Ground water Dependence of Ecological Sites Located in the Table Mountain Group

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DECLARATION

I declare that this dissertation is my own, unaided work. It is being submitted for the degree of Magister Scientiae in the University of the Free State, Bloemfontein. It has not been submitted before for any degree or examination at any University. I furthermore cede the copyright of this thesis in favour of the University of the Free State.

Signed: ____________________

Dale Barrow

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ABBREVIATIONS

CF	Cango Fault
CFB	Cape Fold Belt
CMWL	Cape Meteoric Water Line
CRC	Cumulative Rainfall Collector
CSIR	Council for Scientific and Industrial Research
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
GEOSS	Geohydrological and Spatial Solutions
GMWL	Global Meteoric Water Line
HRM	Hangklip-Riviersonderend Megafault
ICP-AES	Inductively coupled plasma atomic emission spectroscopy
LMWL	Local Meteoric Water Line
MAP	Mean Annual Precipitation
MWL	Meteoric Water Line
SACS	South African Committee for Stratigraphy
STS	Sensor Technik Sirnach
TMG	Table Mountain Group
TMGA	Table Mountain Group Aquifer
TMGA-EMA	Table Mountain Group Aquifer – Ecohydrological Monitoring Alliance
UCT	University of Cape Town
uPVC	Unplasticised Polyvinyl Chloride
WGS84	Since the 1st January 1999, the official co-ordinate system for South Africa is based on the World Geodetic System 1984 ellipsoid, commonly known as WGS84.
WRC	Water Research Commission

MEASUREMENT UNITS

µg/ℓ	micrograms per litre
C	Celsius
km^3	cubic kilometres
ℓ/s	litres per second
m	metres
m/d	meters per day
m^2/d	square meters per day
mamsl	metres above mean sea level
mbch	metres below collar height
mbgl	metres below ground level
meq/ℓ	milliequivalents per litre
mg/ℓ	milligrams per litre
mm/a	millimetres per annum
mS/m	milliSiemens per meter

PARAMETERS

Ch	collar height
EC	Electrical Conductivity
k	Recession Constant
K	Recession Index
ORP	Oxidation Reduction Potential
Q	Flow Volume
Q_o	Initial flow volume
Q_t	Flow volume at critical time

R	Recharge
t	time
T_c	Critical Time
TD	Total chloride deposition at surface
TDS	Total dissolved solids
WL	Water level
α	cut-off frequency (constant) (also expressed fc)

Al	Aluminium
Alkalinity	M and P alkalinity
As	Arsenic
B	Boron
Ba	Barium
Cl	Chlorine
CO3	Carbonate
Cu	Copper
Fe	Iron
HCO3	Bicarbonate
K	Potassium
Mg	Magnesium
Mn	Manganese
Na	Sodium
NH4N	Nitrite (as N)
Ni	Nickel
NO3N	Nitrate (as N)
P	Phosphorous
Si	Silica

SO4	Sulphate
Sr	Strontium
Zn	Zinc

GLOSSARY OF TERMS

Aquifer: A geological formation, which has structures or textures that hold water or permit appreciable water movement through them [from National Water Act (Act No. 36 of 1998)].

Aquitard: A saturated low permeability unit that can restrict the movement of ground water. It may be able to store ground water (DWA, 2010).

Arenaceous: Resembling, derived from, or containing sand.

Argillaceous: Containing, made of, or resembling clay; clayey.

Borehole: Includes a well, excavation, or any other artificially constructed or improved ground water cavity which can be used for the purpose of intercepting, collecting or storing water from an aquifer; observing or collecting data and information on water in an aquifer; or recharging an aquifer [from National Water Act (Act No. 36 of 1998)].

Colluvial: A loose deposit of rock debris accumulated through the action of gravity at the base of slope.

Confined aquifer: Ground water below a layer of solid rock or clay is said to be in a confined aquifer. The rock or clay is called a confining layer. A borehole that goes through a confining layer is known as an artesian borehole. The ground water in confined aquifers is usually under pressure. This pressure causes water in an artesian well to rise above the aquifer level. If the pressure causes the water to rise above ground level, the well overflows and is called a flowing artesian well.

Ecotone: A term used to describe the transition zone between different habitat types.

Flux: Refers to the concentration of flow. It is the quantity of material or energy transferred through a system or a portion of a system in a unit time and is called mass flux. If the moving matter is a fluid, the flux may be measured as volume of fluid moving through a system in a unit time and is called volume flux.

Ground water: Water found in the subsurface in the saturated zone below the water table or piezometric surface i.e. the water table marks the upper surface of ground water systems.

Ground water: Water that is found in the zone of saturation below the piezometric surface or water table, and does not include water stored in soil horizons or the vadose zone.

Hydraulic conductivity: Measure of the ease with which water will pass through earth material; defined as the rate of flow through a cross-section of one square metre under a unit hydraulic gradient at right angles to the direction of flow (in m/d)

Hydraulic gradient: The slope of the water table or piezometric surface; is a ratio of the change of hydraulic head divided by the distances between the two points of measurement.

Hyporheic: A subsurface volume of sediment and porous space adjacent to a stream through which stream water and ground water exchanges.

Phreatic: Refers to matters relating to ground water below the water table.

Semi-confined aquifer: An aquifer that is partly confined by layers of lower permeability material through which recharge and discharge may occur (DWA, 2010).

Stilling well: A tube sunk into a river bank which allows an accurate and constant measurement of the still water surface level of the river itself.

Storativity: The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in head (DWA, 2010).

Titration: A common laboratory method of quantitative chemical analysis that is used to determine the unknown concentration of a known reactant.

Transmissivity: The rate at which a volume of water is transmitted through a unit width of aquifer under a unit hydraulic head (m^2/d); product of the thickness and average hydraulic conductivity of an aquifer.

Transmissivity: Transmissivity is the rate at which water is transmitted through a unit width of an aquifer under a unit hydraulic gradient. It is expressed as the product of the average hydraulic conductivity and thickness of the saturated portion of an aquifer (DWA, 2010).

Unconfined aquifer: These are sometimes also called water table or phreatic aquifers, because their upper boundary is the water table or phreatic surface. Typically (but not always) the shallowest aquifer at a given location is unconfined, meaning it does not have a confining layer between it and the surface. Unconfined aquifers usually receive recharge water directly from the surface, from precipitation or from a body of surface water (e.g., a river, stream, or lake) which is in hydraulic connection with it.

Vadose zone: That part of the geological stratum above the water table where interstices and voids contain a combination of air and water (DWA, 2010).

Water Table: The upper surface of the saturated zone of an unconfined aquifer at which pore pressure is at atmospheric pressure, the depth to which may fluctuate seasonally.

1 Introduction

1.1 Background

The fractured rock ground water systems of the Table Mountain Group (TMG) constitute a vast aquifer system, extending from north of Nieuwoudtville southwards to Cape Agulhas and eastwards to Port Elizabeth (Appendix A).

The full volume of the aquifer rocks in this whole region comprises 100 000 km3 (WRC, 2005). The Table Mountain Group Aquifer (TMGA) represents a water source that could potentially be used to meet the domestic water needs of the City of Cape Town. The Peninsula formation is the thickest formation (575 – 2000 m) within the TMG and is composed largely of thick bedded coarse grained quartzitic sandstone (Theron et al, 1992). This would represent the target formation for production borehole siting and drilling for this proposed ground water development (WRC, 2005).

Ground water discharge within the TMG is mostly locally restricted and linked to lineaments such as fractures or faults (Colvin et al, 2009). This is evident in the abundance of springs, which are either fault controlled, lithologically controlled or controlled by small fractures and fissures (Meyer, 2001). These ground water discharge points support surface water sites of ecological importance, including streams and wetlands. It is a concern that the proposed large scale abstraction from the Peninsula formation will lower the regional water table and decrease the ground water contribution to these types of sites. For this reason monitoring is taking place within the TMG where wetlands and rivers are being monitored. This study aims to investigate a means of evaluating these sites and assessing their ground water dependence.

1.2 Objectives of Research

Surface water and ground water are to be considered as a single resource and nearly all surface water features interact with ground water, although these interactions take many forms (Winter et al, 1999). It is therefore important to understand the nature of these interactions in the TMG in order to ascertain the potential impacts of abstraction.

A regional monitoring network has been established which includes the monitoring of ecological sites. Regional monitoring is being conducted for springs, ground water, rainfall and sites of ecological importance (rivers and wetlands). With regard to the ecological sites, if monitoring is to provide useful information on changes in ground water trends, it is imperative that the sites are indeed linked to ground water. The degree of ground water dependence will influence the degree to which a wetland or river will be impacted if regional water levels were to decrease. The objective of this study is therefore to investigate the ground water dependence of a set of target sites, and to establish a methodology that can be applied to ecological sites within the TMG and similar geohydrological settings. The study will investigate the use of the following as a means of establishing site dependence on ground water, and in particular the Peninsula Formation Aquifer:

- Time-series flow data (in the case of streams/rivers),
- Geohydrological setting of the site,
- Time series water level data,
- Time series temperature data,
- Time series chemical constituent concentrations,
- Time series and seasonal variations in stable isotope concentrations.

1.3 <u>Study Area Selection</u>

Based on the TMGA monitoring conducted as part of the study by TMGA-EMA (2010), a study area was selected which would encompass sufficient monitoring infrastructure to conduct the study. This included TMG monitoring boreholes, ecological monitoring sites (including at least one wetland and one stream) and weather and rainfall monitoring infrastructure.

The Oudebosch Valley within the Kogelberg Reserve was found to be the most suitable study area. The existing infrastructure included a weather station as well as four Peninsula Formation Aquifer monitoring boreholes, three wetland sites and a stilling well in the stream (the Oudebosch River). These sites are all equipped with pressure and temperature loggers. Figure 73 (Appendix A) is a locality map of the area showing the monitoring sites. The geology outcropping in the vicinity of the Oudebosch Valley includes the Peninsula and adjacent formations and belongs to the TMG.

Previous experience in the Oudebosch Valley also meant that it was a favourable area. Previous work in the area had involved the installation of the two monitoring sites Wetland 3 and River 1 (Figure 73, Appendix A) as well as the maintenance and monitoring of other sites.

The Oudebosch Valley was therefore selected as the study area based on the complex structural geology, the presence of the Peninsula Formation (as outcrop and underlying the Cedarberg Formation) and the existing ground water and surface water monitoring infrastructure currently being monitored as part of the TMGA study being conducted by the City of Cape Town. Three wetlands and the Oudebosch River are being monitored and these sites all have potential ground water contributions. The Oudebosch Valley was favourable in this regard as monitoring sites had been installed by the Council for Scientific and Industrial Research (CSIR) for the Water Research Commission (WRC) project (Colvin et al 2009) and by Geohydrological and Spatial Solutions (GEOSS) for the Exploratory phase Monitoring (TMGA-EMA, 2010).

2 Aims

The aim of the study is to investigate three wetlands and one river site within the Oudebosch Valley (regarded as “surface water sites”) with regard to ground water contribution, and in particular ground water contribution from the Peninsula Formation Aquifer. In order for this to be achieved each of the four “surface water” sites (Figure 73, Appendix A) are investigated with regard to geohydrological setting, chemistry, stable isotope chemistry and time series water level and temperature data. The approach adopted was based on previous studies (Colvin et al, 2009 and TMGA-EMA, 2010) as well as guidance provided by relevant ground water experts. The methods and techniques utilized were selected in order to meet the aims and objectives of the study.

2.1 Geohydrological setting

An abundance of springs is a characteristic feature of the TMG and similar fractured rock aquifers. These springs are generally either fault controlled, lithologically controlled or controlled by small fractures. A detailed understanding of the geological setting of a surface water site (spring, stream or wetland) can therefore give a useful indication of the degree and type of dependence of the site on ground water. A perched water table within a shale unit, for the purposes of this study, would not be considered ground water dependant as it is not linked to the main aquifer. A site of this nature would not be affected by a lowering of the regional water table within the Peninsula Formation.

The investigation involved considering the location of each site with regard to the geological setting, considering lithologies, lithological contacts, fractures and their hydrogeological significance. This will provide fundamental indicators of the ground water dependence of a site.

2.2 Time series water level data

This study also aims to investigate whether time-series water level fluctuations in response to rainfall can be used to identify linkages to the Peninsula Formation. This will be investigated by comparing the response of ground water and surface water sites to rainfall, considering response times and water level changes.

2.3 Time-series temperature data

The study also investigates the use of time-series temperature data as an indicator of ground water dependence. The temperature data of the sites will be compared to the air temperature, and possibly be used to identify evidence of ground water contribution to the site.

2.4 Chemistry

Despite the inert nature of the Peninsula Formation quartzitic sandstones, it is thought that the ground water may possibly have diagnostic chemistries that enable an assessment of the ground water contribution to the various sites. The study will consider the parameters analyzed during the TMG study by TMGA-EMA (2010) and attempt to identify those suitable for evaluating ground water dependence.

All site chemistry samples were submitted to the accredited laboratory Bemlab for analysis. All analysis was done by suitable-certified standards with a certified water standard as a quality control sample. At the time of sampling field parameters (pH, EC, temperature, and Oxidation Reduction Potential (ORP)) were measured.

Table 1. Chemical analysis parameters and detection limits.

Parameter	Limit of Detection (µg/l)	Analysis Method
HCO3	3000	Titration
CO3	3000	Titration
Cl	3000	Titration
Alkalinity	500	Titration
NO3N	10	auto-analyzer
NH4N	10	auto-analyzer
SO4	5	ICP-AES
K	4	ICP-AES
P	2	ICP-AES
Na	2	ICP-AES
As	1.5	ICP-AES
Si	1.4	ICP-AES
Cu	0.3	ICP-AES
Ni	0.3	ICP-AES
Al	0.2	ICP-AES
Zn	0.2	ICP-AES
Fe	0.1	ICP-AES
B	0.1	ICP-AES
Mn	0.03	ICP-AES
Ba	0.03	ICP-AES
Mg	0.01	ICP-AES
Sr	0.01	ICP-AES

Alkalinity (which includes both p and m alkalinity), HCO3 and CO3 were determined by titration with 0.05N HCl. NH4-N and NO3-N were determined by Auto Analyzer, which is measured against standards with suitable concentrations and is measured by segmented flow with colour change by using different chemicals. The Cl concentration was determined by titration with Silver Nitrate. All other measured constituent concentrations (Table 1) were determined by inductively coupled plasma atomic emission spectroscopy (ICP-AES). The limits of detection are listed in Table 1.

2.5 Stable Isotopes as an indicator of ground water dependence

Stable isotope samples were taken at each site on a monthly basis and these were analyzed for the stable isotope Deuterium (D) and Oxygen18 (^{18}O) concentrations. Stable isotopes provide a means of characterising different water sources and can provide valuable information with regards to recharge and residence times, as well as potentially indicate ground water dependence. The collected samples were submitted to the laboratory at the University of Cape Town (UCT) for analysis.

2.6 Methodology

This project aims to use physical, chemical and geohydrological properties of three wetland sites and the Oudebosch River site in order to qualitatively assess the ground water dependence of various sites. In order to achieve this, each site will be individually assessed and classified according to each characteristic considered. A ground water dependency rating will be assigned to each site, and these will be averaged to classify the site ground water dependence.

The three wetlands, the river and three boreholes within the Peninsula Formation all are equipped with a pressure logger that measures water level and temperature. By assessing the temperature and water level trends and responses each site will be allocated a ground water dependence rating.

A plot of the flow measurements in the Oudebosch River relative to river stage as measured by the pressure logger can be plotted. A relationship between flow and river stage can be determined which enables the time series water level measurements to be converted to flow measurements. This enables hydrograph recession analysis techniques to be applied to the river to investigate ground water contribution. This enables the allocation of a ground water dependence rating to the site.

Chemistry samples were taken on a monthly basis for both ground water and surface water sites. This serves the purpose of determining the seasonal variation in both ground and surface water quality and could potentially give an indication of the total ground water contribution to surface water. Based on the chemistry analysis the sites were assigned a ground water dependency rating.

Stable Isotope samples were taken and analyzed on a monthly basis and it is anticipated that these will enable a characterisation of the ground water, and therefore a better understanding of the ground water dependence of the various sites. The dependency rating was assigned based on the various sites isotope composition and variation in comparison to ground water and meteoric water.

For each site, and each of the considered characteristics/parameters, a rating number from 0 to 8 is assigned according to Table 2. The number is a qualitative indicator of ground water dependence. The qualitative rating table was utilized due to the qualitative nature of the results and characteristics compared. The assessment of the various sites did not provide a quantitative ground water contribution volume, and from this table a value is assigned which enables the comparison of the various sites. The rating table also enables a final "ground water contribution" assessment of the sites that takes into consideration all the characteristics/parameters considered.

Table 2. Ground water Dependence Classification Table.

8	Strongly groundwater dependant, primary water source
6	Significant Groundwater dependance
4	Intermediate groundwater dependance
2	small/insignificant groundwater dependance
0	No groundwater contribution suspected

Once all sites are investigated a final Ground water Dependency Rating can be specified for each site, and this value is used to classify the sites with regard to ground water dependence.

3 Data Collection

The investigation made use of existing infrastructure, data and studies conducted in the area and therefore involves an assessment of existing work (Chapter 3.1) as well as the field work specific to this study (Chapter 3.2).

3.1 Desktop Study

3.1.1 Review

The TMG Exploratory Phase Monitoring (TMGA-EMA, 2010) involved bi-annual (October and April) regional monitoring. The Kogelberg mountain range and the Oudebosch Valley falls within the monitoring area. The infrastructure was predominantly set up in the Oudebosch Valley as part of the WRC 2009 project (Colvin et al, 2009), but additional sites were added by GEOSS for the Exploratory Phase Monitoring. Data for some of the sites was collected for 2006 up until June 2007 as part of the WRC project (Colvin et al, 2009) but then the sites were left unattended until the TMGA-EMA (2010) adopted them and commenced data collection from 2008 until April 2010. This data is included for the purposes of this investigation. The City of Cape Town who funded the TMG Exploratory phase monitoring (TMGA-EMA, 2010) gave permission for the use of the existing site data for the study. Site data collected in April 2010 and prior to 2010 belong to the City of Cape Town and is taken from TMGA-EMA, 2010.

3.1.2 Data collection and site selection

The previous two projects which involved data collection in the Oudebosch Valley had different purposes, and therefore different monitoring and sampling intervals and specifications. Likewise, this study is detailed and requires more regular sampling and monitoring. Sampling and data collection was therefore conducted on a monthly basis from February 2010 until July 2010 for a select group of sites chosen for the purpose of this study. The sites included four boreholes (of which one is artesian), three wetlands, a weather station, a Cumulative Rainfall Collector (CRC) and a stilling well in the Oudebosch River (Figure 73, Appendix A).

Data from TMGA-EMA (2010) and the detailed monitoring conducted for this study were collected and stored in a designated database at the GEOSS office. All water level data, for the boreholes, wetlands and the river was compensated for barometric influences. The sites were required to be:

- In the Oudebosch valley.
- Either monitoring ground water (borehole) or surface water (wetlands and river).
- Linked to the Peninsula Formation if it is a ground water monitoring site.
- Equipped with the necessary infrastructure (e.g. pressure and temperature loggers).
- Relatively accessible.
- Suitable for sampling and the measuring of water levels.

3.1.3 Weather and Rainfall Data

A weather station and a CRC were included in this study to provide the necessary data and samples. The weather station was not in working condition after the WRC project (Colvin et al, 2009) until 26 May 2009 when it was fixed and once again monitored. Although rainfall was measured by the weather station, it did not have the capability to store the rainfall for sampling purposes. Thus the need arose for the installation of a CRC. This was constructed and installed based on the requirements and recommendations described in the Weaver and Talma (2005) report titled "Cumulative Rainfall Collectors – A tool for assessing ground water recharge." This report contains the details and specifications for collecting rainfall samples and preventing the concentrating of the collected rainfall chemistry by evaporation. A CRC was installed in the month of May 2010 for the purpose of obtaining one cumulative rainfall sample. Figure 78 (Appendix B) is a picture taken within the valley showing the Weather Station and the CRC.

3.1.4 Ecological (Surface Water) sites

Wetland 2 is a piezometer located near the Oudebosch cottages in dense vegetation, installed to a depth of 1.5 mbgl and screened with Unplasticised Polyvinyl Chloride (uPVC) piping. It is equipped with a Solinst pressure and temperature logger. The site was installed as part of the WRC project (Colvin et al, 2009) by the CSIR and a photo of the site is shown in Figure 79 (Appendix B).

Wetland 1 (Figure 80, Appendix B) is a shallow piezometer due to the shallow bedrock, and is situated on the eastern flank of the Oudebosch Valley. It is located within a wetland which is saturated for the most part of the year and from which water flows out as a small stream (spring). The site was installed as part of the WRC project (Colvin et al, 2009) by the CSIR but was only equipped with an automated pressure logger in 2008 by TMGA-EMA (2010).

Wetland 3 is a wetland piezometer installed into the loose sediments towards the middle of the Oudebosch Valley. The site was installed by GEOSS as part of the TMG Exploratory Phase Monitoring (TMGA-EMA, 2010). The piezometer was hand augered to a depth of 2.6 m before bedrock was reached. The site is equipped with a Solinst pressure and temperature logger. The site is characterized by mud and is swampy with poor drainage. Figure 81 (Appendix B) shows the piezometer within the dense wetland vegetation.

River 1 is a stilling well located in the Oudebosch River. The stilling well is secured to a tree located on the edge of the river, it is 1.45 m tall and the logger sensor hangs at a depth of 1.40 m below the top of the stilling well (~0.05 m above the top of the stream bottom). The site was installed by GEOSS as part of the TMG Exploratory Phase Monitoring (TMGA-EMA, 2010) and Figure 82 (Appendix B) is a photograph of the stilling well.

3.1.5 Ground water monitoring sites

Borehole 1 (Figure 83, Appendix B) is drilled into the Peninsula Formation on the access road to the Kogelberg Reserve, 185 m northeast of the northwest-southeast striking meso-fault that runs down the Palmiet valley and ~ 400 m north of the mega-fault running northeast - southwest up the Oudebosch Valley. This borehole targets a regional scale northwest – southeast fault set. A low yielding water strike was intercepted at 3 mbgl, a second water strike was at 16 mbgl and the main strike occurred at 33 mbgl. The borehole is 35 m deep, cased for the top 11 m, and targets the semi-confined Peninsula Formation. The borehole was drilled using percussion drilling, and the blow yield was ~ 6 ℓ/s (Colvin et al, 2009). Although water level logger data was not available for this borehole, manual readings and sampling was still conducted here and this data is included. The borehole was drilled by the CSIR as part of a WRC study (2009).

Borehole 2 (Figure 84, Appendix B) is drilled into the Peninsula Formation next to the access road to the Kogelberg reserve, 185 m southeast of the major northeast – southwest striking fault running up the Oudebosch Valley and 500 m northeast of the antithetic northwest – southeast striking fault that runs up the Palmiet River valley. There are subordinate northwest – southeast fault sets that cross-cut both the Peninsula and Skurweberg Formations. These commonly relate to springs, tributaries and wetlands and are thought to represent shallow to moderate length flow paths with low to moderate discharge rates in discrete, structurally controlled zones (Colvin et al, 2009). Borehole 2 targets one of these subordinate northwest – southeast structures in the Peninsula Formation but it was either not water bearing or not intercepted (Colvin et al, 2009). The borehole is 70 m deep, cased for the top 6 m, and has no significant water strikes. The borehole intersects low permeability matrix and micro-structures. Despite not having any identifiable water strikes during drilling, Borehole 2 is filled with water and shows water level responses to rainfall events within a few days. This indicates the pervasive presence of water in the low permeability matrix and micro-structures of the Peninsula Formation. The borehole was drilled with percussion drilling and has an airlift yield of < 1 ℓ/s.

Borehole 3 (Figure 85, Appendix B) is a narrow diameter borehole drilled relatively close to the Oudebosch huts. It was drilled to a depth of 16 m using a portable rig. Hard bedrock was intercepted at a depth of 2 m and the hole cased to a depth of 4 m, below which water strikes were obtained at 8 and 12.5 mbgl. The borehole is drilled into the Peninsula Formation and intercepts a subordinate northwest – southeast fault/fracture set. The blow yield of the borehole was ~ 3 ℓ/s (Colvin et al, 2009). It is equipped with a LDM Diver which logs pressure and temperature data. The borehole was drilled by the CSIR as part of the WRC project (Colvin et al, 2009).

Borehole 4 (Figure 86, Appendix B) is drilled into the confined Peninsula Formation in a mega-fault zone. The borehole is 47 m deep and the lithology consists of an upper 24 m of Cedarberg Formation overlying the confined Peninsula Formation. The intersection of the major northeast-southwest striking fault is at 38 mbgl and is the cause for the artesian flow. A cap was welded over the borehole and it was equipped with a water pressure logger. On 8 February 2005 the artesian flow was measured as being 2.1 ℓ/s (Colvin et al, 2009). The borehole targets the Hangklip - Riviersonderend Megafault (HRM) system (TMGA-A, 2004) comprised of significant faults and related structures. The borehole was drilled by the CSIR and is equipped with a pressure logger and has a tap for sampling purposes.

3.2 Fieldwork

The field work involved sampling and monitoring the water level of the selected sites for the project on a monthly basis from 17 February up until 17 July 2010. The procedure for each site varied according to its type and will be discussed separately.

3.2.1 Boreholes (unconfined)

Two boreholes (Borehole 1 and Borehole 2) are drilled into the unconfined part of the Peninsula Formation towards the northeast of the Oudebosch Valley. A third borehole (Borehole 3) is drilled into the Peninsula Formation close to the Peninsula - Cedarberg Formation contact on the southern slope of the valley. Water level and temperature monitoring was conducted at all three of these boreholes. The boreholes were also sampled for chemical and isotope analysis. Due to financial and logistical constraints a pump with sufficient yield to purge the boreholes was not available. The boreholes were therefore pumped with a low yielding (~1.5 ℓ/s) pump until the field EC and pH stabilized (~15 minutes) prior to sampling. Manual water level measurements were measured during site visits.

3.2.2 Artesian Borehole

The artesian borehole is equipped with a STS pressure logger. Data is recorded hourly and was downloaded on a monthly basis. A tap on the artesian borehole was opened and allowed to run until the field EC and pH stabilized and the artesian pressure dropped, after which samples were collected. Isotope and chemistry samples were taken on a monthly basis. The installed pressure logger did not have temperature measuring capabilities.

3.2.3 Piezometers

All three wetland piezometers are equipped with Solinst pressure loggers that measure water level and temperature every half hour. These loggers were downloaded monthly and a manual water level measurement taken. These piezometers were purged using either a bailer or pump prior to sampling for chemistry and isotopes.

3.2.4 Stilling Well

The stilling well is installed in the Oudebosch River where it is secured to a tree in a slow flowing part of the stream. Water chemistry and isotope samples were taken monthly during site visits. The stilling well has a Solinst pressure logger which measures and records water level and temperature every half hour. Each monthly visit involved downloading the logger data, taking samples, and then measuring the river flow volume. This was done by using a flow probe which measures the velocity of the stream flow, and a tape measure to determine the cross-sectional area of the stream. The area of the cross-sectional profile of the stream was calculated by measuring the stream depth at ~10 points across its width at evenly spaced intervals. The average stream velocity was then measured for the selected cross-section. The flow volume is then calculated for each interval, and summed to give the total flow volume.

3.2.5 Weather Station

Data was downloaded from the weather station every two months. No manual measurements were taken at this site.

3.2.6 Rainfall Collector

The CRC was installed on 15 May 2010, and was sampled for chemistry and isotopes in July 2010 – the sample representative of rainfall falling between 15 May 2010 and 17 July 2010. Silicon oil was placed inside the rainfall collector to float on the collected rainfall to prevent evaporative losses. Rainfall was tapped out from beneath the oil through a tap installed in the bottom of the collector.

4 Literature Review

Surface water and ground water are under constant interaction with each other in the hydrological cycle (Sophocleous, 2002). They affect each other both quantitatively and qualitatively (DWAF, 2003). This is evidenced when over-exploitation of ground water results in a decline of low-flow in streams and subsequently riverine ecosystems are disrupted (Smakhtin et al, 1997).

But surface – ground water interactions can vary greatly. The ground water contribution to surface water sites can be small (Jaime et al, 2002) or large (Banks et al, 2009). The ground water contribution can originate at shallow depths (Jaime, 2002) or come from deep within fractured bedrock (Banks et al, 2009). Interactions between ground water and surface water form one component of the hydrogeological cycle and are controlled largely by the affects of physiography and climate (Winter et al 1999). In order to determine and characterize these interactions it is therefore important to have a sound hydrogeological conceptual model of the area, understanding climate, landform, geology and ecological features and how they relate to each other (Banks et al, 2009).

4.1 Hydrogeological Cycle

It is commonly understood that all water forms part of the hydrological cycle, however linkages between the various interdependent components are complicated and require an integrated perspective (Parsons, 2004). The hydrological cycle illustrates the continuous movement of water above and below the earth's surface as depicted in Figure 1.

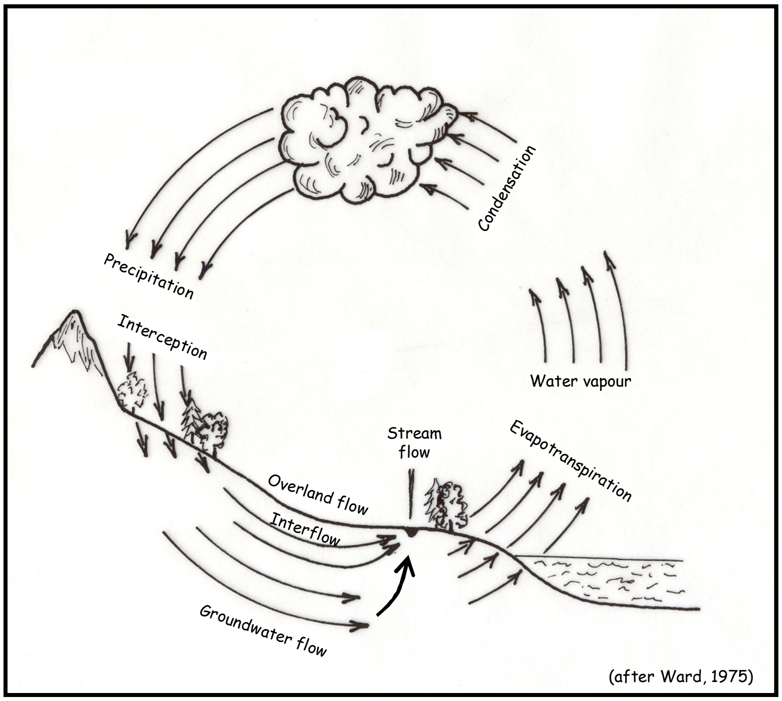

Figure 1. Simplified diagram of the hydrological cycle (Modified from Parsons, 2004)

The water in circulation in the atmosphere is termed meteoric water, surface water refers to all water found in rivers, wetlands, oceans and lakes and subsurface water refers to all water below the earth's surface. While the term subsurface water is a recognised geohydrological term (Davis and DeWeist, 1966; Driscoll, 1995) it must not be confused with the term ground water. Ground water is that water found in the zone of saturation below the piezometric surface or water table, and does not include water stored in soil horizons or the vadose zone. This is illustrated in Figure 2.

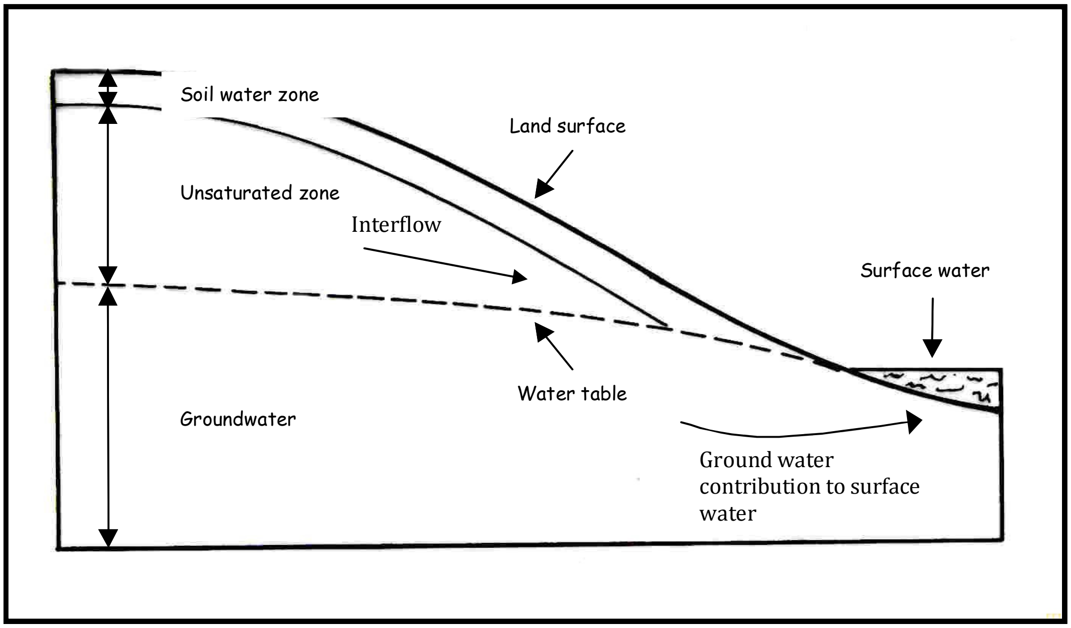

Figure 2. Distinction between ground water and other subsurface waters. (Modified from Parsons, 2004)

Surface and ground water are connected through fluxes of water and chemicals on a range of scales (Winter, 1999). A sound understanding of the controlling factors is required for determining the nature and degree of interactions.

4.2 Ground water and the Vadose zone

There has been lots of research in sedimentary aquifer systems (e.g. Beyerle et al, 1999; Schilling et al, 2006; Krause and Bronstert, 2007) but only a few studies for fractured bedrock systems (eg. Sklash and Farvolden 1979, Haria and Shand 2006, Manning and Caine 2007, Kahn et al 2008). Reasons for this are the complexity brought about by the heterogeneity of the fractured rock aquifer, and the fact that the saprolite/fractured bedrock interface cannot be treated as a no-flow boundary (Banks et al (2009); Van der Hoven et al (2005); Shand et al 2005; Haria & Shand 2006).

Ground water plays a significant role in sustaining base flow for wetlands and perennial rivers under a range of climatic, topographical and geological conditions, but it is important to note that not all subsurface water is ground water. Only that water in the saturated zone is defined as ground water. Also, not all base flow is derived from ground water – base flow also includes the contribution of interflow discharged into streams and rivers from the unsaturated zone (Parsons, 2004). Stream flow originating from subsurface pathways and contributing to base flow is often all termed ground water which leads to conceptual misunderstandings. Water held or percolating through the unsaturated zone plays a key role in the hydrological system and helps to sustain aquatic ecosystems and terrestrial fauna and flora (DWAF, 2003), it can therefore not be neglected for studies involving subsurface water.

Base flow can therefore not be equated to ground water contribution. In a similar way recharge cannot be equated to ground water base flow contribution. Recharge water may be "lost" before it reaches the ground water. This can occur through interflow through the weathered zone, seepage of percolating water from outcropping fractures, springs draining perched water tables, artesian springs, evapotranspiration or even losses to a deep regional ground water system where discharge is far from the point of recharge. For this reason ground water base flow contribution to surface flow is normally significantly less than recharge (DWAF, 2003).

By equating base flow and ground water contribution Hughes (2003) observed estimates of base flow are up to 10 times greater than expected recharge. This order of magnitude increase in ground water discharge to streams predicted by most base flow separation techniques does not match observed changes in ground water levels that would be necessary to induce such an increase. Ground water discharge to rivers is governed by Darcy's Law (Parsons, 2004). Because the transmissivity and aquifer width remain relatively constant, the only mechanism to increase ground water discharge would be to significantly increase the hydraulic gradient.

(1) $q = T\,i\,2L$ (Gaining / Effluent River)

T - Transmissivity (m2/d)

i - average ground water hydraulic gradient

L - Length of river Reach (m)

Where ground water flows into rivers the equation is used. Where a river is disconnected from the underlying ground water, the hydraulic gradient is assumed to be one (DWAF, 2003).

4.2.1 Unsaturated zone

In the unsaturated subsurface the interstices and pore spaces contain both air and water with the water being held in this zone by capillary forces. Although this water is not available to abstraction it is mostly available to plants. This zone (Figure 3) integrates components of the hydrological cycle as it lies between the earth and the atmosphere, the land surface and the underlying aquifer and it controls infiltration and surface runoff processes (Parsons, 2004).

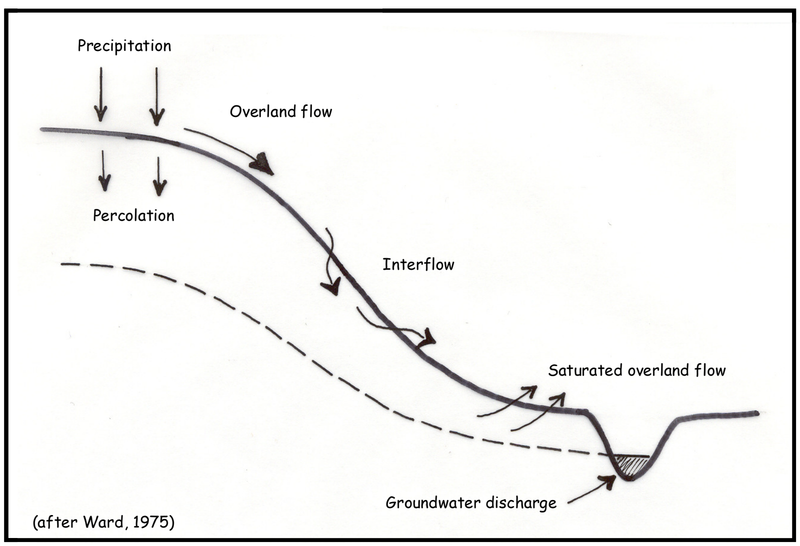

Figure 3. Figure illustrating interflow in relation to ground water and overland flow (Parsons, 2004)

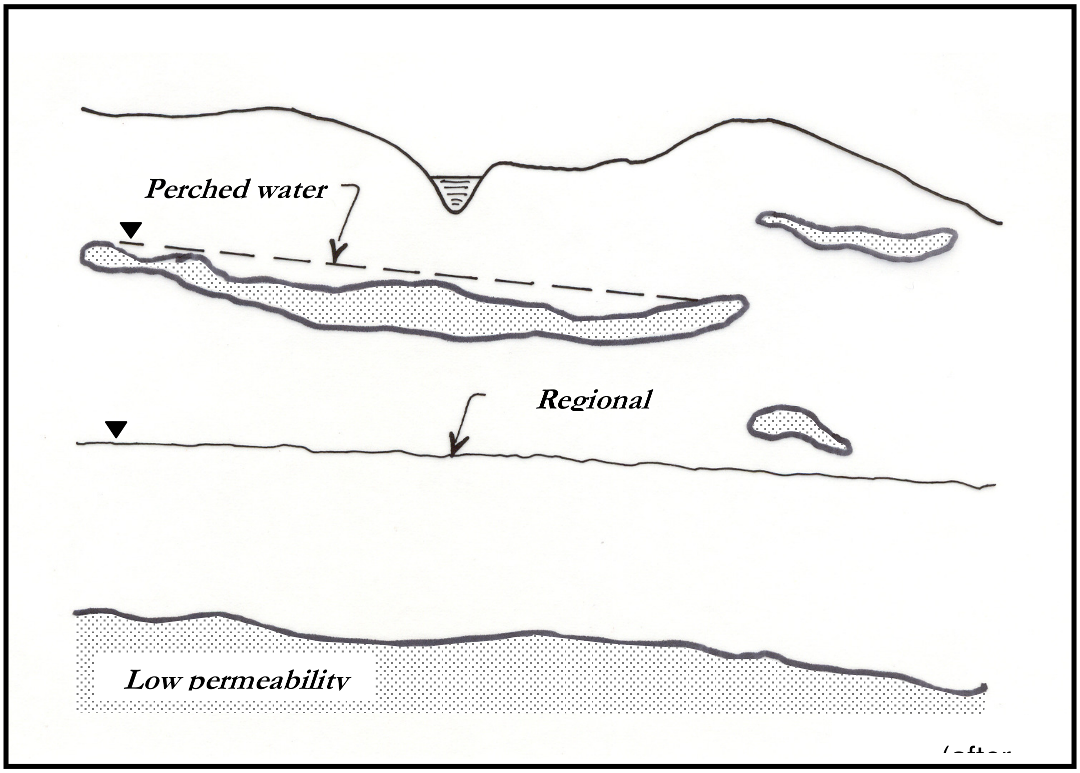

Figure 4. Illustration of a perched water table (Parsons, 2004)

4.2.2 Saturated zone

This zone is bounded above by the water table or piezometric surface, and is characterized by pore spaces that are saturated with water. Water beneath the water table is considered by geohydrologists to be ground water and that above the water table to be soil water or water of the vadose zone. Ground water is stored and transmitted in voids between soil, sediment or rock particles called pore spaces or interstices. These are demonstrated in Figure 5.

Ground water also flows through voids in rock that has been altered by weathering, folding, faulting or uplifting. These are secondary openings and give rise to the concept of primary and secondary aquifers.

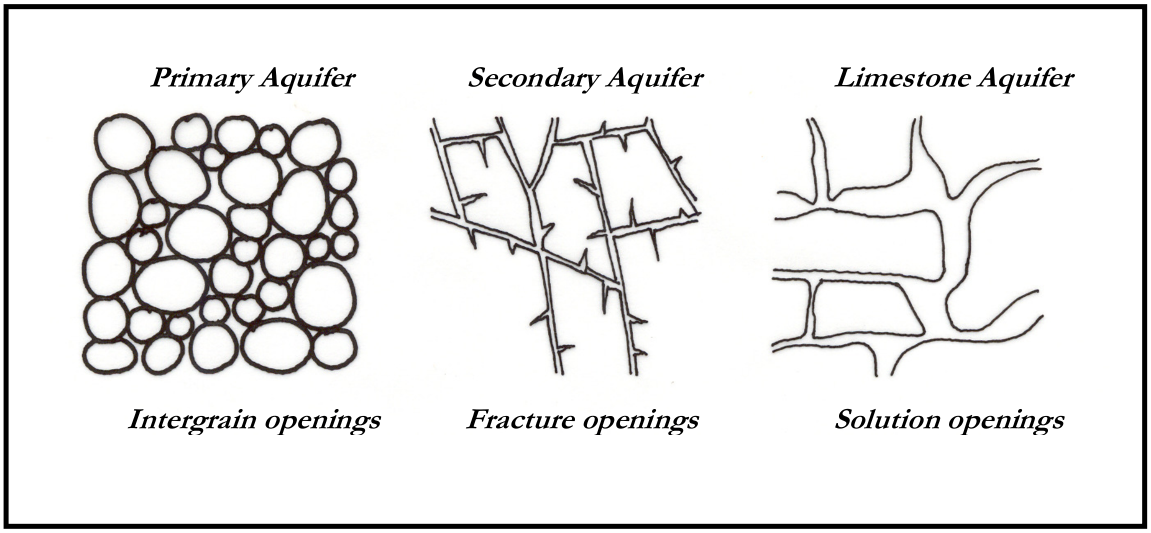

Figure 5. Types of interstitial openings. (Kruseman and de Ridder, 1990)

A significant characteristic of secondary aquifers is the variability of hydrological parameters over short distances. Both the hydraulic conductivity and storativity of fractured rock aquifers can vary by several orders of magnitude over short distances (Parsons, 2004).

Confined and unconfined aquifers are opposite end members of a continuum, ranging from aquifers under pressure to those where the water table is in equilibrium with atmospheric pressures (Brown et al, 2003). Semi-confined and semi-unconfined aquifers are found between the two end members. While not preventing the upward movement of water, differences in hydraulic conductivity hinder the movement of water, thereby resulting in both lateral and vertical localised pressure differences. Most aquifers in South Africa are semi-confined or semi-unconfined (Parsons, 2004).

Numerous techniques are available for relating surface water to ground water. This study will utilize some of these methods in order to determine the ground water contribution to four ecological sites (three wetlands and one stream) located in the Oudebosch Valley of the Kogelberg Reserve.

4.3 Ground water at the surface – Wetlands and Streams

In the WRC funded report on the Ecological and Environmental Impacts of large-scale Ground water Development in the TMG Aquifer system (Colvin et al, 2009) the importance of considering ecology when dealing with ground water is evident. The reason for this is that aquifers provide a source of water to ecosystems that is available for longer in water controlled environments than other rain driven sources and to a select functional group within the ecosystem (Colvin et al, 2009). The report defines an aquifer dependant ecosystem as ecosystems dependant on ground water in or discharging from an aquifer: their structure and function would be fundamentally altered if that ground water were no longer available (Colvin et al, 2009).

The ecological value of wetlands has been widely recognised. Amongst others, wetlands help prevent floods, improve water quality, reduce river sediment loads and provide fish and wildlife habitat. It is less well recognised, however, that many wetlands are ground water driven systems (DWA, 2010).

For this reason numerous wetlands and streams (surface water sites) located in the TMG are being monitored and analyzed in order to ascertain what the impact of abstraction from the Peninsula formation will be. This impact can be determined and assessed by evaluating the dependence of the surface water sites on ground water, and in particular the Peninsula Formation ground water.

This study will investigate the surface water – ground water interaction for surface water sites within the Oudebosch Valley, Western Cape. At this stage the potential impact on vegetation, including the Western Cape's unique fynbos biome, as a result of ground water exploration in the Peninsula Formation is largely unknown (WRC, 2005). The results of this study will provide useful information for future monitoring.

4.3.1 Streams

Ground water discharge at the surface is generally evident in the presence of springs, wetlands, seeps and rivers and streams. If spring flow is substantial and ongoing it forms the start of rivers and streams with a significant base flow component. Elsewhere the relative position of the stream bed and the water table determines whether there is a hydraulic connection. If the base of the stream bed intersects or is connected to the underlying ground water system, an assessment of base flow can be used to quantify the ground water contribution.

A simple classification and description of streams is included in this report. For a comprehensive and locally focussed analysis of local rivers see the report by Xu et al (2002) and Xu and Beekman (2003).

Stream flow and ground water interactions can be broadly classified according to the vertical positioning of the surface relative to the water table (Figure 6).

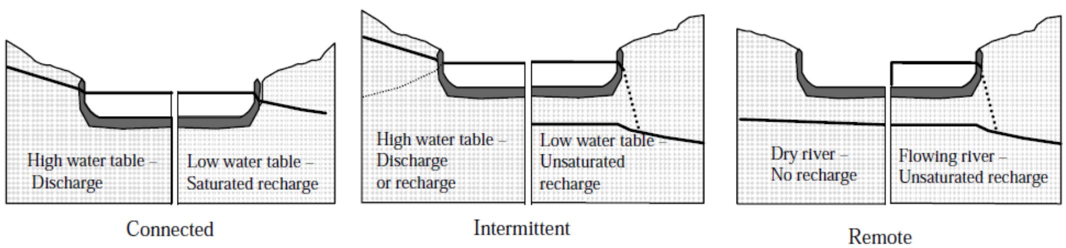

Figure 6. Classification of rivers by vertical positioning relative to the water table. (Xu and Beekman, 2003)

A 'connected stream' has contributions of ground water to the stream flow. This includes interflow from unsaturated zone to hydrograph recession following a storm event, ground water discharged to surface water from the regional aquifer and discharge from temporary or perennial springs located above low permeability layers (Parsons, 2004).

An 'Intermittent stream' has both losses and gains to stream flow dependant on river stage. This occurs when transmission losses are temporary and high flows result in recharging of bank storage and subsequent release during low flow periods.

The 'Remote stream' involves losses from stream flow to ground water and includes the transmission of surface water when the river stage is above the ground water table in phreatic aquifers with a water table in contact with the river as well as losses from detached rivers where water table lies below the channel.

A second classification is by stream flow characteristics, which divide streams into ephemeral (event dominated) and perennial (continuous) rivers (Figure 7).

Perennial rivers are normally connected to- and associated with- ground water discharge, wetter climates, and larger catchments. . Conversely, ephemeral rivers are associated with dryer climates and are normally perched systems. (Xu and Beekman, 2003)

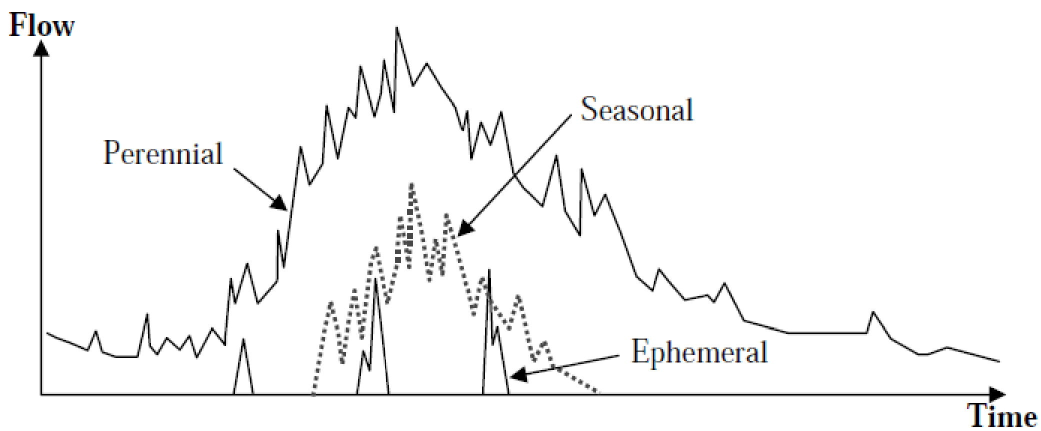

Figure 7. Classification of rivers by flow characteristics. (Xu and Beekman, 2003)

4.3.2 Springs

Springs are an expression of subsurface water discharging at surface. In addition to providing the ground water contribution to river flow, they play a critical role in providing fauna and flora with a source of water. Unique ecosystems develop around springs in response to the permanency of available water.

Not all springs are fed by ground water as some are fed by water in the vadose zone and interflow (Parsons, 2004). These springs - termed perched springs by Cleaver et al (2003) - are unlikely to be impacted by ground water abstraction. Typically, they are seasonal in character, occur above the regional water table and can sometimes be distinguished from ground water by their chemical or isotopic composition. Springs found in mountain headwater areas are characteristically of this type. Because they tend to dry up during prolonged dry periods, they generally only contribute to base flow in the dry months immediately after the rainy season. (Parsons, 2004).

Ground water-fed springs are more permanent in character than perched springs and have chemical and isotopic compositions similar to that of the underlying ground water body. These springs are at a similar elevation as the regional water table or piezometric surface and contribute to the ground water component of base flow. Generally, these springs are found in low-lying areas (Parsons, 2004).

DWAF compiled a report which includes a three tier classification system for springs (DWAF, 2004). The first classification is based on whether the spring is 'gravitational' or 'non-gravitational', where 'non-gravitational' refers to confined conditions. The second tier involves classifying the seasonality of the flow regime as either 'seasonal', or 'non-seasonal'. Finally, springs are classified according to their geomorphological and geological setting. For further details on spring classification and types see the DWAF 2004 report entitled "Standard Descriptors for Geosites."

Cleaver et al (2003) presents three types of spring based on topographic and geological location:

Type 1 – These are shallow seasonal springs and seeps emanating from perched water tables. These represent localised discharge of interflow and are not connected to the ground water flow system. They will therefore not be impacted by ground water abstraction. Type 1 springs occur across the Peninsula and Nardouw aquifers, and are not connected to the greater ground water flow system (Kotze, 2001). The springs seep from a network of fractures within the TMG aquifers directly above localized aquitards and are highly seasonal.

Type 2 – These are lithologically controlled springs, due to the presence of inter-bedded aquitards, located mainly at the Peninsula-Cedarberg, Goudini-Skurweberg and Nardouw-Bokkeveld contacts (Colvin et al, 2009). Flow is therefore more permanent and sustains base flows, and will be susceptible to impacts from localised ground water abstraction (Parsons, 2004).

Type 3 – These are fault controlled Springs that are permanent in character, discharge either hot or cold water and are only potentially impacted by large scale regional abstraction (Parsons, 2004)

Type 2 and 3 springs are significant with regards to the regional water balance (Kotze, 2001). This classification of springs is depicted in Figure 8.

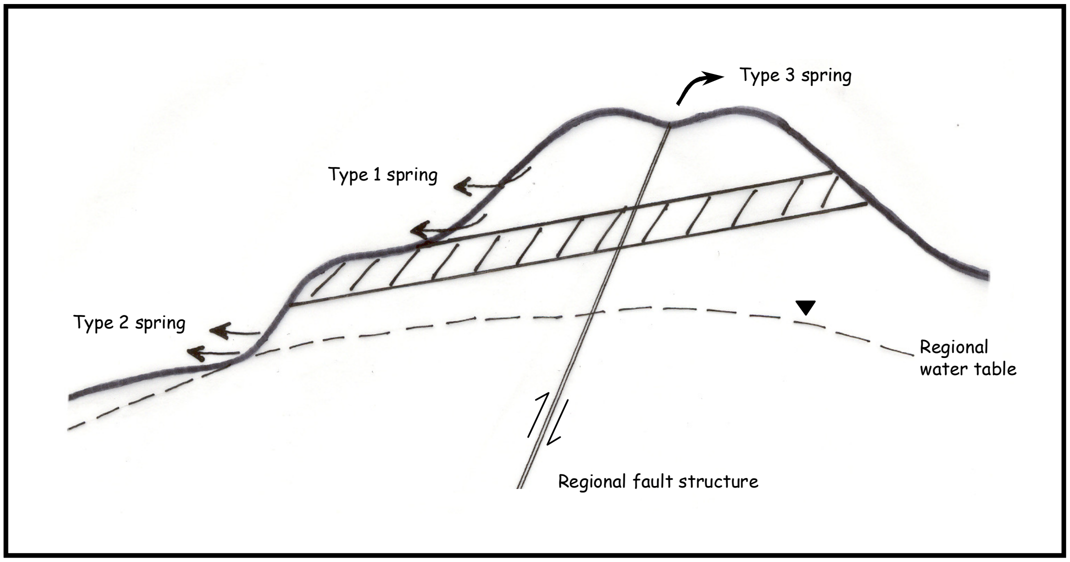

Figure 8. Spring classification system (Parsons, 2004).

Based on the spring classification discussed it is possible to get an indication of whether the site is linked to ground water bearing features by looking at the geological and structural setting. For every spring or seep, there is a geological explanation for its occurrence (Stone and Stone, 1994). In Colvin's report she relates the aquifer discharge setting to the associated habitat within the TMG (Table 3).

Table 3. Table relating wetlands/habitats with Aquifer discharge setting in TMG (Colvin, et al, 2004)

Discharge setting / Habitat	Alluvium	Recent coastal sediments	Lithological contacts	TMG mega-structures	TMG intermediate structures	TMG micro-structures and matrix
Perched high wetland			Direct discharge			Direct discharge
Slope Wetland	Direct discharge		Direct discharge	Direct discharge	Direct discharge	
Valley bottom wetland	Direct discharge		Direct discharge	Direct discharge	Direct discharge	
Coastal wetland		Indirect discharge		Direct discharge		
Spring			Direct discharge	Direct discharge	Direct discharge	
Seasonal river			Direct discharge		Direct discharge	
Perennial river	Direct discharge	Direct discharge	Direct discharge	Direct discharge	Direct discharge	
Riparian zone	Direct discharge		Direct discharge	Direct discharge	Indirect discharge	
Terrestrial fynbos		Indirect discharge				Direct discharge

Direct discharge
Indirect discharge

4.3.3 Degree of ground water dependence

Surface - ground water ecotones form a varied habitat important to both aquatic and wildlife communities (Gardner, 1999). Ecotone is a term used to describe the transition zone between different habitat types. In the context of surface - ground water interaction, the land - water ecotone encompasses both water flow and living and non-living components of the interaction.

The hyporheic zone is contained within the land - water ecotone and is functionally a composite between surface and ground water ecosystems. It provides ecologically important services, including: thermal, temporal and chemical buffering; habitat; flow augmentation and refugia (Parsons, 2004). The zone may be significantly different to the overlying surface water body and the underlying aquifer system. Brown et al (2003) noted upwelling (or discharge) of ground water creates patches of high productivity in the hyporheic zone and aquatic ecosystems, supporting greater animal densities and diversities when compared to non-upwelling situations.

The ground water dependence of surface water features as presented by Brown et al (2003) allows for a five point classification with sites being either:

- Entirely dependent: ecosystems would collapse if ground water fluxes were to diminish or be slightly modified.
- Highly dependent: moderate changes to ground water discharge or water tables would lead to substantial decreases in either the extent or condition of ecosystems.
- Proportionally dependent: a unit change in the ground water system would result in a proportional change in the condition of the ecosystem.
- Facultative dependency: changes to a ground water system would have a minor effect on the condition of the ecosystem.
- No dependence: ecosystems are independent of ground water.

4.4 Factors Affecting interaction

A number of efforts have been made to conceptualise surface water and ground water interactions (e.g. Haevey and Bencala 1993, Nield et al 1994, Wroblicky et al 1998, Sophocleous et al 1999, Smith and Townley 2002, Winter 1999).

Nield et al (1994) identified 39 flow regimes of aquifer and stream interaction, distinguished by geometric factors, physical factors and boundary conditions (Nield et al, 1994, Smith and Townley, 2002). The geometric factor is the length of a water body relative to aquifer thickness. The physical factors consist of the distribution of hydraulic conductivity, and the boundary conditions consist of the location of recharge and discharge (DWAF, 2003). Sophocleous (2002) showed that the effect of topography, climate and geology have important controls on surface water – ground water interactions.

4.4.1 Topography

In ground water flow systems topography can potentially affect the distribution of the water table. Based on the aerial extent of the aquifer, the ground water flow system can be classified as being either local, intermediate or regional. Local flow systems are governed by topography (DWAF, 2003).

4.4.2 Hydraulic Conductivity

The distribution of hydraulic conductivity within the geological framework of an aquifer and adjacent streams influences ground water – surface water interactions (Sophocleous, 2002 and Winter, 1999). This was shown previously with equation 1 (Darcy's Law). In addition to being sites of discharge and/or recharge, surface water bodies act as flow-through in which case they are equivalent to a layer of high hydraulic conductivity, which focuses ground water flow toward and through it (Nield et al, 1994).

4.4.3 Geomorphology and stream characteristics

Other factors that affect surface water – ground water interactions is geomorphology (Sophocleous, 2002) and the significance of the stream bed slope and discontinuities (Haevey and Bencala, 1993). Based on the dominant regional ground water component, stream-aquifer interactions can be classified into three classes; underflow, base flow and mixed. In underflow dominated systems ground water flux moves parallel to the river and in the same direction as stream flow. base flow dominated systems occur when the ground water flux moves perpendicular towards the river. Based on this concept, Smakhtin and Watkins (1997) generally grouped rivers in South Africa as effluent (gaining) and influent (losing) (DWAF, 2003). In reality the influent and effluent nature of a river varies significantly along its length, but the dominant component of ground water flow systems can be inferred from geomorphologic data (Sophocleous, 2002).

The underflow component is predominant in systems with large channel gradients, small sinuosity's, large width to depth ratios, and low river penetrations, in upstream and tributary reaches, and in valley fill depositional environments. Base flow dominated systems are typical of suspended-load streams and occur under opposite conditions to underflow dominated systems. Mixed flow systems occur where the longitudinal valley gradient and channel slope are virtually the same and also where lateral valley slope is negligible.

4.4.4 Climate

Climate affects stream-ground water exchange because of the distribution and seasonal variations in precipitation (Wroblicky et al, 1998). Under condition of high precipitation, surface runoff and interflow increases leading to higher hydraulic pressures in the lower stream reaches, in which case the river may change from an effluent to influent condition. On the other hand, under conditions of low precipitation, base flow constitutes the discharge for most of the year.

4.4.5 Anthropogenic factors

Anthropogenic factors such as surface water and ground water development also affect surface water-ground water interactions. Abstracting ground water from a borehole causes a cone of depression to form around it (Figure 9). The depth and extent of the cone of depression is dependent on the rate and duration of abstraction and prevailing geohydrological properties of the aquifer. (Parsons, 2004)

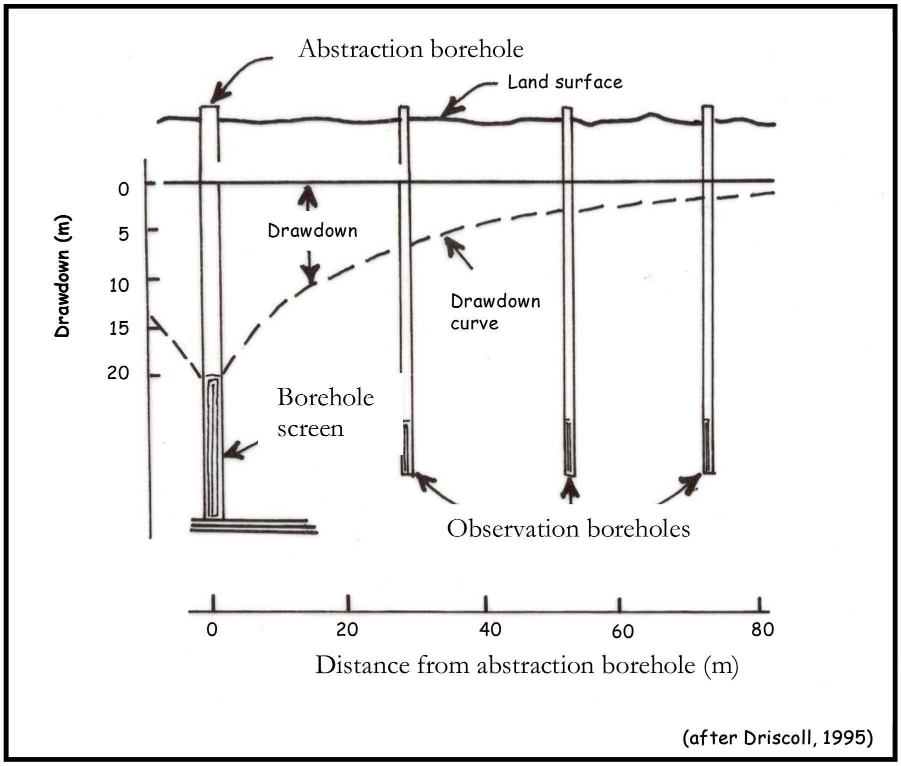

Figure 9. Illustration of drawdown resulting from the abstraction of ground water. (Driscoll, 1995)

Should the cone of depression around the pumped borehole reach a surface water body (river, lake, wetland or estuary), then localised hydraulic gradients can change and induce flow from the surface water body into the subsurface (Parsons, 2004).

Winter (1999) documented the reversal of the direction of ground water flow resulting from the hydraulic head caused by a reservoir formed by the construction of a dam. Excessive pumping of boreholes around water bodies could result in reversals of hydraulic gradient and the capturing of the ambient ground water flow that would have otherwise discharged as base flow to streams, (Sophocleous, 2002), causing stream depletion by induced recharge. (DWAF, 2003)

The dynamics of stream depletion is thoroughly explained by Sophocleous (2002). He indicated that, prior to the development of wells, aquifers approach a state of dynamic equilibrium as a result of long years of recharge offset by long years of discharge. When water is discharged from boreholes the dynamic equilibrium is disrupted. During the early stage, discharge to streams is captured by the borehole, resulting in reduced base flow. With time, water starts to flow from the stream to the aquifer as induced recharge. This may establish a new dynamic equilibrium, whereby induced recharge equals abstraction. The length of time required for equilibrium to be reached between the surface water and ground water flow depends on three factors: aquifer diffusivity, which is expressed as the ratio of aquifer storativity and transmissivity, the distance from the well to stream and the time of pumping. These are the three critical physical parameters affecting the impact of pumping on base flow. (DWAF, 2003)

Diffusivity controls how fast transient head changes transmit through the aquifer system (Sophocleous, 2002). Once a new equilibrium is attained, the discharge from the well is balanced by flow diverted from the streams. Under such conditions, sustainable ground water resources development based on the principle that safe yield equals recharge is misleading, as it ignores the contribution to ground water from stream base flow. Similarly, the concept of a safe ground water yield based on maintaining flow to a river is nonsensical as the impact on base flow is not only dependent on abstraction but also on diffusivity, distance from the stream channel and degree of hydraulic connection.(DWAF, 2003)

The effect of pumping a single borehole will generally remain at a local scale. However, regional-scale abstraction from a well field or multitude of boreholes could significantly reduce flow in a surface water body on a regional scale. The effect of pumping may only be realised years after pumping started, depending on the rate, volume and duration of ground water abstracted and the distance between the river and the abstraction points. (Parsons, 2004)

Forestry is another stream flow reduction activity (Scott and le Maitre, 1997). By assuming base flow was equivalent to ground water discharge, Scott and le Maitre (1997) concluded plantations resulted in a decrease in base flow, and by inference, a markedly reduced ground water discharge. They suggested the roots of the trees could either abstract water directly from the water table (10 m) or could upset the water balance by taking water from the unsaturated zone. This would result in less water percolating beyond this zone as a greater soil moisture deficit would have to be satisfied before water could gravitate beyond into the saturated zone i.e. reduction in recharge (Parsons, 2004).

4.5 Determining Ground water Surface Water interaction

4.5.1 Base flow separation

It is commonly believed that base flow has its origin from ground water discharged into streams, and that estimates of base flow provide an indication of minimum levels of recharge. This method was used by Vegter and Pitman (1996). This, however, is a misconception as base flow comprises both interflow and ground water contribution to the river flow. Hughes (2003) observed that estimates of base flow are up to 10 times greater than the expected recharge. Ground water contribution to river flow may indicate the minimum recharge in the area, but care must be taken to differentiate between interflow and ground water during the base flow separation.

