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Using a Multiple Water Balance Approach to Estimate Recharge for the Optimum Mine, Mpumalanga

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by

Morné van Wyk

Thesis submitted in fulfilment of the requirements in respect of the degree

Master of Science

Majoring in Geohydrology

At the

Institute for Groundwater Studies

In the

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Supervisor: Mr E. Lukas

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Declaration

I, Morné van Wyk, declare that the MSc.Thesis that I herewith submit for the Master's Degree qualification titled: '*Using a Multiple Water Balance Approach to Estimate Recharge for theOptimum Mine, Mpumalanga*' at the University of the Free State is my independent work, and that I have not previously submitted it for a qualification at another institution of higher education.

Morné van Wyk

Bloemfontein, South Africa

February2018

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And lastly, to my beautiful wife Carina, you were an amazing sounding board always encouraging and supporting me throughout this entire process. Without youthis dissertation might never have come to fruition.

Abstract

This dissertation focused on using multiple water balance recharge methods within rehabilitated opencast mines at the Optimum Coal Mine, Mpumalanga,for the aim that a combination of water balance methods will yield more conclusive recharge from rainfall values within spoil material. It is known that different recharge methods yield very different results concerning recharge. New recharge methods were implemented based on the data received from the mine and compared to the recharge method already developed and proven to work.

In the pursuit to solve the complicated issue of calculating recharge from rainfall, four newly formulated methods were produced, called the Rainfall Infiltrated Volume, Stage Curve Volume, Dry and Wet Calculations and Recharge from Stage Curve Volume. These methods were compared to well-known recharge methods which included the Saturated Volume Fluctuation, Cumulative Rainfall Departure and Water Table Fluctuation methods over a five-year period. These methods, combined, narrowed the range between the minimum and maximum recharge values, usually estimated for the study area, and in the process provided a better understanding of the water management systems in this area.

Pit Volume Calculations yielded a 25% void space for spoils, which were used in the recharge calculations. Each method yielded a minimum and maximum recharge value from rainfall, but not all of them produced the results expected from the area. The Zevenfontein opencast rehabilitated pit produced very accurate and believable recharge from rainfall at 18–20% for the new recharge methods and 15–17% for the known recharge methods. The Optimus opencast rehabilitated pit had numerous problems, but in the end also produced believable results at 25–30% for the new recharge methods and 15–20% for the known recharge methods.

Thus, it was concluded that a combination of recharge methods yielded more conclusive recharge values.

Keywords: Optimum, Coal, Recharge, Water Balance Methods, Pit Calculations, Rainfall Infiltrated Volume, Stage Curve Volume, Dry Calculations, Wet Calculations, Saturated Volume Fluctuation, Cumulative Rainfall Departure, Water Table Fluctuation, Void Space, Pumping Cycles, Pumping Rates, Water Levels.

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List of Abbreviations, Acronyms and Symbols

°C	degree Celsius
CRD	Cumulative rainfall departure
IGS	Institute for Groundwater Studies
l/h	litre per hour
km	kilometre
km^2	square kilometre
l/t	litre per ton
m^3/Ton	cubic litre per ton(cubic volume per ton)
ha	hectare (100m×100m)
M	Mega litre
m	metre
mamsl	metres above mean sea level
masl	metres above sea level
mbgl	metres below ground level
mm	millimetre
mm/a	millimetre per annum
RIV	Rainfall Infiltrated Volume
SVF	Saturated Volume Fluctuation
SC	Stage Curve
SCV	Stage Curve Volume
WACCMAN	Water Accounting and Management
WISH	Windows Interpretation Software for the Hydrogeologist
WTF	Water Table Fluctuation method

Chapter 1
Introduction and General Background

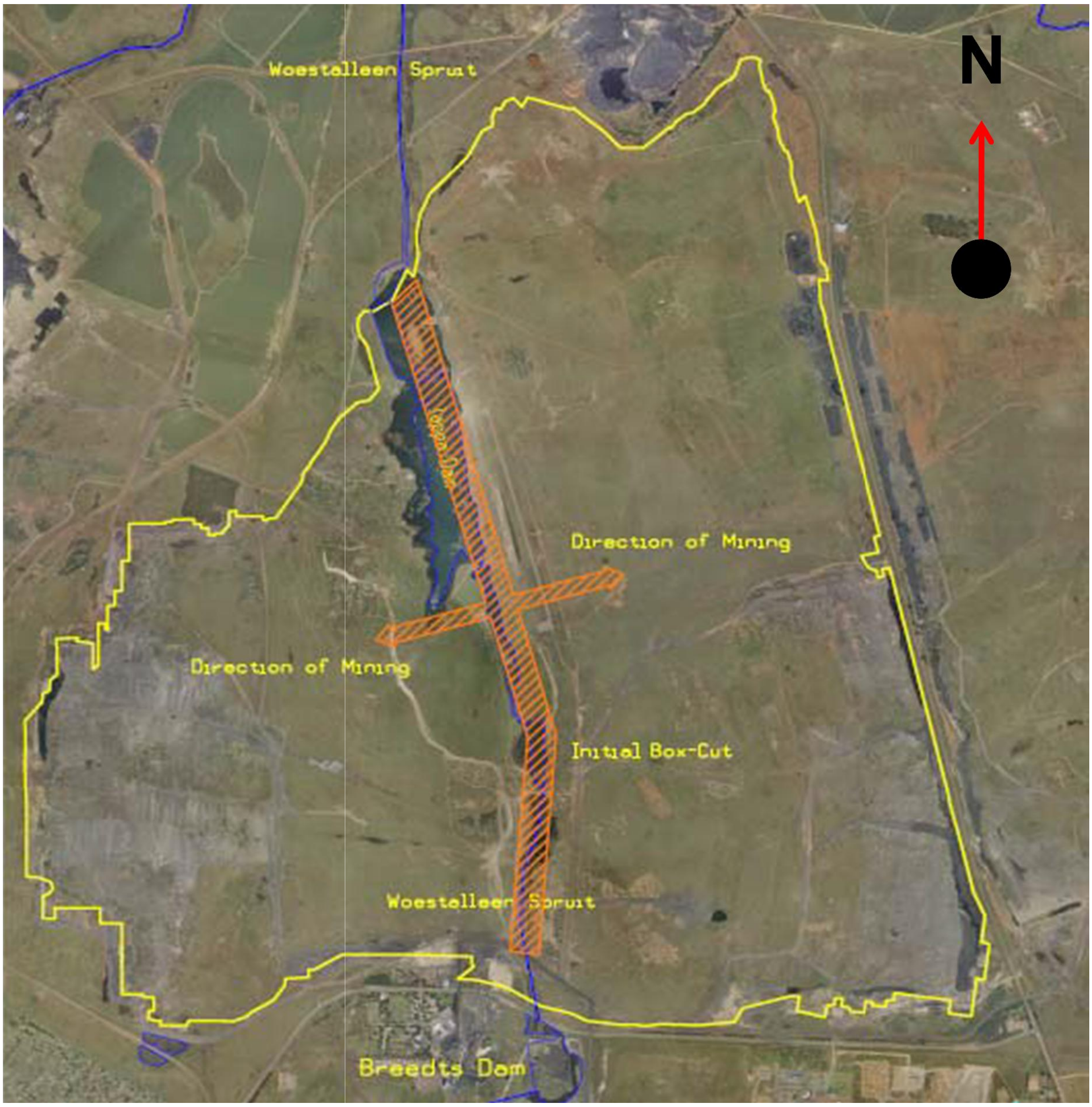
1.1 Introduction

The opencast and underground mining activities have a significant impact on surface and groundwater resources. To ensure that the mine will be able to continue with its mining operation in the catchment, the extent of this impact requires that substantial intervention measures are implemented to ensure the environmental integrity and economic use of the catchment's water resources (Cogho, 2012).

1.1.1 History of mining activities

During the 1970s, the Optimum Coal Mine commenced mining activities as an underground board and pillar mine in the Pullenshoop area. One year later, the mine initiated an opencast strip mine, with mining activities commencing in the Optimus mining area (Cogho & Van Niekerk, 2009). When the initial mining started at the Optimum Coal Mine, little was done in terms of appropriate water management, which meant that the separation of clean and affected water, as well as the re-use of affected water, was not a high priority and led to frequent spills and discharges into the aquatic environment(Cogho & Van Niekerk, 2009).

During this time, little legislation existed that guided the opencast mining activities towards environmentally responsible mining. Strip mining activities started within the Woestalleen East Spruit and proceeded in an easterly and westerly direction. At this stage, no stream diversion was legally required if there was to be mined through a stream, as well as the stripping of topsoil prior to mining, which implied that the rehabilitation of the opencast mining areas received little attention. Figure 1.1represents a closer view of the earlier mining activities at the Optimum Coal Mine(Cogho & Van Niekerk, 2009).

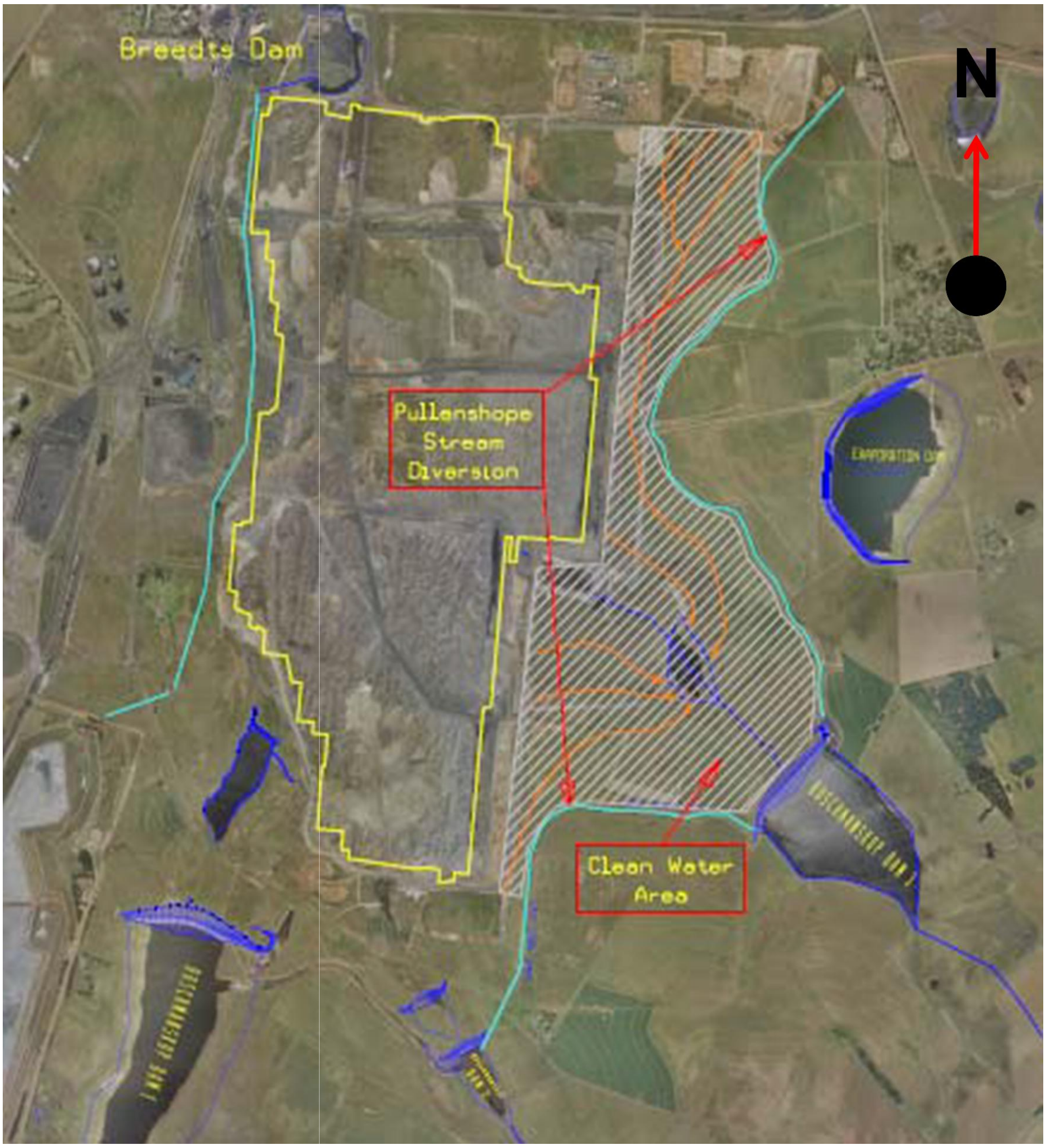


Note: The orange area shows the initial box cut which is mined to the west and east. The initial box cut filled with water and is now known as the Lapa Dam.

Figure 1.1 Aerial photograph of the Optimus area (yellow line)

Due to the lack of legislation concerning the previously mentioned shortcomings, mining within the Woestalleen East Spruit also resulted in voids that were left open which formed the current Lapa Dam(Cogho & Van Niekerk, 2009). During the late 1980s to early 1990s, significant changes to the relevant legislation were made. This suddenly required mining companies to take responsibility of all their environmental issues caused by mining activities and to address all identified impacts in an environmental management programme(Cogho & Van Niekerk, 2009).

After the legislation was implemented, the mine needed to develop the Pullenshoop mining area in 1993. For the mine to further extract coal at the Pullenshoop area they had to implement numerous water management systems, which included the Pullenshoop stream diversion. Figure 1.2 depicts the extent of this diversion, which is still functional and is upgraded on an annual basis as mining progresses in the area.



Note:Marked in white is the area that was upgraded in terms of the environmental legislation. The orange lines indicate mine water, while the light blue lines are clean water. This method keeps the dirty and clean water separate to minimise pollution spreading.

Figure 1.2: Aerial photograph of the Pullenshoop area (yellow line)

1.1.2 Pullenshoop

Optimum Colliery is committed to supplying coal for both the export market and Eskom. To meet this commitment, all available coal reserves, including those in the Pullenshoop field, have to be utilised. The Pullenshoop field (Figure 1.2) is situated upstream of the currently mined Optimus field in the valley of the Woestalleen East Spruit, a tributary of the Klein Olifants River. The catchment area of the Woestalleen East Spruit at the downstream extent of mining measures 119 km^2, and to reduce the risk of flooding to the proposed mining operations, the run-off from the upstream catchment, which measures 72 km^2, should be diverted away from the mining area(Viljoen, n.d).

Pullenshoop, which is one of the reserve areas of Optimum Colliery, was earmarked to be mined in the 1990s to fulfil the contractual obligations of the mine for long-term coal supplies. The Pullenshoop field is situated immediately south of the main current mining area, or the Optimus section. This new field straddles the Woestalleen East Spruit; therefore; some means of dealing with the flow in the stream is obviously required to ensure that the risk of flooding to the mine is kept to a minimum. A diversion scheme would have the added benefit of reducing the flow of water into the Optimus section immediately downstream from the Pullenshoop section, where clean water presently becomes affected by flowing through backfilled spoils before re-entering the stream as decant. It became evident that a total integrated water management plan is required to deal with the current and future mining, bearing in mind closure of the mine as well (Viljoen, n.d).

1.1.3 Optimus

The mine lease area for Optimum Coal Mine is 383 km^2. The average annual run-off prior to mining from the mine lease area, was 14.7 Mm^3/a, which constitutes about 25% of the natural catchment run-off. The mine clearly plays a dominant role in modifying the natural hydrology and run-off to Middelburg Dam. To date, the mine has disturbed roughly 6 870 ha of land and plans to disturb an additional 3 136 ha over the remaining life of the mine. Furthermore, the mine has mined 1 532 ha via underground board and pillar mining and plans to mine an additional 2 687 ha via board and pillar mining(Cogho, 2012).

The Optimum Coal Mine is a multi-product mine with a contract to supply Hendrina Power Station with coal until 2018. The mine also exports a significant quantity of coal. Optimum lies in the upper reaches of the Middelburg Dam Catchment. The dam has a maximum water-holding capacity of 48 Mm^3. It receives run-off from the Klein Olifants catchment with a total drainage area of 1 550 km^2. Run-off from this catchment is in the order of 5.5% of the average annual rainfall, coming to a total of some 60 Mm^3/a. The mean annual rainfall for Optimum Coal Mine based on an 80-year rainfall record is 687 mm, while the annual potential evaporation for the area is estimated at roughly 1 700 mm(Cogho, 2012).

Optimum Colliery, a division of Trans-Natal Coal Corporation, is one of the largest opencast coal mines in South Africa. The mine is situated between Middelburg and Hendrina in the Eastern Transvaal Highveld (Figure 1.3)(Viljoen, n.d).

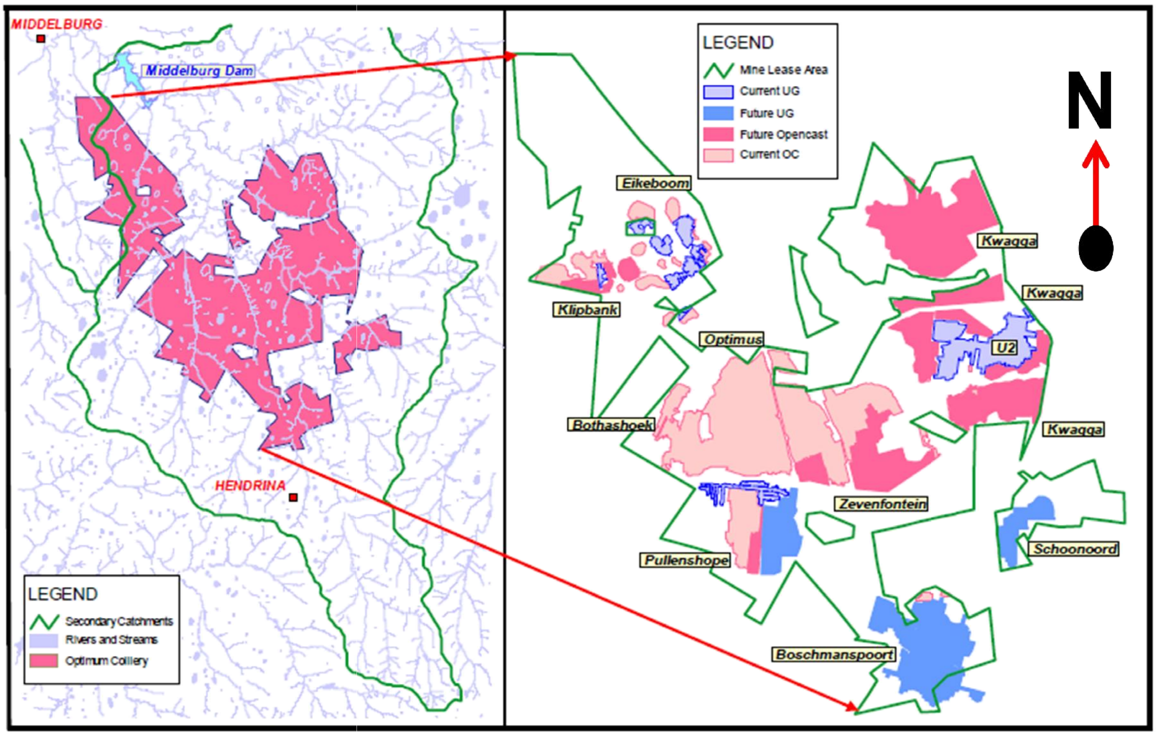


Figure 1.3: Catchment and mining area for the Optimum Mining area

The coal is exposed with draglines and transported by coal haulers to the crushers after which washing and screening are undertaken to prepare certain portions of the coal for the Hendrina Power Station and the export markets(Viljoen, n.d).

During 1990, steps were taken in an attempt to limit the volumes of run-off and stream flow that became affected by the mining operation.A committee of various disciplines and specialists was set up to initiate the necessary investigations and studies(Viljoen, n.d). The committee accepted the broad philosophy that:

- clean water must remain clean;
- affected water must be contained and disposed of in an environmentally acceptable manner.

From the mine's long-term water balance, it is evident that the continued implementation of numerous water management actions is required to mitigate the water resources impact in a sustainable manner. In addition, the installation of a water reclamation plant at Optimum Coal Mine (15 Ml/day) is a key step for the mine to achieve a zero-impact target(Cogho, 2012).

In developing a sustainable long-term mine water management strategy, numerous scenarios had to be analysed. The various scenarios are a combination of water and land management activities(Cogho, 2012). The main components of the mine's integrated water management strategy include:

- Management of water recharge by continual and appropriate rehabilitation of disturbed land.
- Beneficial re-use of impacted mine water for coal plant process water and mining operations.
- Reclamation and desalination of remaining excess impacted mine water to potable standard.

Optimum Coal Mine comprises numerous defunct, active, and future mining sections. The mine is primarily a large opencast coal mine; however, underground mining activities will be increasing steadily over the next five years. Opencast and underground mining activities have a significant impact on surface and groundwater resources. To ensure that the mine will be able to continue with its mining operations in the catchment, the extent of this impact requires that substantial intervention and mitigation measures need to be implemented to ensure the environmental integrity and economic use of the catchment's water resources(Cogho, 2012).

1.2 Problem statement

For this study, the problem statement focused on the issue which currently existed and was addressed by providing the context on which the research was based and generated the questions which needed to be answered.

The focus of the thesis will be on calculating recharge from rainfall on rehabilitated open cast mines.Secondly, existing recharge methodswere selected and compared to recharge methods which were formulated using only the data provided. Through this method of comparison, it was assumed that a more accurate representation of the recharge in the area can be achieved.

It is strongly believed that the data collected over the years by the mine itself, would be sufficient to calculate recharge, and in doing so, gain a clearer understanding of the water balance in that area. Calculating recharge is notoriously complex due to the numerous parameters needed, some of which are difficult to obtain or needs to be estimated. Using inverse modelling techniques, it was hoped that these parameters could be calculated.

Various recharge methods were used and compared to each other to formulate an equation which best suited the area. Recharge needs to be accurately calculated as rainfall that infiltrated the spoils in the open cast pit affects the amount of water that decants and the future cost implications of that water that still needs to be pumped well after the mine has be closed.If recharge from rainfall could be calculated and yielded conclusive results, the subsequent water volumes and water level changes could be anticipated, which would result in a more accurate water management scheme for the mine.

1.3 Methodology

1.3.1 Study design

For this study a quantitative methodological approach was chosen with the experimental design as main category to establish a cause-effect relationship among a group of variables in the study itself. As a further, more accurate outline of the methodology used to conduct the research of this study, the correlational design was chosen. This means that the study focused on the exploration and observation of relationships among variables, as well as being suited for model-testing and descriptive correlation designs.

1.3.2 Study setting

The problem encountered with calculating recharge effectively, was having large data sets of geological and geohydrological information. Mines in South Africa usually have these data basis readily available and appointments or certain agreements with such mines need to be made to acquire specific data. This was the method used to acquire data from the Optimum Mine in the Mpumalanga province of South Africa.

The Optimum coal mine was selected due to the numerous opencast pits in the area and that most of them were either already fully rehabilitated or in the process of rehabilitation. Years of data collection by the mine itself meant that no time had to be spent on fieldwork and only analysis of the data they collected was necessary.

1.3.3 Measurement instruments

No instruments or apparatuses were needed to collect the data, seeing that the Optimum Minehadalready provided the data.

1.3.4 Data collection

The data was collected and captured by the Optimum mining operation during the start of mining and further after rehabilitation of the opencast mining operations took place. Concerning the data requested, only information from 2011 to 2015 was considered up to date and suitable for recharge calculations.

This was due to previous data being erratic and only partially completed and not up to standard for the purpose of calculating recharge. Thus, the data requested and received was as follows:

- **Location data** included the longitude and latitude coordinates of the opencast mining areas, mining information on the topographies, coal seams and rehabilitated elevations. Also included was data on borehole and dam coordinates.
- **Mining data** included the size and depth of all the opencast operations and the stages of rehabilitation expressed as area rehabilitated during a specific time.

- **Hydrological data** included water level elevations, dam elevations, decanting positions and volumes, pumping positions and volumes, monthly rainfall in millimetres and estimated recharge factors for the different stages of rehabilitation.

Various archival and older data was also collected besides those provided by the Optimum Mine. These data sets and documents were collected from the Institute for Groundwater Studies (IGS) data base at the University of the Free State. The information gathered was as follows:

- **Topographical data** included satellite imaging, airborne topographical maps and contour data.
- **Geohydrological data** included water levels and their contours, rainfall in millimetre and basin characteristics.
- **Other data** included water modelling programs such as WISH, Microsoft Excel based on recharge programs, documentation on recharge methods and their applicability.

All the data mentioned above was selected specifically for the use in pit calculations and calculating recharge from rainfall. Before the data analysis was done it was determined that the data provided by the Optimum Mine (2011–2015) and the data collected from IGS would be enough to establish all the parameters needed to calculate void space percentage from pit calculations and recharge from rainfall.

1.4 Research questions

The main issue concerning this study was calculating recharge from rainfall. Finding a suitable location with ample data was the following challenge. After suitable locations were acquired the following was choosing either an underground or opencast mine to do the recharge study on. It was decided to do the study on opencast mines at the Optimum Colliery. The following questions were posed:

- How to choose the correct existing recharge equations for the area and what type of data will be needed to calculate them?
- Will this study be focusing on an active opencast pit or a rehabilitated pit?

Choosing a water balance approach to recharge and its accompanied recharge methods, which will be applied on a rehabilitated pit, the following questions arose:

- Is there enough data on the opencast pit to conduct a meaningful pit calculation study?
- What is the size of the rehabilitated pit, and the composition and volumeof the spoils?
- Can a percentage void space be calculated from the spoils that can be used in the recharge calculations?
- Can the problems encountered when doing pit calculations be solved and estimated or does it require a new approach?
- How will the new calculatedvalues be used in the recharge calculations?

After determining the void space values from the pit calculations, the following criteria that needed attention was the pumping rates and whether or not they had an effect on the water levels; therefore, the following questions were asked:

- What data was available on water levels and pumping rates?
- How will the water levels be compared to each other?
- Is it necessary to compare the water levels with pumping rates and rainfall and will it yield any conclusive values concerning recharge estimates?
- Will calculating the pumping rates and determining the pumping system of the whole mine be useful in determining parameters previously unknown and will it aid in calculating recharge from rainfall?

After all the information was gathered the following main questionswere posed:

- Can recharge be calculated from rainfall using existing and newly formulate recharge methods? Together with:Is it possible for the new and existing recharge methods to calculated recharge from rainfall in spoils of a rehabilitated opencast pit?
- How can the pit calculation values, water level and pumping rate information be used in formulating new recharge methods by using all the data and parameters available?

- Will calculating new recharge methods yield any conclusive data which can be compared to the existing recharge equations?
- Can a complete water balance scenario be calculated and applied to the study area using the recharge values calculated?

1.5 Aim and objectives

1.5.1 Aims

This study aimed at calculating recharge using a water balance approach in an opencast mining environment. In conjunction with a water balance method approach, stage curve volumes together with water levels would be used to calculate the percentage of rainfall that infiltrates the spoils in an opencast pit. The opencast pit volumes would also have to be calculated using pit calculations, and in doing so, establish a void space value that could be used in the recharge calculations.

As a secondary aim, the new calculated recharge values would be compared against tested recharge methods of the same water balance approach. If this comparison would yield conclusive results and confirmed the new calculated recharge values, a more accurate estimation of recharge for the area could be used for future calculations of decanting and in pit water volumes.

1.5.2 Objectives

- To gain a clearer understanding of the area through the literature review by assessing the geology, climate, mining area and different recharge calculations.
- To understand the recharge methods so that the best suited method can be chosen and applied to the mining environment.
- To gather the data required to successfully calculate recharge using a water balance approach.
- To understand the mining process by compiling pumping cycles for the mining areas.
- To interpret the water levels in conjunction with the pumping cycles to understand the effect they have on the aquifers.
- To use the chosen recharge methods in conjunction with the stage curve volume calculations to calculate recharge for the area.

- To use a three-method recharge approach for the calculation of a recharge value for the area.
- To compare the new recharge calculation methods with that of the already tested methods to confirm or deny the accuracy and applicability of the new recharge values on this specific area.

1.6 Limitations of the study

Concerning the limitations of the study, problems were anticipated and encountered during the initial literature review together with the data analysis and implementation of the recharge methods.

For any recharge method to yield conclusive results large data sets are needed for the various parameters included in the recharge methods themselves. Some of these parameters are not always readily available and estimates need to be calculated. Using estimates for various recharge methods can be a great way of closing the information gap in the data gathered, but are inclined to yield some form of errors and inaccuracies. To minimise the errors so that accurate values could be calculated, this study used inverse modelling, a method whereby the model uses available data and constantly recalculates the various parameters until an acceptable value is reached.

For the pit calculations, various forms of errors occurred which could not be anticipated since these methods relied on completing one stage of the calculations before moving on to the next stage. This meant that problems and errors in one stage had to be fixed before moving onto the next stage and fixing those errors. Problems that occurred were mainly the differences in volume and calculating why or how spoil volumes increased and decreased. Although numerous errors were encountered, sound geological and geohydrological principals were used to formulate a void space for the opencast rehabilitated pit and outweighed the small errors when using the void space in recharge calculations.

When receiving and analysing large data sets on geological, geohydrological and recharge parameters, some form of errors in collecting that data was expected. For this study, errors were expected for the field data collection, which included the rainfall, water levels and pumping rates. Since these errors were anticipated, they could be easily detected and corrected when needed.

1.7 Demarcation of the study

Chapter 1: Introduction and General Background

This chapterfocuses on the layout of this research topic concerning the objectives, research questions, problem statements and limitations that can be encountered. It also gives a general background of the mining area, history of mining and the numerous opencast operations in the area.

Chapter 2: Literature Review

Focuses on previous work done concerning recharge methods used and why they were applicable to the area of study. Secondly, a review was carried out on the work done in the study area concerning the problems encountered with recharge methods and the mining environment.

Chapter 3: Geomorphic Environment

In this chapter the general background of the study area is described which includes the topics of topography, climate, rainfall, vegetation, geology, soils and the geohydrological background concerning the weathered and fractured aquifer systems.

Chapter 4: Methodology

The basics of the methods that are used are discussed in this chapter. This includes the mining area, pumping cycles, borehole water levels and recharge methods.

Chapter 5: Pit Calculations

This chapter explains the methods used to calculate void space in rehabilitated spoils using volume differences, together with several influencing parameters.

Chapter 6: Pumping cycles

In this chapter the pumping cycles and rates are determined and analysed to create a flow chart of the pumping cycles in and around the opencast pits of the Optimum mining area, so that a clearer understanding of the flow of water is comprehended.

Chapter 7: Borehole Water Levels and Rainfall

This chapter discusses and analysis the data gathered for the borehole water levels and rainfall data, which in turn is compared to the pumping rates in Chapter 6. Here the mining areas area divided into different aquifer systems by means of water levels and fluctuation trends.

Chapter 8:New Recharge Calculations

In Chapter 8 all the data discussed and analysed in the previous chapters are combined to formulate different recharge methods with the data available, using sound geohydrological principles. Three methods were formulated and are discussed in detail, using the Optimus and Zevenfontein opencast mining areas as the study area.

Chapter 9: Known Recharge Methods

This chapter utilises the data used in Chapter 8 to calculate recharge, using established methods known to work in the field. These methods include the Saturated Volume Fluctuation, Cumulative Rainfall Departure Method and Water Table Fluctuation Method.

Chapter 10: Conclusion

Here the data and the conclusions made in Chapters 5 to 9 are compared to each other so that conclusions can be made on the applicability of the recharge methods used, as well as the recharge values calculated.

Chapter 2
Literature Review

2.1 Introduction

Water over the years has become a scarce resource in South Africa. The availability and the reassurance of water, in general, have becomea major concern in South Africa as was seen in the drought of 2015. As surface water in rivers and dams are steadily being depleted, there is a renewed focus on the management of groundwater resources and the effect of recharge on the replenishment of these aquifers. In South Africa the mining sector, especially coal mining, has a substantial effect on the quality and quantity of the available groundwater resources. This is due to the effect of acid mine drainage and constant dewatering of underground and opencast mining operations, which leaves the area damaged, and takes years of intensive rehabilitation to restore the environment to acceptable levels. It is therefore of key importance to understand the processes involved when recharge from precipitation takes place, and how to accurately predict groundwater resources that are available for future generations, to facilitate the correct management thereof.

2.2 Groundwater recharge

The downward flow of water (groundwater recharge) into the water table, forms an addition to thegroundwater reservoir (Sun, 2005) and the amount of water that may be extracted from an aquifer without causing depletion is primarily dependent upon the groundwater recharge. Rainfall is the principal source for replenishment of moisture in the soil water system as well as recharge of groundwater with other sources including recharge from rivers, streams and irrigation.This effect is especially true for opencast coal mining and varies greatly depending on what state of rehabilitation the opencast pit is in. For example, the recharge percentage is at a 100% in the final void and a mere 14% for grassed over spoils (values provided by the Optimum mining operation). Determining at what state the mining operation is in and what materials are used to rehabilitate the opencast area, can greatly affect the expected amount of water that reaches the water table.Natural recharge by downward flow of water through the unsaturated zone is generally the most important mode of groundwater recharge and determining the void space and porosity of the unsaturated spoils is crucial for determining recharge for opencastmining (Fitzsimons &Misstear, 2006; Lerner, Issar& Simmers, 1990; Oke, Martins, Idowu &Aiyelokun, 2013; Xu & Beekman, 2003).

Despite calculating recharge from rainfall that infiltrated into the ground, run-off into dams also adds a fraction to the total water that seeps into the saturated zone, as is the case for the Optimus rehabilitated pit. For the mining operation, calculating recharge is necessary since the water infiltrated will eventually decant. The whole mining operation then needs to adjust their pumping strategy to prevent potentially hazardous water running onto the surface.

"Groundwater as a dynamic system is located in the subsurface of the earth and moves under the control of different factors" (Xi, Zhang, Zhang, Chen, Qian, & Peng, 2008). For this study, focus was placed on the mining environment and the movement of water, the way the rehabilitation takes place, pumping and decanting. The study of groundwater in various fields of science such as hydrogeology, hydrology and climatology, shows that the factors controlling the stateand fluctuation of groundwater levels are important parameters that need to be assessed thoroughly to understand recharge through precipitation. Although these important factors need to be assessed there are some that take a considerable amount of time and data to calculate. Void space and porosity values in inconsistent spoil material, and water retention when the water level subsides, are all factors that need be calculated to estimate recharge. The estimation of groundwater recharge from precipitation forms a principal part of hydrology and hydrogeology (Xi et al., 2008), since calculating recharge leads to a better understanding of the crucial groundwater recharge cycle as well as the ability to more accurately predict and manage groundwater resources. Although precipitation is the most important source of groundwater recharge (Kumar & Seethapathi, 2002), the accuracy of currently attainable techniques for measuring recharge are not completely adequate (Sumioka & Bauer, 2003).This inadequacy in measuring recharge can be attributed to the lack and quality of data on regional and local scale, as well as research requiring dedicated objectives concerning which parameters need attentionas well as listing them for future research.

