEL:		WATER LEVEL:		WATER LEVEL:	
DATUM LEVEL (magl):	0.54	DISTANCE (m):		DISTANCE (m):		DISTANCE (m):	

Time (min)	Drawdown (m)	Yield (l/s)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)
1	0.60		2.84	1			1			1		
2	0.65		2.81	2			2			2		
3	0.74		2.79	3			3			3		
5	0.77		2.78	5			5			5		
7	0.87		2.76	7			7			7		
10	0.97	10.04	2.74	10			10			10		
15	1.01		2.73	15			15			15		
20	1.02	10.03	2.72	20			20			20		
30	1.04		2.69	30			30			30		
40	1.09	10.04	2.66	40			40			40		
60	1.14		2.64	60			60			60		
90	1.14	10.03	2.62	90			90			90		
120	1.14		2.58	120			120			120		
150	1.15	10.04	2.57	150			150			150		
180	1.21		2.53	180			180			180		
210	1.23	10.05	2.51	210			210			210		
240	1.30		2.50	240			240			240		
300	1.35	10.04	2.46	300			300			300		
360	1.41		2.43	360			360			360		
420	1.48	10.05	2.40	420			420			420		
480	1.53		2.38	480			480			480		
540	1.59	10.04	2.35	540			540			540		
600	1.64		2.33	600			600			600		
720	1.76	10.05	2.29	720			720			720		
840	1.87		2.25	840			840			840		
960	1.96	10.04	2.21	960			960			960		
1080	2.05		2.18	1080			1080			1080		
1200	2.14	10.05	2.15	1200			1200			1200		
1320	2.23		2.12	1320			1320			1320		
1440	2.33	10.04	2.09	1440			1440			1440		
1560	2.43		2.05	1800			1800			1800		
1680	2.53	10.03		2280			2280			2280		
1800	2.64			2880			2880			2880		
1920	2.72	10.02										
2040	2.81											
2160	2.90	10.03										
2280	3.00											

DISCHARGE BOREHOLE				*OBSERVATION BOREHOLE 1*			*OBSERVATION BOREHOLE 2*			*OBSERVATION BOREHOLE 3*		
Time (min)	Drawdown (m)	Yield (l/s)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)
2400	3.10	10.02		1500			1500			1500		
2520	3.17			1560			1560			1560		
2640	3.28	10.04		1620			1620			1620		
2760	3.36			1680			1680			1680		
2880	3.45			1740			1740			1740		

CALIBRATION TEST AND RECOVERY

BOREHOLE NO. :	EC-Q14-661	PROJECT:	GWSE - Middelburg Grootfontein Aquifer
ALTERNATIVE NO. :		SITE NAME:	Rosmead
ALTERNATIVE NO. :		CLIENT:	DWA

BOREHOLE DEPTH (mbdl):	41.30	CASING DEPTH (mbdl):		PUMP TYPE USED:	GW1302
DEPTH OF PUMP (mbdl):	39.00	CASING HEIGHT (magl):	0.18	OPERATOR:	Phineas
PUMP INLET DIAMETER (mm):	140.00	CASING ID (mm):		CONTRACTOR:	AB Pumps
STATIC WATER LEVEL (mbdl):	14.12	DATUM LEVEL (magl):	0.22	SUPERVISOR:	Michael

DISCHARGE RATE 1					*DISCHARGE RATE 2*					*DISCHARGE RATE 3*				
DATE:	8-Jun-08	TIME:	12:10 PM		DATE:	8-Jun-08	TIME:	12:25 PM		DATE:	8-Jun-08	TIME:	12:40 PM	
Time	Drawdown	Yield	Time	Recovery	Time	Drawdown	Yield	Time	Recovery	Time	Drawdown	Yield	Time	Recovery
(min)	(m)	(l/s)	(min)	(m)	(min)	(m)	(l/s)	(min)	(m)	(min)	(m)	(l/s)	(min)	(m)
1	0.86		1		1	6.18		1		1	14.93		1	
2	1.53		2		2	7.00		2		2	16.35	1.66	2	
3	1.96	0.35	3		3	7.62	0.99	3		3	19.28		3	
5	2.58		5		5	8.65		5		5	21.24	1.65	5	
7	3.39	0.51	7		7	9.46	0.98	7		7	24.98		7	
10	4.04		10		10	10.38		10		8	24.98	0.86	10	
15	5.10	0.52	15		15	12.52	0.99	15		9	24.98	0.85	15	
EXISTING EQUIPMENT DETAIL:			20		*EXISTING EQUIPMENT DETAIL:*			20		*EXISTING EQUIPMENT DETAIL:*			20	
TYPE OF RESERVOIR:			30		TYPE OF ENCLOSURE:			30		PRESSURE GAUGE MANUFAC			30	
			40					40		TURER:			40	
RESERVOIR SIZE:			50		MATERIAL OF ENCLOSURE:			50					50	
			60					60		GAUGE READING (KpA):			60	
RESERVOIR CONITION:			70		CONDITION OF ENCLOSURE:			70					70	
			80					80		MONITORING FACILITY:			80	
STAND HEIGHT (m):			90		WATER METER MANUFACTURER:			90					90	
			100					100		MAINTAINED:			100	
			110		WATER METER READING:			110					110	
			120					120					120	
			150					150					150	

DISCHARGE RATE 4					*DISCHARGE RATE 5*					*DISCHARGE RATE 6*				
DATE:	39607	TIME:			DATE:	39607	TIME:			DATE:		TIME:		
Time	Drawdown	Yield	Time	Recovery	Time	Drawdown	Yield	Time	Recovery	Time	Drawdown	Yield	Time	Recovery
(min)	(m)	(l/s)	(min)	(m)	(min)	(m)	(l/s)	(min)	(m)	(min)	(m)	(l/s)	(min)	(m)
1			1		1			1		1			1	21.86
2			2		2			2		2			2	19.25
3			3		3			3		3			3	14.90
5			5		5			5		5			5	9.58
7			7		7			7		7			7	6.65
10			10		10			10		10			10	4.00
15			15		15			15		15			15	1.50
EXISTING EQUIPMENT DETAIL:			20		*EXISTING EQUIPMENT DETAIL:*			20		*EXISTING EQUIPMENT DETAIL:*			20	0.48
PUMP TYPE:			30		TYPE OF POWER:			30		TYPE OF RISER:			30	0.12
			40					40					40	0.07
PUMP MANUFACTURER:			50		ENGINE MANUACTURER:			50		CLASS OF RISER:			50	0.05
			60					60					60	
PUMP SERIAL No:			70		ENGINE MODEL:			70		DIAMETER OF RISER (mm):			70	
			80					80					80	
PUMP PULLEY DIAMETER (mm):			90		ENGINE SERIAL No:			90		CONDITION OF RISER:			90	
			100					100					100	
PUMP INTAKE DEPTH (m):			110		ENGINE PULLEY DIAMETER (mm)			110		SHAFT DIAMETER (mm):			110	
			120					120					120	
PUMP RPM:			150		POWER RATING (kW):			150		ELEMENT DIAMETER (mm):			150	
													180	
PUMP CONDITION:					ENGINE CONDITION:					ELEMENT STROKE (mm):			210	
													240	

FORM 5 E

STEPPED DISCHARGE TEST & RECOVERY

BOREHOLE TEST RECORD SHEET

PROJ NO :	533	MAP REFERENCE:	0	PROVINCE:	Eastern Cape
BOREHOLE NO:	EC-Q14-687	CO-ORDINATES:		DISTRICT:	Middelburg
ALT BH NO:	0	LATITUDE:	0	SITE NAME:	0
ALT BH NO:	0	LONGITUDE:	0		
BOREHOLE DEPTH (m)	43.27	DATUM LEVEL ABOVE CASING (m):	0.19	EXISTING PUMP:	0
WATER LEVEL (mbgl):	14.76	CASING HEIGHT: (magl):	0.40	CONTRACTOR:	AB Pumps
DEPTH OF PUMP (m):	39.00	DIAM PUMP INLET (mm):	155	PUMP TYPE:	GW 1302

STEPPED DISCHARGE TEST & RECOVERY

DISCHARGE RATE 1			RPM		DISCHARGE RATE 2			RPM		DISCHARGE RATE 3			RPM	
DATE:	09/06/2008	TIME:	08h50		DATE:	09/06/2008	TIME:	09h00		DATE:	09/06/200	TIME:	10h50	
TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)	TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)	TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)
1	0.73		1		1	8.54		1		1	19.05		1	20.00
2	1.06	0.43	2		2	9.15	0.92	2		2	20.20	1.36	2	18.81
3	1.62		3		3	9.73		3		3	20.96		3	17.05
5	2.31	0.55	5		5	10.68	1.02	5		5	22.20	1.55	5	16.35
7	2.67		7		7	11.22		7		7	23.22		7	15.93
10	3.26	0.55	10		10	12.03	1.01	10		10	23.80	1.54	10	14.97
15	4.08		15		15	13.10		15		15	24.30		15	13.63
20	4.75	0.54	20		20	13.95	1.01	20		16	24.30	1.10	20	12.30
30	5.95		30		30	15.36		30		18	24.30	1.04	30	11.08
40	6.52	0.53	40		40	16.47	1.00	40		20	24.30	1.04	40	9.92
50	7.21		50		50	17.36		50		50			50	9.26
60	7.80	0.54	60		60	18.15	1.00	60		60			60	8.78
70			70		70			70		70			70	8.25
80			80		80			80		80			80	7.98
90			90		90			90		90			90	7.70
100			100		100			100		100			100	7.44
110			110		110			110		110			110	7.18
120			120		120			120		120			120	7.01
pH			150		pH			150		pH			150	6.43
TEMP		°C	180		TEMP		°C	180		TEMP		°C	180	
EC		ms/cm	210		EC		ms/cm	210		EC		ms/cm	210	
DISCHARGE RATE 4			RPM		DISCHARGE RATE 5			RPM		DISCHARGE RATE 6			RPM	

FORM 5 F

CONSTANT DISCHARGE TEST & RECOVERY

BOREHOLE TEST RECORD SHEET

PROJ NO :	533	MAP REFERENCE:	0	PROVINCE:	Eastern Cape
BOREHOLE NO:	EC-Q14-687	CO-ORDINATES:		DISTRICT:	Middelburg
ALT BH NO:	0	LATITUDE:	0	SITE NAME:	0
ALT BH NO:	0	LONGITUDE:	0		
BOREHOLE DEPTH:	43.27	DATUM LEVEL ABOVE CASING (m):	0.19	EXISTING PUMP:	0
WATER LEVEL (mbgl):	20.12	CASING HEIGHT: (magl):	0.40	CONTRACTOR:	AB Pumps
DEPTH OF PUMP (m):	39.00	DIAM PUMP INLET(mm):	155	PUMP TYPE:	GW 1302

CONSTANT DISCHARGE TEST & RECOVERY

TEST STARTED				**TEST COMPLETED**					**DURATION:**	1440
DATE:	09/06/2008	TIME:	14h00	[redacted]	DATE:	11/06/08	TIME:	14H00	TYPE OF PUMP:	GW 1302

DISTANCE BETWEEN DISCHARGE : AND OBSERVATION HOLES IN M:

DISCHARGE BOREHOLE					OBSERVATION HOLE 1			OBSERVATION HOLE 2			OBSERVATION HOLE 3	
					NR:			NR:			NR:	
					Distance;			Distance:			Distance:	
TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME MIN	RECOVERY (M)	TIME: (min)	Drawdown m	Recovery (m)	TIME: (min)	Drawdown (m)	Recovery	TIME: (min)	Drawdown (m)
1	0.68		1	15.10	1			1			1	
2	1.05	0.39	2	14.40	2			2			2	
3	1.25		3	13.90	3			3			3	
5	1.85	0.55	5	13.70	5			5			5	
7	2.45		7	13.60	7			7			7	
10	3.08	0.52	10	13.42	10			10			10	
15	4.07		15	13.00	15			15			15	
20	4.75	0.53	20	12.64	20			20			20	
30	5.70		30	12.10	30			30			30	
40	6.30	0.53	40	11.62	40			40			40	
60	7.19		60	11.10	60			60			60	
90	8.09	0.51	90	10.53	90			90			90	
120	8.75		120	10.15	120			120			120	
150	9.26	0.51	150	9.81	150			150			150	
180	9.68		180	9.46	180			180			180	
210	10.03	0.51	210	9.20	210			210			210	
240	10.30		240	8.95	240			240			240	
300	10.85	0.50	300	8.49	300			300			300	
360	11.33		360	8.03	360			360			360	
420	11.78	0.50	420	7.57	420			420			420	
480	12.17		480	7.15	480			480			480	
540	12.55	0.52	540	6.72	540			540			540	
600	12.93		600	6.29	600			600			600	
720	13.59	0.53	720	5.42	720			720			720	
840	14.12		840	4.62	840			840			840	
960	14.62	0.51	960	3.86	960			960			960	
1080	15.06		1080	3.07	1080			1080			1080	
1200	15.52	0.53	1200	2.21	1200			1200			1200	
1320	16.00		1320	1.30	1320			1320			1320	
1440	16.51	0.52	1440	0.32	1440			1440			1440	
1560			1560		1560			1560			1560	
1680			1680		1680			1680			1680	
1800			1800		1800			1800			1800	
1920			1920		1920			1920			1920	
2040			2040		2040			2040			2040	
2160			2160		2160			2160			2160	
2280			2280		2280			2280			2280	
2400			2400		2400			2400			2400	
2520			2520		2520			2520			2520	
2640			2640		2640			2640			2640	
2760			2760		2760			2760			2760	
2880			2880		2880			2880			2880	
3000			3000		3000			3000			3000	
3120			3120		3120			3120			3120	
3240			3240		3240			3240			3240	
3360			3360		3360			3360			3360	
3480			3480		3480			3480			3480	
3600			3600		3600			3600			3600	
3720			3720		3720			3720			3720	
3840			3840		3840			3840			3840	
3960			3960		3960			3960			3960	
4080			4080		4080			4080			4080	
4200			4200		4200			4200			4200	
4320			4320		4320			4320			4320	
Total time pumped(min):				1440		W/L			W/L			
Average yield (l/s):				0.51								

STEPPED DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	EC-Q14-968	PROJECT:	GWSE - Middelburg Grootfontein Aquifer
ALTERNATIVE NO. :	0	SITE NAME:	0
ALTERNATIVE NO. :	0	CLIENT:	DWA

BOREHOLE DEPTH (mbdl):	65.80	CASING DEPTH (mbdl):	0.00	PUMP TYPE USED:	P150
DEPTH OF PUMP (mbdl):	64.00	CASING HEIGHT (magl):	0.24	OPERATOR:	0
PUMP INLET DIAMETER (mm):	168.000	CASING ID (mm):	0.000	CONTRACTOR:	AB Pumps
STATIC WATER LEVEL (mbdl):	6.37	DATUM LEVEL (magl):	0.40		

DISCHARGE RATE 1			Time	Recovery 1	DISCHARGE RATE 2			Time	Recovery 2	DISCHARGE RATE 3			Time	Recovery 3
DATE:	06-May-08		(min)	(m)	DATE:	06-May-08		(min)	(m)	DATE:	06-May-08		(min)	(m)
TIME:	7:00 AM		1		TIME:	08:00		1		TIME:	09:00		1	
Time	Drawdown	Yield	2		Time	Drawdown	Yield	2		Time	Drawdown	Yield	2	
(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3	
1	0.76		5		1	6.22		5		1	14.82		5	
2	1.03		7		2	6.64		7		2	15.14		7	
3	1.19		10		3	6.98		10		3	15.65		10	
5	1.49		15		5	7.25		15		5	16.38		15	
7	1.67		20		7	7.34		20		7	17.17	10.890	20	
10	1.92	3.060	30		10	8.02		30		10	18.16		30	
15	2.27		40		15	8.94	5.270	40		15			40	
20	2.52	3.050	50		20	9.69		50		20			50	
30	3.18		60		30	11.02	5.250	60		30			60	
40	3.85	3.060	70		40	12.19		70		40			70	
50	4.51		80		50	13.18	5.270	80		50			80	
60	5.09		90		60	14.09		90		60			90	
70			100		70			100		70			100	
80			110		80			110		80			110	
90			120		90			120		90			120	
100			150		100			150		100			150	
110			180		110			180		110			180	
120			210		120			210		120			210	
	Average yield:	3.0566667	(l/s)			Average yield:	5.2633333				Average yield:	10.89		

DISCHARGE RATE 4			Time	Recovery 4	DISCHARGE RATE 5			Time	Recovery 5	DISCHARGE RATE 6			Time	Recovery
DATE:	06-May-08		(min)	(m)	DATE:	06-May-08		(min)	(m)	DATE:	06-May-08		(min)	(m)
TIME:			1		TIME:			1		TIME:			1	14.03
Time	Drawdown	Yield	2		Time	Drawdown	.	2		Time	Drawdown	Yield	2	13.18
(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3	12.55
1			5		1			5		1			5	11.67
2			7		2			7		2			7	11.05
3			10		3			10		3			10	10.26
5			15		5			15		5			15	9.02
7			20		7			20		7			20	8.16
10			30		10			30		10			30	6.78
15			40		15			40		15			40	5.51
20			50		20			50		20			50	4.50
30			60		30			60		30			60	
40			70		40			70		40			70	
50			80		50			80		50			80	
60			90		60			90		60			90	
70			100		70			100		70			100	
80			110		80			110		80			110	
90			120		90			120		90			120	
100			150		100			150		100			150	
110			180		110			180		110			180	
120			210		120			210		120			210	
	Average yield:	#DIV/0!						240		150			240	
COMMENTS:								300		180			300	
								360		210			360	
								420		240			420	

STEPPED DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	EC-Q14-1041			PROJECT:	GWSE - Middelburg Grootfontein Aquifer
ALTERNATIVE NO. :	0			SITE NAME:	0
ALTERNATIVE NO. :	0			CLIENT:	DWA
BOREHOLE DEPTH (mbdl):	35.83	CASING DEPTH (mbdl):	0.00	PUMP TYPE USED:	BP65
DEPTH OF PUMP (mbdl):	37.35	CASING HEIGHT (magl):	0.10	OPERATOR:	Morgan
PUMP INLET DIAMETER (mm):	180.000	CASING ID (mm):	0.000	CONTRACTOR:	AB Pumps
STATIC WATER LEVEL (mbdl):	5.79	DATUM LEVEL (magl):	0.53		

DISCHARGE RATE 1			Time	Recovery 1	DISCHARGE RATE 2			Time	Recovery 2	DISCHARGE RATE 3			Time	Recovery 3
DATE:	03-Jun-08		(min)	(m)	DATE:	03-Jun-08		(min)	(m)	DATE:	03-Jun-08		(min)	(m)
TIME:	8:30 AM		1		TIME:	9:30 AM		1		TIME:	10:30 AM		1	
Time	Drawdown	Yield	2		Time	Drawdown	Yield	2		Time	Drawdown	Yield	2	
(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3	
1	0.71		5		1	1.45		5		1	4.19		5	
2	0.73		7		2	1.48		7		2	4.38		7	
3	0.75	3.08	10		3	1.51	4.19	10		3	4.50	8.05	10	
5	0.77		15		5	1.75	5.10	15		5	7.17		15	
7	0.77	3.00	20		7	1.95		20		7	7.80	10.60	20	
10	0.78		30		10	2.12	5.10	30		10	8.01		30	
15	0.78	3.00	40		15	2.13		40		15	8.16	10.60	40	
20	0.79		50		20	2.14	5.10	50		20	8.29		50	
30	0.79	3.00	60		30	2.16		60		30	8.45	10.60	60	
40	0.79		70		40	2.18	5.10	70		40	8.50		70	
50	0.80	3.00	80		50	2.18		80		50	8.54	10.60	80	
60	0.80		90		60	2.20	5.10	90		60	8.58		90	
70			100		70			100		70			100	
80			110		80			110		80			110	
90			120		90			120		90			120	
100			150		100			150		100			150	
110			180		110			180		110			180	
120			210		120			210		120			210	
	Average yield:	3.016	(l/s)			Average yield:	4.9483333				Average yield:	10.09		

DISCHARGE RATE 4			Time	Recovery 4	DISCHARGE RATE 5			Time	Recovery 5	DISCHARGE RATE 6			Time	Recovery
DATE:	03-Jun-08		(min)	(m)	DATE:			(min)	(m)	DATE:			(min)	(m)
TIME:	11:30 AM		1		TIME:			1		TIME:			1	5.36
Time	Drawdown	Yield	2		Time	Drawdown	Yield	2		Time	Drawdown	Yield	2	0.43
(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3	0.26
1	9.76		5		1			5		1			5	0.14
2	10.16		7		2			7		2			7	0.13
3	10.39		10		3			10		3			10	0.10
5	10.48		15		5			15		5			15	
7	10.61	11.90	20		7			20		7			20	
10	14.22	15.90	30		10			30		10			30	
15	16.80		40		15			40		15			40	
20	19.15	13.90	50		20			50		20			50	
30	23.90		60		30			60		30			60	
40	23.90	2.60	70		40			70		40			70	
50	23.90	12.30	80		50			80		50			80	
55	23.90	12.50	90		60			90		60			90	
70			100		70			100		70			100	
80			110		80			110		80			110	
90			120		90			120		90			120	
100			150		100			150		100			150	
110			180		110			180		110			180	
120			210		120			210		120			210	
	Average yield:	11.516667						240		150			240	
COMMENTS:								300		180			300	
								360		210			360	
								420		240			420	

CONSTANT DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	EC-Q14-1041	PROJECT:	GWSE - Middelburg Grootfontein Aquifer	CLIENT:	DWA
ALTERNATIVE NO. :	0	SITE NAME:	0		
DEPTH OF PUMP (mbdl):	37.35	PUMP TYPE USED:	BP65	OPERATOR:	Morgan
INLET DIAMETER (mm):	180	EXISTING EQUIPMENT:	0	CONTRACTOR:	AB Pumps

TEST STARTED	DATE: 3-Jun-08	TEST COMPLETED	DATE:	TOTAL TIME - PUMPED (min):		TOTAL TEST TIME (min):	
	TIME: 1:00 PM		TIME:	TOTAL TIME-RECOVERY(min):		AVERAGE YIELD (l/s):	9.77

DISCHARGE BOREHOLE		OBSERVATION BOREHOLE 1		OBSERVATION BOREHOLE 2		OBSERVATION BOREHOLE 3	
CASING HEIGHT (magl):	0.10	No. :		No. :		No. :	
CASING DEPTH (mbdl):	0.00	DATUM LEVEL (magl):		DATUM LEVEL (magl):		DATUM LEVEL (magl):	
CASING ID (mm):	0.00	CASING DEPTH (mbdl):		CASING DEPTH (mbdl):		CASING DEPTH (mbdl):	
BOREHOLE DEPTH (mbdl):	35.83	BOREHOLE DEPTH :		BOREHOLE DEPTH :		BOREHOLE DEPTH :	
WATER LEVEL (mbdl):	5.79	WATER LEVEL:		WATER LEVEL:		WATER LEVEL:	
DATUM LEVEL (magl):	0.53	DISTANCE (m):		DISTANCE (m):		DISTANCE (m):	

Time (min)	Drawdown (m)	Yield (l/s)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)
1	4.48		0.35	1			1			1		
2	4.86	8.10	0.25	2			2			2		
3	5.95			3			3			3		
5	6.48	9.50		5			5			5		
7	6.53			7			7			7		
10	6.56			10			10			10		
15	7.01	9.75		15			15			15		
20	6.48	9.80		20			20			20		
30	7.14			30			30			30		
40	7.20	9.80		40			40			40		
60	7.24			60			60			60		
90	7.29	9.80		90			90			90		
120	7.36			120			120			120		
150	7.40	9.80		150			150			150		
180	7.43			180			180			180		
210	7.45	9.80		210			210			210		
240	7.49			240			240			240		
300	7.54	9.80		300			300			300		
360	7.60			360			360			360		
420	7.63	9.80		420			420			420		
480	7.65			480			480			480		
540	7.67			540			540			540		
600	7.72	9.80		600			600			600		
720	7.83			720			720			720		
840	7.90	9.80		840			840			840		
960	7.94			960			960			960		
1080	7.97	9.80		1080			1080			1080		
1200	7.99			1200			1200			1200		
1320	8.02	9.80		1320			1320			1320		
1440	8.05			1440			1440			1440		
1080				1800			1800			1800		
1140				2280			2280			2280		
1200				2880			2880			2880		
1260												
1320												
1380												
1440												

STEPPED DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	EC-Q14-1107	**PROJECT:**	GWSE - Middelburg Grootfontein Aquifer
ALTERNATIVE NO. :	0	**SITE NAME:**	0
ALTERNATIVE NO. :	0	**CLIENT:**	DWA

BOREHOLE DEPTH (mbdl):	73.80	**CASING DEPTH (mbdl):**	0.00	**PUMP TYPE USED:**	BP65
DEPTH OF PUMP (mbdl):	70.35	**CASING HEIGHT (magl):**	0.12	**OPERATOR:**	Lucky
PUMP INLET DIAMETER (mm):	180.000	**CASING ID (mm):**	0.000	**CONTRACTOR:**	AB Pumps
STATIC WATER LEVEL (mbdl):	21.95	**DATUM LEVEL (magl):**	0.48		

DISCHARGE RATE 1			**Time**	*Recovery 1*	*DISCHARGE RATE 2*			**Time**	*Recovery 2*	*DISCHARGE RATE 3*			**Time**	*Recovery 3*
DATE:	05-Jun-08		**(min)**	**(m)**	**DATE:**	05-Jun-08		**(min)**	**(m)**	**DATE:**	05-Jun-08		**(min)**	**(m)**
TIME:	1:10 PM		**1**		**TIME:**	2:10 PM		**1**		**TIME:**	1:10 PM		**1**	
Time	**Drawdown**	**Yield**	**2**		**Time**	**Drawdown**	**Yield**	**2**		**Time**	**Drawdown**	**Yield**	**2**	
(min)	**(m)**	**(l/s)**	**3**		**(min)**	**(m)**	**(l/s)**	**3**		**(min)**	**(m)**	**(l/s)**	**3**	
1	1.58		**5**		**1**	4.38		**5**		**1**	11.97		**5**	
2	1.75	2.30	**7**		**2**	4.96	3.98	**7**		**2**	13.18	9.00	**7**	
3	1.86		**10**		**3**	5.28		**10**		**3**	13.64		**10**	
5	2.09	2.50	**15**		**5**	7.34	5.49	**15**		**5**	17.79	9.03	**15**	
7	2.40		**20**		**7**	7.98		**20**		**7**	18.56		**20**	
10	2.77	2.50	**30**		**10**	8.43	5.40	**30**		**10**	19.25	9.00	**30**	
15	2.87		**40**		**15**	8.75		**40**		**15**	20.69		**40**	
20	2.95	2.50	**50**		**20**	9.00	5.40	**50**		**20**	22.50	9.00	**50**	
30	3.00		**60**		**30**	9.24		**60**		**30**	23.28		**60**	
40	3.05	2.50	**70**		**40**	9.40	5.40	**70**		**40**	23.74	9.00	**70**	
50	3.07		**80**		**50**	9.53		**80**		**50**	23.90		**80**	
60	3.10	2.50	**90**		**60**	9.65	5.40	**90**		**60**	24.03	9.00	**90**	
70			**100**		**70**			**100**		**70**			**100**	
80			**110**		**80**			**110**		**80**			**110**	
90			**120**		**90**			**120**		**90**			**120**	
100			**150**		**100**			**150**		**100**			**150**	
110			**180**		**110**			**180**		**110**			**180**	
120			**210**		**120**			**210**		**120**			**210**	
	Average yield:	**2.4666667**	**(l/s)**			**Average yield:**	**5.1783333**				**Average yield:**	**9.005**		

DISCHARGE RATE 4			**Time**	*Recovery 4*	*DISCHARGE RATE 5*			**Time**	*Recovery 5*	*DISCHARGE RATE 6*			**Time**	*Recovery*
DATE:	05-Jun-08		**(min)**	**(m)**	**DATE:**	05-Jun-08		**(min)**	**(m)**	**DATE:**	05-Jun-08		**(min)**	**(m)**
TIME:	4:10 PM		**1**		**TIME:**			**1**		**TIME:**			**1**	8.76
Time	**Drawdown**	**Yield**	**2**		**Time**	**Drawdown**	**Yield**	**2**		**Time**	**Drawdown**	**Yield**	**2**	7.02
(min)	**(m)**	**(l/s)**	**3**		**(min)**	**(m)**	**(l/s)**	**3**		**(min)**	**(m)**	**(l/s)**	**3**	6.10
1	29.05		**5**		**1**			**5**		**1**			**5**	5.36
2	31.82	10.20	**7**		**2**			**7**		**2**			**7**	4.70
3	33.73		**10**		**3**			**10**		**3**			**10**	3.24
5	37.00	11.50	**15**		**5**			**15**		**5**			**15**	2.60
7	40.50		**20**		**7**			**20**		**7**			**20**	2.18
10	42.68	11.50	**30**		**10**			**30**		**10**			**30**	1.80
15	44.02		**40**		**15**			**40**		**15**			**40**	1.63
16	46.00	11.50	**50**		**20**			**50**		**20**			**50**	1.50
17	46.00	9.80	**60**		**30**			**60**		**30**			**60**	1.43
18	46.00	9.70	**70**		**40**			**70**		**40**			**70**	1.37
20	46.00	9.50	**80**		**50**			**80**		**50**			**80**	1.31
60			**90**		**60**			**90**		**60**			**90**	1.28
70			**100**		**70**			**100**		**70**			**100**	1.25
80			**110**		**80**			**110**		**80**			**110**	1.23
90			**120**		**90**			**120**		**90**			**120**	1.20
100			**150**		**100**			**150**		**100**			**150**	1.2
110			**180**		**110**			**180**		**110**			**180**	1.19
120			**210**		**120**			**210**		**120**			**210**	1.17
	Average yield:	**10.528571**						**240**		**150**			**240**	
COMMENTS:								**300**		**180**			**300**	
								360		**210**			**360**	
								420		**240**			**420**	

CONSTANT DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	EC-Q14-1107	PROJECT:	GWSE - Middelburg Grootfontein Aquifer	CLIENT:	DWA
ALTERNATIVE NO. :	0	SITE NAME:	0		
DEPTH OF PUMP (mbdl):	70.35	PUMP TYPE USED:	BP65	OPERATOR:	Lucky
INLET DIAMETER (mm):	180	EXISTING EQUIPMENT:	0	CONTRACTOR:	AB Pumps
TEST STARTED DATE:	6-Jun-08	TEST COMPLETED DATE:		TOTAL TIME - PUMPED (min):	
TEST STARTED TIME:	7:35 AM	TEST COMPLETED TIME:		TOTAL TIME-RECOVERY(min):	
TOTAL TEST TIME (min):		AVERAGE YIELD (l/s):	6.65		

DISCHARGE BOREHOLE		*OBSERVATION BOREHOLE 1*		*OBSERVATION BOREHOLE 2*		*OBSERVATION BOREHOLE 3*	
CASING HEIGHT (magl):	0.12	No. :		No. :		No. :	
CASING DEPTH (mbdl):	0.00	DATUM LEVEL (magl):		DATUM LEVEL (magl):		DATUM LEVEL (magl):	
CASING ID (mm):	0.00	CASING DEPTH (mbdl):		CASING DEPTH (mbdl):		CASING DEPTH (mbdl):	
BOREHOLE DEPTH (mbdl):	73.80	BOREHOLE DEPTH :		BOREHOLE DEPTH :		BOREHOLE DEPTH :	
WATER LEVEL (mbdl):	21.95	WATER LEVEL:		WATER LEVEL:		WATER LEVEL:	
DATUM LEVEL (magl):	0.48	DISTANCE (m):		DISTANCE (m):		DISTANCE (m):	

Time (min)	Drawdown (m)	Yield (l/s)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)
1	0.99		7.26	1			1			1		
2	2.38		6.78	2			2			2		
3	2.85	4.50	6.35	3			3			3		
5	3.16	6.80	5.77	5			5			5		
7	7.77		5.34	7			7			7		
10	9.26	6.80	4.98	10			10			10		
15	10.12		4.61	15			15			15		
20	10.50	6.80	4.41	20			20			20		
30	10.91		4.20	30			30			30		
40	11.12	6.80	4.09	40			40			40		
60	11.37		3.97	60			60			60		
90	11.58	6.80	3.85	90			90			90		
120	11.76		3.78	120			120			120		
150	11.85	6.80	3.73	150			150			150		
180	11.93		3.67	180			180			180		
210	12.02	6.80	3.64	210			210			210		
240	12.06		3.60	240			240			240		
300	12.17	6.80	3.51	300			300			300		
360	12.35		3.46	360			360			360		
420	12.48	6.80	3.37	420			420			420		
480	12.63		3.33	480			480			480		
540	12.87	6.80	3.28	540			540			540		
600	13.10		3.22	600			600			600		
720	13.34	6.80	3.14	720			720			720		
840	13.71		3.05	840			840			840		
960	14.00	6.80	2.97	960			960			960		
1080	14.30		2.85	1080			1080			1080		
1200	14.49	6.80	2.78	1200			1200			1200		
1320	14.67		2.72	1320			1320			1320		
1440	14.86	6.80	2.64	1440			1440			1440		
1080				1800			1800			1800		
1140				2280			2280			2280		
1200				2880			2880			2880		
1260												
1320												
1380												
1440												

STEPPED DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	EC-Q14-1247		PROJECT:	GWSE - Middelburg Grootfontein Aquifer	
ALTERNATIVE NO. :	0		SITE NAME:	Dassiesfontein	
ALTERNATIVE NO. :	0		CLIENT:	DWA	
BOREHOLE DEPTH (mbdl):	51.20	CASING DEPTH (mbdl):	0.00	PUMP TYPE USED:	BP105
DEPTH OF PUMP (mbdl):	49.50	CASING HEIGHT (magl):	0.35	OPERATOR:	Phineas
PUMP INLET DIAMETER (mm):	180.000	CASING ID (mm):	0.000	CONTRACTOR:	AB Pumps
STATIC WATER LEVEL (mbdl):	14.62	DATUM LEVEL (magl):	0.20		