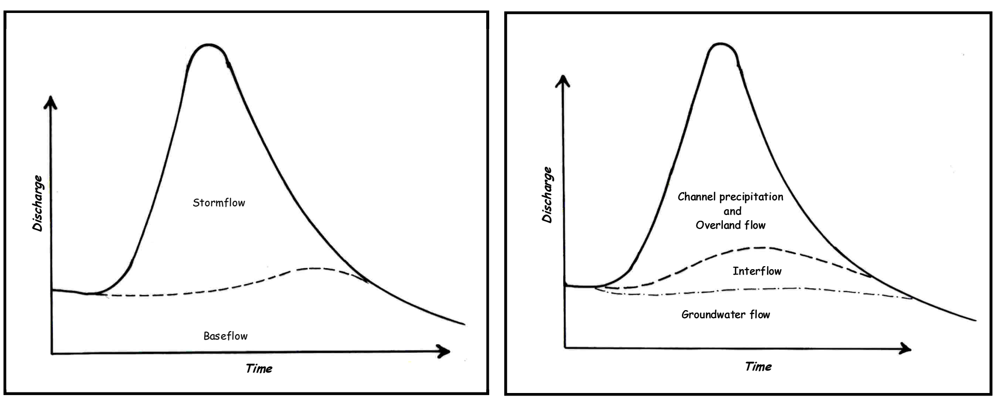

Figure 10. Illustration of base flow, interflow and stream flow on a flow hydrograph (Parsons, 2004)

Hydrological separation techniques are used to separate base flow from total stream flow hydrographs, but generally cannot distinguish between ground water base flow and base flow originating from other subsurface pathways that may not be in hydraulic connection with the regional aquifer (Parsons, 2004).

The value of base flow separation, however, must not be totally dismissed as use of low flow data to quantify the ground water contribution to river flow remains a viable tool. Examination of base flow after prolonged periods without rain may give a good indication of the ground water contribution to flow.(Parsons, 2004) Examination of base flow after extended dry periods was shown to be meaningful by Papini et al (2001) and Parsons (2003) in the Hex River and Thukela River catchments respectively.

For base flow separation techniques to be effective it is necessary to examine the base flow during and after dry periods. It is also recommended that a process based approach is used taking into consideration other indicators. A comprehensive description of ground water - surface water interactions in the TMG aquifer is discussed within the Colvin et al WRC report (2009). The ground water fed base flow is reportedly mainly contributed by springs in the upper part of the river system. The environmental importance of TMG aquifers, specifically in providing base flow to rivers, was shown by Cleaver et al (2003) in a WRC funded study in the Kammanassie Mountains.

Base flow separation techniques are broadly divided into two groups, graphical, which tend to focus on defining the points where base flow intersects the rising and falling limbs of the quick flow response, and filtering, which involves data processing of the entire stream.

An important factor affecting ground water and stream flow interaction is geomorphology and Xu et al (2003) suggested that it is important to characterise a stream in terms of its geomorphologic features and recommended a geomorphologic classification of streams based on their location in upper, middle and lower areas of a catchment and the type of ground water and surface water relationships that could take place. Based on the above classification Xu et al (2003) identified six types of geomorphologic streams which indicate the base flow separation concept as well as the significance of each type of stream on the environmental reserve (Figure 11 and Table 4).

Hydrogeomorphologic Approach

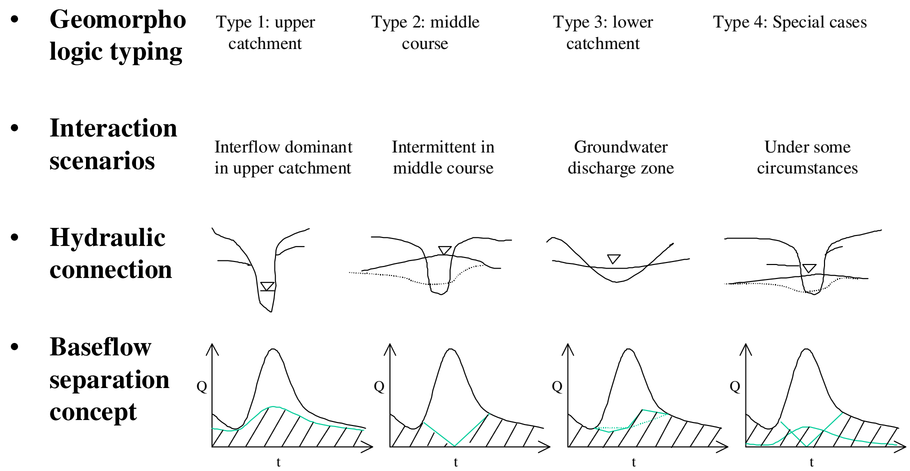

Figure 11. Hydrogeomorphological classification of rivers. (Xu et al, 2003)

Table 4 Type of interaction between ground water and rivers (Xu et al, 2003)

Geomorphologic type		**Description of Interaction**	**Significance to Environmental Reserve**
A–stream without bank storage	1	interflow dominant	No
B-stream controlled by bed morphology	2	Intermittent stream	Yes
C–stream with bank storage	3	Effluent streams, bank storage of high river flows (gaining stream)	Yes
D–stream influenced by channel morphology	3	Effluent streams (gaining stream)	Yes
E–stream controlled by geological structures	3	Effluent streams (gaining stream)	Yes
F-stream with headwater originating as allogenic source	4	Ephemeral, transmission losses possible	No

4.5.2 Use of physical data

While flow logging within streams and rivers is relatively easily achieved, to measure ground water flow below the land surface is considerably more challenging. In Colvin et al (2009) it was noted that temperature and water level responses were shown to be useful physical indicators which can be linked to the reservoir size and responsiveness to changing local boundary conditions. Thus by simply monitoring these two parameters it may prove useful in linking both streams and springs to ground water.

4.5.3 Chemical methods

A number of chemical methods also exist for determining ground water – surface water interaction. The biogeochemical processes within the upper few centimetres of sediments beneath nearly all surface water bodies (hyporheic zone) have a profound effect on the chemistry of the water interchange. (Sophocleous, 2002)

Hydrochemical fingerprinting is a means of linking surface water to ground water. Colvin et al (2009) reports that due to the inert nature of the TMG quartzites, it is difficult to trace different flow paths and differentiate water sources partitioned through different reservoirs in the natural landscape. Dissolved silica and radon have however been shown to be useful chemical tracers for aquifer flow. (Colvin et al, 2009). In some cases microbreccia, mylonite, iron and manganese oxides are present (Meyer, 2001), and could affect the ground water chemistry. (Colvin et al, 2009).

The radon emanation method is an effective tool to detect the concentration of ground water (Levin, 2000). This method is based on the nuclear disequilibrium process of the isotopes of the uranium family of which the radioactive decay series by alpha recoil process is from 234U through 230Th and 226Ra to 222Rn. Because uranium in ground water is soluble under oxidizing conditions, the distribution and magnitude of the radioactivity of the U family consequently reflects the ground water concentration in the aquifer. Therefore the radon isotope 222R is often employed as a natural ground water tracer, and is particularly useful for indicating open fractures in a fractured rock aquifer. (Xu et al, 2009)

A form of hydrograph separation also exists which uses conservative chemical constituent concentrations. Constituents with distinguishable concentrations in surface and subsurface waters are used, including chloride, hydrogen and oxygen isotopes, or silica. Once the chemical concentrations in rainfall (assumed to be equivalent to direct runoff), stream flow and ground water are characterized base flow is generated according to equation 2 below (DWAF, 2003).

2 - $Qg = QT \left((Cr-Cd) / (Cg-Cd)\right)$

(Where Qg is base flow volume, QT is the total streamflow; Cd, Cg and Cr are concentrations in surface runoff, ground water and river, respectively (DWAF, 2003).

4.5.4 Isotopes

Isotope analyses provide a useful tool in linking ground water and surface water in many circumstances. Previous isotope work within the TMG by Colvin et al (2009) suggest that the mixing of ground water derived from different temporal intervals is more complex than was anticipated and that isotopic signatures, in the case of the TMG, may not be reliable indicators of wetland sources.

Colvin found that the range of deuterium values (per mille) sampled at different sources within the Kogelberg did not show any significant contrast and that it is therefore not a reliable tracer for different flow paths in this catchment.

5 Regional Setting

The Oudebosch Valley located in the Western Cape Province of South Africa, between the coastal towns of Betty's Bay and Kleinmond. As has been mentioned, the City of Cape Town Municipality intends to abstract large volumes of ground water from the Peninsula Formation, arguably the most significant aquifer formation within the TMG. The Peninsula Formation is also the thickest formation (575 – 2000 m) within the TMG and is composed predominantly of thick bedded, coarse grained quartzitic sandstone (Theron et al, 1992). Figure 72 (Appendix A) shows the extent of the TMGA, and in particular the Peninsula Formation. The Oudebosch Valley, the study area for this study, is indicated on the map.

The climate of the area is one of predominantly winter rainfall as a result of cold fronts that brush the southern parts of South Africa. The coastal fold mountains also result in orographic rainfall along the coast to a lesser degree. The Western Cape has a Mediterranean climate with relatively moderate temperatures as a result of the affects of the Atlantic and Indian Oceans.

5.1 Topographical Setting

The topography of the South Western Cape is controlled predominantly by the geology of the TMG which forms a regional scale network of folds and faults. This has lead to fold mountains, with synclinal and fault controlled valleys.

5.2 Geological setting

The Cape Supergroup has a maximum thickness of 5 300 m and 9 600 m in the Western and Eastern Capes respectively (SACS, 1980). Deposition of the sediments that make up the Cape Supergroup occurred in a shallow marine environment under tidal, wave and storm influences, as well as in a non-marine braided-fluvial environment. The sequence is predominantly siliclastic and is exposed along the orogenic belt which straddles the west and south coasts of South Africa, known as the Cape Fold Belt (CFB). The CFB consists of two branches forming a mountain chain of about 1 200 km along the south coast and part of the west coast (De Villiers, 1944; Söhnge and Hälbich, 1983). The outcrop of the southern branch is about 200 km, and of the western branch, about 150 km. Both branches are arc shaped and concave towards the coast with northeast-trending folds in the syntaxis of the South-western Cape.

The initial deposition took place within an east-trending basin (Rust, 1973) along the southern and south-western Cape regions. The deposited sequence was then subjected to two major tectonic events, the Cape Orogeny and the fragmentation of South-western Gondwana. The Cape Orogeny resulted in the tectonic thickening of the sequence in areas of high strain like the Southern Cape. It also resulted in further deformation of the metamorphosed Neoproterozic rocks, the Cape Granite Suite, together with its cover sequence of Ordovician to Triassic rocks (Cape Supergroup and part of the Karoo Sequence).

The sequence is comprised of a succession of quartz arenites, shales and siltstones, with minor conglomerate and thin diamictite units. It has be divided into the Table Mountain, Bokkeveld and Witteberg Groups (Du Toit, 1954; Rust, 1967; Theron, 1962; Theron and Loock, 1988; Broquet, 1992). Some of the quartz arenites form favourable ground water targets with regard to both water quality as well as exploitation potential. This is due to coarse to medium grain sizes, the pure nature of the quartz and the brittle fracturing as a result of the folding and faulting in the CFB.

5.2.1 Stratigraphy

The stratigraphy of the Cape Supergroup consists of predominantly sedimentary and metamorphic rocks. The Cape Supergroup overlies the basement rocks of the Cape Granite Suite and Malmesbury formation and underlies the formations of the Karoo Supergroup. The Cape Supergroup is made up by the TMG, Bokkeveld and Witteberg Groups, of which only the TMG is relevant to this study. Figure 12 summarises the lithologies of the Cape Supergroup, the respective thicknesses and graphically depicts the Geological sequence.

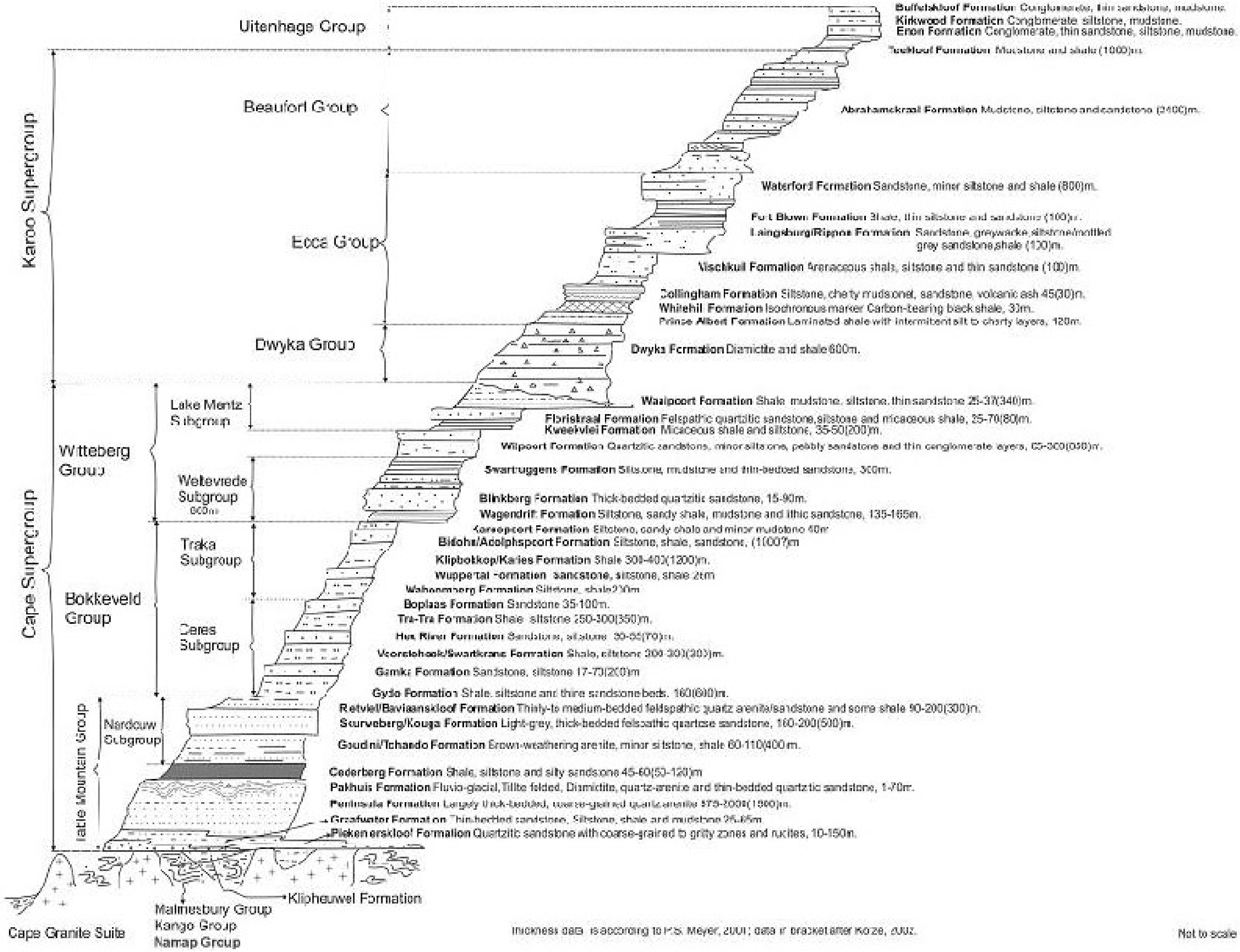

Figure 12. Geological sequences of the Cape Supergroup and surrounding Groups. (Wu, 2005)

The TMG is a ~ 4000 m thick sequence of quartz arenites and minor shale layers deposited in a shallow but extensive basin. The formation has a maximum thickness (in Port Elizabeth) of about 3010 m (Rust, 1973). The formations that constitute the TMG are the Piekenierskloof Formation, Graafwater Formation, Peninsula Formation, Parkhuis Formation, Cedarberg Formation and Nardouw Subgroup. Table 5 shows the lithostratigraphy and Formation thicknesses.

Table 5. Geohydrology of the TMG taken from Colvin et at (2009). Lithostratigraphy from De Beer (2002) and hydrostratigraphy from Hartnady and Hay (2002). Thickness values mostly apply to south-western outcrops.

Lithostratigraphy			Lithology	Maximum thickness (m)	Hydrostratigraphy		
Group	Subgroup	Formation			Subunit	Unit	Super unit
Table Mountain	Nardouw	Rietvlei	feldspathic sandstone; minor shale at base	280	Rietvlei Subaquifer	Nardouw Aquifer	Table Mountain Superaquifer
					Verlorenvalley Mini-aquitard		
		Skurweberg	thickly bedded quartzitic sandstone	290	Skurweberg Subaquifer		
		Goudini	reddish brown quartzitic sandstone and siltstone	230	Goudini Meso-aquitard	Winterhoek Mega-aquitard	
		Cedarberg	dark grey shale and siltstone	120	Cedarberg Meso-aquitard		
		Pakhuis	diamictite and quartz sandstone	40	Pakhuis Mini-aquitard		
		Peninsula	thickly bedded quartzitic sandstone, finer towards base	1800	Platteklip Subaquifer	Peninsula Aquifer	
					Leeukop Subaquifer		
		Graafwater	siltstone and shale	420	Graafwater Meso-aquitard		
		Piekenierskloof	conglomerate, sandstone and minor shale	900	Piekenierskloof Subaquifer		

The lower most formation in the TMG is the Piekenierskloof Formation or the Graafwater Formation. The Piekenierskloof Formation is quartzitic sandstone with coarse-grained to gritty zones, it has a thickness ranging between 10-150 m (Meyer, 2001). The Graafwater Formation has thickness of 25-65 m and comprises of thin - bedded sandstone, siltstone, shale and mudstone (Meyer, 2001).

The name of the Peninsula Formation is derived from Table Mountain and the Cape Peninsula (Rust, 1967) where the full 550 m succession is exposed. The formation comprises a succession of coarse-grained, white quartz arenite with scattered small pebbles and discrete thin beds of matrix-supported conglomerate (Wu, 2005). In the west the formation is about 1 800 m thick near Clanwilliam (Rust, 1967), and is reportedly much thicker in the Eastern Cape (Rust, 1973). The exact unit thickness is difficult to measure due to thickening as a result of thrusting (Booth and Shone, 1992) and the highly folded nature, and the lack of marker subunits. Fuller and Broquet (1990) however identified two informal members within the formation separated by a meter thick conglomerate (probably equating with the Slanghoek Member of Rust, 1967).

Overlying the Peninsula formation is the 40 m thick succession of glacially derived sediments known as the Pakhuis formation. This formation is restricted to the south-western Cape (Broquet, 1992; Rust, 1967).

The prominent marker unit, namely the Cedarberg Formation, is a shale, siltstone and silty sandstone unit with a thickness that varies from 50 to 120 m. The Cedarberg Formation is an aquitard and a prominent ground water flow and recharge boundary. The formation forms a prominent marker band between the Peninsula formation and the Nardouw Subgroup.

The Nardouw Subgroup constitutes the Goudini, Skurweberg and Rietvlei (Baviaanskloof in the Eastern Cape) Formations and varies between quartz arenite, silty and feldspathic arenites, and minor interbedded conglomerates and shales. The subgroup is thick (maximum 1 200 m) and has varied weathering, structural and hydrogeological characteristics due to the lithological diversity and textural, grain size and bedding thickness differences (Wu, 2005).

The Goudini Formation is the basal unit and is characterised by reddish weathering, thin sandstone beds with common shale intercalations. The overlying Skurweberg Formation is a thick-bedded arenite. The topmost unit, the Rietvlei Formation, contains more feldspar and is commonly identified in the field, along with the previously discussed Cedarberg Formation, by the type of vegetation growing on it. The contact with the overlying dark shale of the Bokkeveld Group is usually abrupt.

The basement rocks beneath the TMG are comprised of the Maalgaten Granite and a variety of sedimentary and metamorphic rocks, respectively belonging mainly to the Cango and Kaaimans Groups. The cratonic sheet sandstones (Rust, 1967; Tankard et al, 1982) of the TMG in the lowest part of the Cape Supergroup form the backbone of CFB from Vanrhynsdorp in the west to Port Elizabeth in the east. Alluvial valley deposits are associated with the larger river channels, while colluvial (slope) deposits produced by sheet-wash, occur on gently sloping surfaces away from the river channels. (Wu, 2005).

5.2.2 Structural Geology

Chapter 5.2 (Geological setting, page 38) describes the two major tectonic events that the TMG has been subjected to. During the Cape Orogeny the geology of the CFB was subjected to severe north-south orientated compressive stresses. This is the predominant cause for the variety of the geological features and structures present. The CFB consists of two branches, namely a western branch and a southern branch. These form a mountain chain that lie along the southern and western coasts of South Africa. The two branches meet in a 100 km wide syntaxis area, comprising NE-trending folds between Ceres and Gansbaai (Wu, 2005). The project study area is found within this area and Figure 74 (Appendix A) depicts the syntaxis area and shows the structural geology of the TMG.

The compressional deformation during the Cape Orogeny was followed by extensional tectonics during which the Uitenhage Group was deposited within numerous fault-bounded basins, reaching a thickness of > 2000 m in places. The examples of the extensional tectonics include the following (Duvenhage et al, 1993):

- Reverse faults associated with over-folding during the Cape Orogeny,
- Cango Fault (CF), a reverse fault on a previous thrust fault plane,
- Several more recent normal faults

Several examples of recent tectonic activity (neo-tectonics) exist in the south-eastern Cape (Andreoli et al, 1989; Hill, 1988; Hattingh and Goedhart, 1997; Hartnady, 1998) and Karoo (Woodford and Chevallier, 1998). The tectonic activity suggests that an extensional tectonic regime continues to prevail, with an extension in a north-northeast - south-southwest direction and compression in a west-northwest – east-southeast direction. These features are associated with (Wu, 2005):

- The Cape Orogeny (north-south, northwest-southeast, northeast-southwest, east-west (thrusting) systems),
- Gondwana break-up (extensional tectonics): development of east-west oblique shears.
- Extension with a right-lateral shear component and reactivation of earlier fractures (east - west, west-northwest, and north-south).
- Tertiary to present time: continuation of the extensional stress regime in a north-northeast-south-southwest direction.

The east-west striking branch of the CFB contains long, continuous east-west and west-northwest trending faults which are visible on the 1:250 000 maps. From satellite lineament mapping a more detailed representation of the most predominant fracture sets is attained, which shows east-west, west-northwest and east-northeast trending fracture sets (Wu, 2005).

The north-south trending fracture system consists of shorter, more discontinuous fractures, which generally corresponded to a dense network of north-northwest – south-southeast, north-northeast - south-southwest trending joints and subordinate north-south trending joints, often not showing any displacements on geological maps or satellite images (Wu, 2005). These fractures or joints are a result of the Cape Orogeny and the fragmentation of Gondwanaland.

Most of the east-west trending fractures represent normal faults, with variable components of oblique, often right lateral movement, associated with continental break-up. West-northwest trending fractures may represent Riedel-shears, while east-northeast trending fractures may represent the P-shear direction (Wu, 2005).

The orientation of thrust faults formed during the Cape Orogeny were also east-west trending or parallel and curved with respect to the general trend of the CFB. North - south trending fractures display large variations in geographic distribution. The north-northwest, north-northeast and north - south trending fractures have left a strong overprint over the CFB structures.

As part of the TMG study by TMGA-EMA (2010), geological cross-sections were drawn for significant parts of the study area. A cross section was drawn through the Oudebosch Valley showing the major faults and geology (Figure 75, Appendix A).

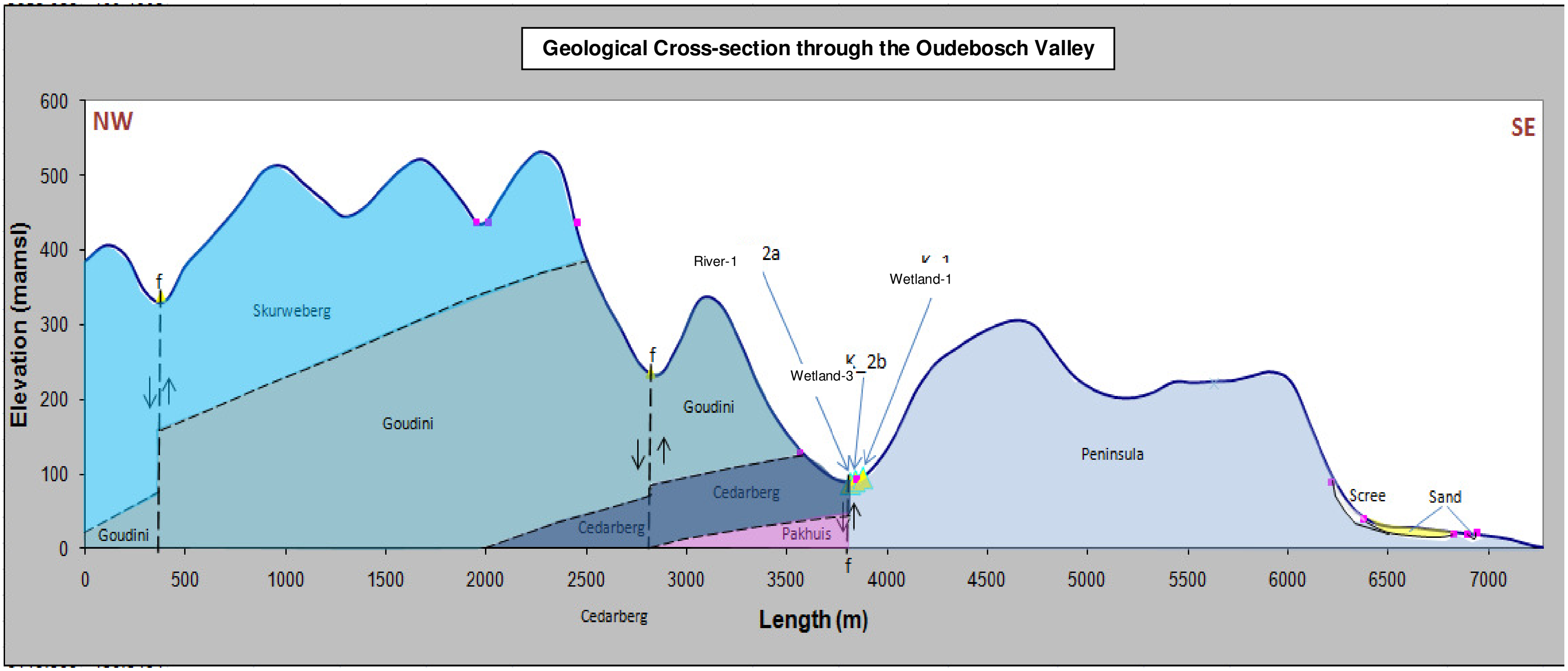

Figure 13. Cross-section through the Oudebosch Valley taken from TMGA-EMA (2010). Cross-section line indicated on Figure 75 (Appendix A).

The cross-section for the profile line that transects the Oudebosch Valley is then shown in Figure 13. In these figures the sites site names are different to those used in this study, and the sites K_2a, K_1 and K_2b relate to sites River-1, Wetland-1 and Wetland-3 respectively.

5.3 Hydrological and Geohydrological setting

The geology also has controls on the hydrology to a large degree with rivers, particularly high order streams, commonly occurring along faults zones. The main river within the Kogelberg region is the Palmiet River which flows from the Nuweberg Mountains in the north towards the coast where it flows out at Kleinmond. The Palmiet River is perennial and ground water and interflow contribute to the flow. The ground water contribution is most significant during the dry summer months. Ground water discharge in a bedrock stream environment occurs primarily through discrete point sources associated with open fractures, as compared to more diffuse, or continuous seepage zones often observed in a porous media environment (Jaime et al, 2002). In the TMG, ground water discharge is mostly locally restricted and linked to lineaments such as fractures or faults (Colvin et al, 2009). The subsurface plays a critical role in storing and releasing precipitation inputs to aquatic and terrestrial ecosystems. The storage and release occurs across a continuum of permeability scales determined by the lithology and structural history of the TMG (Colvin et al, 2009).

The Peninsula Formation is considered a good aquifer (Meyer, 2001). It is a fractured secondary aquifer and its hard and brittle nature means that it is prone to fracturing, which is favourable for ground water flow. The quartzitic nature of the formation results in ground water having a low total dissolved solids (TDS) content, although the pH is typically low (acidic) and the water is sometimes termed "aggressive" – i.e. it easily corrodes piping and metal. It is typically a "soft" water and often the main problem with the use of the water is its "aggressiveness" and the presence of iron and manganese. The Pakhuis Formation is considered a mini-aquitard – i.e. not favourable for ground water flow. The more complex mineralogy also results in a higher TDS. The Cedarberg Formation is considered a meso-aquitard i.e. no flow occurs through this formation. The soft ductile nature of the shale is cause for the lack of fracturing within this formation. The complex mineralogy of the shale also results in the high TDS ground water. Although the Goudini Formation is more arenaceous it is still considered a meso-aquitard and thus not favourable for ground water development.

The structural complexity of the TMG, evidenced in the folding, faulting and fracturing, means that it does not display uniform aquifer characteristics (Meyer, 2001). An intricate network of fissures, joints, fractures and even cavities govern the infiltration, storage and transmission of water within the aquifer. A further characteristic of the TMG is the abundance of springs which are either fault controlled, lithologically controlled or controlled by small fractures and fissures (Meyer, 2001).

6 Local Setting

The Oudebosch Valley is located within the Kogelberg reserve, located to the east of Betty's Bay. The reserve has a diverse population of fynbos species and is one of the most important ecological sites within the Western Cape. The Oudebosch Valley is shown in Figure 73 (Appendix A) bisected by the Oudebosch River which runs from the Oudebosch peak at 339 mamsl to the Palmiet River.

6.1 Topography

The area is mountainous, with a structurally complex geology. The topographical setting of the area is controlled to a large degree by the extremely hard and weathering resistant quartzites and the extensive faulting prevalent in the area. The elevation of the study area ranges from 50 mamsl near the Palmiet River at the base of the Oudebosch Valley, right to the high mountain peaks which define the valley itself. Details regarding the topography were obtained from Colvin et al (2009) who surveyed the area. The highest peak, Platberg at 909 mamsl, forms the northern flank of the valley while the southern flank reaches a maximum height of 552 mamsl (Colvin et al, 2009). The Oudebosch River is a perennial river that flows SW-NE from 339 mamsl from the head of the valley to the Palmiet river at 50 mamsl. The river is about 3 km long and is fed by smaller seasonal streams as it moves down the valley.

6.2 Climate

Although situated in a winter rainfall region, rainfall occurs all year round. The heaviest and most common rainfall events are caused by cold fronts that occur predominantly during winter. The distribution of the rainfall is mostly controlled by orographic effects and Colvin et al (2009) reports that the peak to the north of the valley (Platberg) receives between 1400 and 1600 mmpa.

A weather station is located at the bottom of the Oudebosch Valley in front of the Kogelberg office. The modelling of the spatial distribution of mean annual precipitation (MAP) suggests a MAP of 600 mm in the Oudebosch Valley (DWAF, 2007). This however is an underestimate and for the complete data record obtained from the weather station between 10 July 2009 until 17 July 2010 a total of 1 311 mm of rainfall fell. Of the 401 days for which data was obtained, rain fell on 37.4% of them: 12.7% >10 mm, 6.7% > 20 mm and 8.0% >30 mm. The highest recorded daily rainfall is 64.52 mm which fell on the 12 July 2009. The month in which the most rainfall fell was May 2010 in which 209 mm of rainfall was recorded. The total rainfall for the year period between 17 July 2009 and 17 July 2010 is 1.067 m.

From the obtained data, the highest temperatures occurred during January, February and March, and the lowest during June, July and August. A maximum temperature of 41.03 was recorded on 8 March 2010 and a minimum temperature of 0.5℃ was recorded on 15 June 2010.

As part of the WRC project Colvin et al (2009) collected data from the exact same weather station from May 2004 until July 2007, and this data indicates less rainfall in volume, but more days with rainfall. In 2005 and 2006 Colvin et al (2009) reports 1000 and 910 mm respectively. Of the 1158 days monitored it is reported that 64% experienced rainfall: 9% > 10 mm, 4% > 20 mm and 2% > 30 mm. The highest reading of 183 mm was recorded in April 2005, and further observations suggest that the highest daily rainfall occurs between the months of May and October.

With regards to temperature, Colvin et al's (2009) data is highly comparable to that measured. Colvin et al (2009) reports that the highest temperatures occur in January, February and March. The lowest temperatures are recorded during June, July and August. For the period of data, a maximum temperature of 40℃ was recorded in February 2006 and a minimum temperature of 0℃ in June 2007. Both the seasonal and diurnal variation of maximum and minimum temperatures range over 10 - 15℃.

6.3 <u>Geology</u>

The geology of the Oudebosch Valley is documented in the WRC research report by Colvin et al (2009). The geology map of the site (Figure 76, Appendix A) is shown below, and indicates the formations and faults present in the study area. A north-south geological cross-section has been drawn across the study site (Figure 14), the position of which is indicated on Figure 76 (Appendix A). The cross-section also indicates the position of the artesian borehole, one of the study sites for this project, and the Palmiet River. The geological thickness of the formations is based on literature and boreholes logs. The geological dips of the formations are also indicated.

6.3.1 Stratigraphy

The oldest formation outcropping in the study area (Figure 76, Appendix A) is the Peninsula Formation of the TMG. This formation outcrops to the south of the Oudebosch Valley as well as to the west in the lower reaches near the Oudebosch offices. The Pakhuis formation, the next (i.e. younger) formation in the TMG, is not present in the vicinity of the Oudebosch Valley, but is seen outcropping north of the Palmiet River where it conformably overlies the Peninsula Formation. This formation also conformably underlies the Cedarberg Formation within the Oudebosch Valley.

Table 6. Geological formations in and around the study area

Formation	Sub-Group	Group
Skurweberg (Ss)	Nardouw	Table Mountain Group
Goudini (Sg)		
Cedarberg (O-Sc)	-	
Pakhuis (Opa)		
Peninsula (Ope)		

The bulk of the Oudebosch Valley is comprised of shales of the Cedarberg Formation (dark-grey massive shale). This formation lies adjacent to the Peninsula Formation as a result of a faulted contact. The fault zone trending NE/SW (discussed in more detail later on) along the southern side of the valley is downthrown to the north and has displaced the quartzites of the Peninsula Formation against the Cedarberg Formation.

To the north of the Cedarberg Formation the Nardouw Sub-Group outcrops, and more specifically the Goudini Formation. The Goudini Formation comprises thin bedded quartzitic sandstone. Although not shown in Figure 76 (Appendix A), the Skurweberg Formation conformably overlies the Goudini Formation and outcrops to the north of the area covered. Table 6 lists the formations within the study area and immediate vicinity.

6.3.2 Structure

The study area and immediate vicinity contains mega-faults extending for 10s of kilometres evident on the 1:250 000 scale geological maps. The smaller faults (Meso-scale), fractures and bedding plane structures are prevalent in both the Peninsula and Skurweberg Formations, the two most significant TMG formations with regard to aquifer potential.

The Hangklip-Riviersonderend Megafault (HRM) system is evident in the system of faults in the mountains north-east of Cape Hangklip, where they cross-cut the main syncline (TMGA-A, 2004). The HRM is also a significant eastern boundary structure to the southern segment of the Villiersdorp Syncline (TMGA-A, 2004). The HRM itself is comprised of significant mega-structures, and the study area is located down gradient of multiple potential recharge areas linked to these structures (Colvin et al, 2009). It is also thought to be an important discharge zone to both the Oudebosch stream, Palmiet River and their respective Riparian zones (extended wetlands) (Colvin et al, 2009).

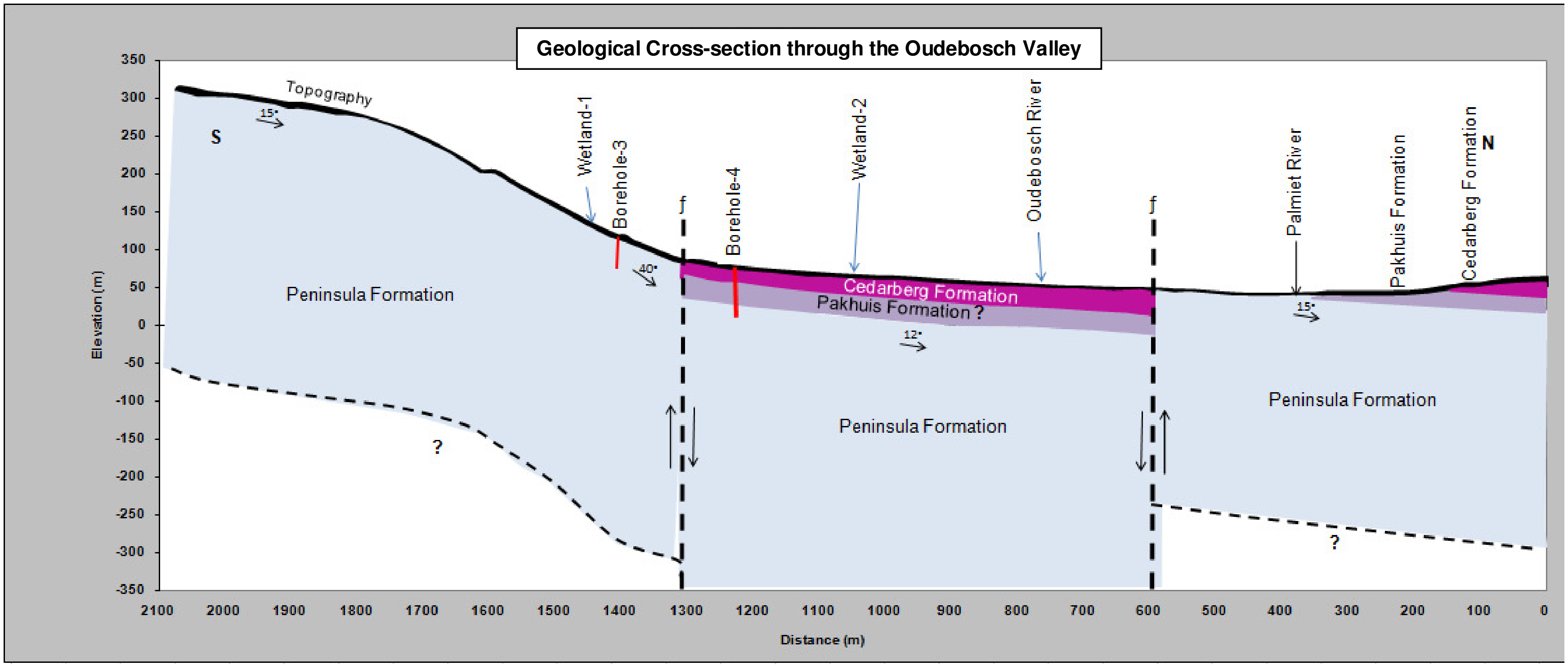

Figure 14. Geological cross-section (South-North) modified from Conrad (2009). Profile Line indicated in Figure 76 (Appendix A).

The dominant structures and HRM are northeast to east-northeast/west-southwest striking normal faults. The Palmiet River, in this part of the reserve, follows a northwest-southeast fault towards the coast, with perennial tributaries controlled by northeast/southwest trending faults (One of which is the Oudebosch valley fault).

Subordinate northwest to west-northwest striking fault sets cross-cut both the Skurweberg and Peninsula Formations and are related to springs, tributaries and small wetlands. According to Colvin et al (2009) these are thought to represent shallow to moderate length flow paths with low to moderate discharge rates in discrete, structurally controlled zones.

The fault which defines the Oudebosch valley (Figure 76, Appendix A) is a mega-fault which extends south west into the Harold Porter Botanical Gardens, and north-east for approximately 22 km where it forms part of the Kleinmond-Botrivier fault, which in turn joins the Greyton fault (Colvin et al, 2009).

6.4 Hydrology and Geohydrology

The lithology and structural characteristics of the TMG control the flow of both surface and ground water in the study area, with the main river systems flowing generally parallel to the fold axes in the synclinal valleys, with tributaries following fracture and fault orientations. These are generally perpendicular to the fold axes. The Oudebosch River that flows through the study area, and is monitored by monitoring site River-1, flows along a major fault zone in its upper reaches and then flows northeast across the down faulted wedge of Cedarberg Formation. The river is perennial although it is low flowing during the summer months. During winter numerous ephemeral and seasonal tributaries within the Oudebosch Valley contribute to the flow in the Oudebosch River.

The most favourable aquifer within the study area is the Peninsula Formation with its hard and brittle nature making it prone to fracturing. The Pakhuis Formation represents a mini-aquitard while the overlying Cedarberg Formation and Goudini Formations are considered to be meso-aquitards.

The Cedarberg Formation has a soft and ductile nature limiting or resisting fracturing. For this reason direct ground water recharge within the Oudebosch Valley will be limited in the Pakhuis/Cedarberg and Goudini Formations. Recharge of ground water in the area occurs primarily in the Skurweberg and Peninsula Formations. Recharge of these formations in this area is expected to be both regionally and locally driven, based on the scales of the structures linked to proximal (Platberg) and distal (Botriver) recharge areas (Colvin et al, 2009).

As part of the City of Cape Town TMG monitoring, sites in and around the Oudebosch Valley were monitored, as indicated in Figure 73 (Appendix A). Based on the obtained data, yields within the Peninsula Formation are relatively low, yet highly variable. For the unconfined Peninsula Formation the yield ranges from <1 ℓ/s to 6 ℓ/s. For the confined Peninsula Formation the average yield is 8 ℓ/s. The ground water quality is characterised as being slightly acidic with a low total dissolved solids content. The ground water does contain iron and manganese and these concentrations vary considerably.

6.4.1 Ground water Recharge

The Peninsula Aquifer is the thickest and most regionally extensive aquifer. The exposed, un- to semi-confined portions of the Peninsula Aquifer contribute to river flow mainly as direct surface runoff and interflow, but may also contribute to base flow where crossed by major rivers and mountain headwater streams (Colvin et al, 2009). Within the Kogelberg reserve area the Peninsula Formation is the dominant unit forming high continuous mountainous ranges. The recharge potential is therefore high, as it is throughout the Western Cape where recharge estimates of up to 50% of mean annual precipitation (MAP) are reported (Weaver et al, 1999). DWAF (2000) estimated the recharge in the Citrusdal area, with a spatially weighted average of 23% MAP. Xu et al (2007) gives recharge estimates for the whole TMG between 0.3% and 12.6%, with an average rate of 30 mm/a.

In contrast, the outcrop and recharge areas of the Skurweberg Formation generally underlie lower-range and hill slope areas alongside the higher Peninsula Formation mountain chains, mostly along northern or eastern, rain-shadow slopes (Colvin et al, 2009). The formation therefore receives less precipitation and has a lower recharge potential. Kotze (2001) estimates the recharge of the Skurweberg Formation to be 5% of MAP (in the Kammanassie Mountains).

A cumulative rainfall sample was collected on 14 November 2010, a mixture of the rainfall events occurring between June and November 2010. The sample was submitted to Bemlab for Chloride analysis with the intention of calculating recharge for the valley.

In order to use the Chloride Mass Balance application it is necessary to use the total Cl deposition which includes the dry atmospheric outfall occurring during dry periods. Estimation of this component is quite complex, especially the sampling procedure (Van Wyk, 2010). According to the Recharge Calculation Spreadsheet developed by Yongxin Xu and Gerrit van Tonder, if the dry deposition of Cl is unknown, the following approximations can be used:

0.1 x (Cl of rainfall) – For inland if no forest exists

2.5 x (Cl of rainfall) – If forest exist

3 x (Cl of rainfall) – If spray of mist/dust is a factor at the coast

The harmonic mean of the ground water Cl concentrations is 25.00 mg/ℓ, and the rainfall Cl concentration is 10.57 mg/ℓ. Therefore, by using an approximate value for the dry deposition of Cl, recharge can be calculated using the equation:

$R = TD/Cl_{gw}$

TD - Total chloride deposition at surface ($mg/m^2/a$)

Cl_{gw} - chloride concentration (mg/l) of ground water (harmonic mean of the Cl content in the boreholes)

If a conservative value (1 mg/l) is used for the dry deposition of Cl, the recharge is calculated to be 46.3%. If a value of 10 mg/l is used then the calculated value is 82.3%. This is a high recharge percentage, and is considered to be incorrect. Based on existing work conducted in the Western Cape, it is thought that the recharge for this area is in the region of 50% of MAP, as was determined by Weaver et al (1999).

6.4.2 Ground water Discharge

Within the semi-confined to confined nature of the Peninsula Formation within the Kogelberg region and around the Winterhoek aquitard contact, springs are hardly or not at all affected by ground water abstraction. In contrast, the unconfined Skurweberg Subaquifers are characterised by low volume seasonal springs. These are near surface lithological or structural features and are more responsive to rainfall (Colvin et al, 2009). The Skurweberg Formation also generally outcrops within synclinal basins, and can contribute to riverine base flow via direct inflow and through springs around the Winterhoek-Skurweberg aquitard-aquifer contact (Colvin et al, 2009).

7 Data Analysis

In this chapter the various study sites will be investigated with regards to ground water dependence. The dependence will be considered by looking at geohydrology, water levels, temperature, chemistry, isotope and hydrograph recession data. Each will be investigated individually. Ground water dependence will be allocated according to Table 2.

7.1 Geohydrological Setting

The occurrences of ground water in the TMGA, and specifically the Peninsula Formation Aquifer, are closely linked to geology. This chapter aims to investigate the geohydrological setting of all the sites (surface and ground water). The intention is to predict the ground water dependence of the wetlands and the Oudebosch River based on both their geological and topographical setting.

The Peninsula Formation outcrops in the eastern lower reaches and along the southern flank of the Oudebosch Valley. The Oudebosch Valley and greater Kogelberg area is an excellent ambient (background) monitoring area as ground water levels are not impacted by abstraction (TMGA-EMA, 2010). Four monitoring boreholes exist within the valley (Table 7 lists the boreholes and their respective locations) and each is discussed in Chapter '3.1.5 Ground water monitoring sites'.

Table 7. Borehole sites within the Oudebosch valley.

Site ID	Area	Type	Long	Lat	Elevation
Borehole 1	Kogel	BH	18.96995	-34.32154	44
Borehole 2	Kogel	BH	18.97728	-34.32465	45
Borehole 4	Kogel	BH	18.96488	-34.32626	70
Borehole 3	Kogel	BH	18.96439	-34.32721	80

All four of the discussed boreholes will be monitored for the purposes of this study, and the data considered to be representative of Peninsula Formation ground water in the Oudebosch Valley.

Three wetlands and the Oudebosch River are the four sites being investigated, and are therefore also monitored for the purposes of this study. The wetland sites were each monitored by means of a single peizometer, hand augered as deep as possible (down to bedrock). Two of the wetlands (Wetland 2 and Wetland 3) overlie the Cedarberg Formation, and one (Wetland 1) the Peninsula Formation. The Oudebosch River was monitored in its middle to lower reaches by means of a stilling well (River 1).

7.1.1 River 1

The Oudebosch River is located in the upper foothills of the Kogelberg Mountains and flows over colluvial valley bottom sediments that overlie the Cedarberg Formation Shales. The River is lined by riparian fynbos shrubland as well as plant species common to the south western species biome (TMGA-EMA, 2010). The vegetation is also classified as belonging to the Shale band vegetation Group by TMGA-EMA (2010).

The Oudebosch River flows down the middle of the Oudebosch Valley in a north-easterly direction towards the Palmiet River. The stilling well in the river (River 1) is located on the alluvial sediments overlying the Cedarberg Formation, and is in relative close proximity to the southwest/northeast striking fault which is downthrown to the northwest. The river is fed by tributaries that flow over the Goudini, Pakhuis and Peninsula Formations. These formations, in particularly the Peninsula Formation, are characterized by brittle fracturing and faulting which support springs. Within the Oudebosch Valley surface runoff flows into the Oudebosch River and it is therefore concluded that spring flow would contribute to the stream flow at River 1. The degree or volume of ground water contribution to River 1 is not possible to calculate from the geology but this will be investigated using additional techniques used in this study, in particular water level analysis and base flow separation. But based on the geohydrological setting, connectivity with the Peninsula Formation Aquifer is highly likely and the ground water contribution to the river flow is expected to be significant.

On 14 November 2010 two flow measurements were taken in the Oudebosch River, one at the stilling well River-1 and another 524 m upstream. The two sites are shown in Figure 77 (Appendix A). The intention was to investigate the contribution of ground water to the stream flow between these two points overlying the Cedarberg Formation. Both measurements were taken at exactly the same time (14 November 2010, 13:30).

The flow measurement at the Stilling well River-1 was 61.6 ℓ/s, similar to but about 4 ℓ/s more than that measured at the point up stream (57.7 ℓ/s). EC and Cl measurements were also taken at both sites and these show an improvement in water quality (lower values) at the lower site. This indicates that cleaner water is feeding into the river along its course despite the underlying Cedarberg Formation. Due to the argillaceous nature of the Cedarberg Formation, it is thought that this contribution comes from ground water and interflow.

Because Cl generally behaves as a conservative (nonreactive) solute, it can be used to indicate ground water contributions. Based on the two samples and flow measurements taken at the same time on 14 November 2010 (524 m apart) it is possible to calculate the volume of water flowing into the river between these two points as well as the Cl concentration of the inflow. Based on the increase in flow from 4985.28 m^3/d to 5322.24 m^3/d over the 524 m between the flow point1 and the site River-1 water is contributed to the River at a rate of 336.96 m^3/d. Based on the sampled Cl concentrations for the River samples (26.43 and 27.31 mg/ℓ at River-1 and flow point 1 respectively), the calculated Cl concentration of the inflow between these points is 13.41 mg/ℓ. This value is lower than the harmonic mean of the Cl concentrations obtained from the 40 samples collected from the four monitoring boreholes within the Peninsula Formation (25 mg/ℓ), and slightly elevated from that of rainfall (10.57 mg/ℓ measured for rainfall falling between June and 14 November 2010). The argillaceous Cedarberg Formation would be expected to result in considerably elevated Cl concentrations. The inflow is therefore thought to be predominantly interflow in the sediments overlying the Cedarberg Formation. A conceptual illustration is shown in Figure 15. The investigation of the relationship between interflow and ground water contribution to this site is discussed in the hydrograph recession analysis section of this document.

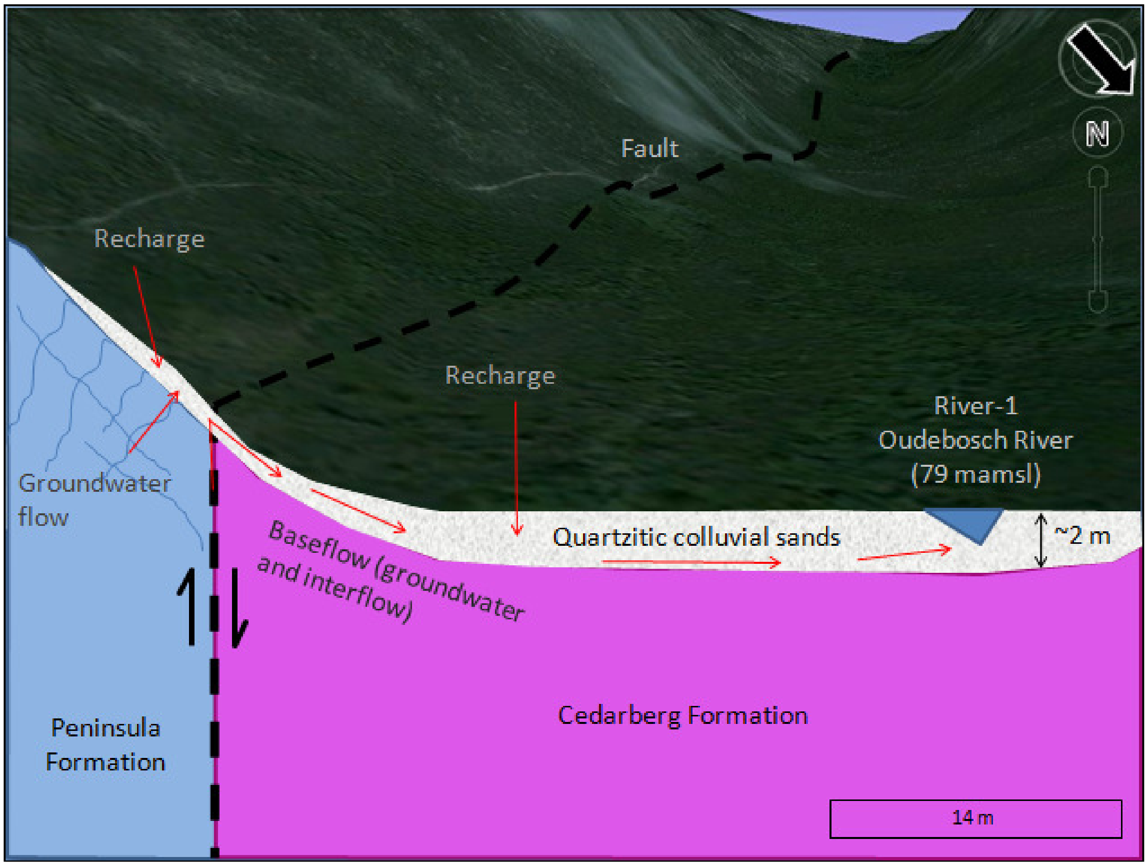

Figure 15. Conceptualization of the ground water contribution to the Oudebosch River at the site River-1.

In Colvin et al (2009) wetland location is related to possible aquifer discharge settings in the TMG. This table is included (Table 3) to aid in the geohydrological investigation of each wetland site, and based on the habitat of each site the various discharge settings are considered.

7.1.2 Wetland 1

Wetland 1 is a piezometer in a wetland located on the Peninsula Formation on the south eastern flank of the Oudebosch Valley, southeast of the faulted contact between the Cedarberg and Peninsula Formation. The wetland is located on the slopes above the Oudebosch valley at a relatively high elevation above the valley bottom, and there is a high probability that a wetland at this sort of location would be fed by ground water. The sediment thickness is shallow and the likelihood of a perched aquifer is highly unlikely. The thin alluvial layer consists of pure quartzitic sands with little organic material. The main plant community at the wetland is the *Psoralea pinnata*, and the wetland is a Myrsine Africana Shrubland Fynbos Wetland (TMGA-EMA, 2010). The wetland has a shallow water level (within 0.38 m of the surface) throughout the year.

Table 3 relates wetland location to aquifer discharge setting within the TMG. The table indicates that discharge could be as a result of features/structures including alluvium, lithological contacts and mega- or intermediate structures. At and around Wetland 1, bedrock of the Peninsula Formation outcrops and the alluvium thickness is shallow. It is suspected that the ground water discharge occurs as the result of intermediate structures linked/related to the mega-fault that runs up the valley. Figure 16 shows the fault structure running up the slope behind Wetland-1, exposed by the fire that burnt the valley on 4 June 2010. Borehole 3, at a lower elevation and nearer the mega-fault and contact with the Cedarberg contact, has a comparatively deep water level.

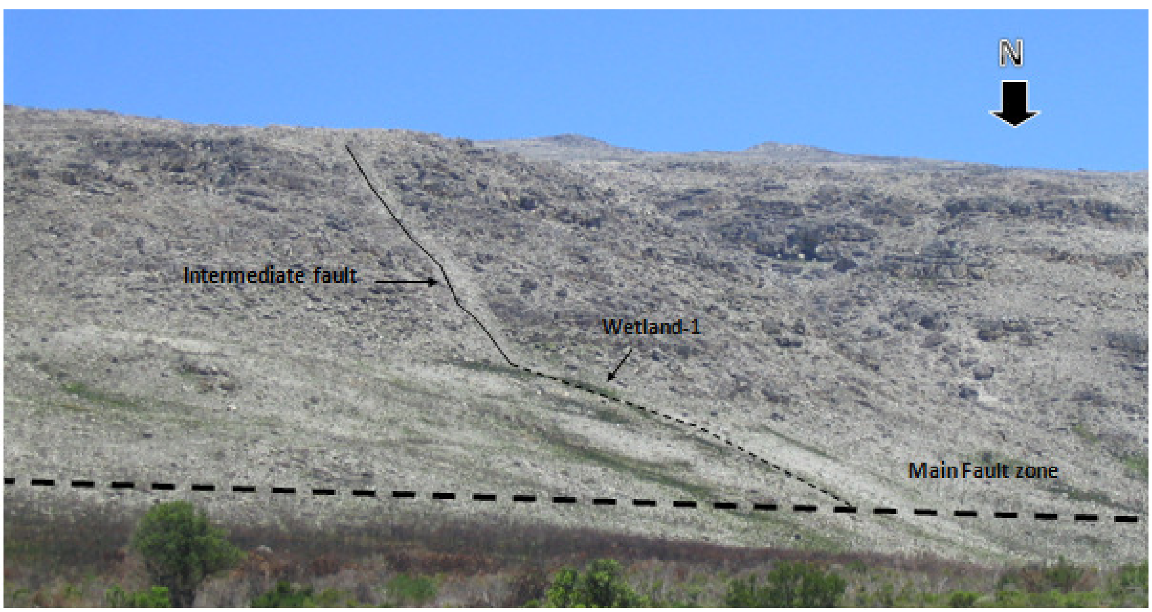

Figure 16. Photograph looking south towards Wetland-1 on the south eastern slope of the Oudebosch Valley.

Based on geohydrology it is suspected that ground water would form a significant contribution of water to Wetland 1. The conceptual understanding of the site position relative to ground water contribution is indicated in Figure 17.

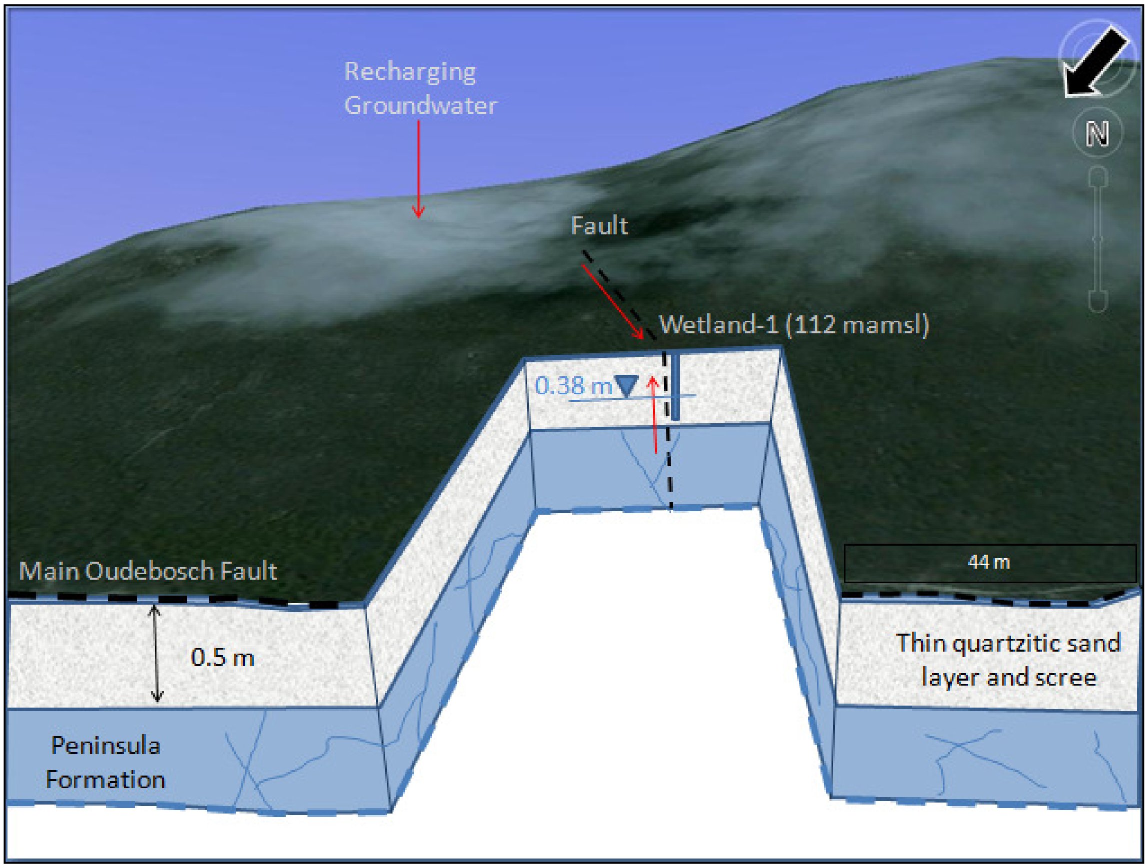

Figure 17. Conceptualisation of Wetland-1.

7.1.3 Wetland 2

Wetland 2 is a 1.6 m deep hand augered piezometer in a wetland site at the bottom of the Oudebosch Valley near the Oudebosch accommodation. The site overlies the Cedarberg Formation and linkage with the Peninsula Formation Aquifer is not anticipated as the site is quite removed from the Peninsula Formation outcrop as well as the mega-fault that runs up the Oudebosch Valley. The alluvium thickness at this site is about 1.5 m and consists of coarse quartzitic sand with a high organic content. The vegetation at the site consists of predominantly *Pteridium aquilinum*, commonly known as bracken. These plants like alkaline soils and the pH values at this site are higher than those measured elsewhere (see chemistry section). These plants are potentially invasive due to their resilient nature that enables them to survive periods of low soil moisture. The water levels at this site drop relatively significantly towards the end of summer.

As a valley bottom wetland it is not expected that TMG structures or lithological contacts contribute to the wetland. The wetland is topographically relatively flat and is expected to be a valley bottom – perched wetland based on the geohydrological and topographical setting. Based on geology it is suspected that Peninsula Formation Aquifer ground water contribution to this wetland is insignificant. A simplified conceptual diagram of the site is shown in Figure 18.

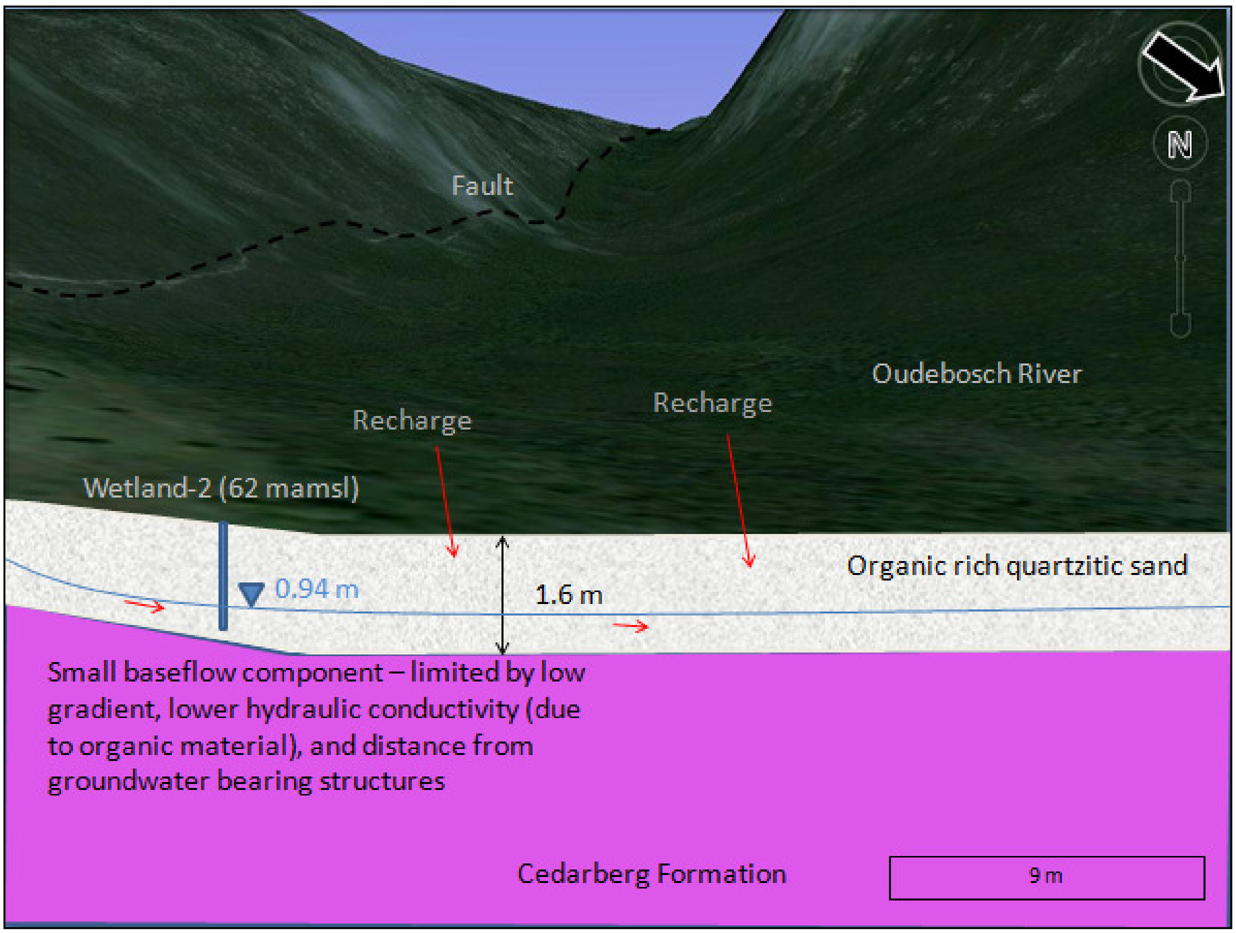

Figure 18. Conceptual diagram of the study site Wetland-2.

7.1.4 Wetland 3

Wetland 3 is a piezometer located in a valley-bottom wetland situated on the Cedarberg Formation in close proximity to the mega-fault running up the Oudebosch Valley which is downthrown to the northwest and displaces the Cedarberg Formation against the Peninsula Formation. The Cedarberg Formation is the confining unit overlying the Peninsula Formation in the Oudebosch Valley and is impermeable due to its argillaceous nature. There is therefore potential for the existence of a perched water table in this type of setting. The close proximity to the southwest/northeast fault and the Peninsula Formation also means that there is a possibility of the wetland being fed by ground water.

The colluvial sands at this wetland are relatively thick (~2.6 m) which is also the depth of the piezometer and the bedrock depth. The sands consist of medium to coarse grained white quartzitic sand (weathered sandstone) and clays weathered from the Cedarberg Formation shales. The vegetation is typical of shale band fynbos, and similar to the site River-1. A conceptual diagram of the Wetland is shown in Figure 19.