The amount of water abstracted from aquifers should betaken into account when looking at the rate of recharge to avoid resource depletion and adverse environmental impacts (Sharma, 1986). Beneficial water abstraction in the mining environment can keep mining operations dry, re-using water for the mining process and to keep decanting water levels low as to not hazardously affect the surface environment. On the other hand, groundwater overexploitation may cause substantial reduction of groundwater discharge into rivers, ground subsidence due the compaction of compressible layers, and the formation of an acidic environment (Alley & Leake, 2004; Jusseret, Baeteman & Dassargues, 2010; Stavric, 2004; Walraevens & Van Camp, 2005; Zhou, 2009).

Estimating groundwater recharge has long been one of the most difficult challenges in hydrological science (Wang, O Dochartaigh, & Macdonald, 2010), and is the determining factor that drives researchers to understand the recharge cycle through constructing new methods for recharge calculation. Through determining parameters not previously understood or lack of data on a regional scale, recharge estimation methods can be updated to incorporate these factors, and as a result give clearer estimations on recharge.

2.3 Previouswork in semi-arid regions

Groundwater recharge studies in arid and semi-arid regions of Southern Africa have been carried out by different researchers over the past couple of years.Recharge has been estimated in semi-arid and arid regions using a variety of techniques, including physical, chemical, isotopic, and modelling techniques. These techniques have been described in previous studies and reviews (Hendrickx & Walker, 1997; Kinzelbach et al., 2002; Lerner et al., 1990; Scanlon, Headly & Cook, 2002). The purpose of recharge estimation for water resources evaluation relies mostly on groundwater-based approaches which integrate over large spatial scales and generally cannot be used to estimate local variability in recharge. The problems faced here are the multitude of parameters such as the local topography, vegetation and rainfall that are not taken into account when calculating recharge on a larger scale.

Beekman and Sunguro (2002), Gieske (1992) and Larsen, Owen, Dahlin, Mangeya and Barmenc (2002) concluded that recharge in semi-arid regions in Southern Africa only contributes to a small amount of water to the aquifer (usually <5% of the average annual rainfall). Nyagwambo (2006) confirmed this by stating, since the potential evapotranspiration is higher than the rainfall, the recharge is dependent on rainfall intensity. This led to the conclusion that fractures, fissures and cracks in the tropical crystalline basement aquifers of Zimbabwe are the main preferential pathways for recharge in semi-arid regions.

The problem in the estimation of groundwater recharge in semi-arid areas is that recharge values are normally small when compared to a larger area of investigation and the specific methods used during the investigation (Allison, Barnes, Hughes, & Leaney, 1984). The greater the aridity of the climate, the smaller and potentially more variable the recharge percentage appears to be in space and time. Direct groundwater recharge from precipitation in semi-arid areas is generally small, usually less than 5% of the average annual precipitation, with a high temporal and spatial variability (Gieske, 1992). Lerner et al. (1990) concluded that determination of groundwater recharge in arid and semi-arid areas is neither straightforward nor easy. This is a consequence of the temporal variability of precipitation and other hydrometeorological variables in such climates, the spatial variability in soil characteristics, geology, topography, land cover characteristics and land use.

Precambrian basement rocks, consolidated sedimentary rocks, unconsolidated sediments, and volcanic rocks are the four major hydrogeological environments in Sub-Saharan Africa (MacDonald, Davies, & Calow, 2008).

Low permeability aquifers with limited storage occupy about 80% of the African land area. MacDonald, Calow, MacDonald, Darling and Dochartaigh (2009) proposed three broad rainfall recharge zones in Africa:

- Negligible groundwater recharge in zones with less than 200 mm/a rainfall.
- About 50 mm/a recharge in the zones with rainfall range of 200−500 mm/a.
- Greater than 50 mm/a recharge in zones where rainfall exceeds 500 mm/a.

There is a gap in information on the regional scale, as well as the temporal and spatial distribution of groundwater recharge across much of Africa due to the cost implications, as well as a lack of management and clear objectives. Most existing recharge estimates have been done on an ad hoc basis using various methods and data, which leads to an inconsistency on estimates in different regions. The distribution of these estimates appears to be patchy and unequal across the African continent (Wang, O Dochartaigh, & Macdonald, 2010).

Several methods for the estimation of groundwater recharge have been applied in African countries in recent decades, with varying success (Xu & Beekman, 2003).This is due to the fact that indirect methods such as fracture recharge is difficult to measure as well as human errors including the quality and quantity of data collected. Results of applications of these methods show that groundwater recharge estimates done by different practitioners vary widely when different methods and input data sets are used.

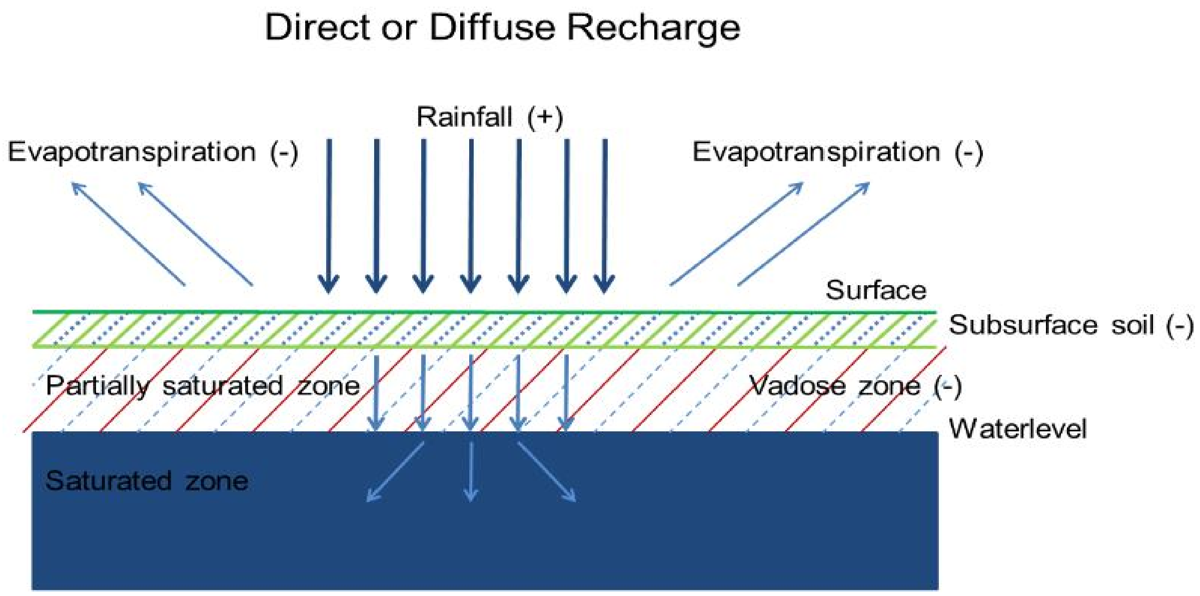
Furthermore, there is no technique for directly measuring recharge due to the lack of universal standard methods (Anderson & Woessner, 1992). Nevertheless, a number of methods are suggested to estimate the recharge for various climates such as arid, semiarid and tropical regions, each with its own advantages and disadvantages. Due to the disadvantages of each of the recharge methods, it is advisable to use a combination of two or more methods to minimise the risk of under- or over-estimating recharge values.

A clearer understanding of recharge processes and aquifer response to a changing future is necessary(Adelana & MacDonald, 2008; Calow & MacDonald, 2009; Foster, Tuinhof & Garduno, 2008) for a successful mining operation to succeed.Estimation of groundwater recharge is a key challenge for determining sustainable groundwater development and management, especially in arid and semi-arid areas, where rainfall and recharge is low while evapotranspiration is high.

De Vries and Simmers (2002) classified natural groundwater recharge mechanisms into three types according to their origin:

1. **Direct** (or diffuse) recharge.
2. **Indirect** (non-diffuse) recharge.
3. **Localised recharge**(De Vries & Simmers, 2002; Marechal et al., 2008).

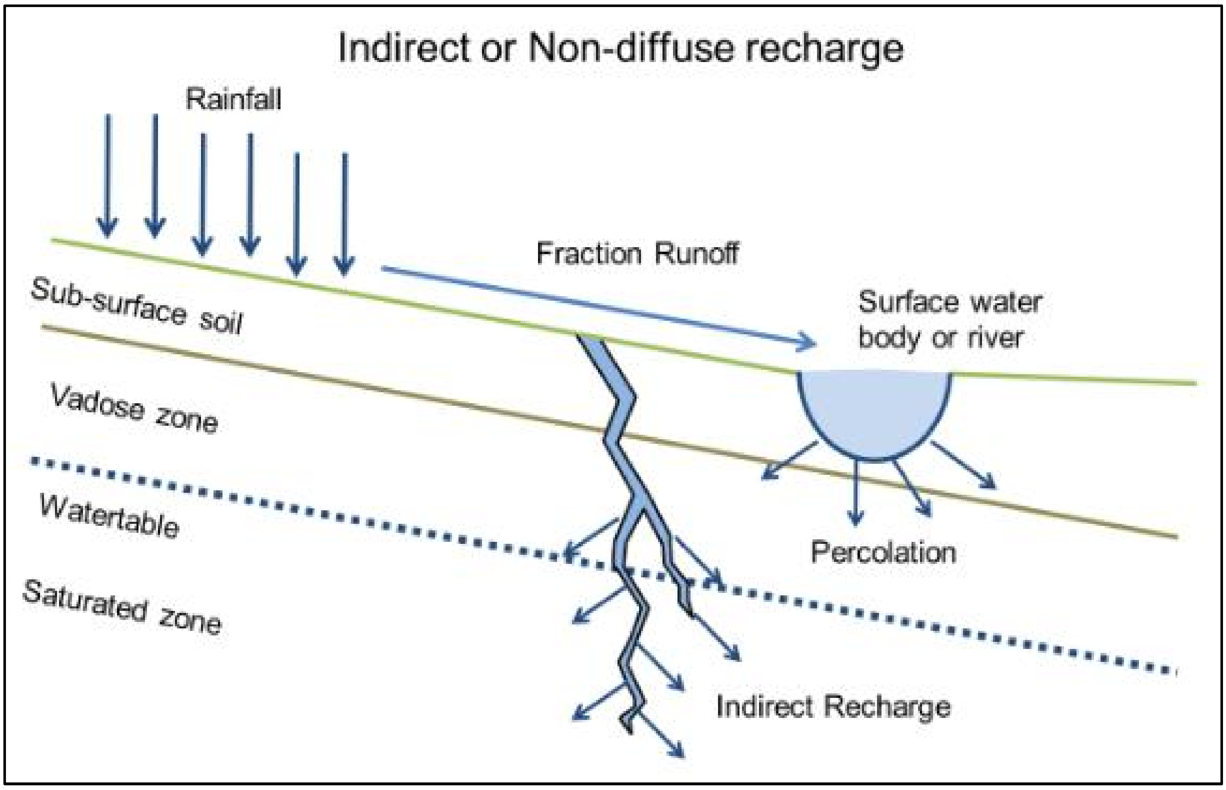
Direct or diffuse recharge occurs when the precipitation falling on the land surface percolates immediately below the point of impact into the subsurface (Figure 2.1). In other words, it is the rain water added to the groundwater reservoir after evapotranspiration and soilmoisturedeficits have been accounted for. Diffuse recharge is spatially distributed and results from widespread percolation through the entire vadose zone(Sophocleous, Sylveira, & Usunoff, 2004). This mode of recharge is typical for the humid climate where regular precipitations maintain the soilwater content to a value close to the field capacity(Dages et al., 2009).



Source: Author's own (2017)

Figure 2.1: Direct or diffuse recharge

Indirect or non-diffuse recharge results from the percolation of a fraction of run-off water through joints, depressions, and surface water bodies. This mode of groundwater recharge can be further subdivided into two categories. The first category of indirect recharge consists of percolation of water through the beds of surface water bodies (streams, rivers and lakes) (Figure 2.2). The second category ofindirect recharge, also called localised or focused, results from horizontal surface concentration of water in the absence of well-defined channels, such as recharge through sloughs, potholes, and playas(floodplains) (Sophocleous, Sylveira, & Usunoff, 2004). The relative proportions of these componentsfluctuate according to climatic conditions, geomorphology and geology. In arid regions, the most important mechanism of groundwater recharge is considered to be indirect recharge by infiltration from floods through the alluvial beds of ephemeral streams in wadi channels (De Vries & Simmers, 2002; Marechal et al., 2008; Xu & Beekman, 2003).



Source: Author's own (2017)

Figure 2.2: Indirect or non-diffuse recharge

Physical and tracer methods, the most commonly used approaches in these studies, were adapted to estimate recharge at local and national scales in Southern Africa.The validity of these methods in arid and semi-arid areas, in terms of the principles, advantages, limitations, and general rules governing the choice of different methods, have been summarised by researchers such as Scanlon, Headly and Cook (2002) and Xu and Beekman (2003).

Recharge depends on a multitude of factors which range from the type of geology, potential of evaporation and the amount of rainfall the area receives. According to Wang et al. (2010) four mechanisms of groundwater recharge can be distinguished:

- Downward flow of water (from precipitation, rivers, canals and lakes) through the unsaturated zone reaching the water table.
- Lateral and/or vertical inter-aquifer flow.
- Induced recharge from nearby surface water bodies resulting from groundwater abstraction.
- Artificial recharge such as from borehole injection or man-made infiltration ponds. (See also Lerner et al., 1990; Xu & Beekman, 2003.)

Another classification for estimation of groundwater recharge offered by Kumar (2000), classified the methods of recharge into four groups: empirical methods, groundwater resource estimation, groundwater balance approach and soil moisture data based methods (Kumar, 2000). Sun (2005) did a similar study in the Montagu area of the Western Klein Karoo. Thisstudy focused on similar aspects of recharge, as applied in the Witbank region of Mpumalanga due to the fact that water balance methods were used in calculating recharge. Sun (2005) uses a water balance approach based on actual evapotranspiration and direct run-off models for recharge estimation with emphasis on its applicability to semi-arid regions. It can be concluded that recharge processes are influenced by a wide variety of factors, including climatic,physiographic, geological and man-made factors which are often overlooked. In Sun (2005), it was observed that if precipitation was less than 400 mm/a in semi-arid regions, recharge wasusually less than 5 mm/a and was mostly linked to a single high rainfall event. This recharge percentage might be true for undisturbed virgin ground but are considerably higher for opencast and rehabilitated pits. The values estimated for recharge were either over- or under-estimated due to the finite number of rainfall stations. As a result, the data collected was insufficient to make an accurate estimation of the actual recharge in the area(Sun, 2005) as with insufficient data on the rehabilitation process and rainfall data when it comes to the time intervals they were taken at. The lack of data due to a limited number of rainfall stations, the intervals the rainfall events were taken at and the number of boreholes monitored, were the main limiting factors in not producing a more accurate recharge percentage for the study area.

2.4 Methods for recharge calculations

Development of a conceptual recharge model in the study area should also precede the selection of the appropriate recharge estimation method in order to reduce both uncertainty as well as costs of quantifying recharge. Such a model should describe the location, timing and probable mechanisms of recharge and provide initial estimates of recharge rates based on climatic, topographic, land use and land cover, soil and vegetation types, geomorphologic and (hydro-)geologic data (including recharge sources, flow mechanisms, piezometry and groundwater exploitation). However, a user-friendly framework for recharge estimationis not yet in existence(Xu, Chen, & Li, 2003).

The choice of the recharge estimation methods would depend on the conceptualisation of the recharge processes and the accuracy required in a given situation (Sun, 2005).

Based on a detailed analysis and interpretation of factors influencing recharge, the water balance method was used to estimate recharge rates by using readily available data(rainfall, run-off, temperatures). Other estimation methods would be difficult to apply due tothe limited information available in the study area. The long-term averagerecharge is modelled as a function of the regional interaction of the site conditions: climate, soil, geology and topography. Modelling is performed according to theoutlined procedure, using long-term climatic and physical data from the differentrainfall periods of different gauge stations. As a result, actual evapotranspiration, directrun-off and recharge can be quantified(Sun, 2005). Recharge calculations are usually more reliable if calculated over a longer period (dry and wet seasons) of time to correct for the variability encountered during high or low rainfall.

Recharge cannot be easily measured directly,especially in hard rock regions where preferential pathways (fracture, faults) are more likely to cause recharge to an aquifer. The recharge estimation methods carried out in this study focused mainlyon water balance methods and are therefore discussed in detail below.

Quantification of the rate of groundwater recharge is a pre-requisite for efficient groundwater resource management in the mining environment, to account for the inflows into an opencast rehabilitated pit and to adjust pumping rates to prevent excess from decanting. However, the rate of aquifer recharge is one of the most difficult factors to measure in the evaluation of groundwater resources due to the numerous environmental parameters, as well as the difficulty in measuring those parameters. Estimation of recharge, by whatever method, is normally subject to large uncertainties and errors (Kumar & Seethapathi, 2002). Various methods of estimating natural groundwater recharge are outlined and critically reviewed with regard to their limitations and associated uncertainties.

Although several methods are suggested for evaluation of groundwater recharge, this parameter is still the most difficult to measure as far as the evaluation of groundwater resources is concerned due to the complexities involved in the measurement of certain parameters needed to calculate recharge. The following methods are most frequently used for estimating natural groundwater recharge (Chandra, 1979).

- Soilwater balance method.
- Zero flux plane method.
- One-dimensional soil water flow model.
- Inverse modelling technique.
- Groundwater level fluctuation method.
- Hybrid water fluctuation method.
- Groundwater balance method.
- Isotope and solute profile techniques.

Several methods for estimating groundwater recharge are in use at present in the South African environmental setting. The use of one method or another depends on the temporal and spatial resolutions of the required estimates (Scanlon, Healy, & Cook, 2002). These methods can be broadly separated into two groups, namely physical and chemical methods. Since chemical methods will not be used and numerous physical methods are available, only the methods that were used are listed below:

- **The water table fluctuationmethod** (Misstear, 2000) (Scanlon, Headly, & Cook, 2002).
- **Inverse modelling**(Kendy, Molden, Steenhuis, Lui, & Wang, 2003) (Prasad & Rastogi, 2001).

Groundwater recharge is indeed a complex function of several factors and mechanisms. These factors and mechanisms include meteorological conditions, soil types, land use, physiographic characteristics, depth to the water table, antecedent soil moisture, properties of the geological materials, interaction between surface water and groundwater and available groundwater storage (Sophocleous, 2004). These may not always be accurately appraised since estimates of groundwater recharge are normally and almost inevitably sullied by considerable errors anduncertainties (Dages et al., 2009; Fitzsimons & Misstear, 2006; Sophocleous, 2004) and that is why only a close estimate can be given if a method was chosen correctly. The optimal manner in which these uncertainties can be minimised is to use a combination of several methods which this study incorporates into the recharge calculations (Scanlon, Healy, & Cook, 2002). It would be time-consuming and expensive to envision a full water balance of the surface, unsaturated, and groundwater compartments (Cook, et al., 1998).

2.5 Methods discussed in this study

2.5.1 Inversemodelling technique

The inverse modelling technique is a two-dimensional finite element (or finite difference) groundwater model of the saturated zone. Current methods of calibrating groundwater flow models are either direct or indirect. The indirect approach is essentially a trial and error procedure that seeks to improve an existing estimate approach of the parameters in an iterative manner, until the model response is sufficiently close to that of the real system. In Chapter 7 this method is applied by using stage curve volumes for the rehabilitated opencast pits and in Chapter 8 and 9 to calculate recharge. The direct approach differs in that it treats the model parameters as dependent variables in a formal inverse boundary value problem.

The inherent non-uniqueness of the solution is one of the major difficulties faced in dealing with the inverse problem. Much of the data entered into the inverse modelling technique represent discrepant measurements and processed information that give a distorted picture of the system's true state. The calculation of recharge of an aquifer by the inverse modelling technique must be regarded with caution, if the true storage coefficient values (-S-) of the aquifer are not known. If, however, the calibrated S values can be regarded as being very close to the real values, this technique can be beneficial in describing the behaviour of the aquifer to the recharge phenomena in general.

2.5.2 Saturatedvolume fluctuation

The saturated volume fluctuation (SVF)method is based on water balance over time based on averaged groundwater levels from monitoring boreholes (Bredenkamp, Botha, van Tonder, & van Rensburg, 1995). In Chapter 9, this method is used using G. van Tonder and Y. Xu's Excel based program,*Program to Estimate Groundwater Recharge and the GW Reserve* (2000).

Recharge is calculated as:

$$S * \frac{\Delta V}{\Delta t} = I - O + RE - Q_a \quad \text{Equation 2.1}$$

Where:

S	=	aquifer storativity
Δv	=	change in saturated volume of the aquifer
Δt	=	time increment over which the water balance is calculated
I	=	inflow
O	=	outflow
RE	=	recharge
Q_a	=	abstraction during period (Δt)(van Tonder & Xu, 2000).

The water level, borehole abstractions and aquifer properties, including storativity andsize of aquifer area are required in this method. A major advantage of SVF typeestimations is that they allow recharge estimations to be made from current data (Xu, Chen, & Li, 2003). A shortcoming of the method is that the measured water levels must berepresentative of the aquifer as a whole andthe inflow value is often assumed equal to the outflow value.

2.5.3 Groundwater level fluctuation

The **water table fluctuation** method is based on the premise that rises in groundwater levels in unconfined aquifers are due to recharge water arriving at the water table (Scanlon, Healy, & Cook, 2002).The method is best applied over short time periods in regions having shallow water tables that display sharp rises and declines in water levels. This is due to the simple fact that shallow water tables receive faster and more recharge from a water source, since there is less ground to move through on the way to the water table.

This is an indirect method of deducing the recharge from the fluctuation of the water table. The rise in the water table during the rainy season is used to estimate the recharge, provided that there is a distinct rainy season with the remainder of the year being relatively dry. The basic assumption is that the rise in the water table is primarily due to the rainfall recharge. It is recognised that other factors such as pumping or irrigation during the rainy season do not have an influence.

If the rise in the water table is >Δs, the rainfall recharge, $R_i$is given by:

$$R_i = S_y * \Delta s + T_p - R_T \quad \text{Equation 2.2}$$

Where:

S_y = specific yield
T_p = the abstraction during the rainy seasons divide by the study area
R_T = the return flow due to any irrigation which occurs during the rainy season
R_i = rainfall recharge
Δs = rise in water table(Kommadath, 2000).

The basic limitation of the above equation is that it neglects the subsurface inflow and outflow. It assumes that every inflow and outflow is uniformly distributed over the area. This may be generally true for the rainfall or even for the return flow from irrigation, but it is rarely true for the abstraction from the aquifer. When pumping is reduced or ceases during the rainy seasons, a redistribution of groundwater heads occurs so that part of the observed increase in the water level may be due to normal well recovery. Moreover, the above equation is dependent on the value of the specific yield, which is difficult to determine since the water table fluctuation occurs in the partially saturated zone.

2.5.4 Cumulative Rainfall Departure

The **Cumulative Rainfall Departure** (CRD)is based on the premise that water level fluctuations are caused by rainfall events. This method is applied extensively with more or less success in South Africa (Xu & van Tonder, 2001). In Chapter 9, this method will be used in an Excel-based program developed by G. van Tonder and Y. Xu's,*Program to Estimate Groundwater Recharge and the GW Reserve* (2000).

Recharge is calculated as:

$$R_t = rCRD_i = S_y\left(\Delta h_i + \left(\frac{Q_{pi}+Q_{outi}}{AS_y}\right)\right) \quad \text{Equation 2.3}$$

with

$$CRD_i = \sum_{i=1}^{N} P_i - \left(2 - \frac{1}{P_{av}i}\sum_{i=1}^{N} P_i\right) iP_t \quad \text{Equation 2.4}$$

Where:

r = fraction of a CRD which contributes to recharge

S_y = specific yield

Δh_i = water level change during month i(L)

Q_p = groundwater abstraction (m^3/T)

Q_{out} = natural outflow

A = recharge area (L^2)

P_i = rainfall for month i(L/T)

P_t = Threshold value representing aquifer boundary conditions (Van Tonder & Xu, 2000).

$P_t$may range from 0 to P_{av},with 0 representing a closed aquifer (no outflow), and P_{av} representing an open aquifersystem (for instance controlled by spring flow).The limitations of deep (multi-layer) aquifers and sensitivity of specific yields do not need to beconsidered with this method. The data requirements of thismethod include monthly rainfall records, water level, borehole abstractions and aquiferproperties including storativity and size of recharge area. Water level fluctuations caused by corresponding rainfall events should be known first. This method can be used in the mining environment, but it has to be kept in mind that abstraction takes place from dams and decanting points and not directly from an underground source.

2.5.5 Groundwater balance method

In general,

$$I - O = \Delta W/\Delta t \quad \text{Equation 2.5}$$

Where:

I = inflow (m^3/day)

O = outflow (m^3/day)

ΔW = change in water volume (m^3)

Δt = change in time (days) (Kommadath, 2000).

Considering the various inflow and outflow components, the groundwater balance equation for a time periodΔt is given as:

$$R_i + R_c + R_r + R_t + S_i + I_g = E_t + T_p + S_e + O_g + \Delta W \quad \text{Equation 2.6}$$

Where:

R_i = Recharge from rainfall

R_c = Recharge from canal recharge

R_r = Recharge from field irrigation

R_t = Recharge from tank

S_i = Influent recharge from rivers

I_g = Inflow from other basins

E_t = Evapotranspiration

T_p = Draftfrom groundwater

S_e = Effluent recharge to rivers

O_g = Outflow to other basins

ΔW = Change in groundwater storage(Kommadath, 2000).

The above equation is the general groundwater balance equation for an unconfined aquifer. The lateral inflow and outflow must be accounted for in the balance equation due to the fact that the boundaries of an area do not represent streamlines and as a result they are not perpendicular to the equipotential line.

Effective porosity (n_e) is a crucial parameter in calculating recharge. In the zone in which the water table fluctuations occur effective porosity changes as the depth of water table changes, especially for water tables less than 3 m deep. Moreover, it should be noted that if the water level drops, part of the water is retained by the soil particles and if it rises, air can be trapped in the interstices that are filling with water. The effective porosity for rising water in general, is therefore less than that of a falling water table. The above equation considers only one aquifer system and does not account for interflows between the aquifers in a multi-aquifer system.

The water balance may be computed for any time interval. To apply the above equation correctly, it is essential that both the area and the period for which the balance is assessed be carefully chosen. All components of the water balance equation other than the rainfall recharge are estimated using the relevant hydrological, meteorological information and the structure of the mining operation to calculate the stage curve volumes. The rainfall recharge is calculated by substituting these estimates in the water balance equation. This approach is valid for the areas in which wet and dry periods occur and the water balance is carried out separately. The above-mentioned yields an estimate of recharge coefficient,whilethe latter determines the degree of accuracy with which the components of the water balance equation have been estimated.

2.6 Summary

It can be deduced from the methods discussed that it was of crucial importance that the appropriate method(s) of recharge estimation were selected depending on the data availability and the area of study. For this area, a water balance approach was selected to do the recharge calculations on and thus the appropriate methods were chosen.

It was also important to first construct a preliminary conceptual model using mine data and all the relevant environmental factors to select the correct method(s) for recharge calculations. Determining the rainfall patterns, surface features as well as geology are all parameters that need to be thoroughly understood before it can be applied into a recharge method. Concerning the data collection, some methods may have parameters that are difficult to determine such as specific yield, void space and even inflows and outflows of an aquifer if it was not specifically measured. Although the methods discussed in this chapter seem as easy a collecting the data and applying the calculations, there are many factors that can complicate or even deter someone from following through. Thus, voids in data will be encountered even after the desk top study and the actual calculations are done. This is why it is of great importance to first understand the environment and all its conditions, to fill the gap in data which will be encountered sooner or later.It must also be understood that no method is perfect and that a combination of similar recharge methods will yield more conclusive and accurate data. This is why it is of importance to use or consider a wide variety of methods based on environmental conditions and the availability and abundance of data.

Chapter 3
Geomorphic Environment

3.1 Introduction

What follows is a detailed discussion on the geomorphic environmental aspects of the Witbank area in the Mpumalanga region of South Africa. The environmental aspect focuses on grasping a clearer understanding of all the factors that comes into play when calculating recharge. Factors that are discussed include topography and how the setting affects climate and rainfall, which in turn affects recharge. Other factors that influence recharge are the type of geology and soils related to the area and how their composition can greatly affect the amount of recharge the groundwater reserves receive. When all of the above-mentioned factors are combined into a basic conceptual model and most of the parameters are known, a basic understanding of the recharge cycle and its workings should become apparent.

3.2 Physical setting

The Olifants River Basin is situated in the north-east of South Africa, spanning the Limpopo and Mpumalanga. Its upper streams drain the Witbank and Middelburg Highveld regions, then pass over the Springbok Flats and end up meandering through the Lowveld to the Kruger National Park and onwards to Mozambique(Aston, 2000). In all, it covers a surface area of 54 575 km^2, receives a meanannual rainfall varying from 500 to 1 000 mm, has a sub-tropical climate with an average evaporation of 1 682 mm/year and would produce, if unexploited, an overall surface run-off at the Mozambique border of some 1 950 million cubic metre can be expected(DWAF, 1996).In 1990, the catchment supported a population of 2.5 million inhabitants(RSA Department of Water Affairs, 1991).

The Mpumalanga Province, with its capital Nelspruit, occupies an area of 78 370 km^2 or 6.4% of the total area of South Africa. Mpumalanga is mainly situated on the high plateau grassland known as Highveld which stretches for hundreds of kilometres eastwards, until it rises towards mountain peaks and deep valleys of the escarpment in the north-east. From the escarpment it plunges hundreds of metres down to the low-lying area known as Lowveld.

The topography of Mpumalanga can be split into three broad zones, namely Highveld, Escarpment and Lowveld. The major urban, mining and agricultural activities take place in the central Highveld, which is situated at an altitude of 1 600−1 700 m. Figure 3.1 shows the elevation for Middelburg and Hendrina which sits at the northern and southern points of the Optimum mining operation at 1 500–1 680 mamsl, respectively.

Elevation maps of the northern and southern boundaries
of the Optimum mining area

Middelburg elevation (north) Hendrina elevation (south)

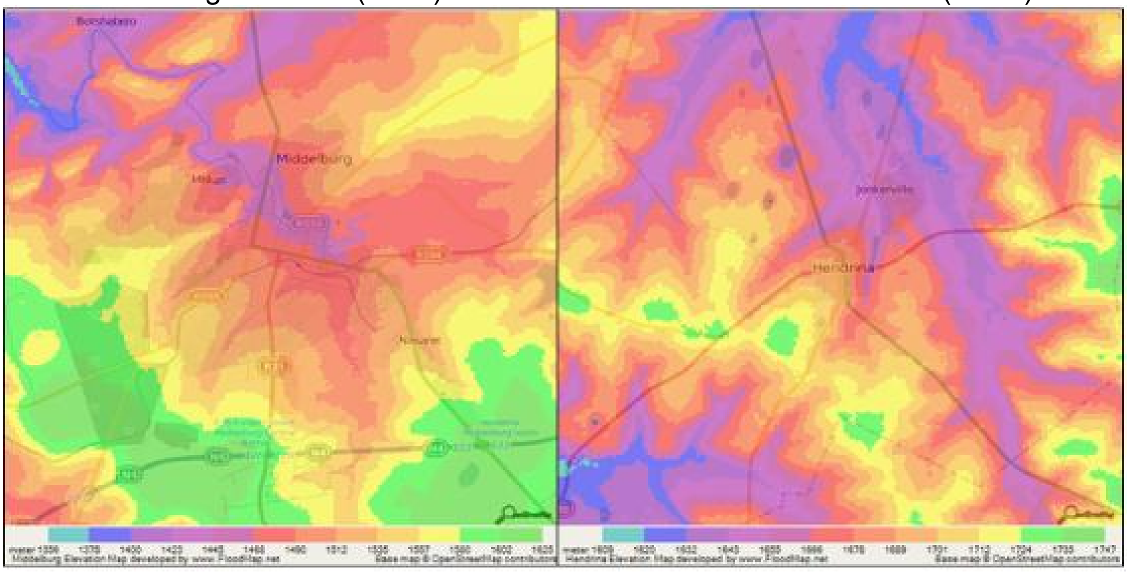
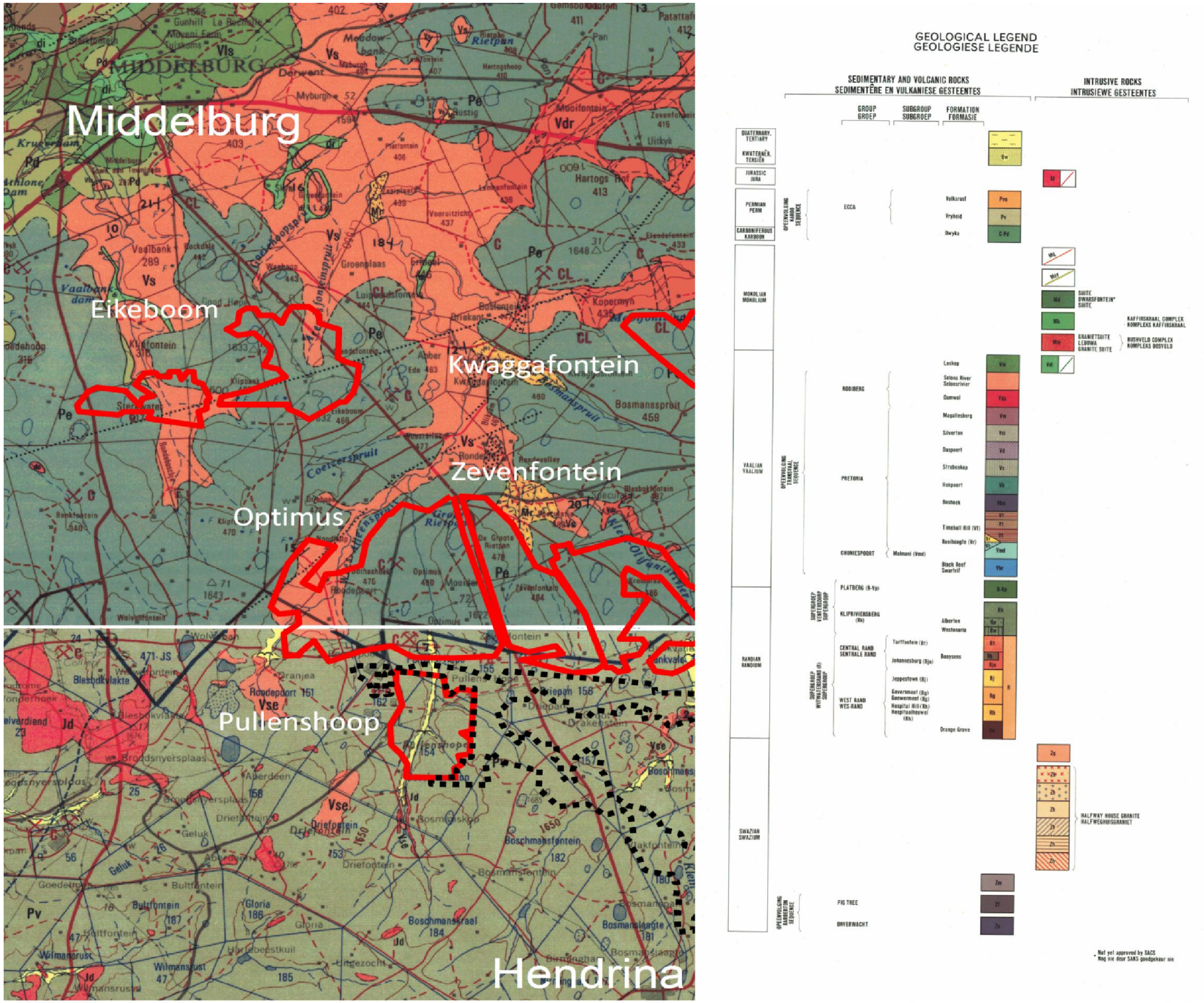


Figure 3.1: The northern (Middelburg) and Southern (Hendrina) elevation maps of the Optimum mining area

The colliery is situated ±30 km south-east of Middelburg on the road to Hendrina/ Ermelo. Figure 3.2 shows the Optimum Coal Mine border together with the individual opencast mining areas. The main geology found in the area is the Ecca group of the Karoo Supergroup and the volcanic intrusions of the Rooiberg Group.