DISCHARGE RATE 1			Time	Recovery 1	DISCHARGE RATE 2			Time	Recovery 2	DISCHARGE RATE 3			Time	Recovery 3
DATE:	12-Jun-08		(min)	(m)	DATE:	12-Jun-08		(min)	(m)	DATE:	12-Jun-08		(min)	(m)
TIME:	3:00 PM		1		TIME:	4:00 PM		1		TIME:	5:00 PM		1	
Time	Drawdown	Yield	2		Time	Drawdown	Yield	2		Time	Drawdown	Yield	2	
(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3	
1	0.32		5		1	2.30		5		1	9.08		5	
2	0.46		7		2	2.56	5.89	7		2	9.44	12.10	7	
3	0.58	3.16	10		3	2.83		10		3	9.83		10	
5	0.72		15		5	3.28	6.15	15		5	10.47	12.10	15	
7	0.95	3.14	20		7	3.68		20		7	11.07		20	
10	1.04		30		10	4.19	6.13	30		10	11.76	12.09	30	
15	1.17	3.14	40		15	4.90		40		15	12.72		40	
20	1.31		50		20	5.54	6.15	50		20	13.52	12.11	50	
30	1.50	3.15	60		30	6.51		60		30	14.77		60	
40	1.73		70		40	7.20	6.15	70		40	15.62	12.10	70	
50	1.92	3.14	80		50	7.80		80		50	16.34		80	
60	2.04		90		60	8.26	6.15	90		60	16.95	12.10	90	
70			100		70			100		70			100	
80			110		80			110		80			110	
90			120		90			120		90			120	
100			150		100			150		100			150	
110			180		110			180		110			180	
120			210		120			210		120			210	
	Average yield:	3.146	(l/s)			Average yield:	6.1033333				Average yield:	12.1		

DISCHARGE RATE 4			Time	Recovery 4	DISCHARGE RATE 5			Time	Recovery 5	DISCHARGE RATE 6			Time	Recovery
DATE:	12-Jun-08		(min)	(m)	DATE:	12-Jun-08		(min)	(m)	DATE:	12-Jun-08		(min)	(m)
TIME:	6:00 PM		1		TIME:			1		TIME:			1	20.37
Time	Drawdown	Yield	2		Time	Drawdown	Yield	2		Time	Drawdown	Yield	2	20.22
(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3	20.16
1	17.28		5		1			5		1			5	20.04
2	17.67	20.33	7		2			7		2			7	19.93
3	18.05		10		3			10		3			10	19.78
5	18.59	20.33	15		5			15		5			15	19.58
7	19.18		20		7			20		7			20	19.35
10	19.57	20.33	30		10			30		10			30	18.94
15	20.19		40		15			40		15			40	18.56
20	20.69	20.34	50		20			50		20			50	18.12
30	21.50		60		30			60		30			60	17.62
40	22.18	20.35	70		40			70		40			70	17.22
50	22.64		80		50			80		50			80	16.78
60	22.90	20.34	90		60			90		60			90	16.25
70			100		70			100		70			100	15.67
80			110		80			110		80			110	15.15
90			120		90			120		90			120	14.51
100			150		100			150		100			150	12.37
110			180		110			180		110			180	9.6
120			210		120			210		120			210	4.38
	Average yield:	20.336667						240		150			240	2.16
COMMENTS:								300		180			300	
								360		210			360	
								420		240			420	

CONSTANT DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	EC-Q14-1247	**PROJECT:**	GWSE - Middelburg Grootfontein Aquifer	**CLIENT:**	DWA
ALTERNATIVE NO. :	0	**SITE NAME:**	Dassiesfontein		
DEPTH OF PUMP (mbdl):	49.50	**PUMP TYPE USED:**	BP105	**OPERATOR:**	Phineas
INLET DIAMETER (mm):	180	**EXISTING EQUIPMENT:**	0	**CONTRACTOR:**	AB Pumps
TEST STARTED DATE:	13-Jun-08	**TEST COMPLETED DATE:**		**TOTAL TIME - PUMPED (min):**	
TEST STARTED TIME:	7:30 AM	**TEST COMPLETED TIME:**		**TOTAL TIME-RECOVERY(min):**	
TOTAL TEST TIME (min):		**AVERAGE YIELD (l/s):**	6.24		

DISCHARGE BOREHOLE		***OBSERVATION BOREHOLE 1***		***OBSERVATION BOREHOLE 2***		***OBSERVATION BOREHOLE 3***	
CASING HEIGHT (magl):	0.35	**No. :**		**No. :**		**No. :**	
CASING DEPTH (mbdl):	0.00	**DATUM LEVEL (magl):**		**DATUM LEVEL (magl):**		**DATUM LEVEL (magl):**	
CASING ID (mm):	0.00	**CASING DEPTH (mbdl):**		**CASING DEPTH (mbdl):**		**CASING DEPTH (mbdl):**	
BOREHOLE DEPTH (mbdl):	51.20	**BOREHOLE DEPTH :**		**BOREHOLE DEPTH :**		**BOREHOLE DEPTH :**	
WATER LEVEL (mbdl):	14.62	**WATER LEVEL:**		**WATER LEVEL:**		**WATER LEVEL:**	
DATUM LEVEL (magl):	0.20	**DISTANCE (m):**		**DISTANCE (m):**		**DISTANCE (m):**	

Time (min)	Drawdown (m)	Yield (l/s)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)
1	0.72		19.90	**1**			**1**			**1**		
2	1.23	6.08	19.78	**2**			**2**			**2**		
3	1.69		19.74	**3**			**3**			**3**		
5	2.53	6.24	19.70	**5**			**5**			**5**		
7	3.41		19.68	**7**			**7**			**7**		
10	4.59	6.35	19.65	**10**			**10**			**10**		
15	6.08		19.54	**15**			**15**			**15**		
20	6.94	6.24	19.45	**20**			**20**			**20**		
30	8.56		19.30	**30**			**30**			**30**		
40	9.74	6.24	19.12	**40**			**40**			**40**		
60	11.54		18.89	**60**			**60**			**60**		
90	13.08	6.25	18.48	**90**			**90**			**90**		
120	14.17		18.05	**120**			**120**			**120**		
150	14.98	6.23	17.58	**150**			**150**			**150**		
180	15.65		17.12	**180**			**180**			**180**		
210	16.14	6.24	16.65	**210**			**210**			**210**		
240	16.59		16.15	**240**			**240**			**240**		
300	17.45	6.25	15.08	**300**			**300**			**300**		
360	17.95		13.98	**360**			**360**			**360**		
420	18.29	6.23	13.18	**420**			**420**			**420**		
480	18.54		12.42	**480**			**480**			**480**		
540	18.80	6.23	11.74	**540**			**540**			**540**		
600	19.01		11.18	**600**			**600**			**600**		
720	19.42	6.25	10.46	**720**			**720**			**720**		
840	19.70		9.70	**840**			**840**			**840**		
960	19.95	6.23	8.93	**960**			**960**			**960**		
1080	20.05		8.17	**1080**			**1080**			**1080**		
1200	20.13	6.23	7.40	**1200**			**1200**			**1200**		
1320	20.21		6.62	**1320**			**1320**			**1320**		
1440	20.28	6.25	5.93	**1440**			**1440**			**1440**		
1080				**1800**			**1800**			**1800**		
1140				**2280**			**2280**			**2280**		
1200				**2880**			**2880**			**2880**		
1260												
1320												
1380												
1440												

STEPPED DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	EC-Q14-1643	PROJECT:	GWSE - Middelburg Grootfontein Aquifer
ALTERNATIVE NO. :	0	SITE NAME:	0
ALTERNATIVE NO. :	0	CLIENT:	DWA

BOREHOLE DEPTH (mbdl):	15.08	CASING DEPTH (mbdl):	0.00	PUMP TYPE USED:	BP16
DEPTH OF PUMP (mbdl):	11.00	CASING HEIGHT (magl):	0.02	OPERATOR:	0
PUMP INLET DIAMETER (mm):	160.000	CASING ID (mm):	0.000	CONTRACTOR:	AB Pumps
STATIC WATER LEVEL (mbdl):	6.34	DATUM LEVEL (magl):	0.53		

DISCHARGE RATE 1			Time	*Recovery 1*	*DISCHARGE RATE 2*			Time	*Recovery 2*	*DISCHARGE RATE 3*			Time	*Recovery 3*
DATE:	17-May-08		(min)	(m)	DATE:	17-May-08		(min)	(m)	DATE:	17-May-08		(min)	(m)
TIME:	8:00 AM		1		TIME:	09:00		1		TIME:	10:00		1	
Time	Drawdown	Yield	2		Time	Drawdown	Yield	2		Time	Drawdown	Yield	2	
(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3	
1	0.16		5		1	0.44		5		1	0.87		5	
2	0.20	0.210	7		2	0.49	0.350	7		2	0.96	0.830	7	
3	0.20		10		3	0.55		10		3	1.06		10	
5	0.22	0.210	15		5	0.57	0.390	15		5	1.12	0.830	15	
7	0.25		20		7	0.57	0.440	20		7	1.17		20	
10	0.28	0.200	30		10	0.60		30		10	1.24	0.820	30	
15	0.31		40		15	0.68	0.440	40		15	1.30		40	
20	0.34	0.210	50		20	0.69		50		20	1.30	0.820	50	
30	0.35		60		30	0.72	0.430	60		30	1.31		60	
40	0.35	0.210	70		40	0.74		70		40	1.32	0.840	70	
50	0.35		80		50	0.76	0.440	80		50	1.33		80	
60	0.35	0.210	90		60	0.77		90		60	1.34	0.830	90	
70			100		70			100		70			100	
80			110		80			110		80			110	
90			120		90			120		90			120	
100			150		100			150		100			150	
110			180		110			180		110			180	
120			210		120			210		120			210	
	Average yield:	0.2083333	(l/s)			Average yield:	0.415				Average yield:	0.8283333		

DISCHARGE RATE 4			Time	*Recovery 4*	*DISCHARGE RATE 5*			Time	*Recovery 5*	*DISCHARGE RATE 6*			Time	*Recovery*
DATE:	17-May-08		(min)	(m)	DATE:	17-May-08		(min)	(m)	DATE:	17-May-08		(min)	(m)
TIME:	11:00		1		TIME:			1		TIME:			1	1.27
Time	Drawdown	Yield	2		Time	Drawdown	Yield	2		Time	Drawdown	Yield	2	0.35
(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3	0.24
1	1.50		5		1			5		1			5	0.24
2	1.52	1.01	7		2			7		2			7	0.23
3	1.60		10		3			10		3			10	0.22
5	1.87	1.25	15		5			15		5			15	0.20
7	2.08		20		7			20		7			20	0.19
10	2.28	1.25	30		10			30		10			30	0.18
15	2.46		40		15			40		15			40	0.17
20	2.62	1.23	50		20			50		20			50	0.16
30	2.85		60		30			60		30			60	0.15
40	3.03	1.24	70		40			70		40			70	0.14
50	3.14		80		50			80		50			80	0.14
60	3.30	1.24	90		60			90		60			90	0.13
70			100		70			100		70			100	0.13
80			110		80			110		80			110	0.12
90			120		90			120		90			120	
100			150		100			150		100			150	
110			180		110			180		110			180	
120			210		120			210		120			210	
	Average yield:	1.2033333						240		150			240	
COMMENTS:								300		180			300	
								360		210			360	
								420		240			420	

CONSTANT DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	EC-Q14-1643	PROJECT:	GWSE - Middelburg Grootfontein Aquifer	CLIENT:	DWA
ALTERNATIVE NO. :	0	SITE NAME:	0		
DEPTH OF PUMP (mbdl):	11.00	PUMP TYPE USED:	BP16	OPERATOR:	0
INLET DIAMETER (mm):	160	EXISTING EQUIPMENT:	0	CONTRACTOR:	AB Pumps

TEST	DATE:	2008/05/17	TEST	DATE:		TOTAL TIME - PUMPED (min):		TOTAL TEST TIME (min):	
STARTED	TIME:	3:00 PM	COMPLETED	TIME:		TOTAL TIME-RECOVERY(min):		AVERAGE YIELD (l/s):	0.92

DISCHARGE BOREHOLE		*OBSERVATION BOREHOLE 1*		*OBSERVATION BOREHOLE 2*		*OBSERVATION BOREHOLE 3*	
CASING HEIGHT (magl):	0.02	No. :		No. :		No. :	
CASING DEPTH (mbdl):	0.00	DATUM LEVEL (magl):		DATUM LEVEL (magl):		DATUM LEVEL (magl):	
CASING ID (mm):	0.00	CASING DEPTH (mbdl):		CASING DEPTH (mbdl):		CASING DEPTH (mbdl):	
BOREHOLE DEPTH (mbdl):	15.08	BOREHOLE DEPTH :		BOREHOLE DEPTH :		BOREHOLE DEPTH :	
WATER LEVEL (mbdl):	6.34	WATER LEVEL:		WATER LEVEL:		WATER LEVEL:	
DATUM LEVEL (magl):	0.53	DISTANCE (m):		DISTANCE (m):		DISTANCE (m):	

Time (min)	Drawdown (m)	Yield (l/s)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)
1	0.51		0.93	1			1			1		
2	0.56	0.78	0.40	2			2			2		
3	0.68		0.27	3			3			3		
5	0.75	0.93	0.25	5			5			5		
7	0.82		0.24	7			7			7		
10	1.08	0.93	0.23	10			10			10		
15	1.17		0.20	15			15			15		
20	1.18	0.92	0.20	20			20			20		
30	1.20		0.20	30			30			30		
40	1.23	0.94	0.20	40			40			40		
60	1.25		0.18	60			60			60		
90	1.28	0.93	0.16	90			90			90		
120	1.32		0.15	120			120			120		
150	1.37	0.92	0.13	150			150			150		
180	1.42		0.12	180			180			180		
210	1.44	0.90	0.10	210			210			210		
240	1.46		0.09	240			240			240		
300	1.48	0.93	0.07	300			300			300		
360	1.48		0.06	360			360			360		
420	1.49	0.94	0.05	420			420			420		
480	1.50		0.04	480			480			480		
540	1.50	0.92	0.03	540			540			540		
600	1.51		0.02	600			600			600		
720	1.50	0.91	0.00	720			720			720		
840	1.49			840			840			840		
960	1.49	0.94		960			960			960		
1080	1.50			1080			1080			1080		
1200	1.51	0.92		1200			1200			1200		
1320	1.51			1320			1320			1320		
1440	1.51	0.93		1440			1440			1440		
1080				1800			1800			1800		
1140				2280			2280			2280		
1200				2880			2880			2880		
1260												
1320												
1380												
1440												

CONSTANT DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	EC-Q14-1645	**PROJECT:**	GWSE - Middelburg Grootfontein Aquifer	**CLIENT:**	DWA
ALTERNATIVE NO. :	0	**SITE NAME:**	0		
DEPTH OF PUMP (mbdl):	18.35	**PUMP TYPE USED:**	Franklin	**OPERATOR:**	Lucky
INLET DIAMETER (mm):	160	**EXISTING EQUIPMENT:**	0	**CONTRACTOR:**	AB Pumps

TEST STARTED	**DATE:**	30-May-08	**TEST COMPLETED**	**DATE:**		**TOTAL TIME - PUMPED (min):**		**TOTAL TEST TIME (min):**	
	TIME:	1:30 PM		**TIME:**		**TOTAL TIME-RECOVERY(min):**		**AVERAGE YIELD (l/s):**	1.82

DISCHARGE BOREHOLE		***OBSERVATION BOREHOLE 1***		***OBSERVATION BOREHOLE 2***		***OBSERVATION BOREHOLE 3***	
CASING HEIGHT (magl):	0.08	**No. :**		**No. :**		**No. :**	
CASING DEPTH (mbdl):	0.00	**DATUM LEVEL (magl):**		**DATUM LEVEL (magl):**		**DATUM LEVEL (magl):**	
CASING ID (mm):	0.00	**CASING DEPTH (mbdl):**		**CASING DEPTH (mbdl):**		**CASING DEPTH (mbdl):**	
BOREHOLE DEPTH (mbdl):	21.60	**BOREHOLE DEPTH :**		**BOREHOLE DEPTH :**		**BOREHOLE DEPTH :**	
WATER LEVEL (mbdl):	7.07	**WATER LEVEL:**		**WATER LEVEL:**		**WATER LEVEL:**	
DATUM LEVEL (magl):	0.38	**DISTANCE (m):**		**DISTANCE (m):**		**DISTANCE (m):**	

Time (min)	Drawdown (m)	Yield (l/s)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)
1	1.80		7.80	**1**			**1**			**1**		
2	1.84	1.90	7.09	**2**			**2**			**2**		
3	1.94		7.03	**3**			**3**			**3**		
5	2.09	2.04	6.99	**5**			**5**			**5**		
7	2.48		6.94	**7**			**7**			**7**		
10	2.75	2.02	6.90	**10**			**10**			**10**		
15	3.04		6.81	**15**			**15**			**15**		
20	3.16	2.02	6.74	**20**			**20**			**20**		
30	3.36		6.60	**30**			**30**			**30**		
40	3.53	2.01	6.42	**40**			**40**			**40**		
60	3.93		6.13	**60**			**60**			**60**		
90	4.62	2.03	5.76	**90**			**90**			**90**		
120	5.33		5.37	**120**			**120**			**120**		
150	5.89	2.00	5.00	**150**			**150**			**150**		
180	6.40		4.75	**180**			**180**			**180**		
210	6.87	2.01	4.42	**210**			**210**			**210**		
240	7.27	2.00	4.12	**240**			**240**			**240**		
300	8.24		3.45	**300**			**300**			**300**		
310	8.92		2.90	**360**			**360**			**360**		
320	8.92	1.37		**420**			**420**			**420**		
330	8.92	1.26		**480**			**480**			**480**		
350	8.92	1.18		**540**			**540**			**540**		
600				**600**			**600**			**600**		
660				**720**			**720**			**720**		
720				**840**			**840**			**840**		
780				**960**			**960**			**960**		
840				**1080**			**1080**			**1080**		
900				**1200**			**1200**			**1200**		
960				**1320**			**1320**			**1320**		
1020				**1440**			**1440**			**1440**		
1080				**1800**			**1800**			**1800**		
1140				**2280**			**2280**			**2280**		
1200				**2880**			**2880**			**2880**		
1260												
1320												
1380												
1440												

STEPPED DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	EC-Q14-1646	PROJECT:	GWSE - Middelburg Grootfontein Aquifer
ALTERNATIVE NO. :	0	SITE NAME:	Redslands
ALTERNATIVE NO. :	0	CLIENT:	DWA

BOREHOLE DEPTH (mbdl):	45.89	CASING DEPTH (mbdl):	0.00	PUMP TYPE USED:	Mono Pump
DEPTH OF PUMP (mbdl):	43.50	CASING HEIGHT (magl):	0.46	OPERATOR:	Petrus
PUMP INLET DIAMETER (mm):	170.000	CASING ID (mm):	0.000	CONTRACTOR:	AB Pumps
STATIC WATER LEVEL (mbdl):	5.35	DATUM LEVEL (magl):	0.19		

DISCHARGE RATE 1			Time	Recovery 1	DISCHARGE RATE 2			Time	Recovery 2	DISCHARGE RATE 3			Time	Recovery 3
DATE:	31-May-08		(min)	(m)	DATE:	31-May-08		(min)	(m)	DATE:	31-May-08		(min)	(m)
TIME:	7:00 AM		1		TIME:	8:00 AM		1		TIME:	9:00 AM		1	
Time	Drawdown	Yield	2		Time	Drawdown	Yield	2		Time	Drawdown	Yield	2	
(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3	
1	0.18		5		1	1.10		5		1	2.24		5	
2	0.22	3.08	7		2	1.15	6.04	7		2	3.38	8.97	7	
3	0.24		10		3	1.19		10		3	3.41		10	
5	0.27	3.08	15		5	1.23	6.04	15		5	3.44	10.03	15	
7	0.32		20		7	1.27		20		7	3.48		20	
10	0.36	3.07	30		10	1.33	6.03	30		10	3.58	10.03	30	
15	0.39		40		15	1.40		40		15	3.79		40	
20	0.42	3.08	50		20	1.47	6.04	50		20	3.93	10.02	50	
30	0.48		60		30	1.58		60		30	4.20		60	
40	0.54	3.06	70		40	1.72	6.05	70		40	4.49	10.03	70	
50	0.60		80		50	1.80		80		50	4.65		80	
60	0.65	3.06	90		60	1.89	6.05	90		60	4.90	10.02	90	
70			100		70			100		70			100	
80			110		80			110		80			110	
90			120		90			120		90			120	
100			150		100			150		100			150	
110			180		110			180		110			180	
120			210		120			210		120			210	
Average yield:	3.0716667	(l/s)			Average yield:	6.0416667				Average yield:	9.85			

DISCHARGE RATE 4			Time	Recovery 4	DISCHARGE RATE 5			Time	Recovery 5	DISCHARGE RATE 6			Time	Recovery
DATE:	31-May-08		(min)	(m)	DATE:	31-May-08		(min)	(m)	DATE:	31-May-08		(min)	(m)
TIME:	10:00 AM		1		TIME:			1		TIME:			1	6.18
Time	Drawdown	Yield	2		Time	Drawdown	Yield	2		Time	Drawdown	Yield	2	6.04
(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3	5.85
1	9.38		5		1			5		1			5	5.48
2	9.84	16.21	7		2			7		2			7	5.15
3	10.16		10		3			10		3			10	4.78
5	10.59	18.33	15		5			15		5			15	4.33
7	11.04		20		7			20		7			20	3.93
10	11.45	18.33	30		10			30		10			30	3.27
15	11.95		40		15			40		15			40	2.73
20	12.49	18.31	50		20			50		20			50	2.50
30	13.18		60		30			60		30			60	2.08
40	13.86	18.30	70		40			70		40			70	1.86
50	14.43		80		50			80		50			80	1.65
60	14.92	18.32	90		60			90		60			90	1.50
70			100		70			100		70			100	1.42
80			110		80			110		80			110	1.27
90			120		90			120		90			120	1.14
100			150		100			150		100			150	0.91
110			180		110			180		110			180	0.75
120			210		120			210		120			210	0.62
Average yield:	17.966667							240		150			240	0.51
COMMENTS:								300		180			300	
								360		210			360	
								420		240			420	

CONSTANT DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	EC-Q14-1646	PROJECT:	GWSE - Middelburg Grootfontein Aquifer	CLIENT:	DWA
ALTERNATIVE NO. :	0	SITE NAME:	Redslands		
DEPTH OF PUMP (mbdl):	43.50	PUMP TYPE USED:	Mono Pump	OPERATOR:	Petrus
INLET DIAMETER (mm):	170	EXISTING EQUIPMENT:	0	CONTRACTOR:	AB Pumps

TEST STARTED	DATE:	31-May-08	TEST COMPLETED	DATE:		TOTAL TIME - PUMPED (min):	TOTAL TEST TIME (min):	
	TIME:	7:00 AM		TIME:		TOTAL TIME-RECOVERY(min):	AVERAGE YIELD (l/s):	16.69

DISCHARGE BOREHOLE		*OBSERVATION BOREHOLE 1*		*OBSERVATION BOREHOLE 2*		*OBSERVATION BOREHOLE 3*	
CASING HEIGHT (magl):	0.46	No. :		No. :		No. :	
CASING DEPTH (mbdl):	0.00	DATUM LEVEL (magl):		DATUM LEVEL (magl):		DATUM LEVEL (magl):	
CASING ID (mm):	0.00	CASING DEPTH (mbdl):		CASING DEPTH (mbdl):		CASING DEPTH (mbdl):	
BOREHOLE DEPTH (mbdl):	45.89	BOREHOLE DEPTH :		BOREHOLE DEPTH :		BOREHOLE DEPTH :	
WATER LEVEL (mbdl):	5.35	WATER LEVEL:		WATER LEVEL:		WATER LEVEL:	
DATUM LEVEL (magl):	0.19	DISTANCE (m):		DISTANCE (m):		DISTANCE (m):	

Time (min)	Drawdown (m)	Yield (l/s)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)
1	5.80		19.17	1			1			1		
2	6.14	16.05	19.04	2			2			2		
3	6.29		18.83	3			3			3		
5	6.33	16.76	18.51	5			5			5		
7	6.55		18.30	7			7			7		
10	7.05	16.76	17.88	10			10			10		
15	7.67		17.39	15			15			15		
20	8.06	16.74	17.08	20			20			20		
30	9.04		16.47	30			30			30		
40	9.76	16.75	16.07	40			40			40		
60	10.90		16.02	60			60			60		
90	12.46	16.73	14.12	90			90			90		
120	13.68		13.13	120			120			120		
150	14.63	16.74	11.96	150			150			150		
180	15.58		10.74	180			180			180		
210	16.39	16.70	9.73	210			210			210		
240	16.96		8.90	240			240			240		
300	17.95	16.70	7.62	300			300			300		
360	19.10		6.49	360			360			360		
420	20.00	16.73	5.64	420			420			420		
480	20.80		4.90	480			480			480		
540	21.57	16.73	4.26	540			540			540		
600	22.36		3.86	600			600			600		
720	23.30	16.71	3.07	720			720			720		
840	24.05		2.38	840			840			840		
960	25.20	16.72	1.86	960			960			960		
1080	25.88		1.49	1080			1080			1080		
1200	26.35	16.74	1.20	1200			1200			1200		
1320	27.78		0.98	1320			1320			1320		
1440	28.53	16.72	0.81	1440			1440			1440		
1080				1800			1800			1800		
1140				2280			2280			2280		
1200				2880			2880			2880		
1260												
1320												
1380												
1440												

STEPPED DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	EC-Q14-1647	PROJECT:	GWSE - Middelburg Grootfontein Aquifer
ALTERNATIVE NO. :	0	SITE NAME:	Redlands
ALTERNATIVE NO. :	0	CLIENT:	DWA

BOREHOLE DEPTH (mbdl):	41.56	CASING DEPTH (mbdl):	0.00	PUMP TYPE USED:	BP105
DEPTH OF PUMP (mbdl):	40.50	CASING HEIGHT (magl):	0.18	OPERATOR:	0
PUMP INLET DIAMETER (mm):	220.000	CASING ID (mm):	0.000	CONTRACTOR:	AB Pumps
STATIC WATER LEVEL (mbdl):	5.94	DATUM LEVEL (magl):	0.24		

DISCHARGE RATE 1			Time	Recovery 1	DISCHARGE RATE 2			Time	Recovery 2	DISCHARGE RATE 3			Time	Recovery 3
DATE:	28-May-08		(min)	(m)	DATE:	28-May-08		(min)	(m)	DATE:	28-May-08		(min)	(m)
TIME:	9:20 AM		1		TIME:	10:20 AM		1		TIME:	11:20		1	
Time	Drawdown	Yield	2		Time	Drawdown	Yield	2		Time	Drawdown	Yield	2	
(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3	
1	1.08		5		1	3.15		5		1	9.54		5	
2	1.10		7		2	4.03	6.670	7		2	13.72	9.240	7	
3	1.13		10		3	4.88		10		3	16.14		10	
5	1.16	3.320	15		5	5.91	6.310	15		5	18.48	9.250	15	
7	1.14		20		7	6.24		20		7	22.46		20	
10	1.15	3.300	30		10	6.49	7.300	30		10	25.11	9.250	30	
15	1.17		40		15	6.80		40		11	29.94		40	
20	1.20	3.300	50		20	7.01	7.310	50		12	33.38	9.250	50	
30	1.23		60		30	7.24		60		15	33.38	8.150	60	
40	1.30	3.310	70		40	7.51	7.320	70		18	33.38	8.790	70	
50	1.28		80		50	7.74		80		20	33.38	8.550	80	
60	1.28	3.280	90		60	7.83	7.320	90		60			90	
70			100		70			100		70			100	
80			110		80			110		80			110	
90			120		90			120		90			120	
100			150		100			150		100			150	
110			180		110			180		110			180	
120			210		120			210		120			210	
	Average yield:	3.302	(l/s)			Average yield:	7.0383333				Average yield:	8.9257143		

DISCHARGE RATE 4			Time	Recovery 4	DISCHARGE RATE 5			Time	Recovery 5	DISCHARGE RATE 6			Time	Recovery
DATE:	28-May-08		(min)	(m)	DATE:	28-May-08		(min)	(m)	DATE:	28-May-08		(min)	(m)
TIME:			1		TIME:			1		TIME:			1	1.48
Time	Drawdown	Yield	2		Time	Drawdown	.	2		Time	Drawdown	Yield	2	0.60
(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3	0.34
1			5		1			5		1			5	0.27
2			7		2			7		2			7	0.22
3			10		3			10		3			10	0.19
5			15		5			15		5			15	0.16
7			20		7			20		7			20	0.14
10			30		10			30		10			30	0.12
15			40		15			40		15			40	0.10
20			50		20			50		20			50	0.08
30			60		30			60		30			60	0.07
40			70		40			70		40			70	0.07
50			80		50			80		50			80	0.06
60			90		60			90		60			90	0.05
70			100		70			100		70			100	0.05
80			110		80			110		80			110	
90			120		90			120		90			120	
100			150		100			150		100			150	
110			180		110			180		110			180	
120			210		120			210		120			210	
	Average yield:	#DIV/0!						240		150			240	
COMMENTS:								300		180			300	
								360		210			360	
								420		240			420	

CONSTANT DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	EC-Q14-1647	PROJECT:	GWSE - Middelburg Grootfontein Aquifer	CLIENT:	DWA
ALTERNATIVE NO. :	0	SITE NAME:	Redlands		
DEPTH OF PUMP (mbdl):	40.50	PUMP TYPE USED:	BP105	OPERATOR:	0
INLET DIAMETER (mm):	220	EXISTING EQUIPMENT:	0	CONTRACTOR:	AB Pumps

TEST STARTED	DATE:	2008/05/28	TEST COMPLETED	DATE:	30-May	TOTAL TIME - PUMPED (min):	1440	TOTAL TEST TIME (min):	1920
	TIME:	1:40 PM		TIME:	1:40 PM	TOTAL TIME-RECOVERY(min):	480	AVERAGE YIELD (l/s):	7.20

DISCHARGE BOREHOLE		*OBSERVATION BOREHOLE 1*		*OBSERVATION BOREHOLE 2*		*OBSERVATION BOREHOLE 3*	
CASING HEIGHT (magl):	0.18	No. :		No. :		No. :	
CASING DEPTH (mbdl):	0.00	DATUM LEVEL (magl):		DATUM LEVEL (magl):		DATUM LEVEL (magl):	
CASING ID (mm):	0.00	CASING DEPTH (mbdl):		CASING DEPTH (mbdl):		CASING DEPTH (mbdl):	
BOREHOLE DEPTH (mbdl):	41.56	BOREHOLE DEPTH :		BOREHOLE DEPTH :		BOREHOLE DEPTH :	
WATER LEVEL (mbdl):	5.94	WATER LEVEL:		WATER LEVEL:		WATER LEVEL:	
DATUM LEVEL (magl):	0.24	DISTANCE (m):		DISTANCE (m):		DISTANCE (m):	

Time (min)	Drawdown (m)	Yield (l/s)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)
1	1.94		1.02	1			1			1		
2	3.80		0.72	2			2			2		
3	4.41		0.57	3			3			3		
5	5.28	7.06	0.51	5			5			5		
7	5.96		0.48	7			7			7		
10	6.20	7.19	0.46	10			10			10		
15	6.67		0.43	15			15			15		
20	6.94	7.22	0.41	20			20			20		
30	7.13		0.38	30			30			30		
40	7.28	7.20	0.35	40			40			40		
60	7.55		0.30	60			60			60		
90	7.89	7.20	0.27	90			90			90		
120	8.35		0.24	120			120			120		
150	8.51	7.21	0.21	150			150			150		
180	8.61		0.20	180			180			180		
210	8.70	7.23	0.18	210			210			210		
240	8.78		0.16	240			240			240		
300	8.94	7.25	0.14	300			300			300		
360	9.10		0.12	360			360			360		
420	9.24	7.23	0.11	420			420			420		
480	9.31		0.10	480			480			480		
540	9.37	7.21		540			540			540		
600	9.43			600			600			600		
720	9.56	7.22		720			720			720		
840	9.69			840			840			840		
960	9.78	7.21		960			960			960		
1080	9.89			1080			1080			1080		
1200	10.01	7.21		1200			1200			1200		
1320	10.13			1320			1320			1320		
1440	10.24	7.21		1440			1440			1440		
1080				1800			1800			1800		
1140				2280			2280			2280		
1200				2880			2880			2880		
1260												
1320												
1380												
1440												

CONSTANT DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	EC-Q14-1651	PROJECT:	GWSE - Middelburg Grootfontein Aquifer	CLIENT:	DWA
ALTERNATIVE NO. :	0	SITE NAME:	Hartbeesfontein		
DEPTH OF PUMP (mbdl):	43.50	PUMP TYPE USED:	Submersible	OPERATOR:	Phineas
INLET DIAMETER (mm):	160	EXISTING EQUIPMENT:	0	CONTRACTOR:	Ab Pumps

TEST STARTED	DATE:	4-Jun-08	TEST COMPLETED	DATE:		TOTAL TIME - PUMPED (min):		TOTAL TEST TIME (min):	
	TIME:	7:30 AM		TIME:		TOTAL TIME-RECOVERY(min):		AVERAGE YIELD (l/s):	22.36

DISCHARGE BOREHOLE		*OBSERVATION BOREHOLE 1*		*OBSERVATION BOREHOLE 2*		*OBSERVATION BOREHOLE 3*	
CASING HEIGHT (magl):	0.22	No. :		No. :		No. :	
CASING DEPTH (mbdl):	0.00	DATUM LEVEL (magl):		DATUM LEVEL (magl):		DATUM LEVEL (magl):	
CASING ID (mm):	0.00	CASING DEPTH (mbdl):		CASING DEPTH (mbdl):		CASING DEPTH (mbdl):	
BOREHOLE DEPTH (mbdl):	45.30	BOREHOLE DEPTH :		BOREHOLE DEPTH :		BOREHOLE DEPTH :	
WATER LEVEL (mbdl):	7.48	WATER LEVEL:		WATER LEVEL:		WATER LEVEL:	
DATUM LEVEL (magl):	0.30	DISTANCE (m):		DISTANCE (m):		DISTANCE (m):	

Time (min)	Drawdown (m)	Yield (l/s)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)
1	0.90		3.64	1			1			1		
2	1.04		3.56	2			2			2		
3	1.14	22.37	3.54	3			3			3		
5	1.24		3.50	5			5			5		
7	1.45	22.36	3.47	7			7			7		
10	1.59		3.43	10			10			10		
15	1.67	22.36	3.38	15			15			15		
20	1.72		3.34	20			20			20		
30	1.78	22.35	3.28	30			30			30		
40	1.84		3.22	40			40			40		
60	1.96	22.35	3.12	60			60			60		
90	2.08		3.02	90			90			90		
120	2.20	22.38	2.93	120			120			120		
150	2.32		2.86	150			150			150		
180	2.41	22.36	2.80	180			180			180		
210	2.48		2.76	210			210			210		
240	2.56	22.34	2.73	240			240			240		
300	2.69		2.64	300			300			300		
360	2.84	22.36	2.56	360			360			360		
420	2.93		2.45	420			420			420		
480	3.04	22.38	2.38	480			480			480		
540	3.13		2.32	540			540			540		
600	3.23	22.38	2.26	600			600			600		
720	3.41		2.16	720			720			720		
840	3.56	22.36	2.08	840			840			840		
960	3.71		2.00	960			960			960		
1080	3.86	22.35	1.93	1080			1080			1080		
1200	4.01		1.86	1200			1200			1200		
1320	4.15	22.35	1.78	1320			1320			1320		
1440	4.29		1.72	1440			1440			1440		
1560	4.39	22.39	1.66	1800			1800			1800		
1680	4.49		1.61	2280			2280			2280		
1800	4.57	22.38	1.56	2880			2880			2880		
1920	4.69		1.50									
2040	4.82	22.38	1.46									
2160	4.96		1.42									