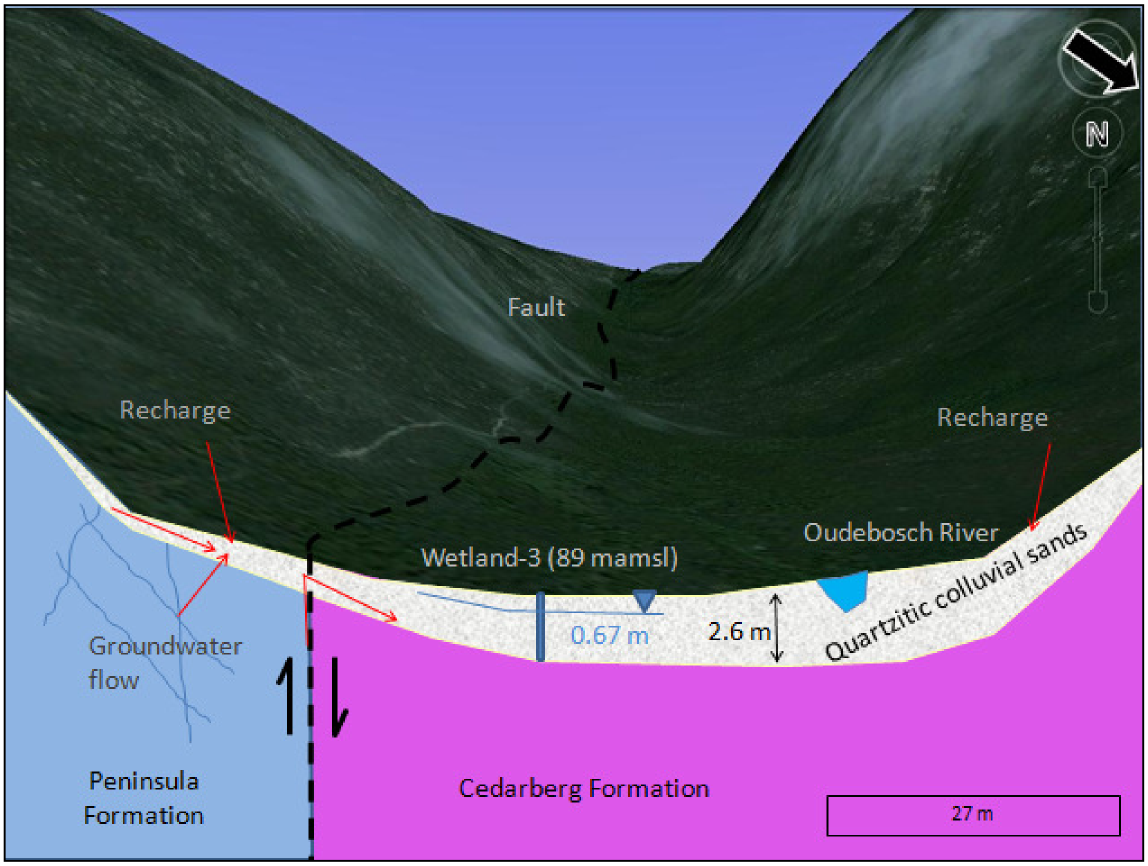

Figure 19. Conceptualization of the study site Wetland-2.

Based on the geohydrology alone it is difficult to determine whether the wetland is ground water fed, but from the aforementioned information it is concluded that there is a moderate probability of the wetland being fed by ground water.

7.1.5 Summary

The wetlands and river ground water dependence based on geohydrology is summarized in Table 8. The dependency rating is allocated according to Table 2 where 8 describes a site which is clearly ground water dependant, and 1 refers to a site where ground water contribution is considered to be non-existent or negligible.

Based on this classification, the three wetland sites and one river site are classified. The river site is allocated a classification of 6, as although it flows over the Cedarberg Formation in the valley bottom, it is fed by tributaries that originate from springs in the Peninsula Formation.

Wetland 1 is located on a slope on the Peninsula Formation in close proximity to a geological fault and the wetland is therefore connected to ground water bearing structures. It therefore has a ground water dependency rating of 8.

Wetland 3 is located on sediments overlying the Cedarberg Formation within the Oudebosch Valley bottom. The ground water dependence rating of 5 is allocated based on the sites relatively close position to the major fault that runs down the length of the valley and the fact that the general ground water flow direction would be down towards the valley bottom.

Wetland 2 is not in close proximity to any prominent geological features and overlies the Cedarberg Formation. Based on geohydrology, the wetland is thought to be related to a perched aquifer and not the regional aquifer, for this reason it has a ground water dependency rating of 0.

Table 8. Ground water dependence based on geohydrology.

Site ID	Groundwater dependance rating	Comment
River 1	6	The River is expected to be groundwater dependant
Wetland 1	8	Expected that groundwater forms the priamry water source to this site
Wetland 3	5	A degree of groundwater dependance is expected
Wetland 2	0	Groundwater contribution is expected to be insignificant

7.2 Water Level Fluctuations

This chapter aims to utilize time-series water level data to assess ground water dependence. The ground water trends will be assessed first, after which the wetlands and river sites can be related and discussed in relation to these trends.

All four of the boreholes are currently equipped with pressure loggers, although Borehole 1 only received one capable of measuring water levels in June 2010. Table 9 documents the range, maximum and minimum water levels per borehole for the given time range. With the exception of Borehole 3, all site pressure logger data was barometrically compensated using a solinst barometric pressure logger designated to the Steenbras Dam and Kogelberg region. Borehole 3 pressure logger data was of a different format to that of the Solinst pressure logger and barometric pressure logger but from the smoothed water level curve it is thought that barometric affects and fluctuations are negligible.

Table 9. Borehole water level range fluctuations

Site ID	Elevation	WL range (m)	Lowest WL (mbgl)	Highest WL (mbgl)	Logger Date range Start - Finish	
Borehole 1	44	1.95	1.95	0.00	2010/06/19	2010/07/17
Borehole 2	45	7.29	7.26	0.00	2007/01/16	2010/07/17
Borehole 4	70	2.46	-2.36	-4.82	2005/06/02	2010/07/17
Borehole 3	80	2.58	7.69	5.10	2007/11/18	2010/07/17

Borehole 1 has manual water level measurements, mostly taken at the end of summer and winter, which are used for calculating the borehole range. It is highly likely that the maximum and minimum water levels in the previous few years have exceeded those measured as the chances that water level is at its maximum/minimum at the time of measurement is small. The calculated range is therefore thought to be an underestimation of the total range for Borehole 1.

The boreholes indicate a water level range in the order of ~ 2.5 m (remember the range at Borehole 1 is less than the actual range) with the exception of Borehole 2. Borehole 2 shows a high range with a marked rise and fall linked to the rainfall. This is indicative of the low storage of the micro-structures that were intercepted during the drilling of this borehole. For the artesian borehole, Borehole 4, the pressure logger data is converted to meters below ground level (mbgl) and because the water level is above ground level the value is negative. This is visually illustrated in Figure 20 where the borehole water levels are plotted as mbgl.

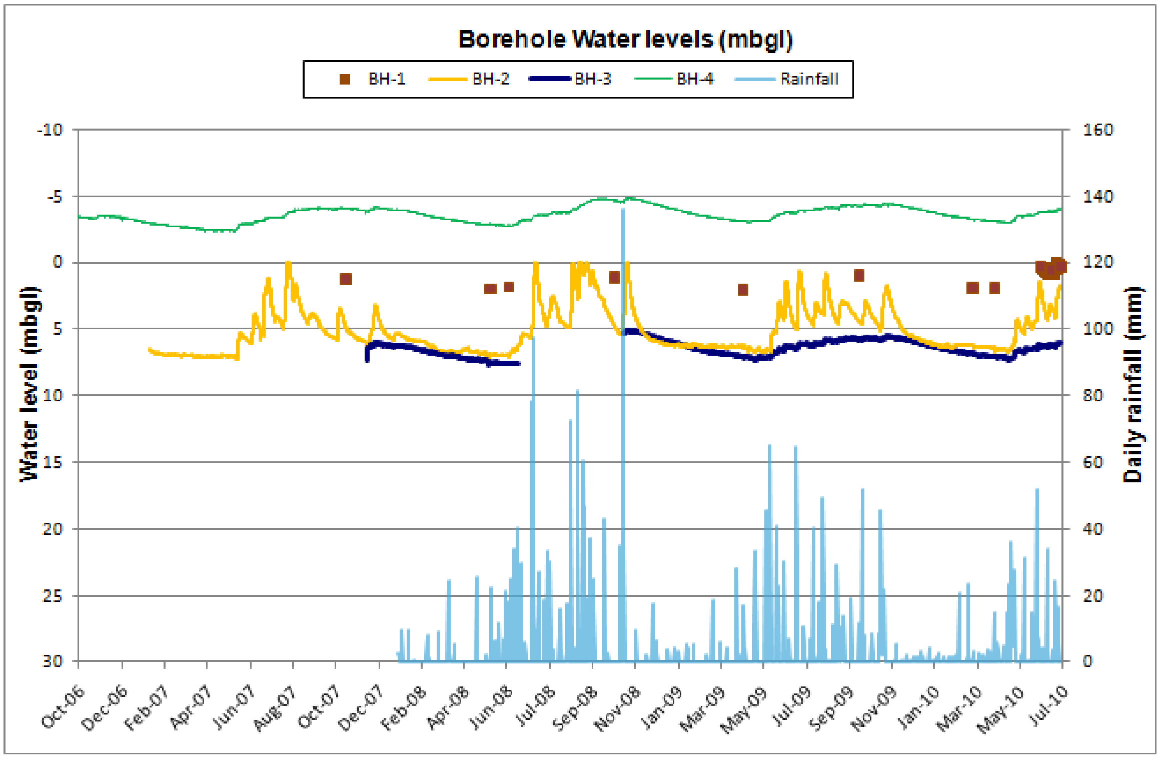

Figure 20. Borehole water level time-series data (mbgl) with rainfall.

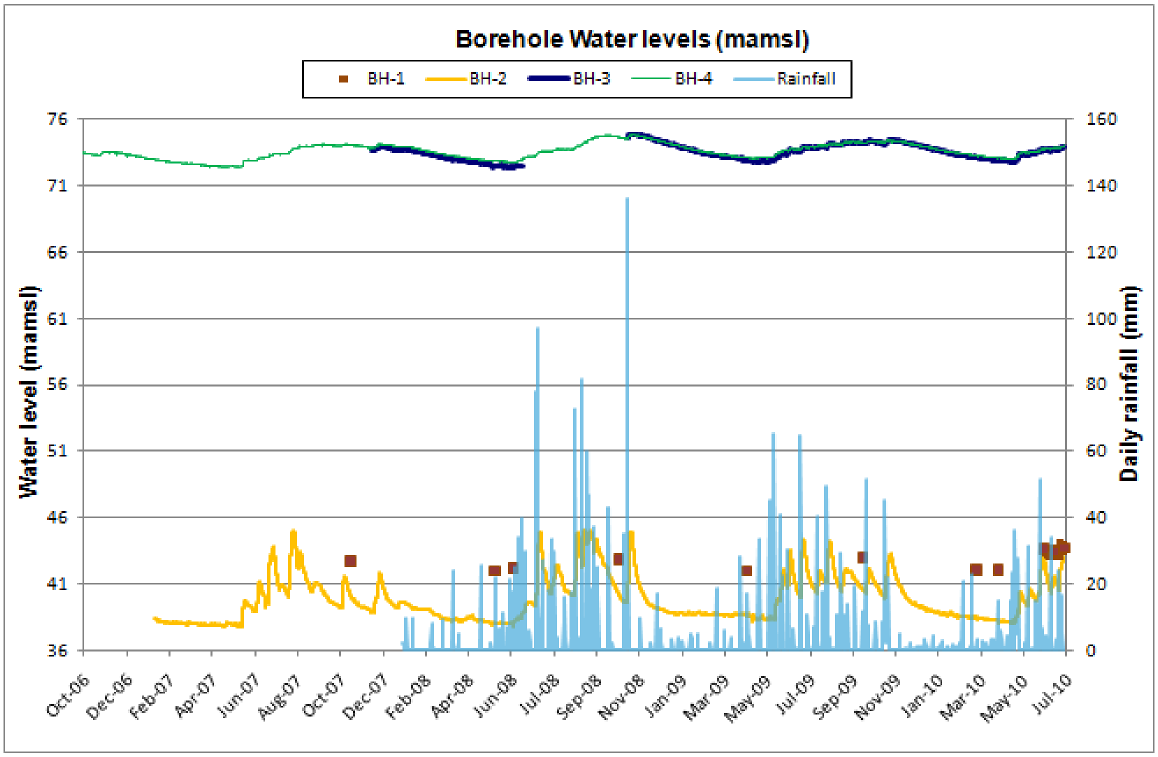

Figure 21. Borehole water level elevation time series data with rainfall.

Due to the different borehole elevations it is useful to view the water level fluctuations as an elevation (mamsl). Figure 21 reveals a similarity between the shallow Borehole 3 and the deeper artesian Borehole 4 with regard to both the piezometric water level and the time-series trend.

In comparison with Borehole 3 and Borehole 4, Borehole 1 and Borehole 2 show a slightly quicker and more prominent response to rainfall (Figure 22). The range in water level fluctuation is greatest for Borehole 2, but the piezometer level for both Borehole 1 and Borehole 2 is similar. At borehole 2 initial winter rains (March and April) do not appear to cause a prominent ground water level increase, while during the later winter months (June onwards) the water level increases by up to 7 meters. The range and response time to rainfall is discussed later in this chapter, and details are recorded in Table 11.

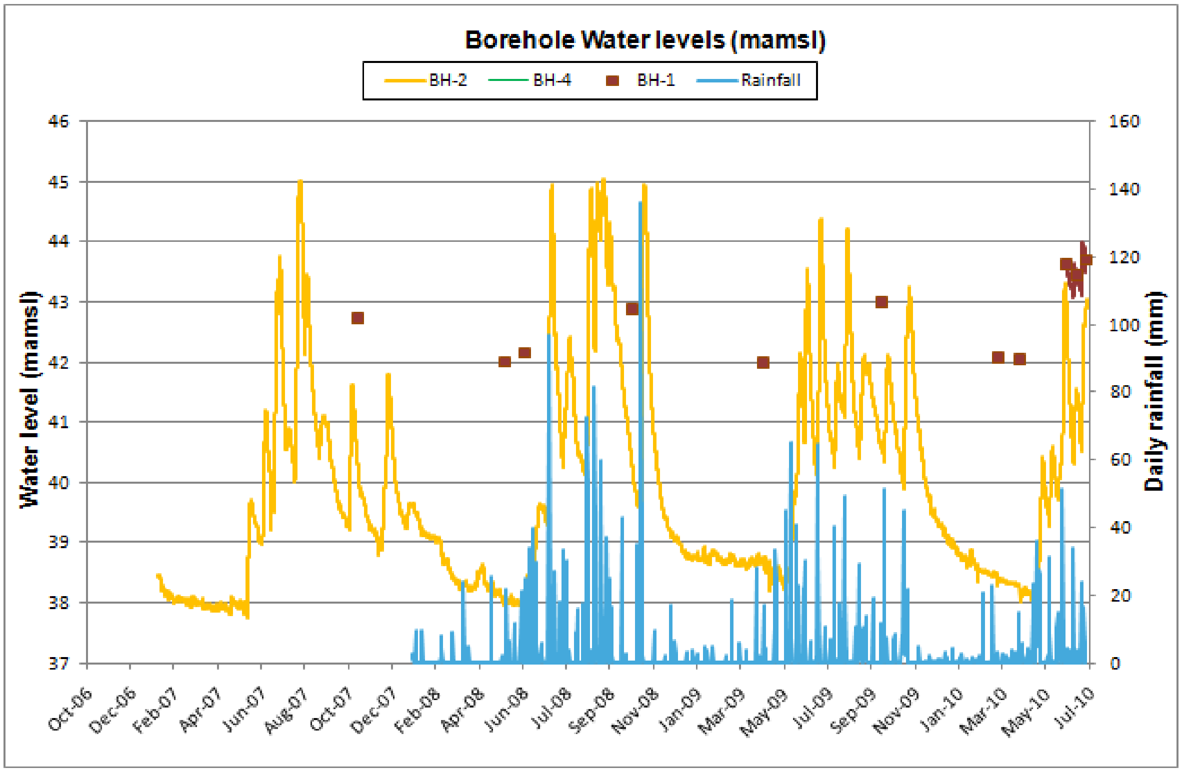

Figure 22. Water level elevation fluctuations (mamsl) for Borehole 1 and Borehole 2.

Borehole 4 and Borehole 3 have almost identical water level trends (Figure 23), although in summer the water level at Borehole 4 does not drop to quite the same degree as Borehole 3. Water level response to rainfall is less irregular and appears to be more delayed than observed for Borehole 1 and Borehole 2.

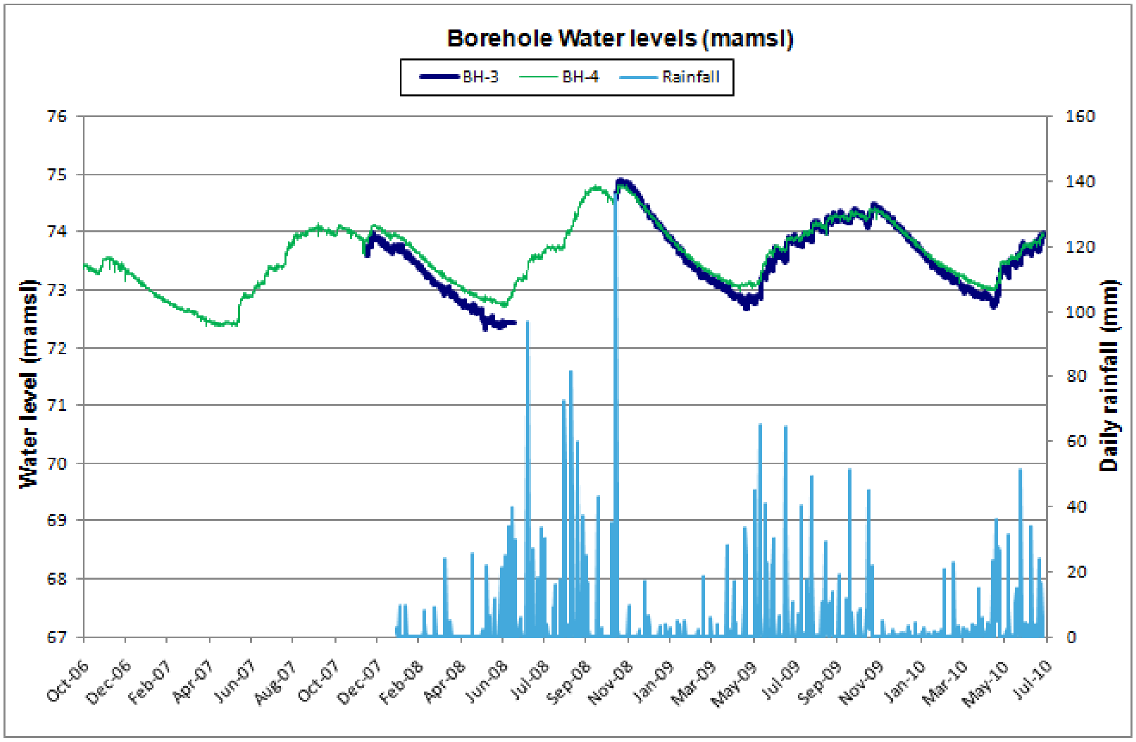

Figure 23. Water level elevation fluctuations (mamsl) for Borehole 4 and Borehole 3.

7.2.1 Response to rainfall events

In order to better determine the response magnitude and delay of water levels to rainfall events, three periods are considered in which rainfall took place (Table 10) and ground water levels were affected. The surface water site responses to these same events will be considered and compared to that of the Peninsula Formation.

Table 10. Rainfall events that will be considered with regard to the effect they had on ground and surface water levels in the Oudebosch valley.

Rainfall event	Start of Rainfall	End of Rainfall	Rainfall (mm)
1	10-Nov-08	13-Nov-08	203
2a	07-Oct-09	15-Oct-09	77
2b	05-Nov-09	14-Nov-09	111
3a	25-Feb-10	25-Feb-10	21
3b	10-Mar-10	10-Mar-10	23

The first event (Figure 24) is for the heavy rainfall that fell on 11 November 2008 (136 mm). This heavy rainfall was followed by 2 months of little rainfall.

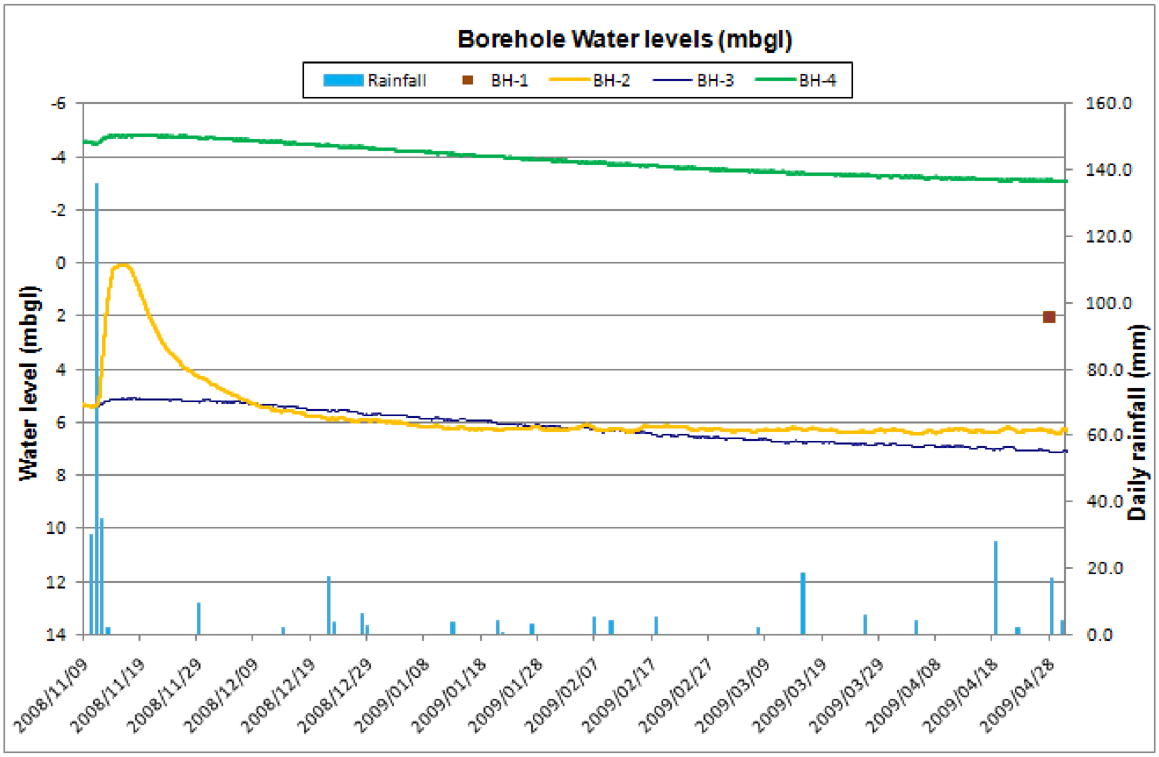

Figure 24. Water level (mbgl) responses to rainfall event 1 (10 – 13 November 2008).

The second period of observation (Figure 25) is between 12 October 2009 and 1 May 2010. Two significant rainfall events occurred during this interval, 11 to 13 October 2009 and 5 to 12 November 2009 with relatively little rainfall in between and following the latter.

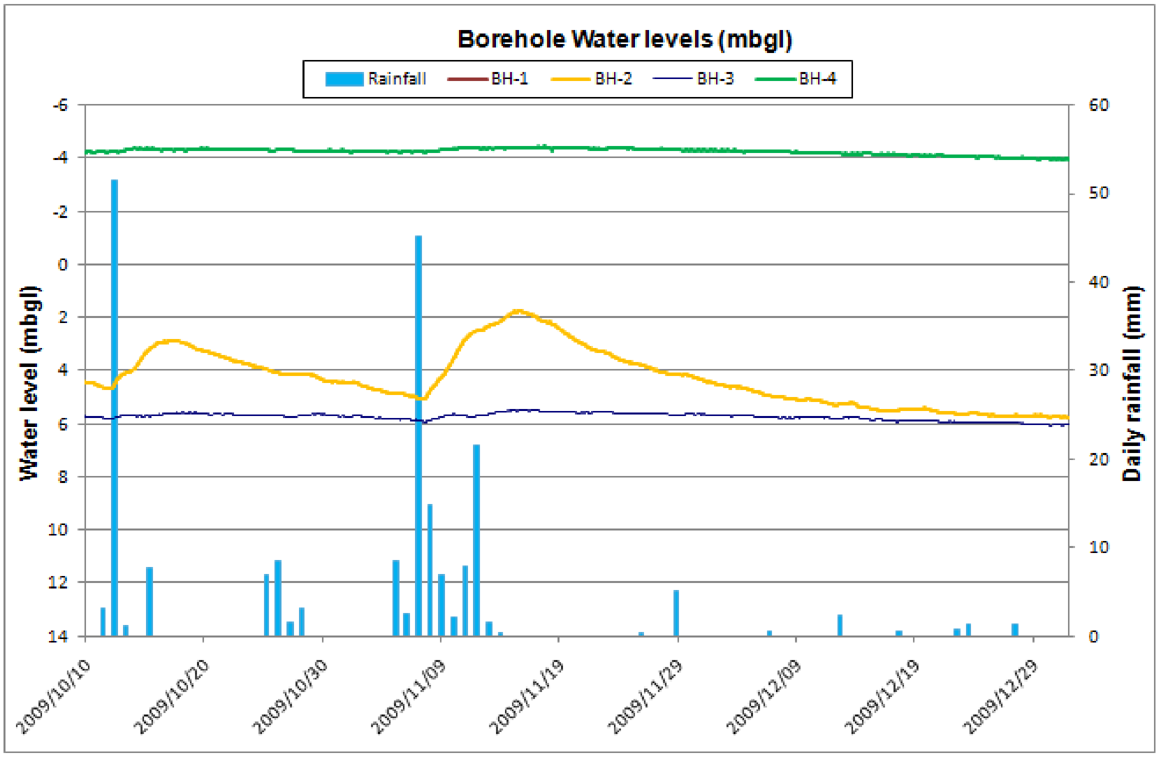

Figure 25. Water level (mbgl) responses to rainfall event 2a (7 – 15 October 2009) and 2b (5 – 14 November 2009).

The third interval (Figure 26) is from 20 February until 17 July 2010 which enables some data for Borehole 1 to be observed. This interval was chosen due to the rain that falls from 21 to 25 February 2010 at the end of summer conditions. This gives an indication of the borehole water levels responses to the first rains of the wet season. This also indicates how the response times of the water level to rainfall decreases as the water level rises during winter.

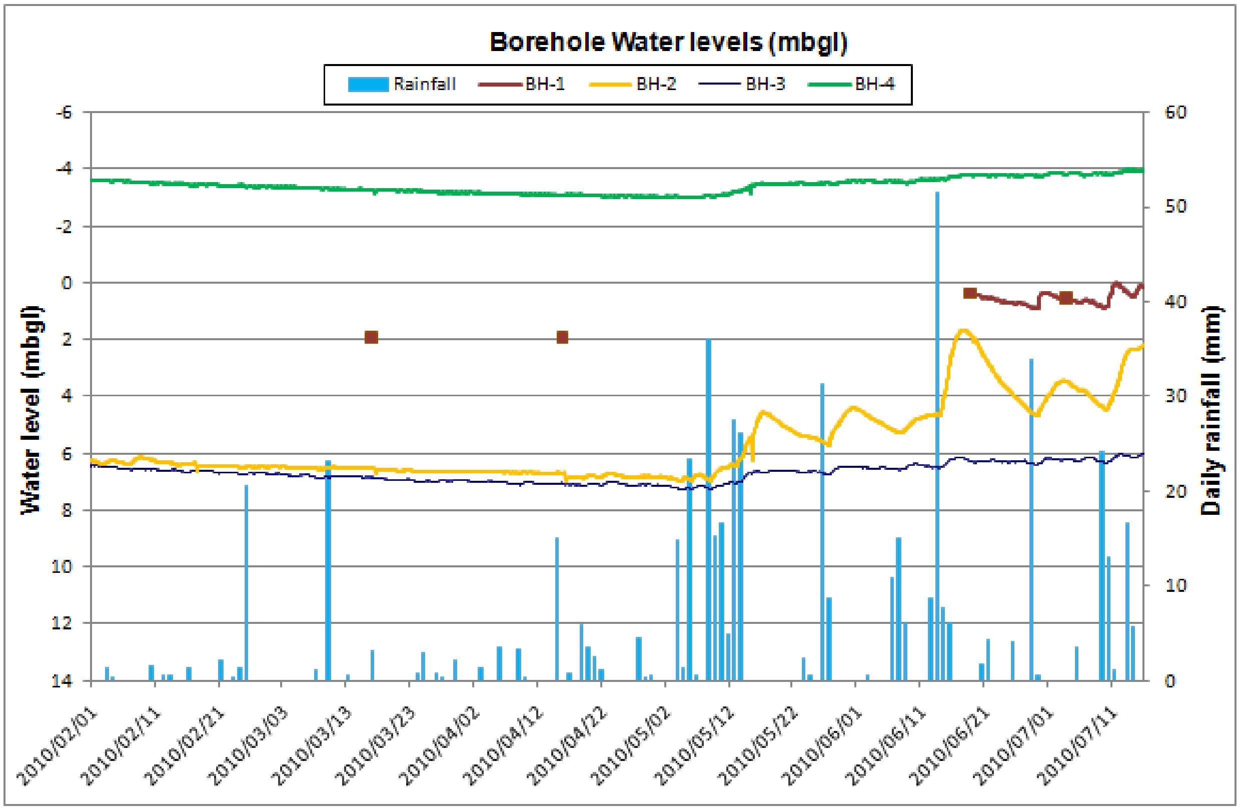

Figure 26. Water level (mbgl) responses to rainfall event 3a (25 February 2010) and 3b (10 March 2010).

The three boreholes with pressure loggers were each analyzed with regards to each rainfall event. Table 11 summarize the results, showing the number of days taken for the water level to respond to the rainfall event, and then the amount of time before the water level returns to its value prior to the event. The water level increase is also displayed in the table as an increase relative to the total annual water level fluctuation of the borehole.

The increase of the borehole water levels after a rainfall event is greater during the winter months than during the summer months. This is attributed to the increased soil moisture and water in the unsaturated zone which enables more of the rainfall to flow through and contribute to the aquifer. During the dry months of February and March the soil is dryer and rainfall has to fill the interstitial pore spaces before it seeps down to the aquifer. All boreholes show similar responses to the summer rainfall with the water levels increasing < 10 cm to both events. During the higher rainfall months Borehole 4 and Borehole 3 show similar responses to rainfall and increases in range from 0.15 to 0.31 m. The magnitude of the water level response also corresponds with the quantity of the rainfall. Figure 27 shows the relative water level as a function of rainfall and once again Borehole 3 and Borehole 4 show highly comparable responses. Borehole 2 shows larger water level fluctuations, which increase significantly with increased rainfall. In November 2008 and 2009 the boreholes water level increased 5.3 and 3.0 m respectively in less than 3 days after a rainfall event.

Table 11. Summary table of borehole water level response to the respective rainfall events.

Borehole	Rainfall Event	Month	Rainfall (mm)	WL Increase after Rainfall (m)	Relative Increase WL increase relative to total annual WL fluctuation	Recharge time (days) Time from rainfall to max WL	Discharge time (days) Time from Max WL till original WL value
Borehole 2	1	November	203	5.34	0.73	2.88	24.13
Borehole 4	1	November	203	0.27	0.11	2.24	26.08
Borehole 3	1	November	203	0.30	0.12	4.92	25.52
Borehole 2	2a	October	77	1.65	0.23	3.71	16.29
Borehole 4	2a	October	77	0.15	0.06	0.13	17.88
Borehole 3	2a	October	77	0.19	0.07	4.38	27.04
Borehole 2	2b	November	111	3.03	0.42	1.67	23.33
Borehole 4	2b	November	111	0.17	0.07	3.25	20.75
Borehole 3	2b	November	111	0.31	0.12	2.00	31.00
Borehole 2	3a	February	20.57	0.03	0.00	2.71	4.96
Borehole 4	3a	February	20.57	0.02	0.01	4.27	3.73
Borehole 3	3a	February	20.57	0.09	0.03	3.25	3.25
Borehole 2	3b	March	23.11	0.08	0.01	1.00	6.42
Borehole 4	3b	March	23.11	0.01	0.01	1.69	7.31
Borehole 3	3b	March	23.11	0.08	0.03	4.19	1.81

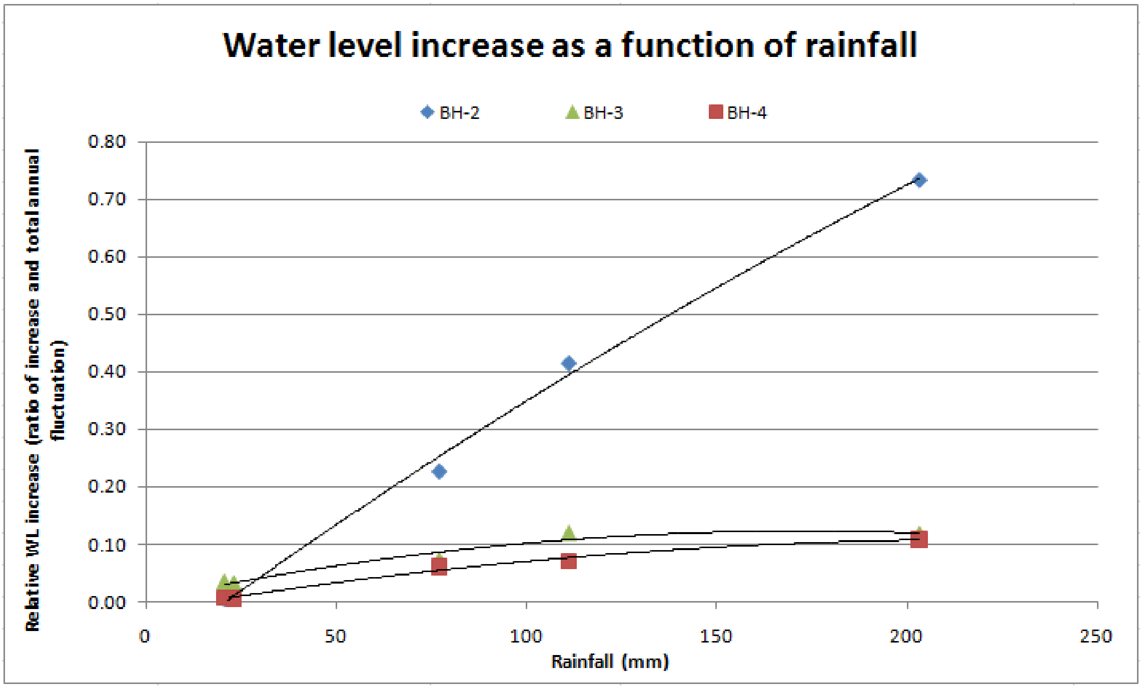

Figure 27. Relative water level (ratio of water level increase to maximum water level fluctuation) response to rainfall.

The time taken from the rainfall event until the water level reaches its highest value thereafter is similar for the three boreholes for all the rainfall events considered and is < 5 days in all cases. The response time varies for each borehole and does not show any clear correlation with water level fluctuation or rainfall magnitude.

The time taken for the water level to return from its maximum value after the rainfall event to the value prior to the event varies depending on the amount of rainfall and water level fluctuation and the time of year. Although rainfall quantity and ground water level increase is a primary controller of time taken until water levels return to the original value, they are not the only determinants. When time taken for water levels to drop to the original value is plotted against rainfall volume or water level rise, no clear relationship is distinguishable. It is therefore thought that the time of year, or dryness of the subsurface soil, is also a determining factor, and the water level decreases quicker in the summer months than in the wet months towards the end of winter. The water level takes between 16 and 31 days to drop down to pre-rainfall event values for all three boreholes after the winter rains. This value drops to between two and seven days for rainfall events during the summer months. Figure

28 shows the general relationship between water level recession time and the magnitude of the rainfall volume.

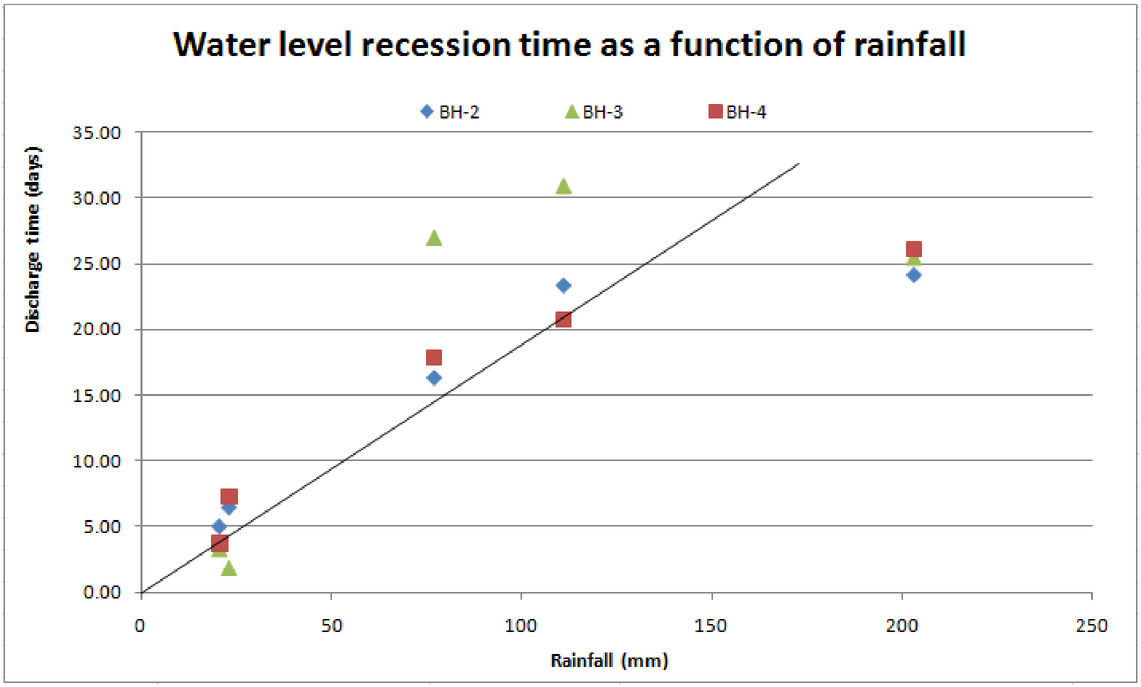

Figure 28. Water Level Recession as a function of the magnitude of the rainfall event.

For the wetlands and the river, water level measurements were taken at all four sites by means of pressure loggers. Measurements were taken every 30 minutes, and data was downloaded monthly. The pressure logger data was barometrically compensated using the Solinst barometric pressure logger designated for the Kogelberg area. Monitoring was conducted in an attempt to evaluate the measure of connectivity to ground water by examining the behaviour of the water level at the ecoseeps and river over the monitoring period. Graphical methods were used to compare water levels over time with the rainfall measured and comparisons are made with the responses and behaviour of the Peninsula Formation Aquifer in the valley. The aim is to determine and refine whether Peninsula Formation ground water is a dominant source of water to the sites. With regards to the wetlands, all three experienced water levels within 0.5 m of the surface for some period in each year confirming their wetland status in line with the Department of Water Affairs (DWA) definition. The river is perennial and flowed throughout the year, although the flow volume is highly seasonal.

The rate of change in water level over the monitoring period in relation to rainfall patterns is expected to be a useful indicator of the connectivity of the wetland to ground water. It was not possible in this analysis to develop a useful regression between rainfall and seep water levels to quantify connectivity, because of the short time series in relation to the variability in the data. Instead, visual interpretation of the pattern of water level change was used to comment on connectivity. The wetland water levels show a distinct seasonality in all three cases with declines over summer and varying degrees of responses to rainfall events.

Table 12. Wetland and river water level fluctuation

Site ID	Elevation	WL range (m)	Lowest WL (mbgl)	Highest WL (mbgl)	Logger Date range Start - Finish	
Borehole 1	44	1.95	1.945	0	19/06/2010	17/07/2010
Borehole 2	45	7.29	7.25674	-0.0334	16/01/2007	17/07/2010
Borehole 4	70	2.46	-2.36232	-4.82256	02/06/2005	17/07/2010
Borehole 3	80	2.58	7.685	5.104	18/11/2007	17/07/2010
Wetland 1	112	0.42810	0.37800	-0.05010	05/09/2008	17/07/2010
Wetland 3	89	0.82390	0.66980	-0.15410	31/10/2008	17/07/2010
Wetland 2	62	1.04241	0.94001	-0.10240	15/11/2006	17/07/2010
River 1	79	1.28190	0.23810	1.52000	31/10/2008	17/07/2010

It is apparent in Table 12 that the water level range is considerably smaller for the wetlands and river sites than for the boreholes. There is also a range distinction between the various sites with increasing water level ranges for Wetland 1, Wetland 3, Wetland 2 and the river site River 1. Although there is no direct correlation between the wetland and river sites and the boreholes, the boreholes strongly linked to ground water show a smaller range in water level than those linked only to micro-structures (Borehole 2). The range of the water level fluctuation relates to the seasonality of the site, and can therefore provide a valuable indication of ground water dependence. Therefore based on water level range the sites can be ordered according to ground water dependence.

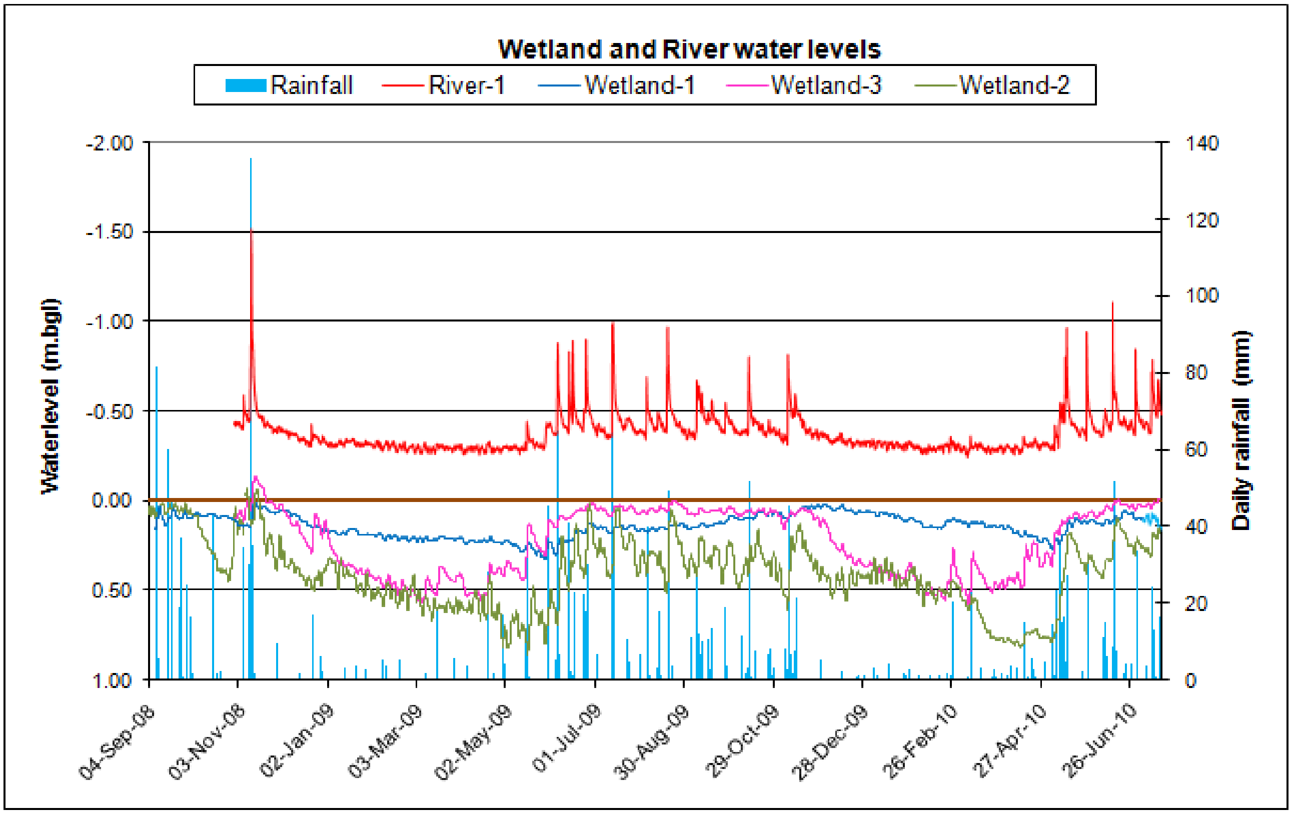

Figure 29. Wetland and River site fluctuations (mbgl).

The Graph of the water levels also makes a distinction between the sites, with River 1 and Wetland 2 both having a considerably more irregular graph shape with sharp peaks related to rainfall events. A less irregular water level trend is evident for Wetland 1 and Wetland 3. The more smoothed response suggests greater connectivity with- and dependence on- ground water.

7.2.1.1 River 1

The Oudebosch River is a perennial stream that is the only significant river in the Oudebosch Valley. The Oudebosch River water level fluctuates ~ 1.28 m above the river bed at the point of monitoring where the stilling well is installed, which is higher than for the three wetland sites. This higher range is anticipated as the entire valley drains into, and is drained by, the Oudebosch River. Ground water flow, interflow and surface runoff all contribute to the stream flow, and the river level shows significant responses to rainfall events. Figure 29 shows the water level trend and the rapid increases and decreases in the water level are directly linked to rainfall events. Discharge of water is also rapid as is the nature of mountain streams.

The ground water contribution to the stream flow is evident in the low rainfall months where the river is reduced to a low flow stream. Figure 29 shows that the water level is relatively constant during the dryer months, and was always more than 0.24 m above the river bed at the stilling well during the monitoring period. The constant water level during the dry months and the perennial nature of the river indicates that the river has significant ground water contributions.

7.2.1.2 Wetland 1

Wetland 1 is a wetland piezometer that recorded water levels within 40 cm of the surface all year round and is perennially saturated and inundated for some parts of the year. Of the sites monitored Wetland 1 has the smallest seasonal fluctuation (only 0.43 m) as well as the least irregular water level trend in comparison to the other wetlands and the river sites. Based on the water level fluctuations a high degree of connectivity with ground water is evident.

7.2.1.3 Wetland 3

Wetland 3 is a wetland that was seasonally inundated, seasonally saturated, but also experienced short intermittent dry periods throughout the year (where the water level was deeper than 0.5 mbgl). The range in the water level fluctuations is greater than for Wetland 1, but less than that of Wetland 2. A water level range of 0.82 m indicates a relatively small seasonal variation, smaller than that of the ground water in the valley. The water level response of Wetland 3 is relatively regular (smooth) but with peaks related to rainfall in the dry season. At the end of the rainy season the water levels declined rapidly, but these stabilized at just above 0.5 mbgl, possibly indicating the contribution of ground water to wetland perenniality over summer (Figure 29). The valley bottom setting of this wetland explains the rapid and significant increase in water levels in this wetland with the onset of rainfall, as rainfall would flow into the valley bottom sediments as runoff and interflow move down the valley slopes, thus rapidly inundating valley bottom wetlands. It is expected that the ground water contribution to this site is comparable to that of River 1 during the dry summer months as ground water feeds the alluvial valley bottom wetlands as it flows through the surface sediments overlying the Cedarberg Formation to the channel where it contributes to the stream flow. The decrease in water level (relatively rapid) is as a result of discharge into the Oudebosch River.

7.2.1.4 Wetland 2

Wetland 2 has a higher range of water levels than obtained at Wetland 1 and Wetland 3, but is less than the range of the river channel site River 1. The water level trend is irregular, and significant spikes in the water level relate closely with rainfall. The decrease of the water level during the summer months, once the water level is below ~ 0.4 mbgl, is slow and gradual. The higher seasonal range and rapid response of water levels to rainfall suggests that this site is not significantly connected to a ground water source but rather that it represents a shallow perched aquifer within the shallow alluvium overlying the Cedarberg Formation. The slow discharge time possibly indicates that flow through the site and discharge into the Oudebosch River is low. The nature of the alluvium, shallow with a high concentration of fines and organic material, would mean that flow rates through and discharge from the wetland is slow due to the low permeability.

7.2.2 Lag time and Responses to Rainfall

Rainfall event 1 was a heavy rainfall that took place in November 2008 and was followed by a period of relatively low rainfall (Figure 30). The summary of the site responses is recorded in Table 13. Because this rainfall event occurred towards the end of the rainy season, and the start of the dry season, the ground water levels are relatively high and recharge and interflow is expected to be rapid. All three wetlands were inundated after the rainfall due to the magnitude of the event and the water level increase does not provide much of an indication of ground water dependence. What is interesting, however is the recharge time (time taken from rainfall event until water level reached the event related peak), as well as the discharge time (the time taken between the rainfall event peak and when the water level returns to its original level prior to the event).

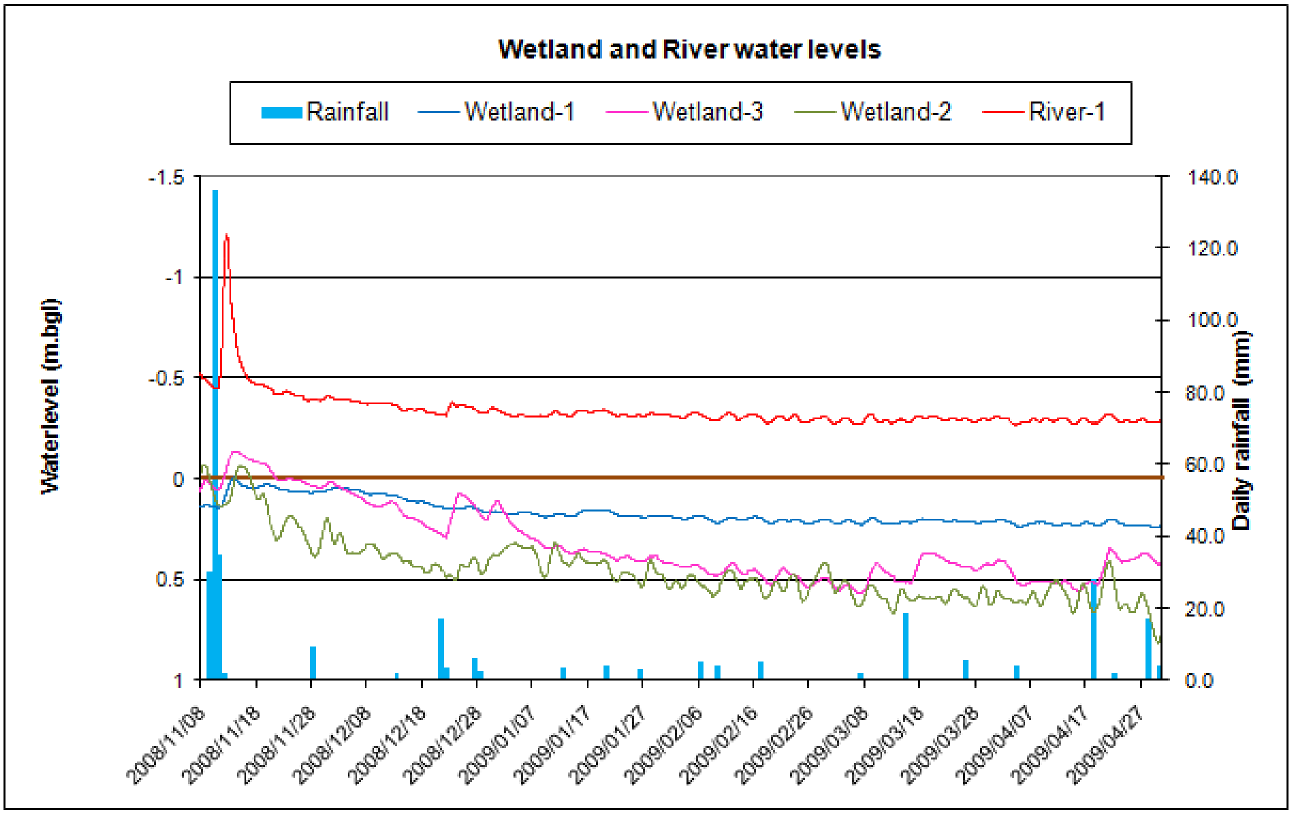

Figure 30. Wetlands and River site response to Rainfall Event 1.

Table 13. Summary Table of Wetlands and River site responses to Rainfall Event 1.

Borehole	Rainfall Event	Month	Rainfall (mm)	WL Increase after Rainfall (m)	Relative Increase WL increase relative to total annual WL fluctuation	Recharge time (days) Time from rainfall to max WL	Discharge time (days) Time from Max WL till original WL value
Wetland 1	1	November	203.0	0.3	0.6	2.1	38.0
River 1	1	November	203.0	1.1	0.8	2.0	8.0
Wetland 3	1	November	203.0	0.2	0.1	3.0	17.0
Wetland 2	1	November	203.0	0.3	0.3	4.3	7.0

For River 1 the recharge and discharge time is rapid, two and eight days respectively. This is expected as the stream flow is fed primarily by interflow and surface flow after such a significant rainfall event. Wetland 2 has the longest recharge time (4.3 days) but then shows rapid discharge. The slow recharge is attributed to the low permeability of the Cedarberg Formation and the organic rich fine alluvium. The wetland is possibly a perched valley bottom wetland, and the relatively rapid “discharge” is attributed to the anticipated small extent of the perched aquifer and the lack of ground water and interflow contributions.

Wetland 1 shows rapid recharge, second only to the Oudebosch River, and then discharges over a long period of time (38 days). Wetland 1 is thought to be strongly linked to ground water and the rapid water level response is due to the saturated nature of the subsurface so that interflow immediately results in recharge. The long discharge time is indicative of the significant ground water contribution to this site. Wetland 3 also shows relatively long discharge times (17 days) indicating probable ground water contribution. Wetland 3 shows longer recharge times than Wetland 1 possibly due to its location at the valley bottom further away from the higher recharge areas at higher elevations.

In relation to the borehole water level responses to rainfall event 1, the wetland sites all show similar water level increases (with regards to magnitude) and recharge times are similar. With regards to “discharge” time, Wetland 1 and Wetland 3 are similar to the boreholes, with Wetland 1 taking a bit longer and Wetland 3 being a bit shorter. River 1 and Wetland 2 show relatively rapid discharge times. This is in an agreement with geological and topographical indicators that suggest Wetland 1 and Wetland 3 are closely linked to ground water. River 1 shows relatively rapid recharge and discharge times as would be expected for a river.

The second two rainfall events are depicted in Figure 31 and summarized in Table 14. Here a rainfall event in October and November are considered, once again at the end of the high rainfall season. The events are only two months apart, so for some of the sites the water levels are still responding to the first event when the second occurs.

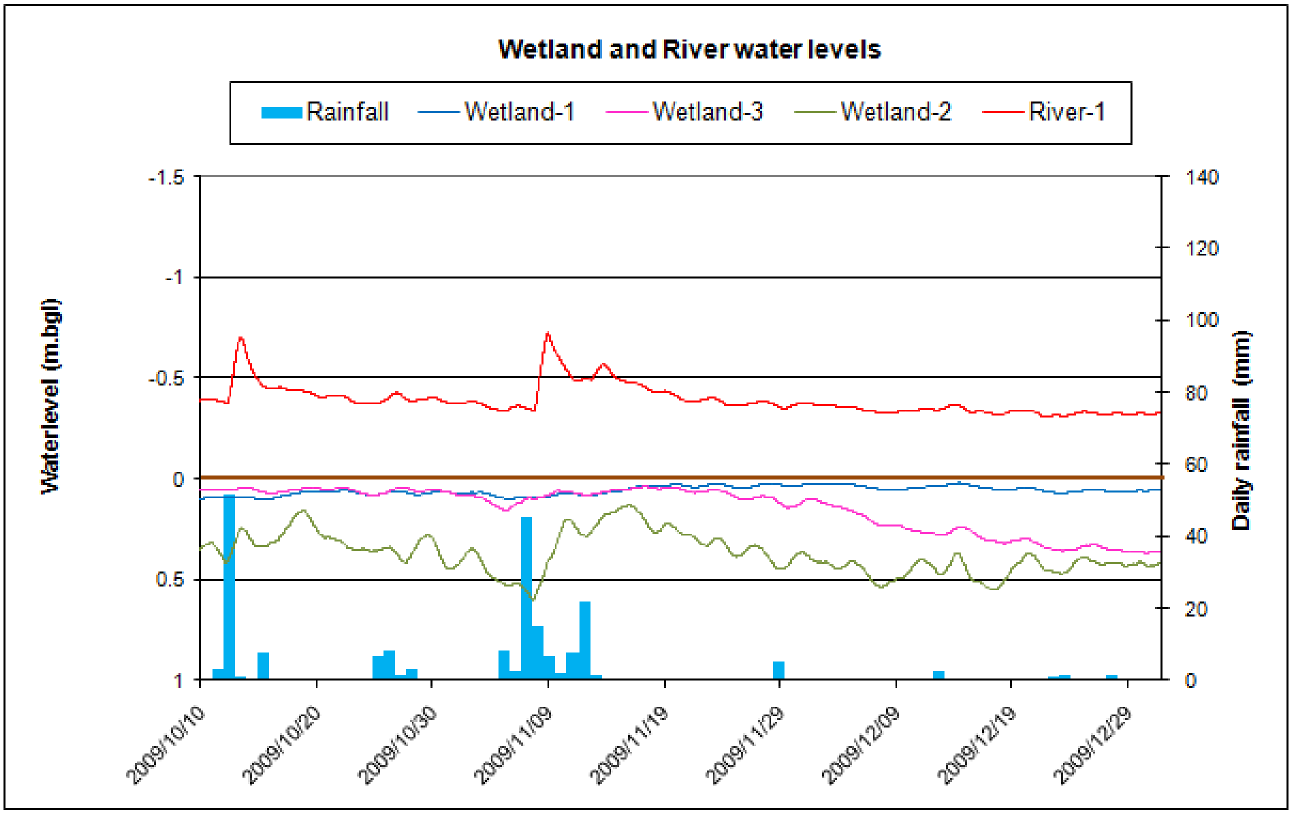

Figure 31. Wetlands and River site response to Rainfall Events 2a and 2b.

Table 14. Summary Table of Wetlands and River site responses to Rainfall Events 2a and 2b.

Borehole	Rainfall Event	Month	Rainfall (mm)	WL Increase after Rainfall (m)	Relative Increase WL increase relative to total annual WL fluctuation	Recharge time (days) Time from rainfall to max WL	Discharge time (days) Time from Max WL till original WL value
Wetland 1	2a	October	77.0	0.6	1.4	12.8	15.8
River 1	2a	October	77.0	0.4	0.3	5.8	9.6
Wetland 3	2a	October	77.0	0.1	0.0	5.3	2.0
Wetland 2	2a	October	77.0	0.3	0.3	10.8	12.6
Wetland 1	2b	November	111.0	0.1	0.1	13.1	48.3
River 1	2b	November	111.0	0.5	0.4	3.1	38.4
Wetland 3	2b	November	111.0	0.2	0.1	11.1	12.5
Wetland 2	2b	November	111.0	0.6	0.5	9.8	122.2

Wetland 1 shows a significant water level increase (0.6 m) to the rainfall event 2a (greatest of the 4 sites) and then only a 0.1 m response to the rainfall event 2b (least of the four sites). This is somewhat different than for the other 4 sites which all show a greater response to the 2b rainfall event in which a greater volume of rain fell than for 2a. This anomalous water level increase at Wetland 1 after the first event possibly relates to earlier recharge and points to longer recharge times than experienced at the other sites. This is evident for Wetland 1 for events 2a and 2b where a recharge time of ~13 days is evident for both, higher than the other sites.

The shortest recharge time for event 2a was obtained for Wetland 3 (5.3 days), just shorter than for River 1 (5.3 hours). For the second event the recharge time for River 1 was much shorter than the other sites.

Once again Wetland 2 and River 1 show a more jagged response to rainfall events than obtained for Wetland 3 and Wetland 1. Wetland 1 has the longest discharge time following rainfall event 1, and this is the case again for event 2a. For 2b Wetland 1 shows the second longest discharge time. Interestingly, for event 2b the discharge time is considerably long for Wetland 2 (122 days). This is evident in the water level graphs for this site where the lowering of the water level ("discharge") becomes gradual when it is in the region of ~ 0.4 mbgl. This is attributed to the perched nature of the wetland (little discharge) and low permeability of the shales and alluvium meaning little/slow outflow and possibly a delayed inflow carrying over from earlier rainfall events.

It is also interesting that Wetland 3 shows the shortest discharge times to events 2a and 2b, shorter even than River 1. This is possibly due to the fact that at the onset of both rainfall events the water level was already close to the surface meaning that water levels returned to normal relatively rapidly following the event. No real correlation between the wetland and river sites and the boreholes are evident for events 2a and 2b. Even amongst the wetland sites themselves they vary with regards to water level increase, recharge and discharge time. Whereas the previously considered rainfall events occurred at the end of winter, and were followed by times of low rainfall, events 3a and 3b occur at the end of summer. In this case the depth of saturation is deeper, the soil moisture is lower and pre event unsaturated flow is low or negligible. The third period is depicted in Figure 32 and summarized in Table 15.

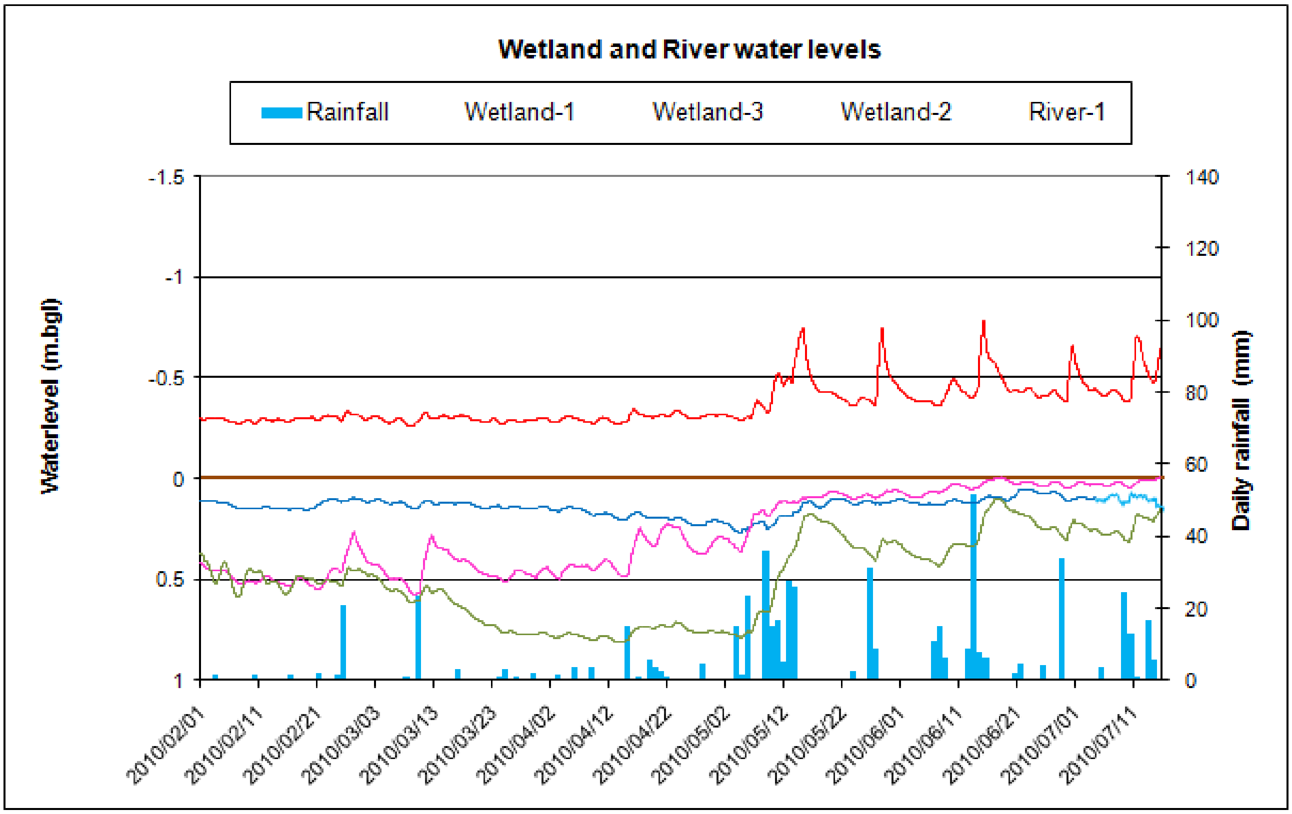

Figure 32. Wetlands and River site response to Rainfall Events 3a and 3b.

Table 15. Summary Table of Wetlands and River site responses to Rainfall Events 3a and 3b.

Borehole	Rainfall Event	Month	Rainfall (mm)	WL Increase after Rainfall (m)	Relative Increase WL increase relative to total annual WL fluctuation	Recharge time (days) Time from rainfall to max WL	Discharge time (days) Time from Max WL till original WL value
Wetland 1	3a	February	20.6	0.1	0.24	0.3	3.3
River 1	3a	February	20.6	0.1	0.07	0.5	7.0
Wetland 3	3a	February	20.6	0.4	0.21	0.6	10.2
Wetland 2	3a	February	20.6	0.2	0.16	0.3	7.2
Wetland 1	3b	March	23.1	0.1	0.21	0.6	1.0
River 1	3b	March	23.1	0.1	0.08	0.8	13.6
Wetland 3	3b	March	23.1	0.4	0.21	2.2	12.8
Wetland 2	3b	March	23.1	0.2	0.14	0.8	4.7

To both events 3a and 3b the water level responses to each event are almost identical with regard to magnitude. The greatest water level increase is evident for Wetland 3 (0.4 m), and the second highest is for Wetland 2 (0.2 m). This is attributed to the topographical setting of these sites as valley bottom wetlands. The greater increase at Wetland 3 is attributed to the higher permeability and its location close to the major fault that runs up the valley. Wetland 1 and River 1 both showed a 0.1 m water level increase.

The recharge time for the first event was less than that of the second event for all four sites. In comparison to the borehole responses to water levels the sites show a greater increase to the rainfall events, although the overall seasonal water level ranges of the boreholes are greater. It is interesting to observe that the discharge time at Wetland 1 and Borehole 3 are similar. These two sites are located close to each other, and have similar characteristics.