Note: The red lines indicate the opencast operation while the dotted black line indicates the underground component.Source: Author's own (2017)

Figure 3.2: Geological map and mine borders of the Optimum Coal Mine

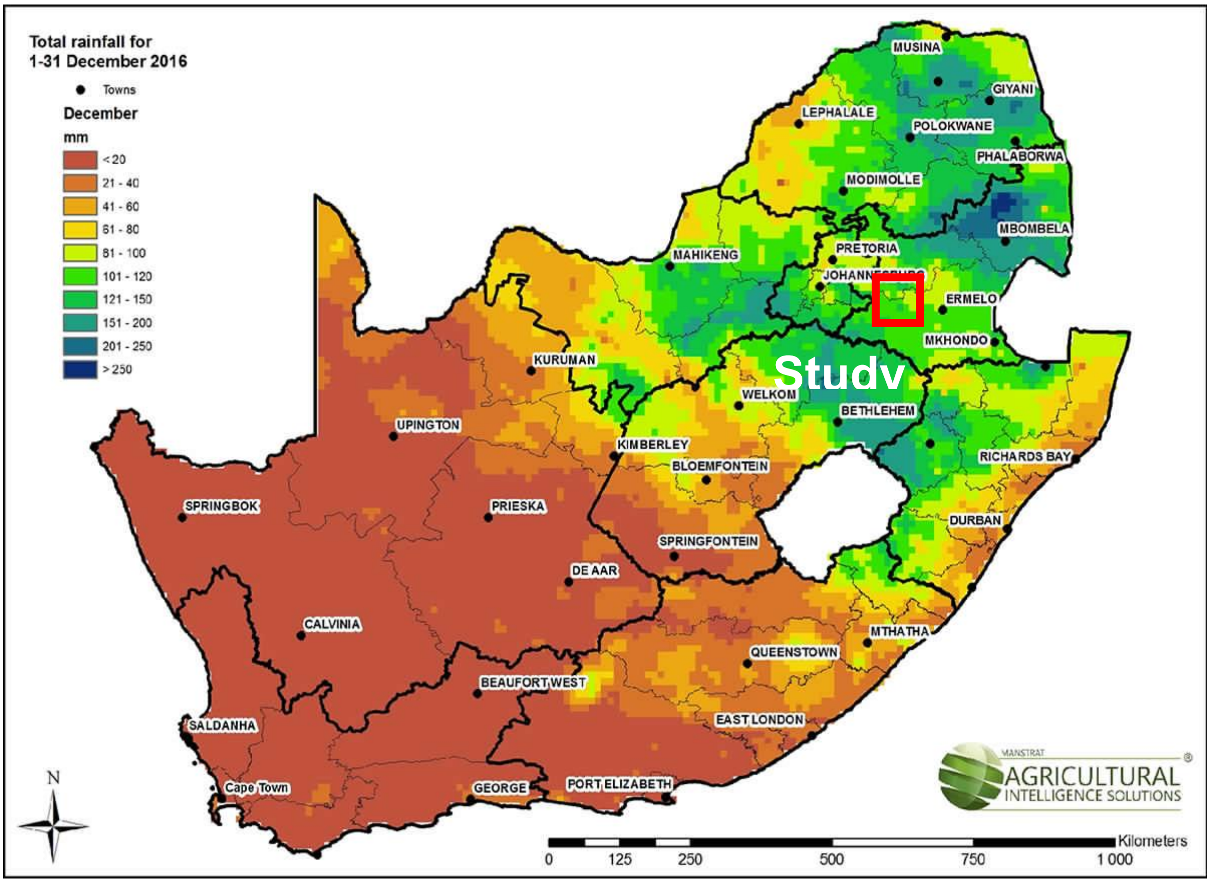
3.3 Climate, rainfall and temperature

South Africa is classified as a semi-arid region and has a mean annual rainfall of approximately 450 mm. There is, however, wide regional variation in annual rainfall as seen in Figure 3.3, from less than 50 mm in the Richtersveld on the border with Namibia, to more than 3 000 mm in the mountains of the south-western Cape. Only 28% of the country receives more than 600 mm (Palmer & Ainslie, 2006).Theannual rainfall occurs mainly during summer in the form of heavy thunderstorms(Palmer & Ainslie, 2006).In South Africa, three major zones of rainfall can be expected:

- Winter rainfall region of the western, south-western and southern Cape.
- The bimodal rainfall region of the Eastern Cape.
- The strong summer seasonality of the central Highveld and KwaZulu-Natal.

The Mpumalanga region falls within the strong summer seasonality region and is strongly influenced by the inter-tropical convergence which moves southwards during the southern hemisphere in the summer. The high seasonalvariations are accompanied by high spatial variability, and the annual potential evapotranspiration may exceed annual precipitation by ratios of up to 20:1. Droughtconditions are therefore a common phenomenon (Schulze, 1997). The Mpumalanga region can be classified as being sub-humid, expecting rainfall of approximately 600–800 mm per annum. The study area received between 520 mm and 830 mm of rain over a three-year period with distinct dry and wet seasons.

The temperatures in South Africa are strongly determined by elevation and distance from thesea. The higher elevations (1 500−1 700 m) situated in the inland regions experiences warm summers around January, with mean daily maximum temperatures of 26−28 °C and cool winters around July with mean daily minimum of 0−2 °C, with frost during the winter months (Palmer & Ainslie, 2006) (Schulze, 1997).



Source: Agricultural Intelligence Solutions

Figure 3.3: General rainfall intensity map for South Africa over 2016

Recharge with in the basin is estimated to be 3% to 6% of the annual rainfall which is estimated to be between 500 mmand 1 700 mm. Specific exceptions are that more than 60% of the basin receives less than 700 mm precipitation per year. On the other hand, recharge of up to 8% of precipitation is suspected in the north-western fringes of the catchment. The range of mean annual precipitation quoted here shows that quite often recharge occurs only locally and is certainly not spatially homogenous(Aston, 2000). Total recharge for the basin per year is estimated at approximately 1 800 million cubic metres (RSA Department of Water Affairs, 1991).

3.4 Vegetation

The diverse climate in the province makes the production of a wide variety of crops possible. The Lowveld is renowned for citrus and subtropical fruits, while the Highveld produces much of the summer grains, such as maize and grain sorghum. The biome in Mpumalanga was originally defined on climatic factors and is limited to summer and strong summer rainfall areas with a summer aridity index between 2.0 and 3.9 (Rutherford & Westfall, 1986).The most common soil in the biome, accounting for 50% of the area, is the red-yellow-grey latosol and is followed by black and red clays, freely drained latosols, and black clays(Rutherford & Westfall, 1986).The grasslands of the Highveld are associated with high nutrient status soils of basalt and andesitic origin(Palmer & Ainslie, 2006).

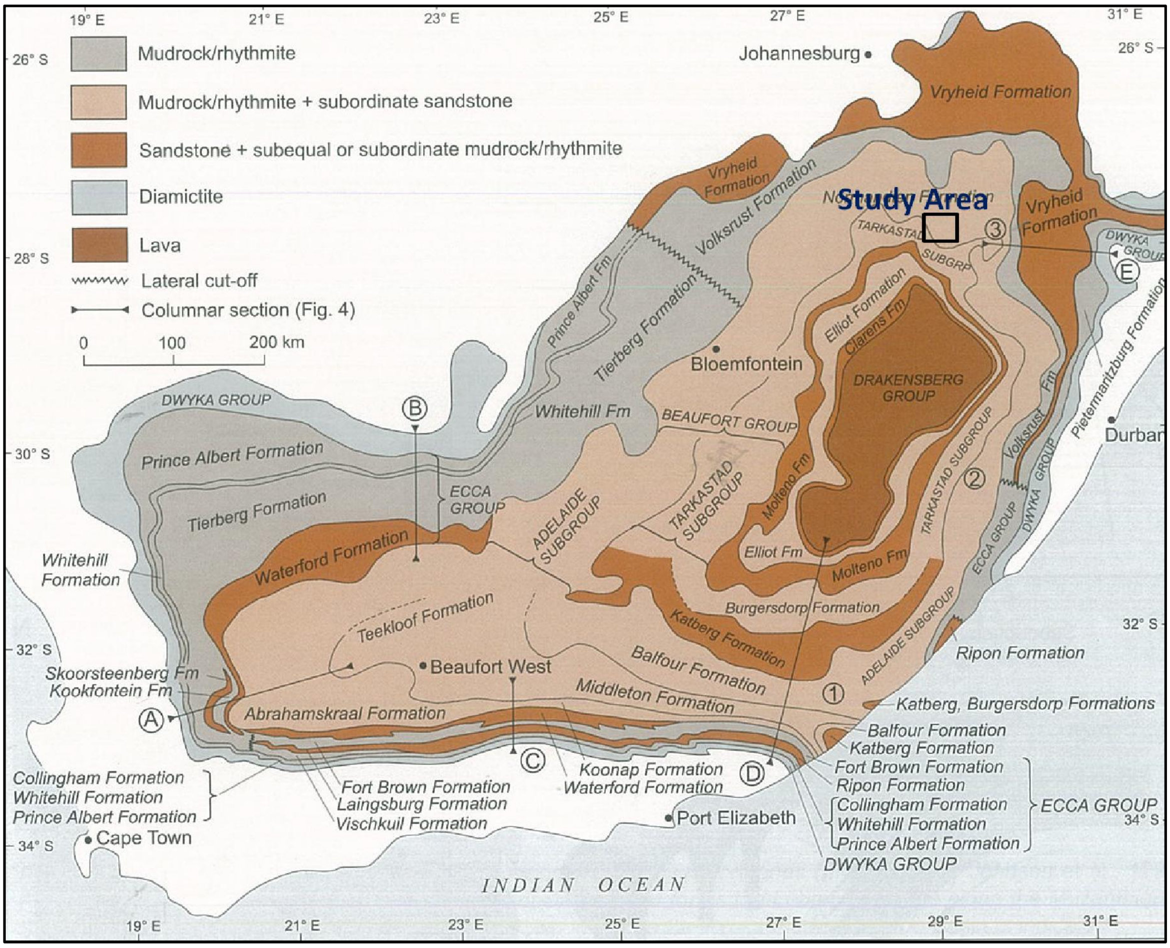
The type of vegetation and its density plays a significant role in controlling the flow of water overland and into the underlying soils. Understanding the local and regional vegetation is an important parameter when trying to calculate the recharge of the area. Rainfall in semi-arid regions, and hence production and nutrient cycling, is more variable than in moister regions.

3.5 Geology and soils

The Witbank Coalfield extends from Brakpan in the west through to Belfast in the east. The study area and adjacent regions consists of pre-Karoo rock successions overlain by Dwyka Formation tillite, followed by Ecca Group sediments, of which the Vryheid Formation is the coal-bearing horizon (Figure 3.4).

The Ecca sediments mainly consist of sandstone, shale, interbedded siltstone, mudstone and coal of varying thickness. The northern boundary is a very irregular sub-crop against the pre-Karoo basement rocks of predominantly Waterberg sandstones with the most northerly limit about 15 km north-west of Witbank, with many ‘inlets’ to the east and west. The south boundary is a prominent pre-Karoo felsite contact called the Smithfield ridge.

This basin was first exploited in the late 1800s in the Brakpan region and has been the focus of concerted exploration and exploitation ever since (Vermeulen & Usher, 2006).

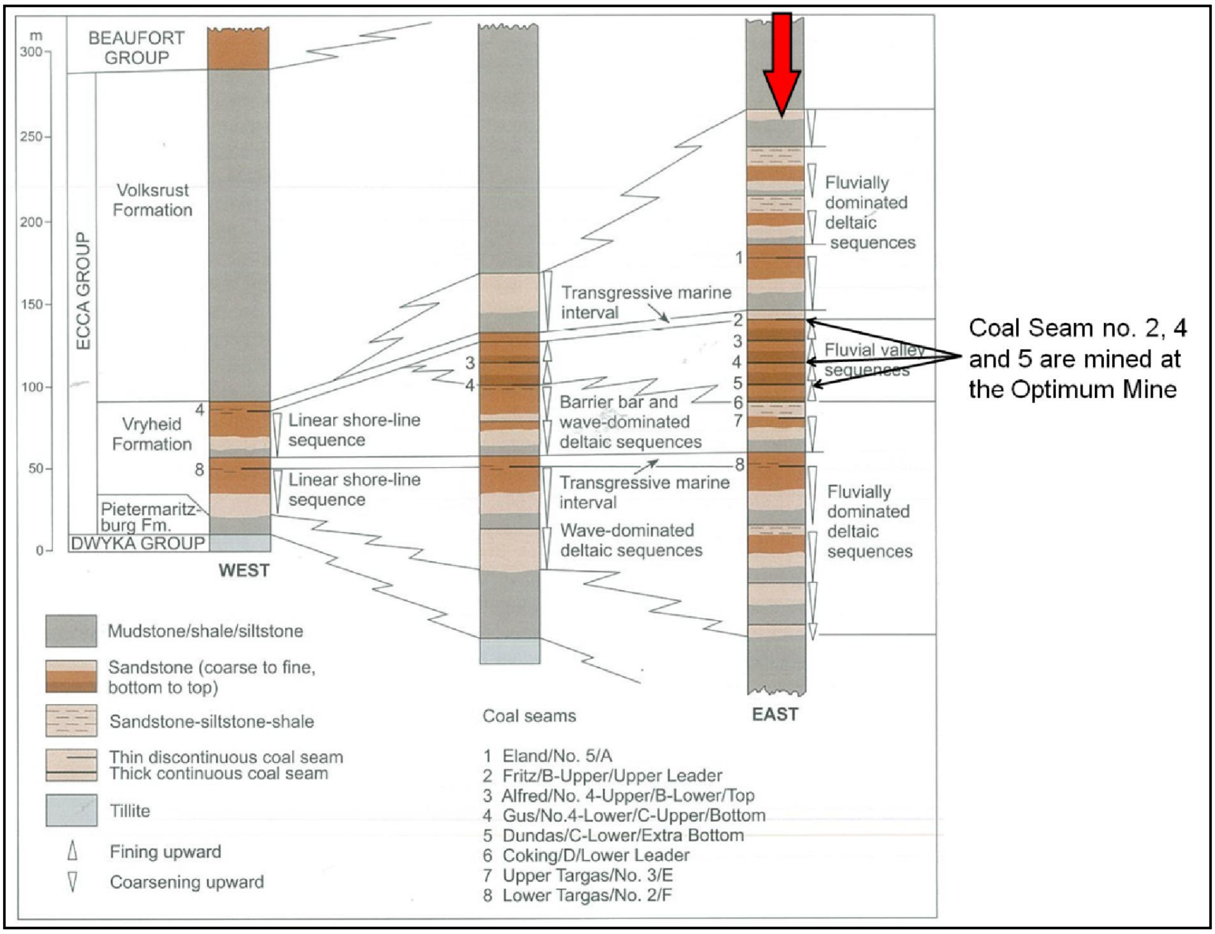


Source: The Geological Society of South Africa (2006)

Figure 3.4: Layout and position of the Karoo Supergroup

The basin is a multiple seam deposit type with the development of five major seam horizons which may in places be composite seams. The major controls for the development of the coal are proximity to undulations of the 'basement' topography, through erosion channelling and sediment influx into swamp beds and finally erosion of the current erosion surface.

The primary economic coal seams have been the No. 2 Seam and No. 4 Lower Seam and, in places, the No. 5 Seam with seams 1 to 5 contained in a 70 m succession (Figure 3.5). Structurally, the coal horizons are un-deformed with each displaying a very slight dip to the south-east of less than a degree and minor discrete faulting events that have a south-west to north-east trend of graben features and other minor faulting events (Vermeulen & Usher, 2006).



Source: The Geological Society of South Africa (2006)

Figure 3.5: Geological succession of the Ecca Group to the east (red arrow)

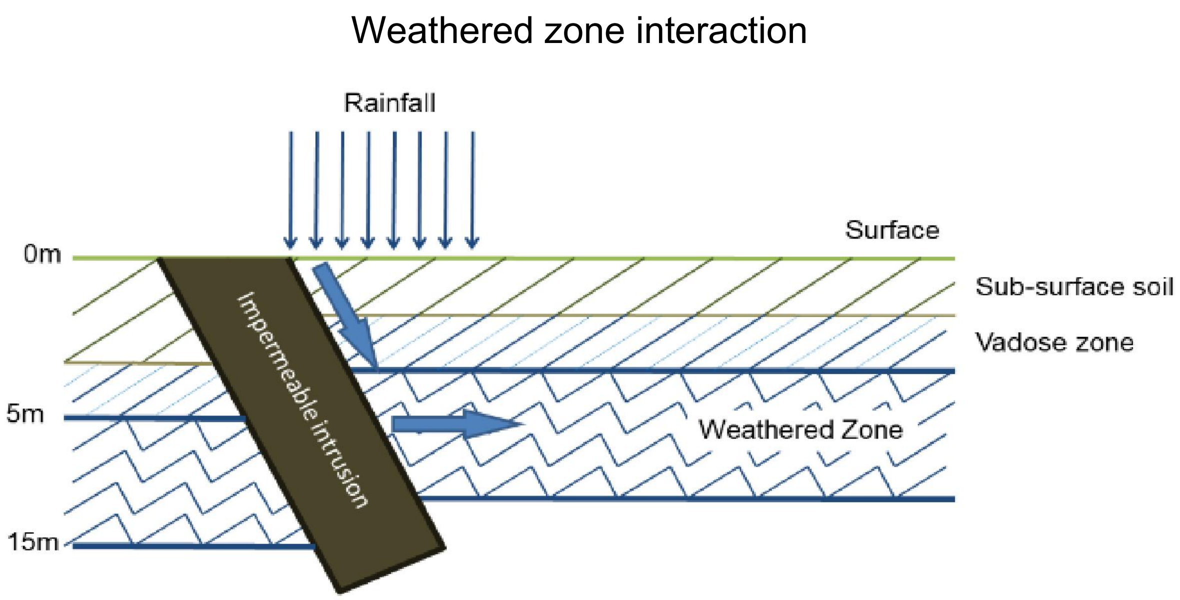
The most distinctive post-depositional feature is the intrusion of dolerites related to the Lesotho Basalts that have resulted in a variety of sills and dykes of various ages found across the entire Mpumalanga coalfield. These sills displace the seams and cause structural complications and often found outcropping on surface.

3.6 Regional geohydrological background

Two distinct and superimposed groundwater systems are present in the Witbank and Highveld coalfields.They are the upper weathered aquifer and the system in the fractured rock below the weathered groundwater system (Grobbelaar & Hodgson, 1997−2001).

3.6.1 Weathered groundwater system

This aquifer type occurs near the ground surface throughout the study region and is the most extensively exploited aquifer. It tends to be 5–12 m deep (Hodgson & Krantz, 1998), although may be as thin as 0.2 m or as thick as 50 m in certain areas (RSA Department of Water Affairs, 1991). In the top 5–15 m the first aquifer system consists of soil and weathered rock.Solid unweathered rock or structural aquifers tend to form the lower boundary of this aquifer. In places, a thick dolerite sill is present close to surface and intersected in boreholes; water may often be found at this boundary (Figure 3.6). A weathered rock aquifer is often of a perched nature (i.e. it has a more extensive aquifer beneath it). The aquifer tends to be rather low yielding because of its limited thickness, giving a typical flow of approximately one litre per second. However, when existing in conjunction with a structural aquifer, yields of up to five litres per second may occur from a borehole penetrating both the weathered aquifer and a deeper aquifer beneath (RSA Department of Water Affairs, 1991).



Source: Author's own (2017)

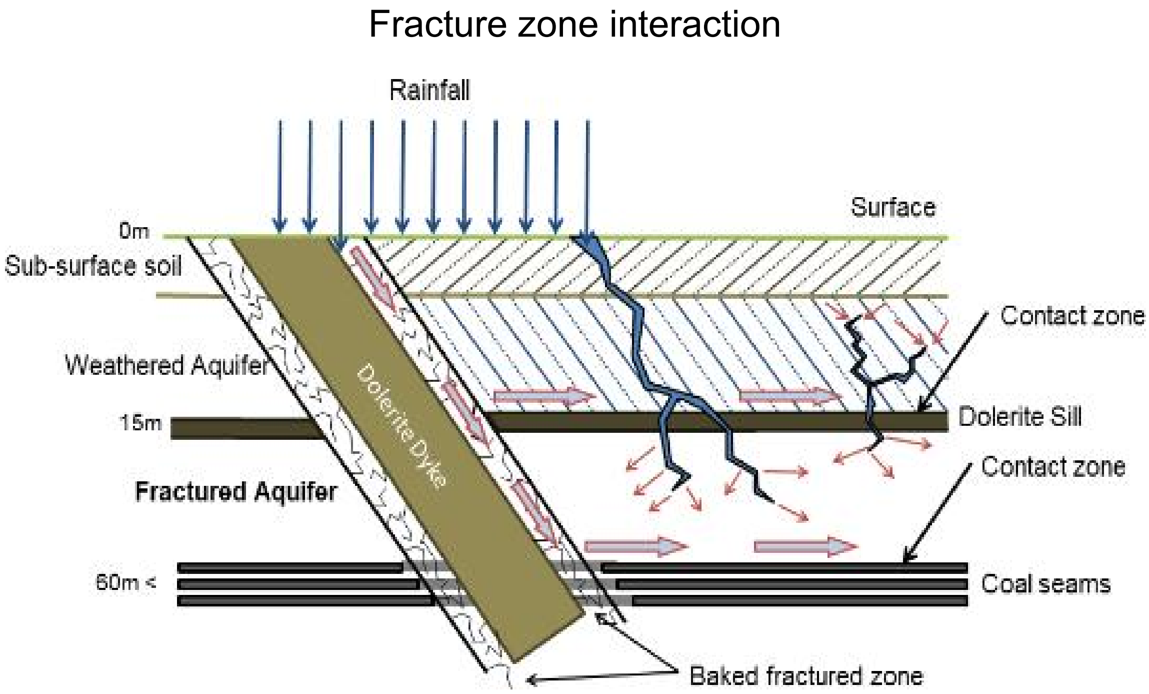
Figure 3.6: Weathered zone interaction

This aquifer is recharged by rainfall that infiltrates into the weathered rock and reaches impermeable layers of solid rock underneath the weathered zone.Movement of groundwater on top of the solid rock is lateral and in the direction of the surface slope. This water reappears on surface at fountains, where the flow paths are obstructed by barriers such as dolerite dykes, paleotopographic highs in the bedrock, or where the surface topography cuts into the groundwater level at streams. It is suggested that less than 60% of the water recharged to the weathered zone eventually emanates in streams. The rest of the water is evapotranspirated or drained by some other means (Vermeulen & Usher, 2006).

3.6.2 Fractured groundwater system

Water storage and transmission occur in what is known as secondary porosity in structural aquifers; secondary porosity being that porosity attributable to fractures, cracks and joints in the rock and not actually to the rock itself. As one gets deeper, however, more and more of these cracks are closed due to the weight exerted by the overlying formations (Aston, 2000). At depths below 30 m, water-bearing fractures with significant yields tend to be rarer, being spaced 100 m or more apart (Hodgson & Krantz, 1998). These fractures may be identified as linear features on air photographs or indeed may often be readily observed in the field. More scientific identification techniques, however, are required to successfully locate these fractures at greater depth (using, for instance, a magnetometer).

Highly variable yields are found in these aquifers. Initially yields may be high, but then show a marked decrease with continued pumping due to the limited storage in some of the cracks. In general, there is insufficient yield from these aquifers for intense irrigation (Ashton, 2000; Hodgson & Krantz 1998). The grains in the fresh rock below the weathered zone are too well cemented to allow any significant water flow. Mostgroundwater movement therefore occurs along secondary structures such as fractures, cracks and joints in the rock (Figure 3.7).



Source: Author's own (2017)

Figure 3.7: Fractured zone interaction

These structures are best developed in sandstone, hence the better water-yielding properties of the latter rock type.Dolerite sills and dykes are generally impermeable to water movement, except in the weathered state. In terms of water quality, the fractured aquifer always contains higher salt loads than the upper weathered aquifer. The higher salt concentrations are attributed to a longer contact time between the water and rock. An important aspect of groundwater occurrence and flow is the layered nature of the rock. It is possible, in theory, for mining to drain water from deep layers, not affecting shallow groundwater resources. This makes an evaluation of the current impact on groundwater reserves very difficult. Additional subsidence may occur, which would have afurther impact on groundwater reserves (Dages et al., 2009; Vermeulen & Usher, 2006).

3.7 Impacts of mining on groundwater

The majority of the mines in the Olifants River basin occur in the Witbank area, at the head of the Olifants River. Run-offs from these mines have had adverse effects on the quality of the surface water, but in recent yearsrun-off has been significantly controlled.

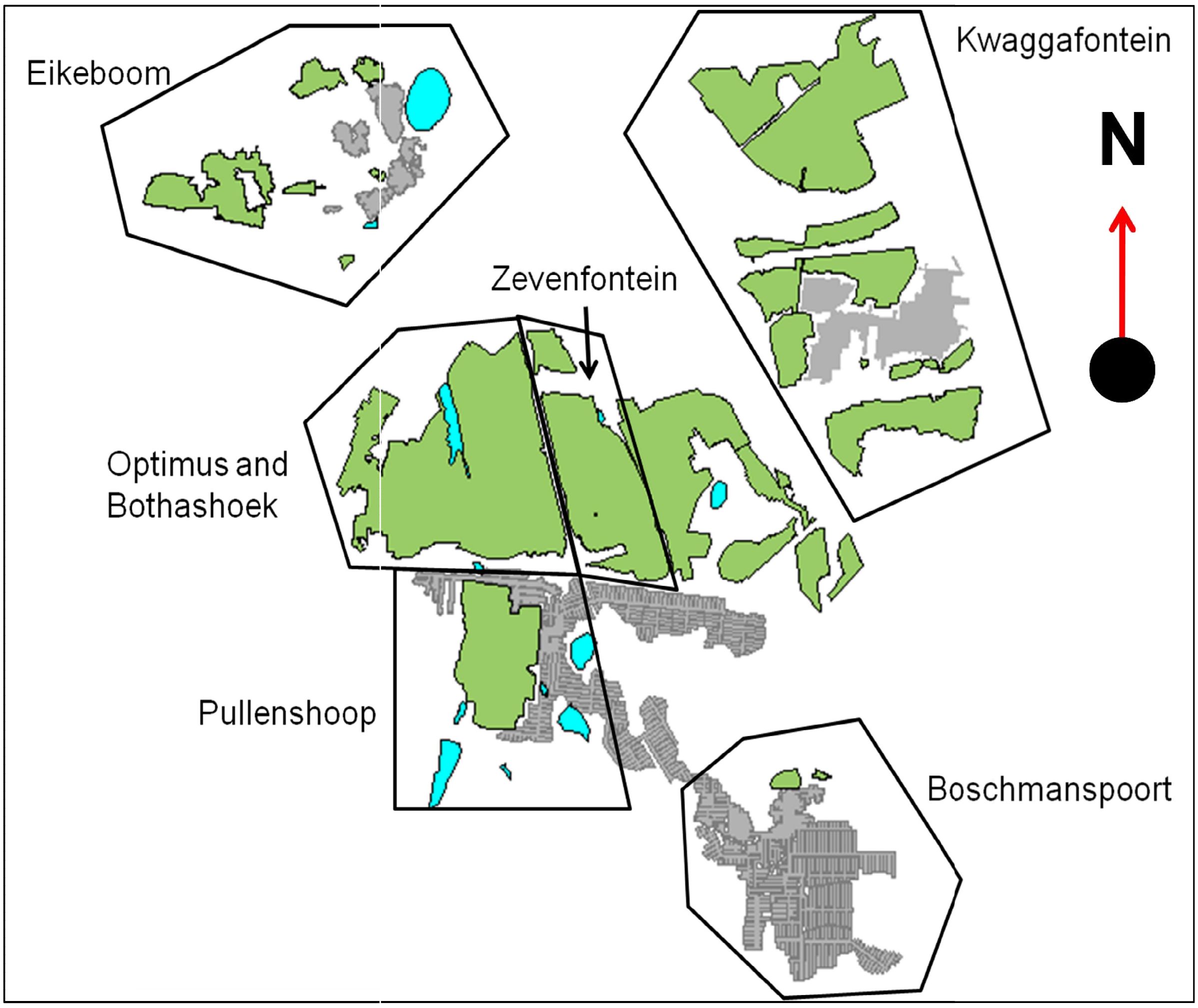
The next step after the mine water (high sulphur content) has been contained; the water pumped in and around the mining area has to be treated before it is released back into the river system. There is a pilot project for the area, which uses mine water (with neutralised pH) as irrigation water. The main objective of this project is to determine if the surrounding land, along with the crops being grown there, can absorb the high sulphur content of the mine water without adversely affecting the crops themselves(Aston, 2000).

When an operational mine pumps water it is for the sole purpose to keep the mine workings dry so that extraction of the ore can progress. To keep the mine workings dry, water is pumped from underground back into the mine in a circular pumping cycle (refer to Chapter 6). This is done to prevent possible contamination of the surrounding environment and its groundwater. However, as mines reach the end of the life of mine and rehabilitation takes place, the water level within these pits fill with highly acidic mineralised water which can seep into the surrounding environment which can lead to disastrous consequences. Under the ‘polluter pays’ policythe mine operators have a vested interest to prevent this.

The closed mines eventually have a large quantity of stored water that could potentially be an attribute to the local irrigation efforts. Obviously, treatment is required to some degree, but the chances are that less treatment would be required if the water were to be used for certain irrigation projects rather than allowed to overflow from the mines into the natural water system(Aston, 2000).

3.8 Geomorphic characteristics of the study area

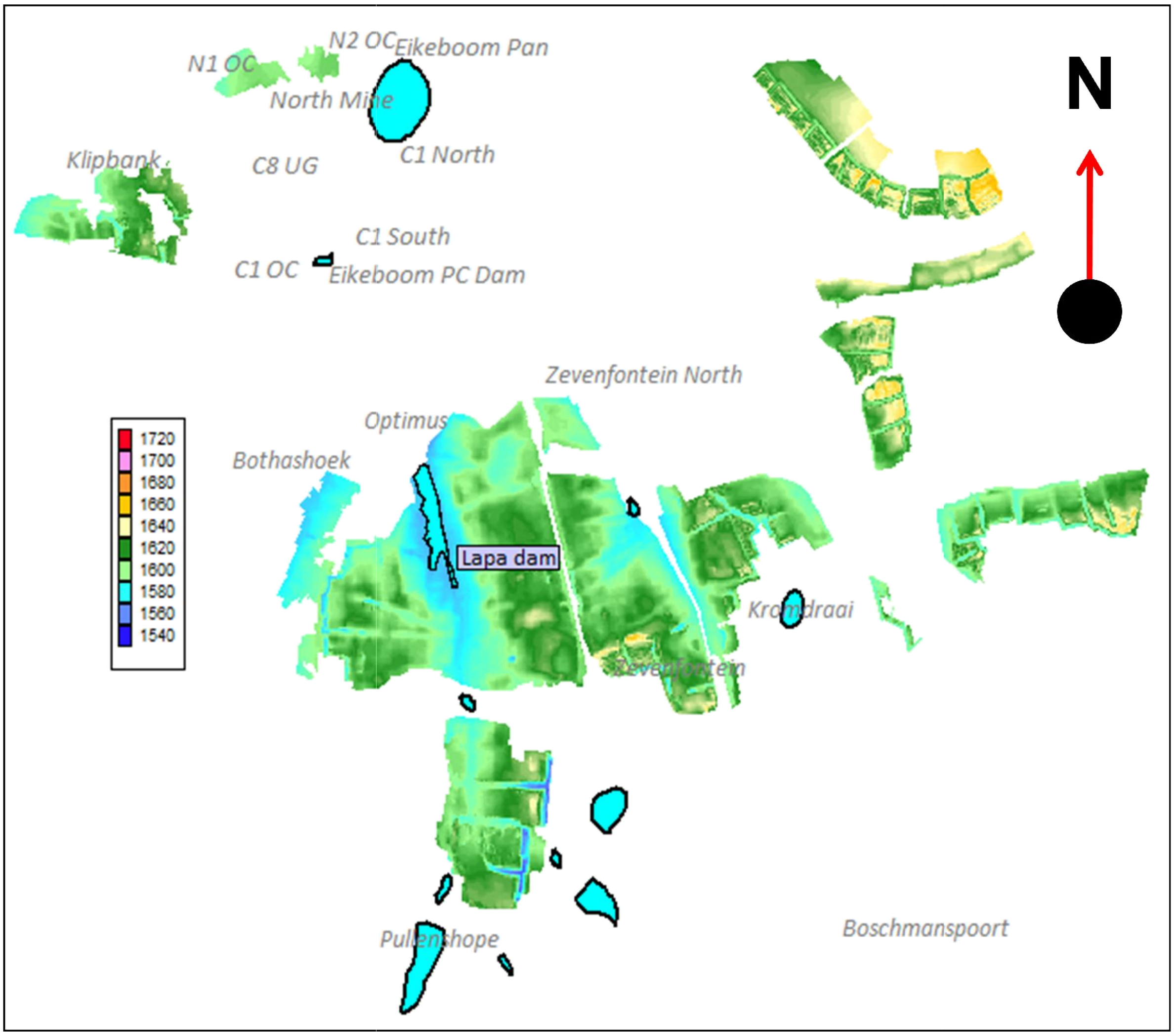
The Optimum area consists of five main mining operations called the Optimus, Zevenfontein, Pullenshoop, Eikeboom and Kwaggafontein areas (Figure 3.8).



Source: Author's own (2017)

Figure 3.8: Site layout of each mining area

All the mining areas are opencast with the Pullenshoop and Eikeboom having an underground section as well. The whole Optimum Area has numerous surface water bodies with include water control dams, rivers and evaporation dams with the Lapa Dam, Coastal Dam, Pullenshoop ring feed system and the Evaporation Dam being the more important water bodies (Figure 3.9).



Source: Author's own (2017)

Figure 3.9: Elevation map of the Optimum mining area and water body locations

The area receives an amount of annual rainfall between 520 mm and 830 mm per annum from 2011−2014. The area is also classified as being a semi-arid region due to the fact that the evapotranspiration is higher than the precipitation in most circumstances and that recharge only takes place during high rainfall events. Taking all the above-mentioned factors into consideration, the area will receive around 20−50 mm rainfall as recharge to the groundwater reservoir (MacDonald, Davies, & Calow, 2008). It has to be kept in mind that the spoils for this area will have a higher recharge capacity since they are unconsolidated material with larger void spaces and porosity potential.Also, the threshold value on rainfall events was set at 5 mmper rainfall event, which meant that no recharge took place for rainfall if it was less than 5 mm.