4.2 New exploration boreholes tested

STEPPED DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	EC-Q14-1631			PROJECT:	GWSE - Middelburg Grootfontein Aquifer
ALTERNATIVE NO. :	0			SITE NAME:	Dunblane
ALTERNATIVE NO. :	0			CLIENT:	DWA
BOREHOLE DEPTH (mbdl):	126.70	CASING DEPTH (mbdl):	0.00	PUMP TYPE USED:	GW9602
DEPTH OF PUMP (mbdl):	110.00	CASING HEIGHT (magl):	0.45	OPERATOR:	Johannes
PUMP INLET DIAMETER (mm):	210.000	CASING ID (mm):	0.000	CONTRACTOR:	AB Pumps
STATIC WATER LEVEL (mbdl):	11.10	DATUM LEVEL (magl):	0.51		

DISCHARGE RATE 1			Time	Recovery 1	DISCHARGE RATE 2			Time	Recovery 2	DISCHARGE RATE 3			Time	Recovery 3
DATE:	29-Jan-08		(min)	(m)	DATE:	29-Jan-08		(min)	(m)	DATE:	29-Jan-08		(min)	(m)
TIME:	2:00 PM		1		TIME:	3:00 PM		1		TIME:	4:00 PM		1	
Time	Drawdown	Yield	2		Time	Drawdown	Yield	2		Time	Drawdown	Yield	2	
(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3	
1	0.33		5		1	3.40		5		1	6.32		5	
2	0.72		7		2	3.59		7		2	7.34		7	
3	0.83		10		3	3.72	7.31	10		3	7.82	9.20	10	
5	1.09		15		5	3.98		15		5	8.68		15	
7	1.21		20		7	4.18	7.33	20		7	9.16	15.70	20	
10	1.48	4.23	30		10	4.38		30		10	9.43	14.64	30	
15	1.76	4.30	40		15	4.66	7.33	40		15	10.00	14.66	40	
20	2.01		50		20	4.89		50		20	10.50	14.65	50	
30	2.32	4.30	60		30	5.53	7.30	60		30	11.30		60	
40	2.60	4.34	70		40	5.65	7.32	70		40	11.98	14.63	70	
50	2.78	4.35	80		50	5.90	7.33	80		50	12.58		80	
60	3.14	4.35	90		60	6.22	7.33	90		60	13.12	14.65	90	
70			100		70			100		70			100	
80			110		80			110		80			110	
90			120		90			120		90			120	
100			150		100			150		100			150	
110			180		110			180		110			180	
120			210		120			210		120			210	
	Average yield:	4.3116667	(l/s)			Average yield:	7.3214286				Average yield:	14.018571		

DISCHARGE RATE 4			Time	Recovery 4	DISCHARGE RATE 5			Time	Recovery 5	DISCHARGE RATE 6			Time	Recovery
DATE:	29-Jan-08		(min)	(m)	DATE:	29-Jan-08		(min)	(m)	DATE:	29-Jan-08		(min)	(m)
TIME:	5:00 PM		1		TIME:			1		TIME:			1	21.16
Time	Drawdown	Yield	2		Time	Drawdown	Yield	2		Time	Drawdown	Yield	2	19.84
(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3	18.75
1	14.00		5		1			5		1			5	17.17
2	14.30		7		2			7		2			7	16.55
3	14.90	28.00	10		3			10		3			10	15.30
5	16.53	26.00	15		5			15		5			15	13.21
7	16.70		20		7			20		7			20	12.33
10	17.10	25.10	30		10			30		10			30	10.28
15	17.94		40		15			40		15			40	8.89
20	18.58	25.10	50		20			50		20			50	7.88
30	19.80	25.10	60		30			60		30			60	7.00
40	20.75		70		40			70		40			70	6.42
50	23.50	25.10	80		50			80		50			80	5.56
60	25.24		90		60			90		60			90	5.40
70			100		70			100		70			100	5.00
80			110		80			110		80			110	4.70
90			120		90			120		90			120	4.34
100			150		100			150		100			150	3.63
110			180		110			180		110			180	3.05
120			210		120			210		120			210	2.68
	Average yield:	25.733333						240		150			240	2.36
COMMENTS:								300		180			300	
								360		210			360	
								420		240			420	

CONSTANT DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	EC-Q14-1631	PROJECT:	GWSE - Middelburg Grootfontein Aquifer	CLIENT:	DWA
ALTERNATIVE NO. :	0	SITE NAME:	Dunblane		
DEPTH OF PUMP (mbdl):	110.00	PUMP TYPE USED:	GW9602	OPERATOR:	Johannes
INLET DIAMETER (mm):	210	EXISTING EQUIPMENT:	0	CONTRACTOR:	AB Pumps

TEST STARTED	DATE:	30-Jan-08	TEST COMPLETED	DATE:		TOTAL TIME - PUMPED (min):		TOTAL TEST TIME (min):	
	TIME:	1:00 PM		TIME:		TOTAL TIME-RECOVERY(min):		AVERAGE YIELD (l/s):	17.12

DISCHARGE BOREHOLE		*OBSERVATION BOREHOLE 1*		*OBSERVATION BOREHOLE 2*		*OBSERVATION BOREHOLE 3*	
CASING HEIGHT (magl):	0.45	No. :		No. :		No. :	
CASING DEPTH (mbdl):	0.00	DATUM LEVEL (magl):		DATUM LEVEL (magl):		DATUM LEVEL (magl):	
CASING ID (mm):	0.00	CASING DEPTH (mbdl):		CASING DEPTH (mbdl):		CASING DEPTH (mbdl):	
BOREHOLE DEPTH (mbdl):	126.70	BOREHOLE DEPTH :		BOREHOLE DEPTH :		BOREHOLE DEPTH :	
WATER LEVEL (mbdl):	11.10	WATER LEVEL:		WATER LEVEL:		WATER LEVEL:	
DATUM LEVEL (magl):	0.51	DISTANCE (m):		DISTANCE (m):		DISTANCE (m):	

Time (min)	Drawdown (m)	Yield (l/s)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)
1	1.86		32.32	1			1			1		
2	2.83		30.76	2			2			2		
3	3.69	18.05	29.79	3			3			3		
5	4.80		27.82	5			5			5		
7	5.39	17.20	26.92	7			7			7		
10	6.07		24.54	10			10			10		
15	7.75	17.00	22.74	15			15			15		
20	8.66	17.03	21.41	20			20			20		
30	10.03	17.05	19.84	30			30			30		
40	10.88	17.03	18.78	40			40			40		
60	12.65	17.09	17.07	60			60			60		
90	14.37	17.10	14.92	90			90			90		
120	15.56	17.10	13.08	120			120			120		
150	16.58	17.08	11.54	150			150			150		
180	17.25	17.08	10.29	180			180			180		
210	17.86	17.09	9.22	210			210			210		
240	18.44	17.08	8.35	240			240			240		
300	20.37	17.10	6.88	300			300			300		
360	22.02	17.12	5.85	360			360			360		
420	23.44	17.10	5.03	420			420			420		
480	24.80	17.10	4.40	480			480			480		
540	25.68	17.09	3.93	540			540			540		
600	26.42	17.08	2.89	600			600			600		
720	26.98	17.09	2.50	720			720			720		
840	27.68	17.10	2.45	840			840			840		
960	28.49	17.12	2.04	960			960			960		
1080	29.70	17.10	1.75	1080			1080			1080		
1200	30.55	17.10	1.52	1200			1200			1200		
1320	32.58	17.12	1.34	1320			1320			1320		
1440	34.53	17.08	1.17	1440			1440			1440		
1560	35.42	17.10	1.03	1800			1800			1800		
1680	35.97	17.12	0.92	2280			2280			2280		
1800	36.58	17.08	0.82	2880			2880			2880		
1920	37.42	17.10	0.73									
2040	37.00	17.12										
2160	38.25	17.12										
2280	38.49	17.09										

DISCHARGE BOREHOLE				*OBSERVATION BOREHOLE 1*			*OBSERVATION BOREHOLE 2*			*OBSERVATION BOREHOLE 3*		
Time (min)	Drawdown (m)	Yield (l/s)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)
2400	38.98	17.08		1500			1500			1500		
2520	38.99	17.10		1560			1560			1560		
2640	39.00	17.18		1620			1620			1620		
2760	39.15	17.10		1680			1680			1680		
2880	39.29	17.10		1740			1740			1740		

STEPPED DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	EC-Q14-1632	PROJECT:	GWSE - Middelburg Grootfontein Aquifer
ALTERNATIVE NO. :	0	SITE NAME:	Dunblane
ALTERNATIVE NO. :	0	CLIENT:	DWA

BOREHOLE DEPTH (mbdl):	236.00	CASING DEPTH (mbdl):	0.00	PUMP TYPE USED:	GW9602
DEPTH OF PUMP (mbdl):	203.00	CASING HEIGHT (magl):	0.49	OPERATOR:	Johannes
PUMP INLET DIAMETER (mm):	210.000	CASING ID (mm):	0.000	CONTRACTOR:	AB Pumps
STATIC WATER LEVEL (mbdl):	9.28	DATUM LEVEL (magl):	0.67		

DISCHARGE RATE 1			Time	Recovery 1	DISCHARGE RATE 2			Time	Recovery 2	DISCHARGE RATE 3			Time	Recovery 3
DATE:	08-Feb-08		(min)	(m)	DATE:	08-Feb-08		(min)	(m)	DATE:	08-Feb-08		(min)	(m)
TIME:	5:20 PM		1		TIME:	6:20 PM		1		TIME:	7:20 PM		1	
Time	Drawdown	Yield	2		Time	Drawdown	Yield	2		Time	Drawdown	Yield	2	
(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3	
1	10.55		5		1	11.61		5		1	14.56		5	
2	10.59		7		2	12.06		7		2	15.55	11.02	7	
3	10.64	3.60	10		3	12.62	5.73	10		3	16.52		10	
5	10.64		15		5	12.83		15		5	17.60	10.28	15	
7	10.64	3.61	20		7	12.88	6.00	20		7	18.54		20	
10	10.64		30		10	12.95		30		10	18.81	10.27	30	
15	10.64	3.60	40		15	13.02	6.02	40		15	18.92		40	
20	10.64		50		20	13.10		50		20	18.99	10.25	50	
30	10.64	3.60	60		30	13.17	6.02	60		30	19.13		60	
40	10.64		70		40	13.25		70		40	19.19	10.28	70	
50	10.64	3.60	80		50	13.35	6.04	80		50	19.24		80	
60	10.64		90		60	13.45	6.04	90		60	19.28	10.29	90	
70			100		70			100		70			100	
80			110		80			110		80			110	
90			120		90			120		90			120	
100			150		100			150		100			150	
110			180		110			180		110			180	
120			210		120			210		120			210	
	Average yield:	3.602	(l/s)			Average yield:	5.975				Average yield:	10.398333		

DISCHARGE RATE 4			Time	Recovery 4	DISCHARGE RATE 5			Time	Recovery 5	DISCHARGE RATE 6			Time	Recovery
DATE:	08-Feb-08		(min)	(m)	DATE:	08-Feb-08		(min)	(m)	DATE:	08-Feb-08		(min)	(m)
TIME:	8:20 PM		1		TIME:			1		TIME:			1	46.45
Time	Drawdown	Yield	2		Time	Drawdown	.	2		Time	Drawdown	Yield	2	23.68
(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3	5.68
1	21.08		5		1			5		1			5	4.23
2	30.25		7		2			7		2			7	3.34
3	38.82	20.00	10		3			10		3			10	10.35
5	47.57		15		5			15		5			15	9.81
7	56.23		20		7			20		7			20	9.54
10	67.80	20.02	30		10			30		10			30	9.42
15	82.25		40		15			40		15			40	9.35
20	97.70		50		20			50		20			50	9.31
30	112.86	20.02	60		30			60		30			60	9.30
40	127.67		70		40			70		40			70	9.28
50	142.00		80		50			80		50			80	9.26
60	165.33	20.04	90		60			90		60			90	9.25
70			100		70			100		70			100	9.24
80			110		80			110		80			110	9.23
90			120		90			120		90			120	
100			150		100			150		100			150	
110			180		110			180		110			180	
120			210		120			210		120			210	
	Average yield:	20.02						240		150			240	
COMMENTS:								300		180			300	
								360		210			360	
								420		240			420	

CONSTANT DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	EC-Q14-1632	PROJECT:	GWSE - Middelburg Grootfontein Aquifer	CLIENT:	DWA
ALTERNATIVE NO. :	0	SITE NAME:	Dunblane		
DEPTH OF PUMP (mbdl):	203.00	PUMP TYPE USED:	GW9602	OPERATOR:	Johannes
INLET DIAMETER (mm):	210	EXISTING EQUIPMENT:	0	CONTRACTOR:	AB Pumps

TEST STARTED	DATE:	09-Feb-08	TEST COMPLETED	DATE:		TOTAL TIME - PUMPED (min):		TOTAL TEST TIME (min):	
	TIME:	7:30 AM		TIME:		TOTAL TIME-RECOVERY(min):		AVERAGE YIELD (l/s):	15.50

DISCHARGE BOREHOLE		OBSERVATION BOREHOLE 1		OBSERVATION BOREHOLE 2		OBSERVATION BOREHOLE 3	
CASING HEIGHT (magl):	0.49	No. :		No. :		No. :	
CASING DEPTH (mbdl):	0.00	DATUM LEVEL (magl):		DATUM LEVEL (magl):		DATUM LEVEL (magl):	
CASING ID (mm):	0.00	CASING DEPTH (mbdl):		CASING DEPTH (mbdl):		CASING DEPTH (mbdl):	
BOREHOLE DEPTH (mbdl):	236.00	BOREHOLE DEPTH :		BOREHOLE DEPTH :		BOREHOLE DEPTH :	
WATER LEVEL (mbdl):	9.28	WATER LEVEL:		WATER LEVEL:		WATER LEVEL:	
DATUM LEVEL (magl):	0.67	DISTANCE (m):		DISTANCE (m):		DISTANCE (m):	

Time (min)	Drawdown (m)	Yield (l/s)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)
1	11.82		25.36	1			1			1		
2	24.98		16.40	2			2			2		
3	27.90		14.00	3			3			3		
5	30.73		10.29	5			5			5		
7	34.05		7.64	7			7			7		
10	40.36	15.90	6.02	10			10			10		
15	43.00		8.94	15			15			15		
20	46.49		10.14	20			20			20		
30	49.58	15.53	9.79	30			30			30		
40	51.26		9.57	40			40			40		
60	52.34	15.62	9.40	60			60			60		
90	54.97		9.35	90			90			90		
120	55.33	15.50	9.35	120			120			120		
150	59.95		9.30	150			150			150		
180	62.45	15.50	9.25	180			180			180		
210	64.10		9.21	210			210			210		
240	67.56	15.48		240			240			240		
300	72.08			300			300			300		
360	76.29			360			360			360		
420	80.14	15.49		420			420			420		
480	84.56			480			480			480		
540	86.00	15.50		540			540			540		
600	88.26			600			600			600		
720	89.89	15.00		720			720			720		
840	91.92			840			840			840		
960	93.36			960			960			960		
1080	96.10	15.50		1080			1080			1080		
1200	100.36			1200			1200			1200		
1320	105.62	15.50		1320			1320			1320		
1140	107.26			1440			1440			1440		
1500	110.45			1800			1800			1800		
1140				2280			2280			2280		
1200				2880			2880			2880		
1260												
1320												
1380												
1440												

STEPPED DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	EC-Q14-1633	PROJECT:	GWSE - Middelburg Grootfontein Aquifer
ALTERNATIVE NO. :	0	SITE NAME:	Dunblane
ALTERNATIVE NO. :	0	CLIENT:	DWA

BOREHOLE DEPTH (mbdl):	256.00	CASING DEPTH (mbdl):	20.00	PUMP TYPE USED:	GW9002
DEPTH OF PUMP (mbdl):	203.00	CASING HEIGHT (magl):	0.46	OPERATOR:	Johannes
PUMP INLET DIAMETER (mm):	270.000	CASING ID (mm):	0.000	CONTRACTOR:	AB Pumps
STATIC WATER LEVEL (mbdl):	32.10	DATUM LEVEL (magl):	0.49		

DISCHARGE RATE 1			Time	Recovery 1	DISCHARGE RATE 2			Time	Recovery 2	DISCHARGE RATE 3			Time	Recovery 3
DATE:	04-Feb-08		(min)	(m)	DATE:	04-Feb-08		(min)	(m)	DATE:	04-Feb-08		(min)	(m)
TIME:	7:00 AM		1		TIME:	8:00 AM		1		TIME:	9:00 AM		1	
Time	Drawdown	Yield	2		Time	Drawdown	Yield	2		Time	Drawdown	Yield	2	
(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3	
1	35.46		5		1	47.65		5		1	72.32		5	
2	36.04	0.39	7		2	50.15		7		2	73.62	2.91	7	
3	36.14		10		3	52.64	1.43	10		3	76.26		10	
5	36.18	0.39	15		5	54.39		15		5	79.18	2.94	15	
7	36.26		20		7	56.96	1.44	20		7	82.20	3.04	20	
10	36.48	0.76	30		10	59.44		30		10	85.06		30	
15	36.70		40		15	62.85		40		15	90.67	3.05	40	
20	39.06	0.77	50		20	65.09	1.50	50		20	97.62		50	
30	40.98		60		30	68.08		60		30	108.58	3.05	60	
40	42.70	0.75	70		40	70.04	1.50	70		40	121.24		70	
50	44.00		80		50	71.99		80		50	127.78	3.05	80	
60	46.05	0.74	90		60	72.71	1.50	90		60	132.65		90	
70			100		70			100		70			100	
80			110		80			110		80			110	
90			120		90			120		90			120	
100			150		100			150		100			150	
110			180		110			180		110			180	
120			210		120			210		120			210	
	Average yield:	0.6333333	(l/s)			Average yield:	1.474				Average yield:	3.0066667		

DISCHARGE RATE 4			Time	Recovery 4	DISCHARGE RATE 5			Time	Recovery 5	DISCHARGE RATE 6			Time	Recovery
DATE:	04-Feb-08		(min)	(m)	DATE:	04-Feb-08		(min)	(m)	DATE:	04-Feb-08		(min)	(m)
TIME:	10:00 AM		1		TIME:			1		TIME:			1	129.50
Time	Drawdown	Yield	2		Time	Drawdown	Yield	2		Time	Drawdown	Yield	2	125.40
(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3	120.35
1	133.45		5		1			5		1			5	115.00
2	133.99	4.00	7		2			7		2			7	110.20
3	135.60	6.00	10		3			10		3			10	104.62
5	137.00		15		5			15		5			15	94.24
7	139.54	6.00	20		7			20		7			20	82.65
10	147.74		30		10			30		10			30	68.00
15	190.20	6.01	40		15			40		15			40	59.49
20	200.05		50		20			50		20			50	53.18
22	200.05	2.05	60		30			60		30			60	48.49
25	200.05	1.90	70		40			70		40			70	46.29
30	200.05	1.90	80		50			80		50			80	45.01
60			90		60			90		60			90	44.75
70			100		70			100		70			100	42.63
80			110		80			110		80			110	42.09
90			120		90			120		90			120	41.10
100			150		100			150		100			150	39.62
110			180		110			180		110			180	38
120			210		120			210		120			210	36.49
	Average yield:	3.98						240		150			240	
COMMENTS:								300		180			300	
								360		210			360	
								420		240			420	

CONSTANT DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	EC-Q14-1633	PROJECT:	GWSE - Middelburg Grootfontein Aquifer	CLIENT:	DWA
ALTERNATIVE NO. :	0	SITE NAME:	Dunblane		
DEPTH OF PUMP (mbdl):	203.00	PUMP TYPE USED:	GW9002	OPERATOR:	Johannes
INLET DIAMETER (mm):	270	EXISTING EQUIPMENT:	0	CONTRACTOR:	AB Pumps

TEST STARTED	DATE:	04-Feb-08	TEST COMPLETED	DATE:	06-Feb-08	TOTAL TIME - PUMPED (min):	1440	TOTAL TEST TIME (min):	2880
	TIME:	2:00 PM		TIME:	2:00 PM	TOTAL TIME-RECOVERY(min):	1440	AVERAGE YIELD (l/s):	1.52

DISCHARGE BOREHOLE		OBSERVATION BOREHOLE 1		OBSERVATION BOREHOLE 2		OBSERVATION BOREHOLE 3	
CASING HEIGHT (magl):	0.46	No. :		No. :		No. :	
CASING DEPTH (mbdl):	20.00	DATUM LEVEL (magl):		DATUM LEVEL (magl):		DATUM LEVEL (magl):	
CASING ID (mm):	0.00	CASING DEPTH (mbdl):		CASING DEPTH (mbdl):		CASING DEPTH (mbdl):	
BOREHOLE DEPTH (mbdl):	256.00	BOREHOLE DEPTH :		BOREHOLE DEPTH :		BOREHOLE DEPTH :	
WATER LEVEL (mbdl):	32.10	WATER LEVEL:		WATER LEVEL:		WATER LEVEL:	
DATUM LEVEL (magl):	0.49	DISTANCE (m):		DISTANCE (m):		DISTANCE (m):	

Time (min)	Drawdown (m)	Yield (l/s)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)
1	37.40		82.32	1			1			1		
2	38.06		79.66	2			2			2		
3	41.20	1.50	75.86	3			3			3		
5	44.93		70.73	5			5			5		
7	47.10	1.51	68.97	7			7			7		
10	51.48		66.83	10			10			10		
15	55.82	1.50	62.96	15			15			15		
20	60.09		60.13	20			20			20		
30	64.35	1.52	55.98	30			30			30		
40	71.80		51.95	40			40			40		
60	75.32	1.52	49.80	60			60			60		
90	76.87		46.13	90			90			90		
120	78.40	1.53	44.30	120			120			120		
150	79.94		42.98	150			150			150		
180	81.48	1.53	41.73	180			180			180		
210	82.98		40.89	210			210			210		
240	84.53	1.54	39.98	240			240			240		
300	86.20		38.67	300			300			300		
360	86.89	1.51	37.67	360			360			360		
420	87.40		36.81	420			420			420		
480	87.76	1.50	36.30	480			480			480		
540	88.25		35.74	540			540			540		
600	88.44	1.52	35.22	600			600			600		
720	88.80		34.83	720			720			720		
840	88.80	1.52	34.60	840			840			840		
960	88.89		34.19	960			960			960		
1080	89.22	1.53	33.98	1080			1080			1080		
1200	89.50		33.85	1200			1200			1200		
1320	90.05	1.54	33.70	1320			1320			1320		
1440	90.75		33.58	1440			1440			1440		
1080				1800			1800			1800		
1140				2280			2280			2280		
1200				2880			2880			2880		
1260												
1320												
1380												
1440												

STEPPED DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	EC-Q14-1634 (A)	**PROJECT:**	GWSE - Middelburg Grootfontein Aquifer
ALTERNATIVE NO. :	0	**SITE NAME:**	Dublaine
ALTERNATIVE NO. :	0	**CLIENT:**	DWA

BOREHOLE DEPTH (mbdl):	298.00	**CASING DEPTH (mbdl):**	0.00	**PUMP TYPE USED:**	GW9002
DEPTH OF PUMP (mbdl):	200.00	**CASING HEIGHT (magl):**	0.30	**OPERATOR:**	Leagen
PUMP INLET DIAMETER (mm):	2.100	**CASING ID (mm):**	0.000	**CONTRACTOR:**	AB Pumps
STATIC WATER LEVEL (mbdl):	10.37	**DATUM LEVEL (magl):**	0.48		

DISCHARGE RATE 1			**Time**	***Recovery 1***	***DISCHARGE RATE 2***			**Time**	***Recovery 2***	***DISCHARGE RATE 3***			**Time**	***Recovery 3***
DATE:	12-Feb-08		**(min)**	**(m)**	**DATE:**	12-Feb-08		**(min)**	**(m)**	**DATE:**	12-Feb-08		**(min)**	**(m)**
TIME:	11:20 AM		**1**		**TIME:**	12:20 PM		**1**		**TIME:**	1:20 PM		**1**	
Time	**Drawdown**	**Yield**	**2**		**Time**	**Drawdown**	**Yield**	**2**		**Time**	**Drawdown**	**Yield**	**2**	
(min)	**(m)**	**(l/s)**	**3**		**(min)**	**(m)**	**(l/s)**	**3**		**(min)**	**(m)**	**(l/s)**	**3**	
1	11.47		**5**		**1**	15.98		**5**		**1**	26.50		**5**	
2	12.33	3.330	**7**		**2**	16.45	7.810	**7**		**2**	28.98	14.500	**7**	
3	13.14		**10**		**3**	16.99		**10**		**3**	30.50		**10**	
5	14.38	4.190	**15**		**5**	17.23	8.010	**15**		**5**	32.37	16.000	**15**	
7	14.56		**20**		**7**	17.30		**20**		**7**	40.23		**20**	
10	14.70	4.190	**30**		**10**	19.28	8.010	**30**		**10**	62.30	16.060	**30**	
15	14.87		**40**		**15**	20.30		**40**		**15**	80.49		**40**	
20	14.99	4.180	**50**		**20**	23.23	8.030	**50**		**20**			**50**	
30	15.18		**60**		**30**	24.07		**60**		**30**			**60**	
40	15.39	4.160	**70**		**40**	24.40	8.040	**70**		**40**			**70**	
50	15.64		**80**		**50**	25.10		**80**		**50**			**80**	
60	15.86	4.170	**90**		**60**	25.39	8.020	**90**		**60**			**90**	
70			**100**		**70**			**100**		**70**			**100**	
80			**110**		**80**			**110**		**80**			**110**	
90			**120**		**90**			**120**		**90**			**120**	
100			**150**		**100**			**150**		**100**			**150**	
110			**180**		**110**			**180**		**110**			**180**	
120			**210**		**120**			**210**		**120**			**210**	
	Average yield:	**4.0366667**	**(l/s)**			**Average yield:**	**7.9866667**				**Average yield:**	**15.52**		

DISCHARGE RATE 4			**Time**	***Recovery 4***	***DISCHARGE RATE 5***			**Time**	***Recovery 5***	***DISCHARGE RATE 6***			**Time**	***Recovery***
DATE:	12-Feb-08		**(min)**	**(m)**	**DATE:**	12-Feb-08		**(min)**	**(m)**	**DATE:**	12-Feb-08		**(min)**	**(m)**
TIME:			**1**		**TIME:**			**1**		**TIME:**			**1**	33.45
Time	**Drawdown**	**Yield**	**2**		**Time**	**Drawdown**	**.**	**2**		**Time**	**Drawdown**	**Yield**	**2**	25.49
(min)	**(m)**	**(l/s)**	**3**		**(min)**	**(m)**	**(l/s)**	**3**		**(min)**	**(m)**	**(l/s)**	**3**	21.80
1			**5**		**1**			**5**		**1**			**5**	16.64
2			**7**		**2**			**7**		**2**			**7**	13.04
3			**10**		**3**			**10**		**3**			**10**	12.49
5			**15**		**5**			**15**		**5**			**15**	11.53
7			**20**		**7**			**20**		**7**			**20**	11.09
10			**30**		**10**			**30**		**10**			**30**	10.91
15			**40**		**15**			**40**		**15**			**40**	10.95
20			**50**		**20**			**50**		**20**			**50**	10.80
30			**60**		**30**			**60**		**30**			**60**	10.76
40			**70**		**40**			**70**		**40**			**70**	10.77
50			**80**		**50**			**80**		**50**			**80**	10.73
60			**90**		**60**			**90**		**60**			**90**	10.72
70			**100**		**70**			**100**		**70**			**100**	10.71
80			**110**		**80**			**110**		**80**			**110**	10.70
90			**120**		**90**			**120**		**90**			**120**	10.70
100			**150**		**100**			**150**		**100**			**150**	10.7
110			**180**		**110**			**180**		**110**			**180**	10.7
120			**210**		**120**			**210**		**120**			**210**	10.7
	Average yield:	**#DIV/0!**						**240**		**150**			**240**	.
COMMENTS:								**300**		**180**			**300**	
								360		**210**			**360**	
								420		**240**			**420**	

CONSTANT DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	EC-Q14-1634(B)	PROJECT:	GWSE - Middelburg Grootfontein Aquifer	CLIENT:	DWA
ALTERNATIVE NO. :	0	SITE NAME:	Dunblaine		

DEPTH OF PUMP (mbdl):	200.00	PUMP TYPE USED:	GW9002	OPERATOR:	Leagen Molomo
INLET DIAMETER (mm):	2.1	EXISTING EQUIPMENT:	0	CONTRACTOR:	AB Pumps

TEST	DATE:	2008/02/14	TEST	DATE:		TOTAL TIME - PUMPED (min):	2880	TOTAL TEST TIME (min):	4440
STARTED	TIME:	3:10 PM	COMPLETED	TIME:		TOTAL TIME-RECOVERY(min):	1560	AVERAGE YIELD (l/s):	8.26

DISCHARGE BOREHOLE		OBSERVATION BOREHOLE 1		OBSERVATION BOREHOLE 2		OBSERVATION BOREHOLE 3	
CASING HEIGHT (magl):	0.30	No. :		No. :		No. :	
CASING DEPTH (mbdl):	0.00	DATUM LEVEL (magl):		DATUM LEVEL (magl):		DATUM LEVEL (magl):	
CASING ID (mm):	0.00	CASING DEPTH (mbdl):		CASING DEPTH (mbdl):		CASING DEPTH (mbdl):	
BOREHOLE DEPTH (mbdl):	298.00	BOREHOLE DEPTH :		BOREHOLE DEPTH :		BOREHOLE DEPTH :	
WATER LEVEL (mbdl):	10.37	WATER LEVEL:		WATER LEVEL:		WATER LEVEL:	
DATUM LEVEL (magl):	0.48	DISTANCE (m):		DISTANCE (m):		DISTANCE (m):	

Time (min)	Drawdown (m)	Yield (l/s)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)
1	11.88		23.65	1			1			1		
2	12.94	8.29	21.29	2			2			2		
3	14.20		19.40	3			3			3		
5	18.19	8.28	16.96	5			5			5		
7	19.80		15.50	7			7			7		
10	21.30	8.24	14.18	10			10			10		
15	22.71		12.92	15			15			15		
20	23.55	8.28	11.89	20			20			20		
30	24.20		11.23	30			30			30		
40	24.56	8.20	11.03	40			40			40		
60	24.96		10.93	60			60			60		
90	25.73	8.21	10.84	90			90			90		
120	26.37		10.80	120			120			120		
150	26.53	8.23	10.78	150			150			150		
180	26.67		10.76	180			180			180		
210	27.22	8.24	10.74	210			210			210		
240	27.33		10.72	240			240			240		
300	28.06	8.24	10.72	300			300			300		
360	28.22		10.72	360			360			360		
420	28.42	8.25	10.70	420			420			420		
480	28.45		10.70	480			480			480		
540	28.61	8.26	10.68	540			540			540		
600	29.21		10.64	600			600			600		
720	29.28	8.25	10.64	720			720			720		
840	29.67		10.62	840			840			840		
960	29.88	8.27	10.62	960			960			960		
1080	30.10		10.62	1080			1080			1080		
1200	30.13	8.27	10.60	1200			1200			1200		
1320	30.24		10.60	1320			1320			1320		
1440	30.26	8.29	10.59	1440			1440			1440		
1560	30.28		10.58	1800			1800			1800		
1680	30.35	8.28		2280			2280			2280		
1800	30.42			2880			2880			2880		
1920	30.44	8.28										
2040	30.48											
2160	30.50	8.27										
2280	30.58											

DISCHARGE BOREHOLE				OBSERVATION BOREHOLE 1			OBSERVATION BOREHOLE 2			OBSERVATION BOREHOLE 3		
Time (min)	Drawdown (m)	Yield (l/s)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)
2400	30.63		8.29	1500			1500			1500		
2520		30.68		1560			1560			1560		
2640	30.83		8.28	1620			1620			1620		
2760		30.85		1680			1680			1680		
2880	30.89		8.26	1740			1740			1740		

STEPPED DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	EC-Q14-1636	PROJECT:	781
ALTERNATIVE NO. :	0	SITE NAME:	GROOTFONTEIN
ALTERNATIVE NO. :	0	CLIENT:	0

BOREHOLE DEPTH (mbdl):	227-22	CASING DEPTH (mbdl):	0.00	PUMP TYPE USED:	GW25002
DEPTH OF PUMP (mbdl):	100.00	CASING HEIGHT (magl):	0.21	OPERATOR:	FICKSON
PUMP INLET DIAMETER (mm):	270.000	CASING ID (mm):	270.00	CONTRACTOR:	AB PUMPS
STATIC WATER LEVEL (mbdl):	18.05	DATUM LEVEL (magl):	0.69		

DISCHARGE RATE 1			Time	Recovery 1	DISCHARGE RATE 2			Time	Recovery 2	DISCHARGE RATE 3			Time	Recovery 3
DATE:	24-Apr-10		(min)	(m)	DATE:	24-Apr-10		(min)	(m)	DATE:	24-Apr-10		(min)	(m)
TIME:	06H35		1		TIME:	08H15		1		TIME:	09H55		1	
Time	Drawdown	Yield	2		Time	Drawdown	Yield	2		Time	Drawdown	Yield	2	
(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3	
1	0.18		5		1	6.65		5		1	14.92		5	
2	0.32		7		2	6.69		7		2	15.13		7	
3	0.64		10		3	6.76		10		3	15.88		10	
5	0.70		15		5	7.02		15		4	16.01		15	
7	0.75	5.34	20		7	7.32	10.01	20		7	16.84		20	
10	1.00		30		10	7.69		30		8	18.06	20.00	30	
15	1.66	5.32	40		12	8.20	10.01	40		9	19.72		40	
20	2.48		50		13	8.78		50		20	21.20	20.01	50	
30	3.22	5.32	60		14	9.64	10.00	60		30	23.44		60	
40	3.85		70		40	10.49		70		40	25.05	20.10	70	
50	4.18	5.33	80		50	11.22	10.01	80		50	28.04		80	
60	4.63		90		60	12.00		90		60	29.57	20.00	90	
70	5.17	5.33	100		70	12.76	10.00	100		70	31.40		100	
80	5.64		110		80	13.45		110		80	32.96	20.02	110	
90	6.07	5.32	120		90	14.09	10.02	120		90	34.66		120	
100	6.44		150		100	14.69		150		100	36.05	20.02	150	
110			180		110			180		110			180	
120			210		120			210		RPM	326.00		210	
	Average yield:	5.3266667	(l/s)			Average yield:	10.008333				Average yield:	20.025	240	