7.2.3 Summary

Although no clear relationships between surface sites and the borehole water level trends were apparent, the investigation of the water level trends provided valuable information. Analysis of the trends enabled comparison between the various wetland and river sites with regards to range, magnitude and time of the various responses to rainfall. The irregular nature (marked by many fluctuations) of the different trends also enabled comparison of the site with the more smoothed plots evident for boreholes Wetland 2 and Borehole 3.

The water level trends (smoothed or irregular), total water level range, behaviour in summer and response to rainfall provide a good qualitative assessment of the sites and can assist in identifying ground water dependence.

It must be reported that it does not appear as if the water levels respond consistently with regards to rainfall events. It is suspected that the controls on the water level responses are complex and many, including rainfall intensity and volume, soil moisture, water level depth, evapotranspiration, humidity as well as additional water inflows and outflows via faults and fractures.

Based on the water level assessment for the study sites, the conclusions with regards to ground water dependence are summarized in Table 16, the ground water dependency rating is allocated according to Table 2.

Table 16. Ground water dependence based on water level responses.

Site ID	Groundwater dependance rating	Comment
River 1	6	Largely Rainfall fed, high range in WL values and irregular timeseries plot. Perrenial nature and constant summer water level indicative of groundwater contribution
Wetland 1	8	Small WL range, smooth timeseries trend, comparable recharge time as Groundwater to Rainfall event 1. Discharge after Rainfall 3a and 3b very similar to borehole TMG544
Wetland 3	6	Intermediate WL range, smooth timeseries trend, Recharge time after rainfall event 1 comparable to Groundwater
Wetland 2	2	Relatively large WL range, irregular timeseries trend

7.3 Water Temperature

The ground water level temperature was measured by means of a logger at Borehole 1, Borehole 2 and Borehole 3. The amplitude of the water temperature is considerably less than that of the air temperature, where the air temperature data ranges 40.5℃, the maximum range of the ground water temperature is 3.1℃ at Borehole 1 (Figure 33).

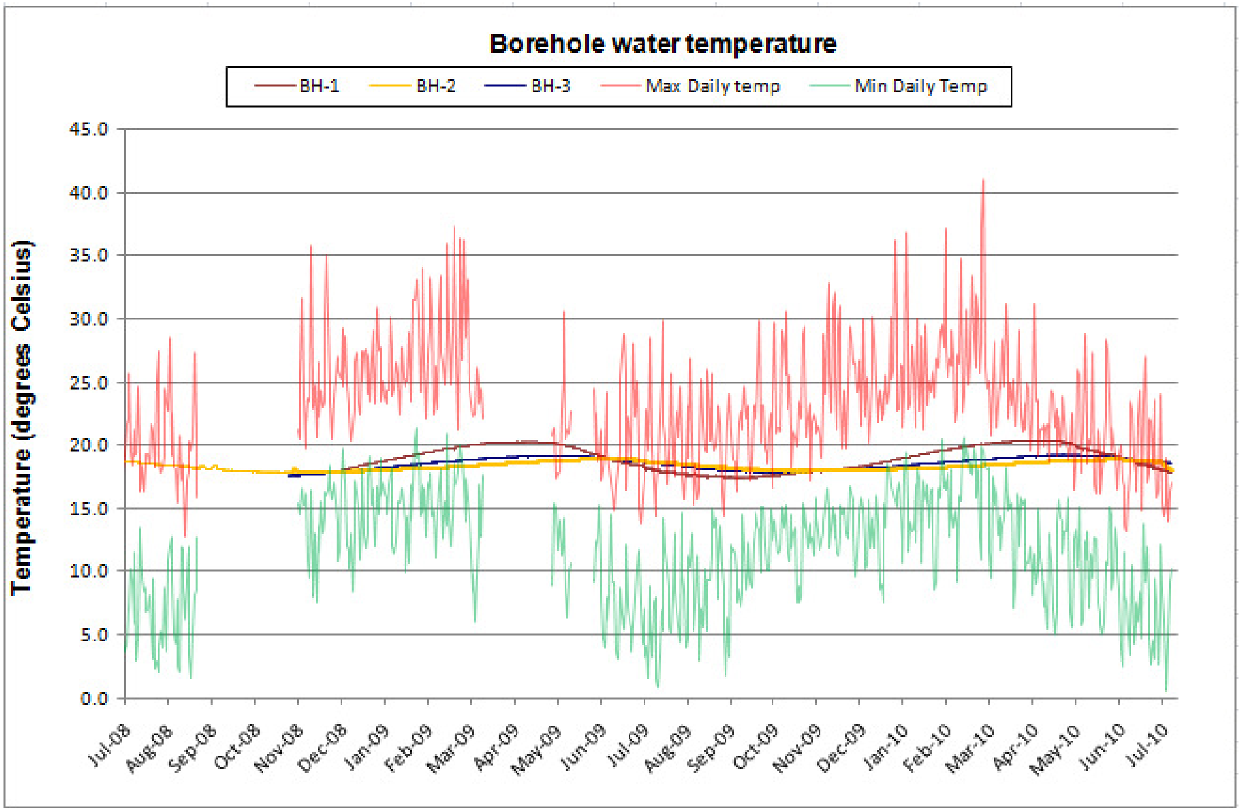

Figure 33. Water temperature and air temperature time-series data (Degrees Celsius).

Figure 34 shows the amplitude of Borehole 1 exceeding that of Borehole 2 and Borehole 3. The time between Borehole 1 maximum and minimum temperatures in correlation to the maximum and minimum air temperatures respectively is also the shortest (in the order of one to two months). Borehole 3 has a 1.72℃ range for the data obtained, and the delay in response to the maximum and minimum air temperatures is in other order of about two months. The amplitude of the Borehole 2 temperature range is similar (1.252℃) and is interestingly the smallest despite this borehole having the largest water level fluctuations. The delay in the water temperature response to air temperature is calculated from the maximum and minimum values and is the longest of all the boreholes (in the order of three months).

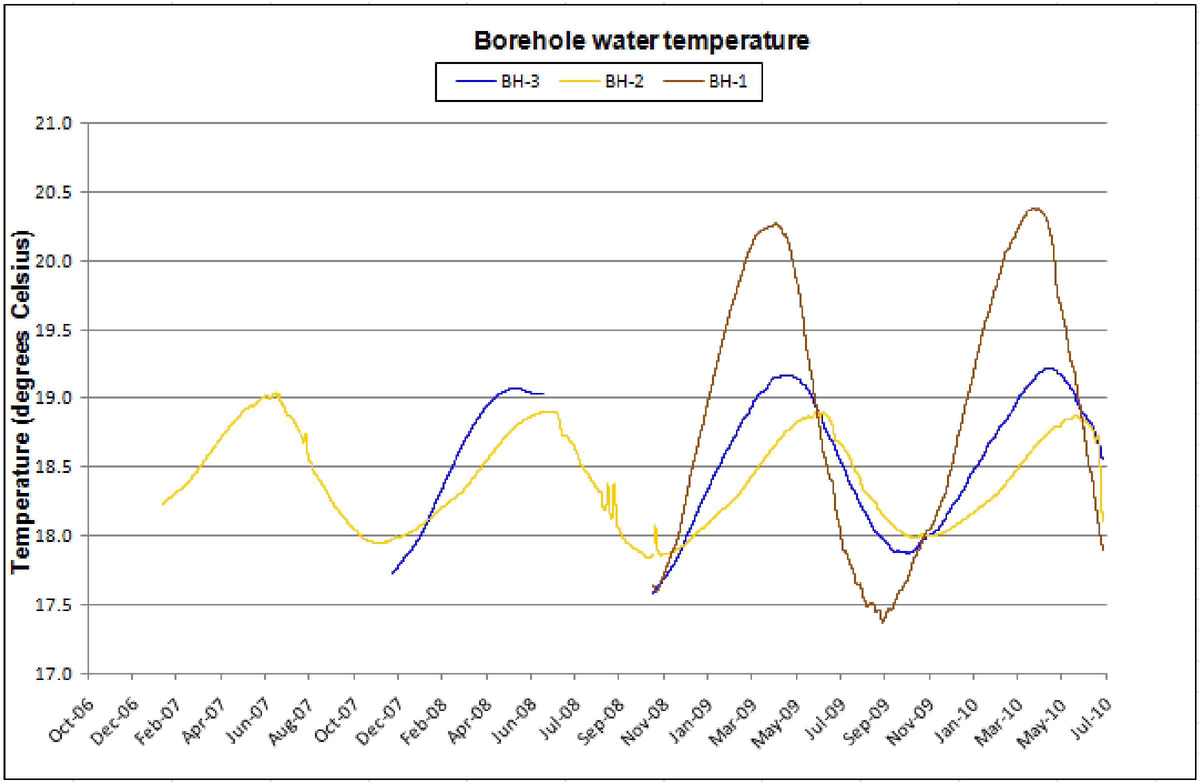

Figure 34. Water temperature time-series data (Degrees Celsius).

The boreholes do not show a diagnostic temperature trend, range or response time. Borehole 1 and Borehole 3 are both boreholes that target water bearing structures and both show relatively similar response times. Borehole 1 and Borehole 2 have similar looking temperature curves but they are displaced by about a month. Table 17 summarizes the ground water temperature data for the three boreholes monitored and the air temperature, as well as for the wetland and river sites.

Table 17. Site temperature fluctuations

Site ID	Temp range (Degrees Celsius)	Max Temp (Degrees Celsius)	Min Temp (Degrees Celsius)	2010 Max (Degrees Celsius)	2009 Min (Degrees Celsius)	Water temp low (days after Air temp low)	Water temp max (days after Air temp max)
Borehole 1	3.10	20.41	17.31	11/04/2010 18:00	18/09/2009 21:30	55.69	34.14
Borehole 2	1.25	19.04	17.79	08/06/2010 10:30	30/10/2009 07:30	97.10	91.83
Borehole 3	1.72	19.26	17.54	04/05/2010 21:30	02/10/2009 12:30	69.31	57.29
Borehole 4	TEMPERATURE NOT LOGGED						
Air Temp	40.53	41.03	0.50	08/03/2010 14:36	25/07/2009 04:59		
Wetland 1	5.70	21.90	16.20	08/03/2010 17:30	03/06/2009 08:00	-51.87	0.12
River 1	10.10	21.10	11.00	08/03/2010 19:00	25/07/2009 09:00	0.17	0.18
Wetland 3	3.30	18.80	15.50	11/03/2010 04:30	15/08/2009 10:30	21.23	2.58
Wetland 2	6.24	19.62	13.38	11/03/2010 00:30	24/08/2009 09:00	30.17	2.41

From Table 17 the wetland and river sites temperatures have a greater range than the boreholes, as well a quicker response to change in air temperatures. Where the time between the maximum air temperature and the maximum borehole water temperature is between 1 and 3 months for the boreholes, it takes less than a day for Wetland 1 and River 1, and less than three days for Wetland 3 and Wetland 2. The graph of the surface water temperature fluctuations are shown in Figure 35.

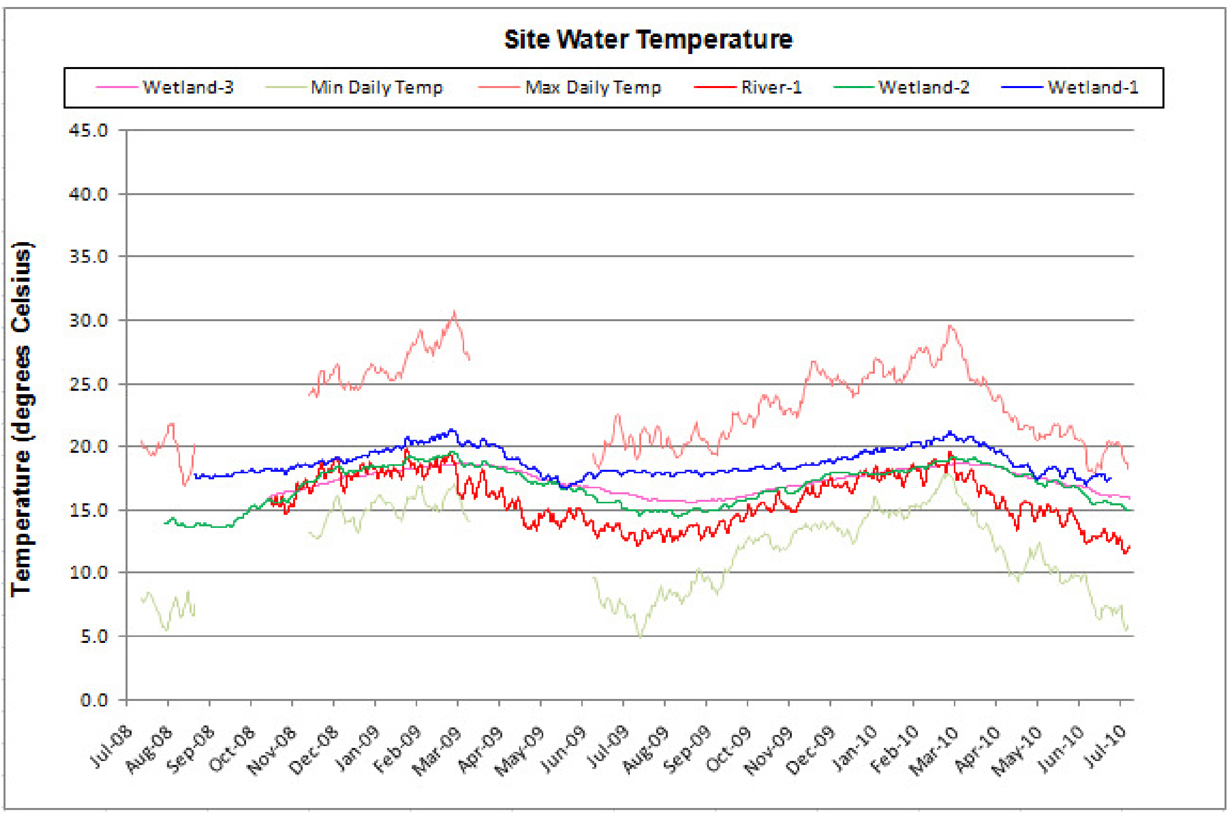

Figure 35. Wetland and River time-series temperature data in comparison to air temperature.

The lower range in borehole water level temperatures indicates that ground water temperature varies less than surface water temperatures, evidenced in the fact that the river site shows the greatest water temperature range. Ground water contribution to a site could therefore potentially decrease the range in temperature. In Figure 35 Wetland 3 shows a relatively stable temperature during the cold and rainy season which suggests a significant ground water contribution. Wetland 3 has the smallest range (3.3℃) of the wetland sites followed by Wetland 1 (5.7℃) and Wetland 2 (6.24℃).

Although ground water contribution has an effect on the water temperature at the respective sites, it is not the only contributor. Depth below ground level of the water, elevation of the site and exposure could also have affects. For example, the river site is fed by ground water during the summer months, yet its temperature shows considerable fluctuations.

Temperature is therefore a useful qualitative indicator of ground water contribution, but needs to be considered in light of other determining characteristics, such as geohydrological setting and water level fluctuation. Wetland 1 shows a relatively stable water level temperature even during the winter months and despite having a water level close to the surface. Wetland 3 has a small range, and is thought to be fed by ground water. Wetland 2 has the highest temperature range of the wetlands, despite having the deepest ground water during the summer months.

Wetland 1 also has the greatest offset in temperature graph from that of air temperature (Figure 36) which is more comparable to that of the ground water temperature fluctuations. Wetland 2 and Wetland 3 show similar responses, while River 1 shows no offset. The Oudebosch River is exposed to the surface temperatures, and this is evident in Figure 35 where the minimum air temperature and River 1 water temperature are closely linked. This does not provide an indication of ground water contribution, although point measurements along the profile of the stream could provide information with regards to ground water contribution sites.

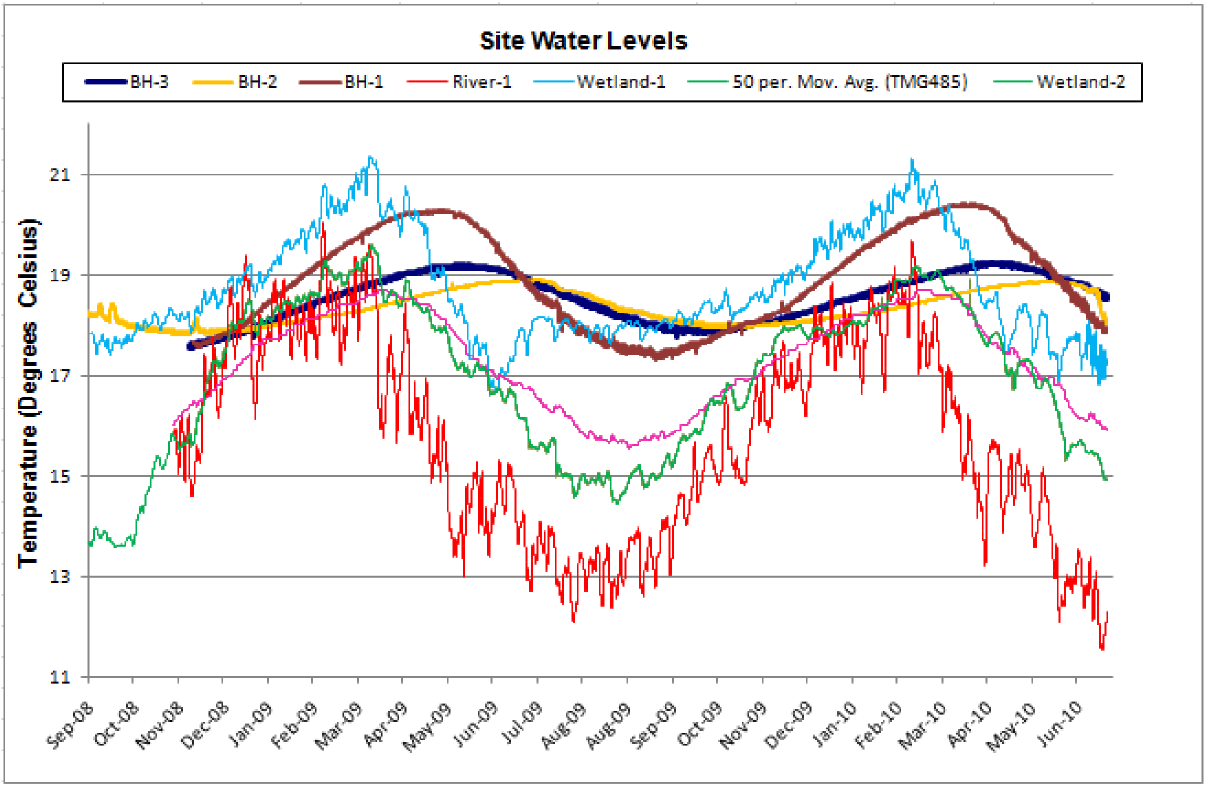

Figure 36. Temperature Time-series data for all the sites showing displacement of maximum and minimum values.

7.3.1 Summary

The temperature investigation proved to be a useful indicator of relative ground water dependence, although it is not conclusive. It is therefore a useful parameter to consider in conjunction with other diagnostic characteristics. The results of the investigation are summarized in Table 18. The ground water dependency rating is defined in Table 2. Temperature data suggests that Wetland 1 and Wetland 3 show a greater ground water dependency than that of Wetland 2.

Table 18. Ground water dependence based on water level responses.

Site ID	Groundwater Dependance Rating	Comment
River 1	-	No indication
Wetland 1	6	Longest lag between site temp and air temp maxima, values realtively stable considering water levels close proximity to surface
Wetland 3	6	Lowest range of all the sites
Wetland 2	2	Highest range of the wetland site despite having the deepest summer water levels.

7.4 Chemistry

7.4.1 General chemistry

Ground water chemistry within the geohydrological cycle has the potential to give useful clues as to the complex interactions that take place between water, bedrock, soil, vegetation and the atmosphere. The chemistry of ground water has a chemistry that is generally different to that of rainfall. During recharge, soil and vegetation can act as a filter selectively retaining certain elements of the water as well as contributing certain elements to the ground water chemistry. Previous studies have found that soil and vegetation retain the elements K and Mn, but also Ca, Mg, Fe and Al to a smaller degree (Compton and Soderberg, 2003). The interaction of ground water with the host rock also potentially alters the chemistry of the water. The challenge with using chemical indicators in the TMGA, and specifically the Peninsula Formation Aquifer, is the inert nature of the quartz arenites with little diagnostic interactions evident. Previous studies have however utilized Fe^{2+}, EC, Na, Cl, pH for this purpose (Roet et al, 2008).

The four boreholes, Borehole 1, Borehole 2, Borehole 4 and Borehole 3, were sampled monthly from 17 February 2010 until 17 July 2010 for the purposes of the geochemical investigation. The chemical constituent concentrations will be analyzed with the purpose of identifying trends, clustering and characteristic plots which could potentially serve as indicators of connectivity to the Peninsula Formation Aquifer.

It must be noted that a fire burnt the Oudebosch Valley on 4 June 2010 at 03:00 AM as a result of a lightning strike. This is expected to have affects on the chemistry of ground and surface water within the Oudebosch Valley. Wright (1976) also reports that runoff is increased after a fire event which would mean a decrease, or at least a change, in recharge as it has been occurring. The fire is expected to increase the nitrate, K and P concentrations, and possibly Ca, Na and Mg (Wright, 1976).

Before the individual element concentrations are discussed a multivariate analysis was conducted on all the chemistry measured for the ground water and the River and Wetland sites. These plots enable an evaluation of the relationships that exist between the various elements. For the analysis all constituents concentrations are plotted as mille-equivalents per litre (meq/ℓ), EC is in mS/m, TDS in mg/ℓ and temperature in degrees Celsius (°C). The plot for the boreholes is displayed in Table 25 (Appendix C).

Multivariate plots are commonly utilized to show the potential relationship between variables. They enable the form and strength of relationships to be determined. In this case "Exploratory factor analysis" is used to uncover the underlying structure of a relatively extensive set of chemistry variables. The various parameters are plotted on orthogonal axes, with the value between the various parameters indicative of the relationship. A value of -1 or 1 indicates a relationship (indirect and direct respectively) between the parameters. In the figures a white block represents a close relationship (close to 1 or -1), while a black block indicates no relationship. Where the correlation between two parameters is greater than 0.7 (or -0.7) the text colour is red.

The multivariate plot for the wetlands and the river site are not comparable with that of the ground water (Table 25, Appendix C). The multivariate analysis for Wetland-1 is shown in Table 26 (Appendix C). Wetland 2 also shows a relationship between the following, as was seen with the ground water:

Al & Fe,

Fe & P,

Zn & temperature and

Ca & Mg

The Multivariate plot for the site Wetland-2 is shown in Table 27 (Appendix C). There are direct and inverse relationships between a number of the chemical parameters considered. As was seen with the ground water, relationships are evident between:

Zn & temperature,

Ca & Mg and

Na & Cl.

Similarly, the multivariate plot for the Wetland-3 (Table 28, Appendix C), shows numerous relationships between chemical constituent parameters. Once again there is a relationship between:

Zn & temperature,

Ca & Mg and

Na & Cl.

There is also a relationship between Fe and pH.

For the site River-1 the multivariate plot is shown in Table 29 (Appendix C). Flow (ℓ/s) was included in the analysis and it shows relationships with:

pH,

Temperature,

Al and

Zn.

7.4.1.1 pH

The pH value of the ground water from the four monitoring boreholes in the Oudebosch Valley is neutral to acidic. During high rainfall periods the pH of the ground water is higher corresponding with the neutral pH of the rainfall. The low pH is a characteristic of the TMGA due to the minimal buffering of recharging organic acids from the weathered quartz sandstone. The low pH also enables a higher concentration of trace metals in solution, particularly iron and manganese. This is evident for the various sites multivariate plots where relationships between Fe, Mn and pH are seen.

These tend to precipitate in the presence of oxygen near the surface (a cause for iron bio-fouling in certain TMGA boreholes). The presence of the trace metals in solution enables the buffering of the addition of the hydroxyl ion (base neutralizing capacity) during acidity titrations. Thus the water has the ability to buffer acid. (Compton and Soderberg, 2003). TMGA-EMA (2010) found that the pH of the unimpacted freshwater ecosystems of the Western Cape were acidic with low concentrations of minerals and salts, as well as that the pH of the topsoil was low, and did not rise above 3.5.

Figure 87 (Appendix D) reveals a degree of correspondence between Borehole 1 and Borehole 2, and Borehole 3 and Borehole 4 for the samples taken from May to July 2010. This could relate to the fire event (4 June 2010, 03:00) which may have raised the pH at Borehole 1 and Borehole 2. The pH of all the sites is shown in Figure 88 (Appendix D) and the values range from acidic to neutral. The stream site samples shows the most acidic water (more so than the ground water) and this is most likely attributed to the leaching of phenolic and other organic acids from plants and roots at the surface (TMGA-EMA, 2010). During the low rainfall months the highest pH values relate to contact with the argillaceous material of the Cedarberg Formation. Borehole 4 is artesian due to the overlying Cedarberg Formation, and the wetland site Wetland 2 overlies the argillaceous Cedarberg Formation. Argillaceous material is known to have more neutral pH values and this is evident in both these cases. The boreholes and wetlands shows different pH response trends with the onset of the high rainfall months.

The wetland sites Wetland 3 and Wetland 1 show a highly similar pH trend, relatively acidic (pH of around 5, increasing during the high rainfall periods). Both these sites show far less fluctuation with regards to pH than Wetland 2 and the river (River 1). Their plots are similar to those of Borehole 3, Borehole 2 during summer, and Borehole 4 during May, June and July. Their relatively low range of fluctuation and high degree of comparability with Borehole 3 indicate that, based on pH, these sites are fed by ground water.

Wetland 2 has a pH trend that is not comparable with that of the ground water. It is interesting to note that the pH at this site decreases with the onset of the high rainfall months, this despite the higher recorded pH value of the rainfall. This decrease in pH is possibly due to some linkage to ground water, probably flowing to the site from the Peninsula Formation through the alluvial sediments overlying the impermeable Cedarberg Formation.

It is interesting to observe that all the sites pH values converge towards each other for the July measurements. It is thought that the cause for this is the increase in the pH for ground water sites as a result of recharge from rainfall, and a decrease in certain sites as the increased recharge results in increased discharge of ground water.

The Oudebosch River site shows an interesting trend with regards to pH (Figure 89, Appendix D). The summer values are low, indicating a significant ground water contribution as well as a contribution of organic acids from the thickly vegetated river banks. Summer rainfall and early winter rainfall events increases the pH as the more neutral rainfall contributes to the stream flow. The pH then decreases with the start of the more intense and longer duration rainfall events after which it increases once more. A possible explanation for this is that as the amount and intensity of the rainfall increases there is also a corresponding increase in the recharge (and therefore discharge) of ground water. This increased discharge results in the pH of the stream being lowered significantly. As the water discharges more recently recharged water starts to daylight and therefore the pH starts to increase again.

7.4.1.2 EC

EC values within the TMG are generally low, although TMGA-EMA (2010) found that values were slightly higher in the coastal areas of the Kogelberg and Steenbras Reserves, for both seeps and boreholes. This was attributed to the proximity to the coast, and suggested a possible ground water link with surface ecosystems. The ECs are still however low. The EC of the boreholes is generally between 10 and 20 mS/m, indicative of excellent quality water. The low EC is a common characteristic of the TMGA and is due to low residence times and the relatively pure and chemically inert nature of the quartz arenites. Borehole 4 shows anomalously high values in February and March 2010, after which it has a close correlation with Borehole 2 EC values, and the lowest EC values of all four boreholes for the June and July 2010 samples. The ground water EC trends are shown in Figure 90 (Appendix D).

The EC values for all the sites are similar, particularly during the winter months where the spread of plots become more concentrated. The EC values of the boreholes and Wetland 2 are low and relatively stable as evidenced in the longer term data. In Figure 91 (Appendix D) all the wetland sites, the river site and Borehole 4 and Borehole 3 show elevated values towards the end of summer (February and March 2010).

Figure 92 (Appendix D) shows a more detailed plot for the samples taken between October 2009 and August 2010. With the onset of the rainfall season during

April the spread of EC values become more concentrated, and generally decrease. The higher summer EC values are possibly due to the longer residence times, and the related increased interaction with the host rock/aquifer material. Borehole 4 targets the Peninsula Formation confined beneath the Cedarberg Formation and the presence of the argillaceous Cedarberg Formation is a possible cause for the higher EC values associated with Borehole 4 and Wetland 2, as well as the other sites which show elevated values. TMGA-EMA (2010) found that higher EC values relate to a more argillaceous geology, while the arenitic Peninsula Formation Aquifer is characterised by low EC values.

Boreholes 1 and Borehole 2 show consistently low EC values unlike the other ground water and surface water sites within the Oudebosch Valley. These sites are furthest from the down faulted wedge of Cedarberg Formation in the Oudebosch Valley and this is possibly the reason for the consistently low EC values.

The Oudebosch River had its highest EC value in late summer when low flow in the rivers and streams leads to a concentration of dissolved materials, and was lower in winter when the dilution factor is high. The increased EC of the ground water also affects the stream EC during the summer months when the river is sustained primarily/entirely by ground water.

7.4.1.3 Water signature

The chemistry of the ground water (Figure 93, Appendix E) shows a diagnostic chloride anion and sodium and potassium cation. The Piper diagram shows macro chemical plots for Borehole 1, Borehole 2, Borehole 4 and Borehole 3 samples taken from 1 February 2010 to 17 July 2010 on a monthly basis.

The description of a Piper Diagram and its application for the TMGA is taken from TMGA-EMA (2010). A Piper diagram is a triangular (trilinear) diagram that show the percentage composition of three ions, or groups of ions. The major ions in most natural waters are Na, K, Ca, Mg, Cl, CO_3, HCO_3 and SO_4. For the TMG data, grouping Na and K allowed the major cations to be displayed on one triangular diagram, with Na + K, Ca and Mg comprising the three sides. Similarly, CO_3 and HCO_3 were grouped to create three groups of major anions. The results were plotted as percentages of each cation/anion, based on the original data, which were expressed as meq/ℓ. The apex of the triangle represents 100% concentration of one of the three constituents. If a sample had two constituent groups present, then the point representing the percentage of each was plotted on the line between the apexes for those two groups. If all three groups were present, the results lie inside the triangle. The diamond-shaped field between the two triangles represents the composition of water with respect to both cations and anions. The cation point is projected onto the diamond-shaped field parallel to the side of the triangle labelled Mg, and the anion point is projected parallel to the side of the triangle labelled SO_4. The intersection of the two lines is plotted as a point on the diamond-shaped field. Thus, the TMG samples could be classified on the basis of the dominant ions.

The Piper diagram borehole plots display a diagnostic plot with the most clustering evident for the cationic species. The anionic species also shows clustering with the exception of Borehole 1 and Borehole 2 plots. On 4 June 2010 a fire burnt most of the Oudebosch Valley including around Borehole 4 and Borehole 3 at the Oudebosch huts. Three of the four anomalous plots are of samples from Borehole 1 and Borehole 2 taken after the fire event which is possibly the cause for the increase alkalinity.

Stiff diagrams are a useful indicator of ground water signature (Figure 96, Appendix F). With the exception of Borehole 1, the water has a characteristic shape with predominant sodium/potassium and chloride ions, secondary magnesium and sulphate ions and then calcium and alkalinity to a lesser degree. Borehole 1 shows an increased alkalinity for June and July 2010, two sample dates after the fire event on 4 June 2010 03:00 am. The general signature evident for the boreholes will be used to serve as an indicator of the Peninsula Formation Aquifer, TMG. The anomalous high alkalinity evident for Borehole 1 could potentially relate to the fire and could serve the function of a ground water tracer and indicate the rapid nature of ground water recharge.

For the wetlands and river sites Piper Diagram (Figure 94, Appendix E), the greatest clustering is evident for Wetland 1 (Stiff diagram shown in Figure 97) where the water has a definite dominant Na and K cation, and Cl anion. This is highly comparable with the borehole plots, and in particular Borehole 3. The STIFF diagrams show a consistent shape, the same as that for the ground water in the valley.

The second highest degree of clustering is seen for the Oudebosch River site River 1, which is similar to Wetland 1 with a dominant Na & K cation and Cl anion. The Stiff plots in Figure 98 show the same diagnostic shape as the boreholes.

Wetland 2 shows considerably more clustering than is evident for Wetland 3, although both sites are located on the Cedarberg Formation. Wetland 2 shows the same general plot as the ground water sites and Wetland 1 and River 1, but with slightly increased concentrations of calcium and alkalinity. The STIFF plots (Figure 97, Figure 98, Figure 99 and Figure 100, Appendix F) also shows the same diagnostic shape, but with increased Cl and alkalinity. The STIFF diagrams show the greatest Ca and Alkalinity concentrations during February and March (late summer), and a gradual decrease during winter.

Wetland 3 shows a general dominant Na and K cation and Cl anion, although the alkalinity and Mg shows some degree of variation. On the piper diagram the plots do not cluster or have a diagnostic plot. The basic chemistry is close to that of the ground water (as is evident in the STIFF diagram in Appendix F), but additional sources of Mg, and to a lesser degree alkalinity and Cl affect the chemistry.

7.4.2 Macro -Chemical constituent concentrations

Borehole samples were collected and analyzed for chemical parameters to identify any that may serve as indicators of the Peninsula Formation with regards to seasonal trends or values. Due to the inert “pure” nature of the Peninsula Formation quartzites it is suspected that numerous chemical tracers are unlikely. Time series chemical constituent concentration data was plotted and analysed. They will be discussed according to chemical elements/compounds. The boreholes were sampled for the chemical parameters as stipulated in the TMGA monitoring project.

7.4.2.1 Mg

Magnesium is another chemical element that shows a similar trend for all the boreholes. The borehole magnesium concentrations (Figure 101, Appendix G) are between 1 and 3 mg/l and are slightly elevated with regard to the rainfall. The general increase in concentration observed for the 17 March 2010 and 15 May 2010 samples are difficult to explain, but they may possibly correspond to the first sustained rainfall event in the case of the May samples.

Four rainfall samples were taken and analysed for Mg concentrations between February 2008 and August 2010, all the concentrations measured are between 0.5 and 1 mg/l and they are relatively constant.

The Mg concentration of Wetland 3 is anomalously high and does not show any correlation with the ground water trend or range of concentration values (Figure 102, Appendix G). It is thought that a significant source of Mg plays a role in altering the wetland water chemistry.

Wetland 1 Mg concentration shows a trend highly comparable with that of ground water (Figure 37) with a relatively small concentration range. As is evident with the ground water, and all the sites monitored for that matter, the Mg concentrations show a spike for the sample taken in May just after the onset of the sustained winter rains.

River 1 and Wetland 2 show values that are comparable with those of ground water (Figure 37), but the range of concentration values are noticeably higher. These sites also show elevated values in February 2010, which are not mirrored in the ground water Mg concentrations.

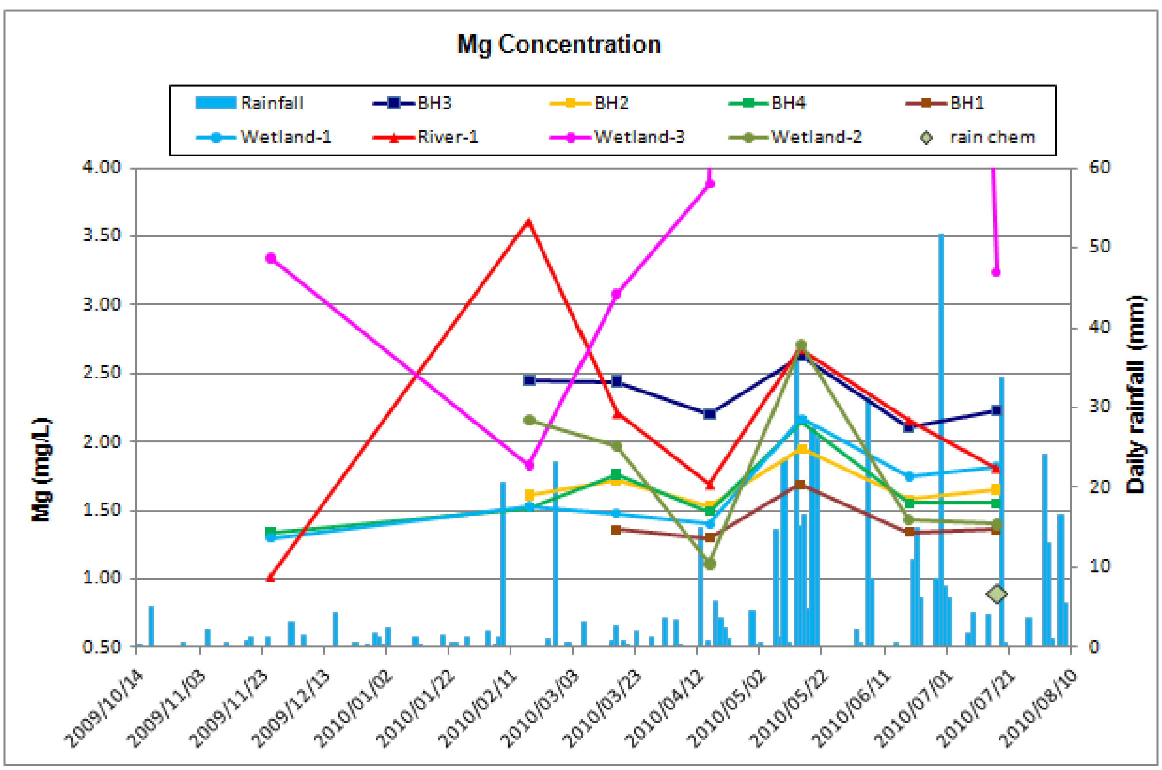

Figure 37. Mg **concentration** ***time-series data plotted with rainfall.***

7.4.2.2 Na

Ground water sodium concentrations range between 10 and 20 mg/L and are elevated with regards to rainfall concentrations (Figure 103, Appendix G). There is a relative degree of clustering of samples for the time-series data with the boreholes showing similar concentration increases/decreases between sampling dates.

The four rainfall samples analyzed have concentrations that range between 3.6 and 7.9 mg/l, relatively consistent and lower than all previously recorded ground water and surface water concentrations. Na is generally the dominant cation, for both the ground water and the surface water sites as was evident in the Piper and Stiff diagrams.

Once again Wetland 3 shows a plot that is different to that of the ground water sites (Figure 38). The plot is similar for the summer readings, but the readings from April onwards follow a relatively different trend. It is thought that during the summer months the site Wetland 3 is fed predominantly, or entirely, by ground water. With the onset of the winter rainfall however, the Oudebosch Valley bottom wetland is significantly fed by interflow within the catchment. This interflow water interaction with the subsurface chemistry is possibly the cause for the anomalous trends evident for Na, and other chemical constituent concentrations.

Wetland 1 and Wetland 2 shows close links with the ground water chemistry, although Wetland 2 Na concentration is slightly elevated in relation to the majority of the ground water sites, attributed to interaction with the Cedarberg Formation or wetland sediments.

River 1 shows high Na concentrations during the low rainfall summer months, but with the onset of the winter rainfall in April the values are lowered and are comparable with the ground water sites. The lowering of the Na concentration during the rainfall season is attributed to the low Na concentration of the rainfall.

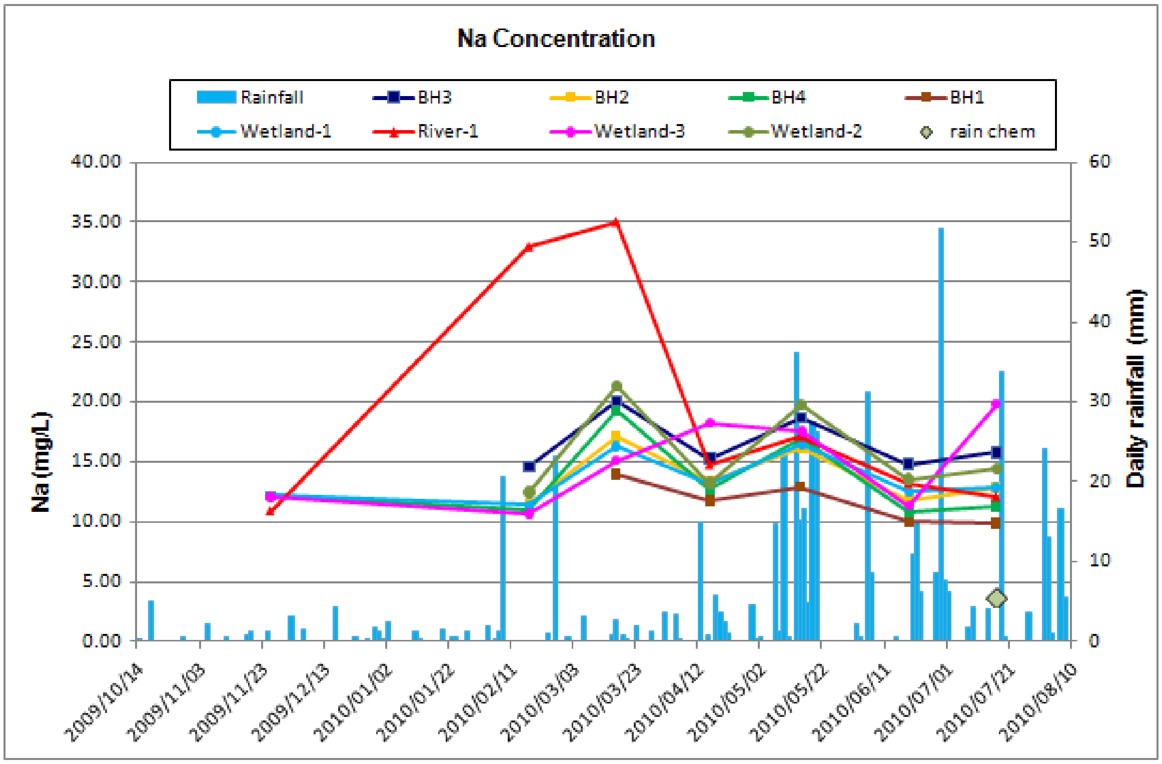

Figure 38. Site Na concentration time-series data.

7.4.2.3 K

The borehole potassium concentrations (Figure 104, Appendix G) show a similar trend to that of Na, increasing and decreasing consistently. The concentrations of K are however lower and range between 0 and 4 mg/ℓ. The ground water K concentration is generally just less than that of rainfall indicative of the filtering/retaining of certain elements by vegetation and soil (Compton et al, 2003). Once again the points show a degree of clustering with synchronised concentration increases and decreases.

The four rainfall samples analysed have K concentrations between 0.9 and 2.68 mg/l. The wetland and river concentration trends are shown in Figure 39. Once again Wetland 1 and Wetland 2 show a similar plot to that of the ground water sites. River 1 shows elevated K concentration values towards the end of summer but values relate to that of ground water from the March 2010 samples until the July 2010 samples. The site Wetland 3 once again shows an elevated constituent concentration in April 2010, possibly related to the onset of the winter rainfall. The Wetland 3 concentrations are elevated, but gradually decrease and are comparable with that of the other sites in July 2010.

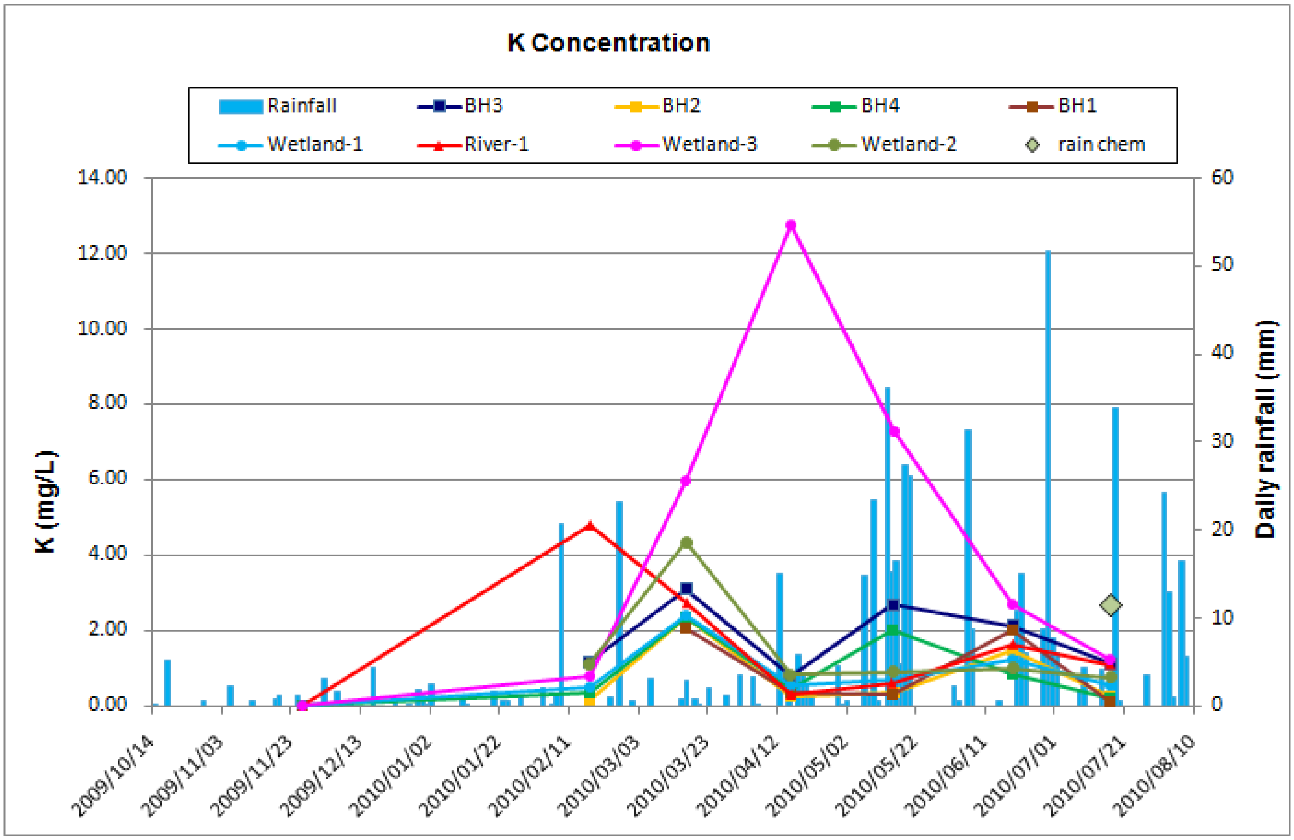

Figure 39. Site K concentration time-series data.

7.4.2.4 Ca

Ca is another element commonly retained by soil and vegetation, and in this case the concentrations are less than that measured in rainfall (4.38 mg/ℓ for cumulative sample of period 15 May – 17 July 2010). It is interesting to note that a marked decrease in Ca ground water concentration was recorded for the 16 April 2010 sample following the first significant rainfall of winter. Retention of Ca by the soil and vegetation is possibly higher for the early winter rains due to the possibly more depleted soil moisture and unsaturated zone water. Ca shows generally good clustering for the boreholes per sampling visit (Figure 105, Appendix G).

The four rainfall samples analysed have Ca concentrations between 2.48 and 4.38 mg/l. With regards to Ca concentration there is an apparent difference between Wetland 2 and Wetland 3 and the other sites. The sites Wetland 1 and River 1 show a close correlation with the Ca concentration of the ground water, showing the same spikes and dips. Wetland 2 and Wetland 3 show elevated Ca concentrations, which is most likely due to their setting on the argillaceous Cedarberg Formation. Figure

106 (Appendix G) shows the anomalously high values of Wetland 3, while a more detailed graph for the trends of the sites is shown in Figure 40.

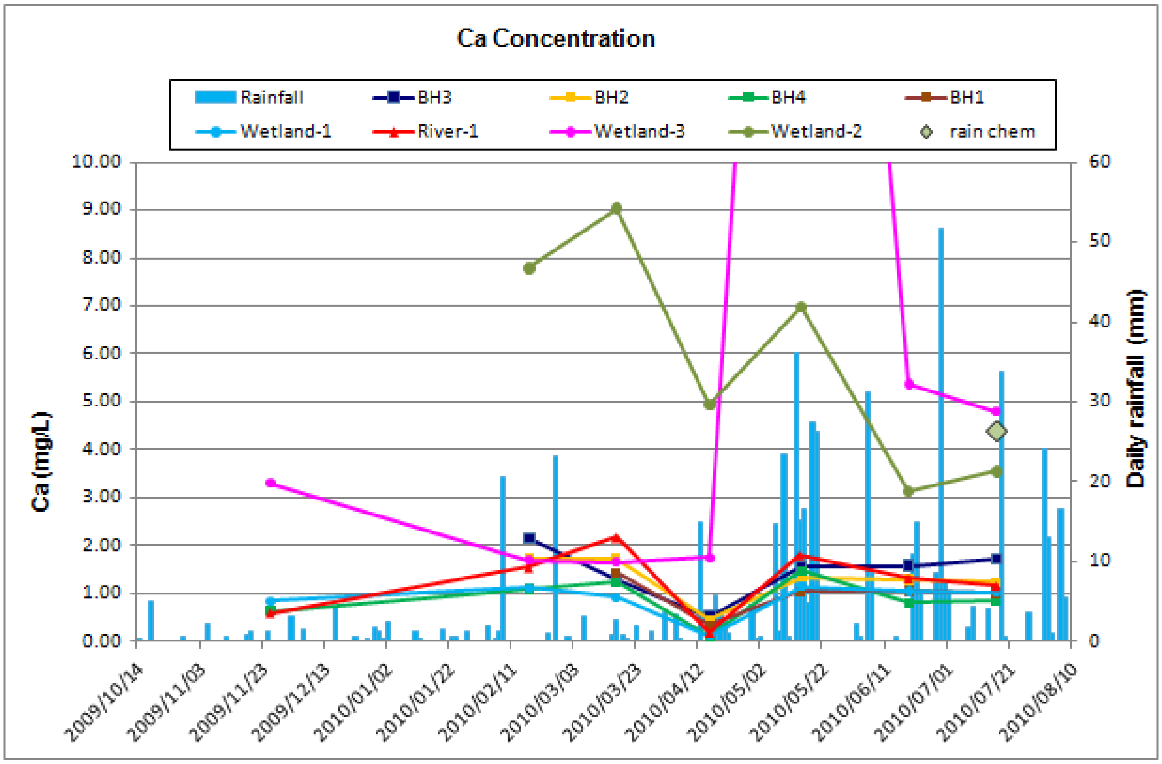

Figure 40. Ca concentration time-series data.

7.4.2.5 Cl

The borehole Cl concentrations are higher than that of rainfall (17.62 mg/L) with the exception of the anomalous Borehole 4 sample from 17 July 2010. There is no clustering of the borehole samples and no diagnostic trends evident (Figure 107, Appendix G).

The Cl anion is the dominant anion for the sites, and the time-series trend for all the sites is depicted in Figure 108 (Appendix G). The rainfall samples have concentrations that range from 9.7 to 30.9, and had a concentration of 17.62 for the cumulative rainfall sample taken of the rainfall that fell between May and July 2010.

Wetland 3 has Cl concentrations that are comparable with those of the other sites with the exception of the anomalously high April and July 2010 Cl concentrations (Figure 26). These anomalously high values are attributed to interaction of surface and ground water with the host materials and vegetation. The other sites show similar values, although a diagnostic ground water and surface water trend is not evident. The concentrations vary from between ~ 17 mg/ℓ (concentration within rainfall) and 36 mg/l. The site Cl concentration trends possibly show a general increase towards the end of summer (May 2010) followed by a general decrease over the higher rainfall months. A more detailed plot is shown in Figure 41.

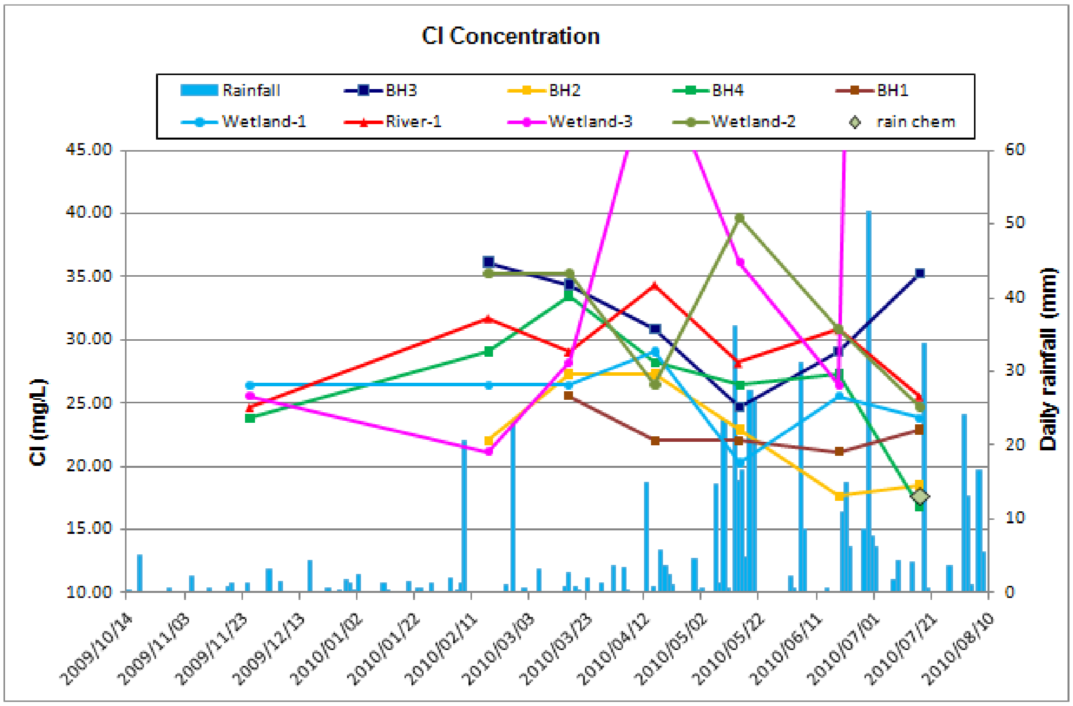

Figure 41. Detailed Cl concentration time-series data.

For site River-1 the Cl concentration is plotted against stream flow (but based on the six samples it is not possible to identify a relationship. This plot is highly comparable with that of EC vs. Flow with no clear relationship evident. It is thought that the rapid recharge/discharge times within the TMG means that the ground water quality is not elevated in Cl concentration or does not have higher EC values.

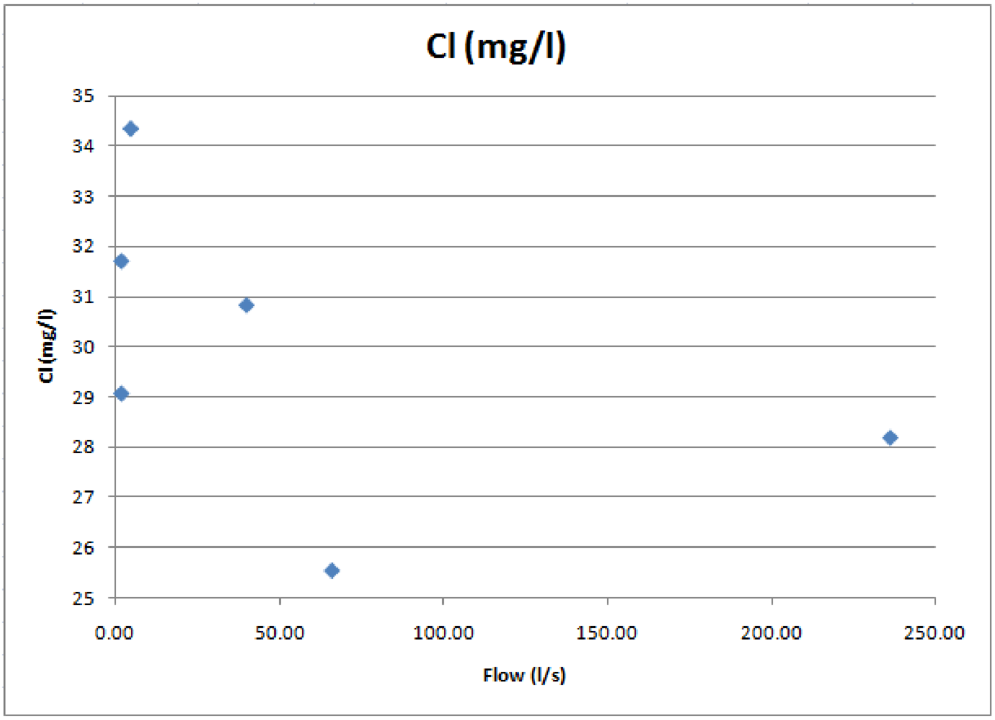

Figure 42. Cl concentration plotted relative to river flow measured at site River-1.

7.4.2.6 SO_4

The sulphate concentrations are all low for the 15 May 2010 sample, with increases in concentrations before and after that date. This is possibly attributed to the heavy rainfalls that preceded that date. The trend is shown in Figure 109 (Appendix G).

Apart from two anomalously high concentrations for Borehole 1 and Borehole 2, all sites show similar SO_4 concentraitons generally below 10 mg/l. All sites show a similar trend (Figure 43), with a concentration decrease for the samples taken in May, after the first prolonged and high volume winter rainfall. The concentrations then gradually increase once more. There are no diagnostic trends amongst the wetlands and river sites, but all are comparable to Borehole 3 and Borehole 4.

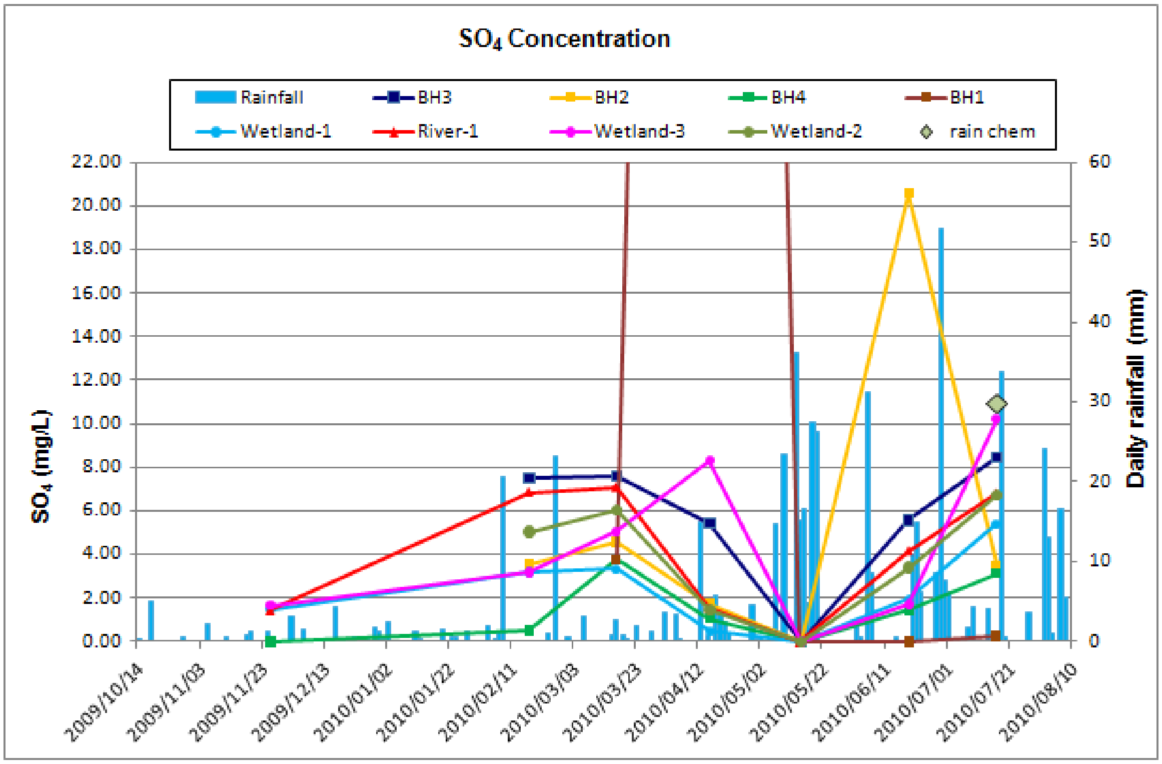

Figure 43. SO_4 concentration time-series data plotted with rainfall.

7.4.2.7 HCO_3

Bicarbonate shows a similar plot for all the boreholes (Figure 110, Appendix G), with concentrations varying between 5 and 30 mg/l for the data obtained between November 2009 and 17 July 2010.

With regards to HCO_3, Wetland 3 shows an anomalously high value, but is comparable to ground water prior to this June sample (Figure 111, Appendix G). It must be noted that this anomaly is possibly attributed to the fire that burnt the study area on the 4 June 2010. Wetland 3 has water close to the surface and it is possible that the increased carbonate is due to this event.

A more detailed plot is shown in Figure 44. Wetland 2 shows slightly elevated concentrations which is most likely related to increased interaction with the Cedarberg Formation and possibly also the fire. Wetland 1 and River 1 have trends that are comparable to that of the ground water.

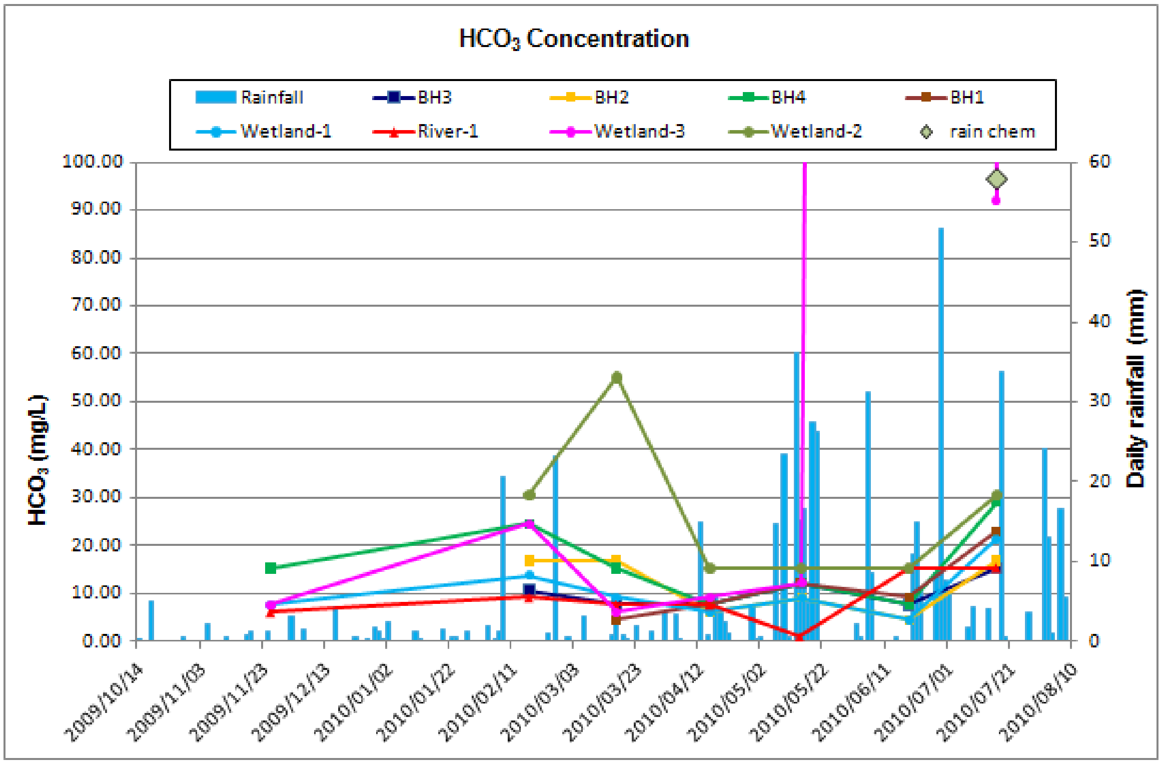

Figure 44. Detailed HCO_3 concentration time-series data.

7.4.3 Micro-chemical constituent concentrations

7.4.3.1 Si

Due to the composition of the Peninsula Formation quartz arenites it is suspected that Silicon may be a diagnostic feature. The plots for the four boreholes are closely linked and plot together for the various months (Figure 45).

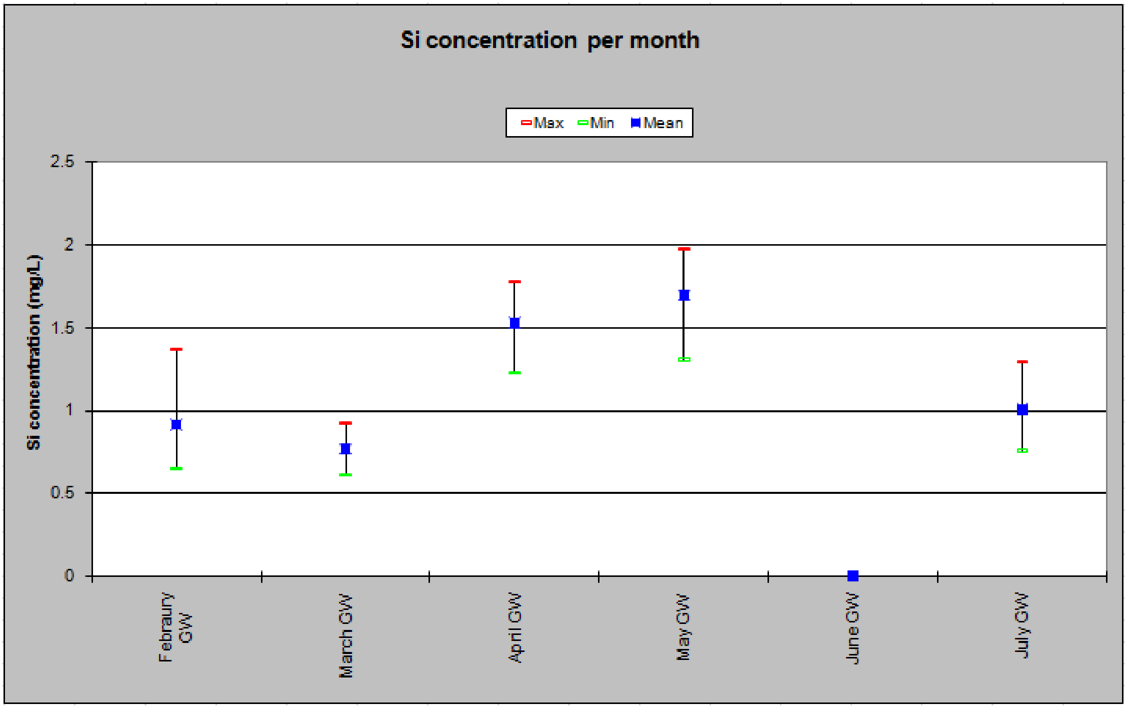

Figure 45. Borehole Si concentration box and whisker plot.