The study area consists of all four hydrogeological environments, with the Transvaal Supergroup representing the basement rocks, the Ecca Group representing the consolidated sedimentary rocks which also contains the coal reserves, the younger sediments on the surface representing the unconsolidated sediments as well as the spoils, and the volcanic rocks represented by the dolerite sills and dykes. Although the study area consists of all four geologies, only two major units are of importance which includes the consolidated Ecca sedimentary rocks and the younger unconsolidated sediments near the surface.

Since the Optimum mining area is mined for coal reserves in the Ecca group of the Karoo Supergroup, the main geologies found at the site consist of coal seams, sandstone, dolerite dykes and sills. Together with the geology the area contains two groundwater aquifers called the weathered zone and the fractured zone. As explained in3.6.1, the first mentioned zone is close to the surface and consists of weathered and eroded material and delivers very low yields. The fracture zone, mentioned in 3.6.2, on the other hand is predominantly found in basement rocks. The site of investigation does not consist of an opencast pit deep enough to reach the basement rocks, but consists rather of contact zones that act like a fractured zone. These are zone created by dolerite dykes and sills as well as the contact barrier between the coal seams and sandstones.

The indirect recharge method occurs in the study area since the climatic conditions are semi-arid and the area contains numerous dams and rivers through which river and dam bottom infiltration can occur. Also during the mining operation joints, fractures and cracks developed within the undisturbed rock which acts as preferential pathways for recharge water. The direct or diffuse method also occurs in this area where opencast mining has occurred, since the virgin ground has been disturbed and thrown back into the opencast, which increased the void space and soil porosity, which in turn increases the amount of recharge that takes place during a rainfall event.

The two study areas that will be focussed on, namely the Optimus and Zevenfontein opencast pits, are partially to fully rehabilitated. Both of these sites decant at their lowest elevation and pumping only occurs to prevent decanting. In this study man-made factors such as the way rehabilitation takes place, has a major impact on the values calculated for recharge, which will be seen when the Zevenfontein and Optimus areas recharge values are compared (Chapter 8 and 9).

For the data available the groundwater balance approach was chosen due to the fact that there was an abundance of water level, pumping and rainfall data from the end of 2011 until the start of 2015. Also, these methods are fairly easy to apply to the study area due to their parameter requirements as well as the basic method they calculate recharge on. This basic method simply states that the inflows and outflows are directly linked to the change in water levels. For this study, more parameters were added in the hope that a more accurate representation of recharge for the area could be obtained.

3.9 Summary

Before recharge calculations can begin the geomorphic environment needs to be understood so that the parameters needed for the recharge calculations are correct or at least correctly estimated. When all the geomorphic characteristics are understood a conceptual model needs to be created and thus all the interactions between these parameters are understood for recharge calculations.

The Optimum mining operation is situated in the coal belt op Mpumalanga in the Olifants River Basin where numerous studies about recharge have already been done. The climate for this area ranges between sub-tropical and semi-arid with an average rainfall of between 500 mm and 1 000 mm, with distinct dry and wet seasons. The average evaporation of the area is 1 700 mm per year which is higher than the annual rainfall. This means that recharge of the area is estimated at 3–6% of rainfall and that only singular high rainfall events lead to the infiltration of rainfall and eventually the replenishment of the groundwater table. It is then safe to assume that setting the rainfall infiltration threshold at nothing less than 5 mm would mimic the environmental conditions for rainfall infiltration. Rainfall for this area only occurs on a local scale. Furthermore, the rainfall is not spatially homogeneous with areas receiving high rainfall and the adjacent areas can stay dry. This leads to the conclusion that studies on regional scale will not provide qualitative data on recharge for rainfall. Local scale recharge calculations would be of more use to get a true representation of actual recharge for an area.

The study area is situated in the Karoo Supergroup which contains mostly sandstones, with the Vryheid Formation being the coal bearing horizon. Overlying the geological formations is the topsoil which mostly consists of red-yellow-grey latosols followed downward by red and black clays.

The mining area contains two aquifer systems:

- The weathered groundwater aquifer is the most prominent in the area and provides shallow (5–15 mbgl), clean water to the area, but at a very low yield.
- The fractured groundwater aquifer is encountered at 30 mbgl, and is not so prominent due to its depth and that recharge only takes place through secondary fracture.

In the past, the mine's run-off adversely affected the surrounding environment by contaminating clean groundwater. Currently, certain legislation dictates that mines have a responsibility for any contamination that can take place and the subsequent rehabilitation and clean-up thereof. Thus, the mines place more emphasis on the containment and treatment of polluted mine water through strategic pumping throughout the mine (circular systems).

The study area (Optimum) consists of five opencast mining areas with some having an underground mining component. The area also contains numerous surface water bodies acting as water control and evaporation dams which all serve the purpose of keeping contamination of the surrounding environment to a minimum.

Chapter 4
Recharge Investigation

4.1 Introduction

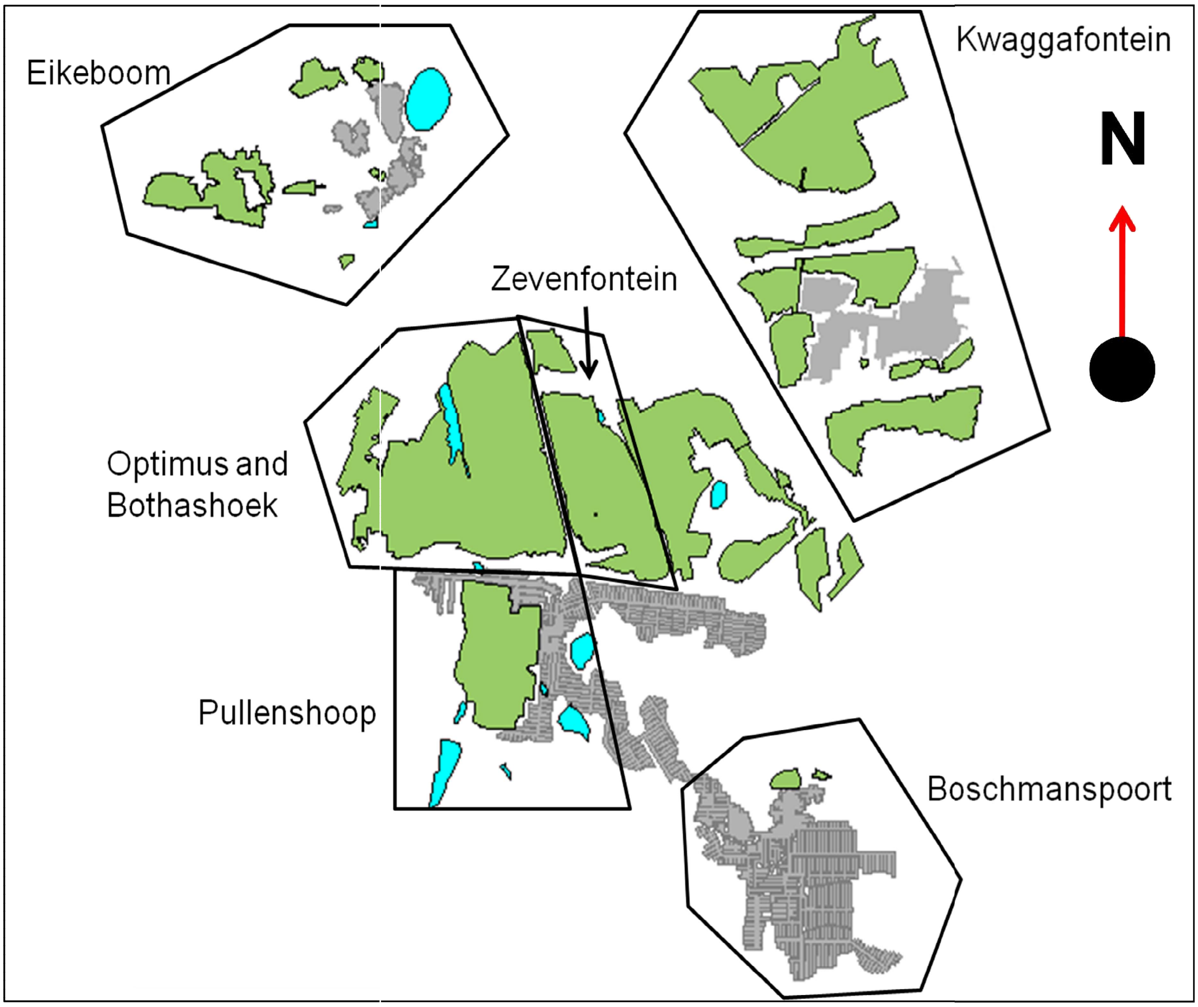
To calculate the recharge value for an area, all the factors that contribute to recharge must first be determined whereby a conceptual model of the area can be made. After the conceptual model is understood the recharge estimation methods can be chosen, which suites the area and conceptual model the best. It must be kept in mind that the method and calculation used to determine an accurate water balance and recharge value is totally dependent on the area. Poorly chosen methods that are more suited to either wet or dry areas can lead to poor results. Since this study focused on drier regions and mining areas, the methods were chosen to accompany these conditions.

The methods chosen (Chapter 2) were mainly structured around the workings of a water balance and require an abundance of data. It is preferable that the data needed was collected systematically, on a monthly basis, over a period stretching three years and onwards. This data included monthly measurements of water levels, rainfall volumes, pumping rates, borehole locations, pit and rehabilitation data.

For this study, the Windows Interpretation Software for the Hydrogeologist (WISH) was used, where the data was read into an Excel file which the program could read. The data previously sorted, could then be used to calculatethe complex geohydrological values (stage curve volumes) and create groundwater maps of the area.

4.2 Mining area

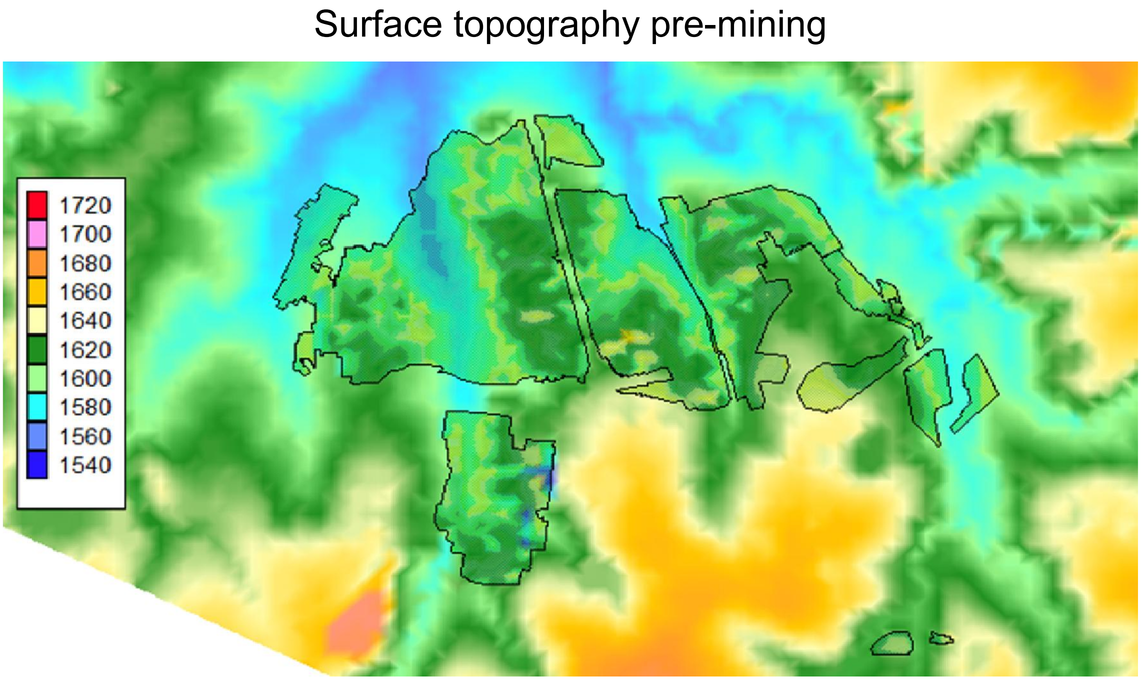
The recharge calculations this study focused on was done at the Optimum Mine for opencast pits, Optimus and Zevenfontein. The Optimum Mine encompasses and area of 169 886 125 m^2 and consists of five main mining areas, both opencast and underground (Figure 4.1).



Source: Author's own (2017)

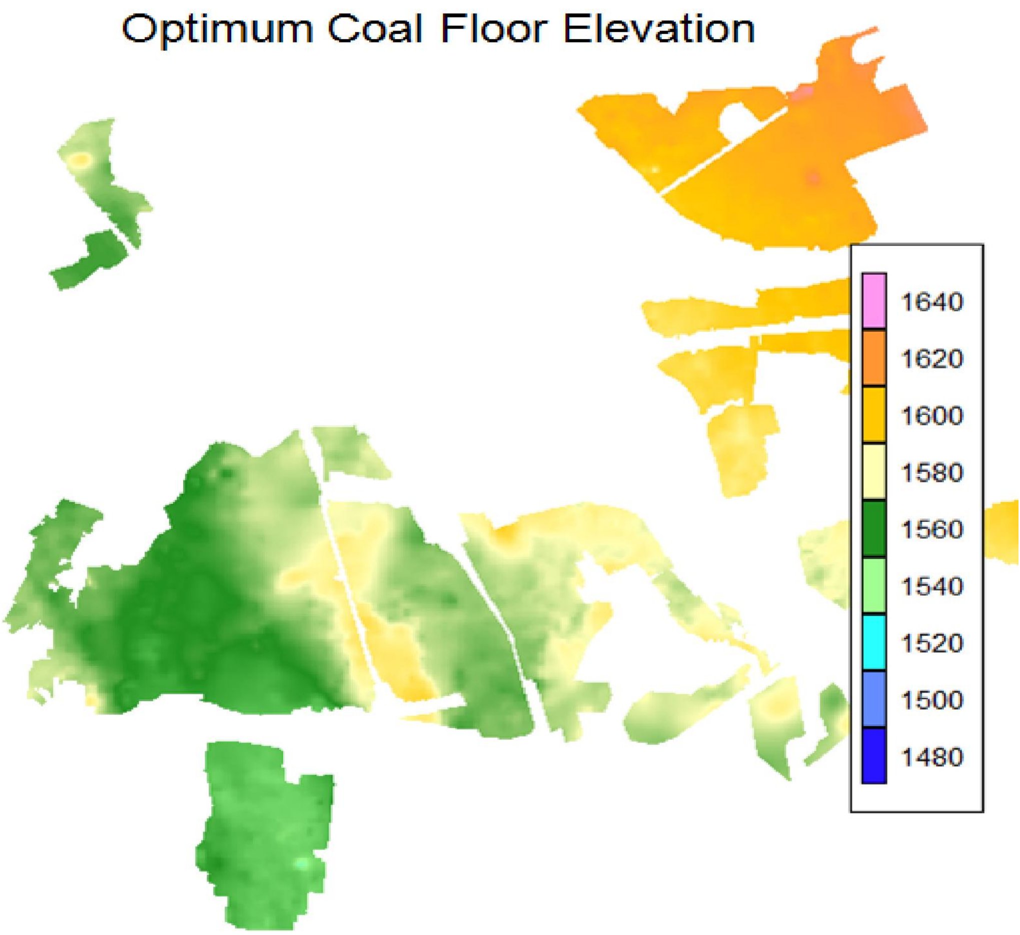
Figure 4.1: Optimum layout and its associated mining operations

For this study, mining data was used to draw the polygons of the outline of the mining areas as well as their associate opencast and underground mining operations. The detail used in this step was crucial (Chapter 5 and 8) since these outlines were used to determine the in-pit spoil volumes, as well as the stage curve volumes for each opencast mine. Data of the coal seam floor, coal seam roof, original topography and rehabilitated surface was also read into the program to interpret and calculate in-pit spoil volumes (Figures 4.2 and 4.3).



Source: WISH (2017)

Figure 4.2: Surface elevation map of the Optimum mining area



Source: WISH (2017)

Figure 4.3: Elevation of the Optimus and Zevenfontein coal seam floors

4.3 Research investigation

4.3.1 Introduction

In this study there will be focused on, if recharge can be calculated for a rehabilitated opencast pit by using readily available data provided by the mine itself. It must be mentioned when calculating in pit volumes to obtain a voidspace percentage, the topsoil removed during the initial mining process is stored on a heap and some of that topsoil is lost due to erosion. This means the capping layer is less than removed and recharge will be higher than that of the virgin ground surrounding the open cast rehabilitated mine.

Secondly, existing recharge methods will be selected and compared to recharge methods which will be formulated using only the data provided. Through this method of comparison, it is assumed that a more accurate representation of the recharge in the area can be achieved. It is of strong believe that the data collected over the years, by the mine itself, will be sufficient to calculate recharge and in doing so gain a clearer understanding of the water balance in that area. Calculating recharge is notoriously complex due to the numerous parameters needed, some of which are difficult to obtain or needs to be estimated. Using inverse modelling techniques, it was hoped that these parameters can be calculated. Various recharge methods will need to be used and compared to each other to formulate an equation which best suites the area. If recharge from rainfall can be calculated and yields conclusive results, the subsequent water volumes and water level changes can be anticipated, which will result in a more accurate water management scheme for the mine.

The research methodology for this study is a brief summary of all the methods used which include all the recharge calculations, pit volume calculations and the analysis method used on the water levels and pumping rates.

4.3.2 Pit volume calculations

The main objective of pit calculations is to produce a void space percentage for the spoils in the Optimus rehabilitated opencast pit. Opencast pit calculations were done in an attempt to determine the void space of the rehabilitated spoils. As explained in the Chapter 3, it is important to have data on the mining environment as this affects recharge calculations.This was done by comparing the coal seam floor, coal seam roof, original surface topography and rehabilitated surface with each other to determine their respective volumes. The volumes calculated for these layers are now compared to the spoils thrown back into the opencast pit.

Although the method seems simple enough there are some limitations and assumptions that need to be accounted for, before the calculations can begin. One major assumption that needs to be made is the composition of the spoils, due to the fact that this parameter is not measured and only volume and area rehabilitate are monitored constantly. Making a decision on the composition of the spoils comes down to the local geology and the general thickness of the layers

First, a mathematical approach needs to be applied to the specific opencast pit. This means that the data collected for pit calculations needs to be applied into the mathematical equations to see if the method is sound and can be applied to the opencast pit. At this stage of pit calculations only the depth, area and volumes are calculated for the original topography, rehabilitated topography and coal seam bottom and top to see if they produce satisfactory results.

$$\text{Volume} = A_m^2 \times D_m$$

Where:

A_m^2 = Area

D_m = Depth of mining

When problems are encountered, and an expected void space percentage cannot be achieved, there are numerous factors that can influence the calculations. In this case the mathematical equations need to be assessed together with the data collected.

Secondly, after the mathematical equations have been corrected and every factor accounted for, the practical approach can be implemented. This means that alongside the mathematical equations, parameters and natural phenomena found in the mining environment can be added to account for any loss or gain in volume during these calculations.

The major factors that were considered included the bulking effect, mechanical compaction and shrinkage factors, which were included into the original mathematical equations.

Step 1: First, thecomposition of the spoils needs to be acquired, in percentage value, whereby the volume can be calculated using the original volume removed (Table 4-1).

Step 2: Secondly the bulking factors are applied to each individual geology volume (Table 4-1). Each geological formation has its own bulking percentage factor and needs to be applied to the calculated volume, as done in Step 1.

TABLE 4-1: SPOIL COMPOSITION AND ITS VOLUME MULTIPLIED BY THE BULKING FACTORS

Bulking Factor Calculations				
Spoil Composition	**Percentage Composition of spoils (%)**	**Volume composition(m3)**	**Bulking factors (%)**	**Bulking Volume**
Geology 1	A	1*A	BF 1	(1*A)BF 1
Geology 2	B	2*B	BF 2	(2*B)BF 2
Geology 3	C	3*C	BF 3	(3*C)BF 3
Geology 4	D	4*D	BF 4	(4*D)BF 4
Geology 5	E	5*E	BF 5	(5*E)BF 5
			Total Bulking Volume	**Total SUM**

Step 3: The loss of spoil material needs to be accounted for when the spoil material is stored on a heap. Erosion is the major contributor to this loss of material and is expressed as a percentage loss of the Total SUM calculated in Table 4-1.As erosion is a parameter seldom measured it has to be estimated and scenarios must be created as seen in Table 4-2.

TABLE 4-2: EROSION FACTORS AND SPOIL VOLUME LEFT OVER AFTER THE LOSS

Erosion Loss on Bulking Volume			
	Scenarios (%)		
	A	B	C
Loss	(Total Sum * A)	(Total Sum * B)	(Total Sum * C)
Total Volume	Total Sum – (Total Sum * A)	Total Sum – (Total Sum * B)	Total Sum – (Total Sum * C)
	TOT Vol. 1	**TOT Vol. 2**	**TOT Vol. 3**

Step 4: Once thetotal volume left over for rehabilitation after erosion has been calculated, the mechanical compaction of heavy machinery has to be factored in to the TOT Vol. 1 calculated in Table 4-2.As with erosion, mechanical compaction is a parameter that is never measured and thus scenarios need to be created for each scenario in Table 4-2 as seen in Table 4-3.

TABLE 4-3: MECHANICAL COMPACTION FACTOR AND THE SCENARIOS CREATED

Mechanical Compaction factor				
Erosion Vol.		**Erosion %**		
		Scenarios for mechanical compaction (%)		
TOT Vol. (1,2 or 3)		**A**	**B**	**C**
		TOT Vol.* A	TOT Vol.* B	TOT Vol.* C
	Volume of spoils left	**TOT VOL A**	**TOT VOL B**	**TOT VOL C**

Step 5: The shrinkage factor is the most important parameter as it is with the bulking factor and is done in the same manner (Table 4-4). Geological composition and shrinkage factor are all calculated as a percentage value and applied to the volume left over for rehabilitation after bulking, erosion and mechanical compaction have been factored in (Table 4-1 to Table 4-3).

TABLE 4-4: SHRINKAGE FACTOR APPLIED TO THE EROSION LOSS AND MECHANICAL COMPACTYION FACTOR VOLUMES

Shrinkage factor						
			Erosion	**A B or C %**		
			Mechanical compaction%	**A%**	**B%**	**C%**
	Percentage Composition of spoils (%)	**Shrinkage Factor**	**Spoil volume**	**TOT VOL**	**TOT VOL**	**TOT VOL**
Geology 1	A	SF 1		TOT VOL * A * SF1		
Geology 2	B	SF 2		TOT VOL * B * SF2		
Geology 3	C	SF 3				
Geology 4	D	SF 4				
Geology 5	E	SF 5				
			TOTAL VOL for rehab	**Final VOL.1**	**Final VOL.2**	**Final VOL.3**

Step 6: The calculated volumes left over for the spoils are now compared to the volume needed to fill the opencast pit. This difference in volume can be considered the void space within the spoil material as seen in Table 4-5.

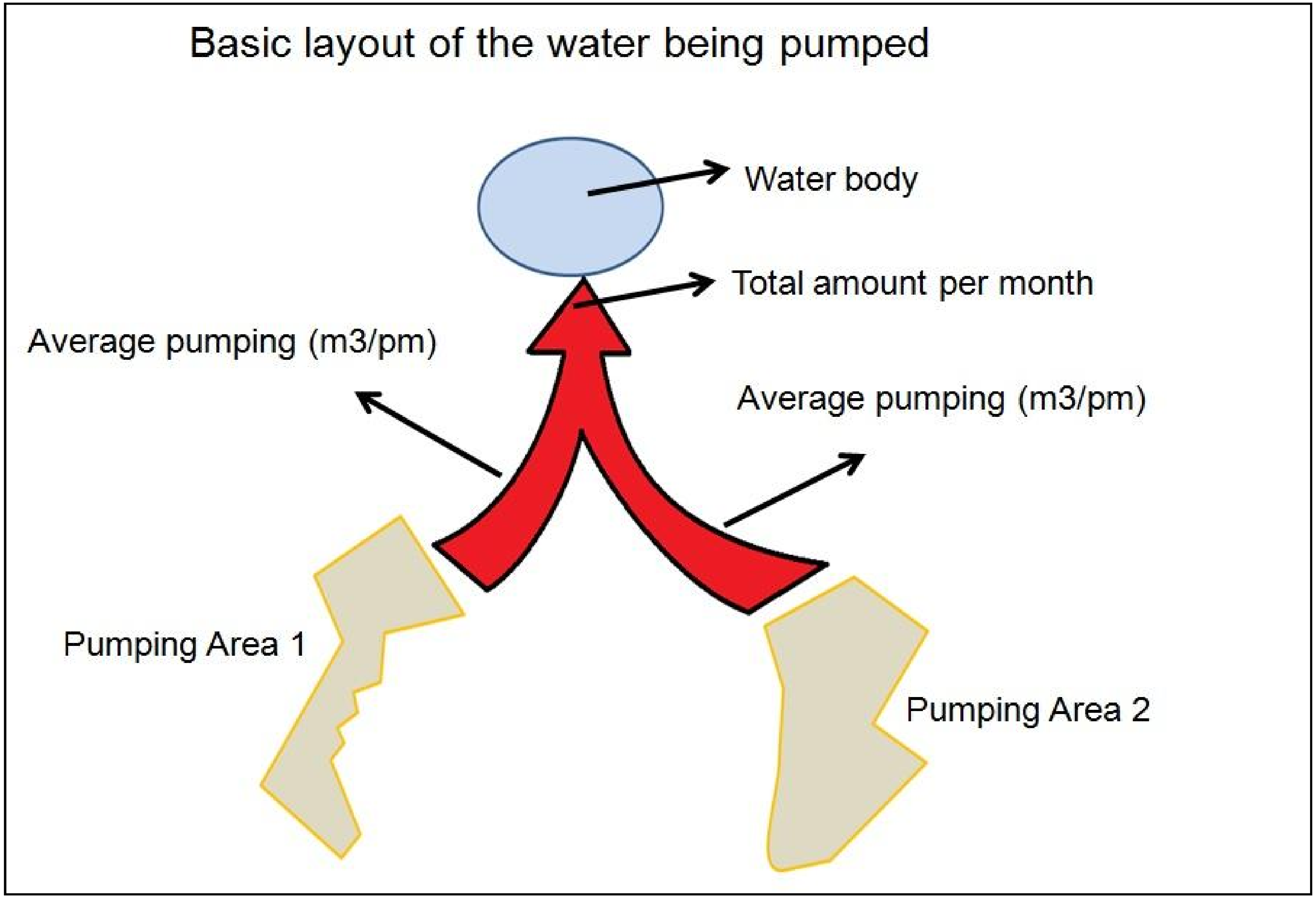
TABLE 4-5: FINAL VOID SPACE CALCULATION

Final Pit Volume Void Space Calculation			
Erosion%	A B or C		
Mechanical Compaction %	**A**	**B**	**C**
TOTAL Vol for rehab	**Final VOL.1**	**Final VOL.2**	**Final VOL.3**
Volume needed to fill pit	**FILL Volume**		
Difference in Volume	FILL Volume - Final VOL.1	FILL Volume - Final VOL.2	FILL Volume - Final VOL.3
Void space	**(Difference 1/FILL Volume) * 100**	**(Difference 2/FILL Volume) * 100**	**(Difference 3/FILL Volume) * 100**

4.3.3 Pumping cycles

In the mining environment, determining the pumping rates are crucial in keeping the mining operation dry and to stop decanting, but are also a crucial parameter in determining recharge from rainfall. When the methods for recharge calculations were discussed, most of the methods required an abstraction rate. Knowing the inflow and outflow values and the amount of water abstracted, the rest of the water left must be recharged from rainfall, run-off, dams and rivers.An advantage of determining the pumping rates and the location of abstraction can also be used in the analysing of water levels. In this study, Chapter 6 explains in a great detail how the water is pumped throughout the mining operation and how the volumes abstracted influences the water levels for that specific area.

Monthly pumping rates and the areas they were extracted from were analysed so that a conceptual model of the area's pumping regime could be established. Averages for the pumping rates, as well as the water's destinations, were established. This information was then represented on the Optimum mining area map as a flow chart which indicates direction of the water extracted and the average volume of that water per month (Figure 4.4).



Source: Author's own (2017)

Figure 4.4: Diagram illustrating the pumping cycle with the direction of pumping (red arrow), pumping average, pumping total and its final destination (blue circle)

4.3.4 Borehole water levels and rainfall

After the location and the layout of the mining operation have been completed, the rainfall and water level data collected from the Optimum Mine could be sorted. Although looking at the water levels and rainfall values can give an idea of the groundwater fluctuations and seasonal rainfall patterns, it would be advisable to group the data according to the date they were taken as well as the specific area they were taken in. This is done due to the fact that the recharge in this study is done on a local scale and detailed data about specific areas and opencast pits are more valued than that of a larger scale study.Here, the rainfall data is analysed as millimetres per month and represented as a 12-month cycle from 2010 to 2014, to determine the dry and wet seasons. Secondly, the rainfall data is represented on one timeline from 2010 to 2015 to determine the trend and average rainfall from that area.

When the areas were decided upon, the water levels and rainfall events were compared to each other. This form of data analysis was implemented to determine if there was any lag time between a rainfall event and a change in water levels. It can also be used to compare each borehole or area separately to determine their response times in comparison to a rainfall event as well as the amount of change in water level over the rainfall period.

When the borehole water levels were analysed, the borehole positions needed to be group together to determine which of them were situated in the same aquifer, as comparing water levels from different aquifers served no meaning. To group the water levels from the same aquifer together, firstly the area needed to be defined. In this case the different opencast areas of the Optimum mining area already served as the boundaries in which the boreholes resided. Secondly, all the borehole water levels of that specific opencast area are grouped together on a water level chart to determine which of those water levels display the same elevations and trends in fluctuations. After the water levels are grouped together different aquifer areas within the opencast area can be defined.

Now that the aquifers have been established the borehole water levels in each aquifer can be compared to the pumping rates and rainfall data. This is done to determine the amount of positive and negative fluctuations in water levels caused by the two previously mentioned parameters.

4.3.5 Recharge calculations

4.3.5.1 Rainfall infiltrated volume method

The rainfall infiltrated volume (RIV) method works on the concept that the rainfall that infiltrates every month is influenced by the amount and type of rehabilitation at that specific time. This method can be used to see if the water infiltrated from rainfall matches that of the pumping rates produced by the mining operation over a period of time. In the table below, an example is given were the RIV method is explained. It basically works on the concept that the rainfall that infiltrates into the spoils, are affected (decreases) by the parameters that are added as seen in Table 4-6.

TABLE 4-6: CALCULATIONS FOR THE RIV METHOD

Rainfall Infiltrated Volume (m^3) = Rainfall (mm) * Rehabilitation area (ha) * Recharge Factor (%) * Porosity (%)

Parameters used for rainfall infiltrated volume calculations

	Different types of spoils					
	Cuts and ramps	**Two rows of spoil**	**Opencast spoils**	**Levelled spoils**	**Top-soiled spoils**	**Grassed spoils**
Rainfall (mm)	R 1	R 2	R 3	R 4	R 5	R 6
Area	A 1	A 2	A 3	A 4	A 5	A 6
Recharge factor (%)	RF 1	RF 2	RF 3	RF 4	RF 5	RF 6
Porosity (%)	P 1	P 2	P 3	P 4	P 5	P 6
RIV	R 1 * A 1 * RF 1 * P1	R 2 * A 2 * RF 2 * P 2	R 3 * A 3 * RF 3 * P 3	R 4 * A 4 * RF 4 * P 4	R 5 * A 5 * RF 5 * P 5	R 6 * A 6 * RF 6 * P 6
	RIV 1	RIV 2	RIV 3	RIV 4	RIV 5	RIV 6

Total RIV	RIV 1+ RIV2+RIV3+RIV4+RIV5+RIV6

After each volume that infiltrated for each spoil has been calculated they are added together to determine the total rainfall that infiltrated for that area.This method was applied to the Optimus and Zevenfontein opencast areas which were already in the process of being completely rehabilitated.

4.3.5.2 Stage curve volume method

The stage curve volume calculation works on the concept that the total volume of water inside the rehabilitated opencast mine is directly affected by the change in water level over a period. To make this method work effectively the following steps need to be taken.

Step 1: Choose a period of time over which the water levels increase or decrease.

Step 2: Make an informed decision on the maximum and minimum allowable void space percentage within the pit.

Step 3: Calculate the volume of water within the pit at those two specific water level elevations using stage curve volumes set at the maximum and minimum void spaces.

Step 4: Subtract the first water level elevation volume from the second volume and the divide that volume by the volume of pumping that took place over that specific time.

Thus, parameters such as water level elevation, stage curve volumes, void space percentages and pumping rates are required for this method to work.

The equation is as follows:

$$Porosity(n) = \frac{StageCurveVol1_{(month1)} - StageCurveVol2_{(month2)}}{Sum\ of\ pumping\ over\ period}$$

4.3.5.3 Dry and wet calculations using stage curve volumes

Dry calculations

The dry calculation using stage curve volumes works on the principal of a basic water balance which takes into account all the relevant or available data and calculates the porosity of the spoils between 10% and 25% void space, which can then finally be used to calculate recharge. The assumption is made is that the volume water inside the spoils with its additional porosity equals the pumping volume and recharge over a certain period.

$$\Delta_{StageCurveVol.} \times (\boldsymbol{Porosity}\,\%) = \boldsymbol{Pumping} + \boldsymbol{Recharge}$$

During dry months there is no rainfall and thus no recharge, which means that the equation needs to be reconstructed and the recharge parameter removed.

Thus, only porosity can be calculated for the dry season.

$$\boldsymbol{Porosity}\,\% = \frac{\boldsymbol{Pumping}\ (\boldsymbol{m^3})}{\Delta_{StageCurveVolume\ (m^3)}} * \mathbf{100}$$

This porosity value can then be used in the wet calculations as an unknown parameter that was calculated to formulate a recharge value.