DISCHARGE RATE 4			Time	Recovery 4	DISCHARGE RATE 5			Time	Recovery 5	DISCHARGE RATE 6			Time	Recovery
DATE:	24-Apr-10		(min)	(m)	DATE:	24-Apr-10		(min)	(m)	DATE:	24-Apr-10		(min)	(m)
TIME:	11H35		1		TIME:	13H15		1	76.92	TIME:			1	
Time	Drawdown	Yield	2		Time	Drawdown	.	2	76.38	Time	Drawdown	Yield	2	
(min)	(m)	(l/s)	3		(min)	(m)	(l/s)	3	75.69	(min)	(m)	(l/s)	3	
1	36.53		5		1	60.80		5	75.30	1			5	
2	36.76		7		2	60.87		7	74.65	2			7	
3	37.41	30.17	10		3	62.06	40.01	10	73.72	3			10	
5	38.32		15		5	63.51		15	71.24	5			15	
7	39.13	30.16	20		7	64.04	40.00	20	70.96	7			20	
10	40.54		30		10	65.14		30	66.11	10			30	
15	42.17	30.15	40		15	66.90	40.02	40	63.75	15			40	
20	43.49		50		20	68.47		50	61.76	20			50	
30	46.10	30.16	60		30	71.55	40.01	60	59.68	30			60	
40	48.73		70		40	74.14		70	56.87	40			70	
50	51.00	30.14	80		50	76.36	40.01	80	55.95	50			80	
60	53.50		90		60	78.25		90	54.34	60			90	
70	55.23	30.15	100		70			100	52.71	70			100	
80	57.30		110		80			110	51.13	80			110	
90	59.19	30.13	120		90			120	49.62	90			120	
100	60.78		150		100			150	45.55	100			150	
110			180		110			180	41.66	110			180	
RPM	458.80		210		RPM	649.20		210	38.84	120			210	
	Average yield:	30.151429						240	36.35	150			240	
COMMENTS:								300	32.53	180			300	
								360	29.26	210			360	
								420	27.67	240			420	
								480	25.24	300			480	
								540	23.41	360			540	
								600	20.47	420			600	

CONSTANT DISCHARGE TEST AND RECOVERY

BOREHOLE NO. :	EC-Q14-1636	PROJECT:	781	CLIENT:	0
ALTERNATIVE NO. :	0	SITE NAME:	GROOTFONTEIN		
DEPTH OF PUMP (mbdl):	0.00	PUMP TYPE USED:	GW25002	OPERATOR:	FICKSON
INLET DIAMETER (mm):	0	EXISTING EQUIPMENT:	N/A	CONTRACTOR:	AB PUMPS

TEST	DATE:	2010/04/25	TEST	DATE:		TOTAL TIME - PUMPED (min):		TOTAL TEST TIME (min):	
STARTED	TIME:	13H25	COMPLETED	TIME:		TOTAL TIME-RECOVERY(min):		AVERAGE YIELD (l/s):	12.68

DISCHARGE BOREHOLE		OBSERVATION BOREHOLE 1		OBSERVATION BOREHOLE 2		OBSERVATION BOREHOLE 3	
CASING HEIGHT (magl):	0.21	No. :	EC-Q14-1668	No. :	EC-Q14-1637	No. :	
CASING DEPTH (mbdl):	0.00	DATUM LEVEL (magl):		DATUM LEVEL (magl):		DATUM LEVEL (magl):	
CASING ID (mm):	270.00	CASING DEPTH (mbdl):		CASING DEPTH (mbdl):		CASING DEPTH (mbdl):	
BOREHOLE DEPTH (mbdl):	227-22	BOREHOLE DEPTH :		BOREHOLE DEPTH :		BOREHOLE DEPTH :	
WATER LEVEL (mbdl):	26.62	WATER LEVEL:	17.51	WATER LEVEL:	27.94	WATER LEVEL:	
DATUM LEVEL (magl):	0.69	DISTANCE (m):	4	DISTANCE (m):	17.5	DISTANCE (m):	

Time (min)	Drawdown (m)	Yield (l/s)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)	Time (min)	Drawdown (m)	Recovery (m)
1	0.10	11.20	54.41	1		0.00	1	0.00	34.09	1		
2	0.35	11.90	54.27	2			2		34.09	2		
3	0.56	21.31	53.74	3			3		34.09	3		
5	0.98		53.32	5			5		34.08	5		
7	2.46	12.32	52.14	7			7		34.08	7		
10	3.23		51.38	10			10		34.08	10		
15	4.51	12.31	50.11	15			15		34.08	15		
20	5.62		48.20	20			20		34.08	20		
30	7.64	12.30	47.69	30			30		34.08	30		
40	9.35		46.54	40			40		34.08	40		
60	10.96	12.31	43.12	60			60	7.31	34.08	60		
90	15.93		39.74	90			90		34.08	90		
120	19.02	12.30	36.62	120			120		34.07	120		
150	21.62		39.74	150			150		34.07	150		
180	23.86	12.32	33.56	180			180	13.54	34.07	180		
210	25.78		31.11	210			210		34.07	210		
240	27.53	12.30	28.79	240			240		34.07	240		
300	30.84		26.82	300			300		34.07	300		
360	33.68	12.32	25.11	360	0.00		360	23.70	34.07	360		
420	35.53		23.24	420			420		34.07	420		
480	37.84	12.31	21.75	480			480		34.07	480		
540	39.85		20.66	540			540	24.94	34.06	540		
600	41.72	12.30	18.87	600			600		34.06	600		
660	43.26		17.90	720	0.00		720	26.16	34.06	720		
720	44.67	12.30	16.74	840			840		34.06	840		
780	45.95		15.62	960	0.00		960	29.43	34.06	960		
840	47.24	12.31	14.58	1080			1080		34.06	1080		
900	48.52		13.61	1200			1200	31.82	34.06	1200		
960	49.51	12.30	12.70	1320	0.00		1320	34.26	34.06	1320		
1020	50.22		11.83	1440			1440	35.38	34.06	1440		
1080	51.10	12.31		1800			1800			1800		
1140	51.93			2280			2280			2280		
1200	52.66	12.31		2880			2880			2880		
1260	53.39											
1320	54.11	12.32										
1380	54.76											
1440	55.41	12.30										

FORM 5 E

STEPPED DISCHARGE TEST & RECOVERY

BOREHOLE TEST RECORD SHEET

PROJ NO : 781	MAP REFERENCE: 0		PROVINCE:	NORTHERN CAPE
BOREHOLE NO: EC-Q14-1637			DISTRICT:	MIDDLEBURG
ALT BH NO: 0			SITE NAME:	MIDDLEBURG
ALT BH NO: 0				
BOREHOLE DEPTH (m) 2.58	DATUM LEVEL ABOVE CASING (m):	0.10	EXISTING PUMP:	0
WATER LEVEL (mbgl): 8.46	CASING HEIGHT: (magl):	0.50	CONTRACTOR:	AB PUMPS
DEPTH OF PUMP (m): 98.00	DIAM PUMP INLET (mm):	170.00	PUMP TYPE:	GW9002

STEPPED DISCHARGE TEST & RECOVERY

DISCHARGE RATE 1			RPM		DISCHARGE RATE 2			RPM		DISCHARGE RATE 3			RPM	
DATE:	05/05/10	TIME:	09H30		DATE:	2010/05/05	TIME:	10H10		DATE:	05/05/201	TIME:	12H50	
TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)	TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)	TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)
1	1.12		1		1	2.79		1		1	5.21		1	
2	1.14		2		2	2.91		2		2	6.73		2	
3	1.37	2.52	3		3	3.80	4.51	3		3	7.41		3	
5	1.64		5		5	3.97		5		5	8.44	8.54	5	
7	1.70	2.51	7		7	4.03	4.50	7		7	8.78		7	
10	1.87		10		10	4.20		10		10	9.60	8.55	10	
15	2.01	2.51	15		15	4.30	4.50	15		15	10.24		15	
20	2.07		20		20	4.37		20		20	10.40	8.55	20	
30	2.19	2.52	30		30	4.49	4.51	30		30	10.68		30	
40	2.24		40		40	4.67		40		40	10.82	8.54	40	
50	2.26	2.52	50		50	4.69	4.51	50		50	10.95		50	
60	2.32		60		60	4.72		60		60	11.03	8.55	60	
70	2.34	2.51	70		70	4.74	4.52	70		70	11.12		70	
80	2.37		80		80	4.76		80		80	11.18	8.54	80	
90	2.40	2.52	90		90	4.78	4.52	90		90	11.22		90	
100	2.44		100		100	4.80		100		100	11.29	8.54	100	
110			110		110			110		110			110	
120			120		120			120		120			120	
pH	7.35		150		pH	6.90		150		pH	7.55		150	
TEMP	22.90	°C	180		TEMP	21.30	°C	180		TEMP	19.60	°C	180	
EC	441.00	µS/cm	210		EC	457.00	µS/cm	210		EC	407.00	µS/cm	210	

DISCHARGE RATE 4			RPM		DISCHARGE RATE 5			RPM		DISCHARGE RATE 6			RPM	
DATE:	05/05/2010	TIME:	14H30		DATE:	05/05/2010	TIME:	16H10		DATE:		TIME:		
TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)	TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)	TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)
1	15.60		1		1	18.31		1	29.73	1			1	
2	15.70	12.33	2		2	19.60		2	18.41	2			2	
3	15.92		3		3	21.45		3	10.22	3			3	
5	16.09	12.32	5		5	27.19	20.20	5	8.27	5			5	
7	16.25		7		7	29.13		7	7.45	7			7	
10	16.35	12.31	10		10	30.17	20.21	10	6.34	10			10	
15	16.53		15		15	30.87		15	5.23	15			15	
20	16.77	12.31	20		20	31.30	20.22	20	4.69	20			20	
30	17.02		30		30	32.20		30	3.31	30			30	
40	17.21	12.32	40		40	32.61	20.21	40	3.02	40			40	
50	17.35		50		50	32.91		50	2.43	50			50	
60	17.42	12.32	60		60	33.14	20.20	60	2.30	60			60	
70	17.54		70		70	33.51		70	2.15	70			70	
80	17.62	12.33	80		80	33.70	20.21	80	2.05	80			80	
90	17.70		90		90	34.01		90	1.91	90			90	
100	17.84	12.33	100		100	34.70	20.21	100	1.85	100			100	
110			110		110			110	1.73	110			110	
120			120		120			120	1.67	120			120	
pH	7.30		150		pH	6.93		150	1.60	pH			150	
TEMP	19.50	°C	180		TEMP	18.10	°C	180	1.56	TEMP		°C	180	
EC	413.00	µS/cm	210		EC	412.00	µS/cm	210	1.50	EC		µS/cm	210	
			240					240	1.41				240	
			300					300	1.32				300	
								360	1.24					
								420	1.17					
			360					480	1.06				360	

FORM 5 F

CONSTANT DISCHARGE TEST & RECOVERY

BOREHOLE TEST RECORD SHEET

PROJ NO :	781	MAP REFERENCE:	31.42006	PROVINCE:	EASTERN CAPE
BOREHOLE NO:	EC-Q14-1637		24.98978	DISTRICT:	MIDDLEBURG
ALT BH NO:	0			SITE NAME:	MIDDLEBURG
ALT BH NO:	0				
BOREHOLE DEPTH:	2.58	DATUM LEVEL ABOVE CASING (m):	0.10	EXISTING PUMP:	0
WATER LEVEL (mbgl):	8.96	CASING HEIGHT: (magl):	0.50	CONTRACTOR:	AB PUMPS
DEPTH OF PUMP (m):	98.00	DIAM PUMP INLET(mm):	170	PUMP TYPE:	GW9002

CONSTANT DISCHARGE TEST & RECOVERY

TEST STARTED				TEST COMPLETED			
DATE:	06/05/10	TIME:	10H00	DATE:	00/01/00	TIME:	0:00

DISCHARGE BOREHOLE					OBSERVATION HOLE 1			OBSERVATION HOLE 2			OBSERVATION HOLE 3	
					NR:			NR:			NR:	
					Distance(m):			Distance(m):			Distance(m):	
TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME MIN	RECOVERY (M)	TIME: (min)	Drawdown m	Recovery (m)	TIME: (min)	Drawdown (m)	Recovery	TIME: (min)	Drawdown (m)
1	7.23		1	25.18	1			1			1	
2	11.20		2	20.11	2			2			2	
3	12.45		3	14.73	3			3			3	
5	15.63	20.21	5	13.17	5			5			5	
7	17.19		7	12.51	7			7			7	
10	20.74	20.20	10	11.73	10			10			10	
15	21.13		15	10.22	15			15			15	
20	22.60	20.20	20	9.47	20			20			20	
30	23.51		30	8.65	30			30			30	
40	24.64	20.20	40	8.05	40			40			40	
60	25.60		60	7.30	60			60			60	
90	26.45	20.24	90	6.90	90			90			90	
120	26.83		120	6.50	120			120			120	
150	27.46	20.21	150	6.21	150			150			150	
180	27.80		180	6.02	180			180			180	
210	28.10	20.22	210	5.87	210			210			210	
240	28.31		240	5.69	240			240			240	
300	28.79	20.22	300	5.20	300			300			300	
360	29.36		360	4.93	360			360			360	
420	29.57	20.21	420	4.75	420			420			420	
480	30.03		480	4.57	480			480			480	
540	30.21	20.20	540	4.39	540			540			540	
600	30.57		600	4.18	600			600			600	
720	31.10	20.20	720	3.98	720			720			720	
840	31.33		840	3.79	840			840			840	
960	31.67	20.21	960	3.60	960			960			960	
1080	31.92		1080	3.53	1080			1080			1080	
1200	32.11	20.21	1200	3.38	1200			1200			1200	
1320	32.42		1320	3.29	1320			1320			1320	
1440	33.02	20.22	1440	3.20	1440			1440			1440	
1560	33.45		1560		1560			1560			1560	
1680	33.76	20.20	1680		1680			1680			1680	
1800	33.93		1800		1800			1800			1800	
1920	34.20	20.21	1920		1920			1920			1920	
2040	34.53		2040		2040			2040			2040	
2160	34.75	20.21	2160		2160			2160			2160	
2280	34.83		2280		2280			2280			2280	
2400	35.02	20.20	2400		2400			2400			2400	
2520	35.27		2520		2520			2520			2520	
2640	35.52	20.20	2640		2640			2640			2640	
2760	35.81		2760		2760			2760			2760	
2880	36.04	20.21	2880		2880			2880			2880	
3000			3000		3000			3000			3000	
3120			3120		3120			3120			3120	
3240			3240		3240			3240			3240	
3360			3360		3360			3360			3360	
3480			3480		3480			3480			3480	
3600			3600		3600			3600			3600	
3720			3720		3720			3720			3720	
3840			3840		3840			3840			3840	
3960			3960		3960			3960			3960	
4080			4080		4080			4080			4080	
4200			4200		4200			4200			4200	
4320			4320		4320			4320			4320	

FORM 5 E

STEPPED DISCHARGE TEST & RECOVERY

BOREHOLE TEST RECORD SHEET

PROJ NO :	793	MAP REFERENCE:	0	PROVINCE:	EASTERN CAPE
BOREHOLE NO:	EC Q14 1655			DISTRICT:	CHRIS HANI
ALT BH NO:	0			SITE NAME:	GROOTFONTEIN
ALT BH NO:	0				
BOREHOLE DEPTH (m)	154.19	DATUM LEVEL ABOVE CASING (m):	0.48	EXISTING PUMP:	0
WATER LEVEL (mbgl):	9.72	CASING HEIGHT: (magl):	0.30	CONTRACTOR:	AB PUMPS
DEPTH OF PUMP (m):	44.00	DIAM PUMP INLET (mm):	130.00	PUMP TYPE:	P400

STEPPED DISCHARGE TEST & RECOVERY

DISCHARGE RATE 1			RPM		DISCHARGE RATE 2			RPM		DISCHARGE RATE 3			RPM	
DATE:	26/03/10	TIME:	16H20		DATE:	2010/03/26	TIME:	18H00		DATE:	26/03/201	TIME:	19H40	
TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)	TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)	TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)
1	0.27		1		1	0.92		1		1	1.93		1	
2	0.34		2		2	1.39	7.29	2		2	2.04	13.79	2	
3	0.41	2.39	3		3	1.60		3		3	2.13		3	
5	0.47	5.09	5		5	1.62	10.09	5		5	2.28	15.10	5	
7	0.49		7		7	1.64		7		7	2.43		7	
10	0.53	5.10	10		10	1.67	10.09	10		10	2.49	15.10	10	
15	0.56		15		15	1.68		15		15	2.51		15	
20	0.61	5.10	20		20	1.69	10.10	20		20	2.53	15.08	20	
30	0.68		30		30	1.71		30		30	2.55		30	
40	0.69	5.10	40		40	1.72	10.09	40		40	2.56	15.09	40	
50	0.71		50		50	1.73		50		50	2.57		50	
60	0.73	5.10	60		60	1.75	10.09	60		60	2.59	15.08	60	
70	0.75		70		70	1.77		70		70	2.60		70	
80	0.76	5.10	80		80	1.80	10.10	80		80	2.61	15.08	80	
90	0.77		90		90	1.82		90		90	2.63		90	
100	0.79	5.10	100		100	1.85	10.09	100		100	2.64	15.08	100	
110			110		110			110		110			110	
120			120		120			120		120			120	
pH			150		pH			150		pH			150	
TEMP		°C	180		TEMP		°C	180		TEMP		°C	180	
EC		µS/cm	210		EC		µS/cm	210		EC		µS/cm	210	

DISCHARGE RATE 4			RPM		DISCHARGE RATE 5			RPM		DISCHARGE RATE 6			RPM	
DATE:	26/03/201	TIME:	21H20		DATE:	26/03/2010	TIME:	23H00		DATE:		TIME:		
TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)	TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)	TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)
1	2.82		1		1	4.64		1	1.83	1			1	
2	2.98	18.20	2		2	4.66	23.60	2	1.26	2			2	
3	3.05	20.05	3		3	4.69	25.08	3	0.88	3			3	
5	3.26		5		5	4.73		5	0.64	5			5	
7	3.51		7		7	4.75		7	0.57	7			7	
10	3.60	20.05	10		10	4.76	25.08	10	0.51	10			10	
15	3.65		15		15	4.77		15	0.46	15			15	
20	3.71	20.04	20		20	4.79	25.07	20	0.43	20			20	
30	3.73		30		30	4.83		30	0.39	30			30	
40	3.76	20.03	40		40	4.84	25.07	40	0.36	40			40	
50	3.80		50		50	4.86		50	0.34	50			50	
60	3.82	20.05	60		60	4.87	25.07	60	0.32	60			60	
70	3.84		70		70	4.88		70	0.29	70			70	
80	3.85	20.03	80		80	4.89	25.08	80	0.27	80			80	
90	3.87		90		90	4.89		90	0.25	90			90	
100	3.88	20.03	100		100	4.90	25.08	100	0.23	100			100	
110			110		110			110	0.20	110			110	
120			120		120			120	0.18	120			120	
pH			150		pH			150	0.17	pH			150	
TEMP		°C	180		TEMP		°C	180	0.16	TEMP		°C	180	
EC		µS/cm	210		EC		µS/cm	210	0.15	EC		µS/cm	210	
			240					240	0.13				240	
			300					300	0.15				300	
								300	0.13					
								300	0.12					
								360	0.11					
								420	0.10					
								480	0.10					
								540	0.27					

FORM 5 F

CONSTANT DISCHARGE TEST & RECOVERY

BOREHOLE TEST RECORD SHEET

PROJ NO :	793	MAP REFERENCE:	31.43135	PROVINCE:	EASTERN CAPE
BOREHOLE NO:	EC Q14 1655		24.98594	DISTRICT:	CHRIS HANI
ALT BH NO:	0			SITE NAME:	GROOTFONTEIN
ALT BH NO:	0				
BOREHOLE DEPTH:	154.19	DATUM LEVEL ABOVE CASING (m):	0.48	EXISTING PUMP:	0
WATER LEVEL (mbgl):	9.80	CASING HEIGHT: (magl):	0.30	CONTRACTOR:	AB PUMPS
DEPTH OF PUMP (m):	44.00	DIAM PUMP INLET(mm):	130	PUMP TYPE:	P400

CONSTANT DISCHARGE TEST & RECOVERY

TEST STARTED				TEST COMPLETED			
DATE:	27/03/10	TIME:	15H30	DATE:	29/03/10	TIME:	21H30

DISCHARGE BOREHOLE					OBSERVATION HOLE 1			OBSERVATION HOLE 2			OBSERVATION HOLE 3	
					NR:	EC-Q14-052		NR:	GLEN FARM	10.72	NR:	EC Q14 1637
					Distance(m):		135	Distance(m):		1.0514	Distanc	1.33
TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME MIN	RECOVERY (M)	TIME: (min)	Drawdown m	Recovery (m)	TIME: (min)	Drawdown (m)	Recovery	TIME: (min)	Drawdown (m)
1	0.62		1	4.70	1	0.00	0.37	1			1	
2	1.02	19.61	2	3.57	2	0.00	0.37	2			2	
3	1.65	25.05	3	1.29	3	0.00	0.37	3			3	
5	3.10		5	1.11	5	0.00	0.36	5			5	
7	3.36	25.05	7	1.04	7	0.00	0.35	7			7	
10	3.62		10	0.97	10	0.00	0.34	10			10	
15	3.78	25.04	15	0.95	15	0.00	0.33	15			15	
20	3.88		20	0.90	20	0.00	0.32	20			20	
30	3.97	25.04	30	0.80	30	0.00	0.32	30			30	
40	4.09		40	0.76	40	0.00	0.24	40			40	
60	4.17	25.04	60	0.68	60	0.00	0.20	60	0.00	0.00	60	
90	4.25		90	0.62	90	0.00	0.16	90			90	
120	4.30	25.04	120	0.55	120	0.00	0.13	120	0.00	0.00	120	
150	4.35		150	0.49	150	0.00	0.09	150			150	
180	4.37	25.47	180	0.45	180	0.00	0.06	180			180	
210	4.54		210	0.31	210	0.00	0.00	210			210	
240	4.63	25.31	240	0.26	240	0.00		240	0.00	0.00	240	
300	4.70		300	0.21	300	0.00		300	0.00		300	0.00
360	4.72	24.51	360	0.17	360	0.00		360	0.00		360	
420	4.80		420		420	0.00		420	0.00		420	
480	4.82	23.51	480		480	0.00		480	0.00		480	
540	4.85		540		540	0.00		540	0.00		540	
600	4.88	25.41	600		600	0.00		600	0.00		600	
660	4.90		660		660	0.00		660	0.00		660	
720	4.91	25.44	720		720	0.00		720	0.00		720	0.00
780	4.92		780		780	0.00		780	0.00		780	
840	4.93	25.39	840		840	0.08		840	0.00		840	
900	4.97		900		900			900	0.00		900	
960	4.98	25.39	960		960	0.11		960	0.00		960	
1020	4.99		1020		1020			1020	0.00		1020	
1080	5.01		1080		1080	0.18		1080	0.00		1080	0.00
1140	5.02	25.41	1140		1140			1140	0.00		1140	
1200	5.02		1200		1200	0.20		1200	0.00		1200	
1260	5.04	25.38	1260		1260			1260	0.00		1260	
1320	5.06		1320		1320	0.23		1320	0.00		1320	
1380	5.08	25.39	1380		1380			1380	0.00		1380	
1440	5.09		1440		1440	0.25		1440	0.00		1440	0.00
1500	5.10	25.38	1500		1500			1500	0.00		1500	
1560	5.11		1560		1560			1560	0.00		1560	
1620	5.12	25.39	1620		1620			1620	0.00		1620	
1680	5.14		1680		1680			1680	0.00		1680	
1740	5.16	25.39	1740		1740			1740	0.00		1740	
1800	5.17		1800		1800	0.30		1800	0.00		1800	0.00
1860	5.18	25.38	1860		1860			1860	0.00		1860	
1920	5.19		1920		1920			1920	0.00		1920	
1980	5.19	25.38	1980		1980			1980	0.00		1980	
2040	5.20		2040		2040			2040	0.00		2040	
2100	5.21	25.38	2100		2100			2100	0.00		2100	
2160	5.22		2160		2160			2160	0.00		2160	
2220	5.23	25.38	2220		2280	0.35		2220	0.00		2220	0.00
2340	5.24		2340		2340			2340	0.00		2340	
2400	5.25	25.38	2400		2400			2400	0.00		2400	
2460	5.27		2460		2460			2460	0.00		2460	
2520	5.28	25.38	2520		2520			2520	0.00		2520	
2580	5.28		2580		2580			2580	0.00		2580	
2640	5.29	25.38	2640		2640			2640	0.00		2640	
2700	5.30		2700		2700			2700	0.00		2700	
2760	5.31	25.38	2760		2760			2760	0.00		2760	
2820	5.32		2820		2820			2820	0.00		2820	
2880	5.34	25.38	2880		2880	0.37		2880	0.00		2880	0.00
	Average	25.04				W/L	11.78		W/L	10.72		W/L 8.63

STEPPED DISCHARGE TEST & RECOVERY

BOREHOLE TEST RECORD SHEET

PROJ NO :	781	MAP REFERENCE:	0	PROVINCE:	EASTERN CAPE
BOREHOLE NO:	EC/Q14/1662			DISTRICT:	MIDDELBURG
ALT BH NO:				SITE NAME:	MIDDELBURG
ALT BH NO:	0				
BOREHOLE DEPTH (m)	148.86	DATUM LEVEL ABOVE CASING (m):	0.00	EXISTING PUMP:	0
WATER LEVEL (mbgl):	18.91	CASING HEIGHT: (magl):	0.00	CONTRACTOR:	AB PUMPS
DEPTH OF PUMP (m):	135.34	DIAM PUMP INLET (mm):	0.00	PUMP TYPE:	BP65

STEPPED DISCHARGE TEST & RECOVERY

DISCHARGE RATE 1 — RPM: — DATE: 04/02/2010 TIME: 17H30

TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)
1	0.23		1	
2	0.25		2	
3	0.25		3	
5	0.26	1.11	5	
7	0.26	1.12	7	
10	0.26		10	
15	0.27	1.07	15	
20	0.17		20	
30	0.17	1.07	30	
40	0.18		40	
50	0.18	1.07	50	
60	0.19		60	
70			70	
80			80	
90			90	
100			100	
110			110	
120			120	
pH			150	
TEMP		°C	180	
EC		µS/cm	210	

DISCHARGE RATE 2 — RPM: — DATE: 04/02/201 TIME: 18H30

TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)
1	0.31		1	
2	0.39		2	
3	0.48	2.14	3	
5	0.45		5	
7	0.49	2.14	7	
10	0.49		10	
15	0.50	2.15	15	
20	0.51		20	
30	0.52	2.15	30	
40	0.53		40	
50	0.53	2.14	50	
60	0.54		60	
70			70	
80			80	
90			90	
100			100	
110			110	
120			120	
pH			150	
TEMP		°C	180	
EC		µS/cm	210	

DISCHARGE RATE 3 — RPM: — DATE: 04/02/201 TIME: 19H30

TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)
1	1.21		1	
2	1.27		2	
3	1.29	4.05	3	
5	1.31		5	
7	1.32	4.05	7	
10	1.36		10	
15	1.36	4.02	15	
20	1.36		20	
30	1.37	4.02	30	
40	1.38		40	
50	1.38	4.02	50	
60	1.39		60	
70			70	
80			80	
90			90	
100			100	
110			110	
120			120	
pH			150	
TEMP		°C	180	
EC		µS/cm	210	

DISCHARGE RATE 4 — RPM: — DATE: 04/02 TIME: 20H30

TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)
1	2.09		1	0.31
2	2.22		2	0.20
3	2.38	7.00	3	0.13
5	2.59		5	0.08
7	2.68	7.01	7	0.06
10	2.68		10	0.06
15	2.68	7.01	15	0.05
20	2.70		20	0.05
30	2.73	7.02	30	0.04
40	2.76		40	0.02
50	2.72	7.02	50	0.00
60	2.72		60	
70			70	
80			80	
90			90	
100			100	
110			110	
120			120	
pH			150	
TEMP		°C	180	
EC		µS/cm	210	
			240	
			300	
			360	

DISCHARGE RATE 5 — RPM: — DATE: TIME:

TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)
1			1	
2			2	
3			3	
5			5	
7			7	
10			10	
15			15	
20			20	
30			30	
40			40	
50			50	
60			60	
70			70	
80			80	
90			90	
100			100	
110			110	
120			120	
pH			150	
TEMP		°C	180	
EC		µS/cm	210	
			240	
			300	
			360	

DISCHARGE RATE 6 — RPM: — DATE: 05/02/201 TIME: 8H50

TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME (MIN)	RECOVERY (M)
1	2.03		1	
2	2.69		2	
3	2.80	9.84	3	
5	3.49		5	
7	4.21	9.84	7	
10	4.36		10	
15	4.40	9.84	15	
20	4.57		20	
30	4.70	8.80	30	
40	4.77		40	
50	4.80	9.81	50	
60	4.81		60	
70			70	
80			80	
90			90	
100			100	
110			110	
120			120	
pH			150	
TEMP		°C	180	
EC		µS/cm	210	
			240	
			300	
			360	

S/W/L: 18.61

FORM 5 F

CONSTANT DISCHARGE TEST & RECOVERY

BOREHOLE TEST RECORD SHEET

PROJ NO :	781	MAP REFERENCE: 0		PROVINCE:	EASTERN CAPE
BOREHOLE NO:	EC/Q14/1662			DISTRICT:	MIDDELBURG
ALT BH NO:	0			SITE NAME:	MIDDELBURG
ALT BH NO:	0				
BOREHOLE DEPTH:	148.86	DATUM LEVEL ABOVE CASING (m):	0.25	EXISTING PUMP:	0
WATER LEVEL (mbgl):	18.91	CASING HEIGHT: (magl):	0.40	CONTRACTOR:	AB PUMPS
DEPTH OF PUMP (m):	135.34	DIAM PUMP INLET(mm):	200	PUMP TYPE:	BP65

CONSTANT DISCHARGE TEST & RECOVERY

TEST STARTED				TEST COMPLETED					
DATE:	05/02/2010	TIME:	17H00	DATE:	05/02/10	TIME:	19H40	TYPE OF PUMP:	GW9002

DISCHARGE BOREHOLE					OBSERVATION HOLE 1			OBSERVATION HOLE 2			OBSERVATION HOLE 3	
					NR:	**EC/Q14/1668**		NR:	**EC/Q14/1687**		NR:	
					Distance(m);		101	Distance(m);		280	Distance(m);	
TIME (MIN)	DRAW DOWN (M)	YIELD (L/S)	TIME MIN	RECOVERY (M)	TIME: (min)	Drawdown m	Recovery (m)	TIME: (min)	Drawdown (m)	Recovery	TIME: (min)	Drawdown (m)
1	0.49		**1**	0.49	**1**	0.00		**1**			**1**	
2	0.99		**2**	0.30	**2**	0.00		**2**			**2**	
3	1.77	12.04	**3**	0.24	**3**			**3**			**3**	
5	2.03		**5**	0.15	**5**	0.00		**5**			**5**	
7	2.95	12.04	**7**	0.12	**7**			**7**			**7**	
10	3.99		**10**	0.10	**10**	0.00		**10**			**10**	
15	8.58	12.05	**15**	0.07	**15**			**15**			**15**	
20	9.01		**20**	0.05	**20**	0.05		**20**			**20**	
30	9.69	12.02	**30**	0.02	**30**			**30**			**30**	
40	10.57		**40**	0.01	**40**	0.05		**40**			**40**	
60	10.85		**60**	0.00	**60**	0.06	0.06	**60**	0.00		**60**	
64	10.85	11.63	**90**		**90**			**90**			**90**	
67	10.85	11.34	**120**		**120**			**120**			**120**	
69	10.85	10.31	**150**		**150**			**150**			**150**	
180			**180**		**180**			**180**			**180**	
210			**210**		**210**			**210**			**210**	
240			**240**		**240**			**240**			**240**	
300			**300**		**300**			**300**			**300**	
360			**360**		**360**			**360**			**360**	
420			**420**		**420**			**420**			**420**	
480			**480**		**480**			**480**			**480**	
540			**540**		**540**			**540**			**540**	
600			**600**		**600**			**600**			**600**	
720			**720**		**720**			**720**			**720**	

5 APPENDIX E: THE GROUNDWATER YIELD MODEL FOR THE RESERVE (GYMR) METHODOLOGY

By Dr. JJP Vivier and AGES (Pty) Ltd.

5.1 Introduction

This section was taken from report no. RDM/K000/02/CON/0507, Reserve determination studies for selected surface water, groundwater, estuaries and wetlands in the Outeniqua catchment: Technical Component – Knysna and Swartvlei, K. Vivier, 2009.

The basic approach and model were developed since the Olifants River Water Resources Development Project: Groundwater Study Task (ORWRDP) (AGES, 2005). It was required to evaluate the groundwater potential of selected regional aquifers on a quaternary catchment scale. The normal approach to these assessments is to develop either numerical groundwater flow models or analytical water balance models. It was found that it is impractical to e.g. develop 114 numerical models for the Olifants River Water management Area (WMA) and obtain groundwater flow balances with assurance levels. A methodology and quantification model was developed that could address the groundwater management problem.

The outcome of the investigation was to provide assurance levels for the groundwater that is available on a quaternary catchment scale. In catchments where the inflow far exceeds the outflow (if losses are accounted for), the regional scale groundwater flow balance model provides sufficient information to allocate groundwater quantities. The model output is used to classify potentially (and not actual) stressed or sensitive catchments by accounting for all important inflow and outflow components, which includes losses. Through this process, catchments are identified, for which more detailed studies are required.

5.2 Methodology

A model was developed termed the GYM that could be used to determine the groundwater balances on a number of quaternary catchments while accounting for variable recharge from rainfall. The variability in rainfall-recharge, aquifer storage and evapo-transpiration potential was identified as one of the factors that influence sustainability of groundwater supply.