The samples collected in June 2010 are anomalously low. These samples were collected after a period of high rainfall which may have caused the Si concentrations to be lower. One would then expect the July concentrations to be similar but they show a marked increase. The plot of the boreholes per month is clustered which will be useful for comparing with the surface water sites. The rainfall Si concentration was measured to be 0.228 mg/l in the cumulative sample of rainfall between 15 May 2010 and 17 July 2010. The borehole Si concentrations are plotted in Figure 112 (Appendix H).

The fact that the June Si concentrations are considerably lower than those both before and after that month means that these analysis results should not carry too much significance and the possibility of analytical errors considered. It is unlikely that such a marked decrease in Si concentration would be observed for all samples taken during the same monitoring visit, and that the next month the concentrations return to normal.

The two valley bottom wetlands, Wetland 3 and Wetland 2 show Si concentrations that exceed that of ground water (Figure 113, Appendix H). The reason for this is that the water is located within alluvium formed from the weathered sandstone overlying the arenaceous Cedarberg Formation. Within sediments water has a far greater surface area to interact with than in a fracture, and this is a possible reason for the higher concentrations. None of the sites show a close Si concentration correlation with the ground water. Wetland 3 has one highly anomalous plot which is considerably higher than the other sites.

A more detailed plot of the site concentrations is shown in Figure 46. The sites Wetland 1 and River 1 show concentrations that are consistently less than that of ground water, which suggests less interaction with the quartz arenites of the Peninsula Formation and possibly shorter residence times. These sites have concentrations which are highly comparable with that of the rainfall sample.

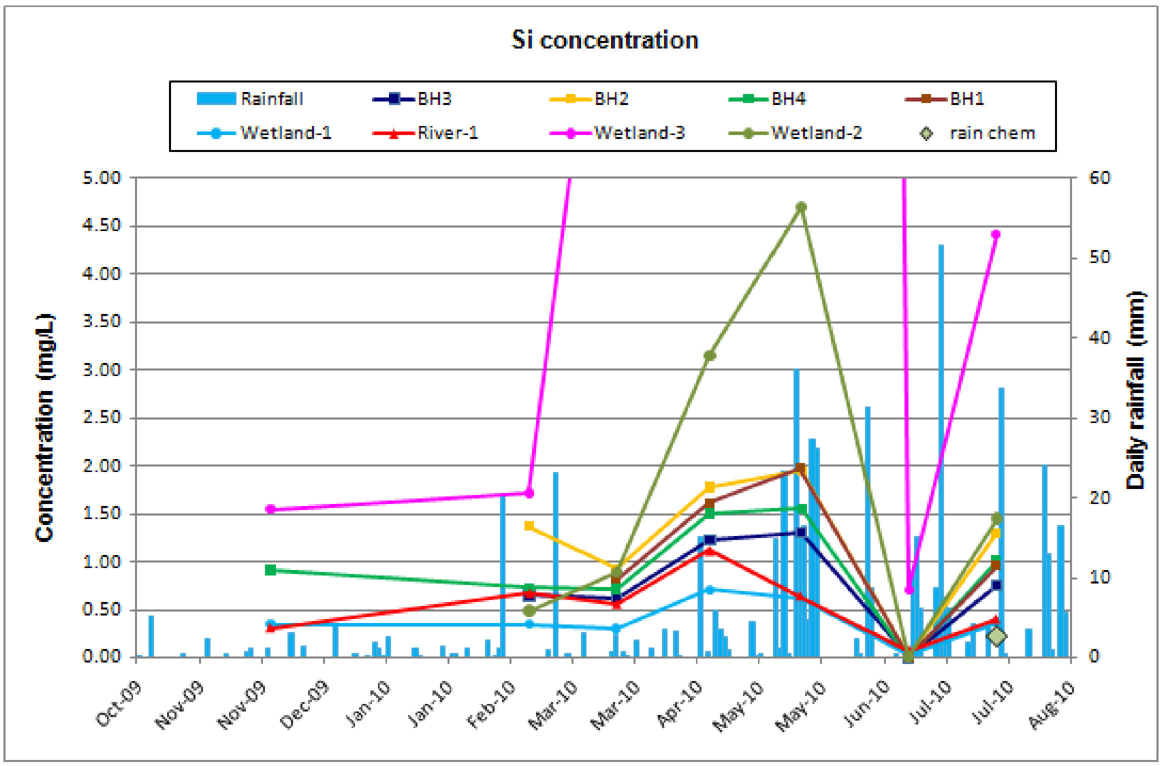

Figure 46. Detailed site Si concentration time-series data plotted with rainfall.

7.4.3.2 Fe

Fe is an element commonly associated with the TMGA, and is a potential cause for iron bio-fouling in abstraction boreholes. It is interesting to note that Borehole 1 and Borehole 2, and Borehole 4 and Borehole 3 show two different trends (Figure 114, Appendix H). Borehole 4 and Borehole 3 are in close proximity to each other and, from other chemistry and water level data, are clearly linked. Borehole 1 and Borehole 2 show a different trend on more than one occasion. They indicate an increase in Fe concentration for June and July 2010 which could potentially relate to the fire event. Borehole concentrations exceed rainfall which was 0.252 mg/L for the rainfall that fell between 15 May 2010 and 17 July 2010.

All the site concentrations are plotted in Figure 47. The Fe concentrations of Wetland 1 and River 1 are consistently low, less even than Borehole 3 and the June and July Borehole 4 samples. The two valley bottom wetlands, Wetland 3 and Wetland 2, have Fe concentrations that are comparable with Borehole 1, Borehole 2 and the late summer Borehole 4 sample Fe concentrations. The time-series concentration trends do not, however, show much correlation to that of the ground water sites. Sites Wetland 1 and River 1 concentrations are similar to that of the rainfall Fe concentration (cumulative sample for May, June and July).

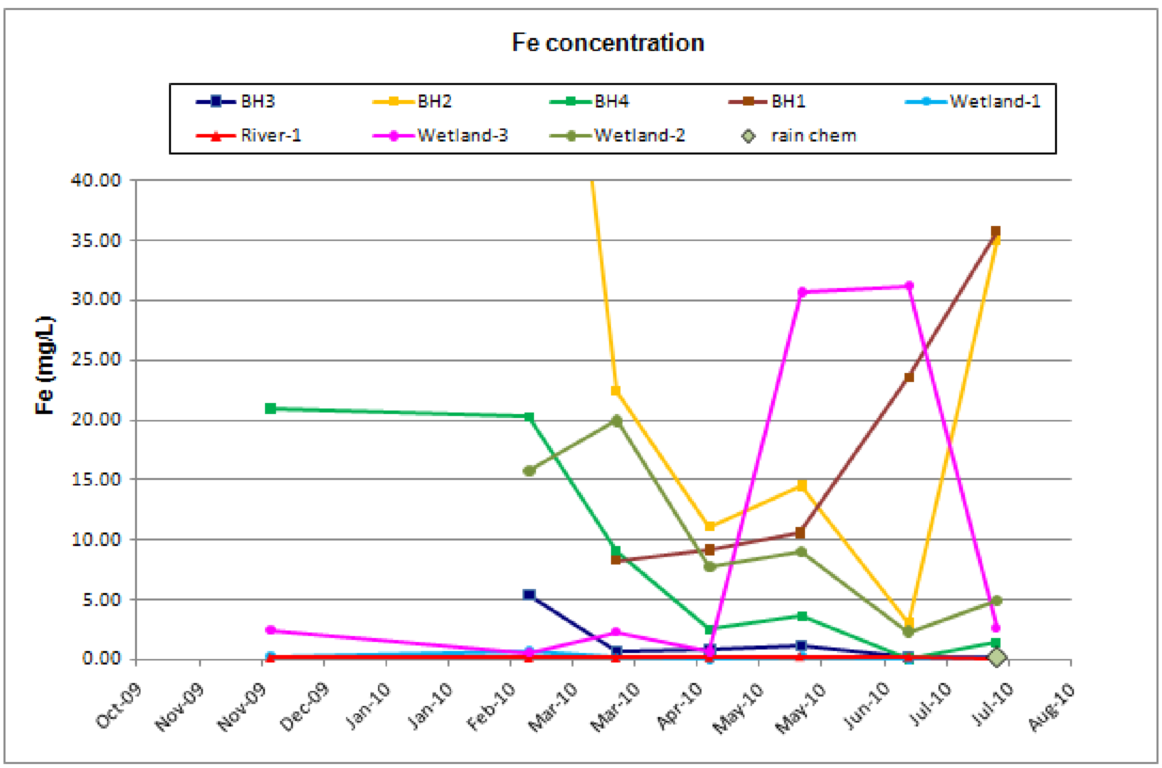

Figure 47. Fe concentration time-series data.

It is interesting to observe that the Fe concentration of Wetland 3 is low, comparable with Wetland 1 and River 1, for the samples up to April but with the onset of the winter rains the value increases considerably. None of the sites show trends that correlate well with the ground water trends of Borehole 3/Borehole 4 or Borehole 1/Borehole 2. As mentioned the Fe concentration is controlled by pH. The relationship between the two for the ground water samples is shown in Figure 48.

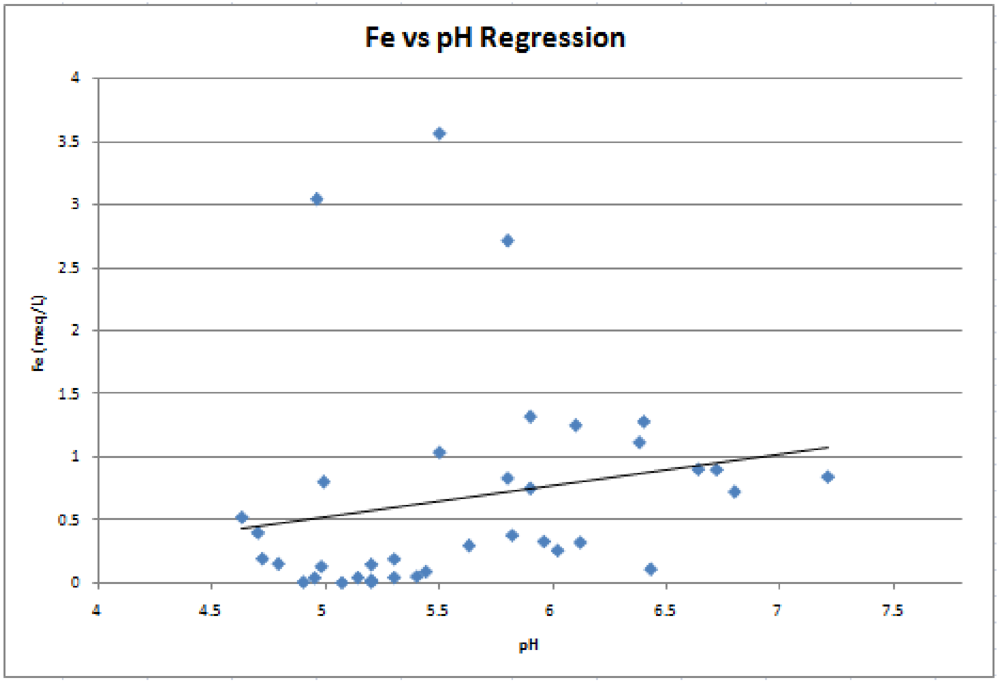

Figure 48. Plot of Fe as a function of pH for borehole sites.

7.4.3.3 Mn

Manganese is another element that shows a distinction between Borehole 1/Borehole 2 and Borehole 4/Borehole 3 (Figure 115, Appendix H). Elevated concentrations are also experienced for the June and July samples after the fire event. Borehole 4/Borehole 3 show a decrease from summer concentrations to winter, with a slight increase for the months of June and July. Rainfall Mn concentration measured for the cumulative sample taken on 17 July 2010 is 0.019 mg/L. Mn concentration is also largely affected by pH, and relationship between the two for the borehole sites is shown in Figure 49.

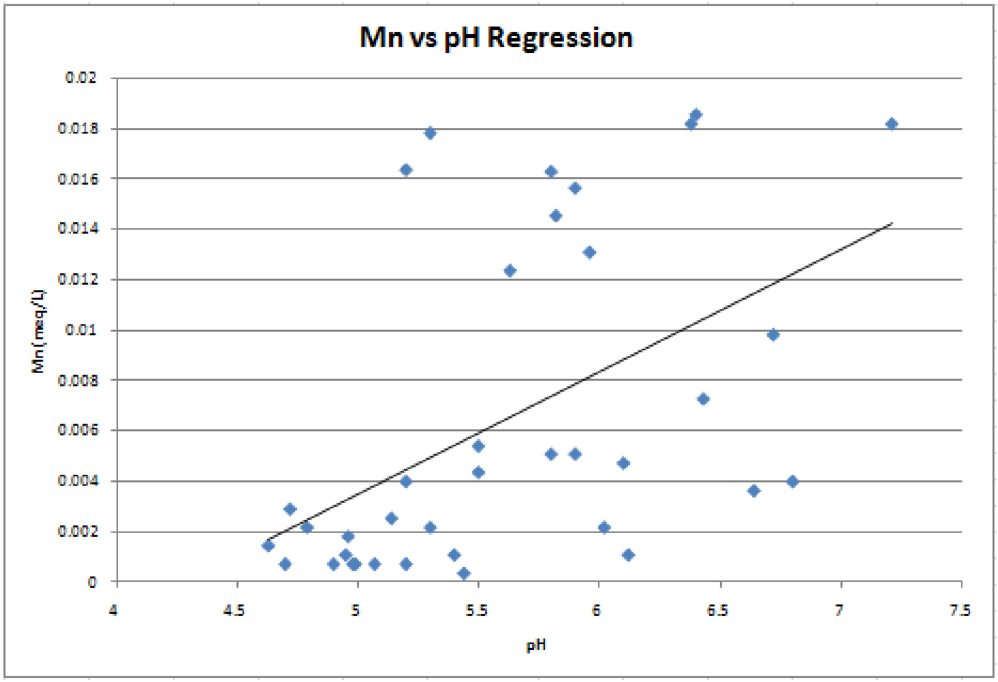

Figure 49. Plot of Mn as a function of pH for borehole sites.

The Mn concentration of the various sites is shown in Figure 116 (Appendix H). Wetland 3 once again has some anomalously high values, and is difficult to compare with ground water. At times the values are comparable with borehole concentrations, but there is a large degree of variation.

A more detailed plot of the site concentrations is shown in Figure 50. Wetland 1, River 1 and Wetland 2 all have concentrations that are generally less than that of Borehole 3 and Borehole 4. If Mn is a ground water tracer for the Peninsula Formation Aquifer then this would indicate low ground water contributions to these sites.

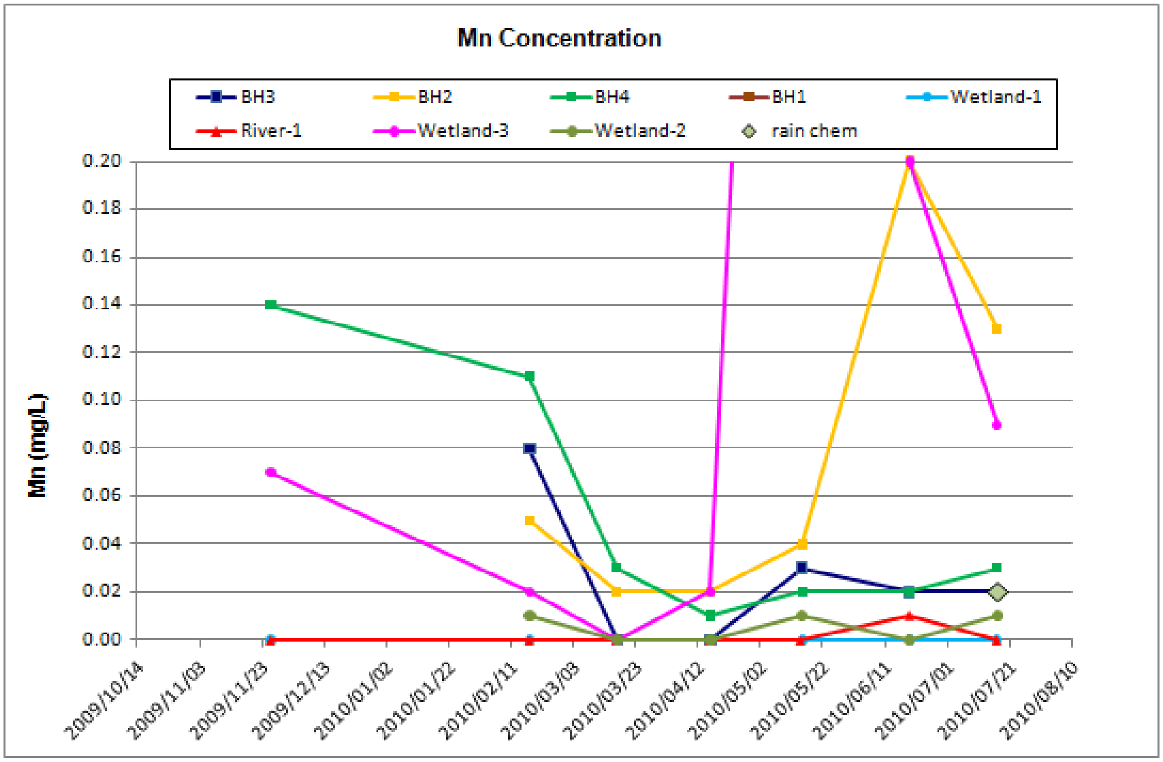

Figure 50. Detailed site Mn concentration time-series data.

7.4.3.4 Al

The borehole Al concentrations are plotted in Figure 117 (Appendix H). Aluminium shows consistently low concentrations, with a possible gradual decline from summer into winter. The rainfall sample had a concentration of 0.5 mg/ℓ, lower than the borehole concentrations.

Wetland 3 shows an anomalous plot once again (Figure 118, Appendix H). The concentrations at this site far exceed those of the other sites.

A more detailed plot of site Al concentrations is shown in Figure 51. In this figure it is clear that both Wetland 2 and Wetland 3 show anomalously high concentrations. These elevated concentrations are once again attributed to the Cedarberg Formation in the area. Wetland 1 shows a relatively good correlation with Borehole 3, suggesting possible linkages with ground water. The river site, River 1, has plot comparable with that of Borehole 4 for the summer months, but shows elevated concentrations during the winter months, more comparable with Borehole 3 and Wetland 1.

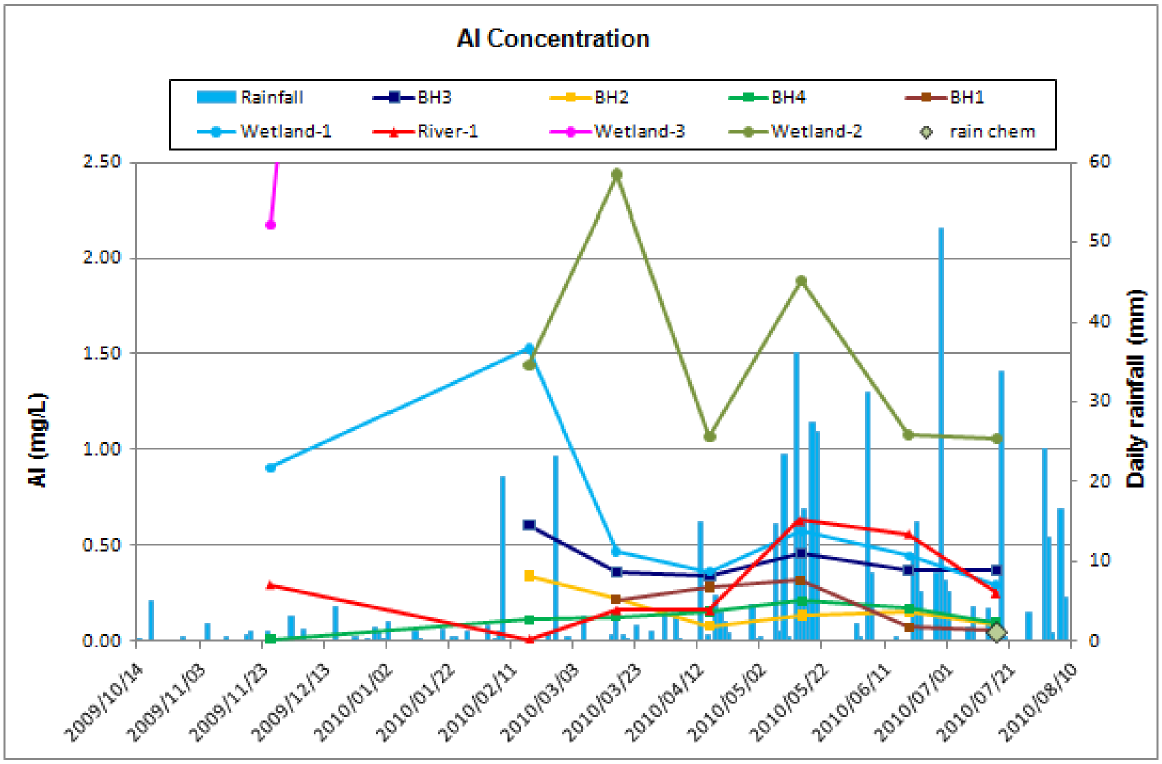

Figure 51. Detailed Al concentration time-series data.

7.4.3.5 Zn

The borehole zinc concentrations, similarly to aluminium, are consistently low concentrations (Figure 119, Appendix H). The rainfall sample had a concentration of 0.045 mg/ℓ. There are not any significant fluctuations and the concentration doesn't exceed 0.1 mg/ℓ.

The Zn concentrations for all the sites are plotted in Figure 52. Wetland 3 shows a concentration trend comparable to that of ground water (Borehole 3) until May when it is once again elevated in comparison to that of ground water. This once again suggests that the sites are possibly fed primarily by ground water during the summer months, but this changes with the onset of the higher rainfall season. Wetland 2 is elevated with regards to the other sites and this is possibly due to interaction with the Cedarberg Formation. The sites Wetland 1 and River 1 have plots comparable to that of ground water, the values are just lower.

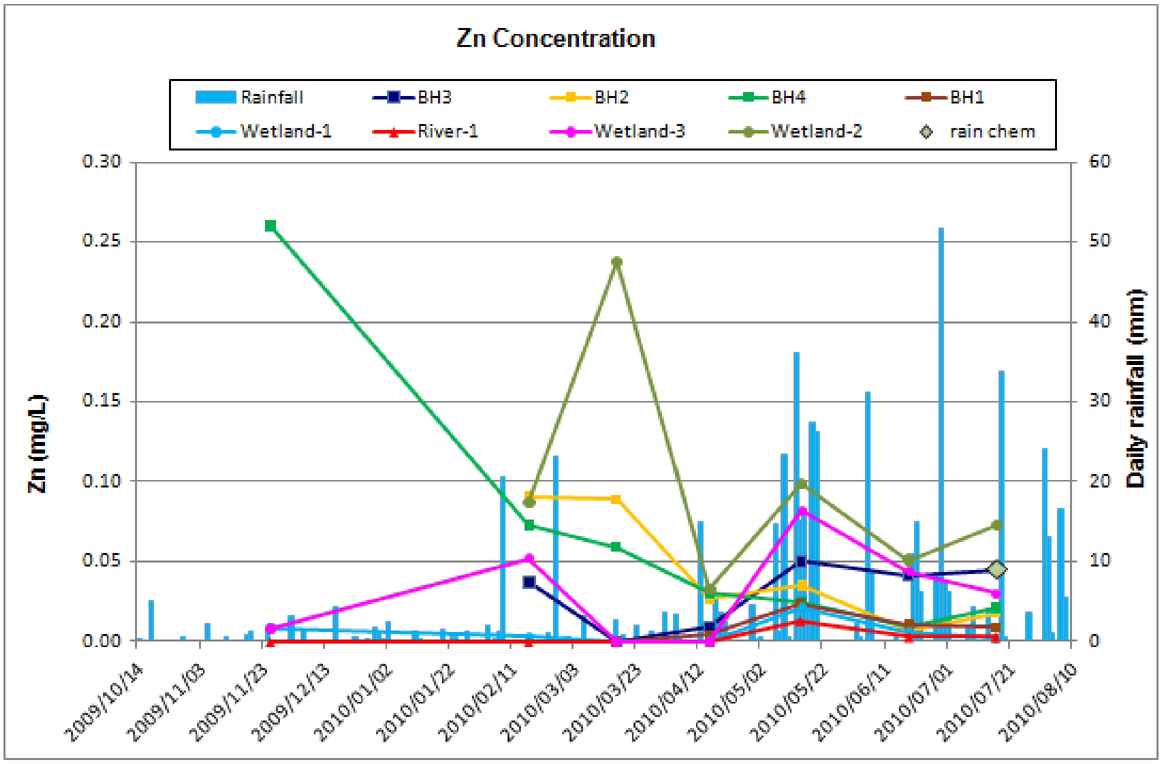

Figure 52. Site Zn concentration time-series data.

7.4.4 Summary

A number of chemical constituents and chemical properties were investigated in an attempt to relate the sites to ground water. Table 19 summarizes the various site properties that showed some similarity to that of the ground water. The Ground water dependence rating is allocated according to the values defined in Table 2.

A few of the chemical constituent concentrations and properties showed similar responses for all sites. These include the EC values and SO_4 concentrations which were similar for all sites, with no clear ground water defining values or trends. The Cl and Mn concentrations of the wetland and river sites on the other hand did not show any real correlation with ground water.

Table 19. Ground water dependence based on water chemistry.

Site ID	Groundwater Dependance Rating	Comment
River 1	6.0	Mg, SO4, Zn and Fe relatively similar to groundwater trends. pH, Si and Al more comparable with groundwater. STIFF plot, Ca and HCO3 highly comparable with groundwater.
Wetland 1	8.0	Si, Fe and Zn show similar trends to groundwater, concentrations are however lower. Water signature, pH, Mg, Na , K, Ca, HCO3, and Al concentrations highly comparable with groundwater
Wetland 3	3	Na and HCO3 show a summer correlation with groundwater. Similar plots as groundwater are seen for Si and Zn, although concentrations are elevated.
Wetland 2	3	Na, K, HCO3, Si and Zn all comparable with groundwater, just slightly elevated.

The evaluation of the chemistry was qualitative. Wetland 1's chemistry was comparable with that of ground water, and in particular Borehole 3. River 1 also showed a chemistry that was similar to ground water. Surprisingly, Wetland 2 chemistry plots were generally more comparable with ground water than Wetland 3. Wetland 3 generally showed anomalous constituent concentrations. This was generally during the winter months, and the summer plots were more comparable with ground water.

7.5 Isotopes

7.5.1 Rainfall and Precipitation

Craig (1961) showed that there was a correlation between ^{2}H (D) and ^{18}O in precipitation waters world-wide, with a best-fit line of $\delta D = 8\delta^{18}O + 10$, which is known as the global meteoric water line (GMWL). Different areas have their own distinctive local meteoric water lines (LMWL), due to differences in temperature and humidity in the source regions for weather systems, and various geographic and climatic factors during rainout, as the weather system moves inland. Diamond and Harris (1997) plotted a local meteoric water line called the Cape Meteoric Water Line (CMWL) for Western Cape precipitation, which has the equation $\delta D = 6.1\delta^{18}O + 8.6$.

Although isotope precision in the laboratory is generally better than 1‰ for δD and 0.2‰ for $\delta^{18}O$, one should refrain from over interpreting minor variations in stable isotope values. The reason for this is the processes that cause isotopic differences are complex and lead to some degree of `noise` in the data.

A cumulative sample of rainfall was collected in July 2010 from the CRC constructed and setup near the weather station in May 2010. Although a greater number of samples would give a better characterization of the isotopic signature for the area, this single point plots close to the CMWL and is used to represent rainfall for the area for the purposes of this study. Figure 53 shows the rainfall point as well as the GMWL and the CMWL.

Different rainfall events can have unique isotopic characteristics or signatures, due to the varying histories of the individual air masses, and the different atmospheric temperatures and the evaporation rates acting on the falling rain droplets. These variations can be used to identify sources of runoff during storm events, and to identify the season during which recharge occurs (Drever, 1988). For instance, water is more depleted of the heavier isotopes during the winter/spring months due to colder temperatures (Domenico & Schwartz, 1990). In this case however, only one rainfall sample was obtained during the 2010 period. The sample was taken on17 July 2010 from the Rainfall collector setup on 15 May 2010. The water within the collector was drained and mixed prior to sampling meaning that the collected sample is an integrated sample of rainfall falling between the date of installation and the sampling date.

The isotope data from the rainfall collector and the boreholes is compared against the CMWL and GMWL in Figure 54. The rainfall plots on the CMWL, which is mutually confirmatory – this rainfall point affirms the accuracy of the CMWL, while the CMWL suggests that no unusual rainfall events, sampling error or other factors have affected the rainfall isotope values.

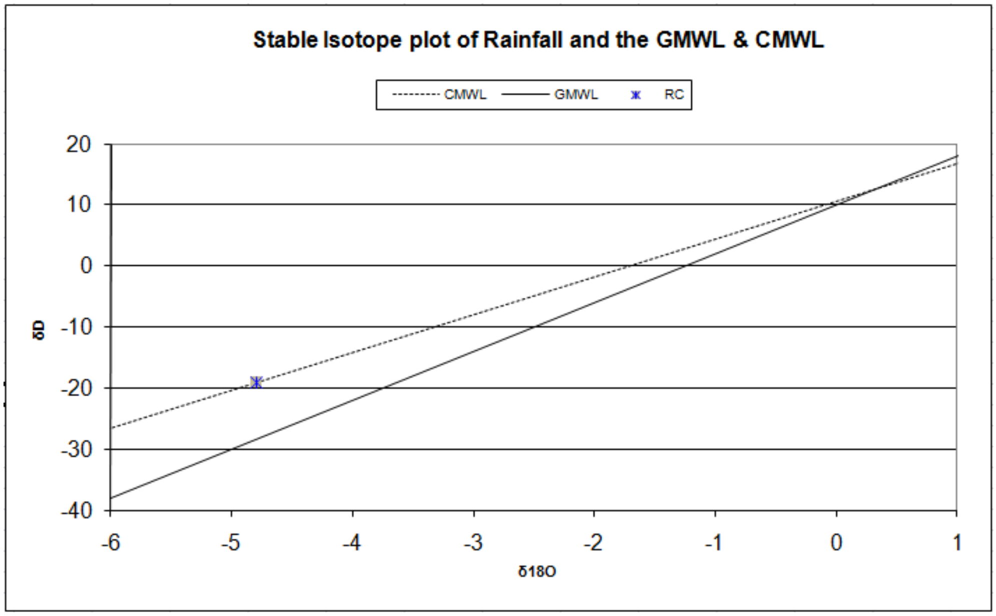

Figure 53. Isotopic values for the data from the rainfall collector (RC), compared against the Cape meteoric water line (CMWL) and global meteoric water line (GMWL).

7.5.2 Ground water

The ground water sample δD and $\delta^{18}O$ concentrations are plotted in Figure 54, with a distinction made between summer (February and March) and winter (June and July) samples. According to Drever (1988), δD is generally unaffected by reactions with aquifer materials at low temperature; and $\delta^{18}O$ is generally unaffected by reaction with silicates at low temperature. The borehole isotope data shows clustering beneath the CMWL. It is interesting to observe that $\delta^{18}O$ doesn't change much, while there appears to be a shift in δD between borehole samples taken in summer and winter.

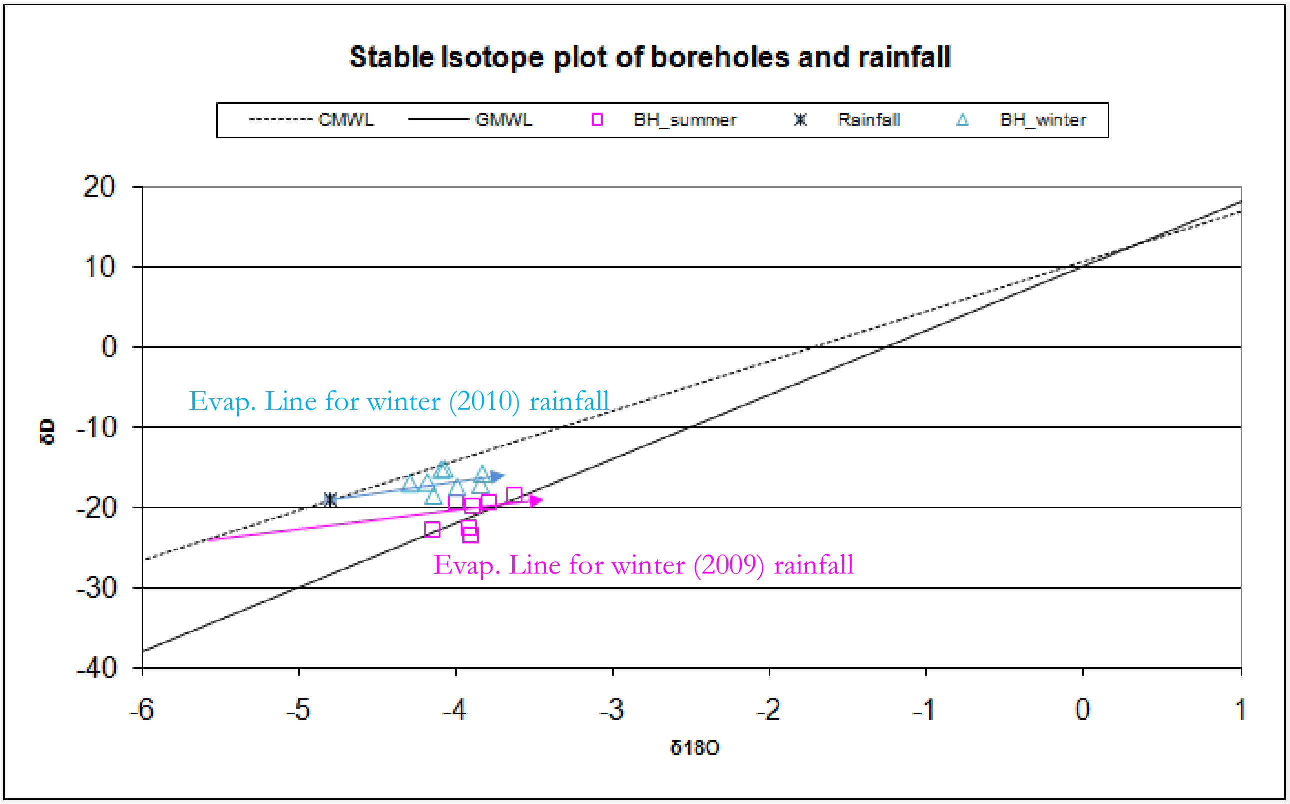

Figure 54. Isotopic variations for the data from the boreholes (BH), compared against the Cape meteoric water line (CMWL) and global meteoric water line (GMWL).

The observed change in δD, but relatively constant $\delta^{18}O$ is unusual. These summer and winter values both represent evaporation lines from their source rainfall. The summer samples are thought to be from the previous winter's rainfall which plots more negatively on the CMWL and represents a 'left over' signature from 2009. After June and July (2010), a few months into the winter rainfall, the evaporated rainfall signature from 2010 starts to show. This interpretation relies on the 2009 winter rainfall being more negative, a hypothesis that cannot be proven within this study based on the collected data. In order to conclusively validate this hypothesis it will be necessary to conduct monthly rainfall monitoring over a multi-year period.

Elevation is commonly known to have an effect on stable isotope composition of rainfall due to the lower temperatures and increased rainfall (rain out). Within the Oudebosch Valley a sample was measured at the valley bottom. The sites sampled (Figure 55 and Figure 56) don't show any real elevation affects within the valley.

This is due to the fact that the elevation differences between the sampling points are too small, and distances too short for the effects of rainout to be evident.

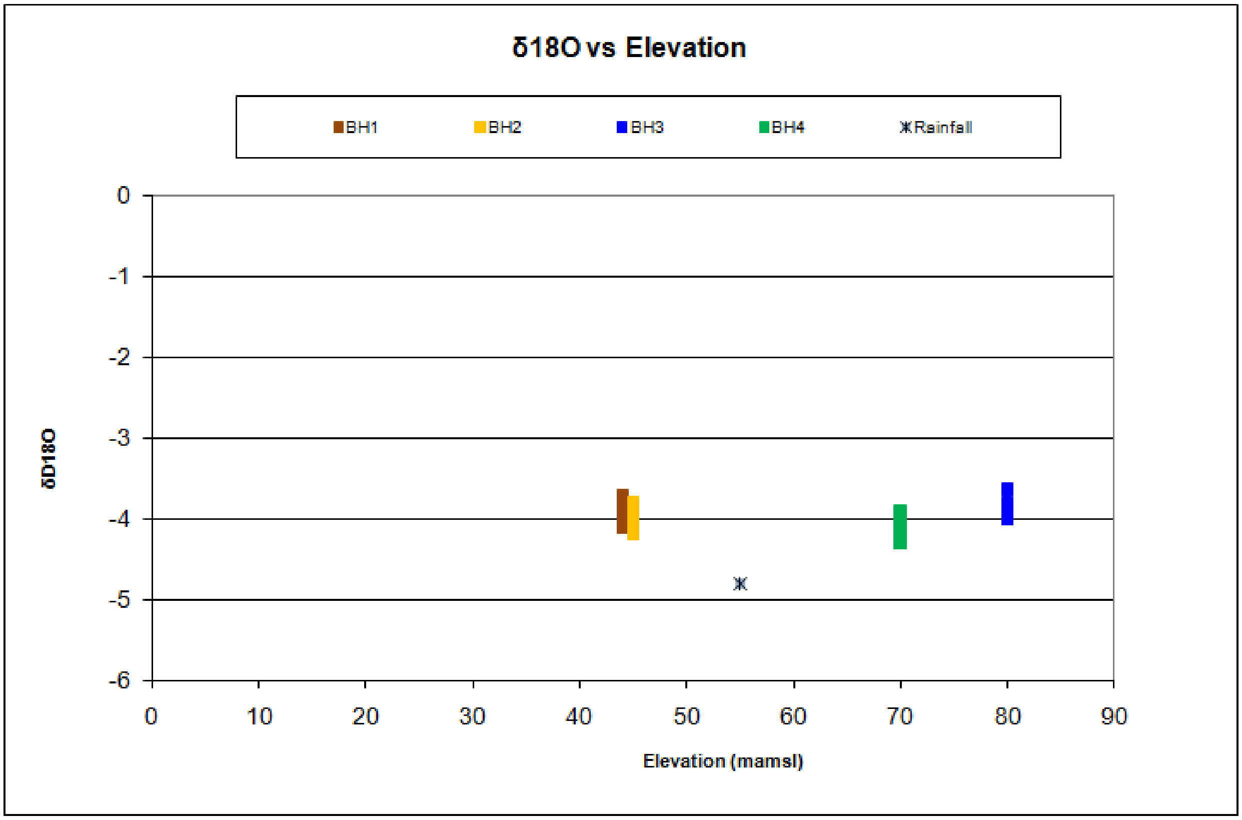

Figure 55. $\delta^{18}O$ plot relative to the sample site elevation.

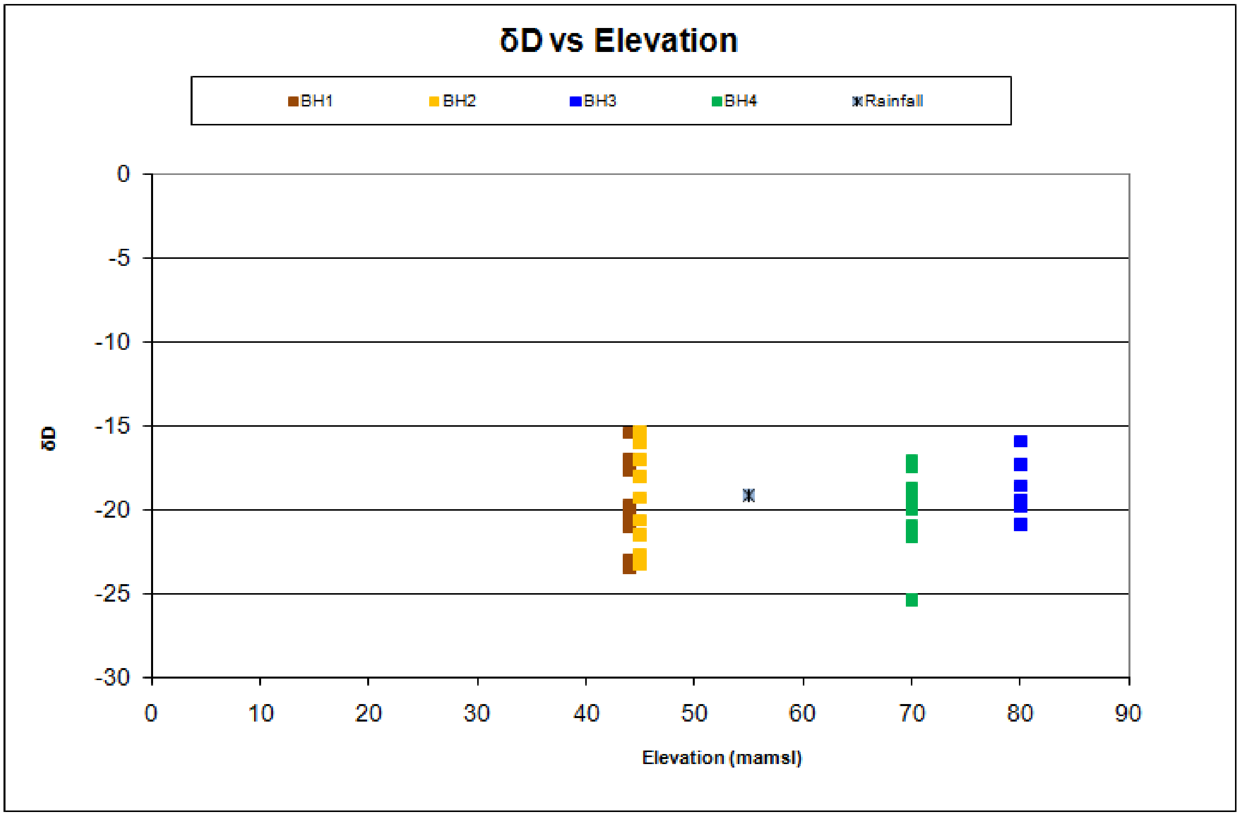

Figure 56. δD plot relative to the sample site elevation.

7.5.3 Wetlands and River sites

The interpretation of isotopic signatures for wetlands and rivers is complicated by the fact that they are exposed to evaporation and may be fed by various amounts of ground water and surface water. The study area, although relatively small with little variation of evaporation rates, is expected to have varying recharge rates based on geology. It is also probable that some of the ground water within the Oudebosch Valley is recharged further afield and transported through regional scale faults or fracture systems. This further complicates interpretations.

When water evaporates, the water left behind is richer in heavier isotopes. The vapour mass is therefore isotopically lighter than seawater, however, when condensation occurs, the heavier isotopes condense preferentially and are rained out first. This means that seawater is relatively rich in heavy isotopes ($\delta^{18}O$ and δD), while rain and snow are relatively poor, and increasingly so the further inland they fall. Cold temperatures which are generally related to higher elevations also result in the depletion in ^{18}O and D.

The stable isotope plots of the wetland and river sites are shown in Figure 57. The values cluster to some degree, plotting mostly between the CMWL and the

GMWL. The displacement to the right of the CMWL indicates that enrichment of the heavier isotopes has taken place as a result of evaporation and/or interaction with aquifer material. In this chapter each site will be discussed individually as related to the isotopic signature of the ground water and that of the rainfall.

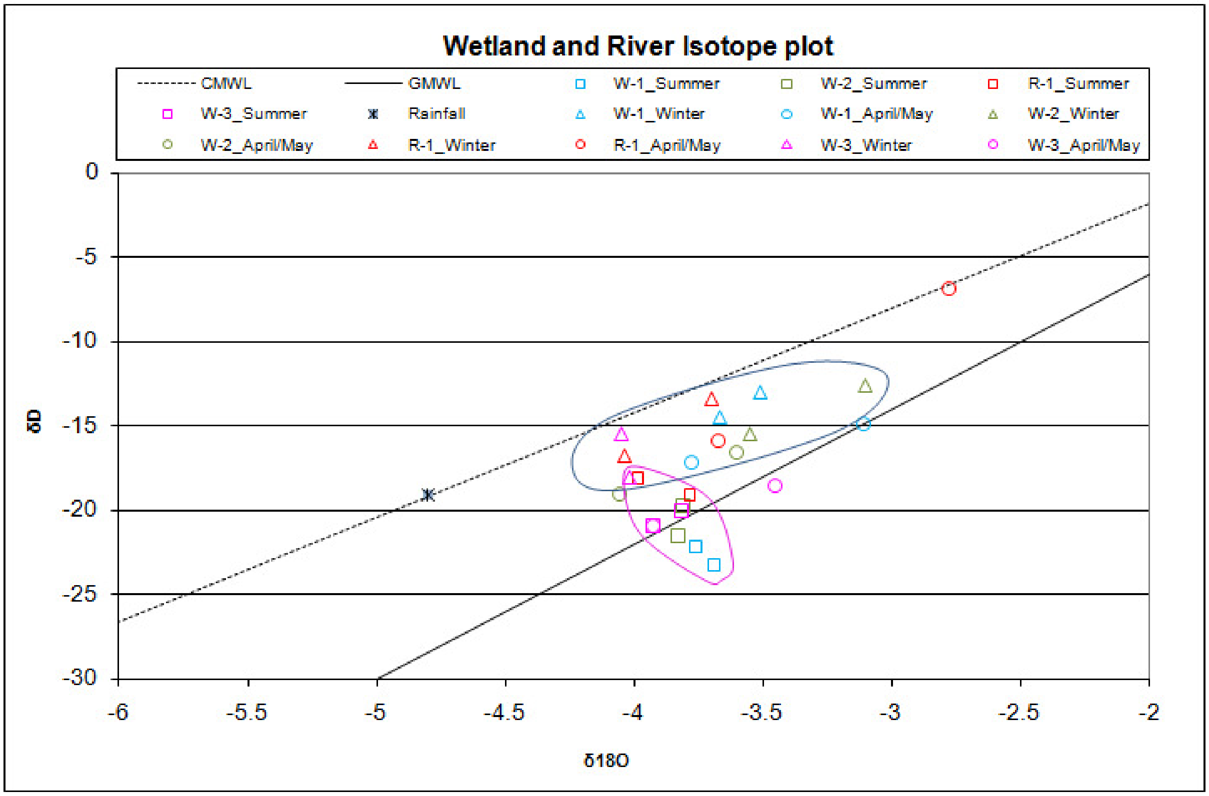

Figure 57. Isotopic variations for the wetlands and river sites compared against the Cape meteoric water line (CMWL) and global meteoric water line (GMWL). Winter (triangular points) and summer (square points) plots have been delineated.

With regards to seasonal affects on the various sites isotopic signature, samples taken at the end of summer (February and March) were compared with those taken during early to mid-winter (June and July). These plots, which include wetland and river sites, indicate that all the sites have a stable isotope plot that is closer to the CMWL during June and July (winter). The plots of the late summer samples show similar $\delta^{18}O$ values, but more negative δD values. This could be for the same reason as described for the boreholes.

7.5.4 River-1

The Oudebosch River site, River-1, has the most removed points distribution from the boreholes and other piezometers due to the wide range of $\delta^{18}O$ values. The various values obtained from sampling during the year are similar with the exception of the May sample. The May sample shows the most evaporated signature, greater than that of ground water and occurring further down the evaporation lines as shown in Figure 54. This sample was taken in May 2010, after heavy rains in the Oudebosch Valley. A graph of the rainfall from the weather station is shown in Figure 58.

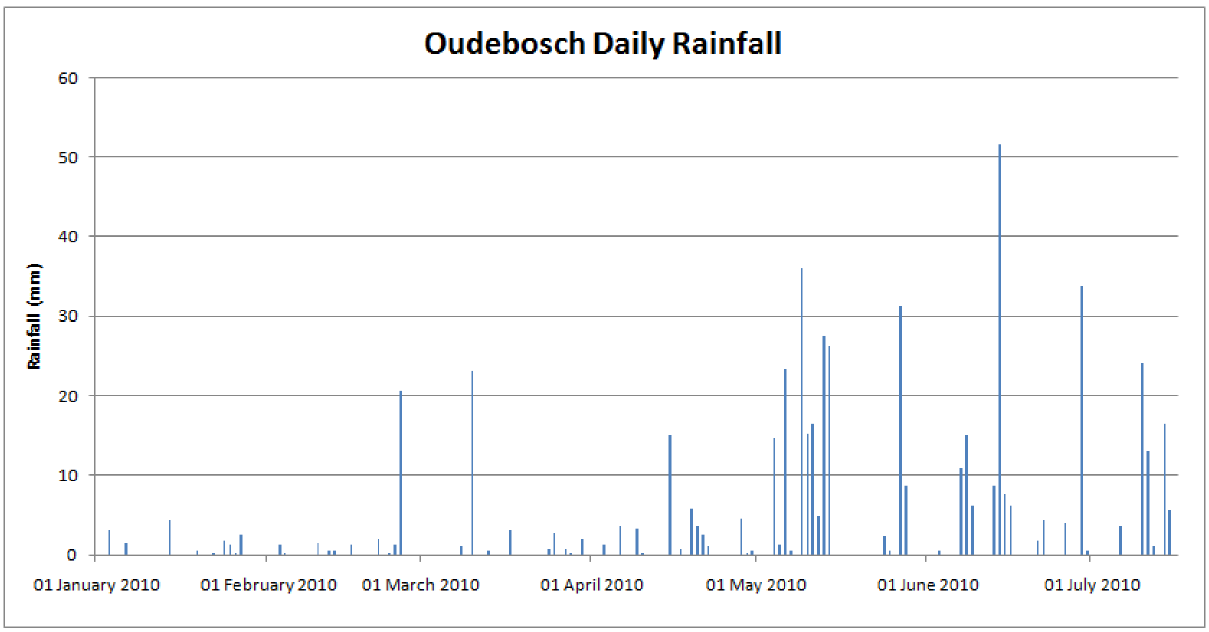

Figure 58. Rainfall data for the Oudebosch Valley.

This rainfall event prior to the May sample may have had a piston effect on the ground water and recharged the aquifer strongly, pumping the existing ground water out, with a highly evaporated signature from the water that has been in the alluvial sands all summer. The highly evaporated signature is due to the shallow nature of the alluvial aquifer overlying the Cedarberg Formation. This explanation corresponds with the conceptual diagram in Figure 15. The same concept was used by Midgley and Scott (1994).

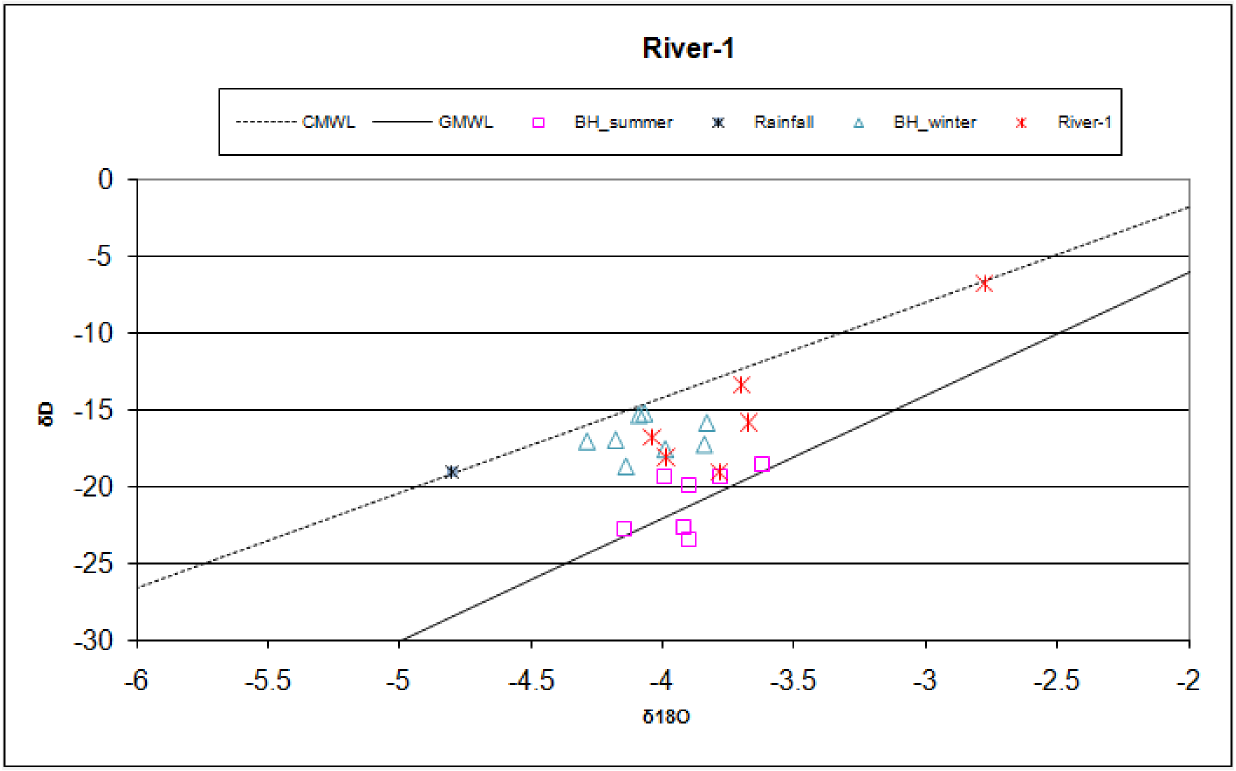

Figure 59. Isotope data for River-1 and the borehole sites plotted against the CMWL and the GMWL.

7.5.5 Wetland-1

The piezometer Wetland-1 shows the greatest variation with regards to displacement from the CMWL of all the sites, surface and ground water (Figure 60). The February and March 2010 samples were the most displaced from the CMWL, while the June and July 2010 samples were the closest. Wetland-1 is suspected to be ground water fed, and water flows out at this site for most of the year. During the dry months the water level is within 0.5 m of the surface. It is suspected that the heavier isotopic nature of the summer samples relates to a ground water source, affected by evaporative concentration. This ground water signature is then diluted during the higher rainfall months through mixing with interflow and surface water flow from recent rainfall events. As expected, the ground water contribution relative to surface water contribution to Wetland-1 is greatest during summer, and the isotope signature plots closely to the borehole plots. Strangely this site shows more evaporated summer values than the boreholes (i.e. they are further along the evaporation line). This suggests that extra evaporation has occurred, either during recharge (slower recharge) or before discharge. The shallow water level, within 0.4

m of the surface all year round at this site, is probably the cause for the increased evaporation.

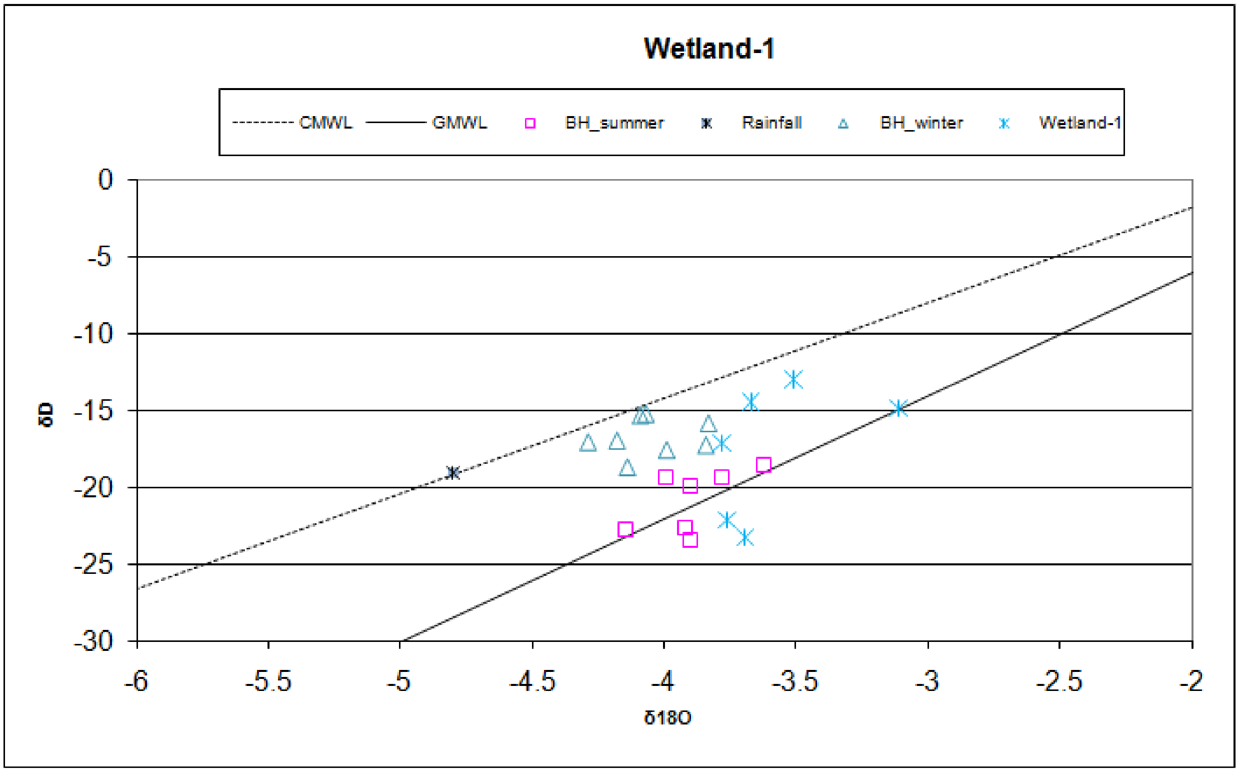

Figure 60. Isotope data for Wetland-1 and the borehole sites plotted against the CMWL and the GMWL.

7.5.6 Wetland-2

Wetland-2 has an isotope plot that is similar to that of ground water during the late summer months of February and March, but which is slightly removed during the higher rainfall months (Figure 61). Unlike the other sites, the winter month plots (June and July 2010) plot away from both the CMWL and the ground water plots. The plots for this site are not too different to that observed at Wetland-1, a site believed to have a strong ground water source. Although the winter plots are anomalous, the summer plots are together with that of ground water, suggesting that this site is possibly seasonally ground water dependant.

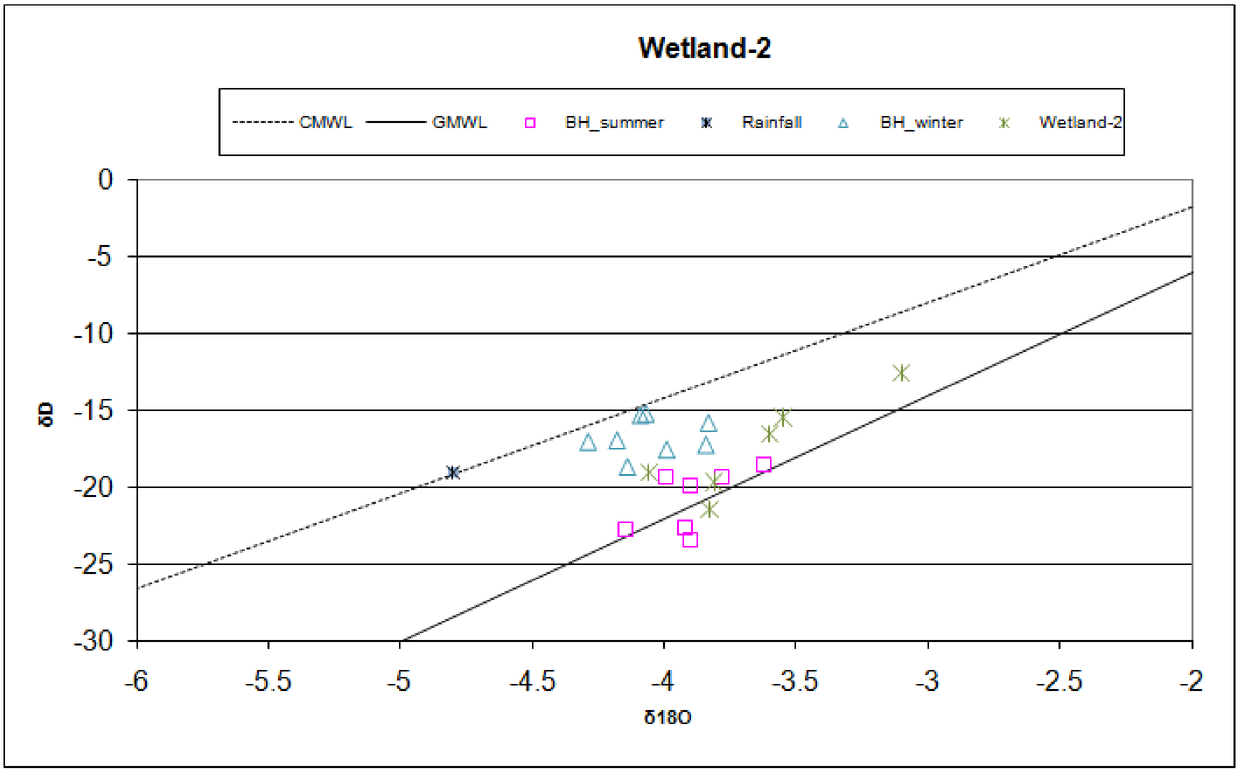

Figure 61. Isotope data for Wetland-2 and the borehole sites plotted against the CMWL and the GMWL.

7.5.7 Wetland-3

The piezometer Wetland-3 shows a similar plot to borehole ground water (Figure 62), and although the plot varies from the summer to winter, the variations correspond with those evident for the boreholes. The February and March 2010 samples were the most displaced from the CMWL, while the June and July 2010 samples were the closest, corresponding with the borehole plots. Wetland-3 is suspected to be ground water fed as it located close to a major fault that runs up the valley. Once again this site shows more evaporated values than the boreholes, and as was the case for River-1, the shallow nature of the water table and alluvial aquifer overlying the Cedarberg Formation is thought to be the cause. During summer the shallow water level of 0.5 m below ground level means the water is still subjected to evaporation.

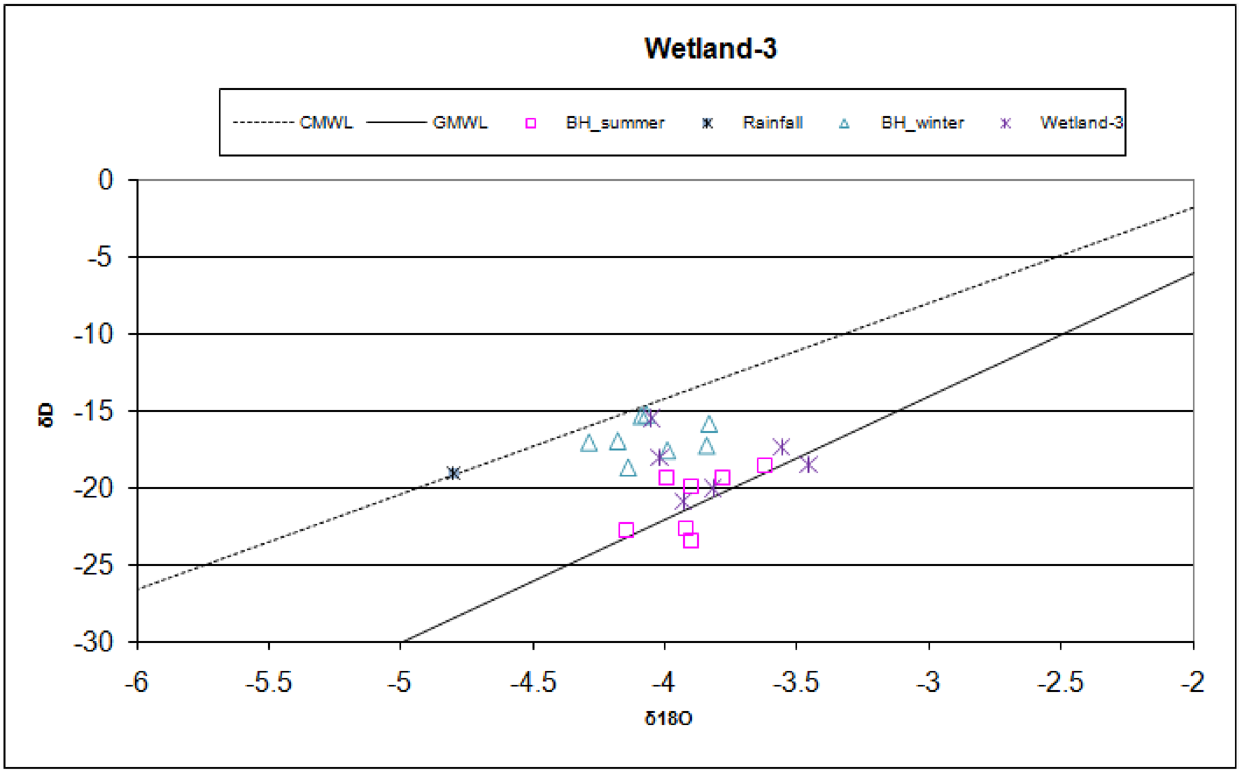

Figure 62. Isotope data for Wetland-3 and the borehole sites plotted against the CMWL and the GMWL.

7.5.8 Summary

Based on the limited data, particularly with regards to rainfall sampling, it is difficult to draw conclusive results on the ground water dependence of these sites. It appears as though the majority of ground water is recharged during winter, after which it is subjected to degrees of evaporation. With the onset of the next year's winter rainfall the ground water is recharged and the isotopic signature reset.

The sites Wetland-2, Wetland-3 and River-1 appear to be fed by relatively shallow water in the alluvial sands overlying the Cedarberg Formation. This water is subjected to evaporation to a greater degree than that of the Peninsula Formation borehole ground water. The shallow discharge of Wetland-1 also means that evaporation of the fault controlled ground water discharge is subjected to increased evaporation.

The investigation of the isotopes in the study area are summarized in Table 20. The ground water dependence rating is defined in Table 2. This study suggests that Wetland-3 shows the greatest ground water contribution. The three wetland sites and the river all appear to have ground water sources which are supplemented during the high rainfall months by meteoric water (direct runoff and interflow).

Table 20. Ground water dependence based on Isotopic Signature.