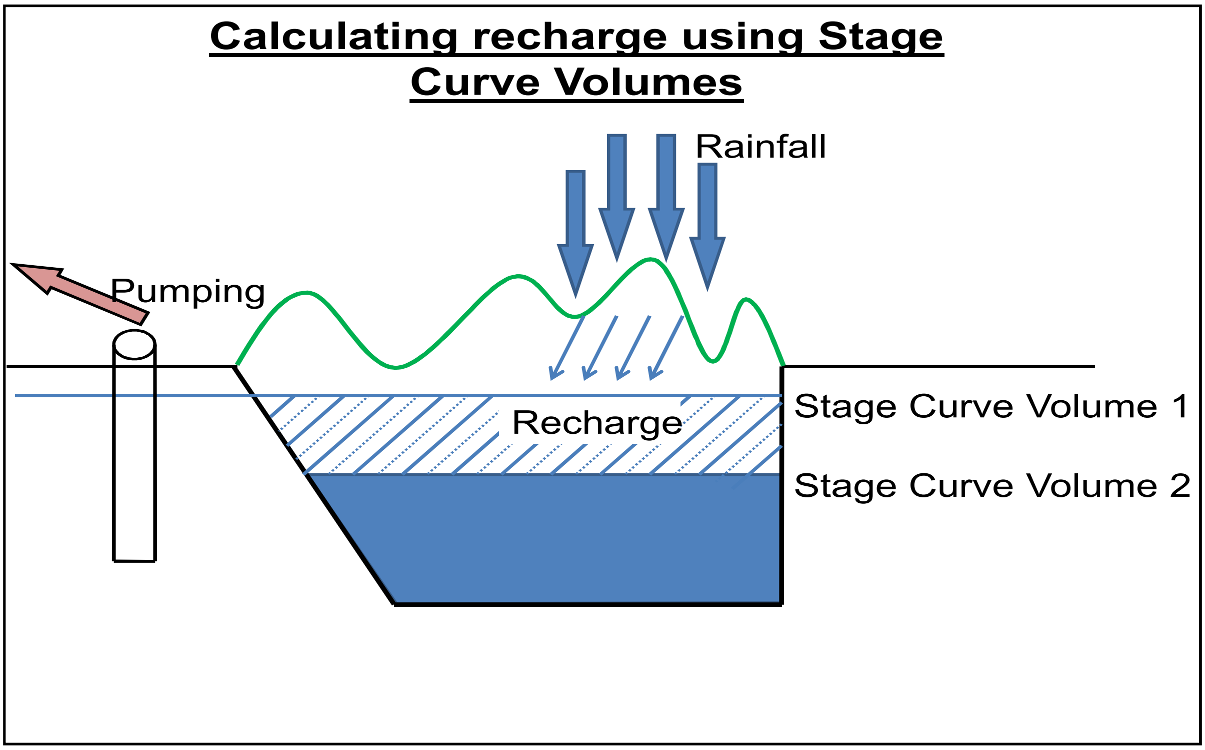
Wet calculations

For the wet seasons recharge is calculated using the porosity values calculated in the dry seasons using the following equation:

$$\boldsymbol{Recharge} = \Delta_{StageCurveVol.} \times (\boldsymbol{Porosity}\,\%) - \boldsymbol{Pumping}$$

4.3.5.4 Calculatingrecharge using stage curve volumes

This method of recharge calculation goes back to the most basic of assumptions that the change in water level, from stage curve volume 1 to volume 2, is as a result of the rainfall that infiltrated (recharge) minus the pumping that took place during that period (Figure 4.5).



Source: Author's own (2017)

Figure 4.5: Diagram illustrating the components to the Stage Curve Volume method

Thus, the equation stands as:

$$SC\ Volume\ 2(m^3) = SC\ Volume\ 1(m^3) + Recharge - Pumping(m^3)$$

Since the recharge is the unknown and is the desired value, the equation can be rewritten as:

$$Recharge = SC\ Volume\ 2(m^3) - SC\ Volume\ 1(m^3) + pumping$$

4.4 Summary

The methods discussed in this chapter only serve as a basic how to on data analysis and recharge calculations. It must be kept in mind that the recharge equations are mathematically sound and work in perfect conditions, but environmental conditions and their parameters do not. That is why some form of assumptions need to be made for the parameters needed in the recharge equations and even adding and calculating new parameters to the equations. This is why so many water balance methods were chosen so that a comparison could be made between the values calculated, and in the process estimating the correct recharge for the spoils.

Chapter 5
Pit Calculations

5.1 Introduction

When trying to determine recharge for a specific opencast pit area(s) and the subsequent water balance that follows, pit volumes need to be calculated first in order to determine thevoid space values for that area. It is important to understand the method of pit calculations, so that all the parameters are collected, and the right procedures are followed, keeping in mind all the assumptions and possible problems that will be encountered.

Determining the void space of the virgin ground is an essential part of doing pit calculations as well as the total amount of spoil that are thrown back into the pit when rehabilitation commences. The previous work on recharge that takes place in different stages of opencast mine rehabilitation serves as an excellent framework for recharge calculations (Hodgson & Krantz, 1998) (Table 5-1). Using this research done by Hodgson and Krantz (1998) and conducting a more accurate study on the research area, a true representation of actual workings can be calculated. This leads to a better understanding of the rehabilitated area and accurate future water balances, alongside long-term water management strategies.

TABLE 5-1: INFILTRATION PERCENTAGES FOR AN OPENCAST MINING ENVIRONMENT

Suggested rainfall infiltration percentage for opencast rehabilitated pits		
Sources of rainfall	**Rainfall percentage infiltrated into pit**	**Suggested average values**
Rain onto ramps and voids	20−100%	70% of rainfall
Rain onto unrehabilitated spoils (run-off and seepage)	30−80%	60%
Rain onto levelled spoils (run-off)	3−7%	5%
Rain onto levelled spoils (seepage)	15−30%	20%
Rain onto rehabilitated spoils (run-off)	5−15%	10%
Rain onto rehabilitated spoils (seepage)	5−10%	8%
Surface run-off from pit surroundings into pits	5−15%	6%
Groundwater seepage	2−15%	10%

Source: Hodgson and Krantz (1998)

5.2 Mathematicalapproach to pit volume calculations

The mathematical approach to pit calculations are based on what should happen in real circumstances concerning the opencast mining operation and formulating an equation(s) for those activities. For obvious reasons these formulas can't be 100% accurate due to the fact that many uncertainties and natural occurrences can't be formulated into mathematical equations and as a result some assumptions are made, and the initial equation is altered. Equations 5a to 5e demonstrates perfect conditions under which the pit calculations can be done and which the calculations that follow are based upon (Figure 5.1).

The first volume that is calculated is of the original virgin ground before mining took place and thus the void space of the virgin ground is unchanged (Figure 5.1).

$$Vol._{V1} = A_m^2 \times D_m \qquad \text{Equation 5a}$$

Where:

$Vol._{V1}$ = Volume of original virgin ground

A_m^2 = Area of virgin ground (area before mining)

D_m = Depth of mining (to base of coal seam)

The second volume that is calculated is of the coal seam. This volume needs to be calculated and subtracted from the virgin ground since the coal seam is removed and not thrown on the spoil dump (Figure 5.1).

$$Vol._{CS} = A1_m^2 \times D1_m \qquad \text{Equation 5b}$$

Where:

$Vol._{CS}$ = Volume of coal seam

$A1_m^2$ = Area of coal seam

$D1_m$ = Thickness of coal seam

$$Vol._{Spoil} = Vol._{V1} - Vol._{CS} \qquad \text{Equation 5c}$$

Where:

$Vol._{Spoil}$ = Spoils available for rehabilitation

$Vol._{CS}$ = Volume of coal seam floor

Assumption: After spoils ($Vol._{Spoil}$) have been used to rehabilitate the opencast mine, a new topographical elevation is created (A2m) (Figure 5.1).

$$\mathbf{A2m} = \mathbf{A1} - \mathbf{Area}(\mathbf{m^2}) * \mathbf{Final\ Void}(\mathbf{m^2}) \qquad \text{Equation 5d}$$

Now that the calculated spoil volume (Eq.5c) has been thrown back into the opencast pit a new topographical surface has been created (A2m) as well as a new depth (D2m) (Figure 5.1 Diagram 2). Calculating the volume for the rehabilitated opencast pit and subtracting the spoils volume from the original volume ($Vol._{V1}$) (Eq. 5a) yields a final void value. As a result, it can be seen that there is less spoils available for rehabilitation than what was removed. This difference can then be used to calculate the porosity of the rehabilitated opencast pit.

$$Vol._{topo} = A2m \times D2m \qquad \text{Equation 5e}$$

Where:

$Vol._{topo}$ = Volume of spoils thrown back into opencast pit

A2m = Area of new levelled topography

$D2_m$ = Depth of new rehabilitated pit (from levelled spoil surface to base of coal seam floor)

Then:

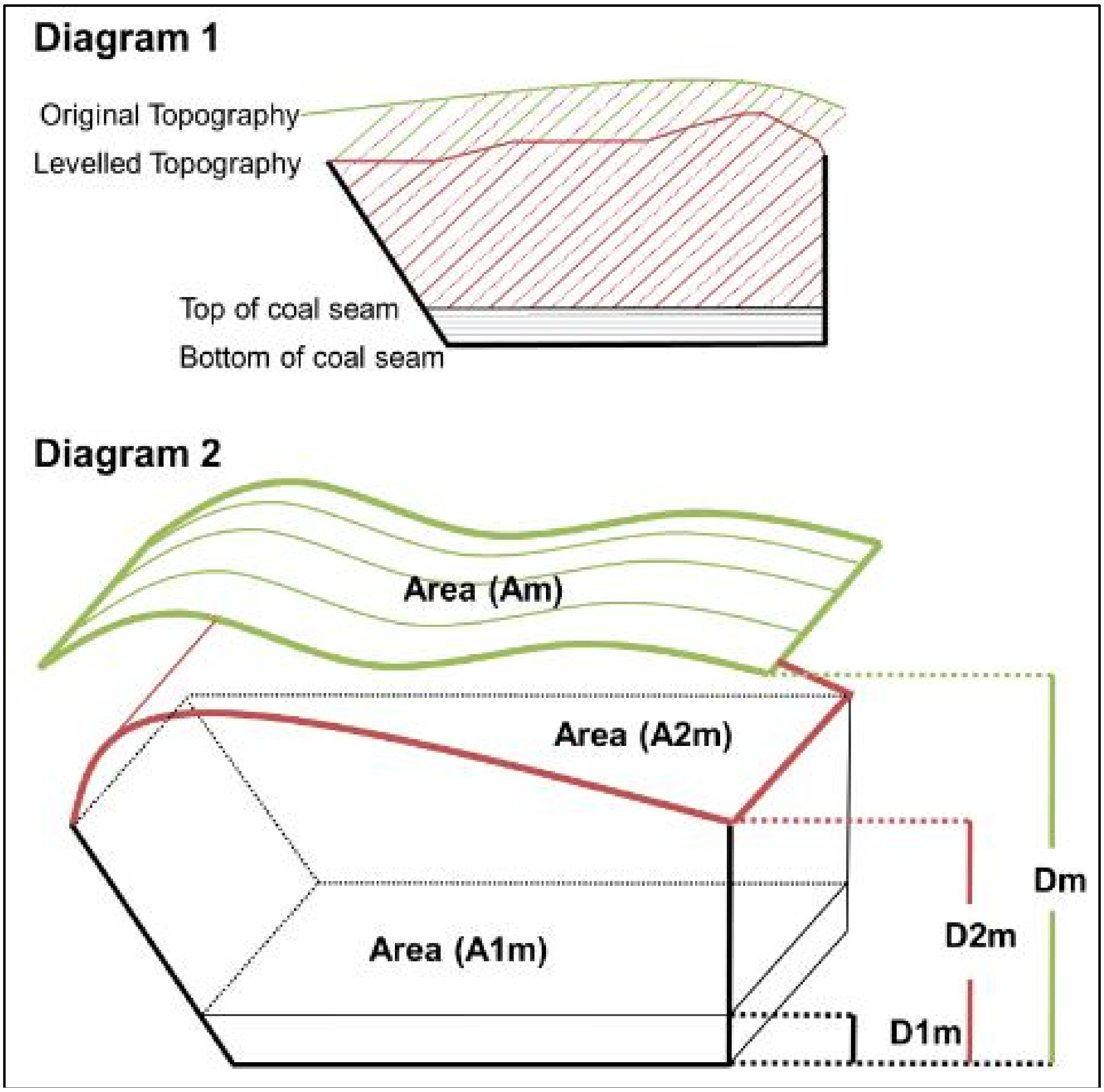
$$\frac{Vol.V1 - Vol.spoils}{Vol.V1} * \mathbf{100} = \text{Rehabilitated void space (\%)} \qquad \text{Equation 5f}$$

Assumption: The spoils consist of numerous geological formations of different grain sizes (from less than 0.1 mm to boulder size). The parent void space (virgin void space) must also be added to the rehabilitated void spaceto account for the boulders that did not break during the extraction of the coal and still have their original porosities.

Thus:

Final pit porosity = Rehabilitated void space (Eq. 5f) +
Virgin void space (area estimate) = true void space

Mathematical approach



Source: Author's own (2017)

Figure 5.1: A graphic representation of theoretical calculations from Equations 5a to 5e

5.2.1 Problems encountered when applying the mathematical approach

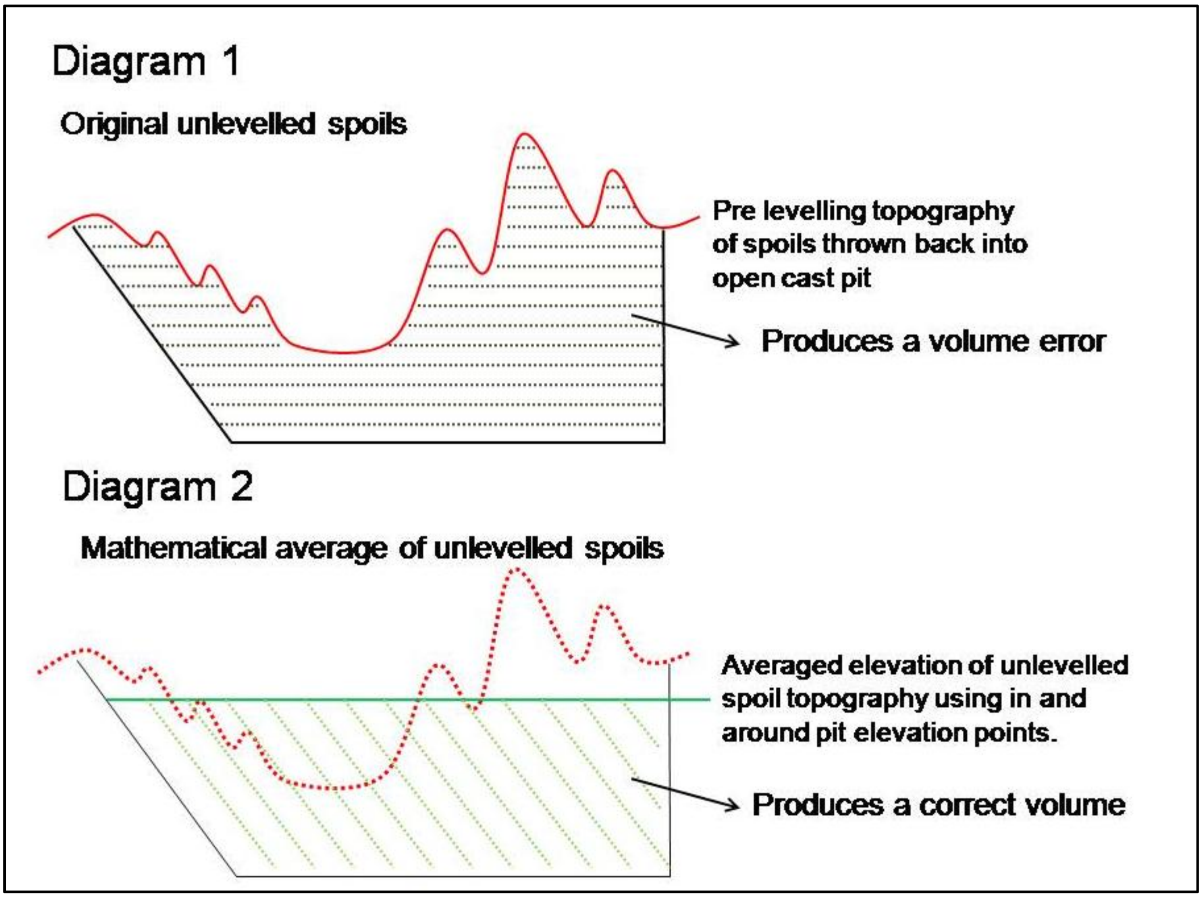
As mentioned before in the mathematical calculations (Chapter 5.2), there are some real-world scenarios that cannot be formulated into mathematical equations or can't represent 100% of the natural and mining environment. In an attempt to counteract these problems assumptions are made that fit the area and can be used to further the calculation of spoil void space.

What follows are problems encountered when trying to apply mathematical equations and real-world scenarios.

First,an accurate record is needed for the amount of material removed from the pit area when mining commenced. In this case, the data was not available and thus the original topography from previously mapped geographic maps was used. Using the depth (surface elevation−top of coal seam elevation) and the area, a volume for the pit could be calculated. The geographic maps also posed a problem, as coordinate changes needed to be done from the WGS 84 to Cape Datum coordinate system. This coordinate change can't be done 100% accurately and thus small errors are incurred. Thus, to solve the problem the elevation points from around the opencast pits were taken, to interpolate an original surface topography in conjunction with the topographical maps (using WISH).

Secondly,the stage of rehabilitation needs to be recorded. In this case rehabilitation was recorded but only in hectares (surface area) and not in volume as required for pit volume calculations. This problem was overcome by using the surface for the already rehabilitated area and multiplied by the depth of the opencast pit. This gave a suspect volume seeing that the volume thrown back into the pit was more than that was originally removed. This phenomenon is due to the bulking factor which means that virgin ground removed, expands in volume from 20−80% depending on the grain and boulders size when thrown on a heap. The bulking factor poses an unsolvable problem as there is no way to accurately estimate the composition of the materials and the grain size of the spoils if no data was collected for this specific pit calculation. Thus, to overcome this problem the only viable solution is to create scenarios with different bulking factors and applying them to best suit the area of study (Table 5-3).

Lastly, the new topography of spoils was given but were not at the stage were levelling and compaction already took place. The significant elevation changes caused a volume error to occur when comparing the original and new spoil topography with each other (Figure 5.2 Diagram 1). To overcome this problem a two-step approach needed to be implemented. Firstly, the data given for the new spoil topography needed to be averaged to produce a believable elevation (Figure 5.2 Diagram 2). Secondly, using the new interpolated topography for both the original surface and spoils, a believable value for both were produced, without the bulking factor.



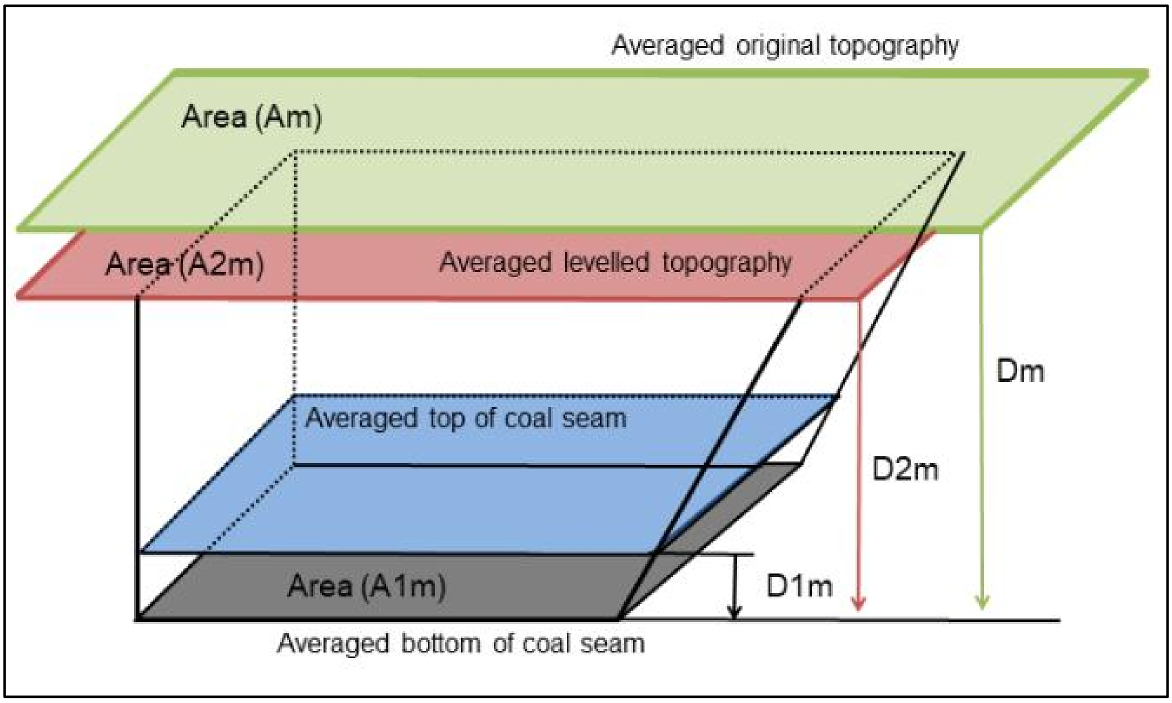
Source: Author's own (2017)

Figure 5.2: Before and after spoil topography has been averaged

5.3 Practical approach to pit volume calculations

The calculations that follow are based upon the mathematical calculations with the addition of new parameters which includes material composition, bulking factors, mechanical compaction, shrinkage factors and erosion. The new parameters that were added need to be calculated in that order otherwise volume errors will occur. The practical approach is essential the same as the mathematical approach but with the addedcalculations of the new parameters.

Practical calculation



Source: Author's own (2017)

Figure 5.3: Visual representation of the practical pit calculations in equations 5a to 5e

As in the mathematical calculations, the first step is to calculate the volume of the opencastpit before mining commenced (Equation 6a). Then calculating the volume of coal removed (Equation 6b) and subtracting these two volumes from each other to produce a total volume of waste available for rehabilitation (Equation 6c). The equation is also the same, but instead the averaged elevations were used (Figure 5.2 Diagram 2).

$$Vol._{V1} = A_m^2 \times D_m \qquad \text{Equation 6a}$$

Where:

$Vol._{V1}$ = Volume of original virgin ground

A_m^2 = Area of virgin ground (averaged topography)

D_m = Depth of mining (averaged elevation)

$$Vol._{CS} = A1_m^2 \times D1_m \qquad \text{Equation 6b}$$

Where:

$Vol._{CS}$ = Volume of coal seam

$A1_m^2$ = Area of coal seam (averaged elevation)

$D1_m$ = Thickness of coal seam

$$Vol._{Spoil} = Vol._{V1} - Vol._{CS}$$ Equation 6c

Where:

$Vol._{Spoil}$ = Spoils available for rehabilitation

$Vol._{CS}$ = Volume of coal seam floor

After the new volumes have been calculated the volume of each geology (Figure 5.4 Stage 1) needs to be calculated and their respective bulking factors areto be applied (Figure 5.4 Stage 2). Thus, the equation that follows needs to be done numerous times depending on how many geologies there are:

$$Vol.Geo\ 1 = Vol_{Spoils} \times \%\ material$$ Equation 6d

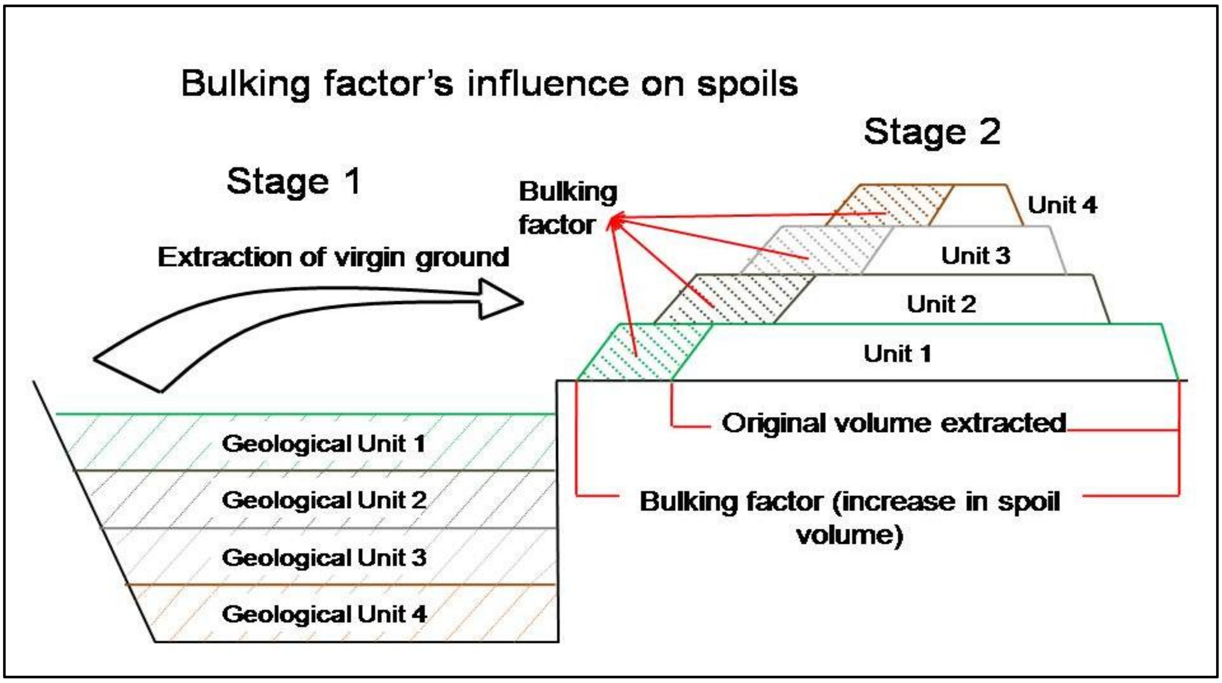
$$\text{Bulking volume 1=Vol.Geo 1*Bulking Factor}$$ Equation 6e

Vol.Geo 1= Volume of geological material 1 of spoils removed

% material = Percent of spoils consisting of spoils removed

Bulking volume 1 = Final volume expanded when thrown on heap

Bulking factor = Percent of volume increase for geological material 1

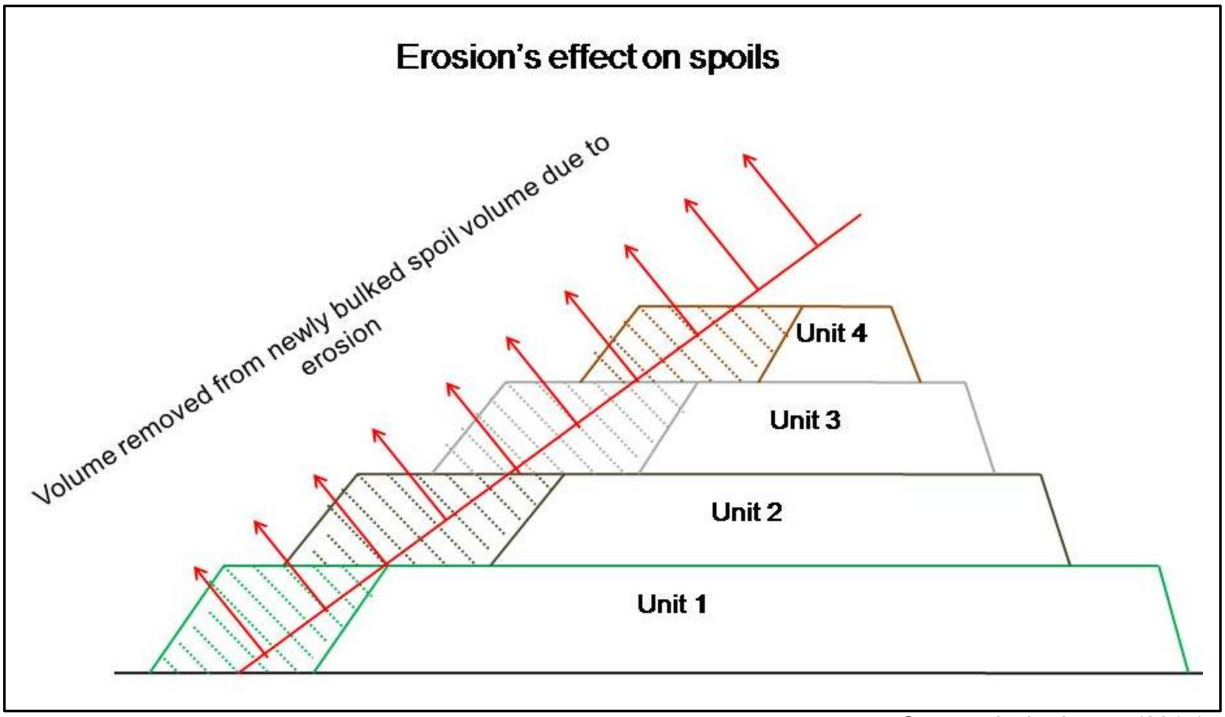


Source: Author's own (2017)

Figure 5.4: Diagram illustrating the effect of the bulking factors on the spoil volume

Now the effect that erosion has on the spoil heap is factored in and subtracted from the new calculated bulked spoil volume (Figure 5.5).

$$Volume\ erosion = Bulked\ volume - Erosion\ volume$$

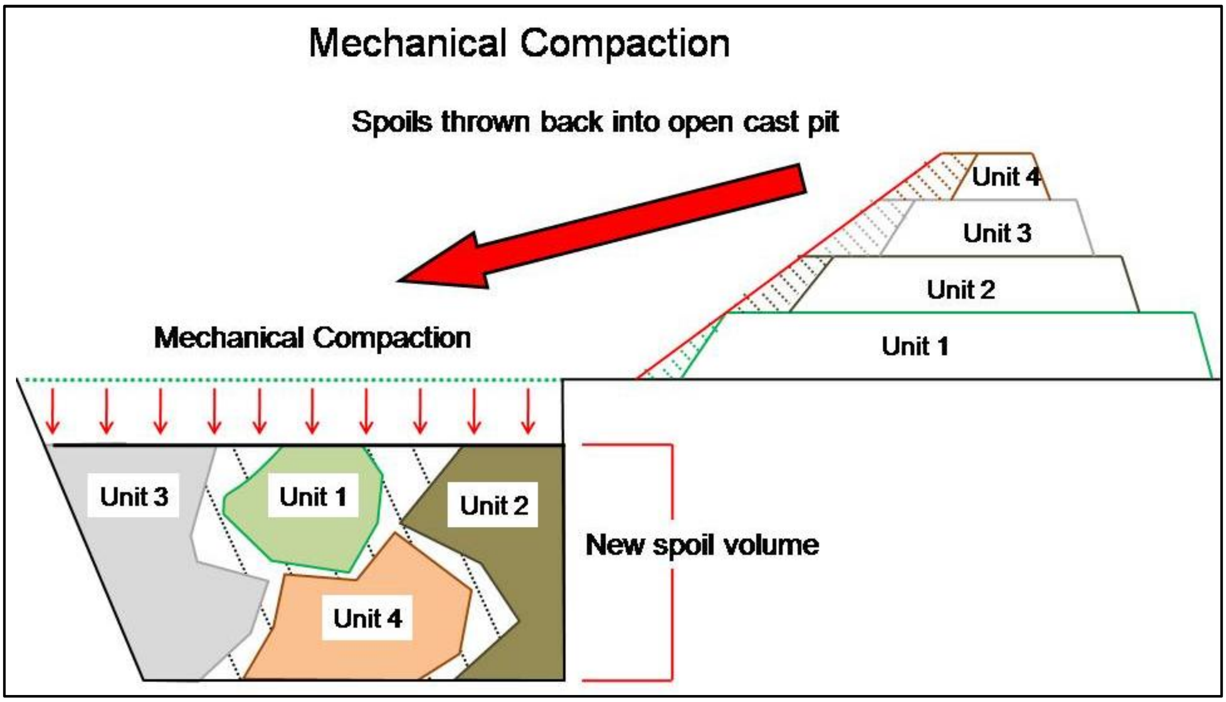


Source: Author's own (2017)

Figure 5.5: Decreasing spoil volume due to erosion

The total spoil volume left after the erosion volume have been subtracted is thrown back into the opencast pit were mechanical compaction takes place (Figure 5.6).

$$Volume\ Mech. = Volume\ erosion - \%\ mechanical\ compaction$$



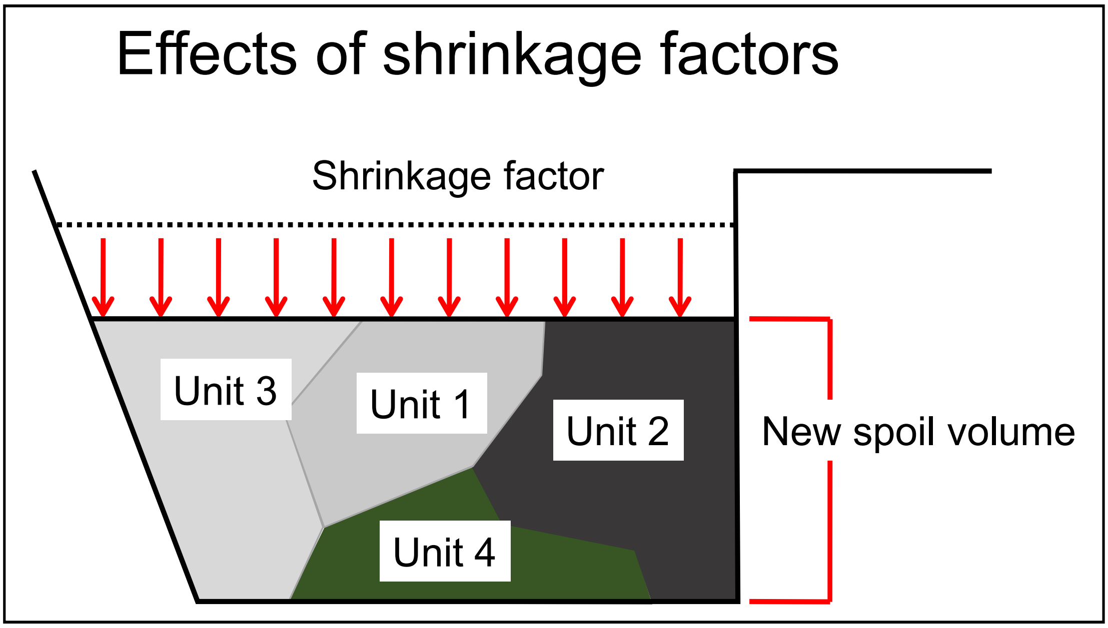
Source: Author's own (2017)

Figure 5.6: The effect of mechanical compaction on the new spoil volume

The new spoil volume calculated in Figure 5.6 is now subjected to the natural shrinkage factors of each geological unit (Figure 5.7). Thus, the new spoil volume, as with the bulking factor, need to be divided up into their own geological units and a volume must be calculated for each. Thus, the equation is as follows:

$$Vol.Geo\ 1 = New\ spoil\ volume\ (mech.comp.) - \%\ shrinkage\ factor$$

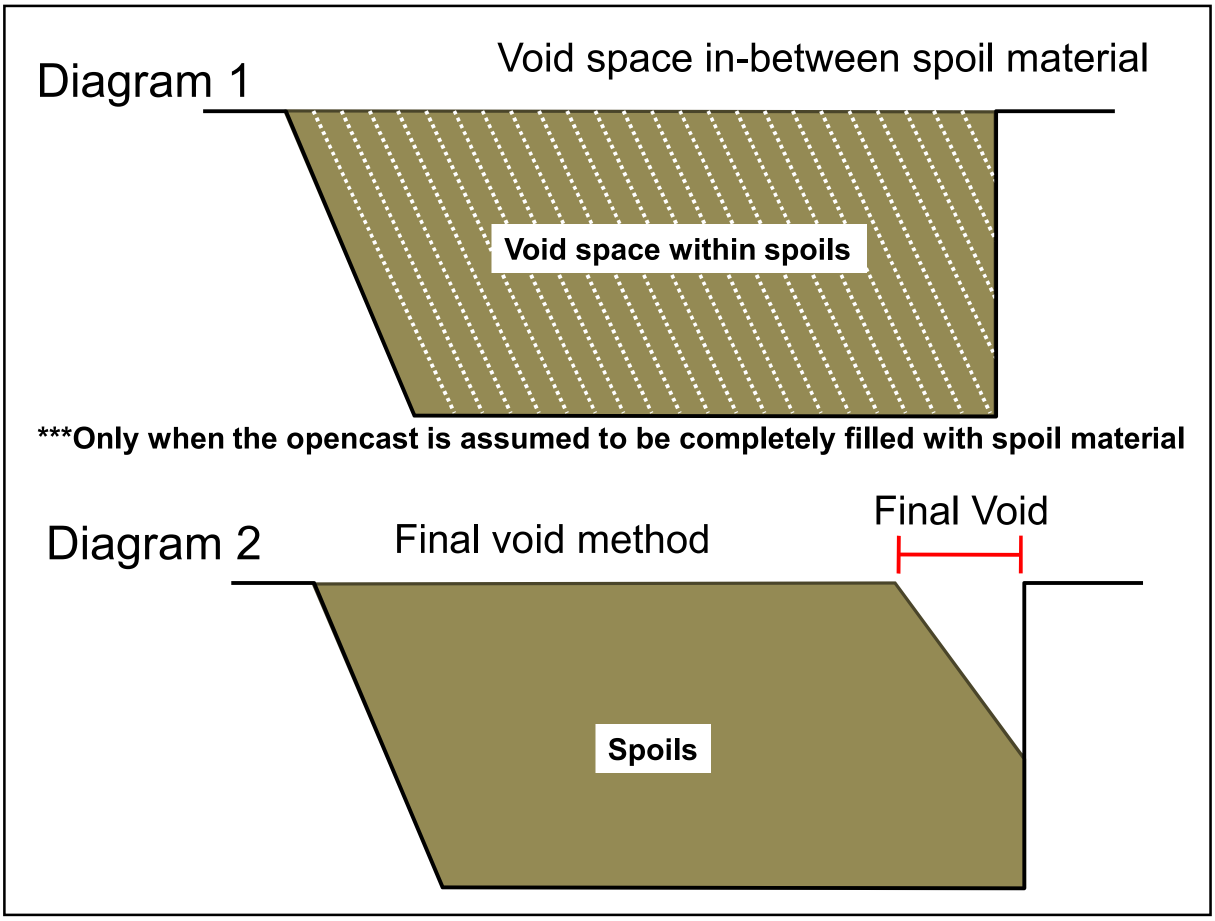
This equation needs to be done as many times as there are different geological units.