The purpose of the model is based on given assumptions, to simulate groundwater flow balances on a regional (primary) catchment scale with quaternary sub-catchment scale resolution, on annual or monthly time steps. The output provide statistical changes in groundwater volume based on rainfall recharge variations, which yields assurance levels for groundwater volumes.

The model was developed to simulate each catchment as a cell. Inflow and outflow components are calculated that must balance between time steps.

5.3 The groundwater flow balance under steady-state conditions

In a groundwater system that is used as a management unit, surface water drainages or rivers act as linear drains for groundwater seepage (Figure 5-1). The volume of groundwater contributing to the flow in rivers is termed the groundwater component of base flow. Base flow consists of both the groundwater component of base flow and a surface water component. The groundwater component of base flow can therefore not be more than base flow. Base flow is important to streams during low flow conditions, during which groundwater acts as a store and release mechanism.

In natural steady-state conditions, the net groundwater inflow from recharge is balanced by base flow (including spring flow if springs exist). In areas where springs exist, it usually supports downstream wetlands that are of environmental significance.

In its basic form, the groundwater flow balance is given by $+Q_r - Q_{GETL} - Q_{BF} = 0$, where;

$+Q_r$	=	Recharge from rainfall
Q_{GETL}	=	Groundwater flow (evapo-transpiration) losses
$-Q_{BF}$	=	Base and spring flow

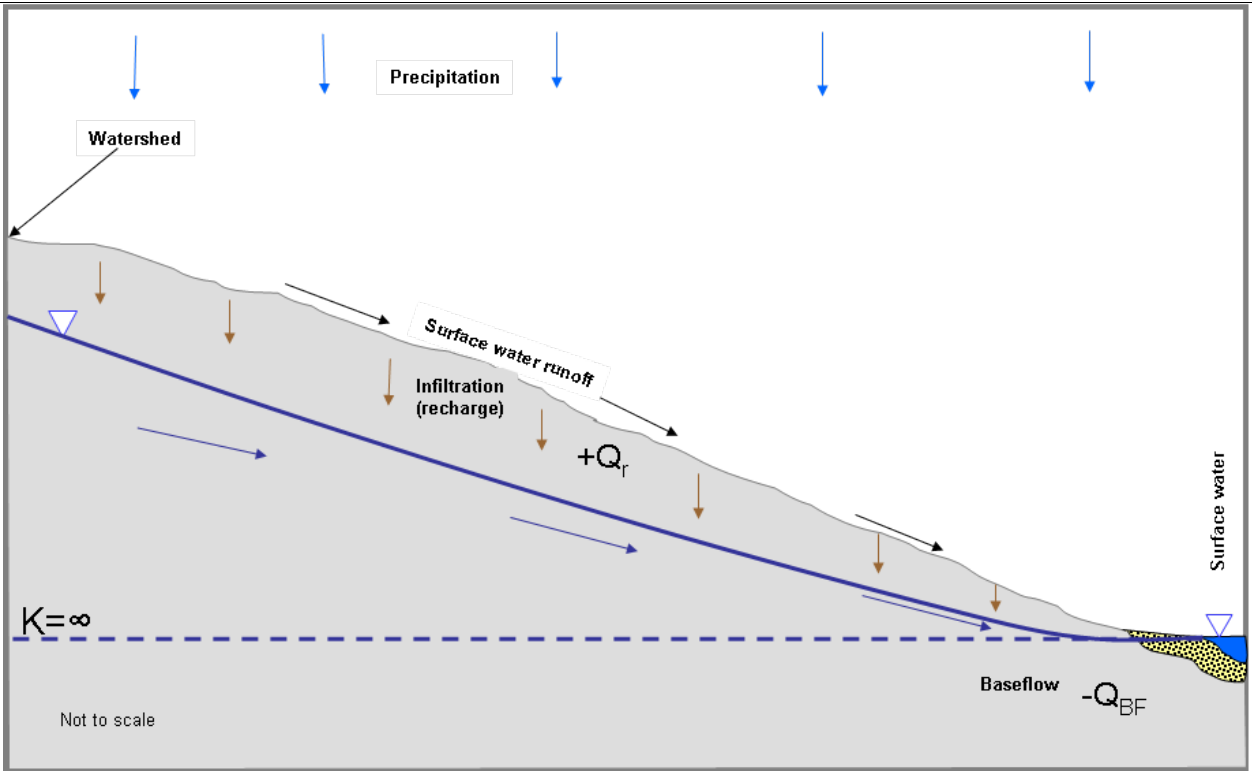

Figure 5-1 Geohydrological steady-state conditions

Spring flow and the groundwater component of base flow are associated with evaporation and transpiration losses that will be discussed later.

The piezometric gradient, which can be measured from site characterization and monitoring boreholes are usually known. Boreholes can be pump tested to determine the transmissivity and hydraulic conductivity (Figure 5-1).

The outflow per unit length (L) of aquifer is given by Darcy's law as,

$q = (K\ {}^{dh}/_{dl}) \times D$, (1) where

q is the Darcy flux in m/d (or $m^3/m^2/d$), K is the hydraulic conductivity, D the aquifer thickness and

${}^{dh}/_{dl}$ the piezometric gradient.

Since K, D and the head gradient can be measured, a steady-state model can be calibrated by changing the recharge value until the measured and simulated head gradients have a small (or acceptable) error. An acceptable error is usually considered as less than 10 % of the aquifer thickness. If the aquifer is for example 40 m thick, then an error of less than 4 m between the measured and simulated head elevations would be considered as acceptable.

A perfectly flat natural head gradient of 0, would imply an infinite hydraulic conductivity (Figure 5-1).

5.4 Transient flow and evaluation of groundwater storage volume buffering capacity during dry periods to provide assurance levels

The groundwater flow balance described in the previous section, can be differentiated in additional basic inflow and outflow components and into e.g. annual or monthly time steps.

The regional, quaternary catchment scale GYM was developed on this basis. The purpose is that it must be able to simulate groundwater volume availability based on assurance levels (typically 95%) through a large number of the sub-catchments. In the model, an aquifer was defined as its surface water quaternary catchment equivalent, which would form one cell in the system.

The output of the model should be able to account for the duration of variable rainfall-recharge periods obtained from statistical simulations based on historical rainfall records. It is therefore important to be able to evaluate the ability of the groundwater reservoir to buffer low recharge periods that are characterized by dry cycles (Figure 5-2). Stochastic generations of the monthly average rainfall-recharge and the standard deviation were used to determine inflow and accounting for outflow, it was used to evaluate the aquifer's ability to sustain supply. The output was then used to calculate the water balance of each quaternary catchment at a 95 % assurance level.

The GYM model was adapted in 2007 and 2008 to account for the components that would be required for the groundwater reserve. The adapted version is known as the Groundwater Yield Model for the Reserve (GYMR).

5.4.1 Groundwater management constraint

The concept of a groundwater management constraint (GMC), which is similar to the surface water concept of a Dead Storage Level (DSL) was obtained from the management of surface water dams. The GMC is defined as the minimum level or management constraint to sustain the environment. The volume of the aquifer below that level, is not considered as available for supply. This constraint is often selected by the groundwater specialist performing the assessment.

This concept was applied on all aquifers as a minimum level management constraint. As a guideline, 10% to 20% of the saturated thickness of the aquifer was used as the GMC level. If an aquifer is for example 50 m thick, then 5 m to 10 m available drawdown over the entire area was used as the GMC level (Figure 5-3).

In practice, there should be a relationship between the volume in storage (equated to the saturated thickness) of an aquifer and the variability in rainfall-recharge (Figure 5-2 – Figure 5-3).

5.4.2 Assumptions

The following assumptions were made:

- In natural steady-state conditions, the recharge equals groundwater base flow minus losses (e.g. evapo-transpiration).
- Any abstraction would result in eventual reductions in groundwater base flow. This approach is conservative, since in reality there would be a time lag, which is longer for distances further away from the base flow or decant point. Under the approach that the model outcomes should be sustainable and to be used in Water Use License applications, this assumption is considered defendable.
- Interaction with surface streams (i.e. base flow) was considered as a net outflow. Inflow from surface water streams was shown as positive groundwater base flow, which indicates a severe depletion in groundwater storage.
- The model considers shallow aquifers (0-100 m). Deep groundwater inflow or outflow is not considered as information or evidence of these processes is not available or readily understood. It is assumed that inflow and outflow from deep groundwater balances.

The conservative assumptions used in the model will yield less water than in the actual case. This approach is in line with the environmental precautionary principle. The aim is not to determine actual groundwater flow balances as it is today, but rather to determine management scenarios that can be used for regulatory requirements and decision making.

5.4.3 Conceptual model

The conceptual groundwater flow model on which the analytical model was based, is shown in Figure 5-5. The inflow from groundwater recharge is balanced by outflow to springs, wetlands and groundwater base flow to rivers or streams under natural conditions. In areas where the recharge to evapo-transpiration ratio is low, most or all of the groundwater could be lost with the result that the streambed is dry (Figure 5-5).

Where anthropogenic influences occur, other losses occur such as boreholes, riparian vegetation and mine dewatering were included.

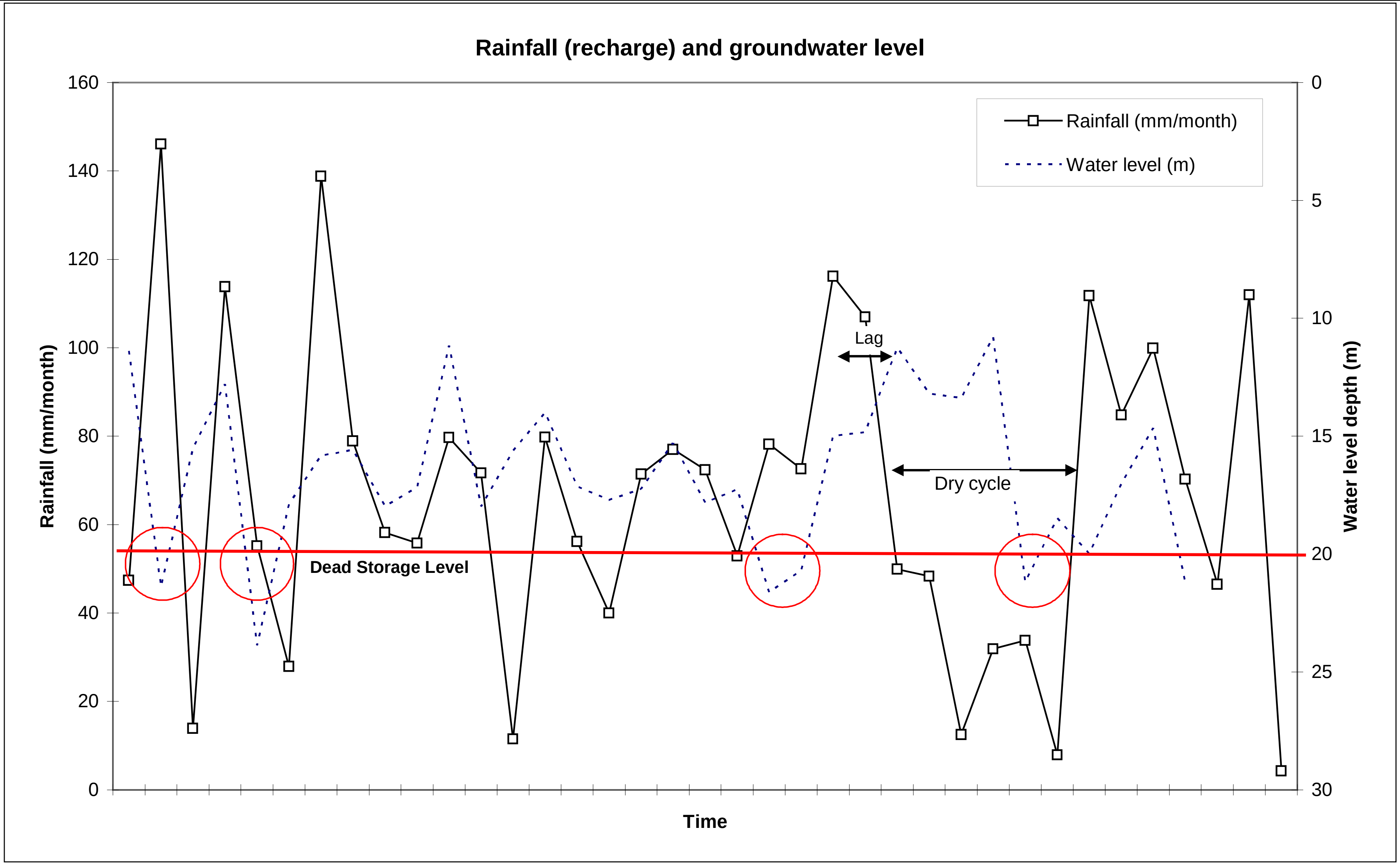

Figure 5-2 Time varying rainfall-recharge conditions showing system failure during dry cycles

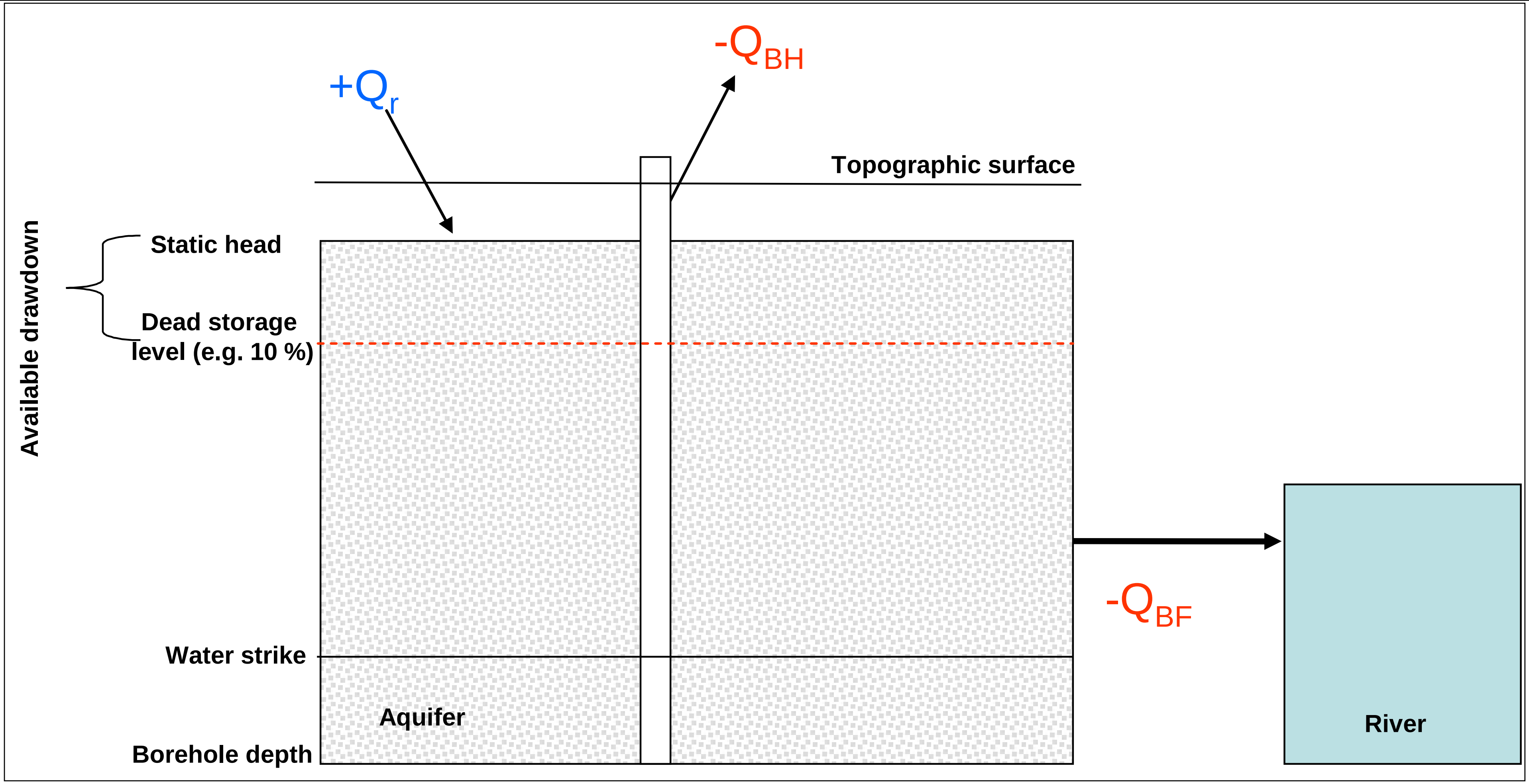

Figure 5-3 **Schematic representation of the GYM conceptual model – dead storage level**

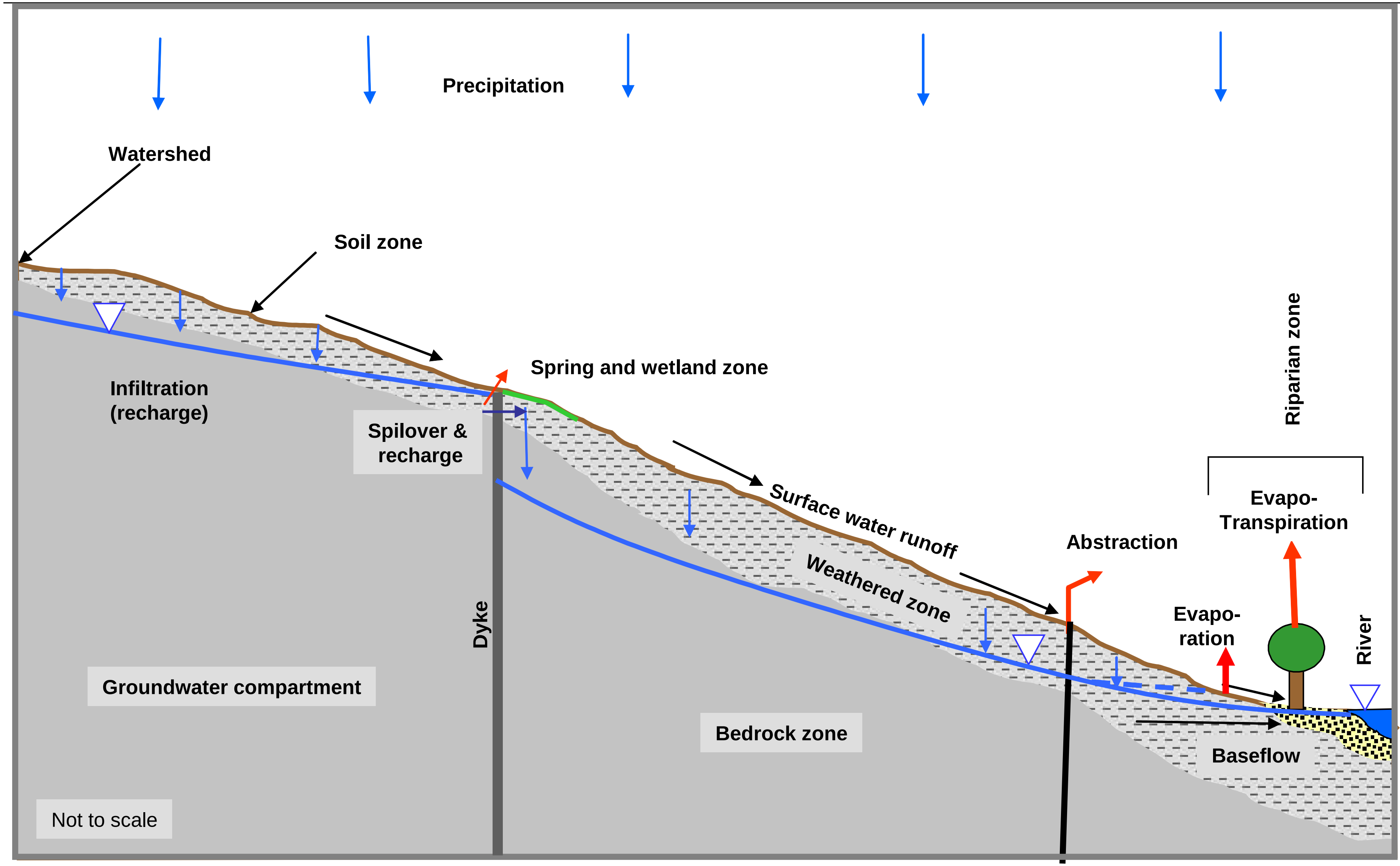

Figure 5-4 Schematic representation of the GYM conceptual model – field conditions (low baseflow loss case)

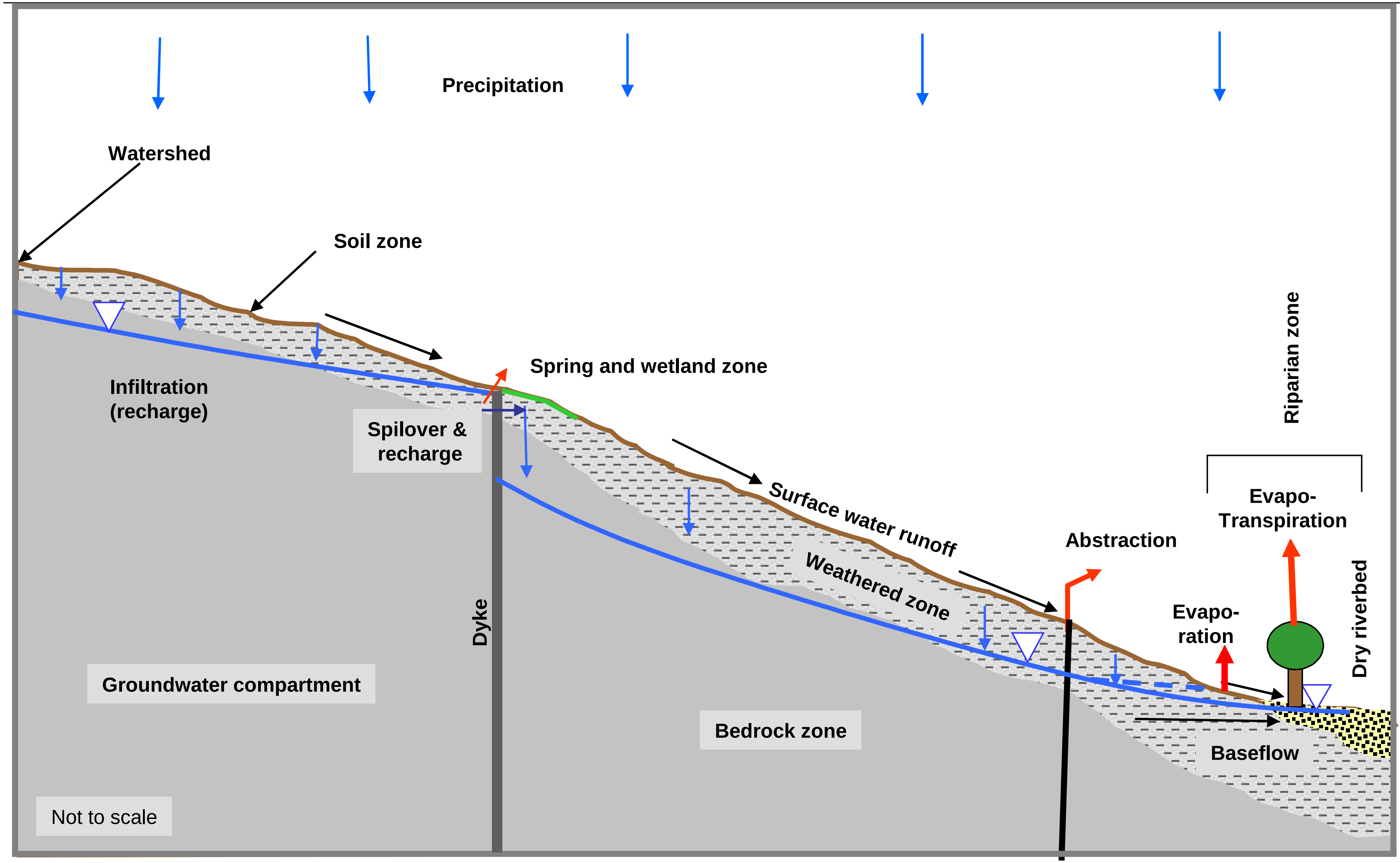

Figure 5-5 Schematic representation of the GYM conceptual model – field conditions (high baseflow loss case)

5.5 Analytical model

The transient model is a differentiation of the steady-state, basic case discussed in section 5.1. Distinction is made between natural and unnatural inflow and outflow components. Also between outflow components that are lost (e.g. evapo-transpiration especially by alien vegetation) and outflow components where groundwater is used (e.g. Basic Human Need Reserve). Groundwater Loss Components (GLC) is less valuable than Groundwater Use Components (GUC). This is due to the fact that it is more sensible to use groundwater for basic human need purposes than to lose it to alien vegetation. Hence if one has the option to prioritise outflow, all outflow components are not considered of the same importance level.

It is the purpose of the model to calculate the volume of groundwater in storage given that the volume of water required by natural systems is allocated for.

The various groundwater flow components are described by the following:

The groundwater inflow from natural systems ($+Q_{GINS}$).

$+Q_R$	=	Recharge from rainfall	$[L.T^{-1}]$[1]

The groundwater inflow from unnatural systems ($+Q_{GIUNS}$).

$+Q_{DS}$	=	Inflow from Dam Seepages	$[L.T^{-1}]$
$+Q_{IRR}$	=	Return recharge from irrigation	$[L.T^{-1}]$

Groundwater loss components ($-Q_{GLC}$).

$-Q_{AVEG}$	=	Alien vegetation	$[L.T^{-1}]$
$-Q_{ETPL}$	=	Evapo-transpiration losses	$[L.T^{-1}]$
$-Q_{MDW}$	=	Mine dewatering	$[L.T^{-1}]$

Groundwater use by natural systems ($-Q_{GUNS}$)

[1] $[L.T^{-1}]$ where L = length and T = time

$-Q_{SF}$	=	Spring flow	$[L.T^{-1}]$
$-Q_{GBF}$	=	Groundwater base flow	$[L.T^{-1}]$
$-Q_{WLD}$	=	Wetland fed by groundwater	$[L.T^{-1}]$
$-Q_{RVEG}$	=	Riparian vegetation	$[L.T^{-1}]$
$-Q_{EWR}$	=	Ecological Water Requirement (component of groundwater base flow)	$[L.T^{-1}]$

Groundwater use by unnatural systems ($+Q_{GUUNS}$)

$-Q_{BH}$	=	Abstraction from boreholes e.g. well fields for water supply	$[L.T^{-1}]$
$-Q_{LSF}$	=	Abstraction from boreholes for livestock farming	$[L.T^{-1}]$
$-Q_{BHN}$	=	Allocation for basic human needs and communities	$[L.T^{-1}]$
$-Q_{IR}$	=	Abstraction for irrigation	$[L.T^{-1}]$
$-Q_{F}$	=	Forestry groundwater use	$[L.T^{-1}]$

Volume of groundwater in storage (GV_{ST})

$+GV_{ST}$	=	Volume of groundwater in storage	$[L^3]$

In a natural, steady-state situation, the groundwater balance equation for the model is given by;

$$\Delta GV_{ST} = Q_R - Q_{GETL} - Q_{GBF} \quad (2)$$

In an unnatural groundwater system, the groundwater flow balance per time step is given by:

$\Delta GV_{ST} = Q_R + Q_{DS} – Q_{BH} - Q_{LSF} – Q_{BHN} – Q_{IR} + Q_{IRR} – Q_{MDW} – Q_F - Q_{AVEG} – Q_{WLD} – Q_{RVEG} – Q_{SF} – Q_{GETL} – Q_{GBF} - Q_{EWR}$ (3)

It is evident that the groundwater used by natural systems (spring flow and groundwater base flow) is last in the flow sequence. This is because in the physical flow system, unnatural groundwater use such as from boreholes and mine shafts can utilise water before it has the opportunity to flow to a natural system. The flow sequence is therefore important. Groundwater base flow of which the Ecological Water Requirement (EWR) is a component, is the last component to receive groundwater. When outflow exceeds inflow in any given time step, water would be taken firstly from storage and then from base flow. A supplementary conservative assumption that can be made, is to allocate a minimum volume to groundwater base flow in the model. If outflow exceeds inflow, water would be taken mainly from storage until the head declines to the defined management constraint. Once the volume in storage is used, it is possible for base flow to reverse (i.e. inflow into the groundwater system, which is implemented as positive base flow in the model, which must be activated in the model) and have a flow reduction effect on the river. A maximum volume was implemented as a constraint in the model as the user need to determine whether the specific surface water resource has a flow constraint prior to activation of the possibility of reverse base flow. This is because most surface water streams in South Africa is dry for most of the times of the year, which would not allow reverse base flow from the stream to the aquifer.

The groundwater balance from (3) is calculated for monthly time steps (Δt) to yield an annual or monthly groundwater balance at a chosen assurance level.

The model output is put into perspective for the groundwater component of the reserve. The various flow components are discussed in more detail in the following section.

Groundwater volume in storage (GV_{ST})

The volume of groundwater in storage is determined from:

$$GV_{ST} = A \times D \times S_0 \qquad (4)$$

A	=	Surface area of the aquifer	$[L^2]$
D_{GMC}	=	Saturated thickness of the groundwater	[L]

management constraint (GMC)

S_0 = Specific Storativity [1]

The volume in storage is calculated for each time step (Δt) and from which an average change in groundwater head is determined by:

$$\Delta h = \frac{V}{S_0} \quad (5)$$

Δh = Change in head during time step [L]

V = Net volume of water during time step [L^3]

The model output graphs are given in terms of average depth to groundwater level based on available volume within the management constraint.

5.5.1 Variable recharge (+Q_R)

The groundwater recharge is calculated as a percentage of rainfall that is assumed to reach the aquifer, on a monthly basis. Data from the historical rainfall records is used to determine the monthly average rainfall (Figure 5-6). The standard deviation for a 95 % assurance level is then used to obtain a range within which the monthly rainfall-recharge is sampled (Figure 5-7). It is important to note that the 95% assurance level is much lower than the average rainfall, which is typical for semi-arid and arid conditions, which is prevalent in South Africa.

The sampling is done on a random basis within the statistical rainfall distribution.

When the aquifer is full, no additional recharge is accepted in the model. In reality, piezometric levels could rise above the static levels during wet periods. Provision could be made to allow e.g. a 10 % over saturation of the aquifer, which would increase the available volume of water.

5.5.2 Dam seepage (+Q_{DS})

Seepage from dams is determined by:

$$Q_{DS} = K_C \frac{dh}{dl} \times A_D \quad (6)$$

K_C	=	Hydraulic conductivity of the colmation layer formed by dam sediments	$[L\ T^{-1}]$
$^{dh}/_{dl}$	=	Head gradient (assumed to be 1 for vertical seepage)	[1]
A_D	=	Surface area of dam/s	$[L^2]$

This component is used conservatively with known dams and parameters, otherwise it is considered to be zero to prevent an overestimation of the groundwater volumes. Provision is made to allow dam seepage for only the wet seasons or e.g. 30% of the hydrological year when it will have a positive head.

5.5.3 Abstraction from boreholes for livestock farming ($-Q_{BH}$)

Abstraction from boreholes that are used for farming is used as an outflow component. For the Lower Vaal reserve determination an average of one head of cattle per 20 ha was used and a consumption of 60L/ 24 hr per head.

5.5.4 Allocation for basic human need ($-Q_{BHN}$)

Groundwater is an important source of water supply for basic human needs, especially for communities in rural areas. For areas that rely on groundwater as a source of supply, the allocation is made on between 25ℓ/person/day to 60ℓ/person/day. The population in the area is obtained from census and spatial GIS data bases, which is then used to calculate the basic human need allocation.

5.5.5 Borehole abstraction for irrigation ($-Q_{IR}$)

Water use for irrigation is obtained from the total surface area that is used for irrigation. The water use is determined by using 1ℓ/s/ha/day (80 m^3/ha/day) in the growing season. The irrigation areas are determined from GIS and remote sensing spatial data (satellite or aerial photographs).

In cases where Water Use Licensing information for sub-catchments is available, it will be considered as backup check. The licensed or registered volumes are usually higher than the actual use. In the Lower Vaal Study the WARMS registered data was used.

5.5.6 Return recharge from irrigation ($+Q_{IRR}$)

The return flows from irrigation acts as a source of groundwater recharge. In some cases, surface water is abstracted which is then used to irrigate on aquifers located further away from the surface water sources. If irrigation is optimal, no through flow to the aquifer should occur. However lower water quality (especially Na and Cl) and certain soil types (clay) pose risks of soil salinization. In these cases, over-irrigation is required to flush the salt load from the soils, which then contaminates the aquifer over time.

The default assumption is made that e.g. 10% to 20 % of the volume used for irrigation, recharges the aquifer.

5.5.7 Mine dewatering ($-Q_{MDW}$)

When mines operate below the groundwater level, it will induce inflow and cone of depression develops around it. Standard practice is to grout (i.e. seal) groundwater inflows, which is effective where the rock mass is competent and inflow occurs from isolated discrete fracture zones. Where the inflow occurs from homogeneously fractured or weathered rock units, sealing is in most cases ineffective or costly. High groundwater head pressure behind mine stopes could also cause failures. In these cases, the aquifer is dewatered to create a safe working environment.

The mine dewatering volume is determined by:

$$Q_{MDW} = K \frac{dh}{dl} \times A_{MS} \quad (7)$$

K	=	Hydraulic conductivity of mine workings	$[L\ T^{-1}]$
$^{dh}/_{dl}$	=	Head gradient (assumed to be 1 for vertical seepage)	[1]
A_{MS}	=	Surface area of mine stopes and shafts	$[L^2]$

The information from (7) is generally too detailed to obtain for a quaternary catchment scale model. Direct information on the volumes dewatered could be obtained from mines, as it is essential data to collect and could be included directly into the model as a flow volume and not a calculated parameter.

5.5.8 Alien vegetation ($-Q_{AVEG}$)

Alien vegetation often accounts for large reductions in groundwater volumes by intercepting seepage along springs and in the riparian zone. The groundwater use by alien vegetation systems are determined by;

$$Q_{AVEG} = (Q_P - Q_{ET}) \times A_{AVEG} \tag{8}$$

Q_P	=	Mean Annual Precipitation	$[L\ T^{-1}]$
Q_{ET}	=	Mean Annual evapo-transpiration (MAE) rate of alien vegetation	$[L\ T^{-1}]$
A_{AVEG}	=	Surface area covered by alien vegetation	$[L^2]$

The areas covered by alien vegetation are determined from GIS and remote sensing and/or field mapping. It is important to determine the depth to groundwater in areas covered by alien vegetation, because the areas used in this component must use groundwater directly. The depth to groundwater in this case should not be greater than e.g. 10 m, because deeper groundwater is unlikely to experience losses due to alien vegetation.