Site ID	Groundwater Dependance Rating	Comment
River-1	4.0	Significant groundwater dependance in summer, predominantly meteoric water during winter
Wetland-1	4.0	Significant groundwater dependance in summer
Wetland-3	5	Closely linked to groundwater - significantly groundwater dependant all year round
Wetland-2	4	Possibly groundwater dependant in summer!

7.6 River Flow Hydrograph Analysis

7.6.1 Flow Determination

The stream site River-1 was monitored by means of a stilling well with a pressure logger. During the six monthly field visits from February to July 2010 manual measurements of the river flow were measured at the stilling well site. In order to approximate the time series flow of the Oudebosch River it was necessary to establish a relationship between river stage (height of the river in the stilling well) and river flow.

Figure 63 shows the plot of the river flow (ℓ/s) measurements plotted against the river stage (height above the river bottom measured at the stilling well). Linear Interpolation was used to establish a means of converting the river stage time-series data into time-series flow data.

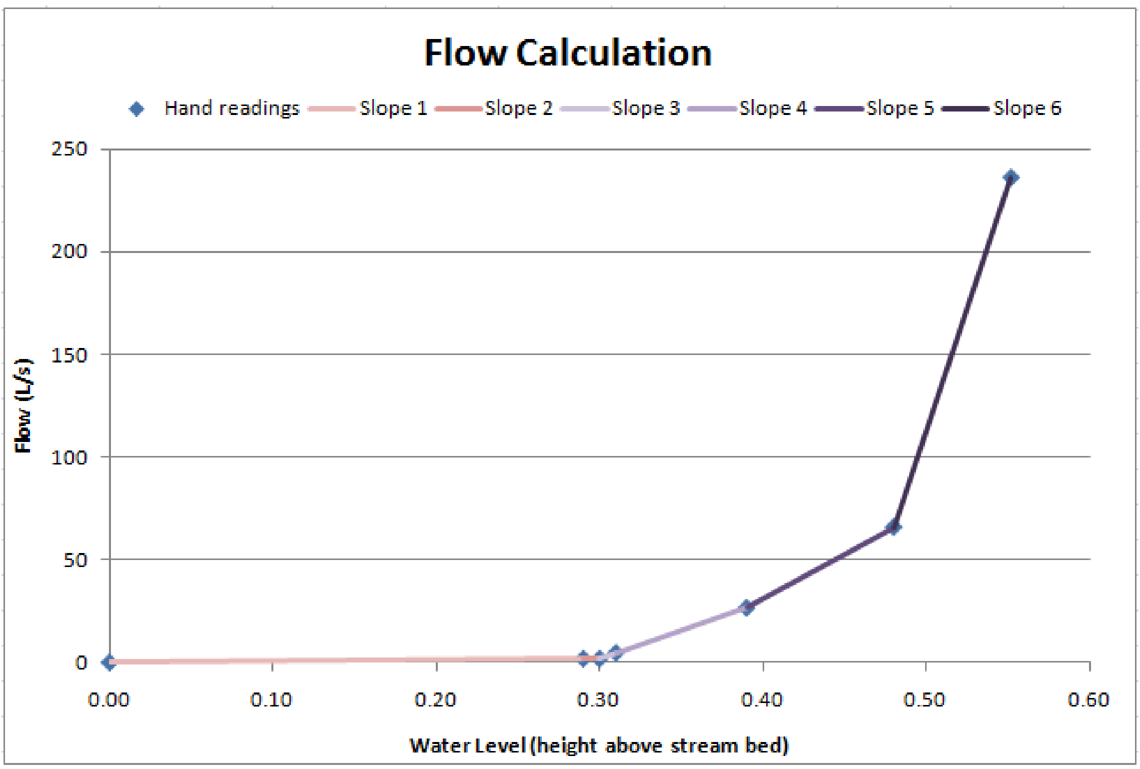

Figure 63. River flow measurements plotted relative to river stage.

This relationship was established using manual flow measurements, of which the highest was 236 ℓ/s for a river stage of 0.55 m. It is therefore not appropriate to apply this relationship to river stage heights that are excessively higher than this.

The calculated time-series flow data is shown in Figure 64, plotted with rainfall. The axis is only extended to 300 ℓ/s as values greater than this are speculative.

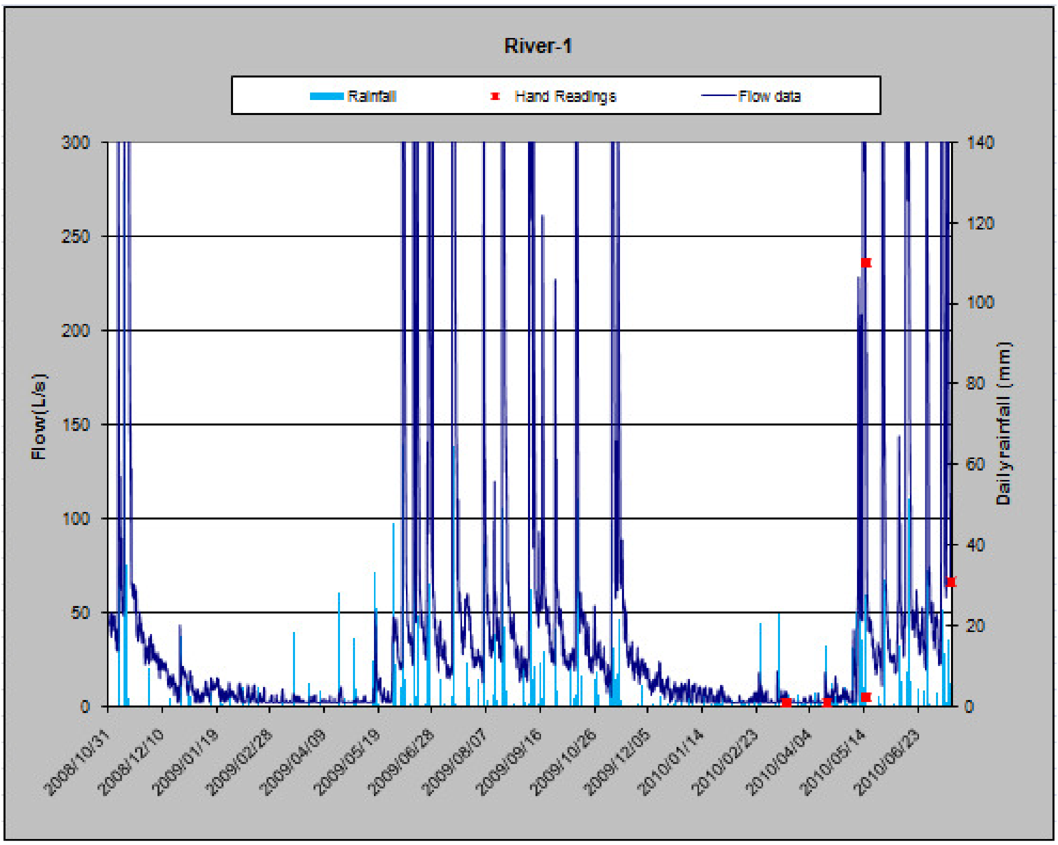

Figure 64. Time-series Flow data for the site River-1.

Figure 65 shows the flow measured during the year 2010, extending from the middle of summer (January 2010) until mid winter (July 2010). This plot shows a more detailed plot of the flow, with a constant low flow until May 2010, after which the stream shows marked responses to rainfall events. The constant nature of the stream flow during the summer months, despite three widely spread rainfall events of ~ 20 mm each and numerous extended dry periods, indicates an almost complete ground water dependence.

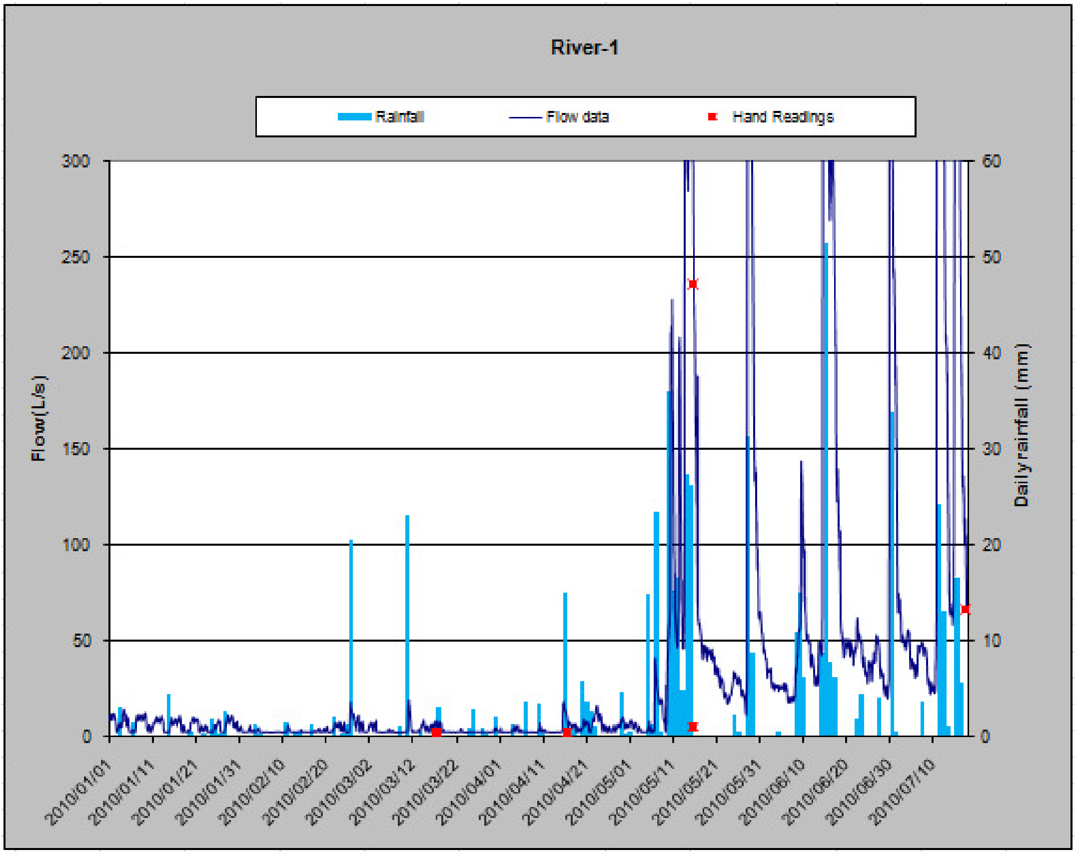

Figure 65. Stream flow during the year from January until July 2010.

7.6.2 Hydrograph Recession Analysis

The decrease in stream flow that follows after a rainfall is known as the recession curve, and refers to the part of the hydrograph after the crest (and the rainfall event) where flow diminishes. The recession period lasts until the flow increases again as the result of subsequent rainfall. The slope of the recession curve is initially steep but it flattens over time as the quick flow component passes and base flow becomes dominant. Recession curves are the parts of the hydrograph that are dominated by the release of water from natural storages (typically assumed to be ground water discharge) (Moore, 1997). These can be analysed individually and collectively, and analysed (graphically, analytically or mathematically) to help understand the discharge processes that make up base flow.

Each recession segment can be treated as a classic exponential decay function (Equation 1).

$$Q_t = Q_0 e^{-\alpha t} \quad \text{Or} \quad Q_t = Q_0 e^{-\frac{t}{T_c}} \qquad \textit{(Equation 1)}$$

Q_t - stream flow at time t
Q_0 - initial stream flow (at the start of the recession segment)
α - cut-off frequency (constant) (also expressed f)
T_c _ residence/ turnover time of the ground water system (ratio of storage to flow)
$e^{-\alpha}$ - Recession constant or depletion factor (also expressed k)

A semi-log recession curve for the Oudebosch River between 11 November 2008 and 8 January 2009, after the last of the winter rains, is plotted in Figure 66. The parameters calculated from the recession curve are shown in Table 21.

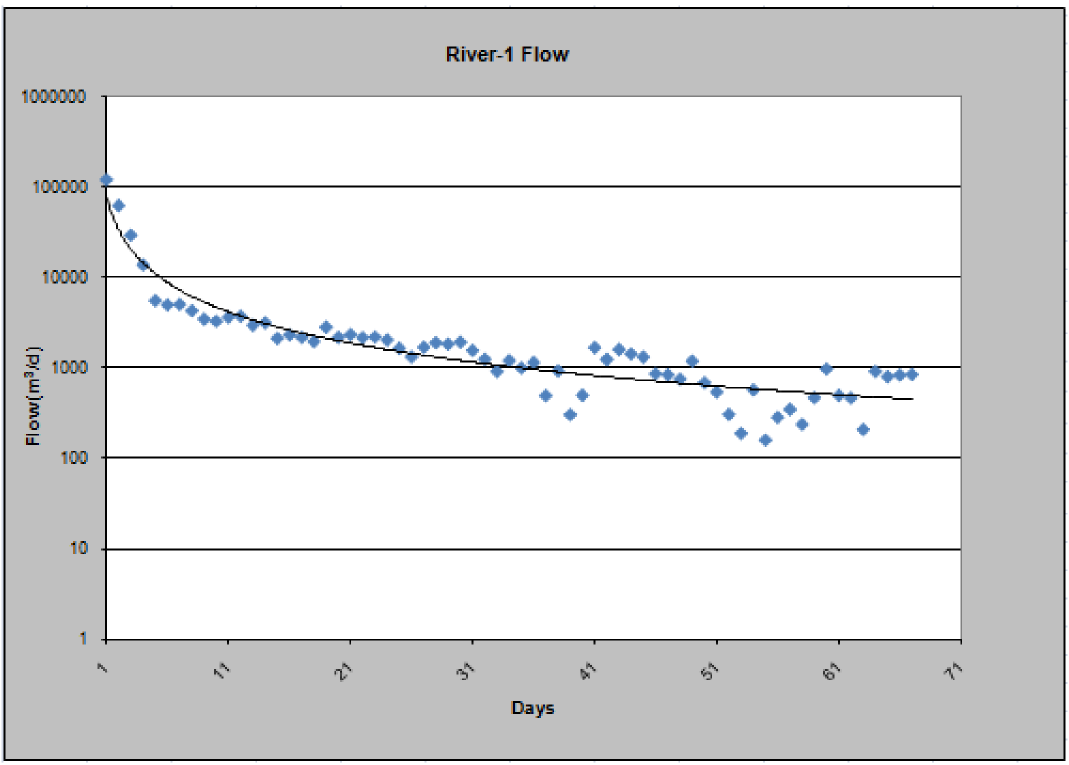

Figure 66. Recession curve from 11 November 2008 until 8 January 2009.

Table 21. Parameters calculated/obtained from the recession curve in Figure 66.

α	0.168	
Q_o	30000.0	m3/d
Q_t	500.0	m3/d
t	37.0	d
e^{at}	500.70	
Q_t	59.9	m3/d
k (e^{-a})	0.8454	
K	29	d
T_c	4.502	d

The depletion factor k is commonly used as an indicator of the extent of base flow (Nathan and McMahon, 1990). The typical ranges of daily recession constants for stream flow components, namely runoff (0.2-0.8), interflow (0.7-0.94) and ground water flow (0.93-0.995) do overlap (Nathan and McMahon, 1990), however high recession constants (e.g. > 0.9) tend to indicate dominance of base flow in stream flow. In this case the k value is 0.85 indicative of interflow. This value was calculated based on the recession of flow from 10 000 to 1 000 ℓ/s. The recession index (K) refers to the time (in days) required for base flow to recede by one log-cycle.

The integrated form of the classic recession function of Equation 1 is shown below (Moore, 1997).

$$Q_t = \alpha S_t \qquad \textit{(Equation 2)}$$

S_t - Storage in the reservoir that is discharging into the stream at time t

This relationship is called a linear storage-outflow model and implies that the recession will plot as a straight line on a semi-logarithmic scale. This is commonly not the case, and in the semi-logarithmic plot of Figure 66 the individual recession is curved rather than linear. This is because other natural storages (eg bank storage, wetlands, deeper confined aquifers) can also contribute to base flow, and these have different regimes of water release to the stream than that of the ground water stored in the shallow aquifer (Sujono *et al*, 2004).

The recession curve is effectively a composite of water discharged in the river from various natural storages (Moore, 1997). This coincides with the concept that a catchment is a series of interconnected reservoirs (such as rainfall, snow, aquifers, soil, biomass etc), each having distinct characteristics in terms of recharge, storage and discharge (Smakhtin, 2001).

A curved semi-logarithmic plot for recessions, as observed with the Oudebosch River, means that the storage-outflow relationship is non-linear. For ground water discharge from a shallow unconfined aquifer there are three main reasons for this non-linearity (Van de Griend *et al*, 2002). These reasons are listed below, and the non-linearity in the case of the Oudebosch River case could be due to one, two, or all three.

A lowering of the water table continually decreases the effective thickness of the aquifer and decreases the ability to drain. Declining water tables can also be attributed to other processes other than stream discharge, such as evapotranspiration or ground water abstraction;

The hydraulic conductivity tends to decrease with depth. This is attributed to increased compaction with depth in unconsolidated sediments, and decreased fracturing with depth in hard rock formations;

With prolonged drainage, the lower order stream channels can run dry, leaving only the highest order reaches receiving base flow.

The recession behaviour of a river can also change, and various shapes and recession segments are apparent in a hydrograph. These can be related to factors such as the areal distribution of rainfall, residual storage in connected surface water bodies, catchment wetness, saturated aquifer thickness or depth of stream penetration into the aquifer (Moore, 1997). Base flows are also influenced by seasonal effects such as variations in rainfall and evapotranspiration. High evapotranspiration rates during warm weather or active growing seasons can reduce the base flow component, particularly in shallow water table areas. In this case this is not evident, as the river flow remains constant at about 2 ℓ/s throughout the dry summer months which suggest a deeper water source.

There are various ways of approaching the non-linearity and variability of a recession. A few suitable methods will be utilized in this study.

7.6.2.1 Method 1

The first involves approximating the semi-logarithmic plot of the recession curve as three straight lines of different slope (Barnes, 1940). The gradients of these three lines are inferred to be the recession constants for the main stream-flow components of runoff, interflow and ground water flow. The plotting of the three lines is difficult because of the gradual nature of the change in curvature in the recession. This is implemented for the Oudebosch River hydrograph as shown in Figure 67.

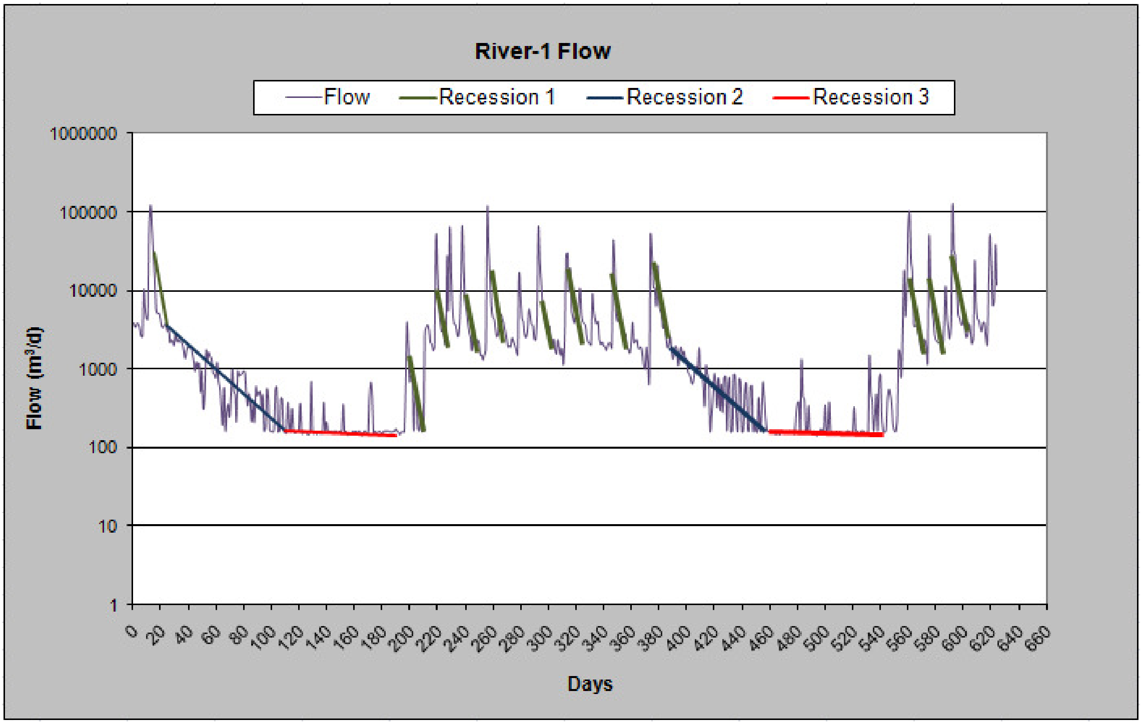

Figure 67. Recession Curves for the various components of flow.

The gradients of the various flow components shown in Figure 67 are listed in Table 22. The high gradients for the recession lines 1 and 2 suggest a low ground water contribution. The very small gradient obtained for the recession line 3 indicates a significant ground water contribution.

Table 22. Recession gradients of the various flow components of the stream flow.

Recession Curve Gradients	
Recession Curve 1	4
Recession Curve 2	0.025449
Recession Curve 3	0.000377

7.6.2.2 Method 2

A second means of addressing the non-linearity of the recession curve is to use a double logarithmic plot of stream flow against time (Hewlett and Hibbert, 1963). Any abrupt change in slope is interpreted to mark the transition from quick flow to base flow. This aids the identification of the three lines used to represent flow components, drawn in method 1. Figure 68 shows the Log-Log plot of the full hydrograph. The black points mark the changes in slope, and therefore the change in flow type.

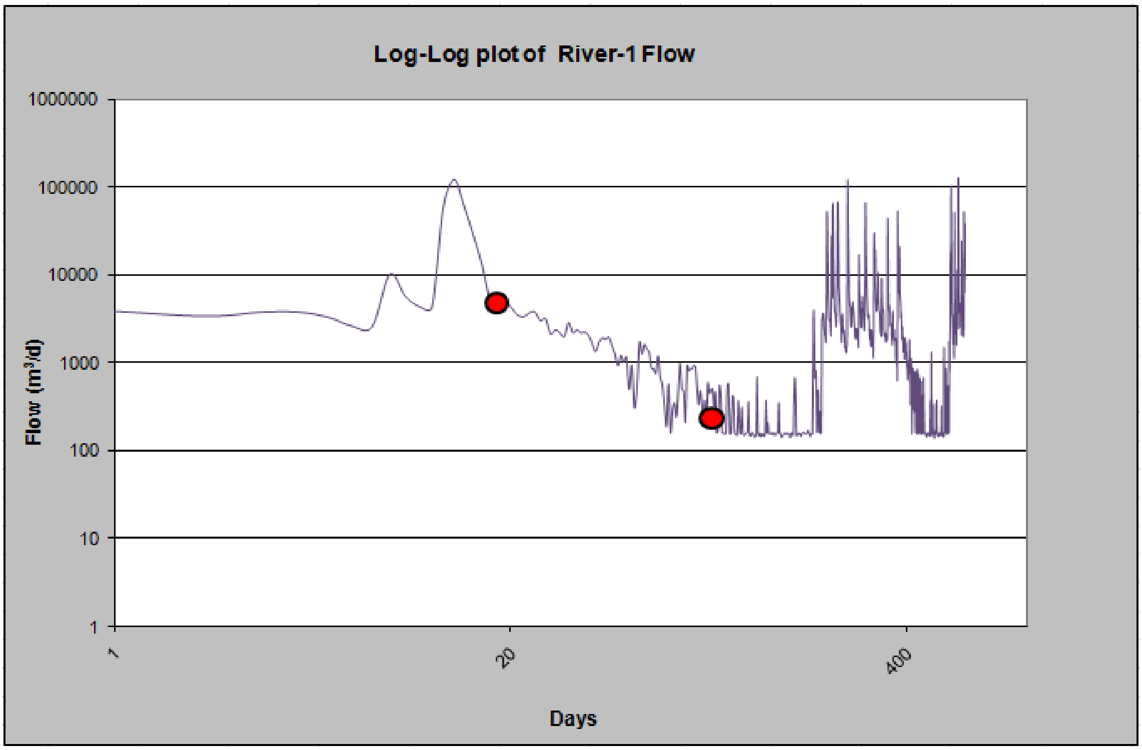

Figure 68. Log-Log plot of the Hydrograph indicating changes in flow type.

7.6.2.3 Method 3

Another method for analysing the recession curve is the "matching strip method" which involves plotting multiple recession curves derived from the hydrograph on the one semi-logarithmic plot in order of increasing minimum discharge (Toebes and Strang, 1964). Each recession curve is superimposed and adjusted horizontally to produce an overlapping sequence (Moore, 1997). The master recession curve is interpreted as the envelope to this sequence, and the recession constant k derived from its slope (Equation 3);

$$k = \left(\frac{Q}{Q_0}\right)^{1/t} \qquad \textit{(Equation 3)}$$

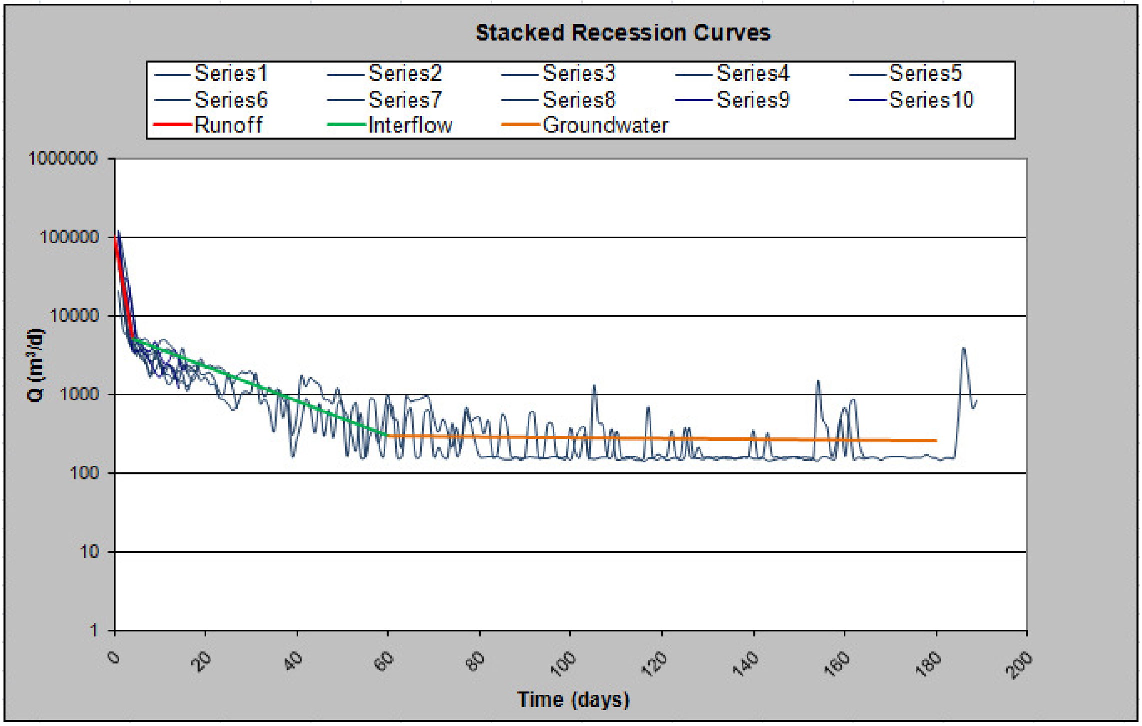

Figure 69. Semi-log plot of the Oudebosch River recession curves.

In Figure 69 ten recession curves for the Oudebosch River are superimposed over each other and a trend line fitted to the curves. There is quite a high degree of correlation between the various curves. The recession constant k is calculated to be 0.97, indicative of a large base flow component.

7.6.2.4 Method 4

The "recession-curve-displacement method" is based on the upward displacement of the recession curve during the rainfall event (Rorabaugh 1964; Rutledge and Daniel, 1994; Rutledge, 1998). The assumption is that the base flow is entirely ground water discharge from an unconfined aquifer of uniform thickness and hydraulic properties, with the stream fully penetrating the aquifer (Moore, 1997). On the basis of the algorithms developed, the total recharge to the ground water system during the rainfall event has been shown to be about twice the total potential discharge to the stream at a critical time (T_c) after the hydrographic peak. Therefore the total volume of ground water recharge due to the rainfall event (*R*) can be estimated from the stream hydrograph by:

$$R = \frac{2(Q_2 - Q_1)K}{2.3026} \qquad \textit{(Equation 4)}$$

Q_t - stream flow at time t
Q_1 – Base flow at the critical time (T_c) extrapolated from the pre-event recession curve).
Q_2 – Base flow at the critical time (T_c) extrapolated from the post-event recession curve).
K – Recession Index

The procedure for the recession curve displacement method (after Rutledge and Daniel 1993) involves firstly estimating the recession index (K) from the hydrograph record, after which the critical time (T_c) is calculated using the relationship:

$$T_c = 0.2144K \qquad \textit{(Equation 5)}$$

At time T_c after the peak, the pre-event and post-event discharge values (Q1 and Q2) are derived. These values are then used to calculate R.

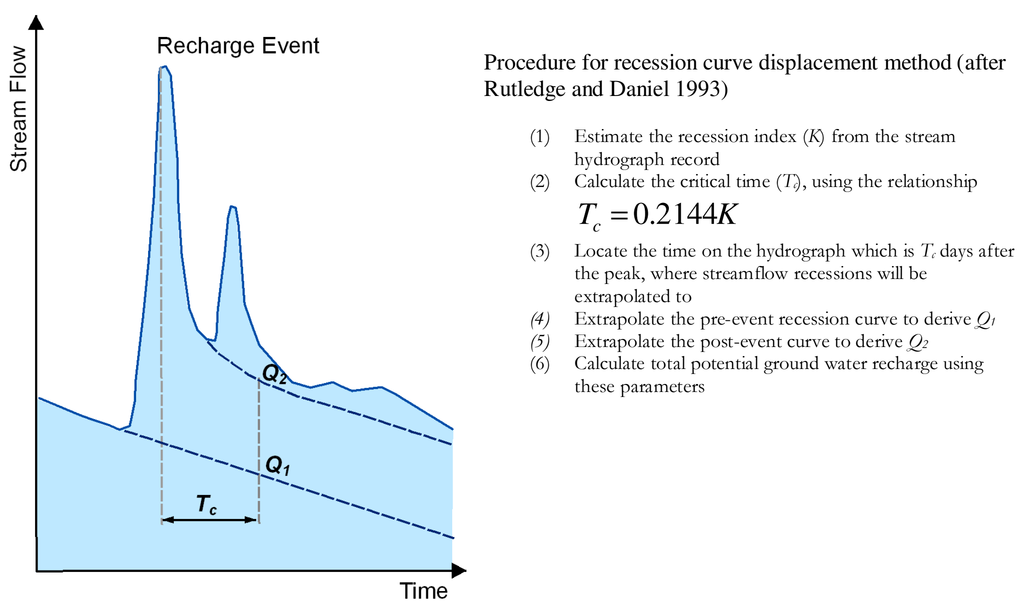

Figure 70. Procedure for recession curve displacement method (From Moore, 1997)

This method was applied to the Oudebosch River, and Table 23 lists the calculated parameters. The calculation was done over the period 26 June 2009 to 30 July 2009 (Figure 71). The main hydrograph peak relates to a rainfall event where 64.5 mm fell on the 12 July 2009, and 31.24 mm on 13 July 2009. The parameters calculated from the recession curve are listed in Table 23.

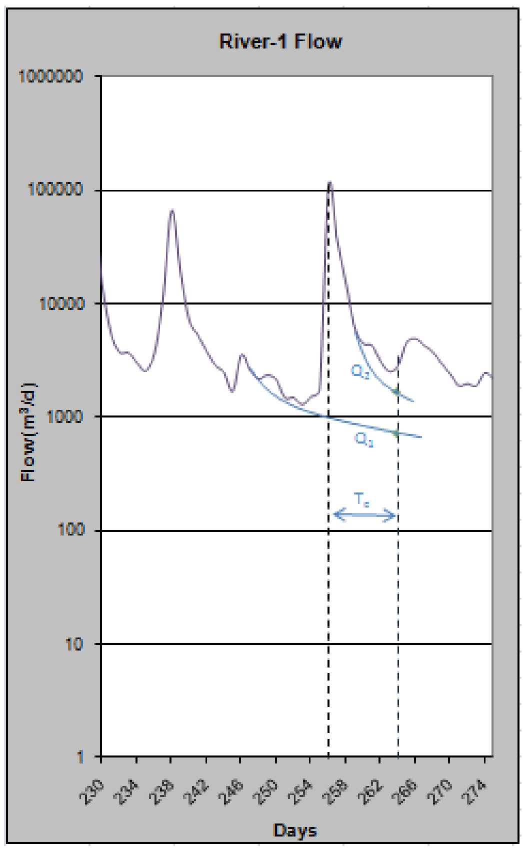

Figure 71. Recession Curve displacement Method

Table 23. Calculated parameters

K	*40*	***d***
T_c	*8.576*	***d***
Q_2	*1650*	m^3/d
Q_1	*720*	m^3/d
R=	*32311.3*	m^3

7.6.3 Summary

Based on the analysis of the river flow there is a significant ground water contribution. The stable summer flows despite the low rainfall indicates ground water dependence. The flow remains relatively constant at about 2 ℓ/s during the low rainfall months and this is thought to be entirely ground water fed.

The analysis of the hydrograph recession indicates that there is a large interflow component, but that during the dryer months the ground water components becomes significant. The recession constant calculated for the matching strips method is 0.97, and this indicates dominant base flow component. The first method used (Barnes 1940) indicates that during the summer months the river is highly ground water dependant with a recession constant of 4.

Although the river is highly ground water dependant (particularly in summer), the reliance on the Peninsula Formation Aquifer cannot be distinguished from the reliance on other possible ground water bearing formations (like the Skurweberg Formation just to the west of the river). The method of looking at hydrograph recession should be considered along with the other methods, and in particular the geohydrology, when trying to ascertain dependence on the Peninsula Formation Aquifer.

Based on the classification outlined in Table 2 it is concluded that in summer the Oudebosch River has a ground water dependency rating of 8, and is almost entirely ground water fed. During winter months direct runoff and interflow become more dominant, but the site is none the less heavily ground water dependant as evidenced in the low rainfall periods when stream flow is ground water fed.

8 Results

All three of the wetlands and the stream site were evaluated with regards to ground water contribution to the site. These assessments were qualitative and were based on geohydrological setting, water level fluctuations, temperature, chemistry and stable isotope composition. The stream hydrograph was also considered for the river site River 1. A ground water dependence rating between 0 and 8 was allocated for each parameter according to the Table 2. The assigned values were averaged and a final ground water dependence value determined. Although the value is not a quantitative measure of the ground water contribution to the sites investigated, it represents a qualitative evaluation based on numerous parameters and characteristics of the sites. Table 24 shows the various sub-ratings, as well as the final average which is considered the rating for the site.

Table 24. Ground water dependence Rating Table.

Site ID	Geology	Water Level fluctuation	Temperature fluctuation	Chemistry	Stable Isotope Composition	Baseflow Seperation	Average
River 1	6	6	-	6	6	7	6.2
Wetland 1	8	8	6	8	6	-	7.2
Wetland 3	4	6	6	3	8	-	5.4
Wetland 2	0	2	2	3	6	-	2.6

Site River 1 was consistently rated as having a significant ground water contribution and the site therefore has a rating of 6.2. The geohydrological setting, water level fluctuations and hydrograph recession analysis were more conclusive than the isotopic and chemical investigation. The River is highly ground water dependant in summer, but in winter interflow and direct runoff dominates. The river is considered highly ground water dependant because if the ground water contribution were to be removed the ecology of the river would change considerably.

Wetland 1 has a rating that varied between being considered to have a significant ground water contribution and being almost completely ground water dependant. The final classification of 7.2 indicates that the site has a high ground water dependence. The geohydrological setting and water level time-series data was the most diagnostic, while chemistry, time-series temperature data and isotopes indicated ground water linkages to a lesser degree.

Wetland 3 shows a range of ratings depending on the parameter considered. The final rating of 5.4 indicates an intermediate to significant ground water contribution. Water level, temperature and geohydrology are indicators of a degree of ground water contribution, while the chemistry does not show much relation to Peninsula Formation ground water. The elevated constituent concentrations observed at this site are thought to be related to the underling argillaceous geology and the organic rich clayey soil.

Wetland 2 showed relatively low ratings and the final rating of 2.6 for the site indicates a small to intermediate ground water dependence. Geohydrological setting, water level and temperature fluctuations were relatively diagnostic, with chemistry and isotopes to a less degree.

9 Conclusion

The aim of the study was to investigate the ground water dependence of a set of target sites and to possibly establish a methodology that can be applied to ecological sites within the TMG and similar geohydrological settings. The study investigated the use of the following data/information as a means of establishing site dependence on ground water:

- Time-series flow data (in the case of streams/rivers),
- Geohydrological setting of the site,
- Time series water level data,
- Time series temperature data,
- Time series chemical constituent concentrations,
- Time series and seasonal variations in stable isotope concentrations.

The evaluation of a wetland or streams dependence on ground water enables the suitable selection of ground water monitoring sites ahead of the proposed large-scale abstraction from the TMGA.

9.1 Addressing Project Objectives

The objectives are primarily two-fold:

- Evaluate sites regarding ground water dependence
- Establish a methodology for site ground water dependence

9.1.1 Evaluate sites regarding ground water dependence

The study was able to identify and qualitatively classify sites with various ground water dependencies. It was found that the sites showed various degrees of ground water contribution, and therefore it is anticipated that the sites would respond differently to a regional decrease in the water table. Based on the investigation the sites considered are ranked according to ground water contribution:

- Wetland-1 (Strongly ground water dependant, primary water source)
- River-1 (Significant ground water dependence)
- Wetland-3 (Intermediate ground water dependence)
- Wetland-2 (Small/no ground water contribution expected)

The results of the methods used were qualitative and no ground water contribution volumes were determined. The study objective was met as sites were evaluated but the results are qualitative.

9.1.2 Establish a methodology for site ground water dependence

The procedure adopted in this study can be applied to numerous sites within the TMG in order to evaluate their suitability as a ground water monitoring site. It does not, however, enable a quantification of the ground water contribution to a surface water site.

The results of the different methods employed had varied degrees of success, and were also varied between the sites. The effectiveness of these methods will be discussed later in this chapter. The varied success means that the results of this study are not thought to be a methodology for site ground water evaluation, but rather a number of individual methods that can potentially be utilised for qualitatively evaluating the ground water dependence of a surface water site. So although the methods and procedures can be implemented for surface water sites, the objective of establishing a methodology was not entirely met. The complexity and diversity of ground and surface water interactions calls for a suitable selection of methods for evaluation the dependence depending on the nature of the site.

9.2 <u>Project Approach</u>

The different approaches utilised for evaluating the site ground water dependencies produced generally concurring results. The methods utilized and there suitability are discussed in this section.

9.2.1 Geohydrological Setting

The evaluation if the geohydrological setting was a very important primary step in the evaluation of the sites. By understanding the location of the surface water sites in relation to geohydrological structures and features enabled a conceptual model of the sites to be constructed. From this possible occurrences of ground water and surface water interactions were identified and investigated further. While other methods utilized in this investigation may not always provide valuable insights into the ground water dependence of a site, it is always important to consider geology, hydrology and topography and how they relate to each other.

9.2.2 Water level fluctuations

The time-series water level analysis indicated that no clear relationships were evident between surface sites and the borehole water level trends. The information did however enable a comparison between the various wetland and river sites with regards to water level range, magnitude and time of the various responses to rainfall. The irregular nature (marked by many fluctuations) of the different trends also enabled comparisons between the sites with the more smoothed plots indicative of ground water contribution. The water level trends (smoothed or irregular), total water level range, behaviour in summer and response to rainfall provided a good qualitative assessment of the sites and can therefore assist in identifying ground water dependence.

The controls on the water level responses are complex and many, including rainfall intensity and volume, soil moisture, water level depth, evapotranspiration, humidity as well as additional water inflows and outflows via faults and fractures. Therefore, because water levels do not respond consistently with regards to rainfall events, the use of time series water level data should not be used as a sole means of evaluating ground water dependence.

9.2.3 Water temperature

Similarly to the time-series water level analysis, the evaluation of the time series water temperature proved to be a useful indicator of relative ground water dependence but needs to be used in conjunction with other methods. This method is limited as site temperature varies both laterally and with depth, and data is therefore varied according to the depth of the sensor. The evaluation of the sites temperature in comparison to air and ground water temperature trends and ranges does enable some degree of evaluation for the wetland sites. Temperature data was not useful in evaluating the streams ground water dependence as the water is in contact with the atmosphere and the temperature mimics the minimum air temperature very closely.

9.2.4 Water chemistry

Water chemistry was found to be a useful indicator of ground water contribution to surface water. A few of the chemical constituent concentrations and properties showed similar responses for all sites (these include the EC values and SO_4 concentrations) while the Cl and Mn concentrations of the wetland and river sites did not show any correlation with ground water. A number of chemical constituents and parameters were diagnostic and indicated a link between certain sites and ground water. The contrast in water chemistry between the argillaceous Cedarberg Formation shales and the inert Peninsula Formation quartzites meant that certain chemistry parameters were useful indicators of ground water dependence (these include Si, Fe, Zn, Al, Ca, HCO3). An evaluation of site chemistry in comparison to that of ground water is an important means of evaluating ground water dependence.

9.2.5 Isotopes

The use of isotopes is an important and useful process in evaluating and understanding surface and ground water relationships. Ideally a longer record of sampling is needed in order to make more definite conclusions than those that were made in this study. From the isotope analysis it appears as though the majority of ground water is recharged during winter, after which it is subjected to degrees of evaporation. With the onset of the next year's winter rainfall the ground water is recharged and the isotopic signature reset. From the isotopes all four sites were thought to have ground water sources which are supplemented during the high rainfall months by meteoric water (direct runoff and interflow). It is not possible to make conclusive comments regarding the ground water dependence of the sites based solely on isotopes, but when considered alongside the other methods it can allow for a better understanding of the type and nature of the interactions taking place.

9.2.6 River Flow Hydrograph Analysis

The hydrograph analysis is a very useful means of assessing ground water contribution but requires time series flow data. This is generally not available for wetlands and seeps and therefore this method was only used for the river site. The method enables an evaluation of the rivers ground water dependence considering contributions from ground water, interflow and direct run off. The hydrograph analysis enables an assessment of the streams reliance on the Peninsula Formation Aquifer but this cannot be distinguished from the reliance on other possible ground water bearing formations (like the Skurweberg Formation just to the west of the river). The method of looking at hydrograph recession should be considered along with the other methods, and in particular the geohydrology and chemistry, when trying to ascertain dependence on the Peninsula Formation Aquifer.

9.3 Applications

With regard to the local TMG monitoring, this type of classification enables a prioritisation of monitoring sites for monitoring, as well as tools for determining which sites should be monitored. The process is based on various site characteristics and parameters, and this increases the reliability of the final site classification. The applied methods of assessing the wetlands and river with regards to ground water contribution is one that can be applied to sites throughout the TMG, and even further afield in different geographical and geological settings. The assessment requires a thorough investigation of each site as well as comprehensive understanding of the local and regional setting.

9.4 Limitations

Associated with the applied classification of the sites and approach used are limitations that must be considered. These include:

The qualitative nature of the results

The non-reproducibility of the assigned ground water dependencies (different people ascribe different ratings to the same site).

The fact that the approach utilized may need to be adjusted for different geohydrological environments

In conclusion, the approach adopted in this study should be considered a means of developing a better understanding of wetland and river geohydrology, as well as providing a means of rating wetlands and rivers with regard to ground water dependence.

10 Recommendations

The following recommendations are made so as to improve the approach utilized in this study:

- For the monitoring of wetland sites increase the number of piezometers and water level and temperature loggers per site.
- Hang temperature sensors at the same depth in monitoring boreholes.
- Conduct chemistry monitoring for a smaller select set of chemical parameters.
- Conduct more regular flow measurements at the river site, particularly during high flow periods after rainfall events.
- Conduct monitoring and sampling over a longer time period.
- For a more detailed Isotope investigation rainfall samplers could be established at the various sites.

The following recommendations are made so as to improve and advance the classification process:

- The approach should be tested and implemented in additional settings, both within and outside of the TMGA region.
- Additional physical and chemical monitoring criteria could be included to further develop the process. In the TMG, the monitoring of the unstable isotope Radon should be considered.
- The classification process can be compared and evaluated with quantitative analyses of wetland sites.
- The classification process should be improved and refined and a methodology possibly developed.

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APPENDIX A: MAPS

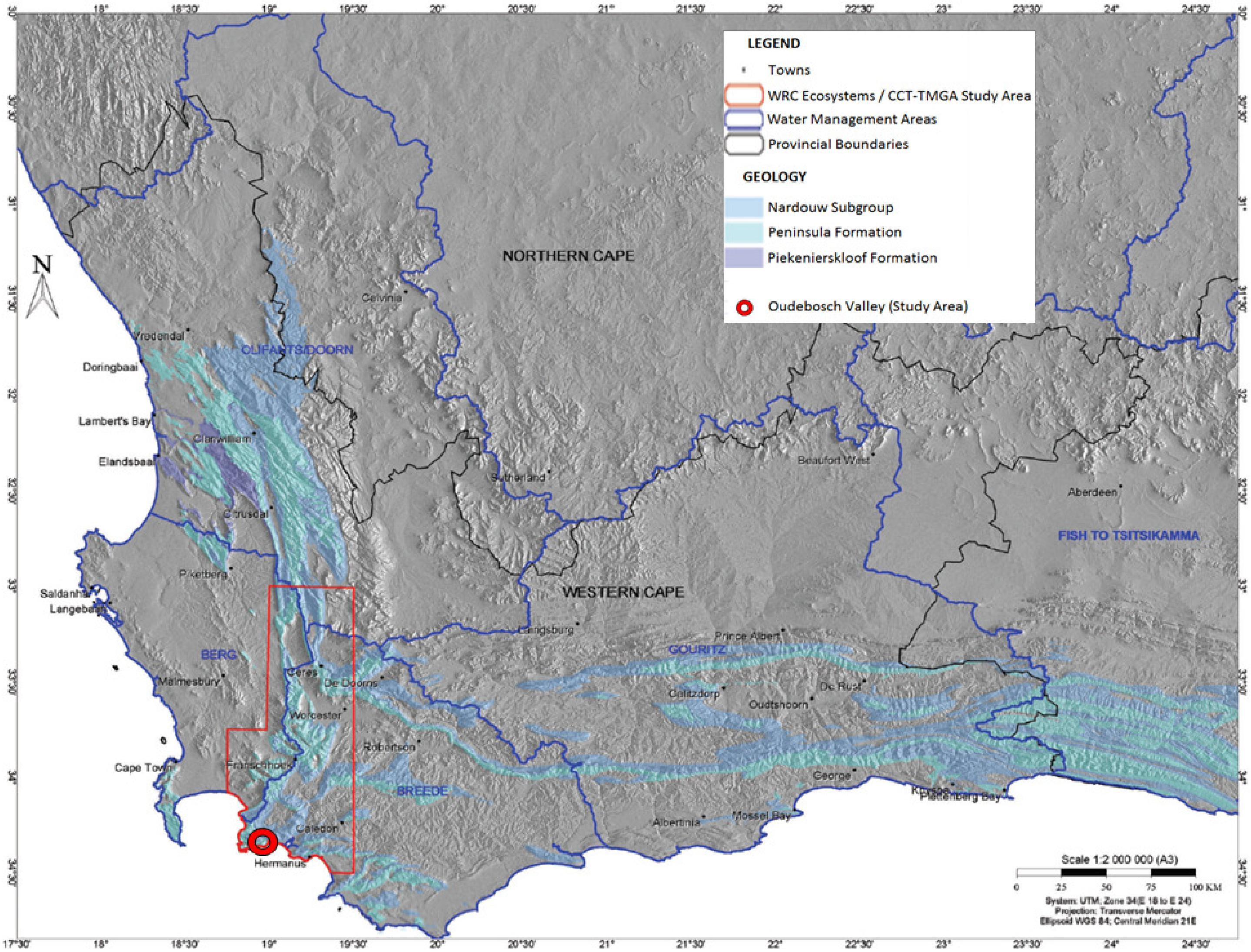


Figure 72. Map showing the WRC Ecosystems and City of Cape Town TMGA study area, as well as the aerial extent of the Peninsula and adjacent Formations. Modified from Colvin et al (2009).

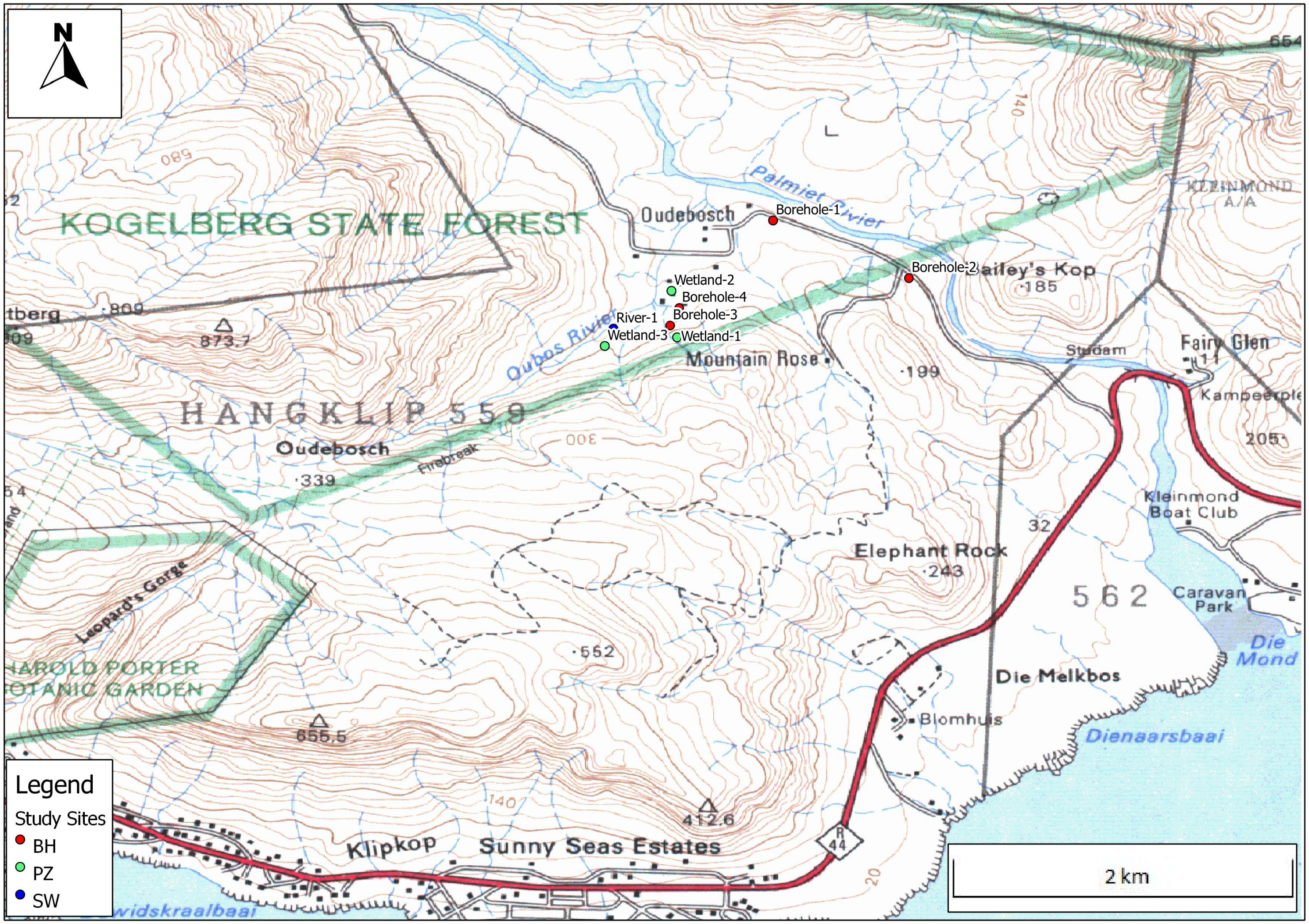


Figure 73. Topographical map of Oudebosch Valley showing study sites and proximity to the Palmiet River mouth. PZ, SW and BH relate to piezometers, the stilling well and borehole sites respectively.

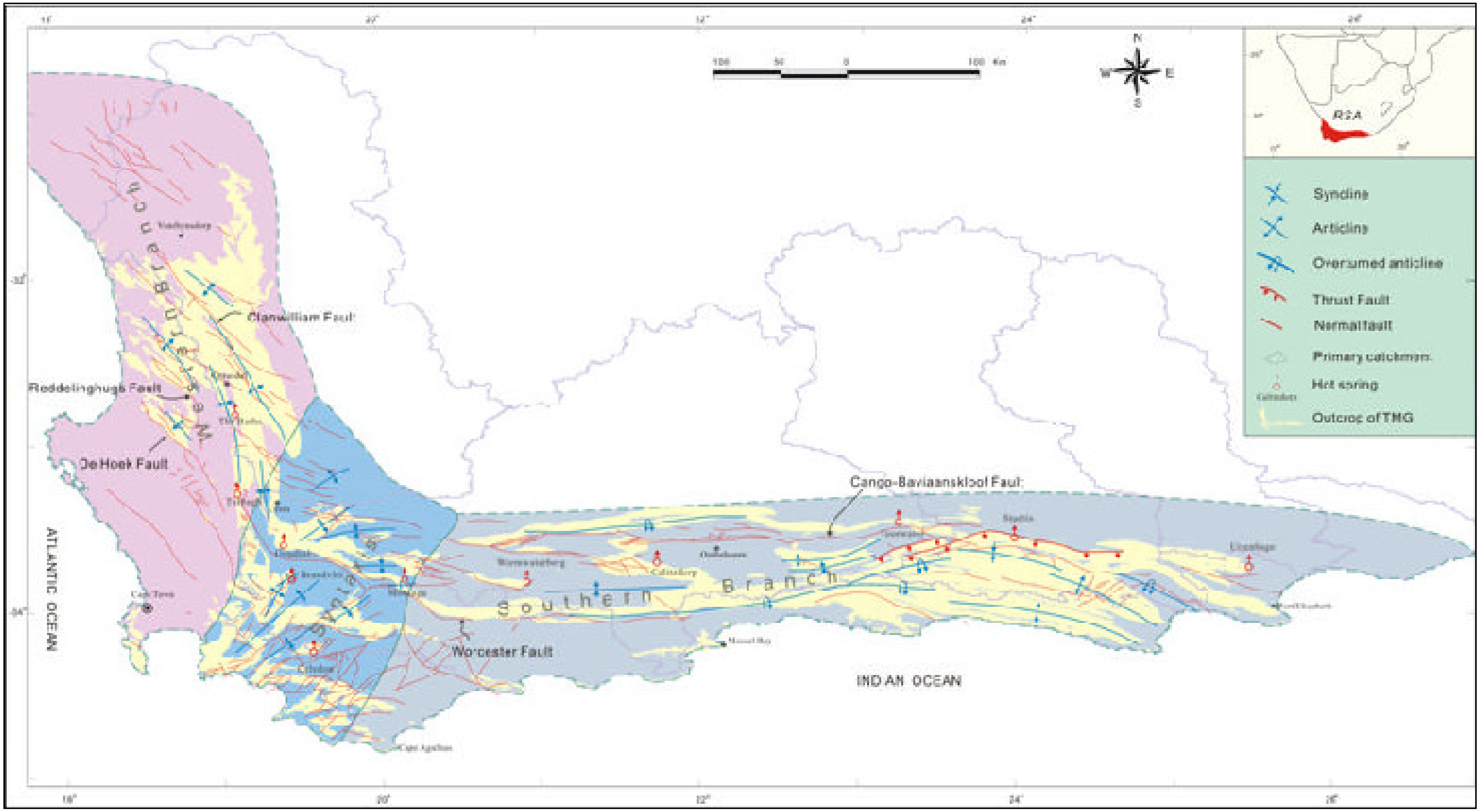


Figure 74. Main structural features in the TMG. (Wu, 2005 and the Council for Geoscience, 1997)

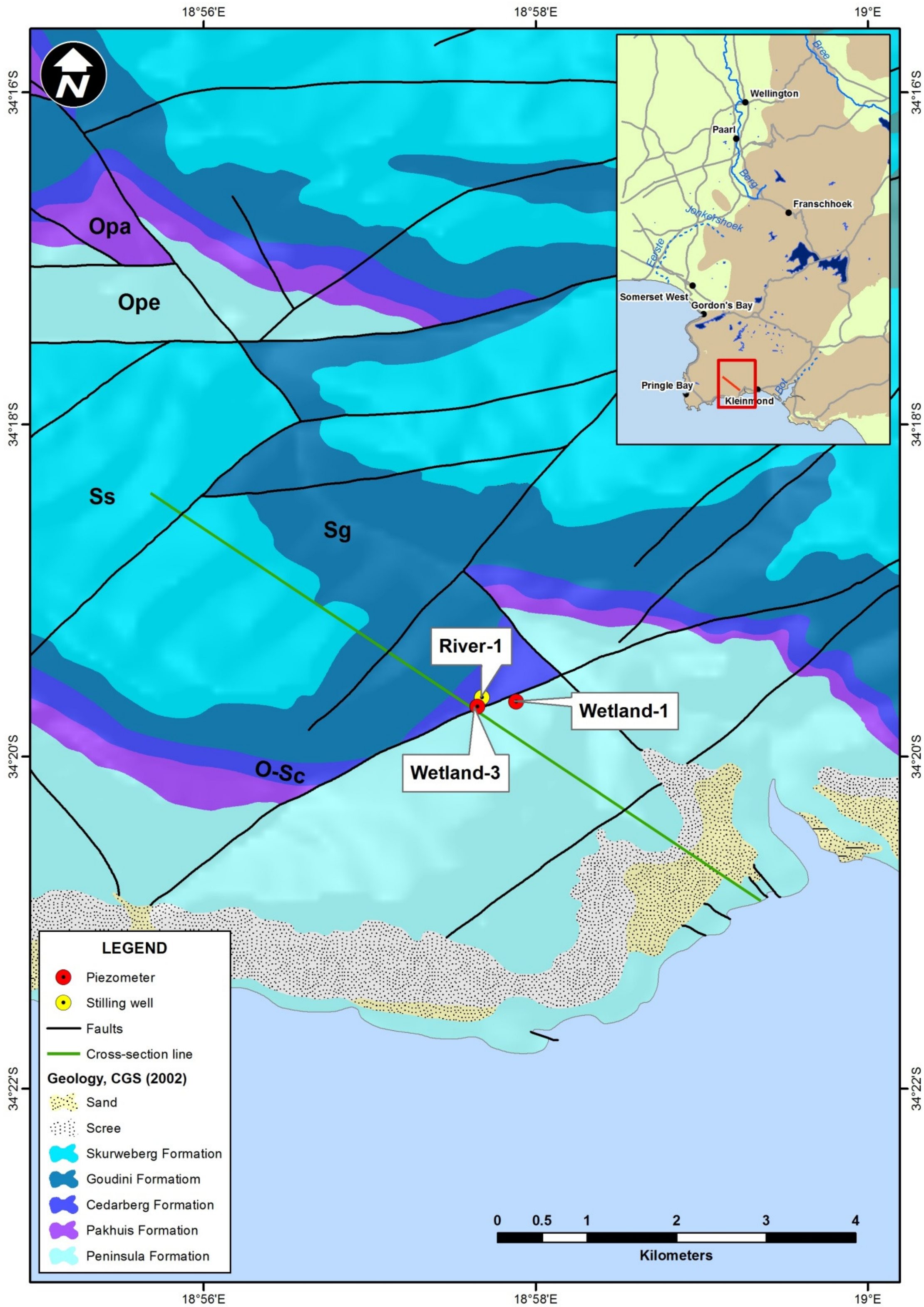


Figure 75. Geology map of the Oudebosch Valley modified from TMGA-EMA (2010).

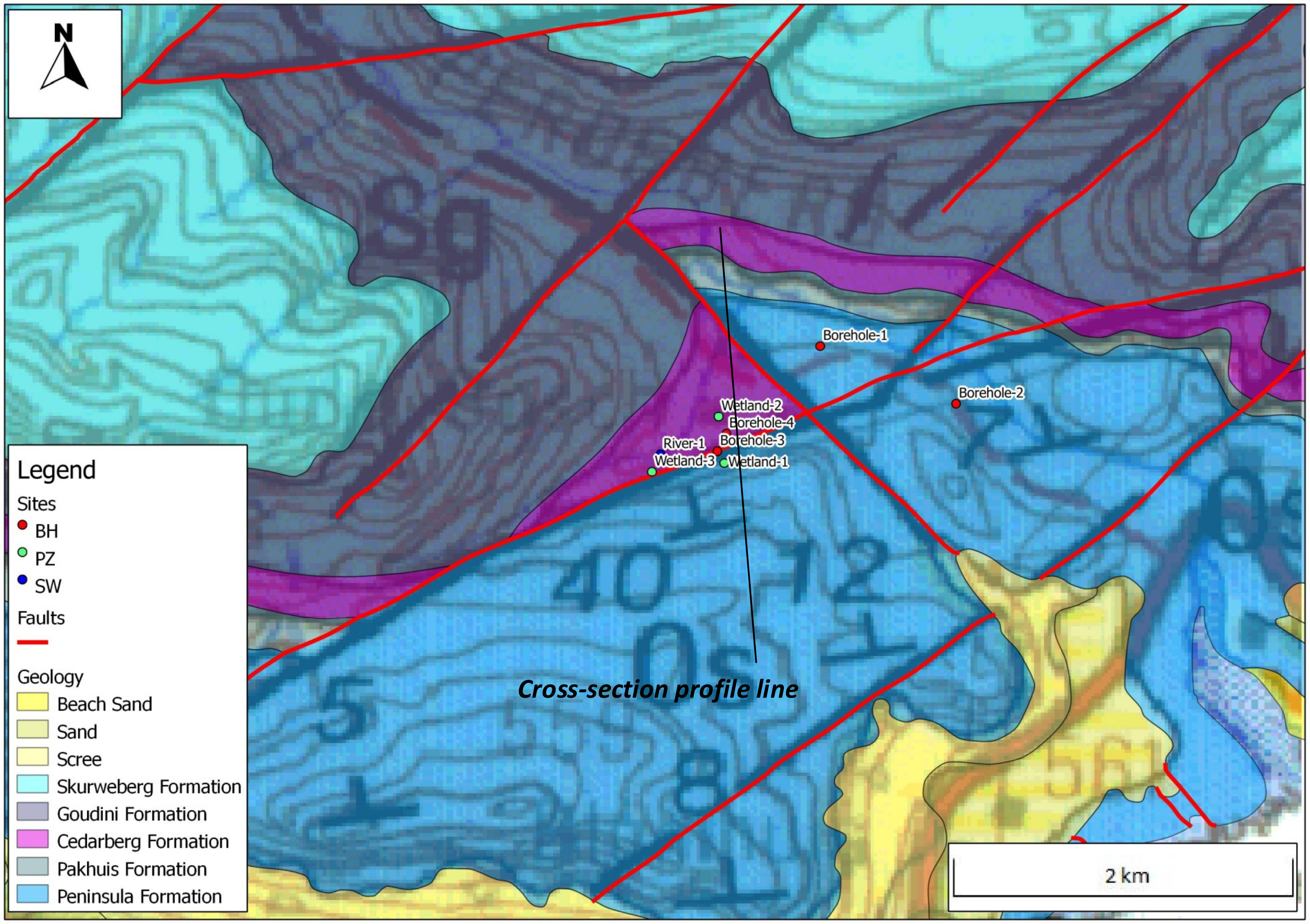


Figure 76. Geology map of the study area showing Cross-section profile line (Geology from Council for Geoscience 1:50 000, 2002).

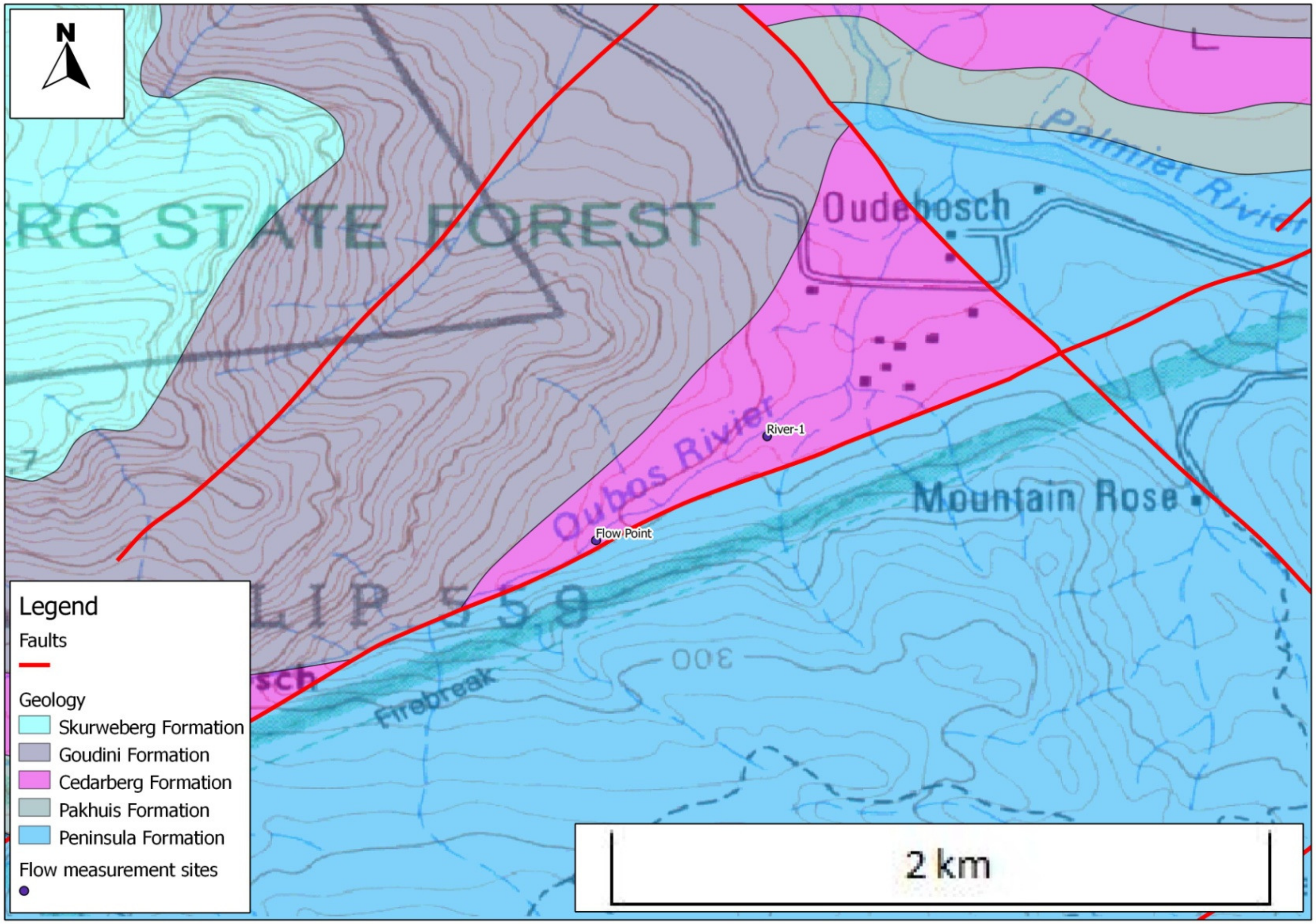


Figure 77. Sites at which flow measurements were taken on 14 November 2010. Geology from the Council for Geoscience (2002).