Source: Author's own (2017)

Figure 5.7: Diagram illustrating the effects of shrinkage factors

All the parameters chosen, have now been factored into the volume of the spoils. The volume calculated for the spoils after the shrinkage factors have been applied can now be subtracted for the volume of the opencast pit. The difference in these two volumes can be seen as the void space of the spoil material (Figure 5.8 Diagram 1) or as the final void in the opencast pit (Figure 5.8 Diagram 2).



Source: Author's own (2017)

Figure 5.8: Different representations of void space

5.4 Optimus pit calculations

Using WISH and Water Accounting and Management (WACCMAN) the area, volume and water level (when fully saturated), was calculated and can be seen in Table 5-2. Furthermore, the total volume available for rehabilitation was calculated when the amount of coal extracted (at 7.7%) was subtracted from the total volume.

TABLE 5-2: AREA, VOLUME AND WATER LEVEL FOR THE OPTIMUS OPENCAST PIT

Optimus Opencast	
Area	27 280 827 m^2
Total volume extracted	1 062 589 890 m^3
Total coal volume extracted	81 741 167 m^3
Total volume for rehabilitation	980 848 723 m^3
Coal % Removed	7.7

Source: Research results (2017)

Table 5-3 describes and calculates the effect that the bulking factor has on spoils. The spoil was firstly divided up into the major groups of materials that is usually found in the study area and in the spoils and was given a percentage value. The percentage was then multiplied by the total volume available for rehabilitation (Table 5-2) to determine the volume each material contributes to the total spoils. The bulking factor was then multiplied by the volume composition to determine the volume of expansion of each individual material. In the end the virgin ground extracted expanded by 460 998 900 m^3 or 32%.

TABLE5-3: BULKING FACTOR CALCULATIONS

Spoil materials	Percentage composition of spoils	Volume composition (m^3)	Bulking factors	Bulking volume (m^3)
Clay	5%	49 042 436	1.4	68 659 410
Soil	10%	98 084 872	1.15	112 797 603
Sand	10%	98 084 872	1.05	102 989 115
Sandstone	50%	490 424 361	1.61	789 583 222
Shale	25%	245 212 180	1.5	367 818 271
Total bulking volume				1441847623

Source: Research results (2017)

Now that the volume of bulking is known we can apply the effects that erosion has on the spoil heap. This means that the total bulked spoils calculated in Table 5-3 are now subjected to erosion. Erosion is expressed as a percentage which is then subtracted from the total bulked spoils (Table 5-4). As erosion is not a parameter specifically measured it has to be estimated based on the environmental conditions and expert opinions. This is why scenarios are created for 5%, 10% and 15%. These erosion percentages might seem high for wind and water erosion, but keep in mind that these spoils are exposed to the elements as long as mining takes place which might be a period of up to 10years.

TABLE 5-4: THE SCENARIOS AND FINAL VOLUME OF THE SPOILS FOR THE EFFECT OF EROSION

Erosion Loss			
	Scenarios		
	5%	10%	15%
Loss in Volume	72 092 381,1	144 184 762	216 277143
Total left for rehab (m^3)	1 369 755 242	1 297 662 861	1225 570479

As seen in Table 5-4 there are now three volumes that are possible for the spoils that can be thrown back into the opencast pit. When they are thrown back into the pit they are compacted by heavy machinery which also decreases the volume within the pit. Mechanical compaction thus needs to be factored in as a parameter to the final spoils available for rehabilitation. Mechanical compaction only plays a minor role in volume change and as before with erosion, mechanical compaction is not a parameter that is specifically measured and needs to be estimated. Scenarios for mechanical compaction of the spoils were set at 5%, 7% and 10% on the already calculated scenarios of erosion (Table 5-5).

TABLE 5-5: MECHANICAL COMPACTION ON THE FINAL EROSION VOLUMES

Compaction factor				
Erosion volumes Calculated (m^3)		5% Erosion Volumes		
		Scenarios for mechanical compaction		
1369755242		**5,00%**	**7,00%**	**10,00%**
		68487762,1	95882866,9	136975524
	Volume of spoils left	1301267480	1273872375	1232779718
		10% Erosion Volumes		
		Scenarios for mechanical compaction		
1297662861		**5,00%**	**7,00%**	**10,00%**
		64883143	90836400,2	129766286
	Volume of spoils left	1232779718	1206826460	1167896574
		15% Erosion Volumes		
		Scenarios for mechanical compaction		
1225570479		**5,00%**	**7,00%**	**10,00%**
		61278524	85789933,6	122557048
	Volume of spoils left	1164291955	1139780546	1103013431

Source: Research Result (2017)

Now that the mechanical compaction has been factored in on the final erosion volumes nine possible volumes have been created for the spoils left for rehabilitation (Table 5-5). The last parameter called the shrinkage factor might possibly be the most important parameter concerning pit volume calculations. As before seen in Table 5-3 with the bulking factors, the shrinkage factors are done on the same principle of dividing the spoils into their own geological composition and assigning each a percentage of shrinkage. After the previously mentioned steps have been completed, these percentages can be applied to the nine scenario volumes calculated during the mechanical compaction.

TABLE 5-6: SHRINKAGE FACTORS APPLIED ON THE MECHANICAL COMPACTION VOLUMES

Shrinkage factor						
			Erosion %	**5%**		
			Mechanical compaction%	**5,00%**	**7,00%**	**10,00%**
	Geological composition	**Shrinkage Factor**	**Spoil volume**	**1301267479,59**	**1273872374,75**	**1232779717,50**
clay	5%	10%		6506337,398	6369361,874	6163898,588
soil	10%	12%		15615209,76	15286468,5	14793356,61
sand	10%	11%		14313942,28	14012596,12	13560576,89
Sandstone	50%	34%		221215471,53	216558303,71	209572551,98
Shale	25%	49%		159405266,2	156049365,9	151015515,4
			Total left over for rehab:	884211252,38	865596278,64	837673818,04

			Erosion %	**10%**		
			Mechanical compaction%	**5,00%**	**7,00%**	**10,00%**
	Geological composition	**Shrinkage Factor**	**Spoil volume**	**1232779718**	**1206826460**	**1167896574**
clay	5%	10%		6163898,588	6034132,301	5839482,872
soil	10%	12%		14793356,61	14481917,52	14014758,89
sand	10%	11%		13560576,89	13275091,06	12846862,32
Sandstone	50%	34%		209572552	205160498,2	198542417,7
Shale	25%	49%		151015515,4	147836241,4	143067330,4
			Total left over for rehab:	837673818	820038579,8	793585722,4

			Erosion %	15%		
			Mechanical compaction%	5,00%	7,00%	10,00%
	Geological composition	Shrinkage Factor	Spoil volume	1164291955	1139780546	1103013431
clay	5%	10%		5821459,777	5698902,729	5515067,157
soil	10%	12%		13971503,47	13677366,55	13236161,18
sand	10%	11%		12807211,51	12537586	12133147,75
Sandstone	50%	34%		197929632,4	193762692,8	187512283,3
Shale	25%	49%		142625764,5	139623116,9	135119145,4
			Total left over for rehab:	791136383,7	774480880,9	749497626,7

Source: Research result (2017)

Now there are nine spoil volumes that are possible for the rehabilitation of the opencast pit. These spoil volumes can final be compared to the volume needed to fill the opencast pit and the difference between the two are the void spacewithinopencast pit spoils as seen in Table 5-7.

TABLE 5-7: FINAL VOID SPACE CALCULATIONS

Final Pit Calculations	
Pit Calculation Information	
Total Coal Volume Extracted (m^3)	81 741 167
Original virgin ground removed (m^3)	1 062 589 890
Volume needed to fill pit (averaged flat surface)(m^3)	980825701

	5%		
	5,00%	**7,00%**	**10,00%**
	884211252,38	865596278,64	837673818,04
Volume left over for Rehabilitation (m^3)	96614448,62	115229422,36	143151882,96
Percentage void space %	9,85	11,75	14,60

	10%		
	5,00%	**7,00%**	**10,00%**
	837673818,04	820038579,77	793585722,36
Volume left over for Rehabilitation (m^3)	143151882,96	160787121,23	187239978,64
Percentage void space %	14,60	16,39	19,09

	15%		
	5,00%	**7,00%**	**10,00%**
	791136383,71	774480880,89	749497626,67
Volume left over for Rehabilitation (m^3)	189689317,29	206344820,11	231328074,33
Percentage void space %	19,34	21,04	23,59

Source: Research results (2017)

Seeing from the research result in Table 5-7 the void space for the rehabilitated spoils range from around 10% to 24%. From estimated guesses and expert opinion on void space for rehabilitated spoils it is safe to assume that the void space is definitively higher than 19%. This leads to the conclusion that the spoils lost during erosion is around 15% and that the mechanical compaction can range from 5% to 10%. Keeping in mind that the boulders of the original virgin ground are still intact and thrown back as is, they also possess their own void space. Thus, the void space calculated for the spoils and the void space of the virgin ground need to be added together for a completed void space total. Void space for virgin ground can range from 3% up until 10% and needs to be added to the spoil void space. This means that the final void space calculated for the entire opencast pit is around 25%.

5.5 Summary

To conclude this chapter, pit volume calculations comprises of a multitude of unknown parameters and requires a substantial amount of excavation and rehabilitation data over the entire life of mine. As well as data from the mine, qualified and estimated guesses from experts can also steer the pit calculations in the area in the right direction.

As well as the data and estimations about environmental conditions, certain assumptions also need to be made before pit calculations can be done. These estimations are also an essential part of pit calculations and guide the equations in the correct direction towards calculating void space from volume differences. The most important assumption that was made concerning these volumes used is that the different elevations of the layers had to be levelled and averaged to produce believable volumes.

The bulking factor that is crucial for rehabilitation proved to be a difficult task to apply to real-world situations. Although there are numerous tables with bulking factors available, a best estimate needs to be chosen since the composition of the spoils and the size of the materials (grain to boulder sizes) were not known. This means that although a given bulking factor for sandstone is given as 60% of its original volume, the composition of the material size, influences this factor significantly and thus can either increase or decrease the percentage of bulking. In the end an excellent knowledge of the geology will significantly help to estimate a close to near accurate bulking factor. The beforementioned problem also counts for the shrinkage factor which can either increase or decrease depending on the circumstances of extraction and environmental conditions.

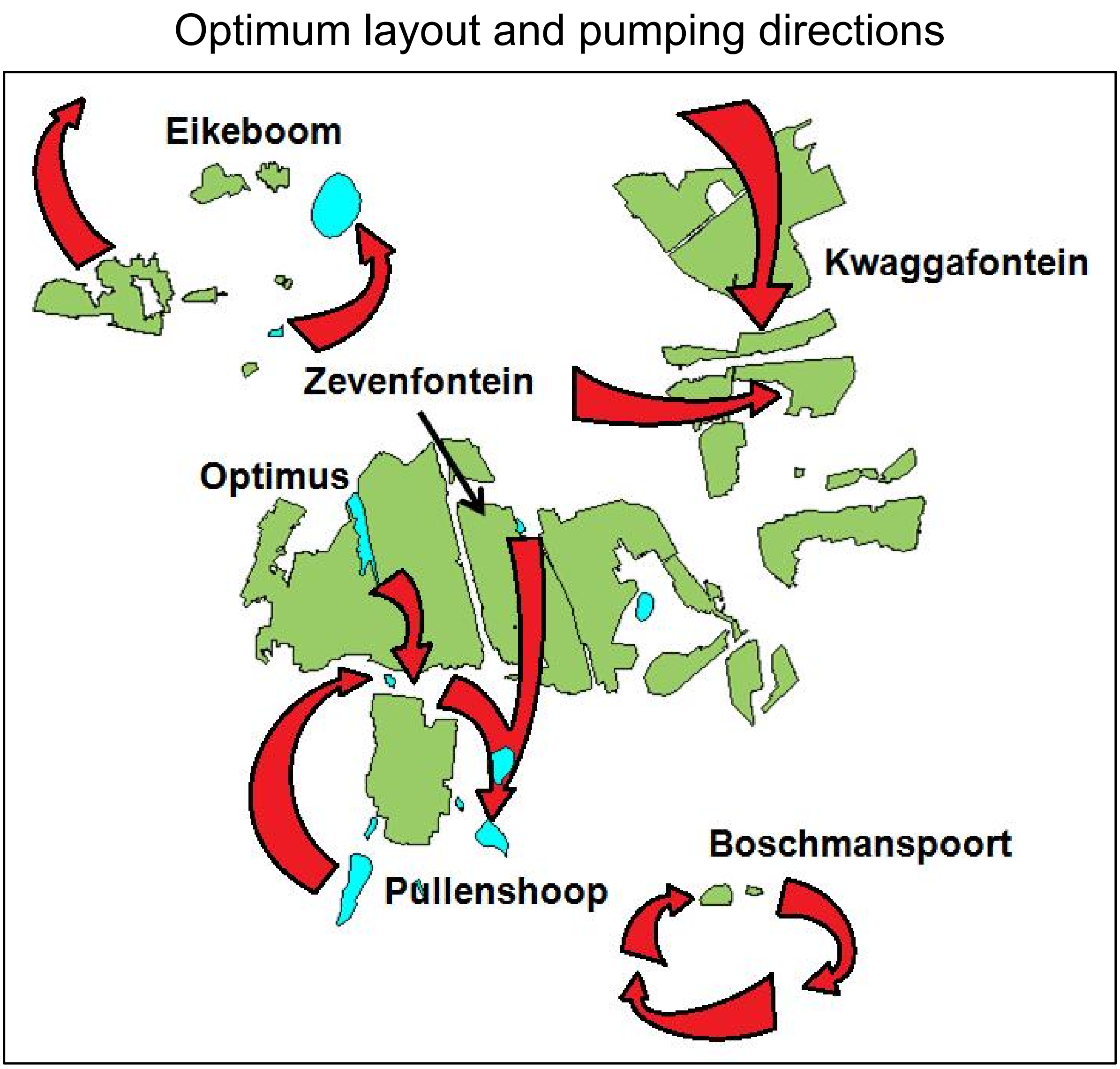
In conclusion, without proper data stretching over an extended period that fulfils all the parameters needed to calculated pit volumes, the best results will be obtained from simple elevation and area calculations. Although the calculations points towards a 25% void space for the spoils and confirmed by various sources, it is of the author's strong believe that more data and more parameters need to be added to minimize the assumptions that needed to be made in this dissertation.

Chapter 6
Pumping Cycles

6.1 Introduction

Pumping excess water around and away from mining areas has been around as long as mining itself. Pumping water away from the mining operation to keep the area clear of water is the main objective when mining. Sometimes pumping is also used to send water to active mining operations and to prevent decanting. Knowing and monitoring these pumping volumes, will give an idea of the water volumes in the area which can then be linked to the changes in water levels. Knowing that pumping affects the water levels for the area these volumes can be adjusted to prevent decanting.

Optimum consists of five main mining areas, each of which has its own pumping cycles. The Optimus and Zevenfontein areas contain a free drainage system were groundwater and run-off flows towards the respective dams from where the water is then pumped to its final destination. Pullenshoop has a direct system where the water is pumped directly from the mine workings to storage dams. Boschmanspoort and Eikeboom have direct systems and secluded from the main Optimum operation. Most of the water that is pumped from Zevenfontein, Optimus and Pullenshoop pass through the Pullenshoop ring feed system. From there on out the water is either pumped to where it's needed or to the Evaporation dam for evaporation and treatment (Figure 6.1).



Source: Author's own (2017)

Figure 6.1: Optimum layout and pumping directions

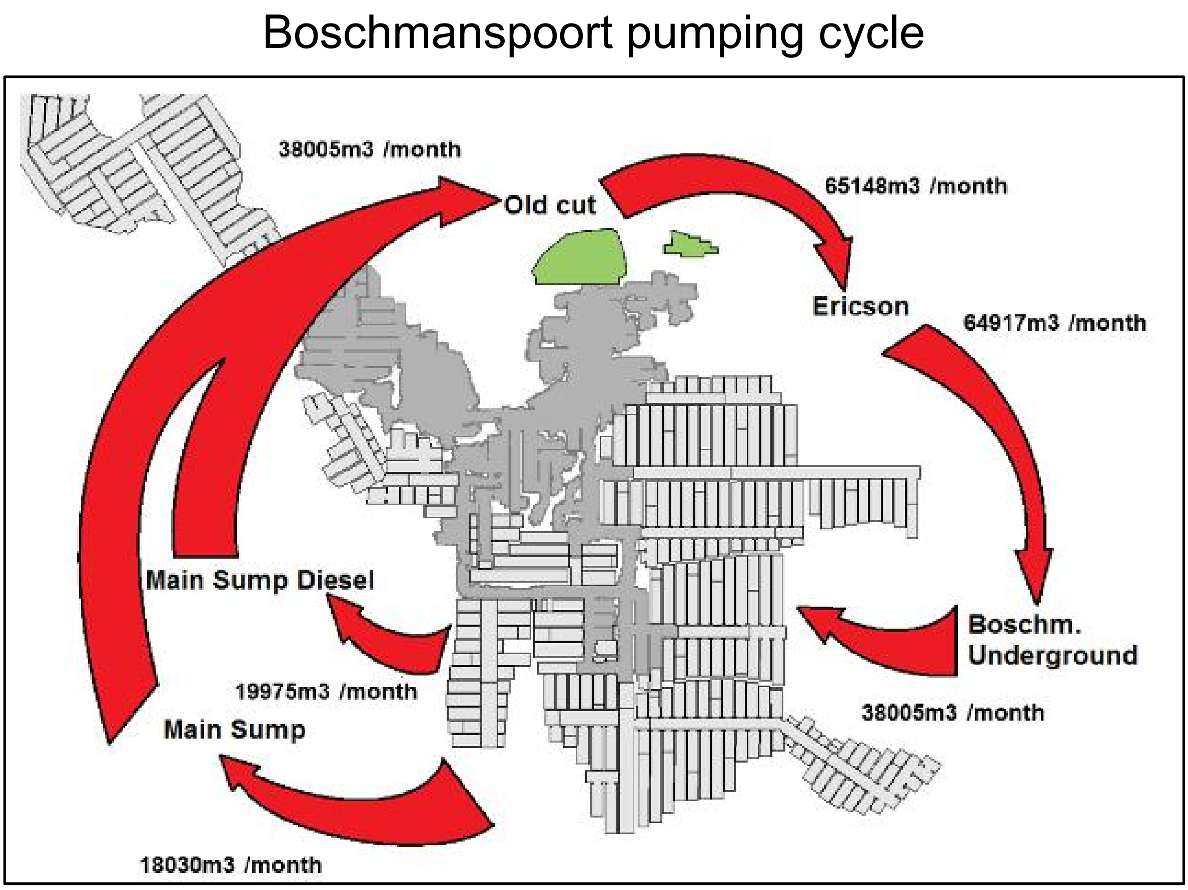
6.2 Boschmanspoort pumping cycle

The Boschmanspoort mining area is situated South East of the main mining area (Optimus opencast pit) and is primarily an underground mining operation. In Figure 6.2, the green represents the opencast cut which serves as an entrance to the underground operation, indicated as grey lines and blocks.

The Boschmanspoort underground operation has a circulatory pumping system, where water is pumped from and then around the mine workings to keep the underground mining works clear of water.

6.2.1 Boschmanspoort circulatory system:

The pumping starts at the entrance of the underground mining operation, called the Old cut, where 65 148 m^3/month of water is pumped to the Ericson holding area. 231 m^3/month is lost either to leaking pipes, evaporation at the old cut or use in the mining operation (Table 6-1). From there on out the 64 917 m^3/month of water is pumped to the Boschmanspoort underground where the water moves through the mining operation as artificial recharge and also used in the underground workings. Nearly half of the water pumped to the underground is lost to the water system, which can be seen in the pumping data from the main sump diesel and main sump which equates to half of that pumped from the Ericson holding area. Between the Boschmanspoort underground and Main sump diesel as well as Main sump, equilibrium is struck between what was pumped into the underground and what was extracted, and thus there is enough water from the mining operation and at the same time the underground workings stay dry. From the main sump diesel and main sump, a combined total of 38 005 m^3/month excess water then is pumped back to the old cut, which completes the circulatory pumping system.



Source: Research results (2017)

Figure 6.2: Pumping cycle of the Boschmanspoort mining area

TABLE 6-1: PUMPING DATA FOR THE BOSCHMANSPOORT MINING AREA

Boschmanspoort pumping data			
From	**To**	**Amount pumped(m^3/month)**	**Difference (m^3/month)**
Old cut	Ericson	65148	N/A
Ericson	Boschmanspoort Underground	64917	−231
Boschmanspoort Underground	Main sump and diesel	38005	−26912
Main sump diesel	Old cut	19975	
Main sump	Old cut	18030	0
Total:			−27143
Total loss:			–27143

Source: Research results (2017)

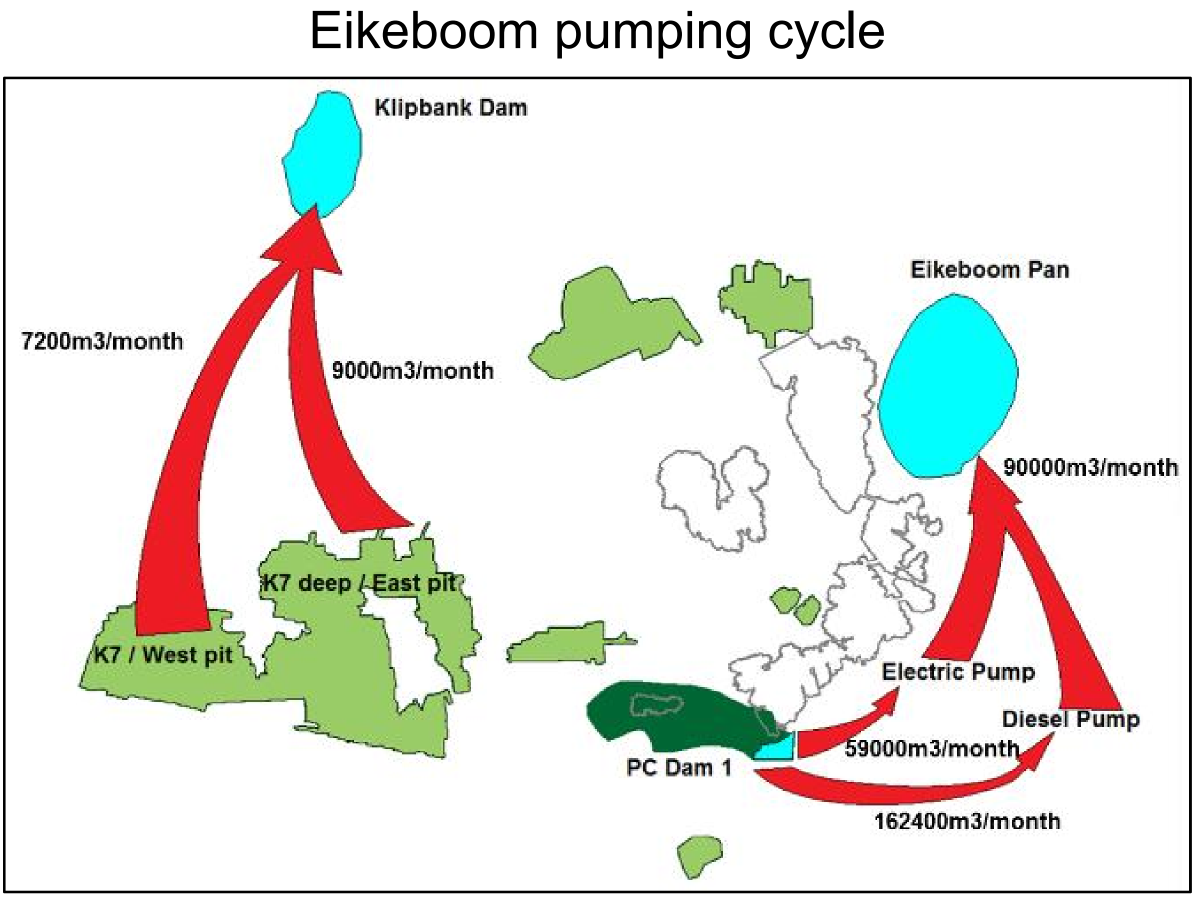
6.3 Eikeboom pumping cycle

The Eikeboom mining operation is situated North West of the main Optimus mining area and consists of twoopencast workings. In Figure 6.3, the K7 east and west opencast pits can be seen where as to the east the Eikeboom opencast pits can be observed. This area is surrounded by numerous man-made and natural dams which serves as water storage facilities and as water control dams for the mining operations.

6.3.1 Eikeboom direct pumping system

In the West the K7 opencast operation pumps directly to the Klipbank Dam from the K7 West and K7 East pits with 7 200 m^3/month and 9 000 m^3/month respectively, with a total of 16 200 m^3/month (Figure 6.3; Table 6-2).

The Eikeboom operation starts directly at PC Dam 1 were the water is pumped to an electric and diesel pump. The electric pump receives an average of 59 000 m^3/month whereas the diesel pump receives around 162 400 m^3/month. From there on out the water is pumped directly into the water control dam, Eikeboom Pan, at an average of 90 000 m^3/month. There is a major loss of water between the respective pumps and Eikeboom Pan, which equates to around 131 400 m^3/month, and can be attribute to water needed from the mining operation and artificial recharge implemented by this system (Figure 6.3).



Source: Research results (2017)

Figure 6.3: Pumping cycle of the Eikeboom mining area

TABLE 6-2:PUMPING DATA FOR THE EIKEBOOM MINING AREA

K7 Operation			
From	**To**	**Amount pumped (m^3/month)**	**Difference (m^3/month)**
K7 West	Klipbank dam	7200	N/A
K7 East	Klipbank dam	9000	N/A
Total to Klipbankdam		16200	
Eikeboom Operation			
From:	**To:**	**Amount pumped (m^3/month)**	**Difference (m^3/month)**
PC Dam 1	Electric pump	59000	N/A
	Diesel pump	162400	N/A
Electric pump Diesel pump	Eikeboom pan	90000	131400
Total water loss		131400	

Source: Research results (2017)

6.4 Kwaggafontein pumping cycle

The Kwaggafontein opencast mine is the latest mining operation undertaken in the area, situated North West of the Optimus mining operation. The Kwaggafontein operation consists of both opencast and underground mine working and is divided into two sections, called the north and central areas with the rail open void separating the two (Figure 6.4).

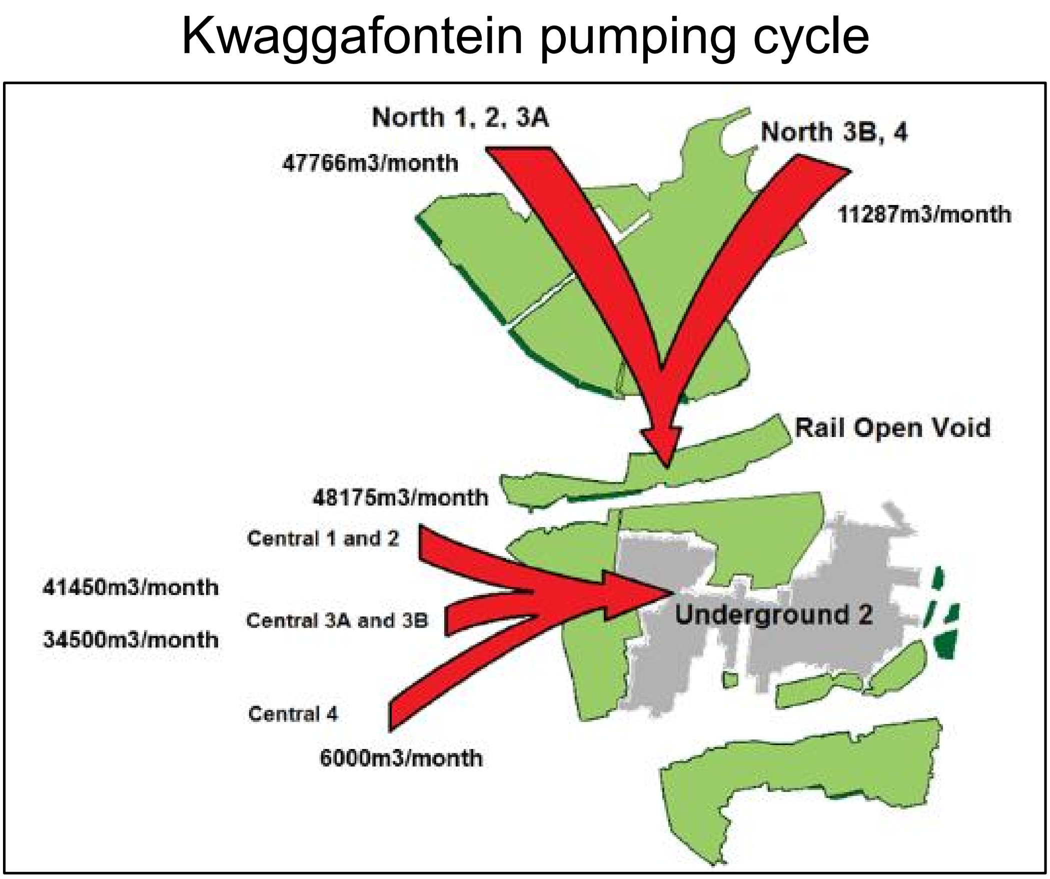
6.4.1 Kwaggafontein direct pumping system

The Northern part of the Kwaggafontein operation pumps water for two areas. The first is a combined area collectively called the North 1, 2 and 3A and pumps on average 47 766 m^3/month of water into the Rail Open Void. The second combined area consists of the North 3B and 4 and collectively pumps 11 287 m^3/month of water also into the Rail Open Void. A combined total of 59 023 m^3/month water is pumped to the Rail Open Void from the north (Table 6-3).

The central area also consists of a direct pumping system were water is pumped into underground two from three combined areas, called: (1) Central 1 and 2; (2) Central 3A and 3B; and (3) Central 4.The amount of water pumped from these areas into the underground 2 area is as follows:

- Central 1 and 2 48 175 m^3/month
- Central 3A and 3B 41 450 m^3/pm and 34 500m^3/month
- Central 4 6 000 m^3/month

In total a combined amount of 130 125 m^3/month is pumped into the underground 2 area (Table 6-3).



Source: Research results (2017)

Figure 6.4: Pumping cycle of the Kwaggafontein mining area

TABLE 6-3: PUMPING DATA FOR THE KWAGGAFONTEIN MINING AREA

Northern area			
From	**To**	**Amount pumped (m^3/month)**	**Difference (m^3/month)**
North 1, 2 and 3A	Rail open void	47766	N/A
North 3B and 4	Rail open void	11287	N/A
Total:		59053	
Central area			
From:	**To:**	**Amount pumped (m^3/month)**	**Difference (m^3/month)**
Central 1 and 2	Underground 2	48175	N/A
Central 3A and 3B	Underground 2	75950	N/A
Central 4	Underground 2	6000	N/A
Total:		130125	

Source: Research results (2017)

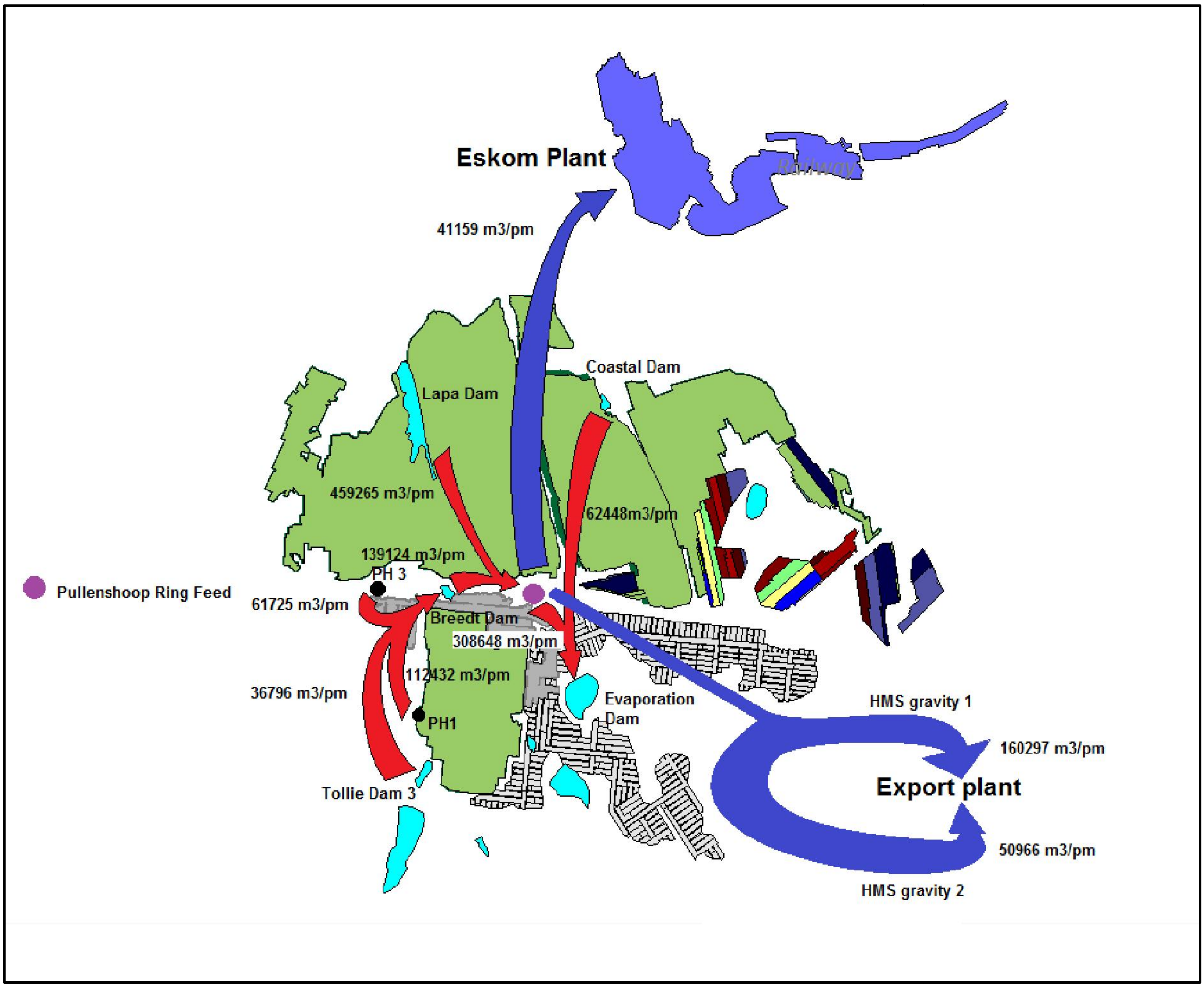
6.5 Optimus and Pullenshoop pumping cycle

The Optimus opencast mine is the main mining operation in the area in conjunction with the Pullenshoop and the New Eskom Plant operation (Kwaggafontein). This mining operation is centrally located with Pullenshoop to the South and the Eskom Plant operation to the North West which is adjacent to the Kwaggafontein operation. All the water for the area will at one stage or the next, move through the Pullenshoop ring feedsystem, were it will either be used in mine workings or is pumped to water control dams and evaporation dams.