5.5.9 Forestry ($-Q_F$)

Forests that intersect the groundwater zone would have a similar effect on groundwater reduction than alien vegetation. The groundwater use by forests are determined in a similar way from:

$$Q_F = (Q_P - Q_{ET}) \times A_F \tag{9}$$

Q_P	=	Mean Annual Precipitation	$[L\ T^{-1}]$
Q_{ET}	=	Mean Annual evapo-transpiration (MAE) rate of alien vegetation	$[L\ T^{-1}]$
A_F	=	Surface area covered by alien forests	$[L^2]$

5.5.10 Wetlands fed by groundwater ($-Q_{WLD}$)

Permanent wetlands that are sustained by groundwater would use water equal to the net evapo-transpiration;

$$Q_{WLD} = (Q_P - Q_{ET}) \times A_{WLD}$$
(10)

Q_P	=	Mean Annual Precipitation	$[L^3\ T^{-1}]$
Q_{ET}	=	MAE rate of wetland and wetland vegetation	$[L^3\ T^{-1}]$
A_{WLD}	=	Surface area of wetland	$[L^2]$

The information is obtained from GIS coverage and field mapping of the total surface area covered by wetlands that are supported by groundwater. Wetlands within 1 km from a river are assumed to be supported by surface water. Only those wetlands located away from surface water features are included in the groundwater assessment.

5.5.11 Riparian vegetation (-Q_{RVEG})

Riparian vegetation also accounts for reductions in groundwater volumes by intercepting seepage along springs and in the riparian zone. Riparian vegetation is indigenous and in general does not use as much water as alien vegetation. Riparian vegetation has environmental importance because it supports ecosystems. The groundwater use by natural riparian vegetation systems are determined by:

$$Q_{RVEG} = (Q_P - Q_{ET}) \times A_{RVEG}$$
(11)

Q_P	=	Mean Annual Precipitation	$[L^3\ T^{-1}]$
Q_{ET}	=	Potential MAE rate of riparian vegetation	$[L^3\ T^{-1}]$
A_{RVEG}	=	Surface area covered by riparian vegetation	$[L^2]$

5.5.12 Spring flow (-Q_{SF})

The outflow to springs is directly determined by measuring the cumulative flow of springs (-Q_{SF}) in the catchment. It is assumed that there would be losses between the aquifer and the spring if e.g. groundwater seeps out in a zone around the actual spring eye and opportunity exists for evapo-transpiration losses.

5.5.13 Groundwater evapo-transpiration losses (-Q_{GETL})

Groundwater evapo-transpiration losses occur in the groundwater-surface water interaction zone, where the groundwater level is shallow, along drainages and streams, springs and at seepage zones. It was found that in the Olifants Catchment, the MAP is e.g. 600 mm, while the MAE is in the order of 1400-1800 mm. The MAE is more than double the MAP. Groundwater recharge is in the order of 2 - 4% (except dolomites, where it is much higher at 8 - 15 %) of the MAP. The potential groundwater evapo-transpiration losses are therefore 50-70 times higher than the recharge. It means that the total groundwater recharge could be lost over a groundwater evapo-transpiration loss area of 1 - 2% of the catchment area.

The groundwater evapo-transpiration loss is determined from:

$$Q_{GETL} = MAE \; x \; A_{ET} \qquad (11)$$

Q_{GETL}	=	Groundwater evapo-transpiration loss	[L T^{-1}]
MAE	=	Potential MAE	[L]

5.5.14 Groundwater base flow (-Q_{GBF})

Groundwater base flow is a function of the groundwater recharge minus losses in the aquifer system. Groundwater base flow is often the last component in the flow sequence to receive water. It is influenced by recharge and the hydraulic parameters of the aquifer.

Groundwater base flow can be determined from:

$$Q_{BF} = K \frac{dh}{dl} \times D \times L \qquad (12)$$

K	=	Hydraulic conductivity of the general aquifer	[L T^{-1}]
$^{dh}/_{dl}$	=	Head gradient (assumed to be correlated to topography)	[1]
D	=	Saturated thickness	[L]
L	=	Length of drainage system along which groundwater base flow occurs	[L]

If the recharge, aquifer losses, aquifer thickness (D) and length of outflow (L) is known, the minimum transmissivity (or hydraulic conductivity) of the aquifer to allow groundwater base flow can be determined.

5.5.15 Groundwater base flow, Ecological Water Requirement ($-Q_{EWR}$)

The component of base flow that is required for the ecological reserve is determined by ecological water specialists. If this value is provided, it can and should be included in the model to determine whether it can be sustained by groundwater alone or which percentage of e.g. the drought low flow component could be sustained by groundwater. More research on the model implementation is required on this section.

The component of groundwater that could be utilised in a catchment, would typically be the groundwater base flow minus the ecological water requirement. It is for now assumed that the flow loss component is fixed. In practice alien vegetation could be reduced to reduce the flow losses or groundwater could be used before it is allowed to undergo flow losses. This would be a management decision taken for each catchment based on the flow and environmental character.

5.5.16 Deep groundwater inflow and outflow

There are possibilities for inflow from or outflow to deep seated aquifers, which stretches beyond the quaternary boundary. Provision is made for deep groundwater inflow and outflow as a flow component $+Q_{DGW}$ and $–Q_{DGW}$. Unless data from e.g. shallow and deep boreholes with piezometric head elevations can be provided to prove that deep groundwater flows into or out of the system, the assumption is made that these two components are zero. The assumption could also be made that outflow to and inflow from deep aquifers balance with a zero effect.

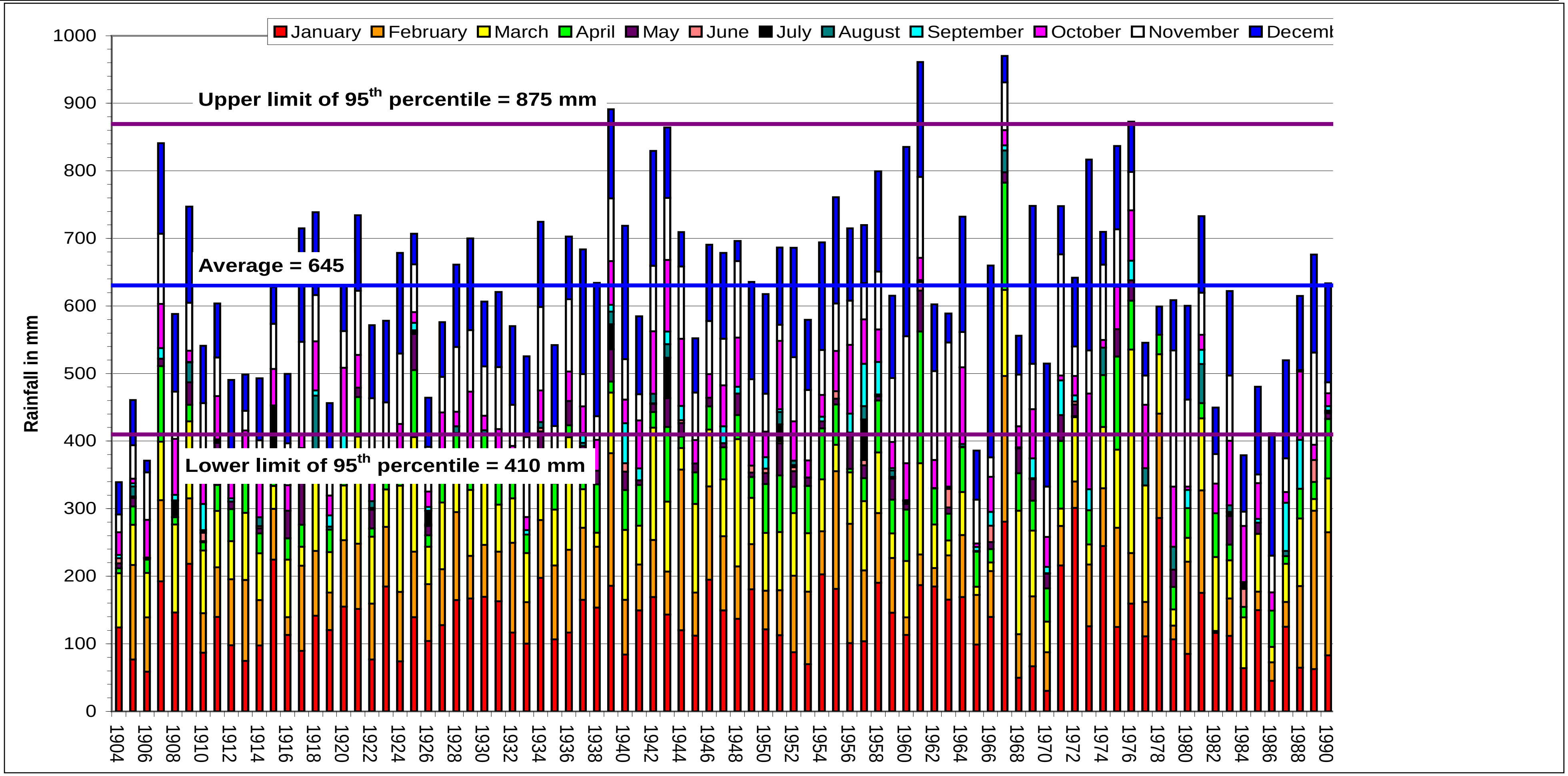

Figure 5-6 **Monthly and annual rainfall data for station 0548280 (Saulspoort Hospital) from 1904 to 2002**

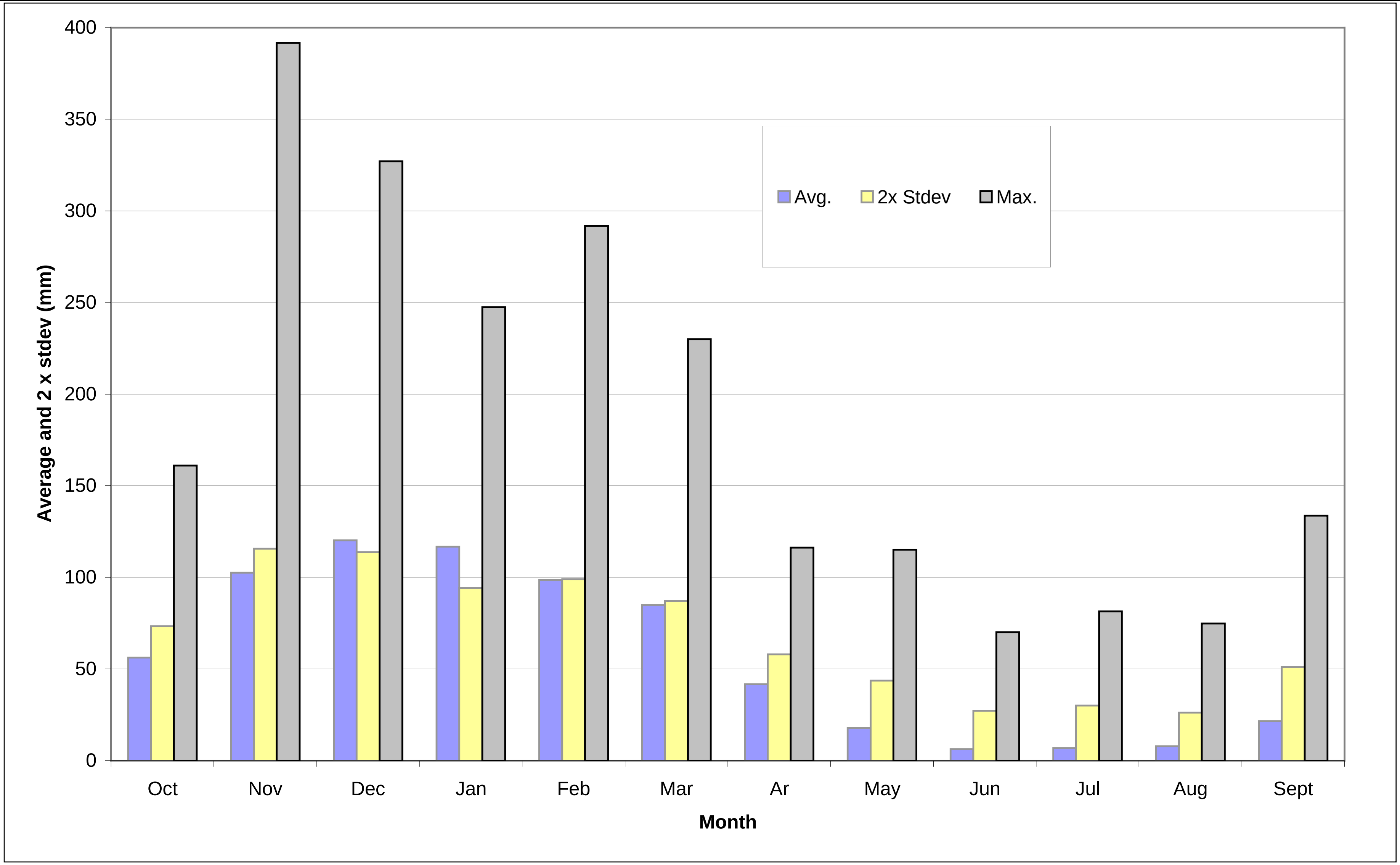

Figure 5-7 Average monthly rainfall and standard deviations – showing the variability

5.6 References

Van Tonder GJ, Usher, B and Hughes D. (2007) Groundwater/surface water interaction: A new perspective. In proceedings of the Groundwater Conference. 8-9 October 2007. Bloemfontein. South Africa.

Vivier JJP, Gouws, WJ and Wydeman R. (2005) Olifants River Water Resources Development Project: Groundwater Study Task (ORWRDP). AS-R-2005-05-24

6 APPENDIX F: GROUNDWATER MANAGEMENT PLAN BY AGES (PTY) LTD

By JJP Vivier

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MIDDELBURG GROUNDWATER SUPPLY: GROUNDWATER DEVELOPMENT AND MANAGEMENT PLAN

1. GROUNDWATER DEVELOPMENT AND MANAGEMENT PLAN

a. Introduction

The supply of groundwater to Middelburg must be done based on an approach that would ensure sustainability of supply. This poses a challenge in the face of the fact that the existing Municipal Aquifer have proven to be unsustainable. For the purpose of the development of a groundwater development and management plan, the future demand for Middelburg is taken at 3500 m^3/d (40 L/s) with the purpose of this investigation to supply in 50% of the future demand.

Apart from the existing Municipal Aquifer, there are no long-term water level data available for the regional groundwater system. Groundwater supply is associated with uncertainties regarding recharge from rainfall, transmissivity, storativity etc. These parameters vary spatially and temporally. Apart from the variations, only water levels and abstraction rates can be determined directly. Other parameters such as transmissivity are derived from field tests. Field tests are done on e.g. 48 h or 72 h and to determine the sustainable yields, much longer time periods of e.g. 20 years or more is required. Actually, sustainable groundwater supply equates to steady-state supply where time does not play a role, which may not seem practicable or even possible, given the uncertainties. This is due to the large number of unknowns and variables that is unknown. These variables include land use changes, geological uncertainty en even changes in rainfall patterns that influence the sustainability of groundwater. Some of these parameters like recharge and storativity are qualified guesses at best.

The question is how do we develop and manage such a resource? There are two options; the first is to accept that groundwater is associated with uncertainties and to follow a development and management approach that caters for the groundwater characteristics. The second is to conclude that groundwater is such an uncertain resource that we should abandon it and look for other alternatives. The second option is according to this team not an option as will be discussed in this section. It was internationally accepted that groundwater investigation techniques (and statistics for that matter) are all wrong, but still the most useful options that exist (Poeter, 2006).

In this section the approach to groundwater resource development and management is described.

b. Minimum Groundwater Balance approach to groundwater development

The groundwater development plan was done based on a phased approach as follows:

1. The existing groundwater data (borehole distribution, water levels, rainfall, water quality) was evaluated in terms of groundwater performance and history. It is known that the Municipal Aquifer is over utilised as water levels declined in the past 20 years to levels that could not sustain the required abstraction rate of 83 L/s to 100 L/s. The decline in water levels equates to abstraction that exceeded the natural recharge and the surplus volume had to be obtained from storage until it was partially depleted. It was also found that the abstraction at the Municipal Aquifer is focused in one area.

2. A regional hydrocensus was done to determine the groundwater status in terms of distribution of the regional boreholes, water levels and abstraction rates.

3. A regional *minimum groundwater balance* was determined that was based on quaternary catchments and defined sub-catchments which were delineated based on the hydrogeological character of identified groundwater development target areas. The purpose was to evaluate the potential for groundwater supply on a regional scale. It is note that the groundwater balance approach, if applied incorrectly can lead to unsustainable groundwater abstraction evaluations (Bredehoeft et al, 1982; Devlin and Sophocleous, 2005, Seward et al, 2006 and Zhou, 2009).

    a. The *minimum groundwater balance* approach was applied here, which is different from the classic groundwater balance approach in that the aim was not to determine the *actual or natural groundwater balance* based on natural recharge, but a *minimum groundwater balance* based on assured rainfall, for the purposes of planning for water supply (Vivier et al, 2009b). *It is accepted that the actual groundwater balance is unknown and that there are too many uncertain parameters at this stage of the investigation to aim and identify it*.

b. In the absence of actual groundwater information (which costs money to obtain), conservative assumptions were made. The assumptions were conservative in that the MAP was not considered for recharge estimations, but the lower 95th percentile (which represents a 1:20 year drought) and aquifer storativity was neglected at this stage.

c. The groundwater balance was then determined for smaller surface water catchments to obtain groundwater supply potential. These smaller sub-catchments were delineated based on geological structures such as dolerite rings as well as dolerite dyke intrusions that were targeted for well-field development. The reason for this approach is that the actual groundwater catchment is unknown. The assured recharge, existing abstraction, discharge to springs and losses to evaporation was considered in the minimum groundwater balance approach. The groundwater balance indicated that new groundwater resource development could be possible in 3 new undeveloped aquifer areas such as Dunblane, The Glen, Karmel and Lusernvlei. High volume production boreholes are absent in these identified target areas and the assessment was done based only on surface water catchments and recharge potential based on the lower 95th percentile. It must be noted that the MAP is 350 mm/a and the lower 95th percentile is 180 mm/a, which is only 52% of the MAP (i.e. conservative). Analogue information on regional geological structures such as regional linear dykes and ring dykes, further assisted in the predetermination of groundwater supply potential.

d. During this stage of the investigation, no high volume production boreholes or other aquifer information existed in these areas. The *minimum groundwater balance* approach was used as a planning tool to determine where is would be cost-efficient to spend money on drilling of new boreholes. It would be illogical to drill boreholes in areas where recharge is low or limited, abstraction or borehole density is already high or catchment areas are small. The minimum groundwater balance approach also considers economical considerations as sustainability is defined by the triple bottom line that includes development, environment and economy (Brundtland, 1987; Vivier, 2006).

e. The minimum groundwater balance approach is based on a Bayesian methodology where prior information is used in the absence of actual data.

f. The uncertainty with prior information is high and hence conservative assumptions are made. The information is re-assessed iteratively as field data becomes available until it converges to the analyst satisfaction (Freeze et al, 1990). It is accepted that perfect data does not exist and that we will have to deal with uncertain information until we can reduce uncertainty with monitoring (Vivier, et al, 2009c). Prior information includes only minimum groundwater balance and regional geological information. Posterior information includes drilling and aquifer testing information.

4. The minimum groundwater balance approach was therefore used to focus further work. The areas that indicated potential for additional groundwater supply based on the groundwater balance evaluations were evaluated for local hydrogeological structures such as dolerite dykes and ring intrusions and associated fractured zones.

5. This was followed by the site investigation, exploration borehole drilling and aquifer testing which comprise the main portion of the project expenditure.

6. The aquifer tests were used to determine how much water can be abstracted successfully from boreholes. The principle of constraints was used (Goldratt, 1990) to determine the initial recommended abstraction rates. If the constraint is the borehole yield, then it was used as the limiting factor for water supply (and not the minimum groundwater balance figure) and if the constraint was the minimum recharge based on the 1:20 year drought, then it was used and the borehole yields were scaled down. Safety factors were included following the analysis of the aquifer tests to estimate the initial sustainable yields. At this stage, it is accepted that the actual groundwater recharge and the spatial extent of the borehole capture zone is unknown and that a more sustainable yield can only be determined through monitoring.

Following this methodology, a systems approach to sustainable groundwater development and management was followed for Middelburg.

c. Systems approach to groundwater development and management

The effect of uncertainties in groundwater development and management on the determination of sustainable yields is that it drives the recommended yields lower, to minimise or avoid risk. This is the so called risk-averse approach (Freeze et al, 1990). In this approach, the groundwater yields from boreholes are considered very low to aim and obtain supply that can last virtually "forever" (steady-state approach). To obtain the required future supply of 40 L/s, boreholes would be recommended at very low rates of typically 2 L/s/borehole (illustrative values are used) even if the pump tests indicated yields of up to 20 L/s or 10% of the tested yields (**Figure 6-1**).

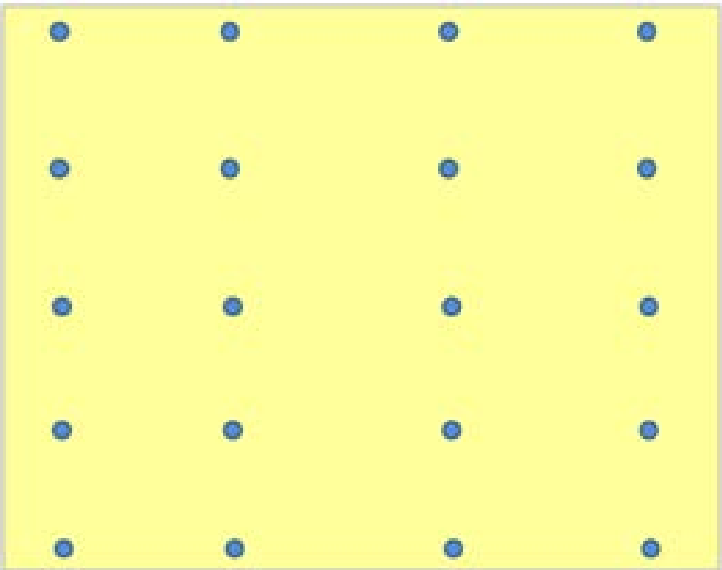

Figure 6-1 Sustainability from a steady-state approach (40 L/s at 2 L/s/borehole = 20 boreholes).

The problem with this approach is that due to the risk-cost relationship, it drives costs up (**Figure 6-2**). The engineering design of infra-structure has to take cognisance of not only risk but also cost. Due to the fact that sustainability is not only defined by environmental considerations, but also by development and the economy (Brundtland, 1987), *sustainable yield is not the lowest yield*.

The terminology used for *sustainable yield* in the groundwater papers evaluated in this investigation (Seward et al, 2006 and Zhou, 2009) neglects development and economical effects and only concentrates on environmental Geohydrological requirements. Following these approaches would lead to the most expensive groundwater development possible (**Figure 6-2**). *Sustainable yield in terms of the definition of sustainability* can only be defined if economic considerations were accounted for. Another terminology (such as *environmental safe yield*) will have to be used for what is meant with *sustainable yield* in the papers.

For reference purposes, at Middelburg, the surface water option is estimated to be in the order of R300 million capital with a high operating energy cost as water has to be lifted at 300 m head and pumped across a long distance.

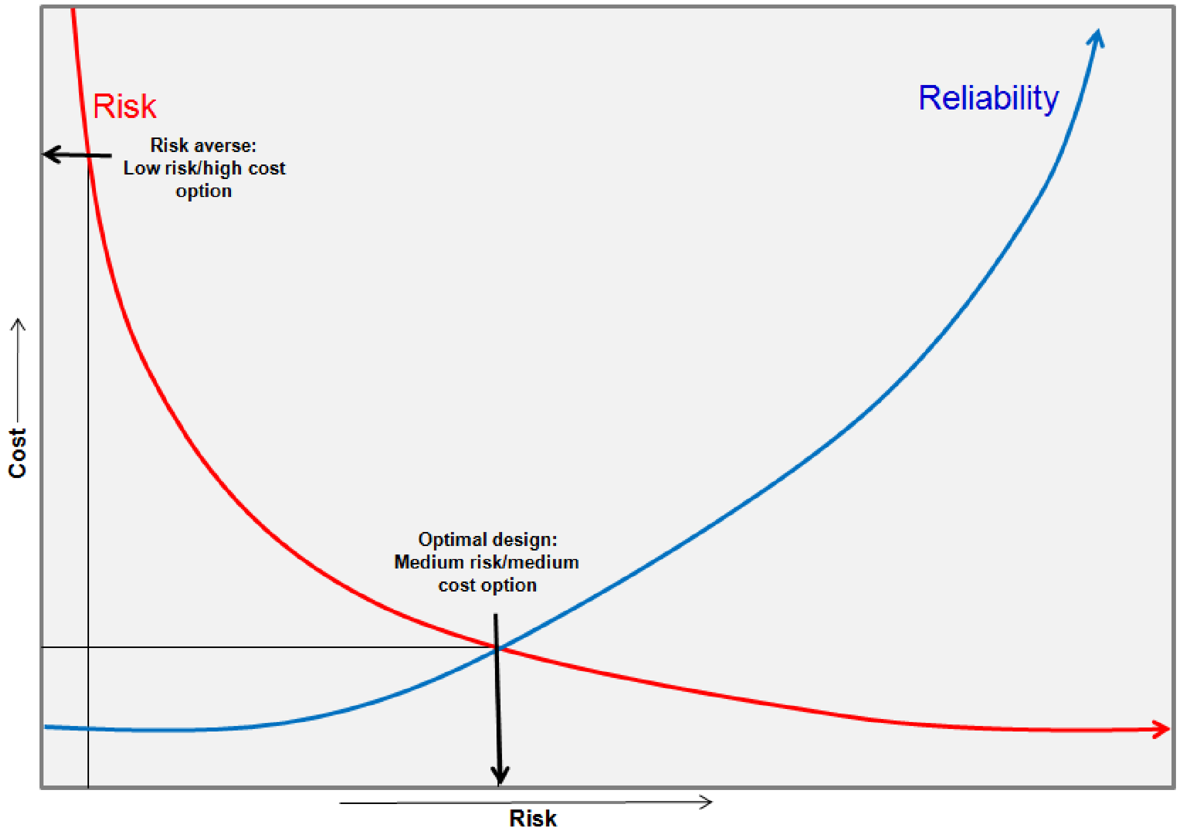

Figure 6-2 Risk-cost and reliability relationship (Freeze et al, 1990).

A conceptual calculation was done for groundwater development at Middelburg using the same estimated groundwater development and infra-structure capital costing (**Table 6-1**). Operational costs were not considered for now. The conceptual costs assumed that there are a number of options for groundwater development that ranges from using 2 boreholes at 20

L/s/borehole which is associated with a high risk (i.e. risky) to using 20 boreholes at 2L/s/borehole associated with very low risk (risk-averse) of failure (**Table 6-1**). The unit costs were assumed to be the same. The figures indicate an exponential increase in costs with lowering in abstraction rate per borehole (**Figure 6-3**).

Table 6-1 Middelburg: Conceptual comparative costs for groundwater development following various options.

No	No of boreholes	Yield per borehole (L/s/borehole)	Cost of boreholes (R mil)	Cost of infra-structure (R mil)	Total capital cost (R mil)	Total yield (L/s)	Unit capital cost over 20 year period (R/m^3)
1	2	20	R 0.60	R 10.00	R 10.60	40	R 0.42
2	4	10	R 1.20	R 20.00	R 21.20	40	R 0.84
3	8	5	R 2.40	R 40.00	R 42.40	40	R 1.68
4	16	2.5	R 4.80	R 80.00	R 84.80	40	R 3.36
5	20	2	R 6.00	R 100.00	R 106.00	40	R 4.20

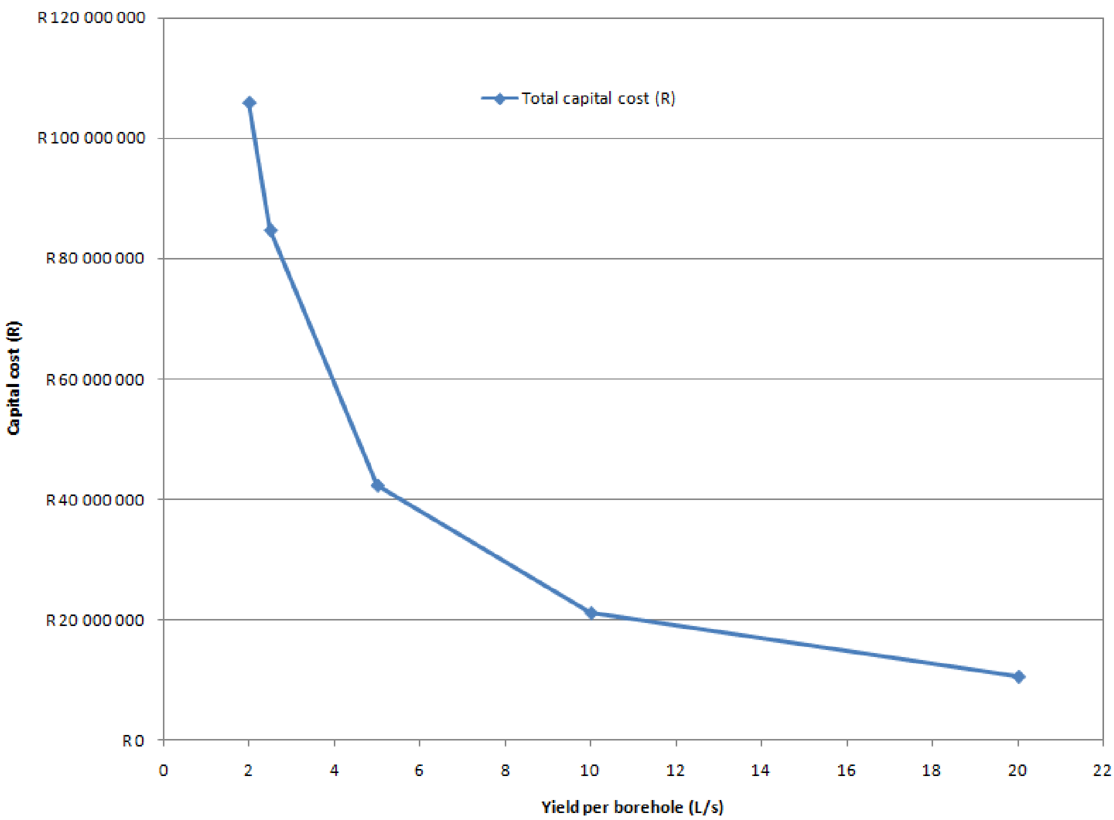

Figure 6-3 Middelburg groundwater development options vs cost.

The problem with the risky approach is that if the analyst is wrong, then the groundwater resource could be depleted but at a low infra-structure cost at R10.6 million. The problem with the risk-averse approach is that if the analyst is wrong and higher abstraction rates were possible then a total of R106 million of tax payers money was unnecessarily spent. If the middle road is taken, then groundwater can be supplied at around R 45 million. The interest of the alternative of R300 million would amount to around R 30 million per year. The payback on the groundwater option would be 1.5 or in the worst case 3 years, which is a good financial option.

By considering a systems approach to sustainable groundwater development and management, this problem could be overcome (Sterman, 2002). In systems theory, it is known that a problem can be exacerbated if the interactions between sub-systems are not understood (Sterman, 2002). If water is used liberally and leaks in the system are the main problem, then provision of more water would lead to more losses in the system.

With a systems approach, the water supply problem is considered as different but inter-dependant components and does not only consider groundwater and the environment but also economics. The problem is differentiated in terms of spatial and temporal components (**Figure 6-4**).

Figure 6-4 Systems approach to sustainable groundwater development and management at Middelburg (40 L/s at 5 L/s/borehole = 8 boreholes).

With this approach, the aquifer is developed at an initial solution that is expected to be near-optimal, but on the higher risk and lower cost side of the curve (**Figure 6-5**). It is accepted that recharge, aquifer boundaries, geological interactions and storativity is unknown and that conservative qualified calculations and estimations were used to determine the *initial conditions* for abstraction. This would entail using a slightly higher initial abstraction rate for the boreholes that were tested.

The approach entails that according to level of understanding or knowledge, there are 3 different aquifer types at Middelburg:

1. Existing aquifer with long term monitoring of water levels and abstraction rates. High level of information/knowledge and confidence. It is known that over-abstraction takes place.
2. New aquifers that were evaluated in terms of potential based on the *minimum groundwater balance* approach and where drilling and testing were done. The actual recharge, storativity and long term groundwater behaviour is unknown and can only be determined through monitoring.
3. New aquifers that were evaluated in terms of potential based on the minimum groundwater balance approach and where no drilling and testing were done. The groundwater potential indicates that it could be viable future options for groundwater development. The papers evaluated in this investigation that condemn the groundwater balance approach, deny the opportunity to follow this step. This is due to the fact that practical and economic considerations are not considered (Bredehoeft et al, 1982; Devlin and Sophocleous, 2005 and Seward et al, 2006).

The systems approach would be as follows:

1. The aquifer would initially be operated at a near-optimal solution that is on the medium to high risk and medium to low cost side of the curve – for a limited period of time (**Figure 6-5**).
    a. The time limit for the recommended abstraction rates would be 1 to 2 years.
    b. In the case of Middelburg, it would be illustratively - to abstract 5 boreholes at 8 L/s each to obtain 40 L/s.
    c. Monitoring is done (using automated systems) to prove the sustainability of the abstraction rates in the mean time.

2. If the abstraction rates are sustainable, then no unnecessary costs were incurred and the system can continue to operate on recommended abstraction rates. If not, the next one or two aquifer areas can be developed well in advance (1 to 2 years). The monitoring will be used as early warning systems to pre-detect excessive decline in groundwater heads with time before it can occur.
3. The abstraction rates at the initial two aquifers can be reduced that allow recovery once the third and fourth aquifers are online.
4. The same process can be re-iterated until the optimal (i.e. sustainable) solution is found.

By following this approach, the sustainable groundwater situation can be obtained iteratively with time without incurring undue high costs from the start.

d. Middelburg groundwater development and management plan

The sustainability of groundwater at Middelburg will depend on how the resources are developed and managed. A phased groundwater development and management plan was compiled based on a systems approach for sustainable management (Section c). The purpose of the management plan is not to manage a single aquifer so that a decline in water levels would never occur, but rather the collective management of all the aquifers for a cumulative sustainable supply. The sustainable management plan also accounts for the economics of the resource development and aim to prevent over-expenditure due to a risk-averse approach (**Table 6-2**, **Figure 6-6**).