APPENDIX B: MONITORING SITES

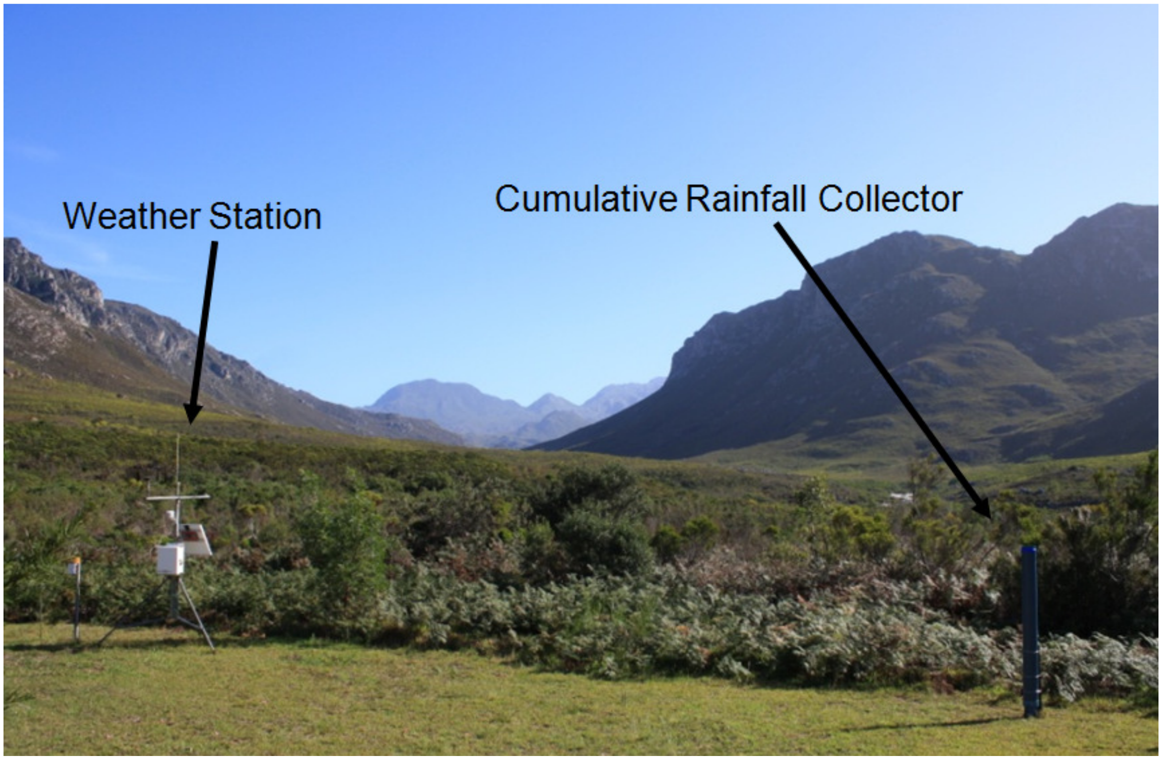


Figure 78. Weather station and Cumulative Rainfall Collector (CRC) at the lower parts of the Oudebosch Valley. Palmiet River Valley in the background.

Figure 79. Wetland 2 piezometer located in a wetland near the Oudebosch cottages.

Figure 80. Wetland 1 piezometer in a wetland on the southern slope of the Oudebosch Valley.

Figure 81. Wetland 3 piezometer in a wetland located towards the middle of the Oudebosch Valley.

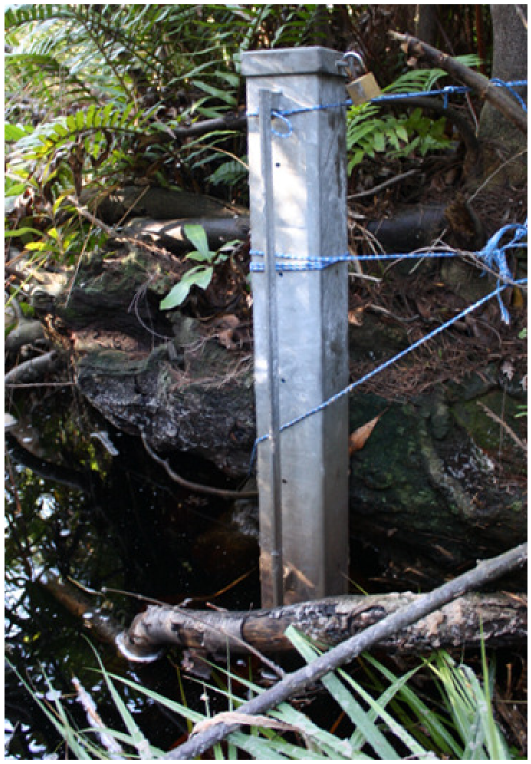


Figure 82. River 1 stilling well located in the Oudebosch River that flows down the middle of the valley.

Figure 83. Borehole 1 located in the main access road to the Kogelberg Reserve.

Figure 84. Borehole 2 located just next to the entrance road to the Kogelberg Reserve.

Figure 85. Borehole 3 located on the eastern slopes of the Oudebosch valley.

Figure 86. Artesian Borehole 4 located right next to the Oudebosch cottages.

APPENDIX C: MULTIVARIATE CHEMISTRY PLOTS

Table 25. Multivariate Plot of all ground water chemistry from the four boreholes.

	pH	EC	TDS	Temp	Ca	Mg	Na	K	Cl	SO4	HCO3	Al	Fe	Mn	NH4	P	NO2	Ba	Si	Sr	Zn
pH	1.00	0.08	0.29	-0.14	-0.32	-0.60	-0.51	-0.19	-0.42	-0.10	0.28	-0.54	0.50	0.60	0.44	-0.66	0.46	-0.08	-0.29	-0.25	-0.03
EC	0.08	1.00	0.68	-0.01	0.17	0.28	0.22	0.33	0.28	0.18	-0.05	0.35	-0.05	0.08	-0.21	-0.26	-0.15	0.70	-0.30	0.47	-0.16
TDS	0.29	0.68	1.00	0.04	0.03	-0.08	[illegible]	[illegible]	0.23	0.10	0.00	0.23	0.23	0.45	-0.06	-0.23	0.10	0.66	-0.39	0.33	0.22
Temp	-0.14	-0.01	0.04	1.00	-0.02	0.11	0.06	0.28	0.22	0.09	0.10	0.46	0.19	0.02	-0.36	0.39	-0.13	0.27	0.15	0.15	0.70
Ca	-0.32	0.17	0.03	-0.02	1.00	0.48	0.47	0.35	0.24	0.35	0.19	0.56	-0.22	-0.10	0.19	0.24	-0.15	0.52	-0.36	0.55	0.18
Mg	-0.60	0.28	-0.08	0.11	0.48	1.00	0.59	0.39	0.39	0.32	0.02	0.73	-0.49	-0.54	-0.19	[illegible]	-0.56	0.62	-0.14	0.75	0.16
Na	-0.51	0.22	[illegible]	0.06	0.47	0.59	1.00	0.38	0.54	0.38	-0.16	0.57	-0.35	-0.43	-0.09	0.26	-0.42	0.47	0.00	0.52	0.26
K	-0.19	0.33	[illegible]	0.28	0.35	0.39	0.38	1.00	0.41	0.55	-0.31	0.45	-0.51	-0.19	[illegible]	-0.36	-0.31	0.68	-0.53	0.72	0.30
Cl	-0.42	0.28	0.23	0.22	0.24	0.39	0.54	0.41	1.00	0.22	-0.15	0.43	-0.45	-0.52	-0.44	0.22	-0.34	0.43	-0.24	0.50	0.36
SO4	-0.10	0.18	0.10	0.09	0.35	0.32	0.38	0.55	0.22	1.00	-0.39	0.68	-0.26	0.08	0.12	-0.27	-0.16	0.53	-0.38	0.42	-0.07
HCO3	0.28	-0.05	0.00	0.10	0.19	0.02	-0.16	-0.31	-0.15	-0.39	1.00	-0.24	0.46	0.08	0.11	0.15	0.18	0.00	0.06	-0.05	0.44
Al	-0.54	0.35	0.23	0.46	0.56	0.73	0.57	0.45	0.43	0.68	-0.24	1.00	-0.60	-0.37	-0.20	0.08	-0.53	0.64	-0.08	0.63	0.20
Fe	0.50	-0.05	0.23	0.19	-0.22	-0.49	-0.35	-0.51	-0.45	-0.26	0.46	-0.60	1.00	0.50	0.35	0.42	0.80	-0.42	0.26	-0.70	0.11
Mn	0.60	0.08	0.45	0.02	-0.10	-0.54	-0.43	-0.19	-0.52	0.08	0.08	-0.37	0.50	1.00	0.52	-0.36	0.63	0.03	-0.10	-0.37	-0.28
NH4	0.44	-0.21	-0.06	-0.36	0.19	-0.19	-0.09	[illegible]	-0.44	0.12	0.11	-0.20	0.35	0.52	1.00	-0.23	0.60	0.13	-0.32	-0.07	-0.06
P	-0.66	-0.26	-0.23	0.39	0.24	[illegible]	0.26	-0.36	0.22	-0.27	0.15	0.08	0.42	-0.36	-0.23	1.00	0.27	-0.37	0.29	-0.34	0.48
NO2	0.46	-0.15	0.10	-0.13	-0.15	-0.56	-0.42	-0.31	-0.34	-0.16	0.18	-0.53	0.80	0.63	0.60	0.27	1.00	-0.28	-0.08	-0.57	-0.14
Ba	-0.08	0.70	0.66	0.27	0.52	0.62	0.47	0.68	0.43	0.53	0.00	0.64	-0.42	0.03	0.13	-0.37	-0.28	1.00	-0.62	0.85	0.28
Si	-0.29	-0.30	-0.39	0.15	-0.36	-0.14	0.00	-0.53	-0.24	-0.38	0.06	-0.08	0.26	-0.10	-0.32	0.29	-0.08	-0.62	1.00	-0.60	-0.14
Sr	-0.25	0.47	0.33	0.15	0.55	0.75	0.52	0.72	0.50	0.42	-0.05	0.63	-0.70	-0.37	-0.07	-0.34	-0.57	0.85	-0.60	1.00	0.21
Zn	-0.03	-0.16	0.22	0.70	0.18	0.16	0.26	0.30	0.36	-0.07	0.44	0.20	0.11	-0.28	-0.06	0.48	-0.14	0.28	-0.14	0.21	1.00

Table 26. Multivariate Plot of ground water chemistry from the site Wetland-1.

	pH	EC	TDS	Temp	Ca	Mg	Na	K	Cl	SO4	HCO3	Al	Fe	NH4	NO2	Ba	Si	Sr	Zn
pH	1.00	0.58	0.44	-0.49	0.18	0.43	-0.25	-0.43	-0.19	0.49	0.25	-0.57	-0.46	-0.38	-0.28	0.04	-0.21	0.30	-0.80
EC	0.58	1.00	0.96	0.03	0.21	0.00	0.11	-0.09	0.37	0.14	0.21	0.29	0.32	-0.40	0.82	0.31	-0.11	-0.37	0.00
TDS	0.44	0.96	1.00	0.09	-0.09	-0.54	-0.03	-0.26	0.58	0.10	0.37	0.60	0.71	-0.41	0.79	0.00	0.14	-0.75	0.00
Temp	-0.49	0.03	0.09	1.00	-0.09	-0.54	-0.03	-0.26	0.58	0.10	0.37	0.60	0.71	-0.41	0.79	0.00	0.14	-0.75	0.00
Ca	0.18	0.21	-0.09	-0.09	1.00	0.82	0.04	-0.20	-0.74	0.54	0.29	0.36	0.46	-0.27	-0.24	0.42	-0.21	0.70	0.30
Mg	0.43	0.00	-0.54	-0.54	0.82	1.00	0.36	-0.09	-0.89	0.71	0.32	-0.21		-0.23	-0.49	0.06	0.04	0.78	0.10
Na	-0.25	0.11	-0.03	-0.03	0.04	0.36	1.00	0.54	-0.30	0.14	-0.04	-0.39	-0.14	0.23	0.11	-0.28	0.39	0.11	0.30
K	-0.43	-0.09	-0.26	-0.26	-0.20	-0.09	0.54	1.00	-0.06	-0.10	-0.54	-0.03	-0.37	0.90	0.29	0.44	-0.43	0.29	0.60
Cl	-0.19	0.37	0.58	0.58	-0.74	-0.89	-0.30	-0.06	1.00	-0.70	-0.26	0.11	-0.11	-0.09	0.70	-0.06	0.04	-0.88	-0.21
SO4	0.49	0.14	0.10	0.10	0.54	0.71	0.14	-0.10	-0.70	1.00	0.77	-0.14	0.20	0.14	-0.15	0.09	-0.26	0.52	-1.00
HCO3	0.25	0.21	0.37	0.37	0.29	0.32	-0.04	-0.54	-0.26	0.77	1.00		0.54	-0.20	-0.07	-0.24		-0.07	-0.60
Al	-0.57	0.29	0.60	0.60	0.36	-0.21	-0.39	-0.03	0.11	-0.14		1.00	0.82	-0.04	0.32	0.46	-0.25	-0.11	0.30
Fe	-0.46	0.32	0.71	0.71	0.46		-0.14	-0.37	-0.11	0.20	0.54	0.82	1.00	-0.23	0.17	0.06	0.11	-0.15	0.20
NH4	-0.38	-0.40	-0.41	-0.41	-0.27	-0.23	0.23	0.90	-0.09	0.14	-0.20	-0.04	-0.23	1.00	0.02	0.31	-0.49	0.21	0.41
P	0.00	0.00	-0.87	-0.87	0.00	0.00	0.00	0.87	0.00	-0.87	-0.87	0.00	-0.87	0.87	0.00	0.87	-0.87	0.87	0.87
NO2	-0.28	0.82	0.79	0.79	-0.24	-0.49	0.11	0.29	0.70	-0.15	-0.07	0.32	0.17	0.02	1.00	0.33	-0.19	-0.62	0.22
Ba	0.04	0.31	0.00	0.00	0.42	0.06	-0.28	0.44	-0.06	0.09	-0.24	0.46	0.06	0.31	0.33	1.00	-0.90	0.40	0.15
Si	-0.21	-0.11	0.14	0.14	-0.21	0.04	0.39	-0.43	0.04	-0.26		-0.25	0.11	-0.49	-0.19	-0.90	1.00	-0.37	0.30
Sr	0.30	-0.37	-0.75	-0.75	0.70	0.78	0.11	0.29	-0.88	0.52	-0.07	-0.11	-0.15	0.21	-0.62	0.40	-0.37	1.00	0.21
Zn	-0.80	0.00	0.00	0.00	0.30	0.10	0.30	0.60	-0.21	-1.00	-0.60	0.30	0.20	0.41	0.22	0.15	0.30	0.21	1.00

Table 27. Multivariate Plot of ground water chemistry from the site Wetland-2.

	pH	EC	TDS	Temp	Ca	Mg	Na	K	Cl	SO4	HCO3	Al	Fe	NH4	P	NO2	Ba	Si	Sr	Zn
pH	1.00	0.66	0.51	-0.03	0.43	-0.27	-0.30	0.03	0.32	-0.17	0.12	0.14	0.68	-0.20	0.37	-0.09	-0.14	-0.14	0.23	-0.26
EC	0.66	1.00	0.94	0.14	0.78	0.30	-0.02	0.28	0.67	0.00	0.35	0.60	0.72	0.05	0.83	0.37	0.00	-0.14	0.67	0.37
TDS	0.51	0.94	1.00	0.10	0.82	0.58	0.18	0.43	0.76	-0.05	0.26	0.77	0.70	0.08	0.89	[illegible]	0.17	-0.09	0.81	0.60
Temp	-0.03	0.14	0.10	1.00	0.83	0.37	-0.26	0.71	0.52	-0.20	0.35	0.60	0.83	-0.26	0.83	0.37	0.00	-0.14	0.67	0.37
Ca	0.43	0.78	0.82	0.83	1.00	0.48	0.18	0.10	0.80	0.17	0.47	0.77	0.67	0.35	1.00	0.54	0.23	0.14	0.84	0.77
Mg	-0.27	0.30	0.58	0.37	0.48	1.00	0.40	[illegible]	0.71	0.12	-0.12	0.77	0.08	0.38	0.54	0.31	0.46	0.03	0.72	0.77
Na	-0.30	-0.02	0.18	-0.26	0.18	0.40	1.00	0.47	0.29	0.26	0.15	0.49	0.22	0.62	0.26	0.26	0.70	0.31	0.46	0.66
K	0.03	0.28	0.43	0.71	0.10	[illegible]	0.47	1.00	0.09	0.02	0.44	0.83	0.12	0.07	0.66	0.66	0.32	-0.54	0.78	0.60
Cl	0.32	0.67	0.76	0.52	0.80	0.71	0.29	0.09	1.00	0.10	-0.19	0.90	0.59	0.52	0.64	0.17	0.66	0.12	0.88	0.72
SO4	-0.17	0.00	-0.05	-0.20	0.17	0.12	0.26	0.02	0.10	1.00	0.79	0.00	0.48	0.62	0.20	0.70	-0.21	0.00	-0.05	0.70
HCO3	0.12	0.35	0.26	0.35	0.47	-0.12	0.15	0.44	-0.19	0.79	1.00	0.15	0.47	0.47	0.47	0.88	-0.39	-0.44	0.15	0.38
Al	0.14	0.60	0.77	0.60	0.77	0.77	0.49	0.83	0.90	0.00	0.15	1.00	0.77	0.37	0.77	[illegible]	0.70	-0.03	0.99	0.83
Fe	0.68	0.72	0.70	0.83	0.67	0.08	0.22	0.12	0.59	0.48	0.47	0.77	1.00	0.37	1.00	0.54	0.23	0.14	0.84	0.77
NH4	-0.20	0.05	0.08	-0.26	0.35	0.38	0.62	0.07	0.52	0.62	0.47	0.37	0.37	1.00	0.26	0.60	0.35	0.03	0.32	0.71
P	0.37	0.83	0.89	0.83	1.00	0.54	0.26	0.66	0.64	0.20	0.47	0.77	1.00	0.26	1.00	0.54	0.23	0.14	0.84	0.77
NO2	-0.09	0.37	[illegible]	0.37	0.54	0.31	0.26	0.66	0.17	0.70	0.88	[illegible]	0.54	0.60	0.54	1.00	-0.17	-0.54	0.38	0.66
Ba	-0.14	0.00	0.17	0.00	0.23	0.46	0.70	0.32	0.66	-0.21	-0.39	0.70	0.23	0.35	0.23	-0.17	1.00	0.32	0.68	0.46
Si	-0.14	-0.14	-0.09	-0.14	0.14	0.03	0.31	-0.54	0.12	0.00	-0.44	-0.03	0.14	0.03	0.14	-0.54	0.32	1.00	0.09	0.09
Sr	0.23	0.67	0.81	0.67	0.84	0.72	0.46	0.78	0.88	-0.05	0.15	0.99	0.84	0.32	0.84	0.38	0.68	0.09	1.00	0.81
Zn	-0.26	0.37	0.60	0.37	0.77	0.77	0.66	0.60	0.72	0.70	0.38	0.83	0.77	0.71	0.77	0.66	0.46	0.09	0.81	1.00

Table 28. Multivariate Plot of ground water chemistry from the site Wetland-3.

	pH	EC	TDS	Temp	Ca	Mg	Na	K	Cl	SO4	HCO3	Al	Fe	Mn	NH4	P	NO2	Ba	Si	Sr	Zn
pH	1.00	-0.62	-0.61	-0.89	0.68	0.46	0.14	-0.03	[illegible]	-0.14	0.46	0.00	0.89	0.64	0.00	-0.22	0.29	0.36	-0.46	0.71	-0.50
EC	-0.62	1.00	1.00	0.57	-0.39	0.11	0.07	0.77	0.11	0.14	-0.50	0.43	-0.43	-0.20	-0.29	0.29	-0.61	0.36	0.64	-0.29	0.90
TDS	-0.61	1.00	1.00	0.57	-0.37	0.03	0.03	0.77	0.03	0.00	-0.89	0.14	-0.43	-0.21	-0.71	-0.06	-0.94	0.20	0.66	-0.26	1.00
Temp	-0.89	0.57	0.57	1.00	-0.71	-0.60	-0.60	-0.03	-0.60	-0.40	-0.60	0.09	-0.77	-0.56	-0.09	0.29	-0.37	-0.31	0.09	-0.77	0.80
Ca	0.68	-0.39	-0.37	-0.71	1.00	0.82	[illegible]	0.20	0.29	-0.14	0.57	0.32	0.86	0.99	-0.18	0.25	0.25	0.54	0.00	0.93	0.40
Mg	0.46	0.11	0.03	-0.60	0.82	1.00	0.25	0.60	0.32	-0.20	[illegible]	0.43	0.71	0.70	-0.57	0.18	-0.29	0.75	[illegible]	0.89	0.30
Na	0.14	0.07	0.03	-0.60	[illegible]	0.25	1.00	0.43	0.96	0.77	-0.11	-0.21	0.14	0.14	0.04	-0.34	-0.11	0.25	0.64	0.18	-0.20
K	-0.03	0.77	0.77	-0.03	0.20	0.60	0.43	1.00	0.43	0.20	-0.60	0.26	0.14	0.21	-0.89	-0.14	-0.89	0.60	0.77	0.37	0.40
Cl	[illegible]	0.11	0.03	-0.60	0.29	0.32	0.96	0.43	1.00	0.83	0.07	-0.04	0.25	0.26	0.14	-0.20	0.00	0.39	0.61	[illegible]	0.00
SO4	-0.14	0.14	0.00	-0.40	-0.14	-0.20	0.77	0.20	0.83	1.00	0.09	-0.09	-0.14	-0.15	0.60	-0.06	0.26	0.09	0.77	-0.37	0.40
HCO3	0.46	-0.50	-0.89	-0.60	0.57	[illegible]	-0.11	-0.60	0.07	0.09	1.00	[illegible]	0.46	0.38	0.46	0.34	0.75	0.07	-0.39	0.29	0.10
Al	0.00	0.43	0.14	0.09	0.32	0.43	-0.21	0.26	-0.04	-0.09	[illegible]	1.00	0.39	0.52	0.11	0.88	0.14	0.79	0.29	0.32	0.90
Fe	0.89	-0.43	-0.43	-0.77	0.86	0.71	0.14	0.14	0.25	-0.14	0.46	0.39	1.00	0.93	-0.07	0.16	0.25	0.68	-0.18	0.89	0.20
Mn	0.64	-0.20	-0.21	-0.56	0.99	0.70	0.14	0.21	0.26	-0.15	0.38	0.52	0.93	1.00	0.12	0.40	0.20	0.75	0.09	0.93	0.40
NH4	0.00	-0.29	-0.71	-0.09	-0.18	-0.57	0.04	-0.89	0.14	0.60	0.46	0.11	-0.07	0.12	1.00	0.31	0.86	-0.18	-0.07	-0.43	0.10
P	-0.22	0.29	-0.06	0.29	0.25	0.18	-0.34	-0.14	-0.20	-0.06	0.34	0.88	0.16	0.40	0.31	1.00	0.40	0.45	0.25	0.13	1.00
NO2	0.29	-0.61	-0.94	-0.37	0.25	-0.29	-0.11	-0.89	0.00	0.26	0.75	0.14	0.25	0.20	0.86	0.40	1.00	-0.14	-0.29	-0.04	0.10
Ba	0.36	0.36	0.20	-0.31	0.54	0.75	0.25	0.60	0.39	0.09	0.07	0.79	0.68	0.75	-0.18	0.45	-0.14	1.00	0.39	0.64	0.40
Si	-0.46	0.64	0.66	0.09	0.00	[illegible]	0.64	0.77	0.61	0.77	-0.39	0.29	-0.18	0.09	-0.07	0.25	-0.29	0.39	1.00	0.00	0.50
Sr	0.71	-0.29	-0.26	-0.77	0.93	0.89	0.18	0.37	[illegible]	-0.37	0.29	0.32	0.89	0.93	-0.43	0.13	-0.04	0.64	0.00	1.00	0.30
Zn	-0.50	0.90	1.00	0.80	0.40	0.30	-0.20	0.40	0.00	0.40	0.10	0.90	0.20	0.40	0.10	1.00	0.10	0.40	0.50	0.30	1.00

Table 29. Multivariate Plot of ground water chemistry from the site River-1.

	pH	EC	TDS	Temp	Ca	Mg	Na	K	Cl	SO4	HCO3	Al	Fe	NH4	NO2	Ba	Si	Sr	Zn	Flow
pH	1.00	0.48	0.20	0.38	-0.21	0.04	0.39	0.09	0.75	0.37	0.38	-0.93	-0.46	-0.46	-0.49	-0.93	0.61	-0.09	-0.87	-0.77
EC	0.48	1.00	0.75	0.42	0.75	0.79	1.00	0.49	0.54	0.77	-0.15	-0.39	0.00	-0.43	-0.65	-0.03	0.57	0.71	0.87	-0.60
TDS	0.20	0.75	1.00	0.42	0.68	0.57	0.79	0.49	0.14	0.43	-0.53	-0.29	0.00	-0.07	-0.35	-0.03	0.39	0.47	0.87	-0.60
Temp	0.38	0.42	0.42	1.00	0.43	0.54	0.89	0.49	0.60	0.50	-0.44	-0.71	-0.09	-0.43	-0.44	-0.41	0.66	0.38	0.87	-0.83
Ca	-0.21	0.75	0.68	0.43	1.00	0.82	0.75	0.54	-0.04	0.89	-0.13	0.14	0.04	0.00	-0.60	0.55	0.00	0.80	0.87	-0.14
Mg	0.04	0.79	0.57	0.54	0.82	1.00	0.79	0.66	0.32	0.89	0.04	-0.11	0.00	-0.54	-0.65	0.32	0.32	0.98	0.87	-0.26
Na	0.39	1.00	0.79	0.89	0.75	0.79	1.00	0.49	0.54	0.77	-0.15	-0.39	0.00	-0.43	-0.65	-0.03	0.57	0.71	0.87	-0.60
K	0.09	0.49	0.49	0.49	0.54	0.66	0.49	1.00	0.03	0.80	0.35	-0.37	-0.43	0.09	-0.91	0.09	-0.26	0.53	-0.87	-0.66
Cl	0.75	0.54	0.14	0.60	-0.04	0.32	0.54	0.03	1.00	0.14	0.25	-0.57	0.14	-0.79	-0.33	-0.55	0.61	0.29	0.00	-0.66
SO4	0.37	0.77	0.43	0.50	0.89	0.89	0.77	0.80	0.14	1.00	0.35	-0.43	-0.54	-0.20	-0.99	0.30	0.26	0.81	0.00	-0.50
HCO3	0.38	-0.15	-0.53	-0.44	-0.13	0.04	-0.15	0.35	0.25	0.35	1.00	-0.27	-0.49	-0.13	-0.56	-0.04	-0.31	0.02	-1.00	-0.09
Al	-0.93	-0.39	-0.29	-0.71	0.14	-0.11	-0.39	-0.37	-0.57	-0.43	-0.27	1.00	0.64	0.39	0.53	0.87	-0.61	0.05	0.87	0.89
Fe	-0.46	0.00	0.00	-0.09	0.04	0.00	0.00	-0.43	0.14	-0.54	-0.49	0.64	1.00	-0.14	0.60	0.58	-0.04	0.15	0.87	0.43
NH4	-0.46	-0.43	-0.07	-0.43	0.00	-0.54	-0.43	0.09	-0.79	-0.20	-0.13	0.39	-0.14	1.00	0.22	0.46	-0.71	-0.55	-0.87	0.26
NO2	-0.49	-0.65	-0.35	-0.44	-0.60	-0.65	-0.65	-0.91	-0.33	-0.99	-0.56	0.53	0.60	0.22	1.00	0.13	-0.15	-0.55	0.87	0.68
Ba	-0.93	-0.03	-0.03	-0.41	0.55	0.32	-0.03	0.09	-0.55	0.30	-0.04	0.87	0.58	0.46	0.13	1.00	-0.70	0.48	0.50	0.55
Si	0.61	0.57	0.39	0.66	0.00	0.32	0.57	-0.26	0.61	0.26	-0.31	-0.61	-0.04	-0.71	-0.15	-0.70	1.00	0.25	0.87	-0.37
Sr	-0.09	0.71	0.47	0.38	0.80	0.98	0.71	0.53	0.29	0.81	0.02	0.05	0.15	-0.55	-0.55	0.48	0.25	1.00	0.87	-0.06
Zn	-0.87	0.87	0.87	0.87	0.87	0.87	0.87	-0.87	0.00	0.00	-1.00	0.87	0.87	-0.87	0.87	0.50	0.87	0.87	1.00	0.87
Flow	-0.77	-0.60	-0.60	-0.83	-0.14	-0.26	-0.60	-0.66	-0.66	-0.50	-0.09	0.89	0.43	0.26	0.68	0.55	-0.37	-0.06	0.87	1.00

APPENDIX D: EC AND PH GRAPHS

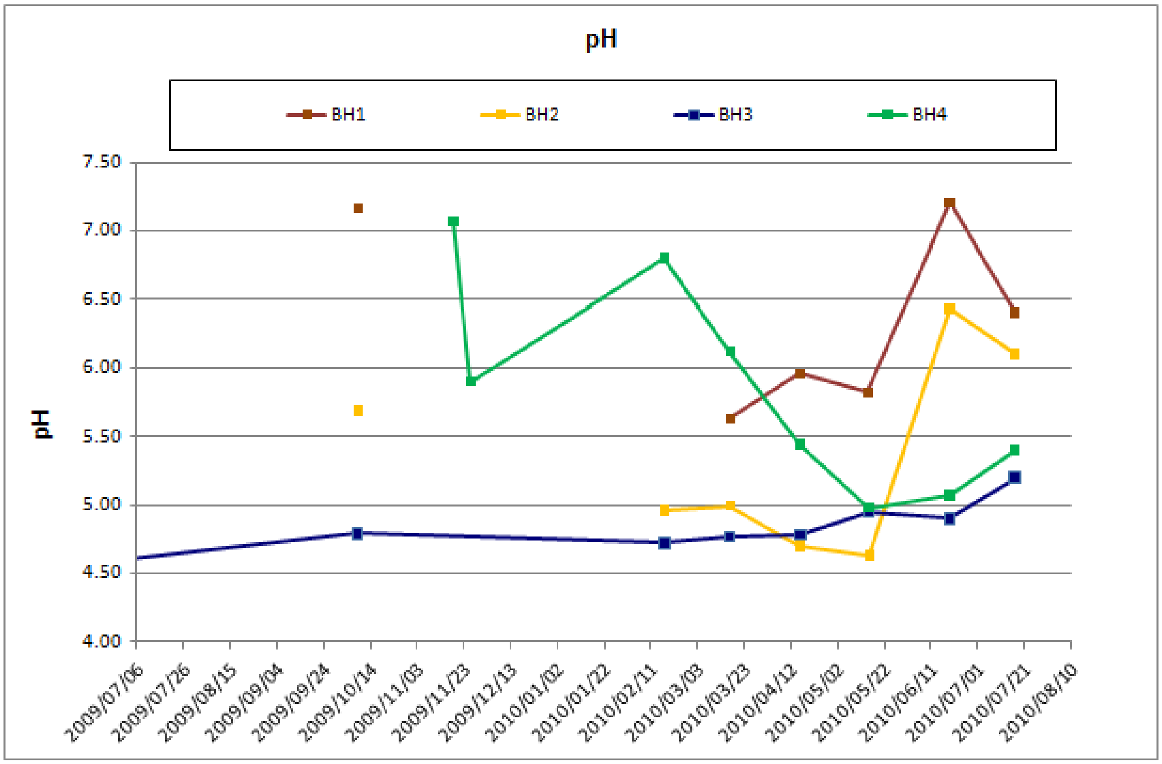


Figure 87. Borehole pH time-series data

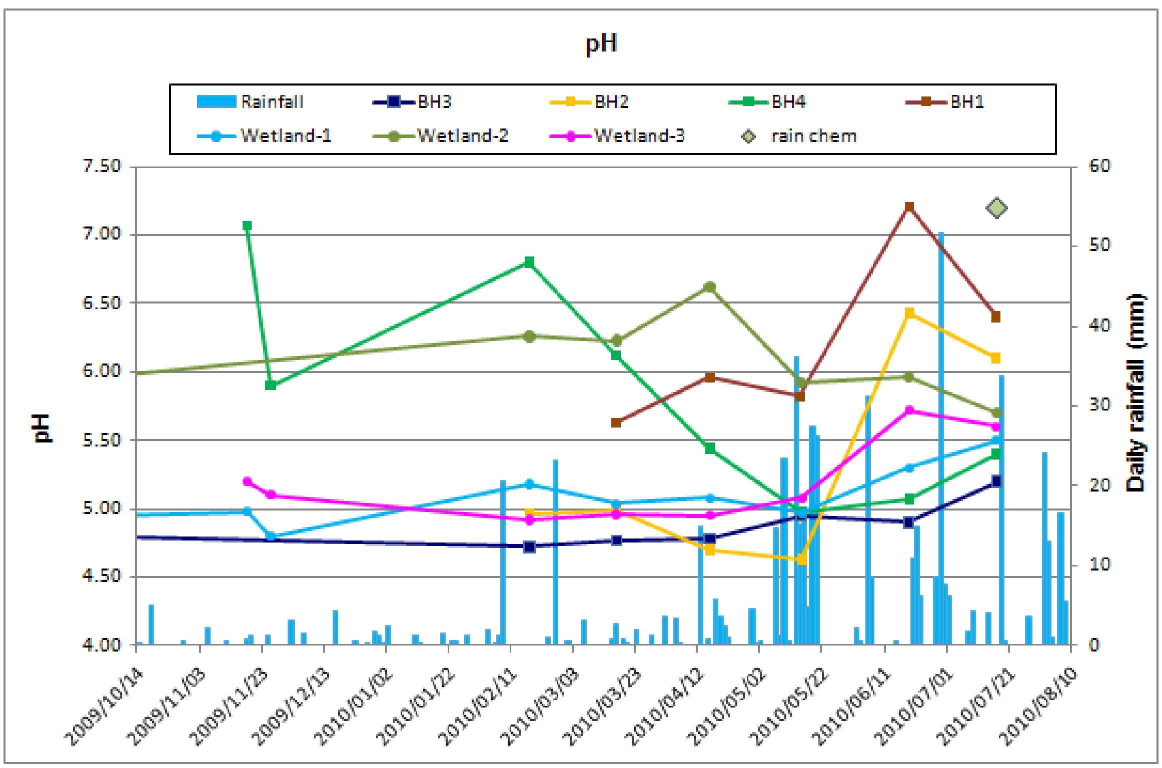


Figure 88. Site pH time-series data

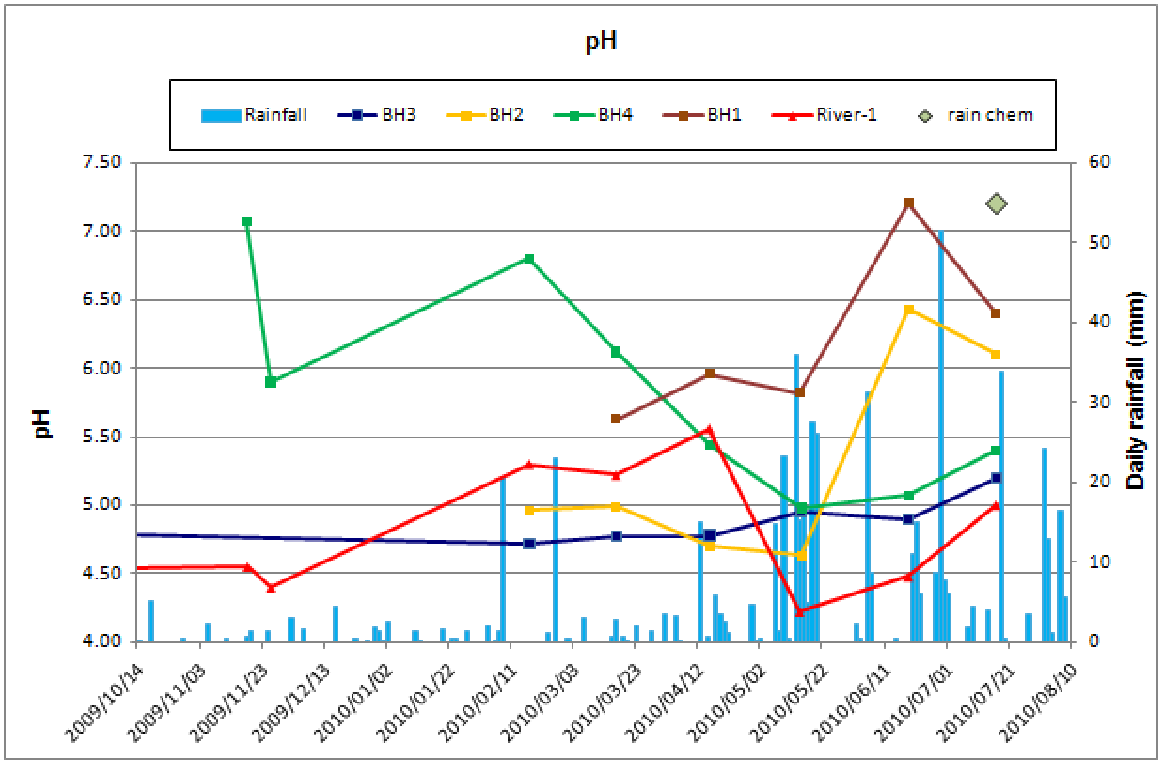


Figure 89. Site pH time-series data

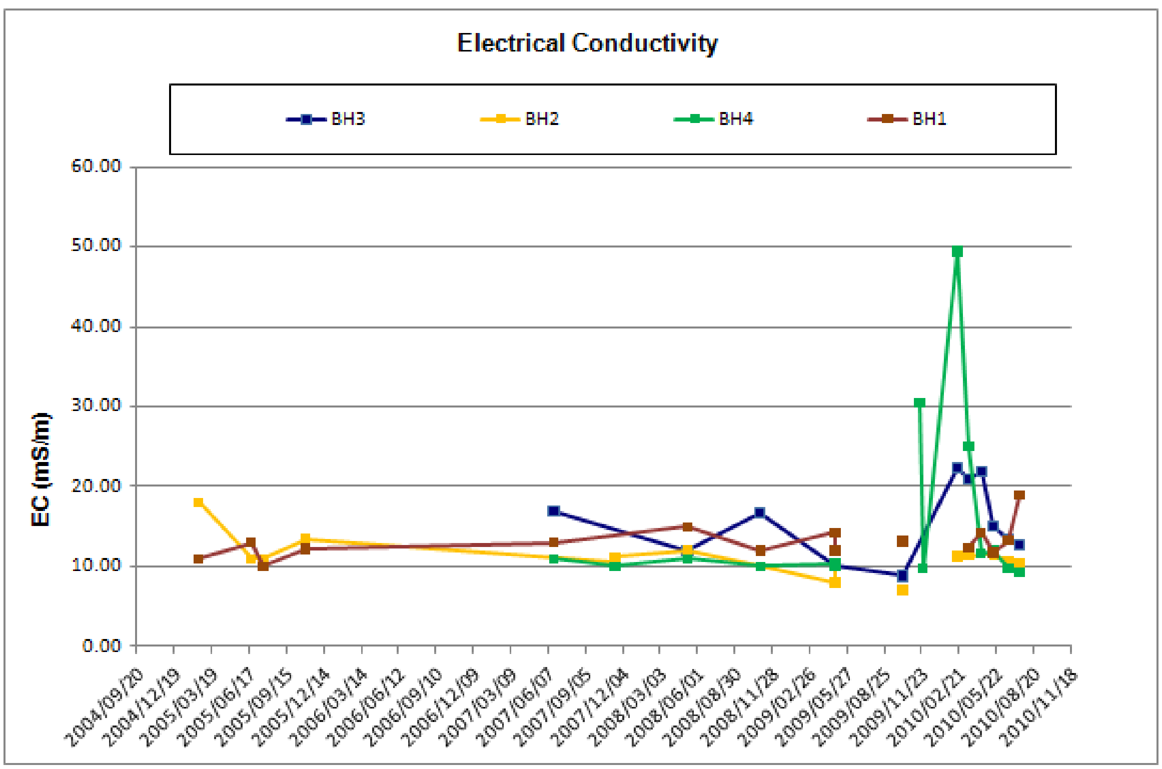


Figure 90. Borehole EC time-series data

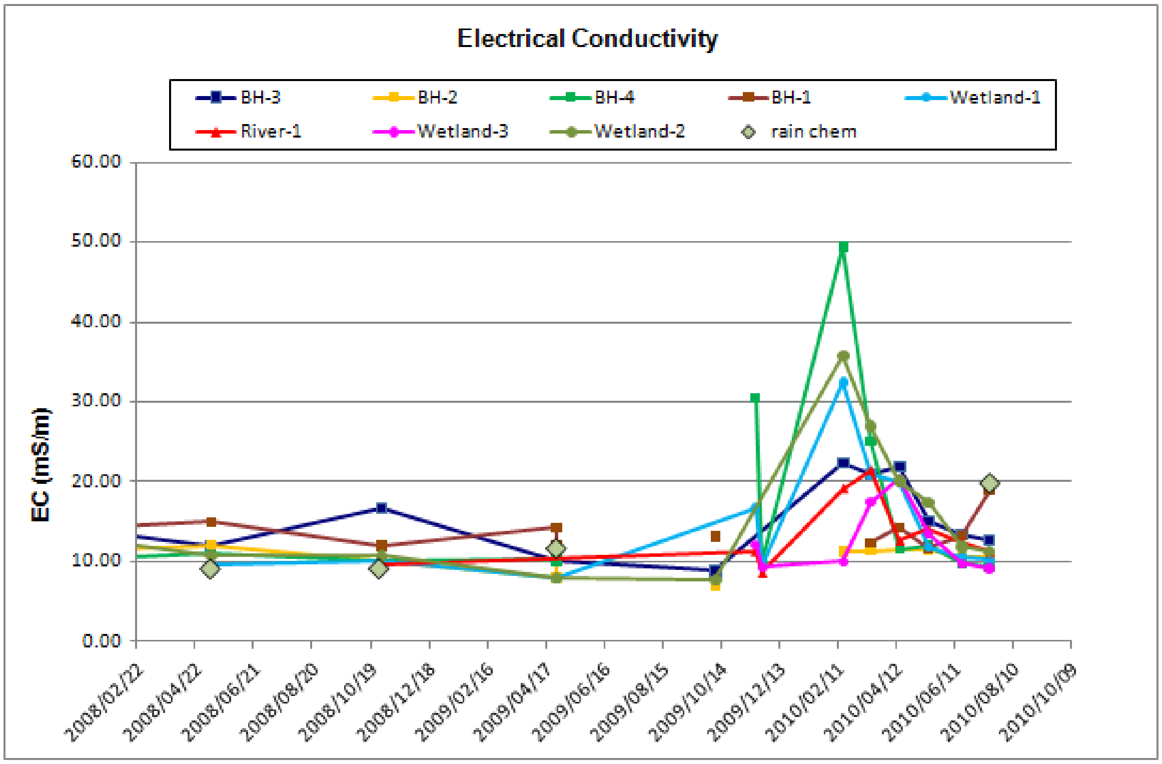


Figure 91. EC time-series data for all the sites monitored.

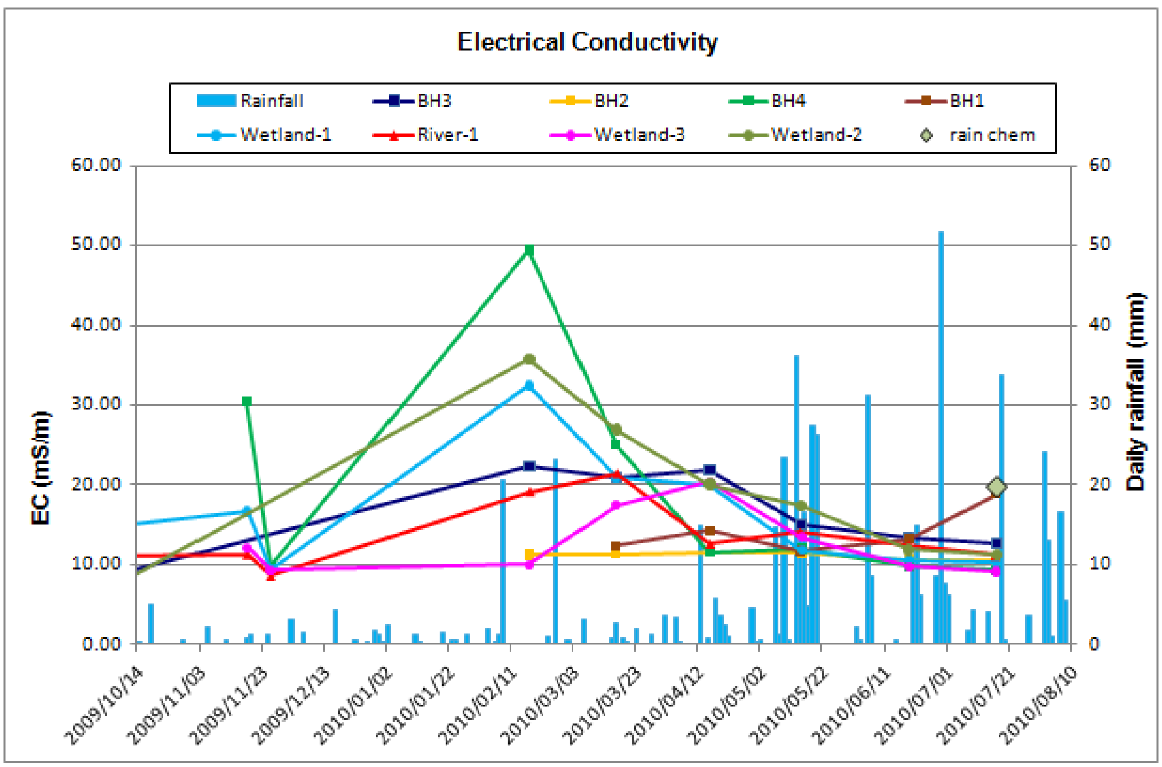


Figure 92. EC time-series data between October 2009 and August 2010 for all the sites monitored.

APPENDIX E: WATER CHEMISTRY PIPER DIAGRAMS

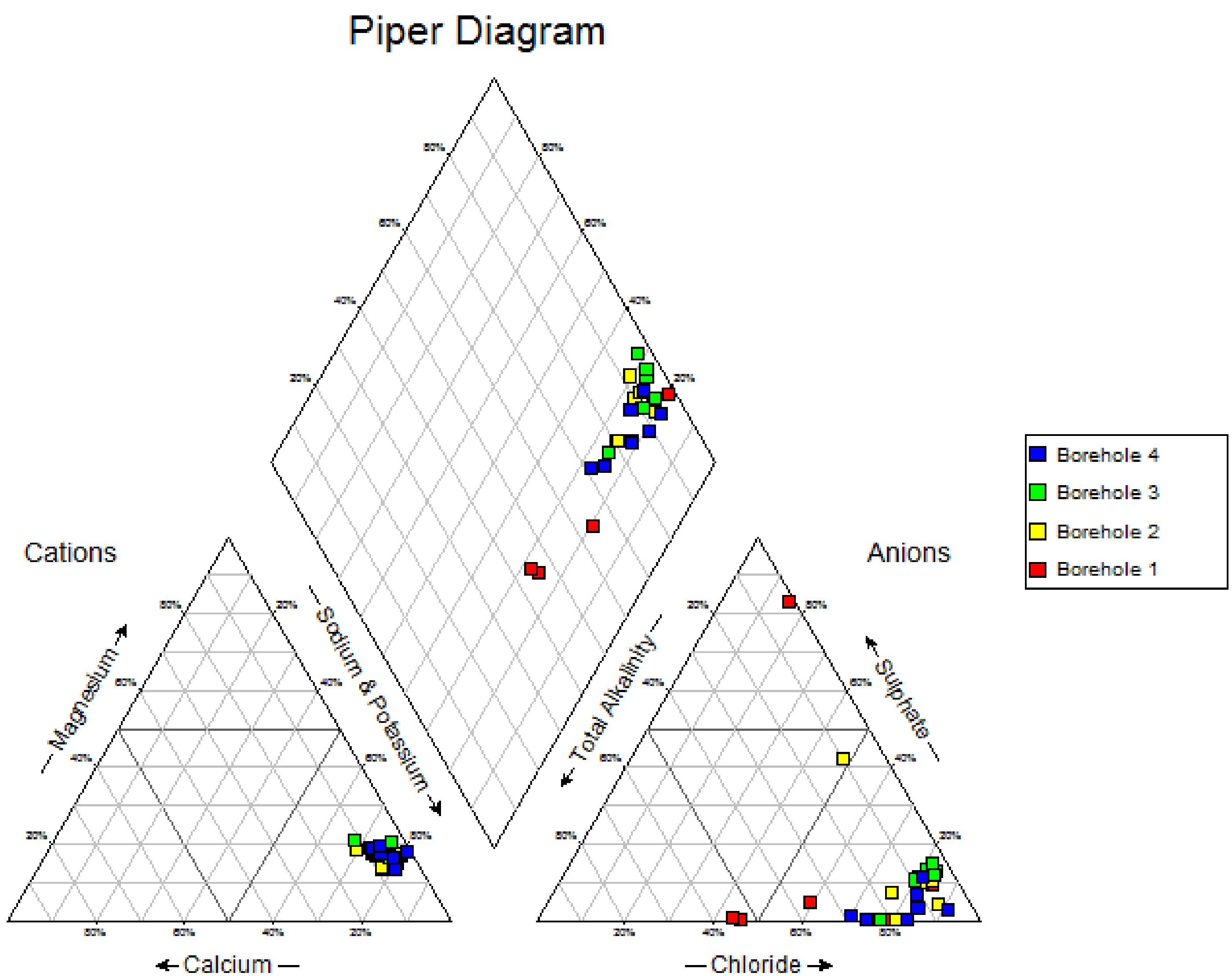


Figure 93. Piper diagram of the borehole samples taken during 2010.

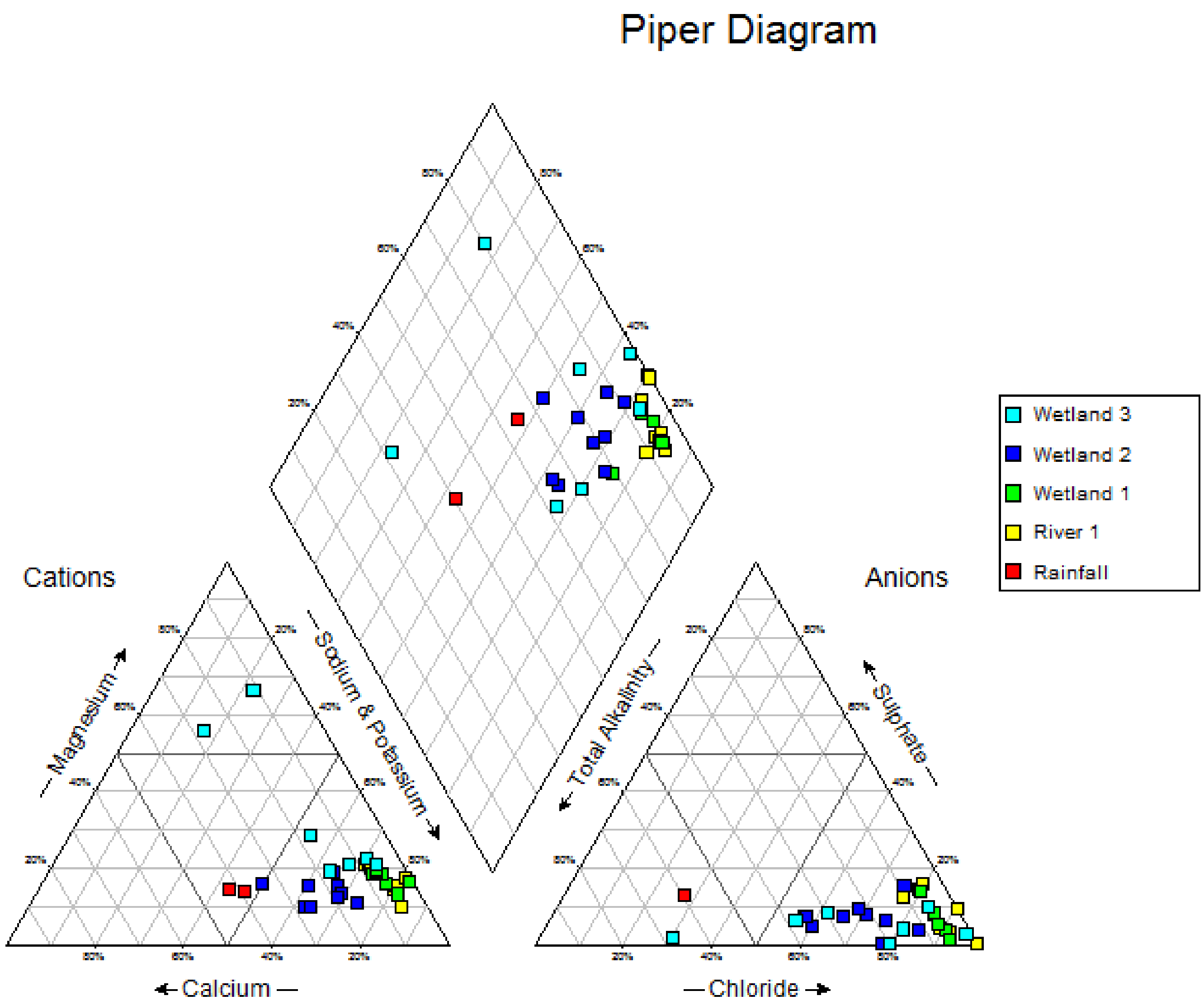


Figure 94. Piper Diagram of the wetland and river sites.

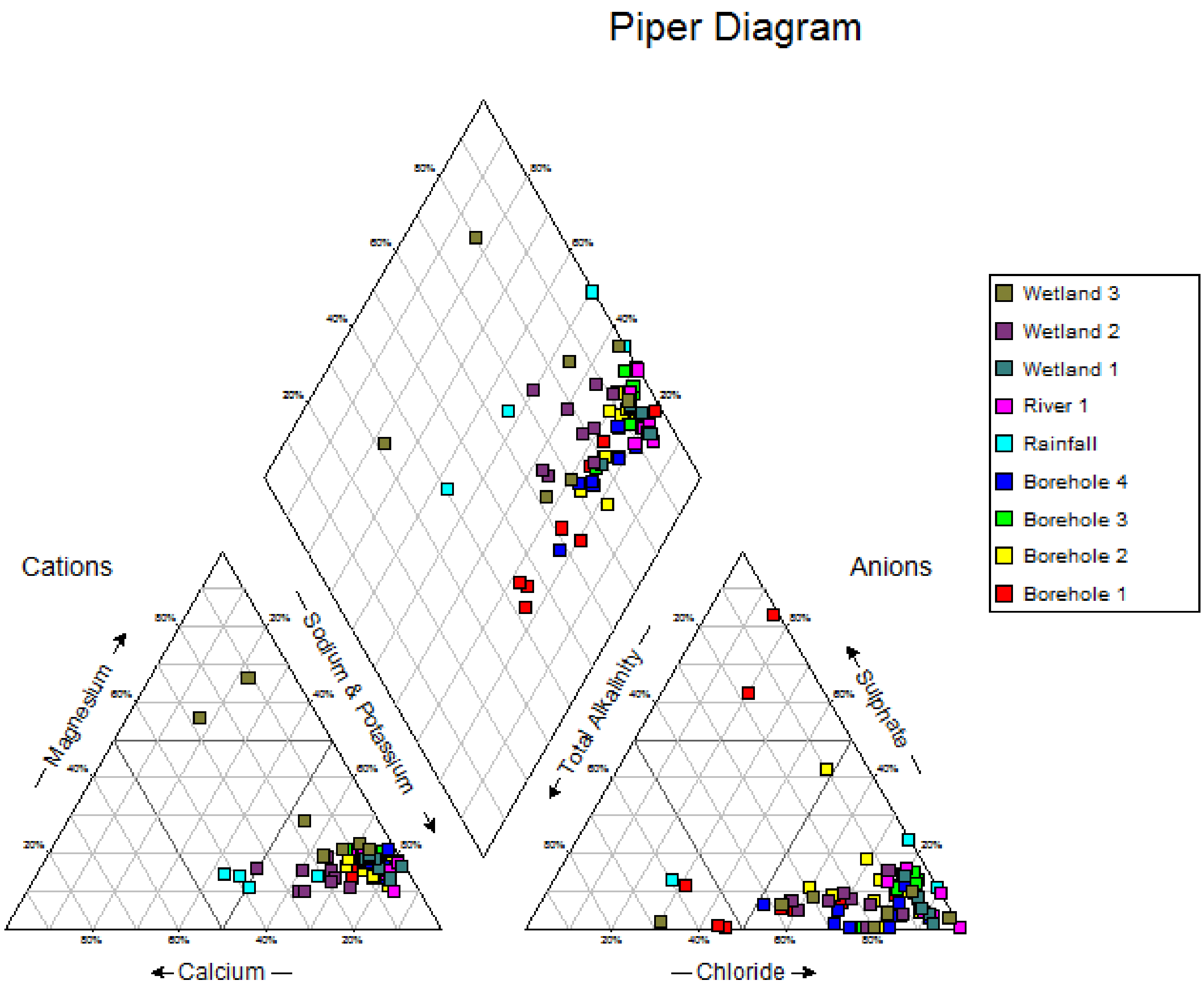
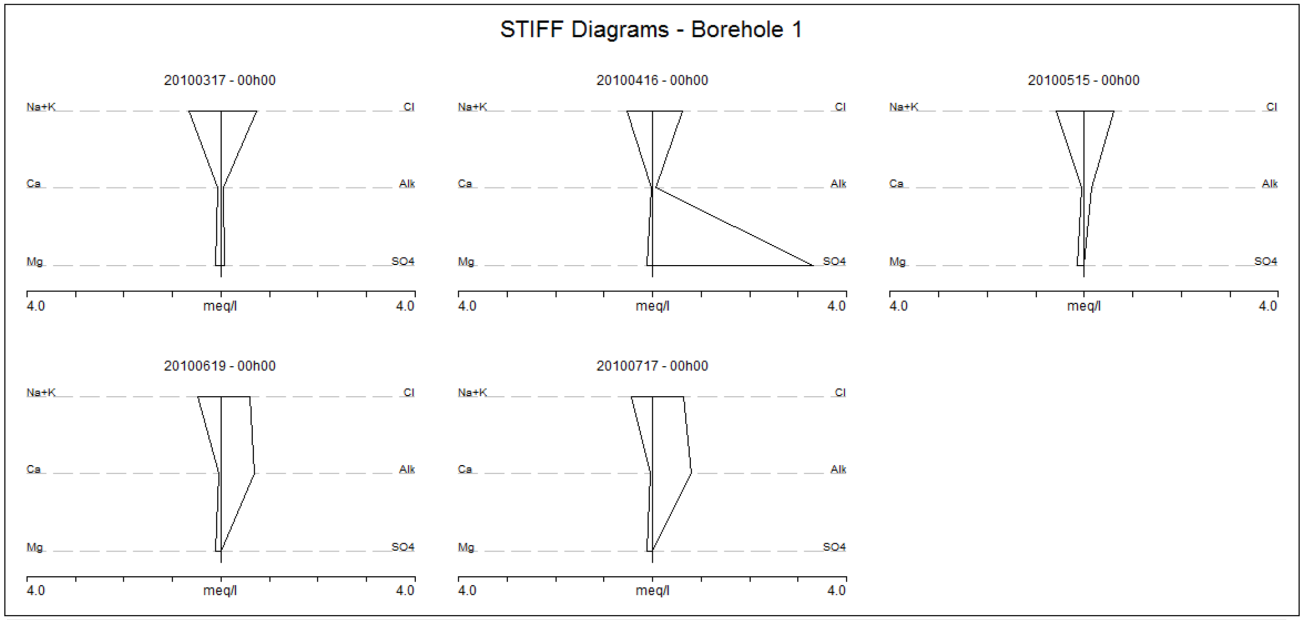
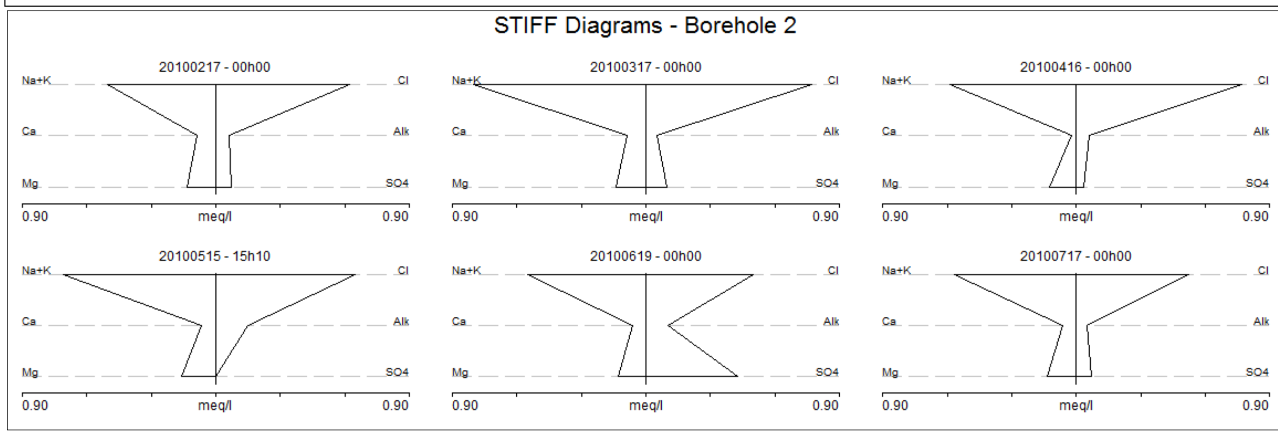


Figure 95. Piper Diagram of all the sites.

APPENDIX F: WATER CHEMISTRY STIFF DIAGRAMS


STIFF Diagrams - Borehole 1
20100317 - 00h00
20100416 - 00h00
20100515 - 00h00
20100619 - 00h00
20100717 - 00h00
Na+K
Ca
Mg
Cl
Alk
SO4
4.0
meq/l
4.0


STIFF Diagrams - Borehole 2
20100217 - 00h00
20100317 - 00h00
20100416 - 00h00
20100515 - 15h10
20100619 - 00h00
20100717 - 00h00
Na+K
Ca
Mg
Cl
Alk
SO4
0.90
meq/l
0.90

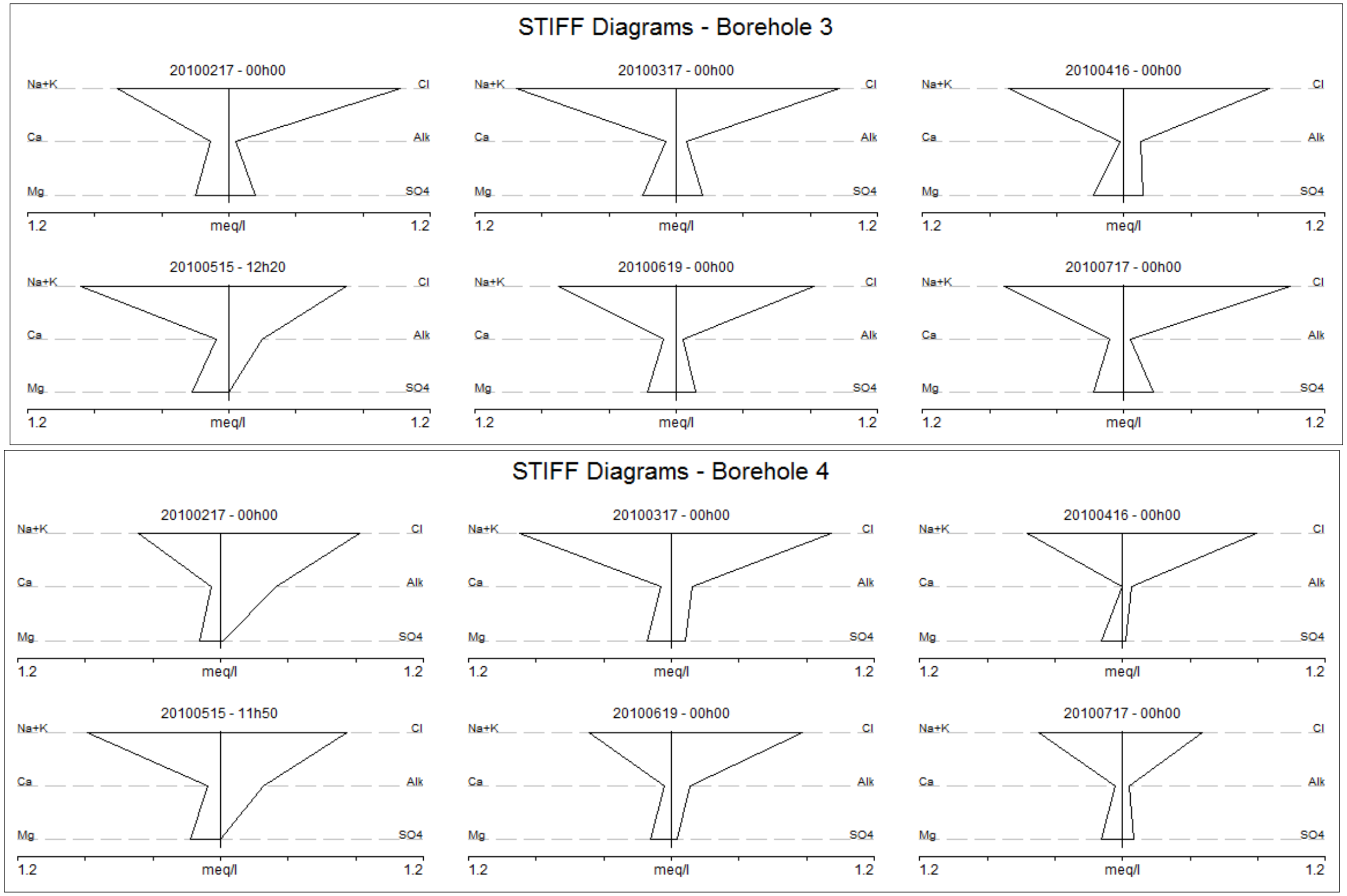


Figure 96. Stiff diagrams of the borehole samples taken during 2010.