6.5.1 Optimus and Pullenshoop ring feed system

The system starts at the Pullenshoop opencast operation, which is surrounded by numerous natural and man-made dams. The water is pumped from Tollie Dam 3, borehole PH1 and borehole PH3, which are all, situated on the edge of the Pullenshoop open, cast mine directly to the west(Figure 6.5). The combined total of water per month equates to around 210 953 m^3/month and is directly pumped into the Breedt holding dam. From there on out water is extracted and pumped from the Breedt dam as well as the Lapa dam, situated in the middle of the Optimum opencast operation, to the Pullenshoop ring feed system. The ring feed system is centrally located between the mining operations and serves as the main pumping junctions for receiving and extracting water. At the Pullenshoop ring feed junction around 41 159 m^3/month of water is sent to the Eskom Plant to be used in the mine workings. As well as the Eskom plant, HMS gravity 1 and 2 receives its water from the ring feed system that will later be used in the mining operation. The excess water is then pumped from the Coastal dam and the ring feed system to an evaporation dam, which also serves as a control point for the water (Table 6-4).

Optimus pumping cycle



Source: Research results (2017)

Figure 6.5: Pumping cycle of the Optimus mining area

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TABLE 6-4: PUMPING DATA FOR THE OPTIMUS MINING AREA

Ring feed system					
Pullenshoop					
From:	**To:**	**Amount pumped (m^3/month)**	**Extracted**	**Excess**	**Loss to system**
Tollie Dam 3	Breedt Dam	36796			
PH1	Breedt Dam	112432			
PH3	Breedt Dam	61725	210953		
Breedt Dam	Ring feed system	139124			71829
Ring feed system	Evaporation Dam	308648		169524	
Total excess water added from external source:			169524		
Total water for evaporation:			308648		
Optimus					
From:	**To:**	**Amount pumped (m^3/month)**	**Extracted**	**Excess**	**Loss to system**
Lapa Dam	Ring feed system	459265	459265		
Ring feed system	Eskom Plant	41159			
Ring feed system	HMS gravity 1	160297			
Ring feed system	HMS gravity 2	50966		206843	252422
Coastal Dam	Evaporation Dam	62448		62448	
Total water for evaporation:			269 291		

Summary	
Data	**Amount in m^3/month**
Total water in the system:	670218
Total water used:2	252422
Total excess water for evaporation:	577939
Total water from external sources:	−160143

Source: Research results (2017)

6.6 Summary

It is clear from the pumping rates, areas from where the pumping takes place and to where it is pumped that the objectives of the Optimum coal mining operation is to keep the mine water in circulation and the rest is treated or evaporated, doing all of this while keeping the contaminated run-off and decanting water clear of clean groundwater.

The Boschmanspoort area is mainly an underground mining operation which utilises a circulatory pumping system which re-uses the mine water for mining. Although there is a loss of water into the system from where it starts out and ends again at the Old Cut, the loss will eventually be pumped out again around the mining operation, effectively containing the pollution.

The two areas of the Eikeboom operation utilises a direct pumping system from where the water is abstracted (to keep the mining area dry) and excess water is directly pumped to water control dams for evaporation and treatment.

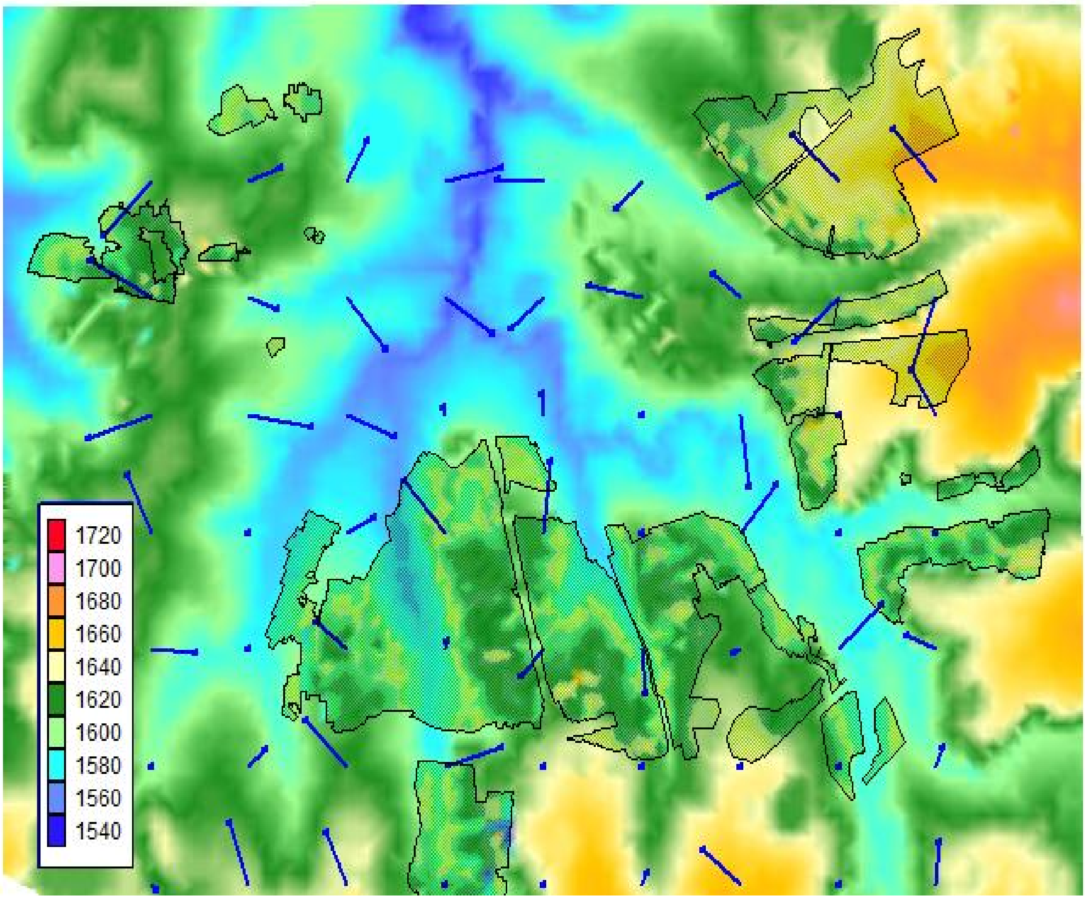
The Kwaggafontein area uses the same direct pumping system on their active mining operations, pumping excess water away from mine workings. The key difference between the Eikeboom and Kwaggafontein areas is that Eikeboom pumps to water control dams for treatment and evaporation, while Kwaggafontein pumps the water into old opencast voids as a method of storage until a later stage when disposal is possible*.

The Optimus and Pullenshoop area is centrally located and serves as a junction point for the water pumped from around the area. The Pullenshoop ring feed system serves as this junction point for the Optimus, Pullenshoop and Zevenfontein areas, where all the excess water is pumped to. From there on the water will either be evaporated at the Evaporation Dam or pumped to the HMS Gravity 1 and 2 for treatment or any other use thereof.

Chapter 7
Borehole Water Levels and Rainfall

7.1 Introduction

Water levels in and around the Optimum underground and opencast pits are on average quite close to surface level with some exceptions, considering that considerable amounts of water are being pumped daily to regulate water levels. This indicates that the whole area contains a strong groundwater flow which is closely monitored as seen in the water level charts and pumping data which follows. As an indication of the relationship between the topography and water levels (Figure 7.1), crosssections of the specific opencast pit will be given with each mining area. This will indicate how close the water levels are to the surface as well as a general idea of the opencast pits.



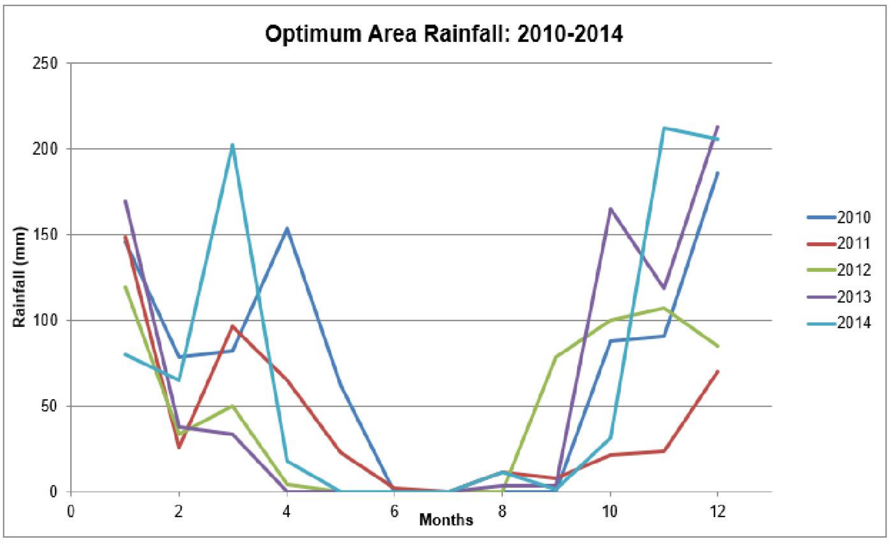
Note: The blue dots represent the data point and the blue line represents the direction of flow.

Source: Research result (2017)

Figure 7.1: Water flow direction in accordance with the topography

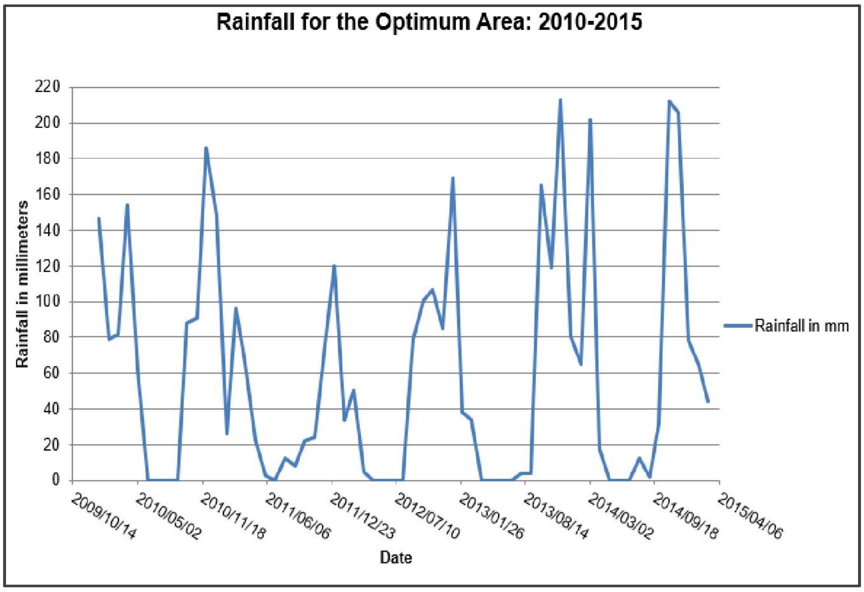
7.2 Rainfall from 2010 to 2015

The Optimus mining area is classified as being semi-arid, receiving approximately 450 mm of rainfall each year, with the wet season starting in September and ending in March as seen in Figure 7.1. Figure 7.2 shows that in 2013 and in 2014 the area received an above average rainfall and that in 2011 and in 2012 the rainfall was below average with longer periods of no rainfall and lower amounts of rainfall per month.



Source: Research results (2017)

Figure 7.2: Rainfall recorded from 2010 to 2014 for the Optimum Mine



Source: Research results (2017)

Figure 7.3: Rainfall for the Optimum area: 2010−2015

7.3 Boschmanspoortboreholewater levels

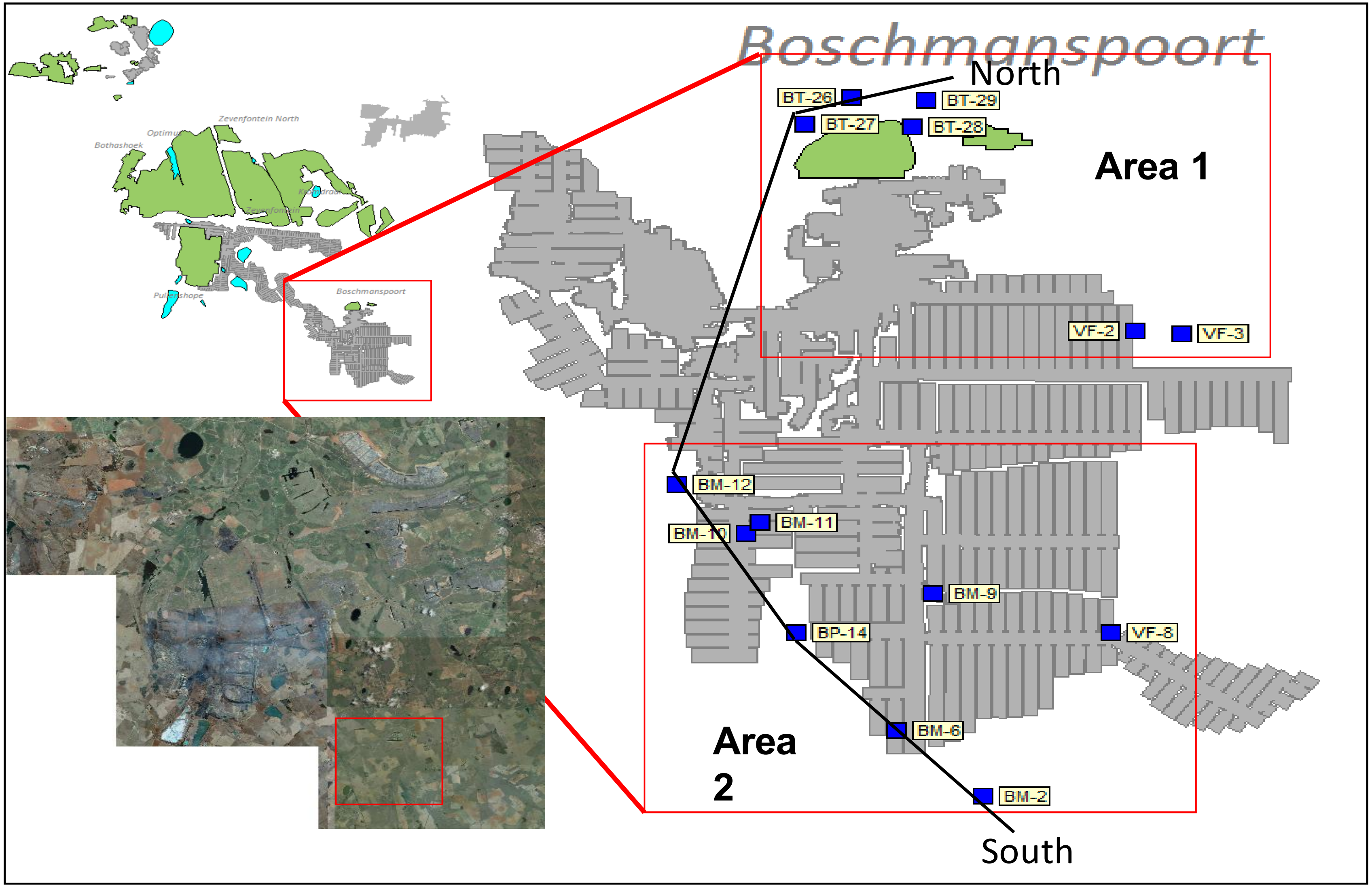
7.3.1 Sitelocation, water levels and pumping rates

The Boschmanspoort operation is relatively small (27 387 266.24 m^2) in comparison to the surrounding open and underground mining operations and is situated in the most southerly position on the mining property (Figure 7.4). This mining operation started as an initial opencast cut (old cut), which from there on proceeds underground in a southerly direction.

The Boschmanspoort underground mining operation started with the old cut as the green marked area (Area 1) and progressed as an underground mining operation(dark grey)(Figure 7.4). The planned underground mining that still needs to take place from 2016 to 2024 is indicated as light grey elongated rectangles and there are plans to connect the Pullenshoop underground mining operation with that of the Boschmanspoort underground mining in 2024.

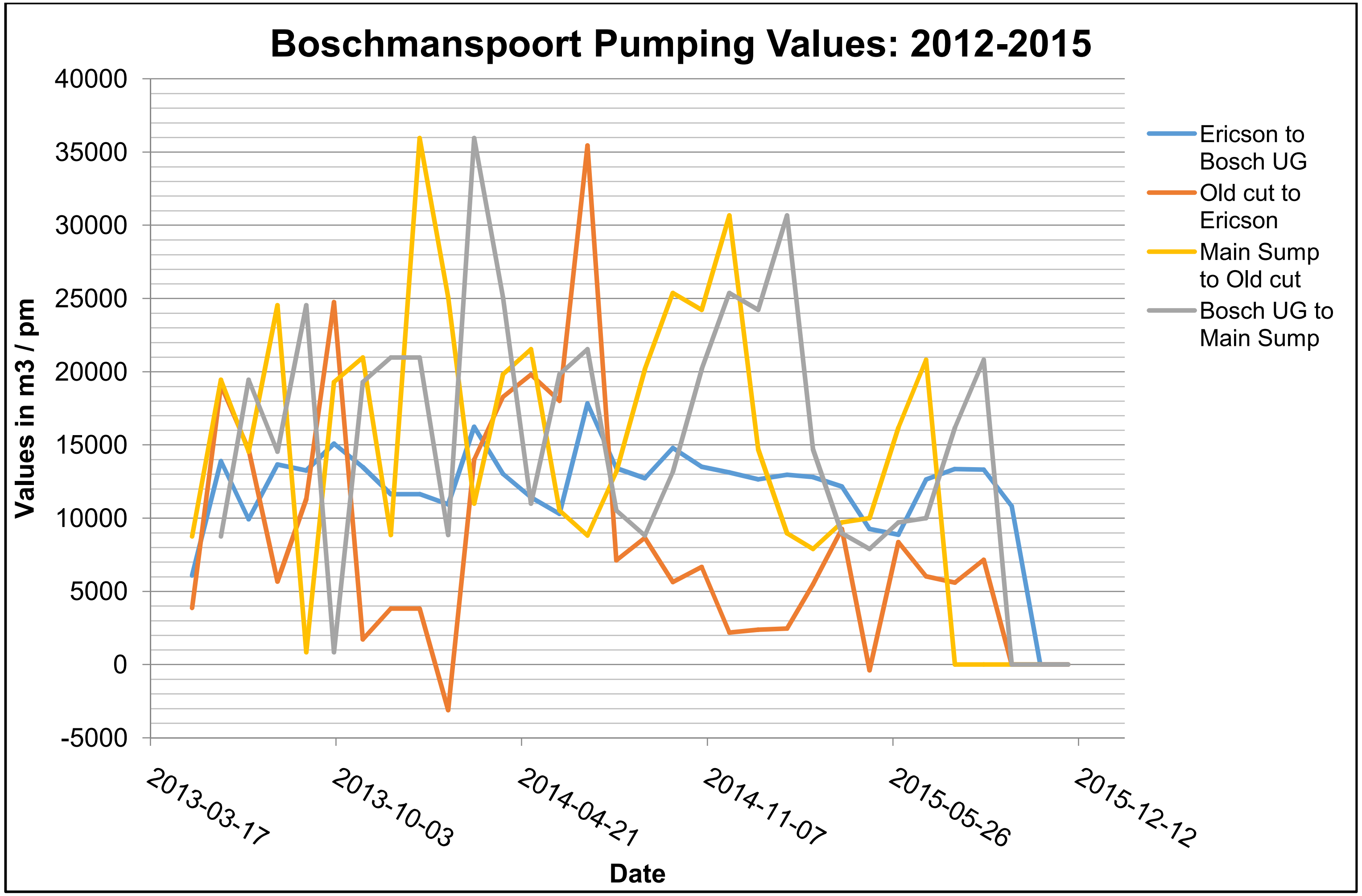
Since the Boschmanspoort area is a circulatory pumping system the water is pumped in and around the area with various pumping stations along the way (Figure 6.2). The pumping rates of the different pumping stationsdo not differ immensely from each other since water received is nearly the same as the water pumped out. In this case the average water circulated around the area is in the vicinity of 20 000 m^3/pm (Table 6-1).

From 2011/09/04 until 2013/05/06 the old cut to Ericson had large pumping values, around 125 000 m^3. This large pumping value is due to the fact that mining was still active in this period and the workings needed to be kept dry. After this period the water levels just needed to be kept in check and thus the fluctuating pumping values can be seen in Figure 7.5 from 2013/05/06 until 2015/07/15. The water levels in the area are generally shallow, ranging between 2 mbgl and 10 mbgl (Figure 7.6 and 7.7). The water table in this area is also quick to respond to any extraction (pumping rates) that may take place close or around the mining operation when the pumping rates are compared to that of the fluctuating water levels.



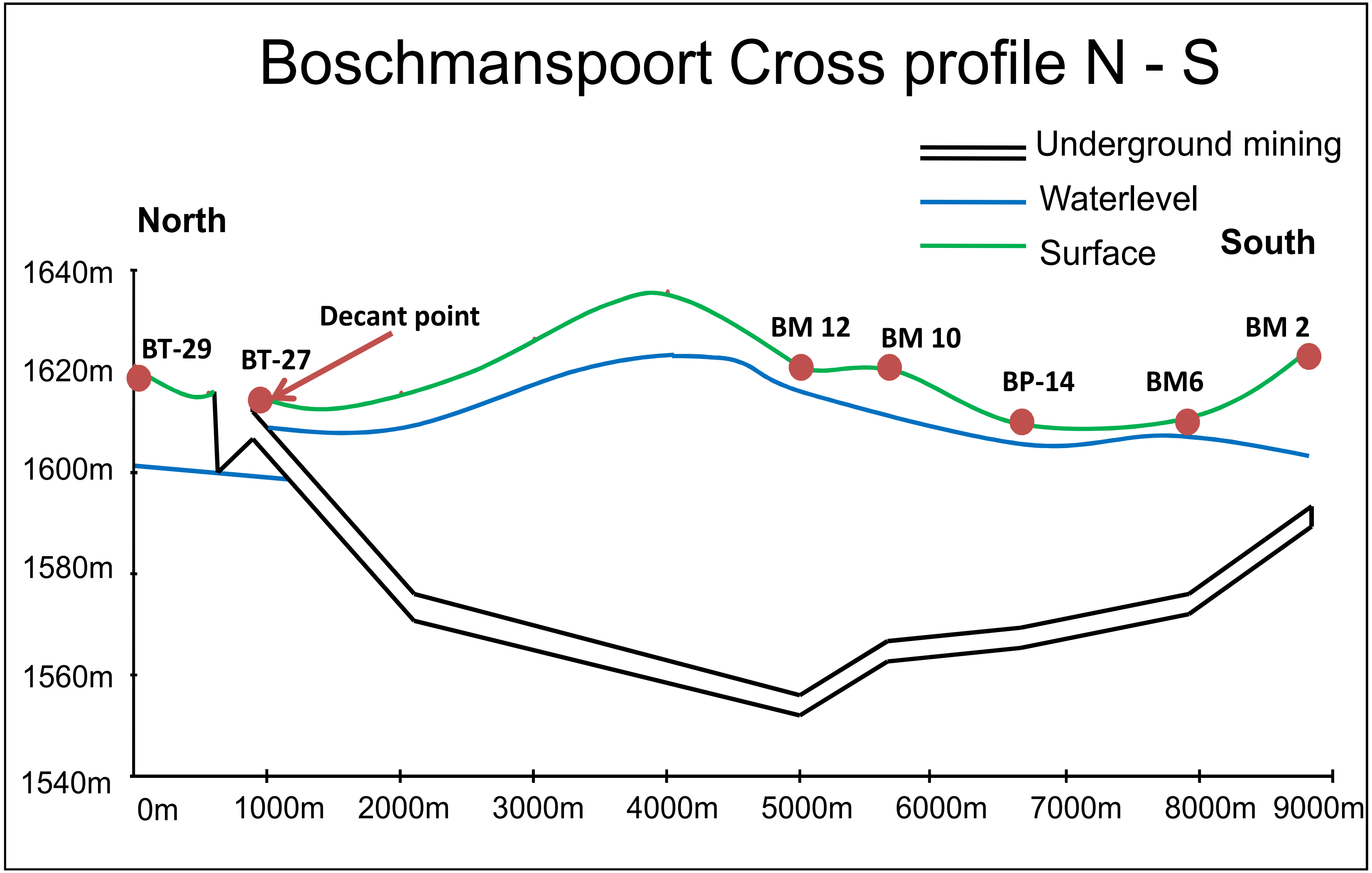
Source: Research results (2017)

Figure 7.4: Southerly position of mining property



Source: Research results (2017)

Figure 7.5: Boschmanspoort pumping values: 2012−2015



Source: Author's own (2017)

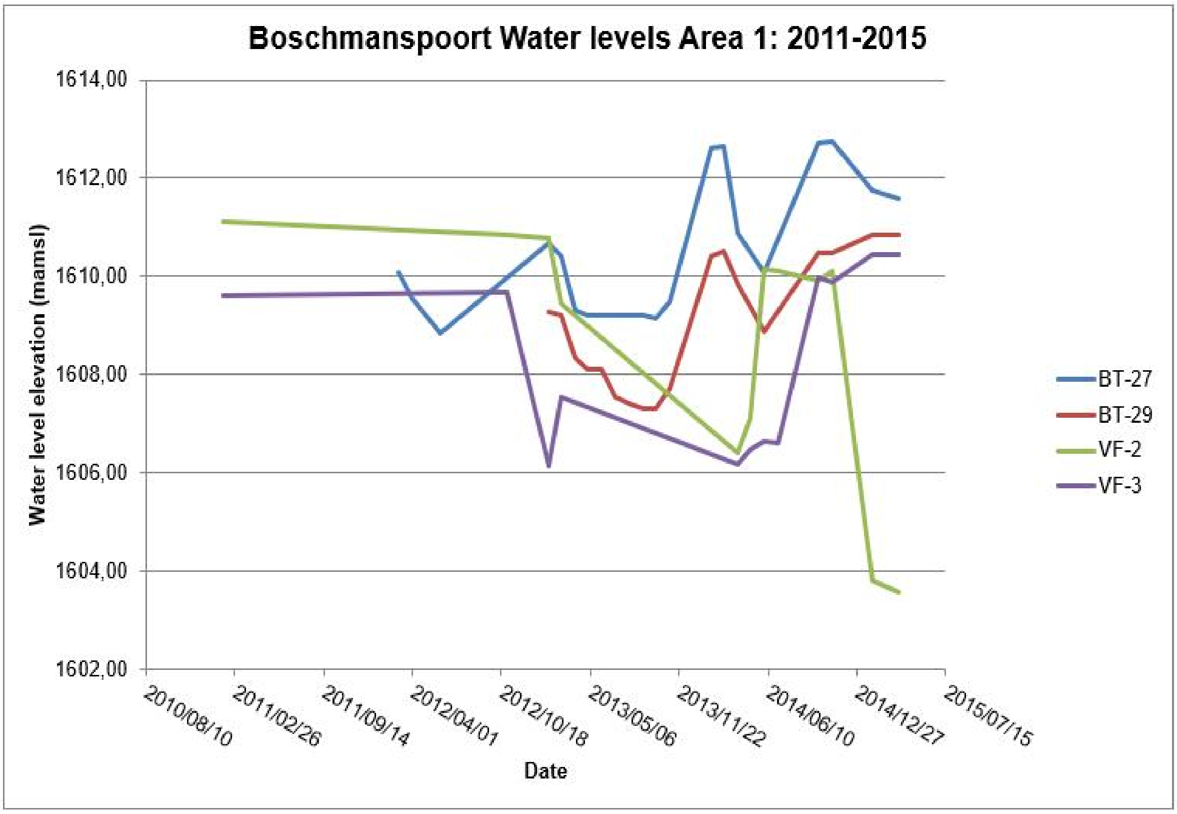
Figure 7.6: Cross profile of the Boschmanspoort underground mining area

7.3.1.1 Area 1

The BT-26, BT-27, BT-28 and BT-29 boreholes in Figure 7.5 are located around the Old Cut entrance to the Boschmanspoort underground mining operation. BT-27 and BT-29 are assumed that they are situated in the same aquifer since they show the same water level fluctuations in comparison to each other. Figure 7.7 clearly shows a positive correlation between the borehole water levels of BT-27 and 29 and also between the water levels and the pumping rates for their pumping. Between 2013/04/01 and 2013/10/01 and also between 2014/04/01 and 2014/06/01, the pumping rate increased to around 24 750 m^3/month which showed a decrease in water levels. The opposite is true for the period between 2013/10/01 and 2014/04/01 and between 2014/06/01 and 2015/04/01, when pumping decreased (average 3 000 m^3/month) and consequently a rise in water levels were seen. According to the pump data for the old cut to Ericson area, more than 15 000 m^3/month will subsequently lower water levels in these boreholes and vice versa (Also see Figure 7.6).

Borehole VF-2 and VF-3 is situated just east of the Boschmanspoort underground operation between the old cut and Ericson pumping areas (Figure 7.4). These two boreholes are quite close together and thus come as no surprise that their water levels follow the same trend as they are situated in the same aquifer seen. These two water levels also show a strong and definite correlation with that of the pumping data over the same period. It was concluded that when more than 18 000 m^3/month of water was pumped from the old cut to the Ericson area a decrease in water levels could be observed and anything less would result in a rise in water levels.

When BT-27, BT-29, VF-2 and VF-3 were compared to each other, it showed the same fluctuations over the same period as well as that of the pumping volume over the same period. It can thus be concluded that all four boreholes are situated in the same aquifer and shows a decrease in water level when pumping volumes are more than 15 000−18 000 m^3. It is also safe to assume that the pumping done is only to keep water levels stable since the average pumping done over a four-year period is constantly around 20 000 m^3/month and does not fluctuated between the pumping areas.



Source: Research results (2017)

Figure 7.7: Boschmanspoort water levels Area 1: 2011−2015

7.3.1.2 Area 2

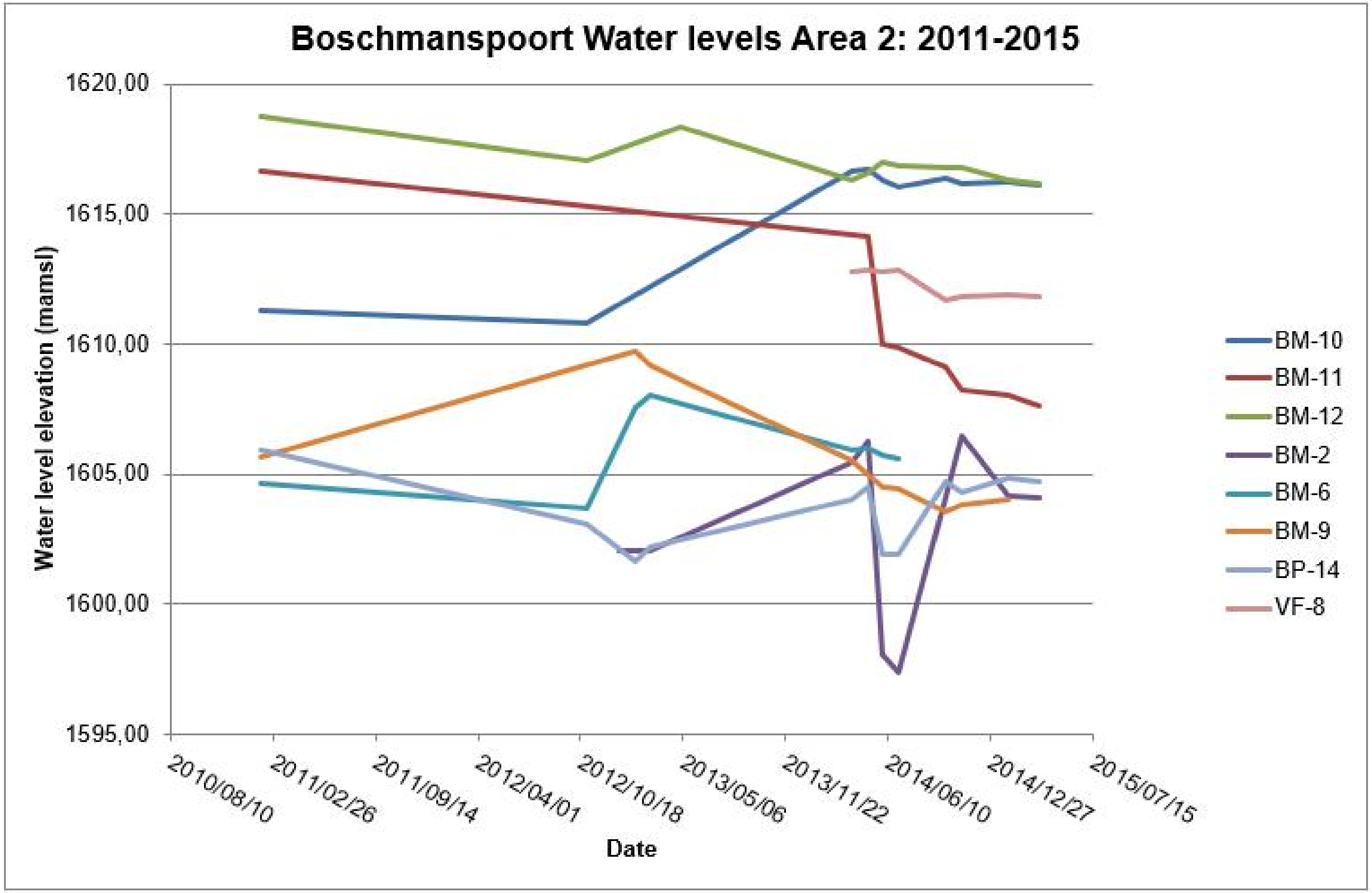
Due to the Boschmanspoort mining operation being a circulatory pumping system a balance needs to be struck in order for this system to keep circulating the same amount of water in and around the mining operation. This is exactly what is seen in Figure 6.2 and 7.5, where average pumping rates are maintained and when a need or excess water is required the pumping rates are adjusted.