Automated monitoring and control of abstraction rates, with water levels, rainfall and water quality (manual sampling) must be done to determine the system behavior is developed so that it builds confidence.

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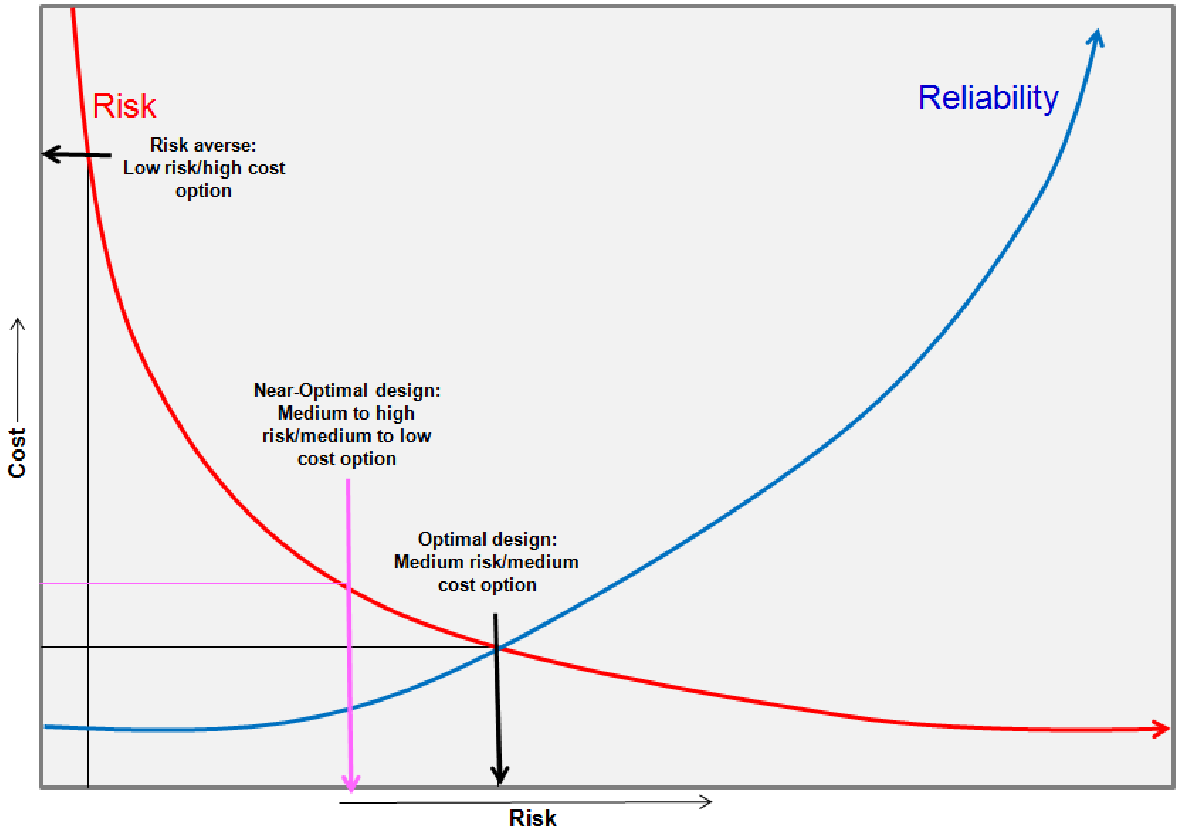

Figure 6-5 Risk-cost and reliability relationship with expected near optimal solution.

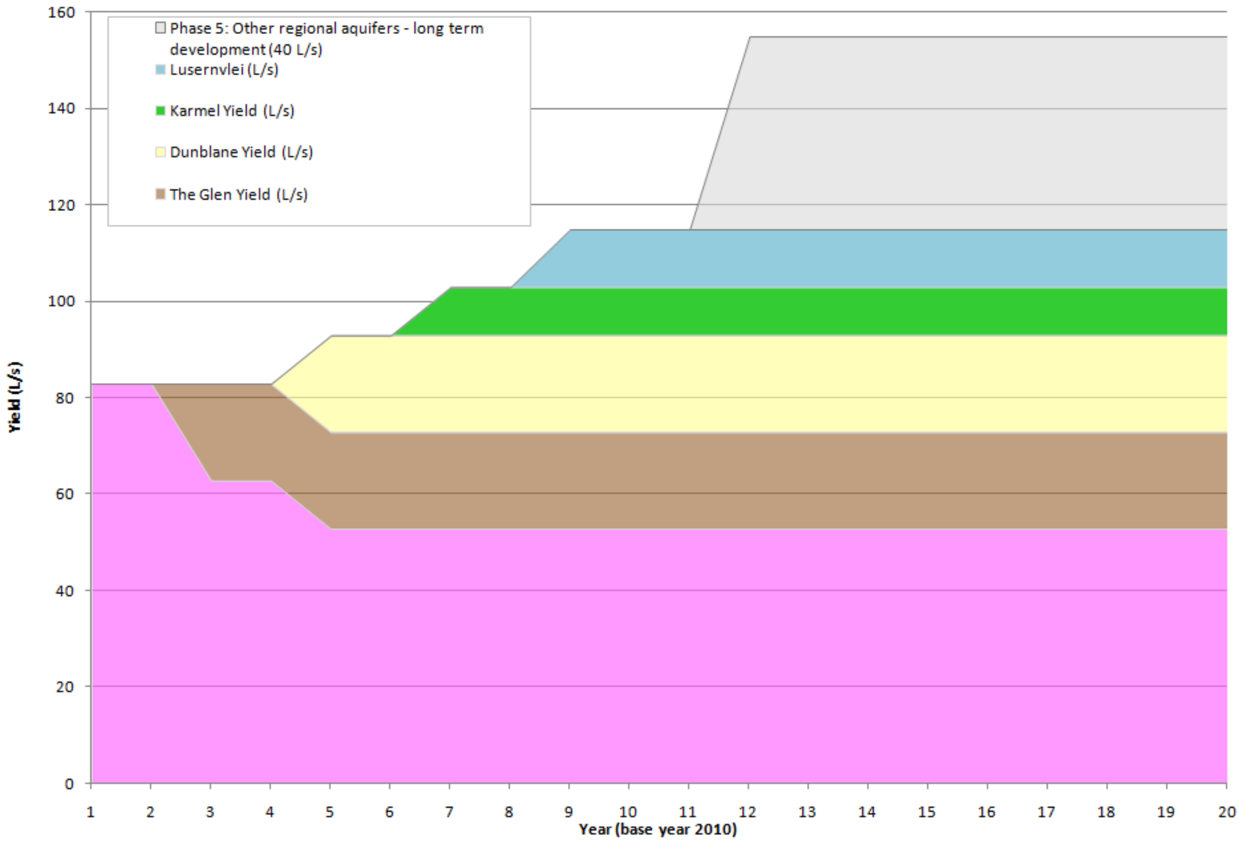

Figure 6-6 Middelburg groundwater development and management phases with yield.

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Table 6-2 Middelburg groundwater development and management plan.

0	**Phase 0: Base case: Existing Municipal Aquifer abstracting at 83 L/s**																				
0.1	Continue abstraction at existing Municipal Aquifer at 83 L/s for a period of 1-2 years until the new aquifer systems are activated																				
0.2	Reduce the abstraction at the existing Municipal Aquifer from 83 L/s to 63 L/s (25% reduction from current status). This should also allow the aquifer to recover to within the next 3-8 years																				
0.3	Reduce the abstraction at the existing Municipal Aquifer from 63 L/s to 53 L/s (35% reduction from current status). This should also allow the aquifer to recover to within the next 3-8 years																				
	Municipal Aquifer Yield (L/s)	83	83	63	63	53	53	53	53	53	53	53	53	53	53	53	53	53	53	53	53
1	**Phase 1: Development of The Glen Aquifer (103 L/s total supply)**																				
1.1	Abstract for 1-2 years while monitoring																				
1.2	Adust after 1 or 2 years if required																				
1.3	Continue monitoring and re-adjust if required																				
	The Glen Yield (L/s)			20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
2	**Phase 2: Development of Dunblane Aquifer and reduction of Municipal Aquifer (103 L/s)**																				
2.1	Develop Dunblane Aquifer for 15 L/s and monitor for a period of 1-2 years																				
2.3	Continue monitoring and re-adjust if required																				
	Dunblane Yield (L/s)					20	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
3	**Phase 3: Development of Karmel Aquifer and reduction of Municipal Aquifer (103 L/s)**																				
3.1	Develop Karmel Aquifer for 10 L/s and monitoring for a period of 1-2 years																				
	Karmel Yield (L/s)							10	10	10	10	10	10	10	10	10	10	10	10	10	10
4	**Phase 4: Development of Lusernvlei Aquifer (123 L/s)**																				
4.1	Develop Lusernvlei Aquifer for 12 L/s and monitor for 1-2 years																				
4.2	Continue monitoring an re-adjust of required																				
	Lusernvlei (L/s)									12	12	12	12	12	12	12	12	12	12	12	12
5	**Phase 5: Other regional aquifers - long term development (40 L/s)**											40	40	40	40	40	40	40	40	40

7 APPENDIX G: PAPER PRESENTED AT GROUNDWATER CONFERENCE

DEEP EXPLORATION DRILLING, GROUNDWATER RESOURCE DEVELOPMENT AND AQUIFER CHARACTERISATION IN MIDDELBURG, EASTERN CAPE

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Abstract

The Karoo town of Middelburg in the Eastern Cape Province is solely dependent on groundwater for water supply, as no large surface water bodies are present in the town's vicinity. Previously (1987) water supply from existing municipal production boreholes was adequate to supply the town, but town growth has now resulted in a water supply shortage. The shallow aquifer with alluvial character currently used as sole source is under severe stress and water levels are declining steadily. Piping water from the Orange-Fish river scheme was considered, but this option was shown to be very expensive (~R 360 million). Instead, regional and deep groundwater potential was investigated. Deep exploration borehole drilling to around 300mbgl was used as discussed in Woodford *et al.* (2002). A detailed GRIP hydrocensus and groundwater sampling was conducted across the study area. A total of 1695 geosites were surveyed. Of 414 boreholes sampled, the water quality of 16% were good, 45% were marginal, 30% were poor and 9% were dangerous. Six sub-catchments were delineated based on hydrogeological principles and groundwater potential. For each sub-catchment a minimum groundwater balance was calculated, based on a 95% assurance level. The Glen, Dunblane, Karmel and Grootfontein sub-catchments were targeted for groundwater exploration based on their favourable groundwater balances. Geophysical surveys comprised magnetic, electromagnetic and electrical resistivity profiling to determine the orientation of dolerite intrusions. Drilling targets were mainly deep fracturing associated with dolerite ring structures and dyke intrusions. The 18 new boreholes drilled using rotary air-percussion and water-hammer drilling techniques delivered an accumulated airlift yield in excess of 187ℓ/s with the deepest strike at 236mbgl. Aquifer tests were conducted and aquifer parameters were calculated using the Constant Discharge test data and applying the Cooper-Jacob-, FC- and derivative equations. A total of 26 pumping tests were performed on selected new and existing boreholes. An accumulated sustainable yield was calculated to be approximately 80 ℓ/s. Water balance and aquifer parameters were compared with modelling results obtained from numerical modelling using. The shallow Middelburg aquifer has excellent geohydrological properties. Production boreholes were historically developed in too close proximity to each other, resulting in the local aquifer being stressed beyond its capacity. Significant losses occur in the water reticulation network associated with the RDP housing. The key during new groundwater resource development is a wider borehole distribution and monitoring network and the exploration and development of deeper boreholes associated with fracturing within and adjacent to dolerite ring structures. Results predict a connection between the shallow and deep aquifers. The optimised use of shallow aquifers, combined with monitoring and the use of newly developed deep regional boreholes will ensure a more sustainable groundwater supply to Middelburg.

1. INTRODUCTION

Middelburg is a Karoo town situated in the the north-western parts of the Eastern Cape Province and has a population of approximately 50 000 people. It is also, like many other Karoo towns, dependent on groundwater as its sole source for water supply, as no large surface water bodies exist in the vicinity of the town. Previously (1987) water supply from existing municipal production boreholes was adequate to supply the town, but in more recent years town growth has resulted in a water supply shortage. The shallow aquifer with alluvial character currently used as sole source is under stress and water levels are declining steadily. Piping water from the Orange-Fish river scheme was considered, but this option was shown to be very expensive (~R 360 million). Instead, the more regional and deep groundwater potential in and around the Middelburg town was investigated. Deep exploration borehole drilling to around 300mbgl was to be performed as discussed in Woodford et al. (2002). The regional and deep approach was chosen in order to move away from the concentrated abstraction occurring in the immediate vicinity of Middelburg, and target the deeper fractured rock aquifer water strikes to increase the sustainability of the groundwater resources.

2. GEOHYDROLOGICAL OVERVIEW

3. Geology

The Middelburg study area is primarily underlain by sedimentary rocks. Igneous rocks, mostly dolerite, make up the subordinate component of rocks in the study area (Council for Geoscience SA, 2004: IV). Few metamorphic rocks are present in the study area; their occurrence is limited to contact metamormphism zones between the dolerite intrusions and the sedimentary country rock. The sedimentary rocks of the study area belong to the Karoo Supergroup sequence of sedimentary rocks which underlie approximately 50% of the surface area of South Africa (Woodford *et al.*, 2002: 1).

Only formations of the Beaufort Group of the Karoo Supergroup occur in the study area. The two subgroups that are present are the Adelaide- and Tarkastad Subgroups. Due to an absence of marker horizons in the Adelaide Subgroup in the study area, this subgroup has not been differentiated into its component formations. The Permian aged Adelaide Subgroup consists of mudstone with subordinate sandstone (Council for Geoscience, 1996; Council for Geoscience, 2004). The Tarkastad Subgroup is of Triassic age (240-248 Ma) and it is only the Katberg Formation of this Subgroup, which is present in the study area (Council for Geoscience, 1996). The Katberg Formation is sandstone rich with subordinate red and greenish-grey mudstone (Council for Geoscience, 2004).

The igneous rocks in the study area were formed when magma intruded the Karoo sedimentary rocks and extruded onto the surface during a period of intense magmatic activity presumably related to the tectonic movement and break-up of Gondwanaland (Botha *et al.*, 1998; Woodford *et al*., 2002). This period of volcanism also created a very large number of hypabassal dolerite dyke and sill intrusions that outcrop in an area equivalent to almost two-thirds of South Africa (Woodford *et al*., 2002).

The valley-fill alluvium found in the study area is generally made up of cyclic units of coarse-grained, reddish sand with scattered pebbles, grading upward into clay (Cole *et al*., 2004). The alluvial deposits found on the pediplain are primarily associated with well-established drainage systems and are mainly comprised of medium- to fine-grained sand (Cole *et al*., 2004). Pebbles of up to 30mm in diameter are found with the coarser grained sand. Calcrete was also quite common in the upper one to one and a half metres of the coarse-grained pediment alluvium profiles surveyed by Cole *et al.* (2004).Valley alluvium is believed to have been formed from cut-and-fill processes and was deposited by steep, swiftly flowing mountain streams.

No faulting was observed in the study area during field investigations and no faulting is indicated on the 1: 250 000 geology map and explanation for Middelburg in the Eastern Cape province. The geology for the Middelburg study area is presented in Figure 10.

4. Hydrogeology

In the explanation to the Middelburg Geological map Cole *et al.* (2004) characterised the Beaufort Group as having a virtual absence of primary porosity and permeability, while its geometry is further complicated by changes in lateral facies. According to Cole *et al.* (2004) frequent recharge to the Beaufort Group is critical for the lifespan of a borehole situated in the non-fractured, unweathered part of the formations. If the Beaufort Group is uninfluenced by alluvium or fracturing, but weathered to 20 or 30 m, borehole yields in the order of 0,5 to 1,0 ℓ/s can be expected if the aquifer is recharged frequently (Cole *et al*., 2004). Weathering of the top part of Beaufort Group formations increases the aquifer's yielding ability and where the upper part of the formation is weathered and the lower unweathered part of the formation is fractured, potentially high yielding aquifers develop. The dominant type of weathering found in the Beaufort Group in the study area is chemical weathering.

The larger part of the study area is underlain by the Katberg Formation of which up to 90 % is quartzite sandstone. Both the effective primary porosity and permeability of the sandstone is much better than that of siltstone or mudstone and fractured sandstone aquifers are normally good aquifers. The Katberg Formation is however limited in thickness in the study area, but where fractured it can create good shallow aquifers.

A smaller southern part of the Middelburg study area is directly underlain by the Adelaide Subgroup consisting of mudrock and subordinate sandstone. When considering groundwater exploration it must be remembered that although the Katberg Formation of the Beaufort Group covers a larger surface area in the study area, it again is underlain by a much thicker succession of units from the Adelaide Subgroup, and at reasonable depth they will form the primary groundwater reservoir if dolerite is absent. The effective primary porosity and permeability of the predominantly mudstone Adelaide Subgroup does generally not create as good an aquifer as would the Katberg predominantly sandstone aquifer. This was important information to the Middelburg groundwater investigation and directly influenced deeper borehole yields.

To date, extensive groundwater resource development has not been conducted on dolerite sill- and ring-complexes. Woodford *et al.* (2002) states the reasons for overlooking these structures are due to their size, thickness, rock hardness and structural complexity.

Results from exploration drilling projects on a few ring structures in the Karoo have provided useful information regarding hydrogeologically significant zones within the dolerite ring and sill complexes. As reviewed in Woodford et al. (2002) open water-bearing fractures are formed at specific locations within the dolerite and surrounding country rock. Such locations are:

- at the junction between the feeder dyke/ inclined sheet and a sill,
- in the sediment above an up-stepping hill or
- at the base of an inner-sill.

At the first location mentioned, fracturing is very localised. In the sediment above an up-stepping hill or at the base of an inner-sill open and shear fractures can extend for some distance into the country rock from the dolerite/country rock contact (Woodford et al., 2002).

During the comprehensive geohydrological investigation conducted in Middelburg, Eastern Cape by Vandoolaeghe (1979) as described in Woodford et al. (2002) and Cole et al., (2004), high yields (up to 50ℓ/s) were obtained in the lower-contact of an inclined-sheet which is part of the Matjieskloof ring-complex.

The three zones identified above occur at depths of 200 to 350 mbgl and represent challenging targets that would require deeper than normal drilling (Woodford et al., 2002).

Dolerite dykes as linear intrusion structures create a thin linear zone of relatively higher permeability along their strikes that act as conduits for groundwater flow within the aquifer (Woodford et al., 2002). Van Wyk (1963) states in Woodford *et al.* (2002) that the high permeability encountered in dyke contact zones results from shrinkage joints developed during the cooling of the intrusion. There are numerous dykes within the study area boundary outside of the close proximity of the municipal boreholes that were considered promising targets.

The most prominent dyke in the Middelburg study area is undoubtedly the Dunblane dyke, and it is a typical example of a dyke that has been transgressed by a fracture. The fracture transgresses the 20m thick Dunblane dyke and has been reported to extend up to 90 m away from the dyke into the country rock (Woodford *et al.*, 2002). Transgressive fractures typically form near the surface, where advanced stages of weathering have already taken place (Woodford *et al.*, 2002).

In the Explanation of the Geological Map of Middelburg 3124, Cole *et al.* (2004) noted that the E-W dykes commonly display an En-échelon pattern. The hydrogeological significance of the En-échelon dyke formations is the vertical offsets that occur due to lateral displacement which is associated with intense fracturing and also high yields (Woodford *et al.*, 2002)

The largest part of the Middelburg study area is covered by unconsolidated sediments, primarily alluvium and secondarily calcrete. From the types of aquifers found within the study area, unconsolidated sediment porous aquifers form arguably the best aquifers. The large amounts of alluvium found in the study area have a very high effective porosity and permeability. Unfortunately, these are also the aquifers that have been exploited to a large extent within the direct vicinity of the Middelburg town and are also exploited regionally in some areas by the farmers for irrigation. According to Vandoolaeghe (1979) from his geohydrological investigations in the Middelburg study area, the boreholes with the highest yields are located along the Klein Brak River and its tributaries in the alluvial valleys where they tap the shallow porous aquifer. Boreholes successfully targeting alluvial aquifers with a reasonable thickness (>20m) and larger lateral extent can yield groundwater in excess of 5ℓ/s on a 12-hour duty cycle.

5. PREVIOUS STUDIES: GEOHYDROLOGICAL INVESTIGATION FOR MIDDELBURG CAPE PROVINCE, VANDOOLAEGHE(1979)

Vandoolaeghe (1979) conducted a detailed geohydrological investigation for the Middelburg town and immediate surrounds in order to provide information on the available groundwater resources to the Middelburg town council, who envisaged expansion of the town primarily through industrial development.

The study area used for the Vandoolaeghe (1979) investigation was the catchment of the Klein-Brak River and its tributaries around Middelburg. The investigation involved site characterisation, borehole survey (hydrocensus), geophysics, drilling, aquifer and water quality testing, a water balance and a full set of recommendations and conclusions. Vandoolaeghe (1979) noted that there were strong indications of a significant alluvial/weathered zone aquifer and used geophysics and the electrical resistivity method to determine the geometry of the alluvial reservoir and create an isopach map for the alluvial aquifer in the area investigated. Magnetic geophysics was used to site boreholes on dolerite dykes to study these intrusive structures during the 1979 investigation. A total of 81 boreholes (39 Exploration and 42 observation) were drilled for groundwater exploration, alluvial depth mapping as well as for observation boreholes at 9 test sites for detailed site characterisation.

Vandoolaeghe (1979) also calculated a groundwater balance estimate during his geohydrological investigation to get an idea of the volumes of groundwater involved. Most of the information used for his water balance was obtained during the borehole survey. The surface area of the Klein-Brak River catchment was used as 1740 km^2, with a MAP of 356 mm/a (Vandoolaeghe, 1979:95). An infiltration figure of 4% was used resulting in a recharge volume of 2,48 x 10^7 m^3/a that could reach the aquifer(s). The western valley was delineated as a sub-catchment and its water balance calculated with more detail. A 7% infiltration figure was used for the mountainous areas while a 2% infiltration rate was used for the valley parts of the compartment. The conclusion reached on the water balance estimate during the 1979 investigation was that during years with average rainfall the resulting balance would be a gain in the groundwater volume in the order of 10^6 m^3/ a (Vandoolaeghe, 1979: 95).The Vandoolaeghe investigation also provided some insight into what the water levels were during 1979 compared to present water levels for the area and the water level decline could be calculated.

6. HISTORICAL WATER LEVELS & MUNICIPAL ABSTRACTION RATES

Historical time series water levels available for the Middelburg study area were obtained from the Department of Water Affairs (DWA) technical operations office in Cradock with the earliest monitoring data spanning from 1959 until present. The records were obtained in order to confirm reports of recent water shortages and water level decline. The data shows an overall water level decline with certain areas such as the Matjieskloof well field showing a sharper decline in water levels than others (Figure 76 shows the water level of an observation borehole close to 3 of the municipal abstraction boreholes). Abstraction data of the Middelburg municipality was also obtained for the time period 2001 to 2006 when abstraction volumes were recorded. The abstraction rates correlate with the water levels and show that with the declining water levels came a decline in volumes that could be abstracted.

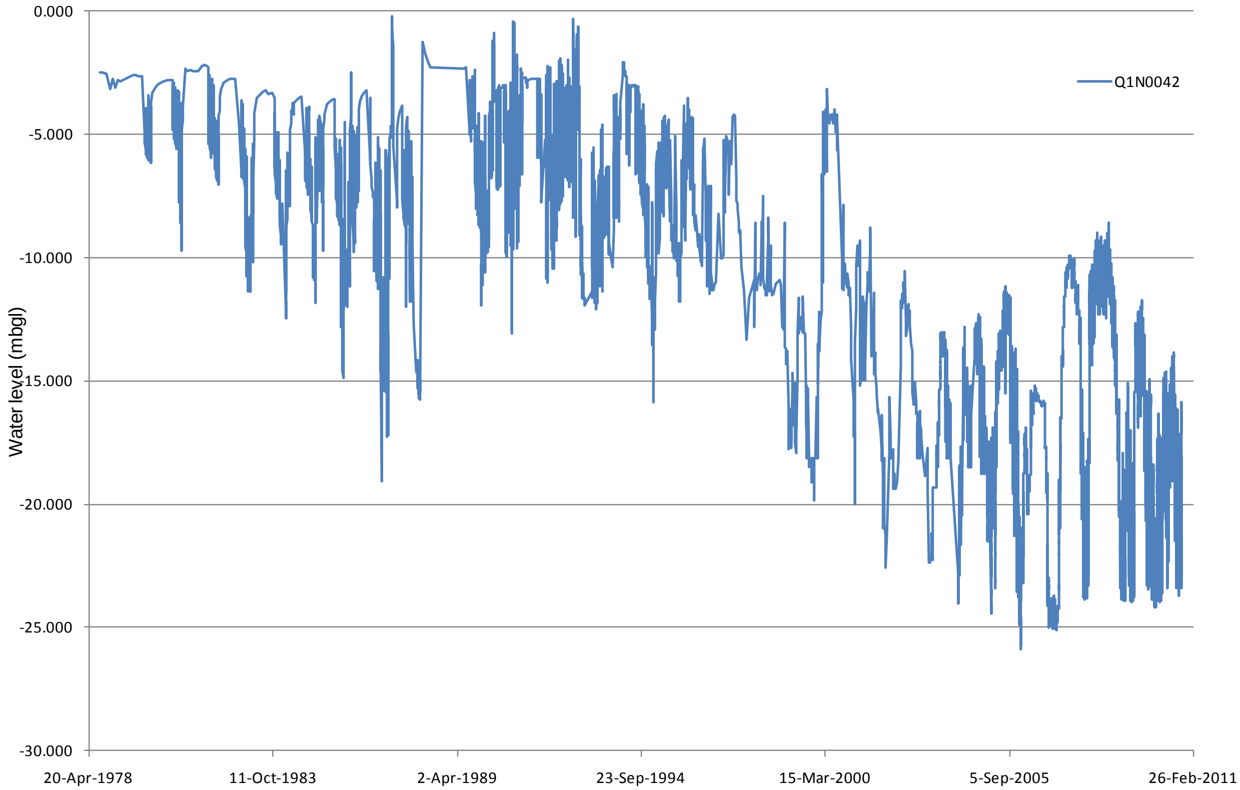

Figure 7. Water level over time for monitoring borehole Q1N0042 at Matjieskloof well field

7. HYDROCENSUS & CATCHMENT DELINEATION & WATER QUALITY

8. Hydrocensus

A total of 1695 Geosites were surveyed during the investigation, their coordinates taken and details noted during the Hydrocensus. Initially the Hydrocensus for the investigation was conducted within a 30km radius around Middelburg as suggested by the DWA. Later the study area boundary was adjusted to the outside farm boundaries of all the farms surveyed during the hydrocensus and the study area covered a total surface area of 2968km^2. The geosites included 1616 boreholes, 45 springs and 25 Geosites of the shallow dug well type. The shallow dug wells that are present in the study area provide evidence that there was at some point in time a very shallow water level in the Middelburg vicinity. These dug wells were noted during the hydrocensus to be located close to the Klein-Brak River and its tributaries, where turbine or shallow submersible installations are used by farmers for irrigation.

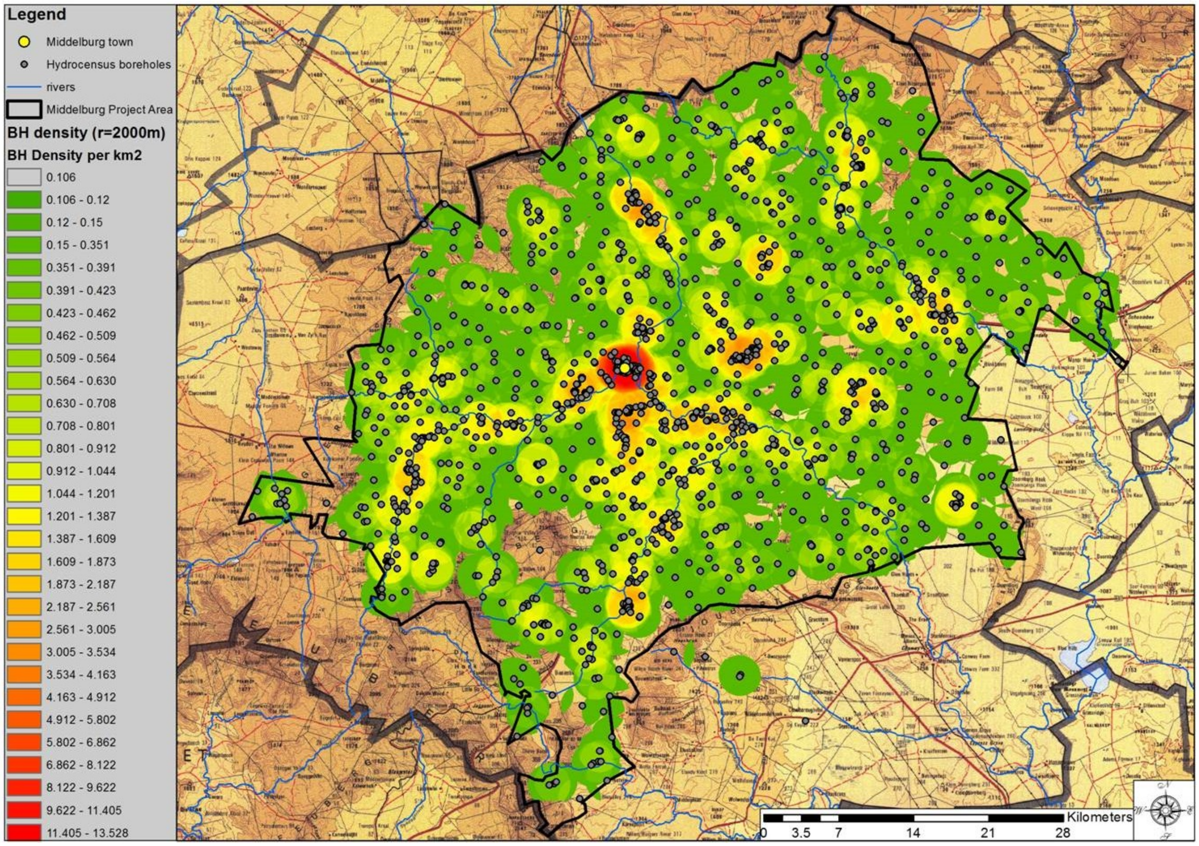

Figure 8. Boreholes surveyed during Middelburg GRIP Hydrocensus with borehole density raster

A borehole database was compiled and data cleaning was performed to ensure accuracy of the dataset. Only 3 records were removed due to gaps in these records and the Middelburg borehole database finally had 1692 records. Borehole statistics were performed based on the attributes of the borehole database. A total of 1037 boreholes (61%) within the study area are in use, 568 boreholes are unused (34%) and 87 boreholes surveyed are destroyed (5%). From the borehole installation types surveyed in the study area there were 774 wind pumps, 250 submersible pumps, 61mono type pumps, 19 Centrifugal pumps, 19 solar pumps and16 turbine pumps with the rest being other installation types such as water level recorders. Many of the private boreholes in Middelburg itself had submersible installations, again contributing to the concentrated groundwater abstraction taking place in the immediate vicinity of Middelburg.

The Hydrocensus was also conducted in a comprehensive way in order to obtain relevant information of the current groundwater use and abstraction volumes so that the information can be used to calculate a more accurate final groundwater balance. This will in turn show, which areas are over exploited and do not warrant further groundwater exploration and which areas have a large recharge component and small abstraction component.

Water levels in boreholes and dug wells were measured where possible in order to determine a hydraulic head distribution across the study area. After data cleaning was performed on the database, a total of 888 water levels were measured and could be used for interpretation. The study area had a minimum water level of 0,0 metres below ground level(mbgl), i.e. artesian and a maximum depth water level of 51,43mbgl. An average water level of 10,48mbgl was calculated for the study area. The 888 water levels were relayed back to metres above mean sea level (mamsl) and interpolated using the Kriging interpolation method as it was found to produce the most representative contours given the type of dataset (Figure 78).

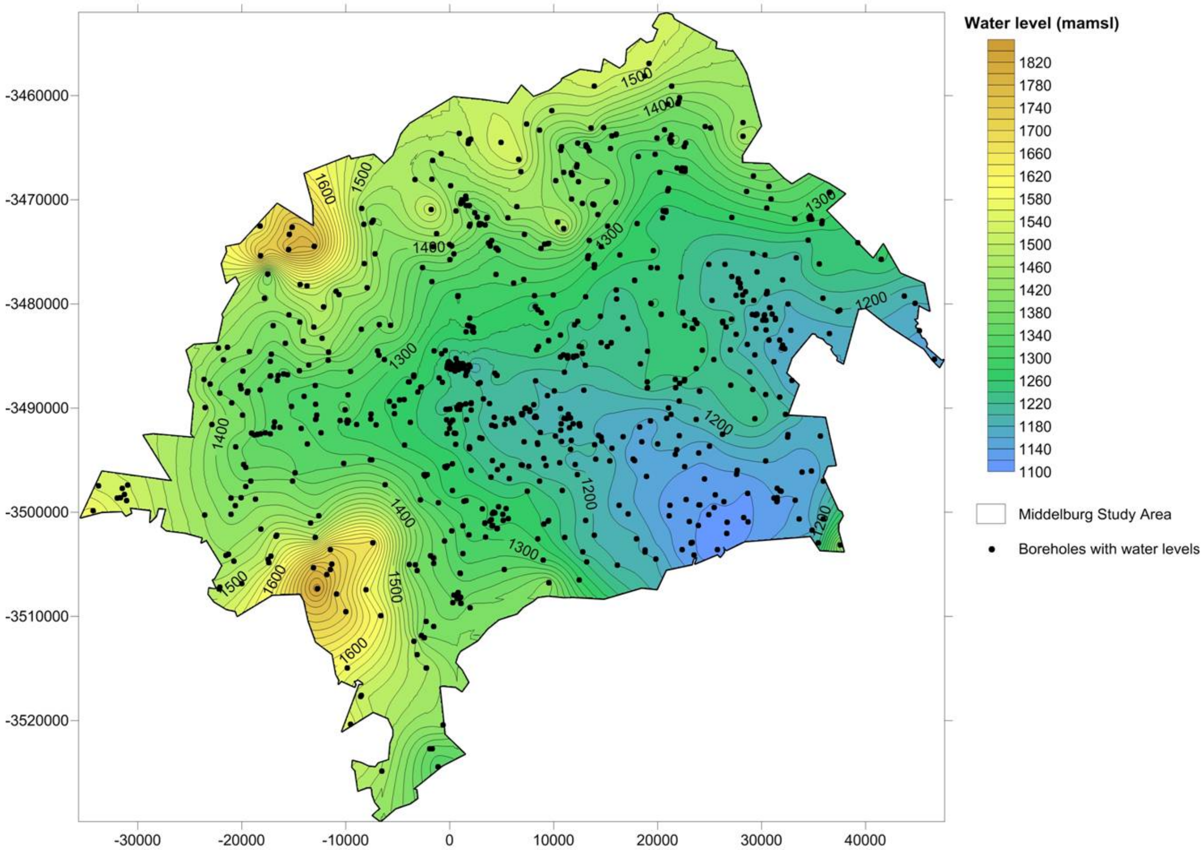

Figure 9. Water level contour map interpolated from 885 borehole water levels obtained in Hydrocensus

9. Water quality

During the hydrocensus, samples of the groundwater were also taken where an open and running stream of water was available for sampling of the borehole. The water quality sampling and analysis was conducted in order to rule out areas where unacceptably poor water quality was present and areas where groundwater exploration would not be feasible for penultimate water supply to Middelburg, due to high water treatment costs associated with these areas. A Total of 416 boreholes were sampled during the hydrocensus, their hydro-chemistries analysed and their results interpreted according to the DWA Minimum standards and guidelines. The samples were analysed at a SANAS accredited laboratory for microbiological and macro element constituents. After data cleaning and quality checking was complete a final database with 404 borehole sample results was used for representing water quality results and in performing statistical analysis. The water quality of the Middelburg study area is predominantly of a DWAF Class 2(Marginal) water quality type. Of the 404 borehole water qualities sampled; 64 boreholes (16%) were Class 1 (Good), 186 boreholes (46%) were Class 2 (Marginal), 118 boreholes (29%) were Class 3 (Poor) and 35 boreholes (9%) were Class 4 (Unacceptable) water quality.