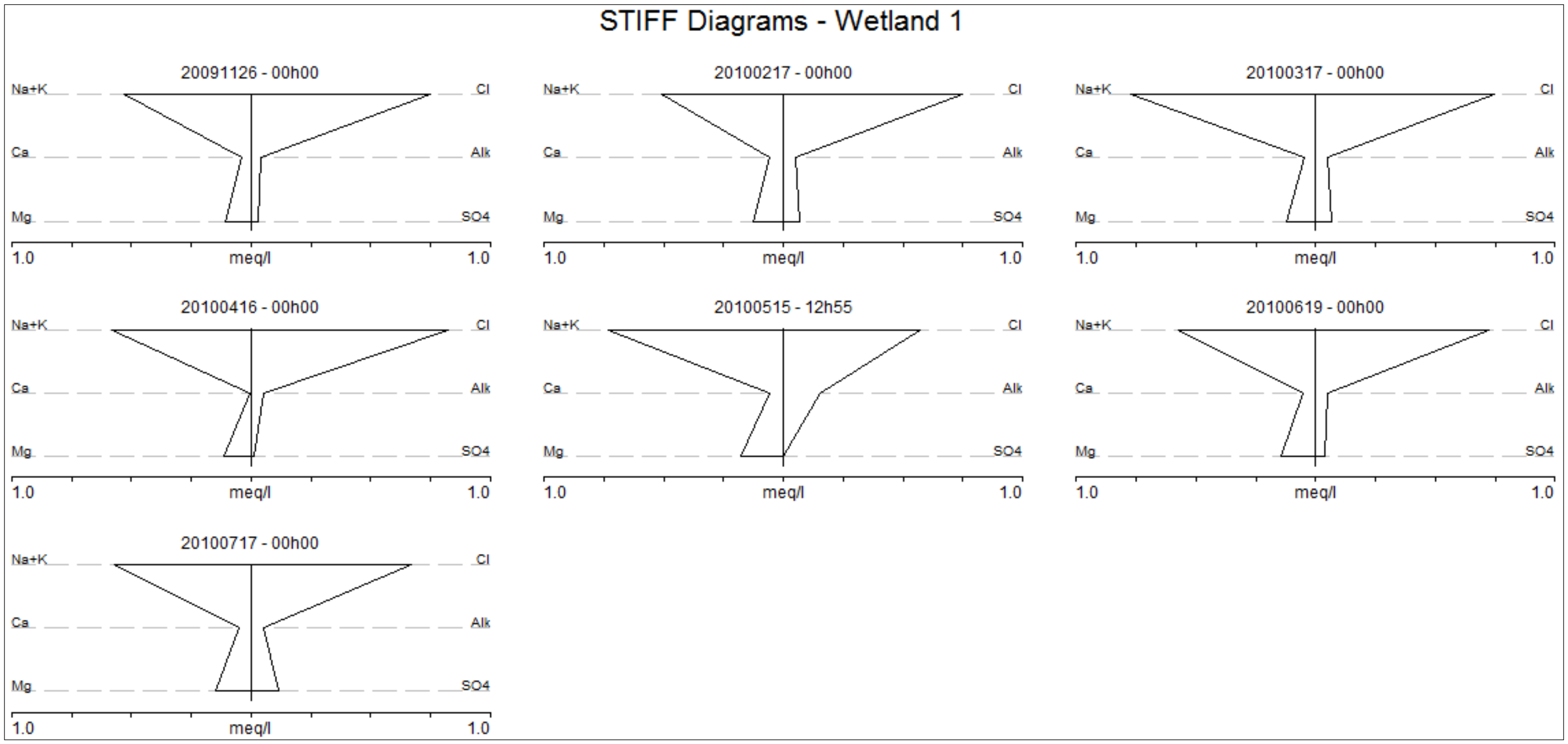


Figure 97. Time-series Stiff plot for site Wetland 1.

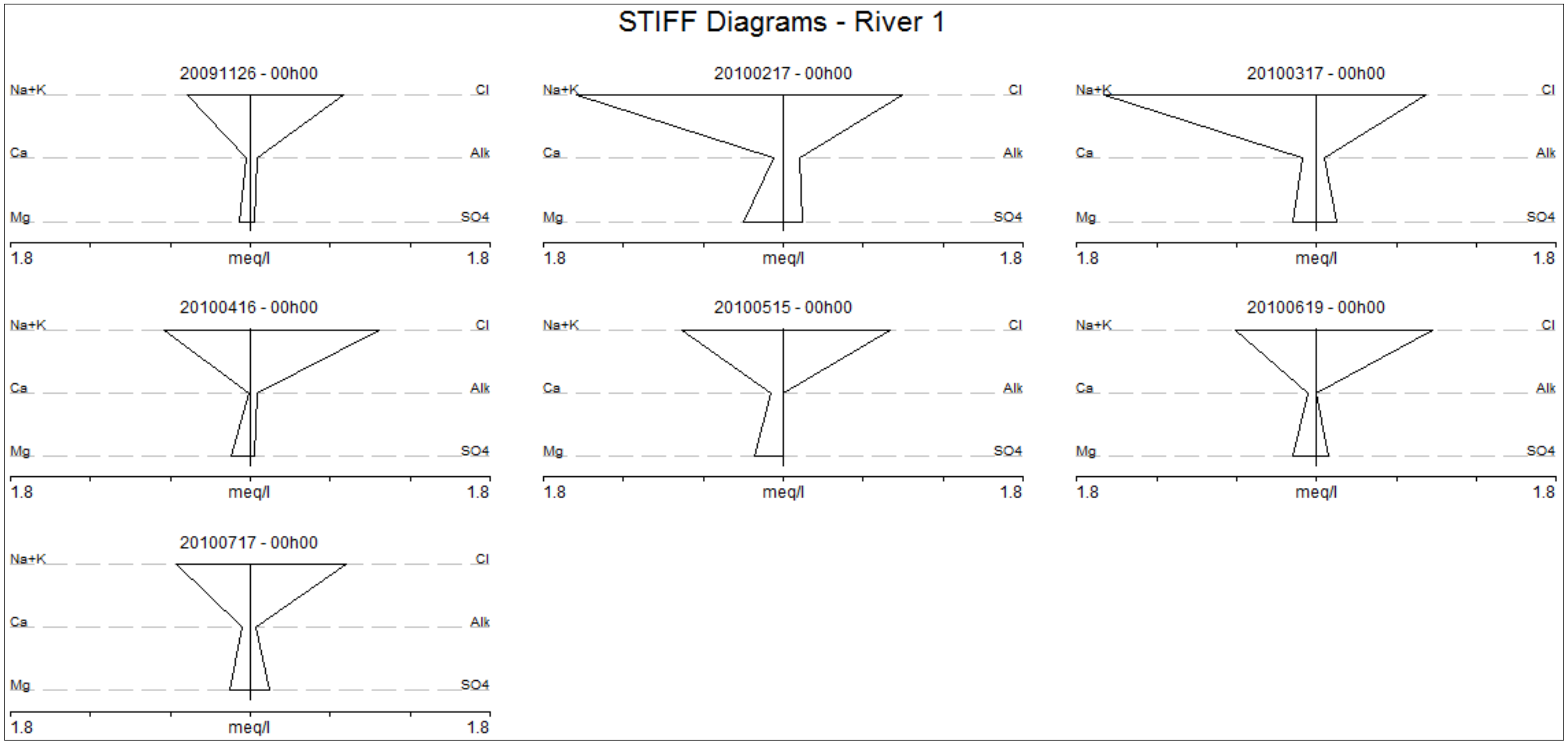


Figure 98. Time-series Stiff plot for site River 1.

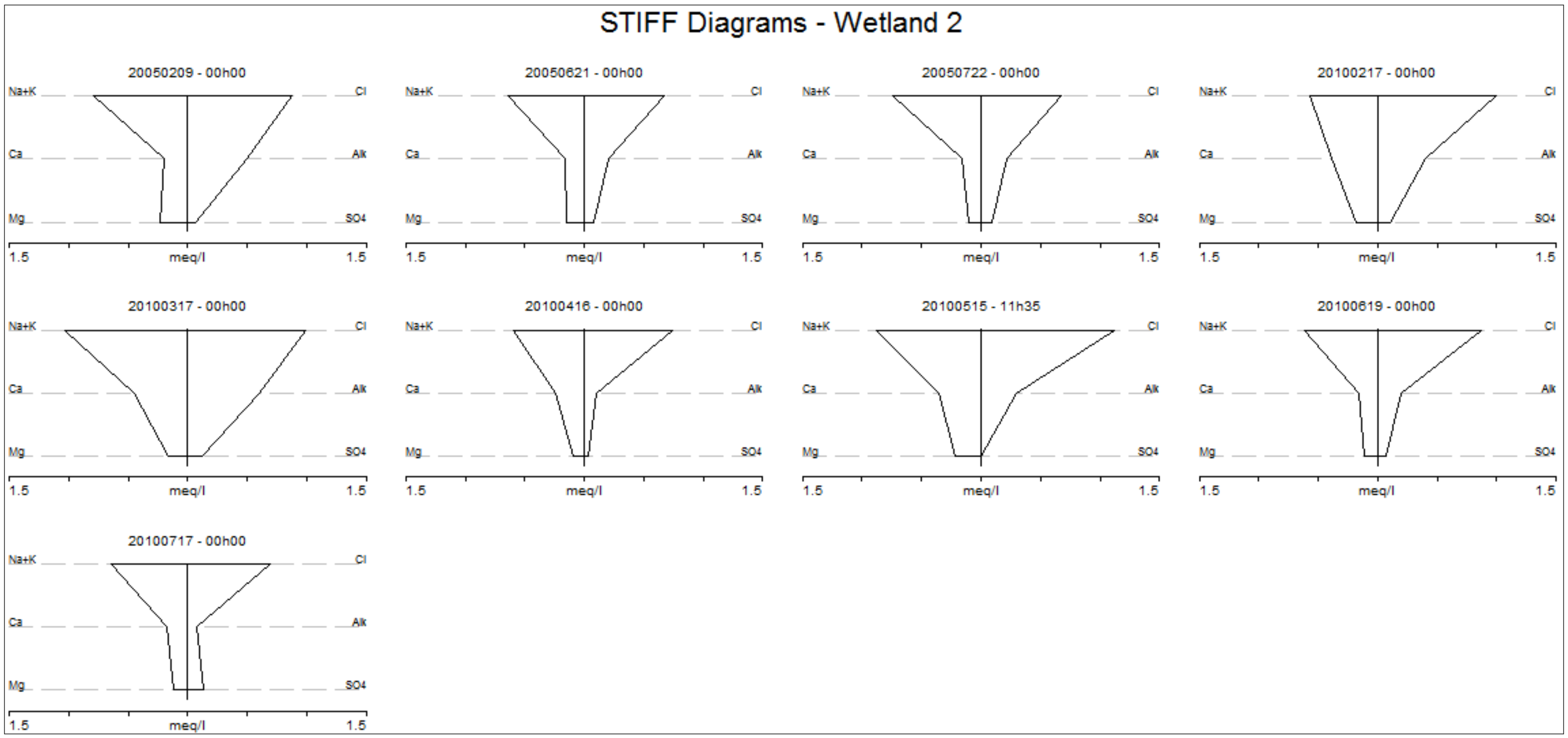


Figure 99. Time-series Stiff plot for site Wetland 2.

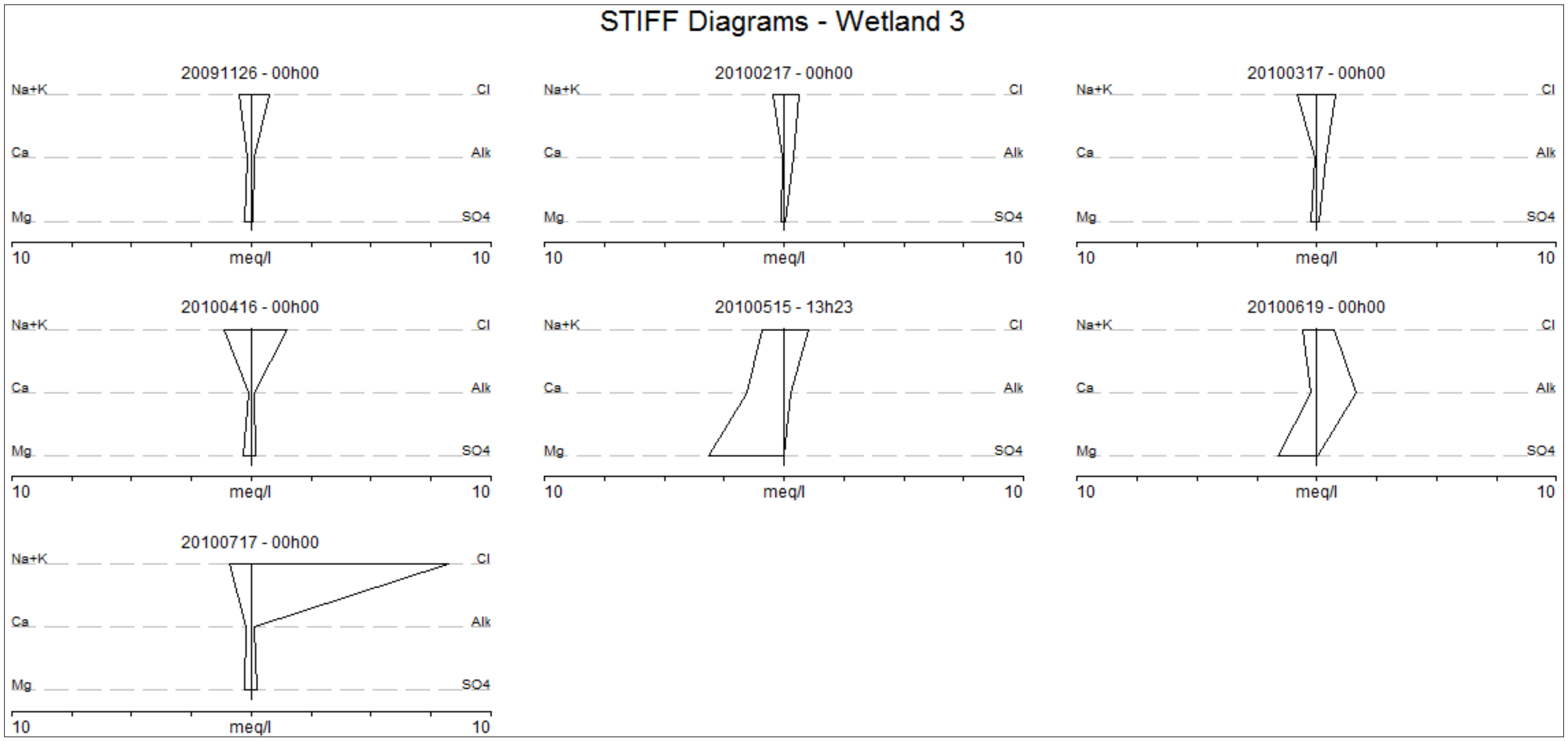


Figure 100. Time-series Stiff plot for site Wetland 3.

APPENDIX G: TIME-SERIES MACRO-CHEMICAL CONCENTRATION GRAPHS

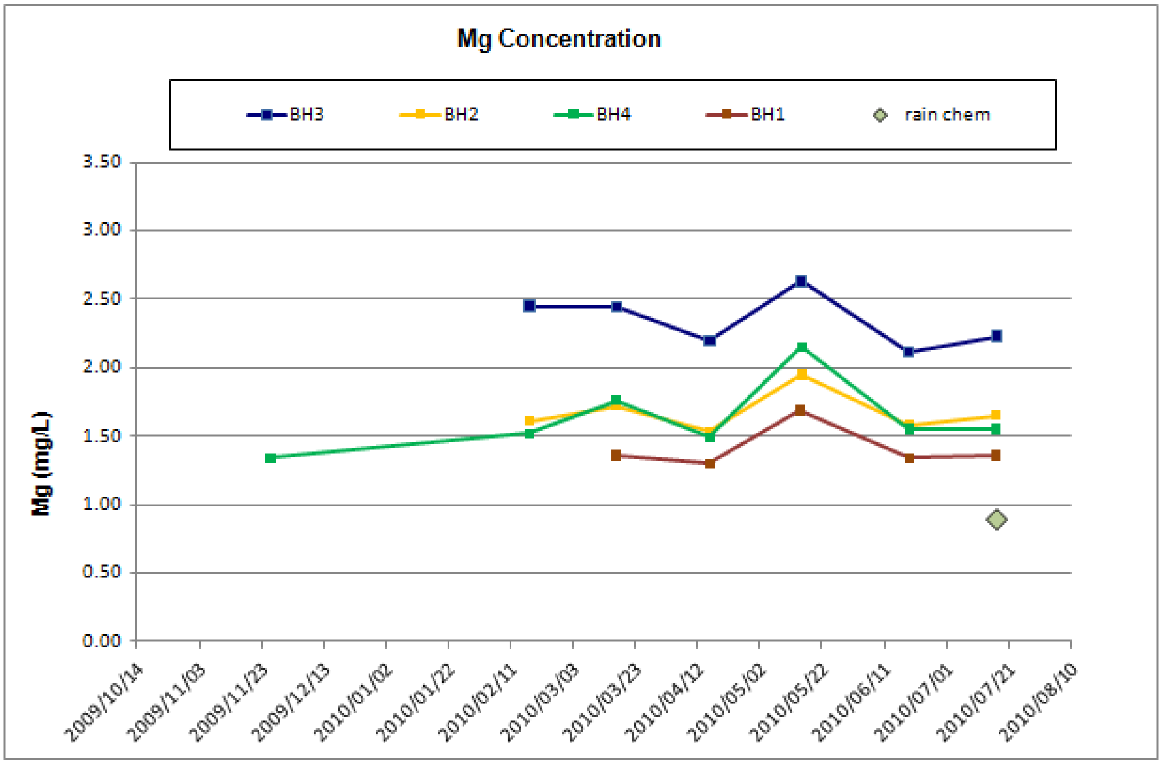


Figure 101. Borehole Mg concentration time-series data plotted with rainfall.

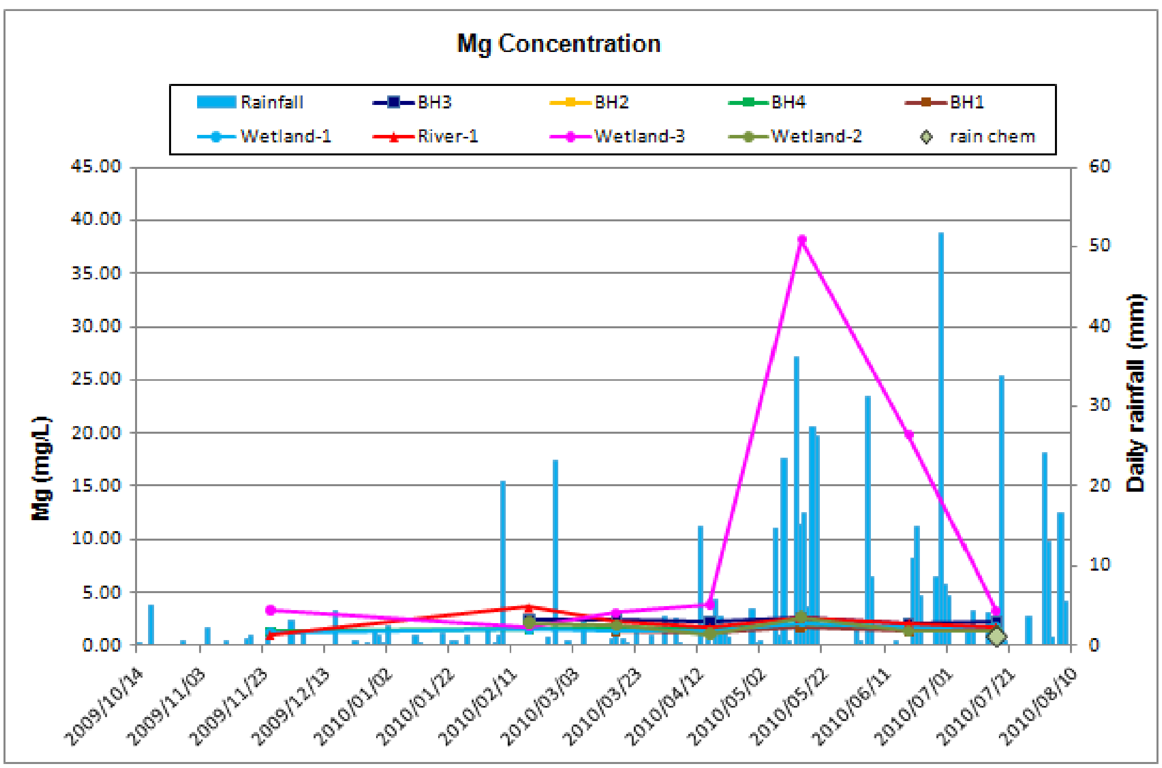


Figure 102. Mg concentration time-series data plotted with rainfall.

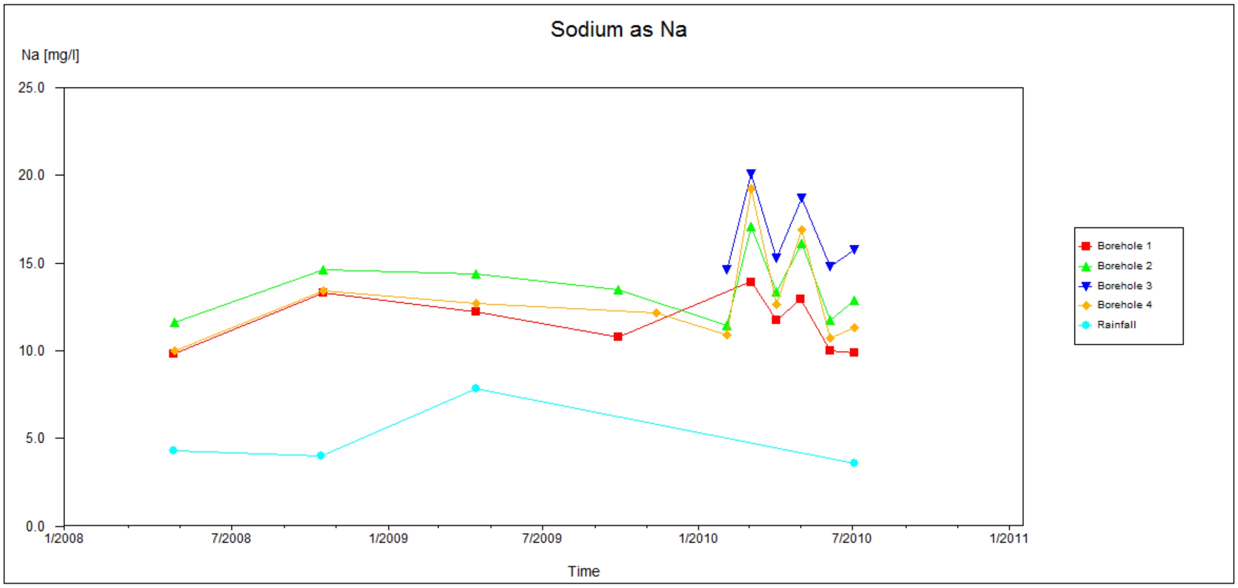


Figure 103. Borehole Na concentration time-series data.

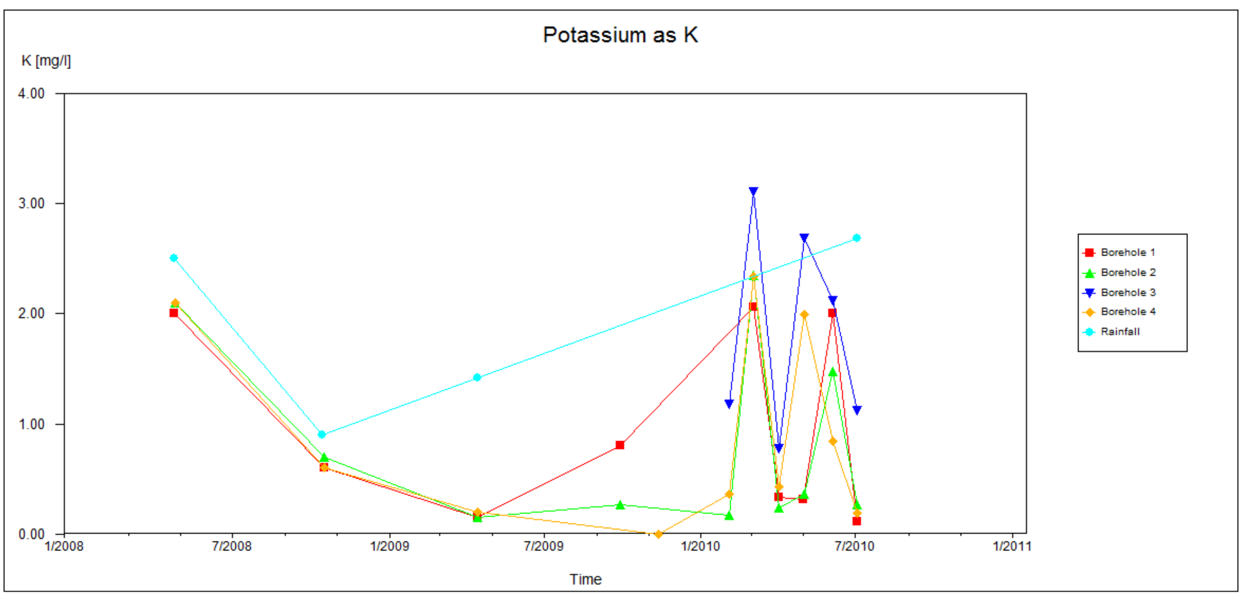


Figure 104. Borehole and rainfall K concentration time series data.

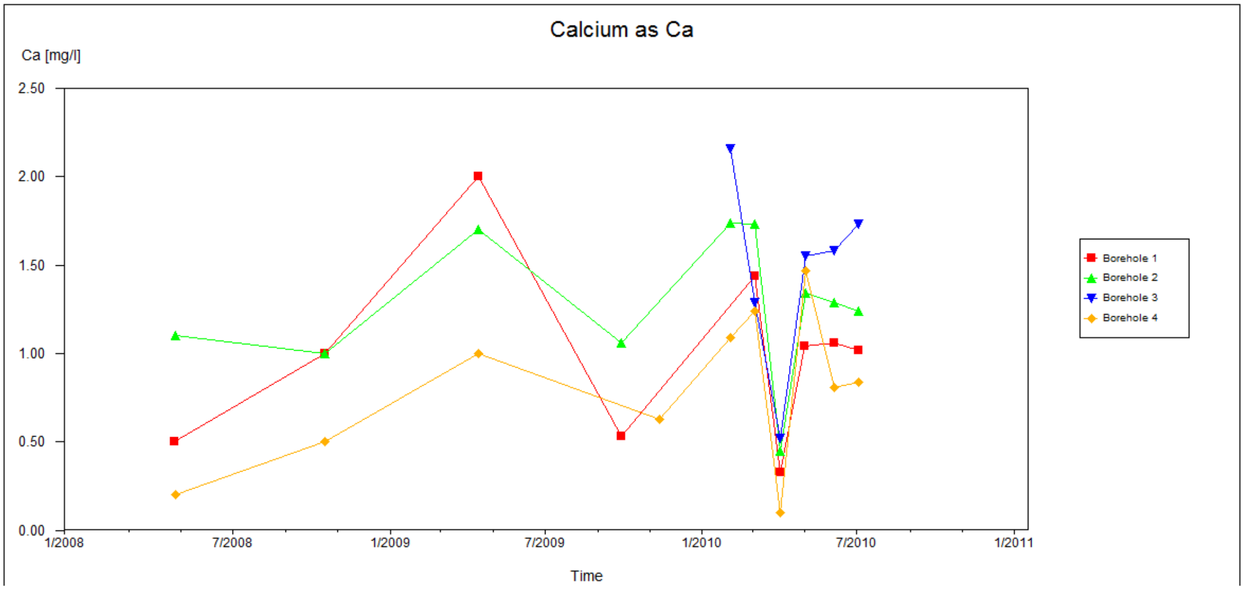


Figure 105. Borehole Ca concentration time-series data.

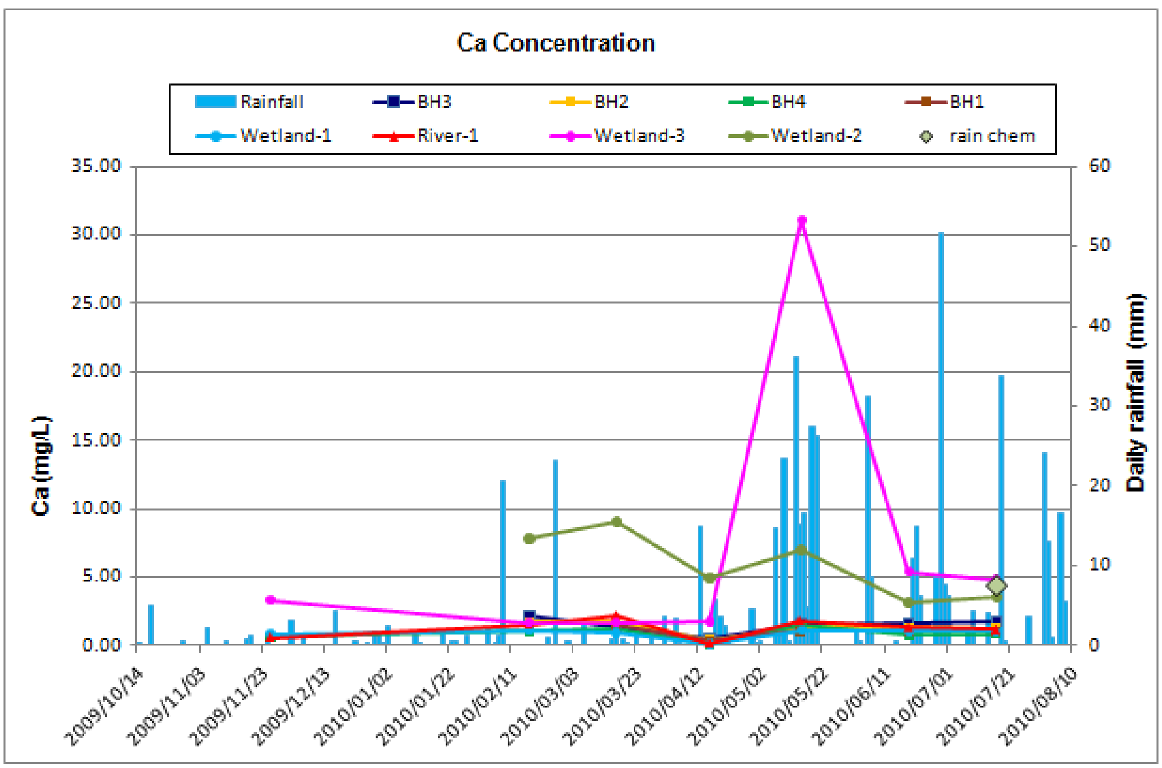


Figure 106. Ca concentration time-series data.

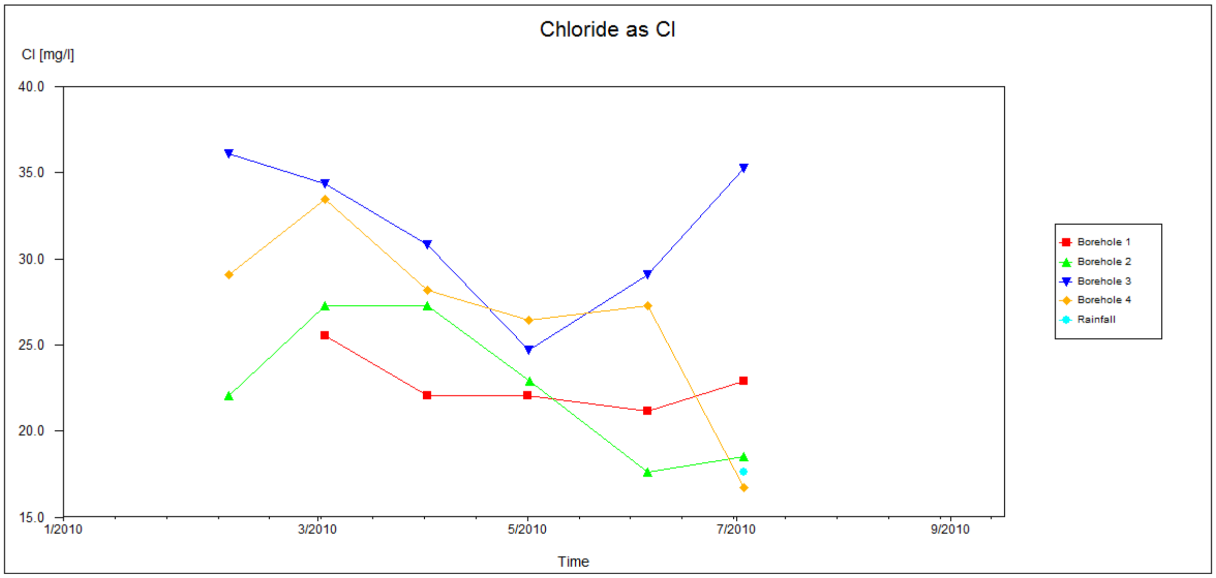


Figure 107. Borehole Cl concentration time-series data.

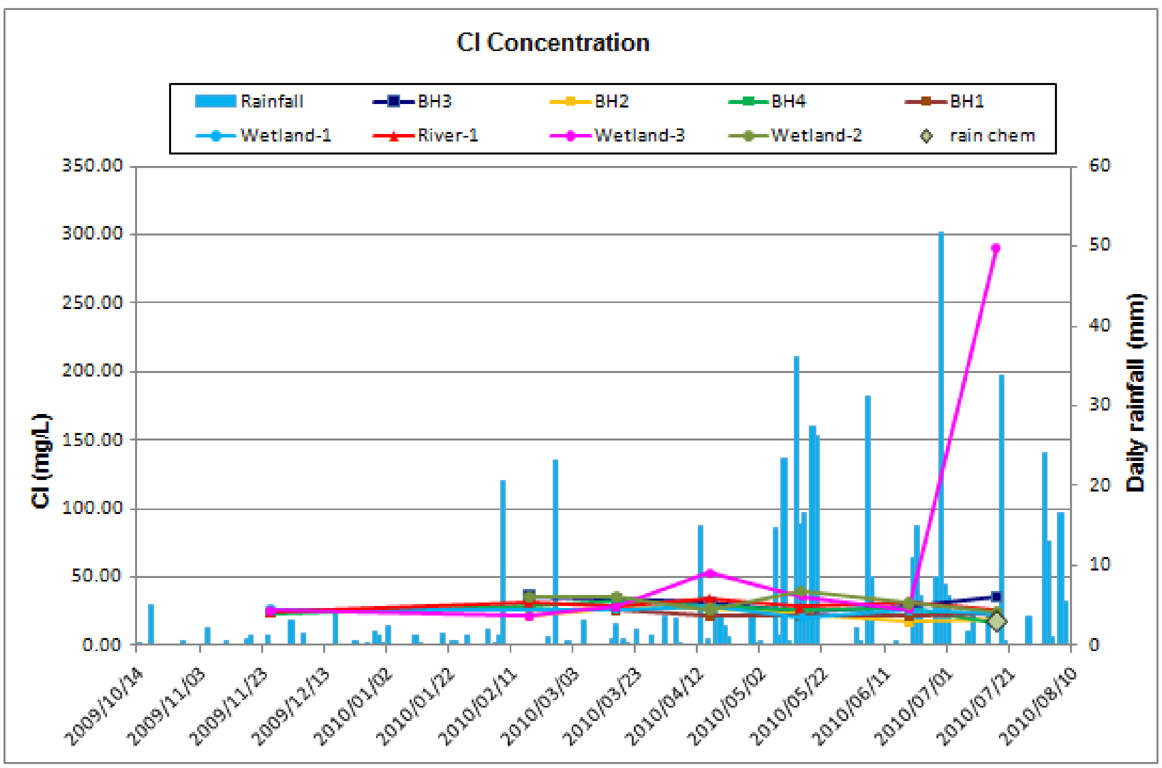


Figure 108. Cl concentration time-series data.

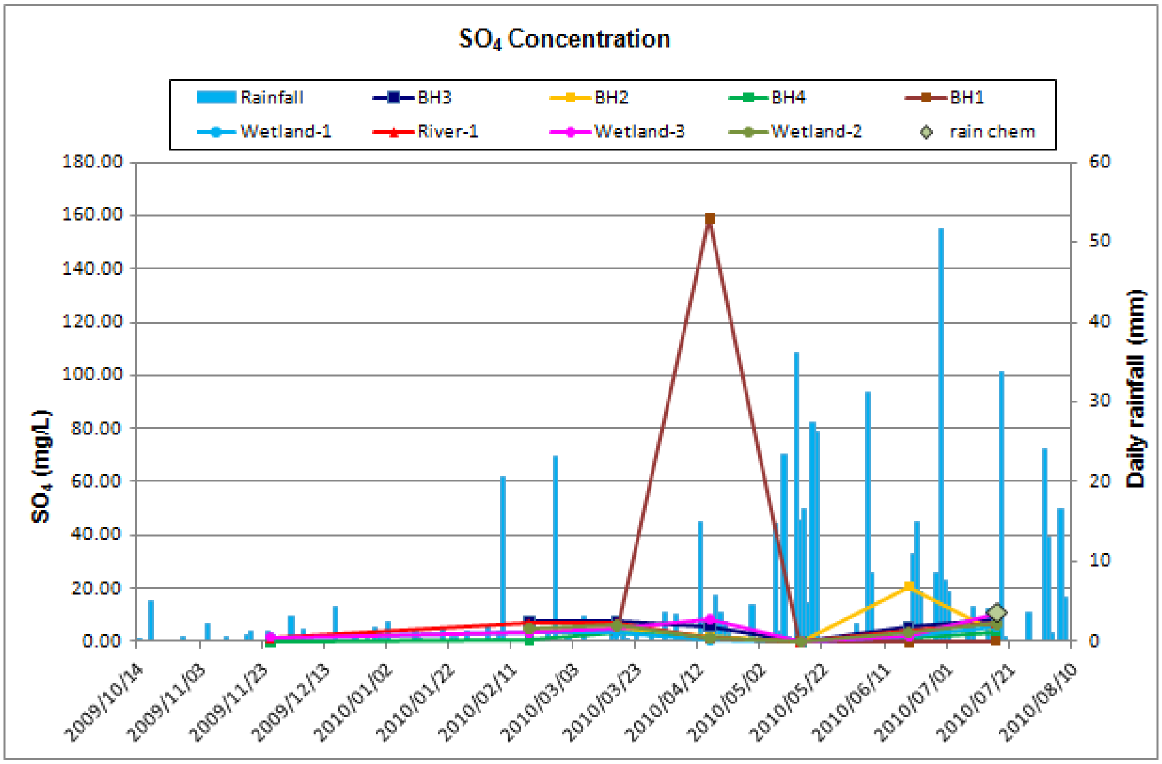


Figure 109. Borehole SO_4 concentration time-series data plotted with rainfall.

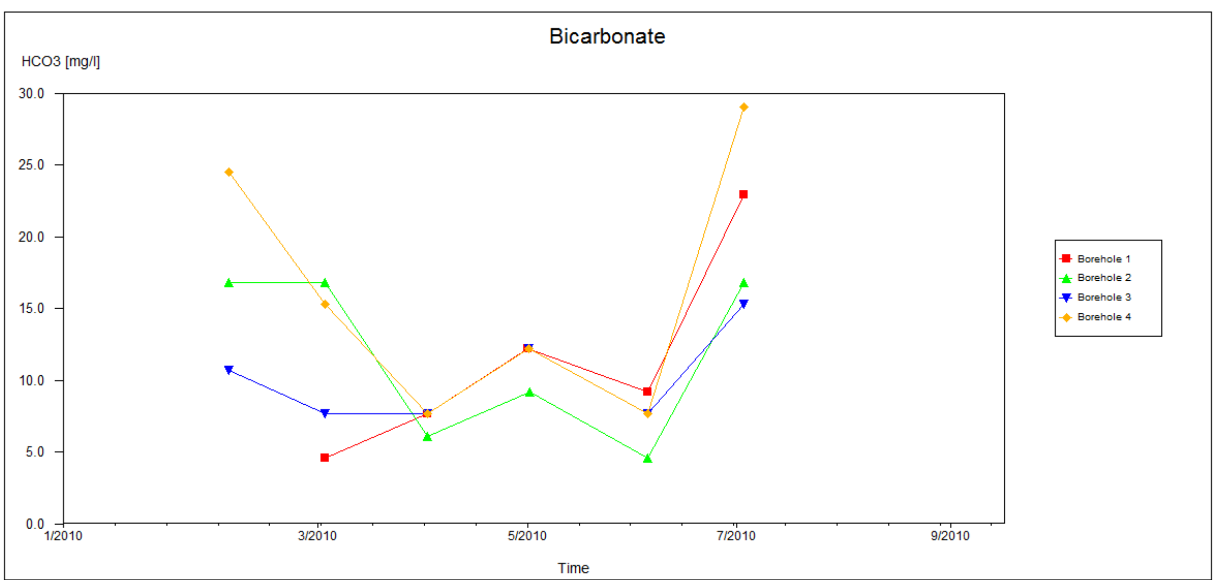


Figure 110. Borehole HCO_3 concentration time-series data.

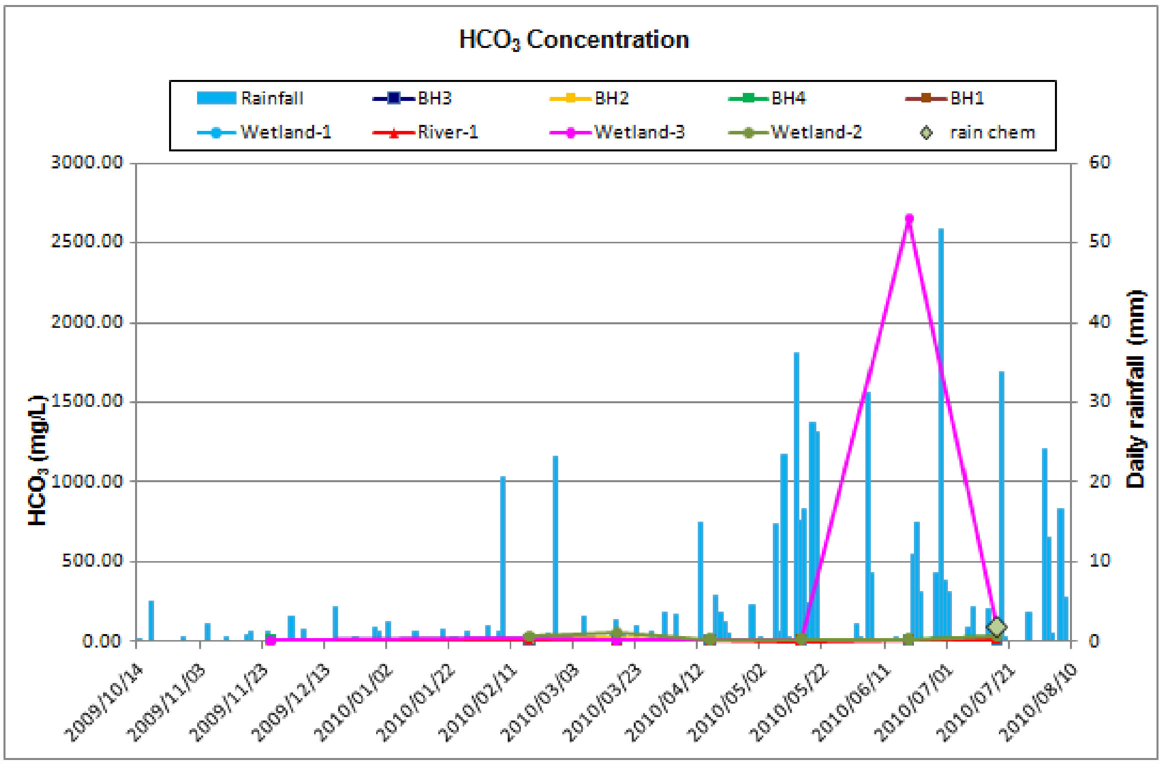


Figure 111. HCO_3 concentration time-series data.

APPENDIX H: TIME-SERIES MICRO-CHEMICAL CONCENTRATION GRAPHS

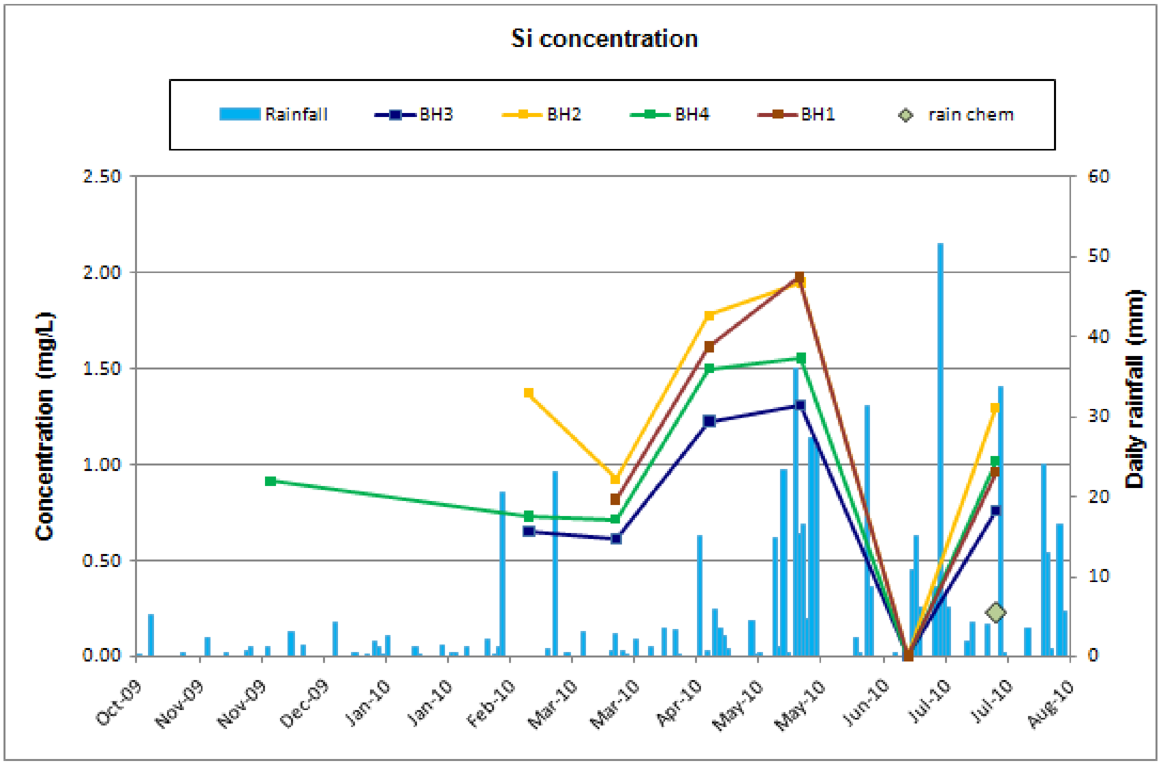


Figure 112. Borehole Si concentration time-series data plotted with rainfall.

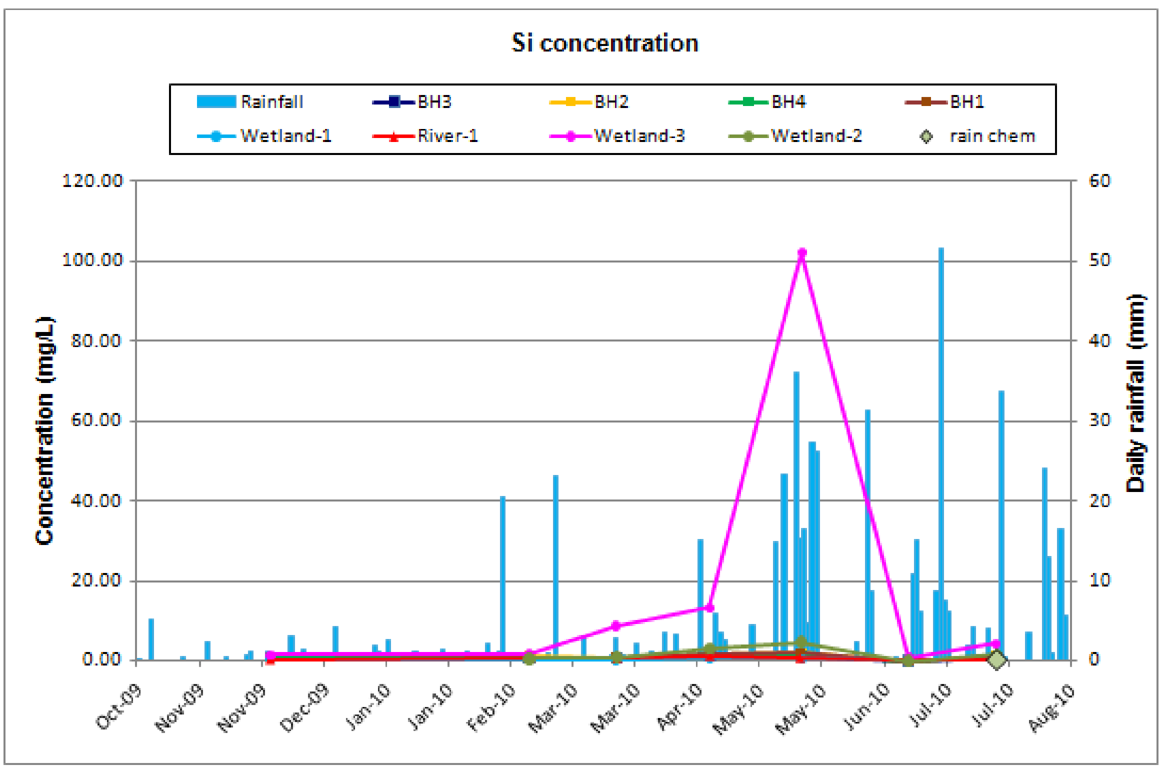


Figure 113. Site Si concentration time-series data plotted with rainfall.

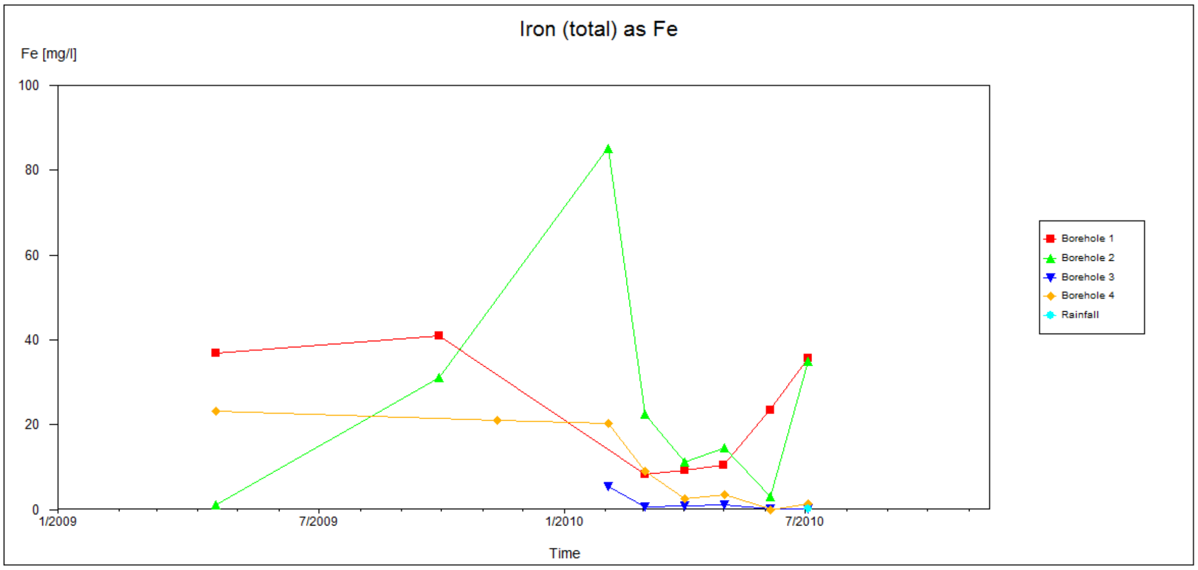


Figure 114. Borehole Fe concentration time-series data.

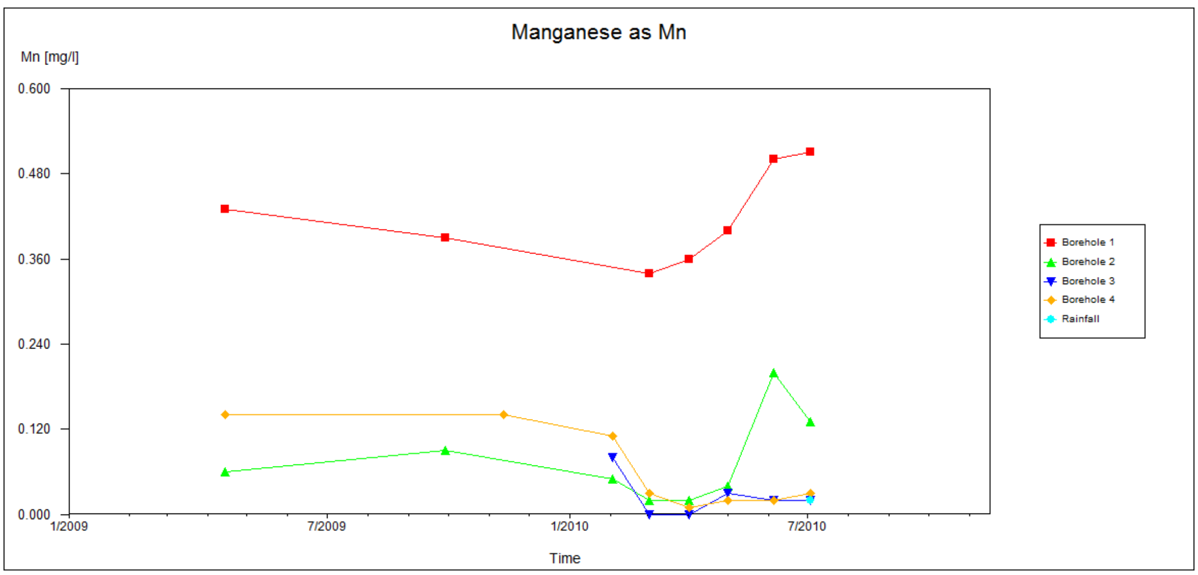


Figure 115. Borehole Mn concentration time-series data.

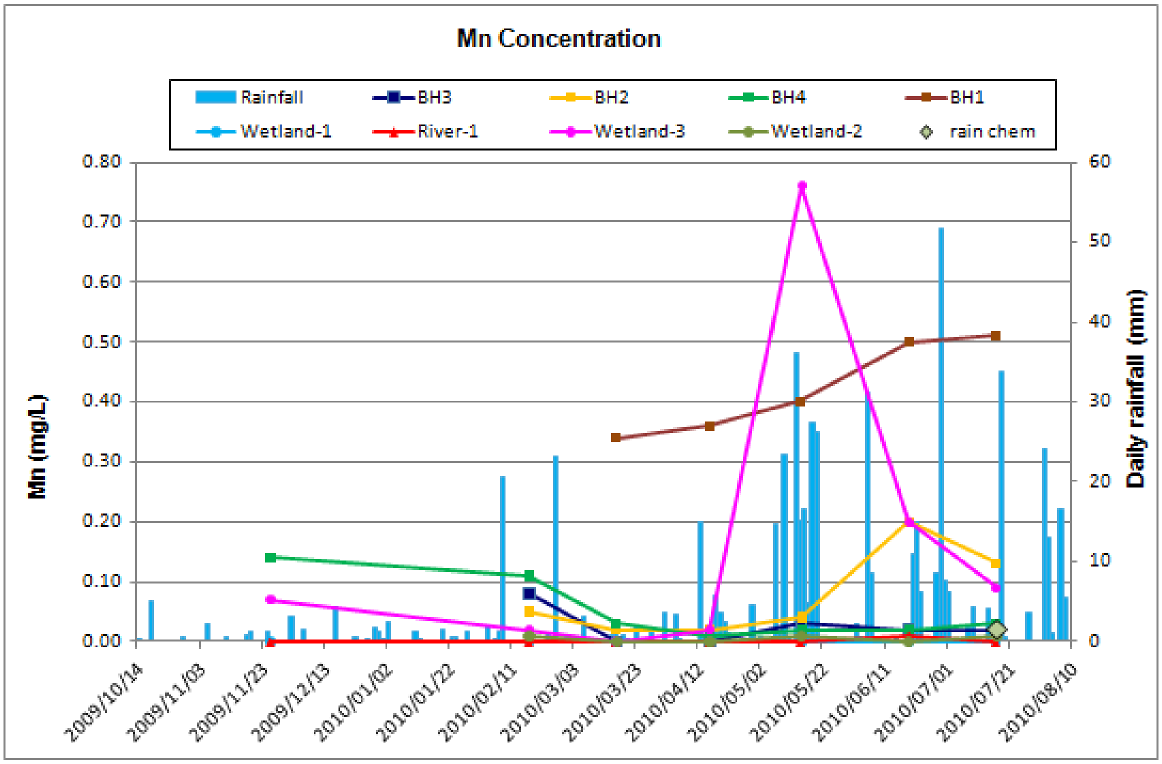


Figure 116. Mn concentration time-series data.

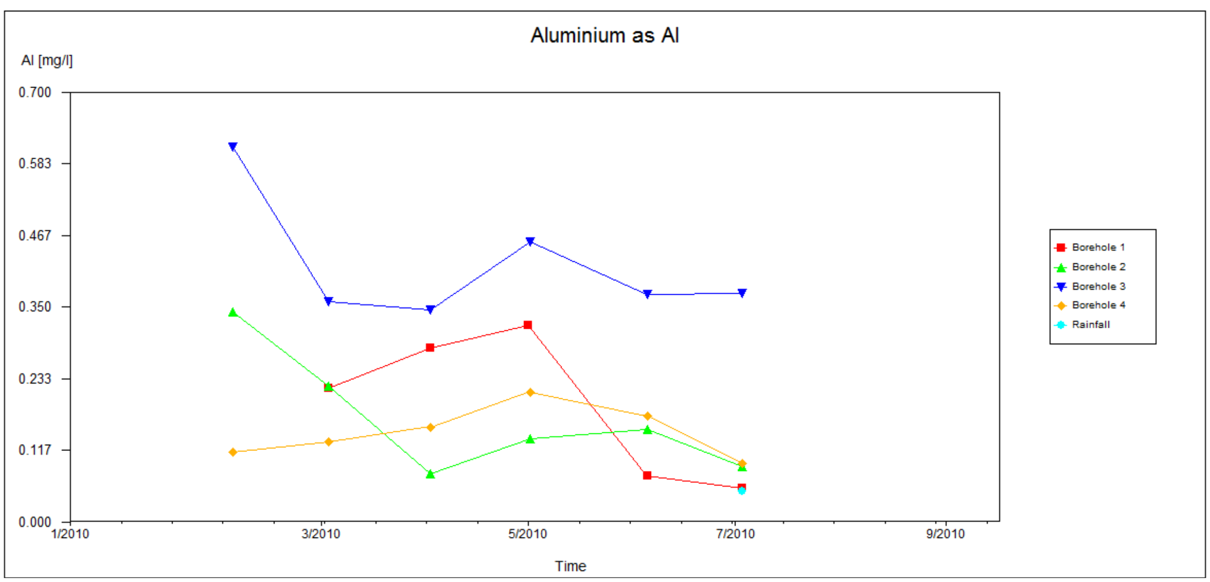


Figure 117. Borehole Al concentration time-series data.

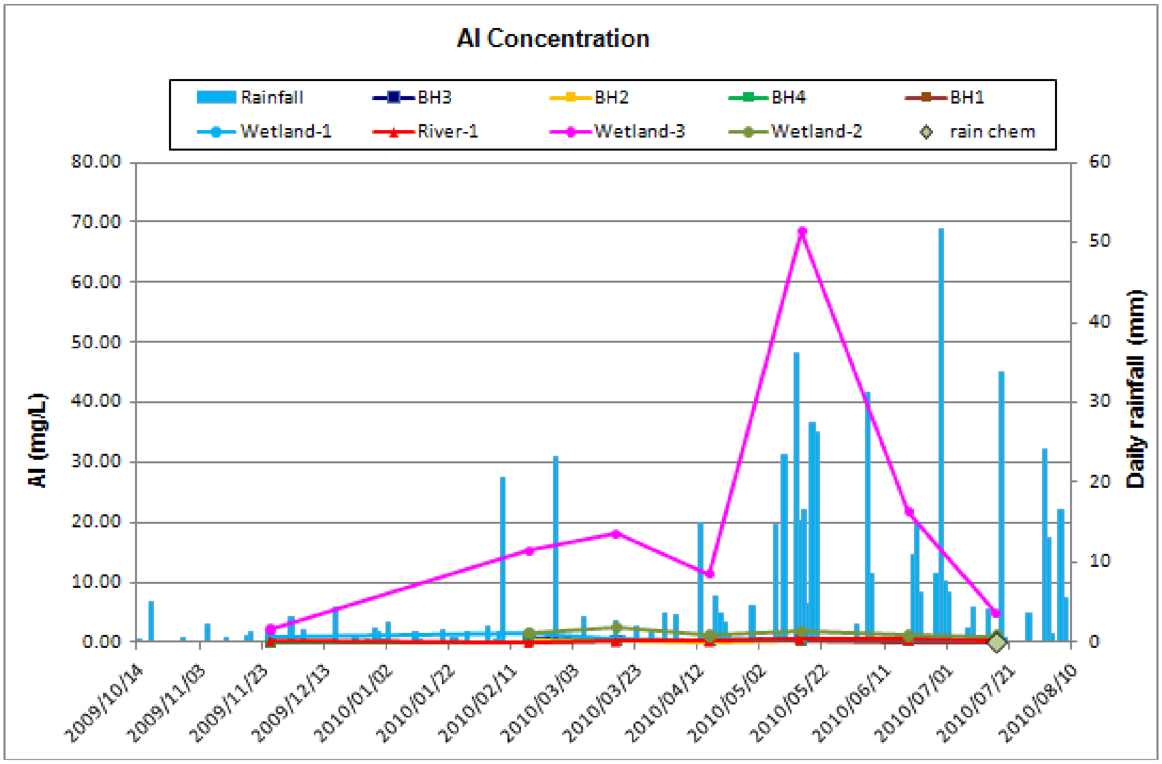


Figure 118. Al concentration time-series data.

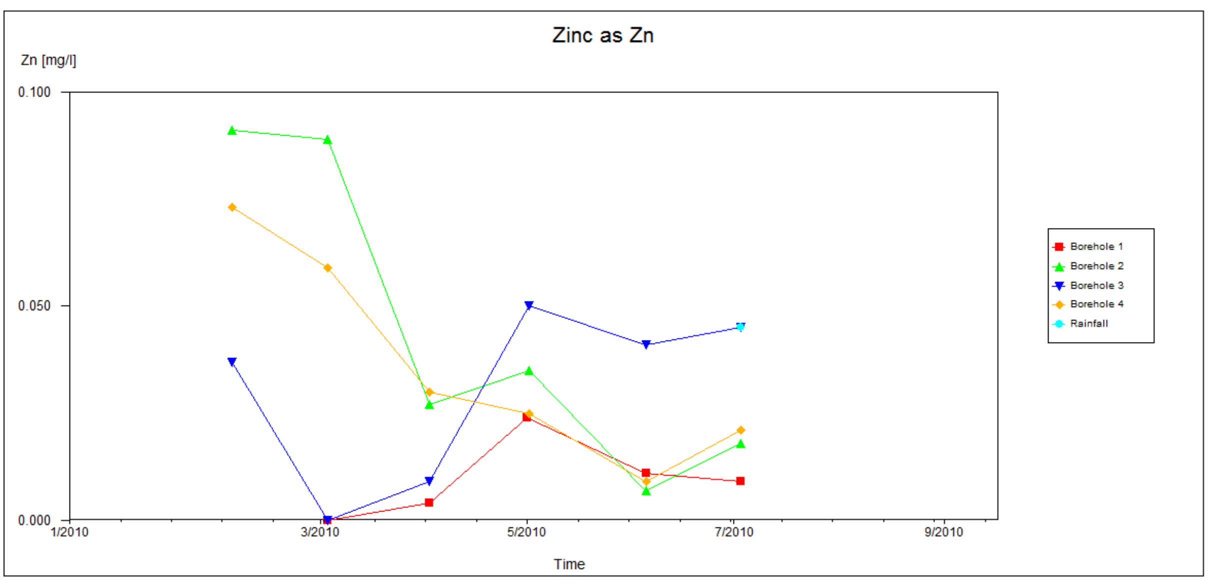


Figure 119. Borehole Zn concentration time-series data.