10. Sub-catchment delineation

Sub-catchments were delineated around dolerite sill- and ring- complex structures as well as prominent dykes that represent good groundwater potential. Watersheds formed by these geomophologically prominent features where used as sub-catchment boundaries. Where important aquifers were located such as the alluvial Municipal aquifer within the Matjieskloof dolerite ring complex, these aquifers were also delineated. Sub-catchments delineated where the Municipal(108km^2)-, Dunblane(286km^2)-, The Glen(108km^2)-, Karmel(82km^2)-, Lusernvlei(124km^2)- and Grootfontein(143km^2)- sub-catchments. The sub-catchments formed the regional groundwater target areas for geophysics and exploration drilling. The sub-catchments were also used as the basic groundwater flow balance units. For each sub-catchment a water balance was calculated using the detailed hydrocensus, water quality, rainfall and surface area information. The geology and delineated sub-catchments are presented in Figure 10.

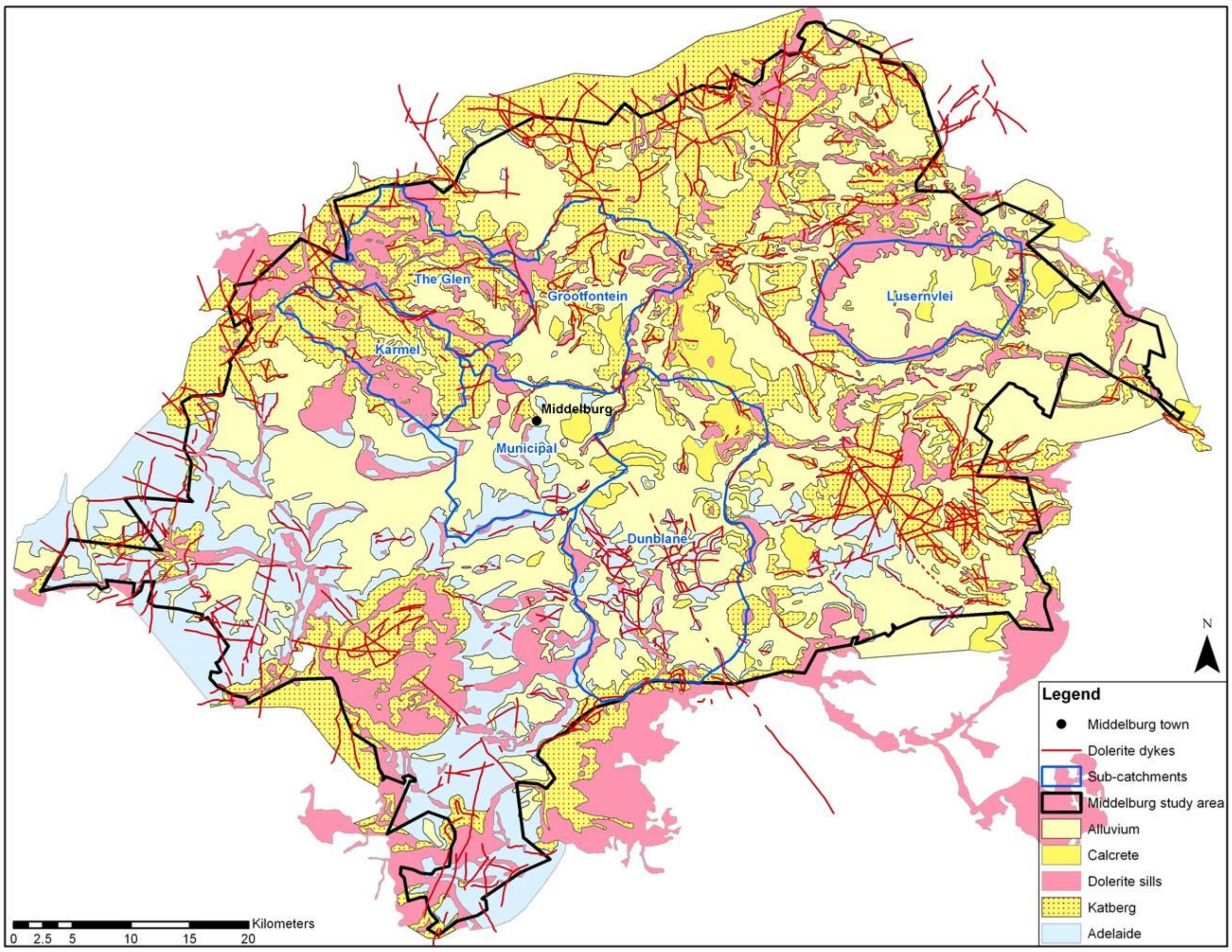

Figure 10. Geological map for the Middelburg study area with delineated sub-catchments

11. Preliminary groundwater balance

A preliminary groundwater flow balance was calculated based on a lower 95% level of assurance rainfall for each sub-catchment. The preliminary nature of the initial water balance was due to the urgency of the drought relief to the town of Middelburg and the need to immediately start with the geophysics and drilling programs. Abstraction rates based on installation type, pump inlet and hours per week were not yet processed and interpreted, as the hydrocensus was not fully complete at the time and regional groundwater abstraction was calculated based on Hydrocensus data available at the time. Accurate abstraction volumes for the Middelburg municipality and residential use were however available and used in the preliminary water balance. The purpose of the groundwater flow balance as mentioned was to calculate a minimum amount of groundwater available in each sub-catchment to identify sub-catchments where groundwater resource development and supply would be sustainable. A groundwater recharge (Re.) estimate was calculated from the chloride method. Based on the rainfall with 95% assurance level, the preliminary groundwater flow balance showed that there is approximately 37 ℓ/s available in the Dunblane sub-catchment (Re. 3,5%), 21 ℓ/s in The Glen sub-catchment (Re. 3,5%) and 22 ℓ/s in the Lusernvlei sub-catchment (Re. 3,5%). The Middelburg municipal sub-catchment (Re. 5%) was shown to have a negative groundwater balance of -37 ℓ/s. Abstraction from the Municipal sub-catchment aquifer amounted to approximately $2{,}5x10^6 m^3/a$.

The preliminary groundwater balance was completed to select and prioritise target areas for geophysics and exploration drilling based on the information available at this early time in the project. The groundwater flow balance was updated close to the end of the project and also to compare the groundwater flow balance with the numerically modelled values for each sub-catchment.

12. GROUNDWATER GEOPHYSICS

Dolerite sill- and ring- complex structures as well as dolerite dykes were identified that showed high groundwater potential from a structural geology, remote sensing and previous investigations point of view. The approach was to look at more regional structures and drill deep boreholes in order to intersect deep fractures that will provide a more sustainable groundwater resource. Groundwater geophysics was performed on these selected structures as the specific groundwater exploration target areas. The magnetic method, Frequency Domain Electro-magnetic (FDEM) method and electrical resistivity method were used to cross-correlate and narrow down areas for the siting of exploration boreholes.

The magnetic method and the use of a Geotron G5 magnetometer was the most commonly used method during the geophysical investigation. Readings from the magnetometer were taken at a 5m station interval. A total of 38 magnetic profiles were completed of the 47 set out lines resulting in a total profiling length of 30 285m. All anomalies in the profiles were noted as well as suspicious readings and anomalies caused by manmade objects and human interference (AGES, 2010).

A Frequency Domain Electromagnetic Method (FDEM) instrument was used for the electro-magnetic profiling of the geophysical investigation across identified structures and formations. Readings were taken at 10m intervals on both 20 and 40m coil spacings depending on the degree of depth penetration required for the geology of an area. A total of 45 traverses were completed and readings taken out of the 47 lines set out resulting in a total profiling length of 32125 m (AGES, 2010).

A Geotron Resistivity instrument was used to also gain an electrical method insight into the subsurface of the identified target areas. A Wenner configuration of the four electrodes was used with an electrode spacing of 40m and 60m respectively. The resistivity process is a tedious process and therefore resistivity profiles were only conducted on 11 of the 47 delineated lines, where a depth profile of the structure was essential. A total profiling length of 3010 m was conducted with a 40m electrode separation and a total profiling length of 2950 m was conducted with a 60 m electrode separation (AGES, 2010).

13. DRILLING

A total of 18 new boreholes were drilled with an accumulated drilling depth of 4025m. The boreholes had a minimum drilling depth of 63mbgl (EC-Q14-1662-Monitoring borehole) and a maximum drilling depth of 298mbgl (EC-Q14-1634-Monitoring borehole). An average borehole drilling depth of 212mbgl was calculated for the drilled boreholes. The total accumulated airlift yield from the boreholes drilled during the project was greater than 186,7 ℓ/s excluding smaller yields. Boreholes that were immediately of interest for aquifer testing were EC-Q14-1631 targeting the Dunblane dyke in the Dublane sub-catchment with an airlift yield of >24,7 ℓ/s; EC-Q14-1636 that was sited on the intersection of the Dunblane dyke and the inclined sheet of The Glen dolerite ring structure delivering a blow yield of 31,4 ℓ/s and EC-Q14-1655 in the Glen, sited on an anomaly close to the inclined sheet of a dolerite ring structure and delivering a constant airlift yield of 21,8 ℓ/s.

14. WATER LEVEL MONITORING NETWORK INSTALLATION

Except for the four boreholes currently being monitored by DWA in the close proximity of the Middelburg well fields, a more regionally spaced groundwater monitoring network was needed in order to evaluate the regional groundwater levels and identify areas/sub-catchments of concern. During December 2008 a total of 12 pressure transducer water level loggers were installed in strategically located boreholes. 2 Real time water level loggers were also installed upstream and downstream of Middelburg in the Municipal sub-catchment. Water level measurements from the downloaded groundwater level logs from the 12 new monitoring boreholes do not show a sharp decline in the water levels given the approximately one and a half years of monitoring in the new monitoring boreholes. There was however a simultaneous sharp pulse decline in 5 of the monitoring boreholes observed around Febuary 2009. It is expected that this was a large simultaneous abstraction event that occurred when all the submersibles in the municipal boreholes were started around the same time. The combined graphs of the new monitoring network water levels are shown in Figure 80.

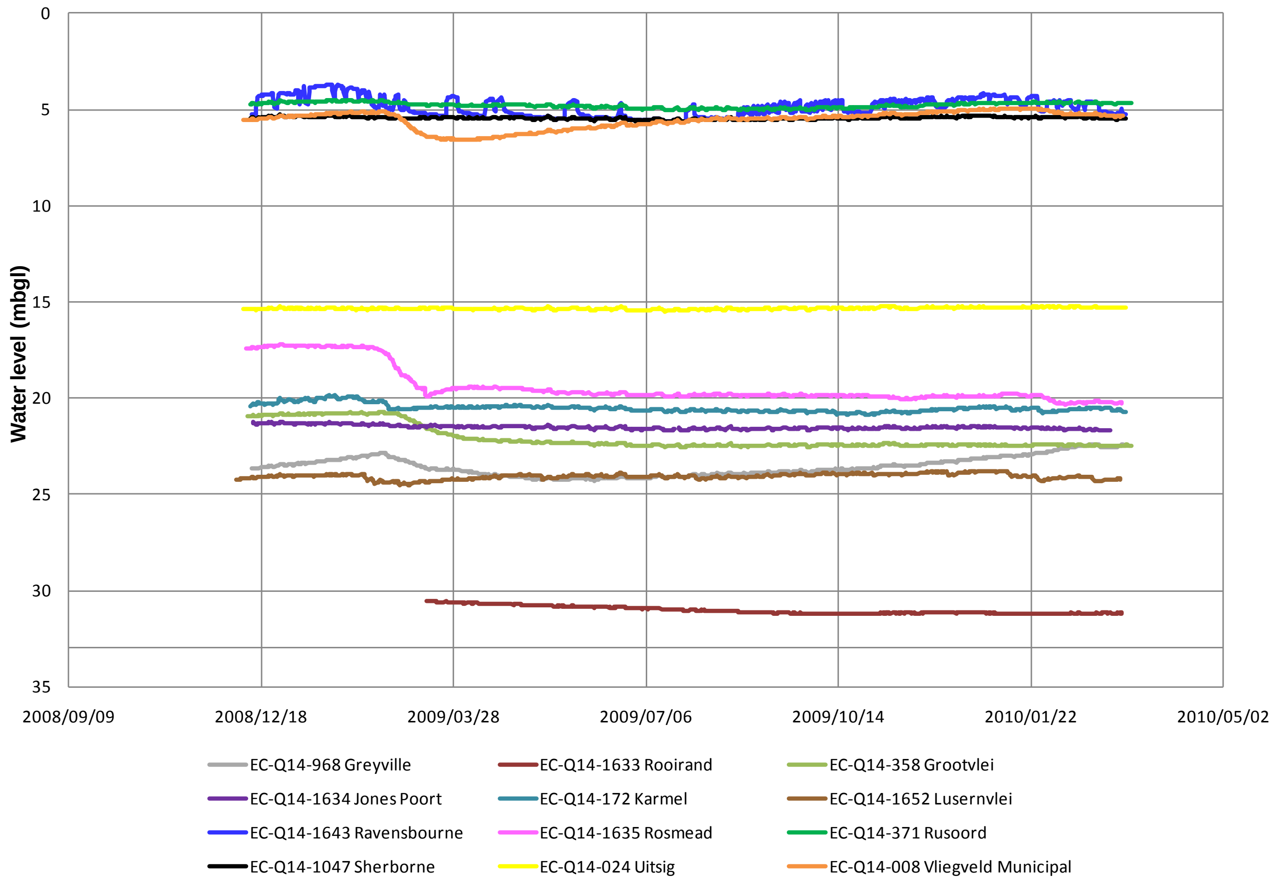

Figure 11. Comparison of water level data from the 12 new monitoring boreholes

15. AQUIFER TESTING & ANALYSIS

Through the hydrocensus as well as through correspondence with the Middelburg municipality and land owners, high yielding existing boreholes were identified for aquifer testing. Most of these boreholes were also unused. Full aquifer tests including Constant Discarge (CD) tests were performed on 17 existing boreholes and on 8 newly drilled exploration boreholes. Both the Flow characteristic (FC) and Cooper-Jacob approximations of the Theis equation were used during pump test analysis to derive aquifer parameters for assured yield recommendations. The aquifer test results for recommended boreholes are given in Table 3 and the aquifer tests analysis and parameters for these boreholes are summarised in Table 4.

With the selected existing and new boreholes aquifer tested and analysed; a maximum accumulated assured yield of approximately 40 ℓ/s can be abstracted from the new boreholes and maximum accumulated assured yield of approximately 43 l/s can be abstracted from the existing boreholes. Unsustainable boreholes, boreholes with low aquifer tested yields and boreholes that were found to have detrimental outer boundary conditions were excluded from the accumulated assured yield calculations. The volume required by the Middelburg town for Phase A drought relief was 20 l/s. Only boreholes that were feasible to be included in the engineering of the Phase A pipeline to the Middelburg town were finally used. Even with the high yields from the aquifer tested boreholes, the GYMR groundwater flow balance volumes of groundwater available in each sub-catchment were used to cap the use of the accumulated assured yields in each sub-catchment.

Table 3. Recommended boreholes information and aquifer test summarized results

BOREHOLE INFORMATION		AQUIFER TEST INFORMATION							
				Constant Rate Test				Recovery Test	
SUB-CATCHMENT/ DRAINAGE	ALLOCATED BOREHOLE NUMBER	Static water level (mbgl)	Borehole depth (m)	Rate (l/s)	Max drawdown (mbgl)	% of Available Drawdown	Duration (min)	%	Duration (min)
Dunblane	EC-Q14-1603	8.68	40.54	20.07	18.16	68.61	1320	94.00	480
Dunblane	EC-Q14-1631	11.10	126.70	17.12	39.29	39.73	2880	90.00	540
Middelburg Municipal	EC-Q14-1632	9.28	236.00	15.50	110.45	57.02	1500	90.81	20
The Glen	EC-Q14-1637	8.46	258.00	20.21	36.04	40.25	2880	90.01	360
The Glen	EC-Q14-1655	9.72	282.00	25.04	5.34	15.6%	2880	90.82	150

Table 4. Aquifer test analysis parameters for selected boreholes

AQUIFER TEST ANALYSIS									
ALLOCATED BOREHOLE NUMBER	FC				Cooper-Jacob				
	Qsust (l/s)	Ave Q sust(l/s)	T early (m2/d)	T late (m2/d)	Qsust (l/s)	Ave Q sust(l/s)	T late (m2/d)	S	Comments
EC-Q14-1603	7.41	3.75	69.08	29.69	8.04	4.18	34.40	1.00E-03	Strong borehole, fractured at depth, good recovery as well
EC-Q14-1631	6.56	3.15	35.11	7.23	9.36	4.86	12.90	1.00E-03	High Yielding Fractured Karoo rock aquifer, 1 no-flow boundary reached
EC-Q14-1632	5.78	2.93	11.88	3.78	7.59	3.95	5.70	1.00E-03	Multiple fractures dewatered, good high yielding fractured rock aquifer, use CJ
EC-Q14-1637	11.17	6.48	42.26	28.19	11.02	5.73	27.30	1.00E-03	Good borehole, good recovery of 90% of water level, dewatering of top 2 m of water level. Recommended 5.5 - 7.5 l/s - Conservative
EC-Q14-1655	15.33	9.56	382.50	321.20	15.52	8.07	310.40	1.00E-03	Borehole influenced by recharge boundary. Composite alluvial and highly fractured aquifer. Only 5m AD used for analysis. Conservative

16. GROUNDWATER CHEMISTRY

Hydrochemical analysis was performed for selected existing boreholes as well as most new boreholes that were considered for water supply to Middelburg. Water quality analysis and groundwater characterisation of existing boreholes that were aquifer tested was performed in order to classify the shallow aquifer system. The water quality of 5 existing boreholes and 10 new boreholes were sampled, analysed and classified. The groundwater was also characterised using a Piper diagram. The water quality of the constituents concentrations were classified according to DWA water quality guidelines. All the boreholes drilled and tested in The Glen sub-catchment/ aquifer have a DWA Class 1(Good) water quality. The new boreholes in the Dunblane sub-catchment had a typical water quality of DWA Class 2 or Class 3 due to elevated concentrations of the constituents; total hardness and magnesium and in two cases elevated fluoride. The water quality of borehole EC-Q14-1653 drilled and tested in the Karmel sub-catchment classified as Class 2 (Marginal water quality), but only due to total coliforms. It is expected that with resampling EC-Q14-1653 will also have a Class 1 water quality. From the existing boreholes that were aquifer- and water quality- tested, 60% of the boreholes had a water quality of Class 3 due to elevated concentrations of the constituents Total coliforms, Total hardness, magnesium and fluoride. 40% of the existing boreholes had a DWA Class 1 Good water quality.

The macro elements and constituents of these existing and new boreholes were plotted on a Tri-linear Piper diagram to identify the different water facies present. Some clear aquifer and groundwater types emerged from the Piper diagram in Figure 81, such as representation of specific aquifers. Boreholes EC-Q14-1634, EC-Q14-1637 and EC-Q14-1655 all fall within The Glen sub-catchment and their similar groundwater type is easily recognisable in Figure 81. The grey open circles represent the existing boreholes that were sampled and from the Piper diagram these boreholes also plot in approximately the same area. The existing boreholes in the shallow aquifer have a relatively even cation distribution with a slightly more dominant Na-HCO_3 character. This confirms the hydrochemistry's ability to identify that the boreholes are all situated in the same groundwater type, the shallow alluvial aquifer.

The hydrochemistry results also have to be seen in the light of the conditions they were sampled under. Borehole EC-Q14-1630 was not pump tested and so the samples were taken during or just after drilling, hence the much higher TDS and other constituent concentrations when compared to other boreholes. The physical breaking of the formations into smaller pieces and sometimes very small pieces of rock particles result in much more exposed rock and dissolvable mineral area.

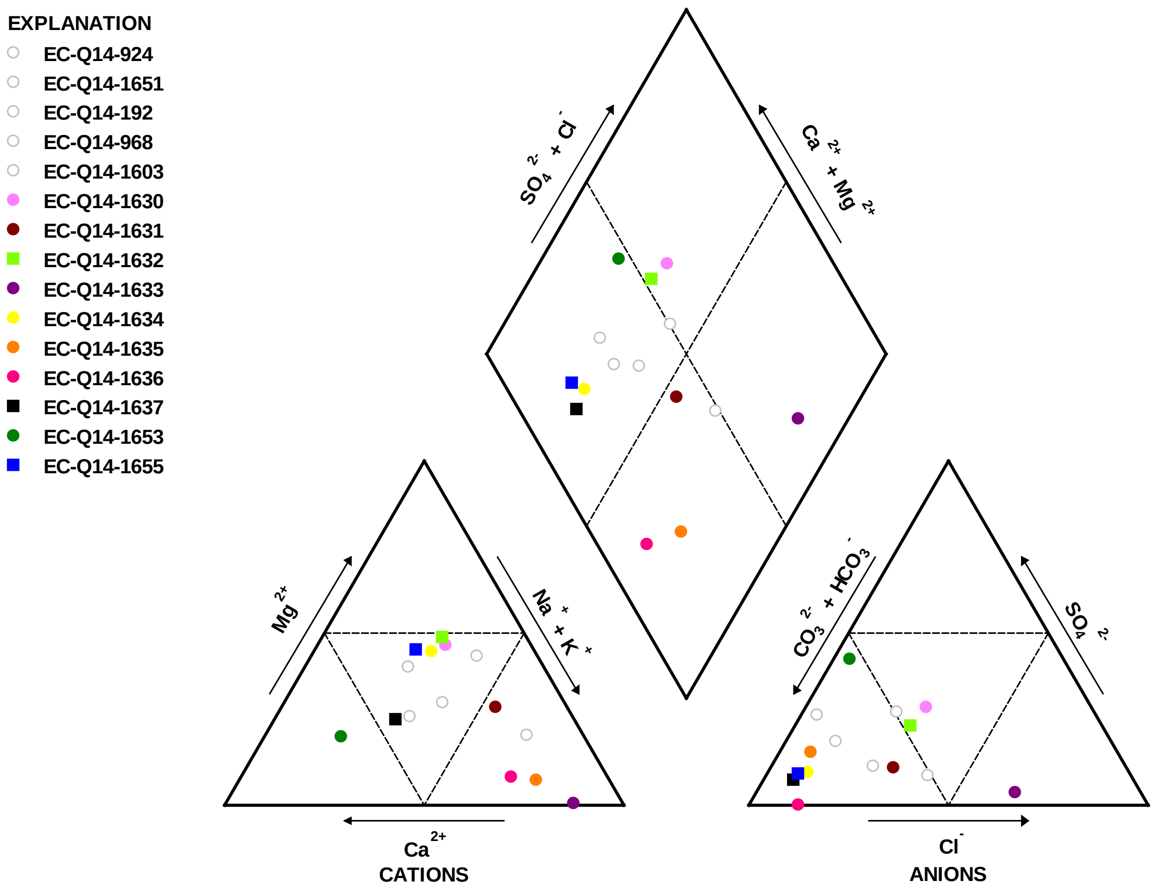

Figure 12. Piper diagram of existing boreholes in grey open circles and the new boreholes described in colour

17. FINAL WATER BALANCE GYMR

The preliminary water balance was updated with completed hydrocensus results as well as information obtained through the course of the investigation to calculate a final groundwater flow balance for the sub-catchments. The groundwater flow balance was compiled in the form of a Groundwater Yield Model for the Reserve (GYMR) as developed by K. Vivier of AGES (AGES, 2010). The water balance was again calculated with a 95% assurance level of rainfall, meaning that the water balance takes a 1in 20 year drought into account. The approach of the GYMR is in short an equation that systematically takes components into account in the order that they would normally participate in, in nature and provides a minimum amount of groundwater available for use after all components have been considered. The final groundwater flow balance for the Middelburg sub-catchments is summarised in Table 5.

With the existing and new boreholes aquifer tested, the accumulated assured yield in each sub-catchment was compared with the available groundwater volumes calculated with the GYMR groundwater flow balance. For pipeline design to augment the water supply of Middelburg, a number of factors were considered including distance of pipeline. The Lusernvlei sub-catchment was then excluded as it was too far from the town reservoirs. Finally, The Glen sub-catchment was chosen for water supply implementation as it has very little existing abstraction and water use in it, a higher groundwarter recharge value due to the mountainous inclined sheet dolerite structures that was confirmed with the chloride concentrations and the new boreholes drilled within it performed very well during aquifer testing. Furthermore, water quality was also very good compared to some of the other boreholes tested that generally had elevated total hardness and magnesium concentrations.

The recent alluvial mapping in the 1: 250 000 geological map of Middelburg 3124 and previous mapping of the alluvium by Vandoolaehe(1979) was used to determine an accurate spatial extent of the alluvial aquifers. The isopach map and borehole log information from Vandoolaeghe (1979) could be used to create a thickness distribution of the alluvial deposits in the GIS. Together with the spatial extent and thickness distribution, a volumetric determination of the alluvial reservoir could be performed in order to obtain an accurate value of the volume of the aquifer given a certain water level. The volume that can be abstracted from the Municipal boreholes without impacting negatively on the aquifer can also be determined accurately given the accurate spatial extent and groundwater recharge to the alluvial aquifer s. With the above information in a water balance, effective and accurate management of the alluvial aquifer is possible as would be possible for any other normal surface water reservoir. This will enable the municipality to better manage the alluvial aquifer in the future, given certain water levels measured.

Table 5. Summarised Middelburg GYMR groundwater flow balance

Sub-catchment	The Glen	Dunblane	Middelburg Municipal	Karmel	Lusernvlei	Grootfontein Compartment
Surface Area (Km2)	108	286	133	82	124	143
MAP (mm/a) WRIMS Data	326.8	326.8	326.8	326.8	326.8	326.8
Recharge Chloride method & calibration (% of MAP)	5.00%	3.50%	3.50%	4.81%	5.00%	5.00%
Rainfall 95% ass. (mm/a)	158.6	158.6	158.6	158.6	158.6	158.6
Recharge (m3/a)	856,278	1,587,286	738,143	627,725	979,224	1,133,776
Basic Human Needs for Reserve [l/p/p/d] (m3/a)	-5475	-10950	-13,300	-5475	-5475	-5475
Number of abstraction boreholes (Other)	6	109	134	6	37	52
Total borehole abstraction (m3/a)	-44,150	-898,305	-2,115,936	-64,266	-411,516	-657,352
Total livestock farm usage (m3/a)	0	-15768	-15768	-15768	-15768	0
Wetlands (Ground water) (km2) (Vlei areas on topo map)	3.00	2.00	1.00	2.00	1.00	3.00
Wetland water use (m3/a)	-750	-500	-250	-500	-250	-750
No of springs	1.0	0.0	0.0	1.0	0.0	1.0
Spring flow (m3/a)	-9,461	0	0	-9,461	0	-270,000
Total inflow (m3/a)	856,278	1,587,286	738,143	627,725	979,224	1,133,826
Total outflow before losses (sinks) m3/a	-59,836	-925,523	-2,145,254	-95,470	-433,009	-933,577
Usable GW component from Base Flow (m3/a)	796,442	661,763	-1,407,111	532,255	546,215	200,248
Usable GW Litres/ second (ℓ/s)	25.3	21.0	-44.6	16.9	17.3	6.3
Potential stressed status % - Total inflow / total outflow	7%	58%	291%	15%	44%	82%

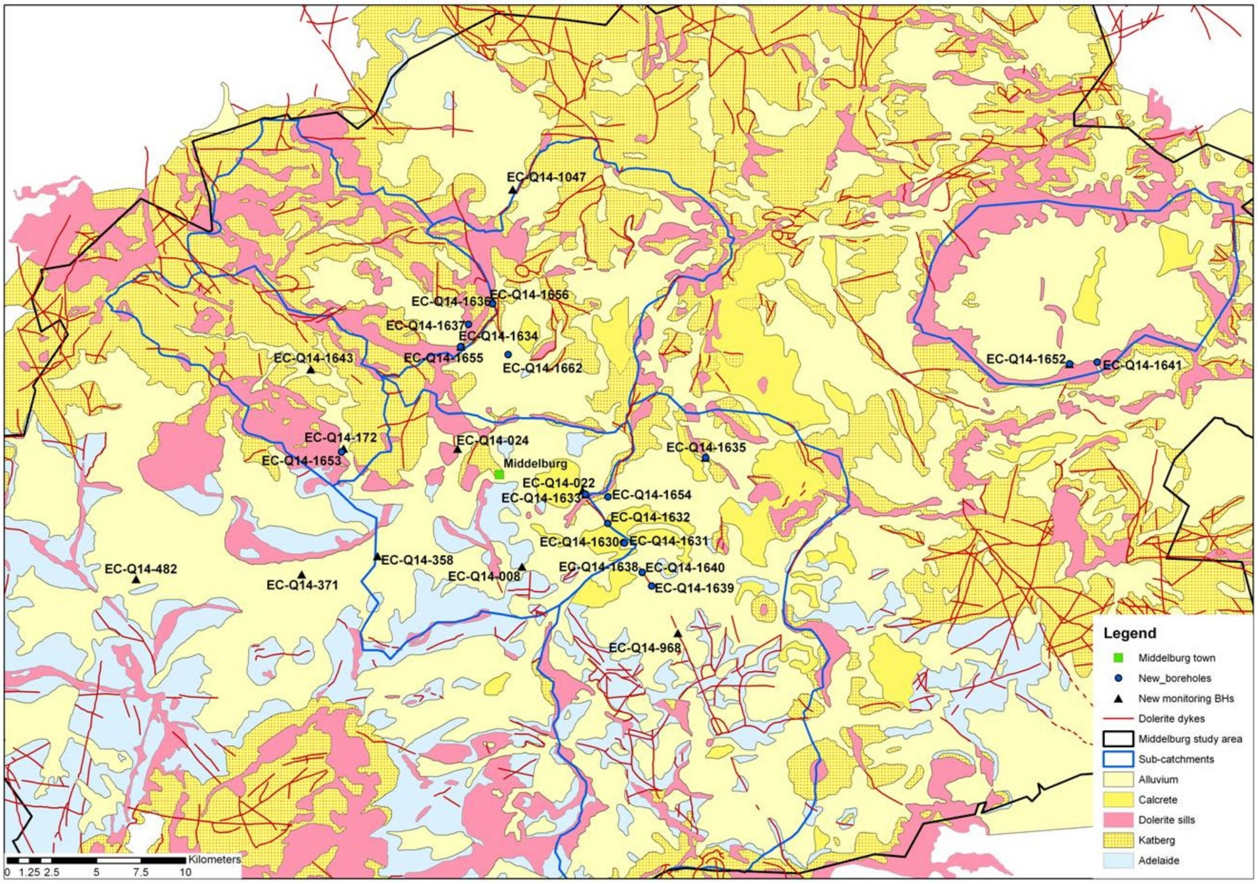

Figure 13. New monitoring and water supply boreholes drilled

18. NUMERICAL MODELLING

Numerical modelling will be performed on each of the sub-catchments as a final and accurate check of the groundwater flow balance volumes obtained. The Numerical model would also give an indication whether the proposed abstraction volumes would be sustainable in the long term. It is expected that the numerical model for each sub-catchment will show a larger volume of water available as the numerical model is based on MAP rainfall and the groundwater flow balance conveys a minimum amount of groundwater available in each sub-catchment. Thus the GYMR groundwater flow balance approach leads to the case that in reality, there will almost always be more groundwater available than what is calculated using the GYMR flow balance and lower risk decision making is possible.

19. CONCLUSIONS

The number of leaking pipes throughout the town and sub-standard valves and other infrastructure fitted to all the low cost houses must be assessed and addressed. Leaking pipes can often amount to 30-40% of water being lost before it reaches the intended water uses. South Africa and especially the Karoo is an arid country and water waste is one of the first aspects that need to be looked at.

The alluvial aquifer is the ideal aquifer in terms of aquifer characteristics and its ability to recover quickly after pumping. It however needs to be managed much more diligently and concentrated abstraction needs to be reduced. Sustainable recommendations for this kind of aquifer need to be adhered to. Proper management of the alluvial aquifer will result in a sustainable groundwater resource and long term water supply to Middelburg.

The key during new groundwater resource development was a regional borehole distribution and monitoring network and the exploration and development of deeper boreholes associated with fracturing within- and adjacent to- dolerite ring structures. The deep boreholes with deeper water strikes result in a larger aquifer thickness and a more sustainable borehole during drought periods. Results predict a connection between the shallow and deep aquifers. The optimised use of shallow aquifers, combined with monitoring and the use of newly developed deep boreholes will ensure a more sustainable groundwater supply to Middelburg.

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