Figure 7.8 shows a steady decrease in water levels for boreholes BM-10, BM-11 and BM-12 over a period of five years. This is due to the pumping schedule of Boschmanspoort shown in Figure 7.5. The boreholes are situated between the Boschmanspoort Underground and Main Sump pumping areas. Between these two pumping areas the trend showed a slight increase in pumping over a five-year period just below 15 000 m^3/month, with more periods of high pumping above the average trend than below it.

This explains the steadily decreasing water levels in this area. From 2014/05/01 the water levels showed the same pattern, which is steadily decreasing. This can indicate that these borehole water levels are connected which each other and the mine finally fine-tuned their pumping rates correctly to maintain a stable water level for Area 2.

Boreholes BM-2, BM-6 and BM-9 form a north to south line between the Boschmanspoort underground and Main Sump pumping areas (Figure 6.2 and 7.5). As in Area 1 the average pumping shows and slight increase in volume at an average of 15 000 m^3/month. BM-9 shows a strong correlation between the pumping rates from 2013/02/01 until 2014/06/01, where an increase in volume pumped, directly equates to a drop in water level. From 2014/06/01 the water level and pumping rates are in equilibrium and no fluctuations in either the pumping rates or water levels are noticed. BM-2 show little to no correlation between pumping and water level fluctuations, but was determined that a minimum of 24 000 m^3/month of water pumped, is needed to affect the water level. BM-6 also shows a small correlation between pumping and water level fluctuations.

When comparing the BM series in Area 2 with each other there are some similarities in the water level fluctuations. Due to the fact that these boreholes are inside the underground mining area and that there is a large distance separating BM-10, BM-11 and BM-12 with BM-2, BM-6 and BM-9, it can be concluded that they are linked to each other due to the similar water level fluctuations with only water level elevation differing slightly and the water level trend having a one-month delay between the boreholes (also see Figure7.6).



Source: Research results (2017)

Figure 7.8: Boschmanspoort water levels Area 2: 2011−2015

7.4 Eikeboom borehole water levels

7.4.1 Site location, water levels, pumping rates and dam water levels

The Eikeboom mining operation is the most northerly located mining area and consists of two mining areas called Klipbank and Eikeboom which, combined, covers an area of 35 200 000 m^2. The Eikeboom operation consists of mainly opencast mining with a later stage of underground mining to a smaller extent (Figure 7.9).The Klipbank area consists of only opencast mining whereas the Eikeboom Pan area consists of both opencast and underground mining. At the Eikeboom Pan operation the opencast pit areas serves an initial cut to start underground mining and serves as an entrance to the future underground operation (Figure 7.12 and 7.13).

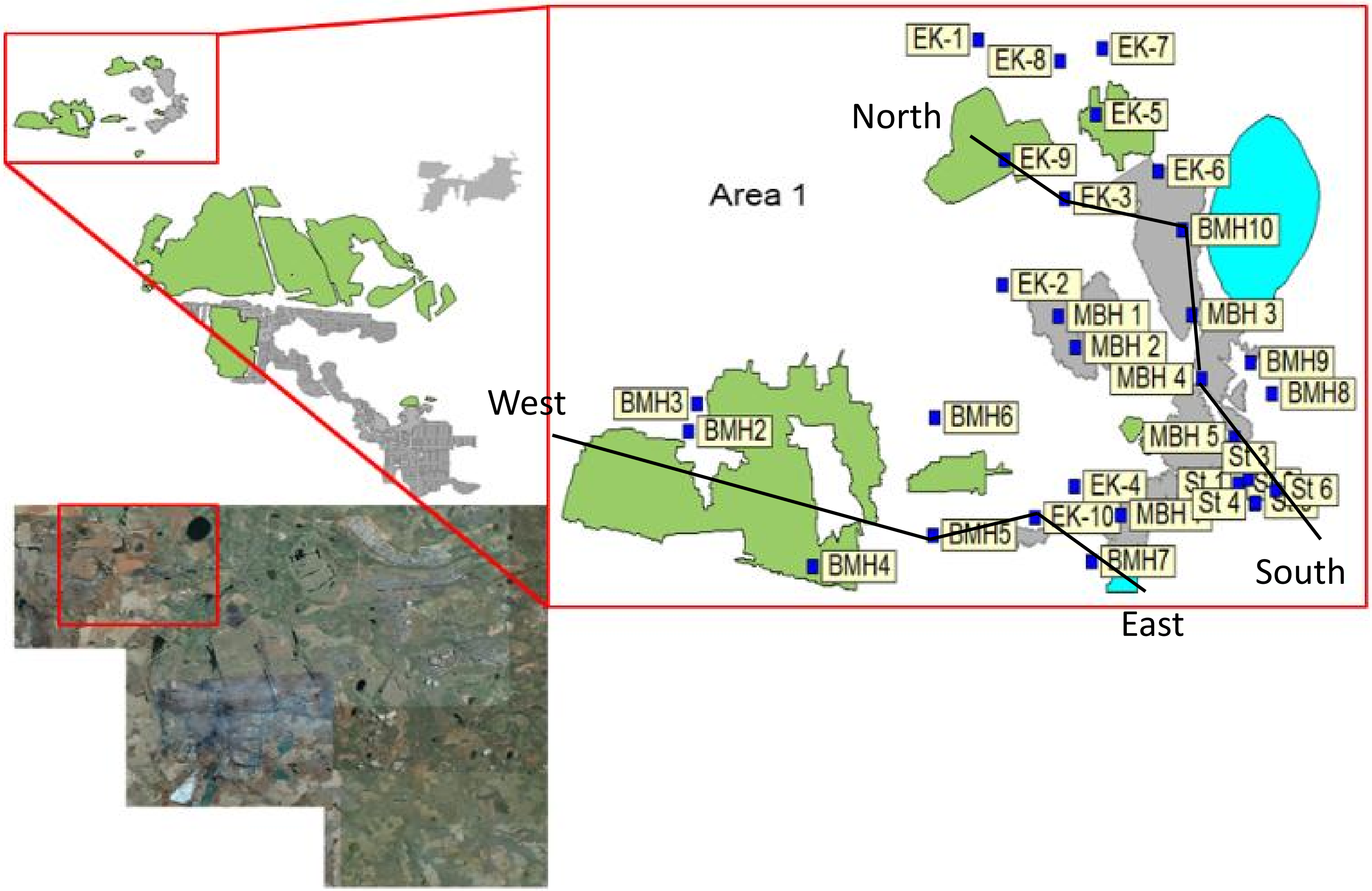
The Eikeboom Pan PC Dam 1 pumping rates, shown in Figure 7.10, consists of large fluctuations from 200 000 m^3/month when pumping takes place with an average pumping rate of 50 000 m^3/month over a five-year period. The K7 opencast pumping area was only pumped until 2013/05/06, where an average pumping rate of 5 000 m^3/month over a one-year period was recorded, with the exception of K7 deep/east pit to Klipbank Dam (Figure 7.11) where a once-off pumping rate of 53 000 m^3/month was achieved after which no pumping took place.

Although there are numerous dams in the area, there are only three that are of key importance. Firstly, the main water control dam, Eikeboom Pan, drains Area 1 and can be seen in Figure 7.14. Secondly, the PC Dam serves as temporary water storage for excess water due to pumping from the opencast pits, from where it is pumped to the Eikeboom Pan. Lastly, the Klipbank Dam is situated north of the K7 opencast pit operation, were water is pumped to the dam.

There is only one area in the combined K7 and Eikeboom mining areas. As seen in Figure 7.9, Area 1 shares the same aquifer with both having one artesian borehole and a maximum water level depth of 11 mbgl.

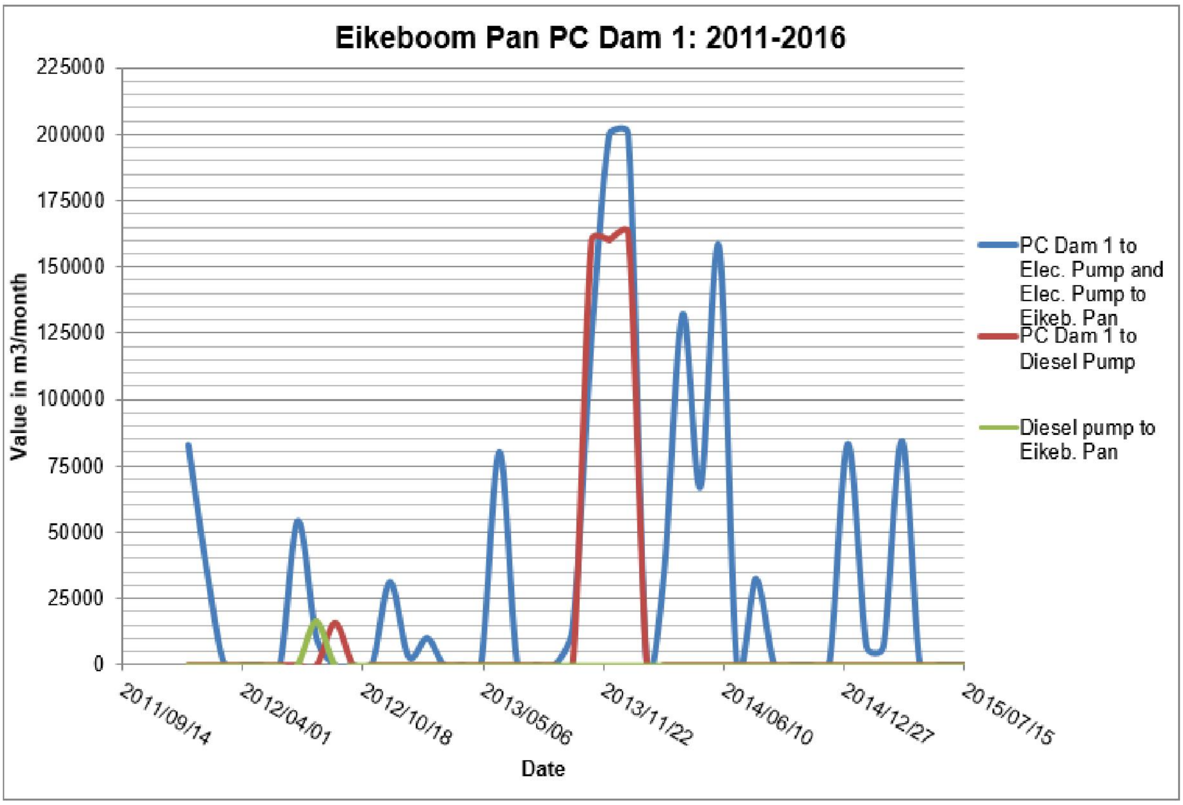
When comparing Figure 7.10 and 7.14, there is a clear correlation between the pumping rates and the PC Dam water level, from where the pumping stopped (start of 2015) and the rise in the PC Dam water levels. This rise in the water level is quite large when looking at the time period that passed and the amount the water level rose (10 m rise over four months). The Eikeboom pan serves as a water control dam and although there is no pumping in the area and the water level in the dam fluctuates constantly around the 1 m mark, the water level in this dam is stable.

Area1 has varying water levels which follow the same exact water level fluctuation pattern and is directly linked to the pumping rates which affect the aquifer two to three months later. When comparing the pumping rates and the PC Dam water level, there is a clear correlation from when the pumping stopped (start of 2015) and the rise in the PC Dam water levels.



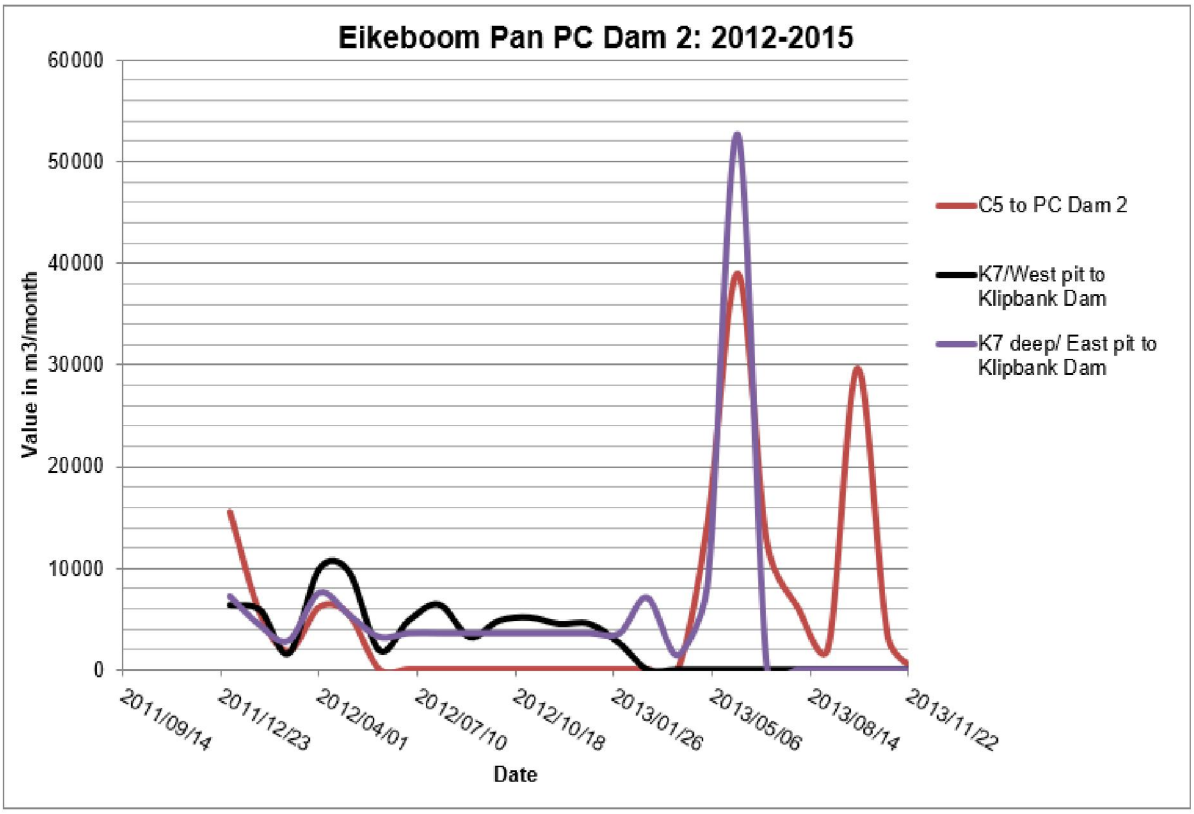
Source: Research Results (2017)

Figure 7.9: Eikeboom Pan area



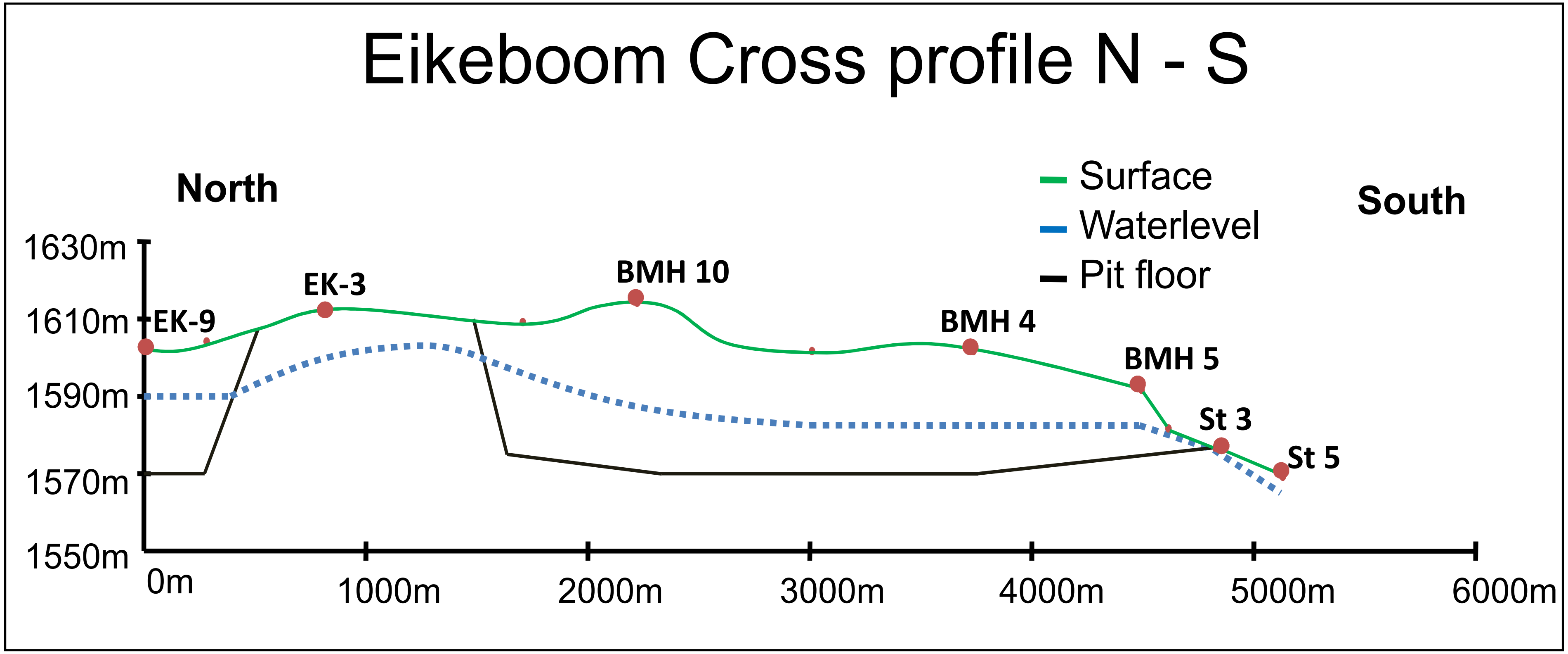
Source: Research results (2017)

Figure 7.10: EikeboomPan PC Dam 1: 2011−2016



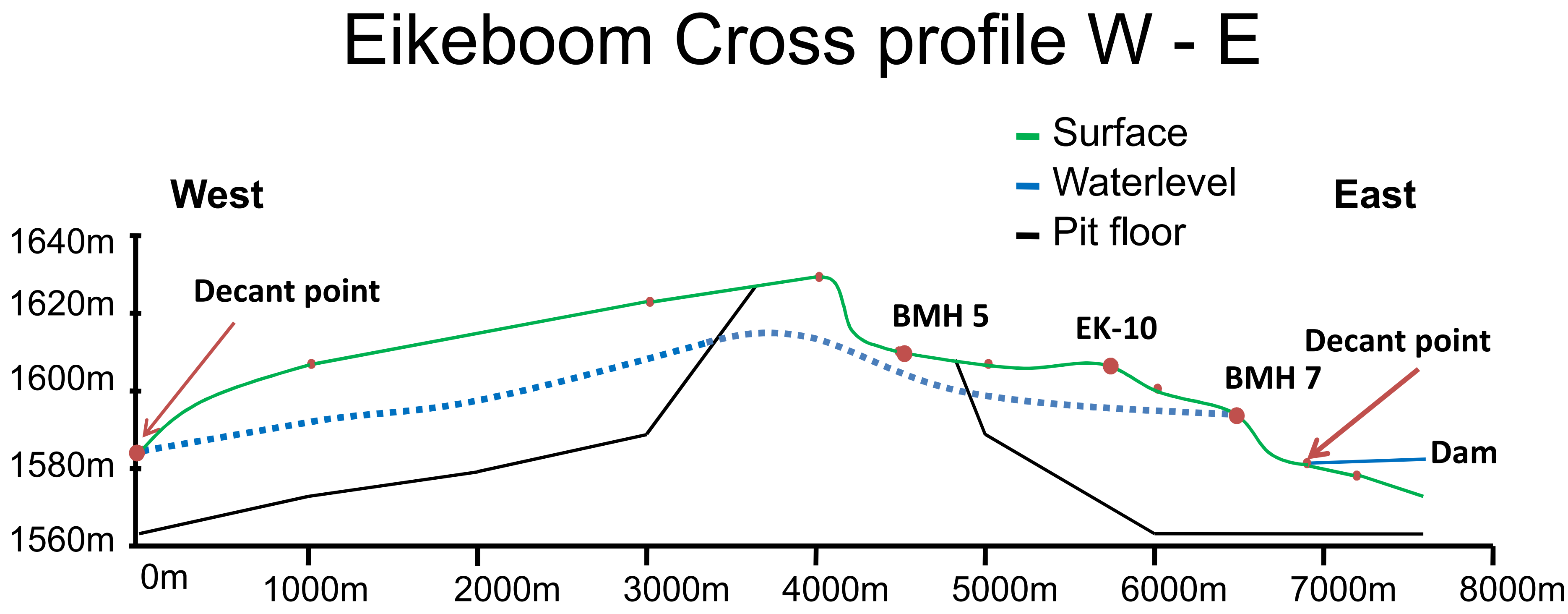
Source: Research results (2017)

Figure 7.11: Eikeboom Pan PC Dam 2: 2012−2015



Source: Author's own (2017)

Figure7.12: Eikeboom west–east cross profile.



Source: Author's own (2017)

Figure 7.13: Eikeboom north–south cross profile

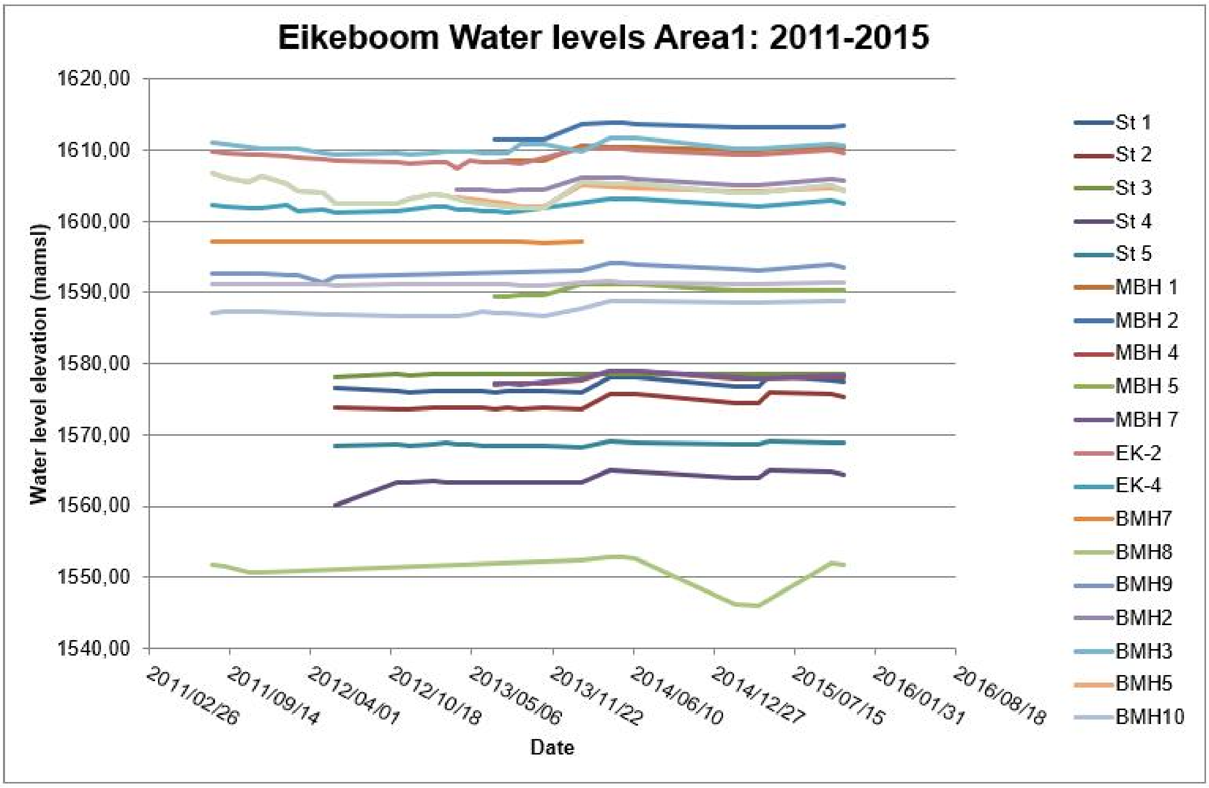
7.4.1.1 Area 1: Eikeboom

When looking at Figure 7.14, there is a clear correlation between all the boreholes present in Area 1. They all follow the same trend in water level fluctuations with only the water level elevations differing from each other, which can be attributed to their distance from each other as well as the topography for that specific area. The one exception is borehole BMH-8 which shows some correlation, and is due to the fact that it is situated just outside the mining area. Although all the water levels correspond to each other on a large scale there are subtle differences when the pumping rates are compared to water levels of that specific area of pumping. When the pumping rates from PC Dam 1 to electric pump, PC Dam 1 to diesel pump and electric pump to Eikeboom Pan are compared to the water levels for that area, they all correspond and show correlation between the amount pumped and the fluctuation in water levels. When looking at PC Dam 1 (Figure 7.10), pumping rates fluctuated between 200 000 m^3/month to 0 m^3/month, showing a steadily decreasing step-wise pattern, which correlates perfectly with what has been seen in Figure 7.14 water levels. It was also noticed that the pumping also takes between one and two months to affect the water levels in this area.

The area containing boreholes EK-4, MBH 7 and BMH 7 correlates with the pumping rates of Figure 7.10and Figure 7.11. These water levels correlate with both of the K7 and Eikeboom pumping rates due to the fact that they are so closely situated between the two of them, as seen in Figure 7.9.The area around these boreholes contains a point which it is artesian, and water levels only dips once below ground level. Borehole BHM-3 closely situated to the artesian point, is also artesian, which leads to the conclusion that the area has relatively strong water, and explains why the area surrounding BHM-3 shows pumping that fluctuates, to keep decanting at a minimum. Also, the fact that BHM 3 is artesian is an indication that the area is low lying and the pressure head is higher somewhere outside the mining area causing BHM 3 to become artesian and is the reason for the large pumping rate seen in Figure 7.11 from 2013/03/01 until 2013/06/01, in an attempt to lower the whole water table.

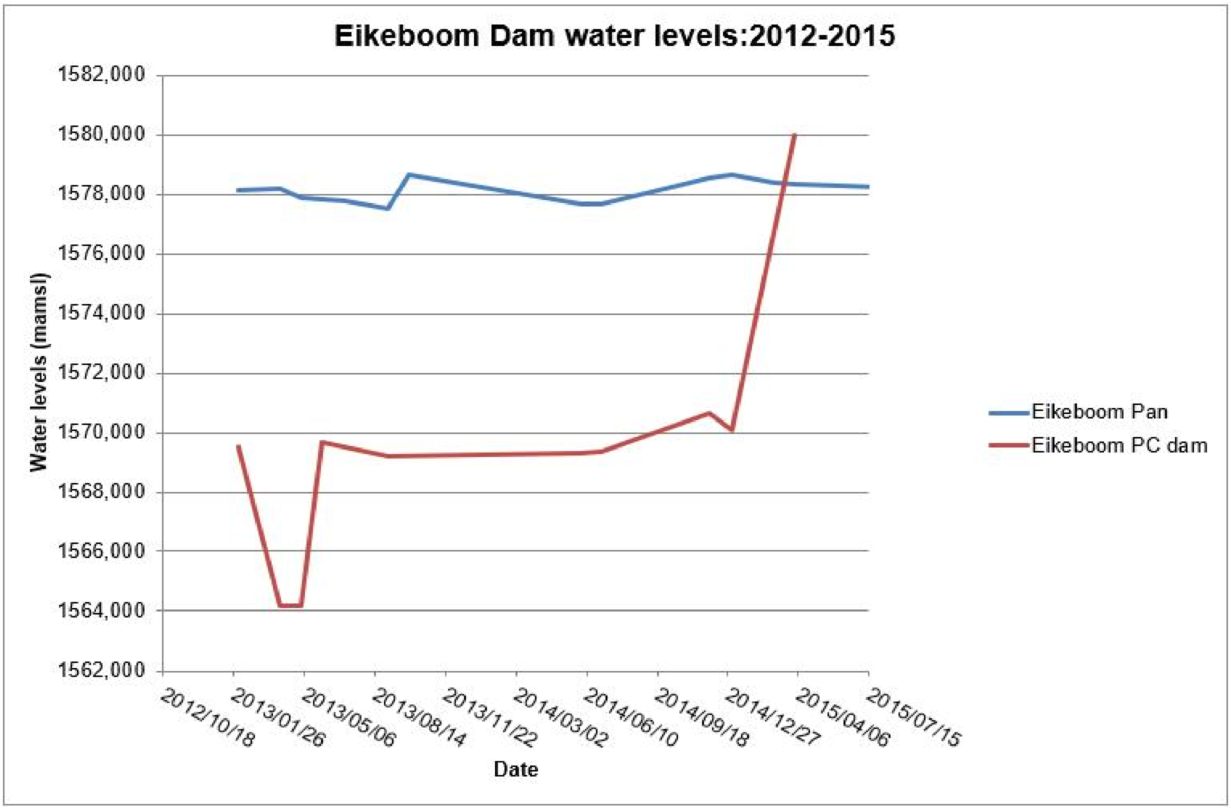
This area is situated closest to the water control dam (Eikeboom Pan) and serves as an indication of water level fluctuations in that area, whereby the water levels can be monitored constantly. This easy monitoring results in relatively stable water levels for this area as seen in Figure 7.14. No pumping occurs in this region to the Eikeboom Pan, since water levels are controlled at the Eikeboom Pan itself. As a result, none of the pumping data in Figure 7.10 and Figure 7.11 correlates with these boreholes seen in Figure 7.14, and rather follows a general trend of the whole water table elevation. Since no pumping takes place at the Eikeboom Pan area the fluctuation in water levels for that area mimics the surrounding fluctuating water table which is a direct result of pumping. It can thus be concluded that all the borehole water levels for this area are connected and thus located in the same aquifer, and that fluctuation in water levels will be duplicated farther away, despite were pumping takes place. The only factor that affects this area is the amount of pumping that takes place and will be seen in the water level fluctuations.

As an added reason that the area of Eikeboom has a connected water table, the dam water levels of the PC Dam and Eikeboom Pan also correlate with the change in water level elevation as seen in Figure 7.15, and that the area has a very shallow water table also indicated by the artesian boreholes mentionedpreviously.



Source: Research results (2017)

Figure 7.14: Eikeboom water levels Area 1: 2011−2015



Source: Research results (2017)

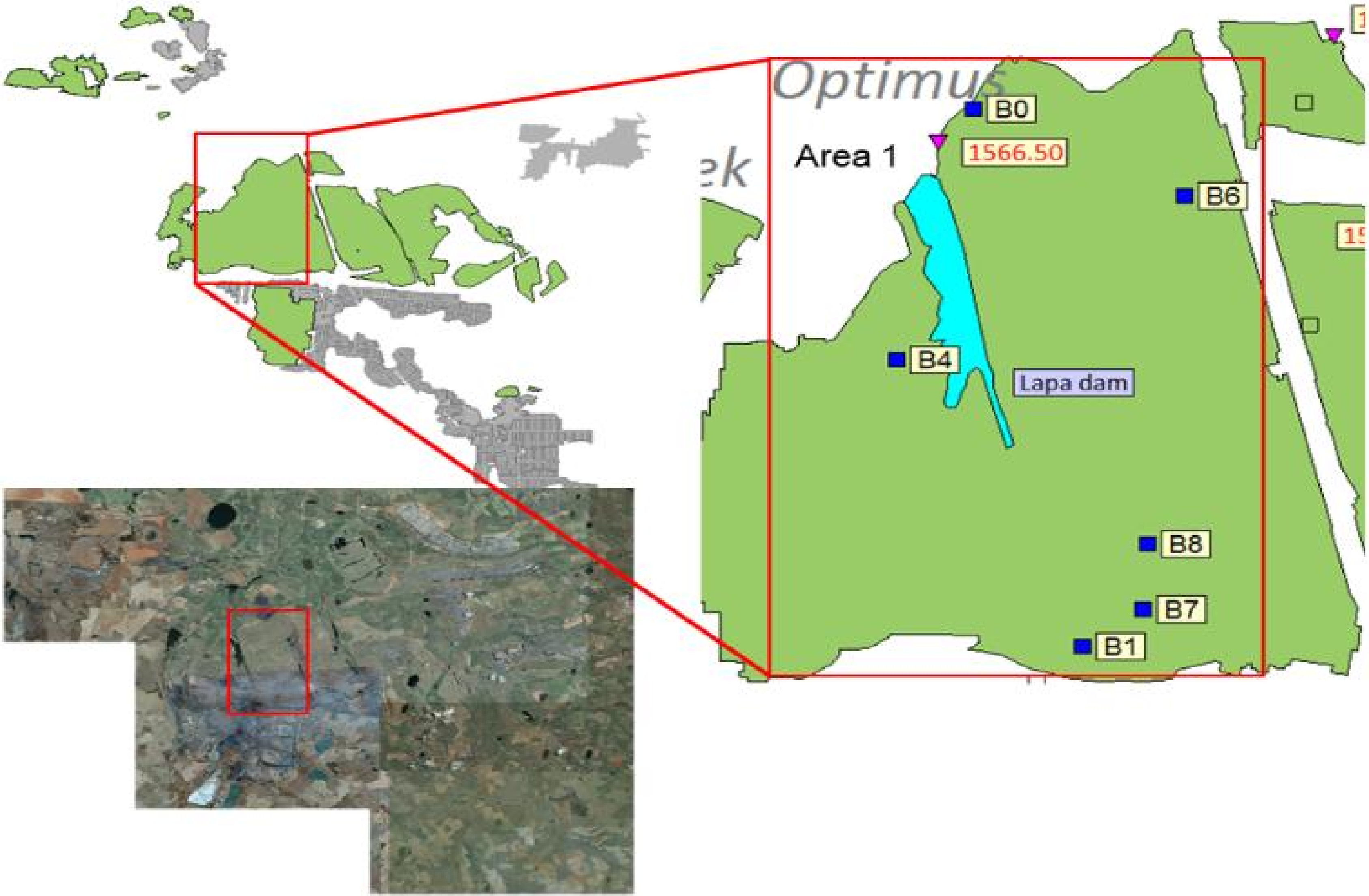
Figure 7.15: Eikeboom Dam water levels: 2012−2015

7.5 Optimusboreholewater levels

7.5.1 Site location, water levels, pumping rates and dam water levels

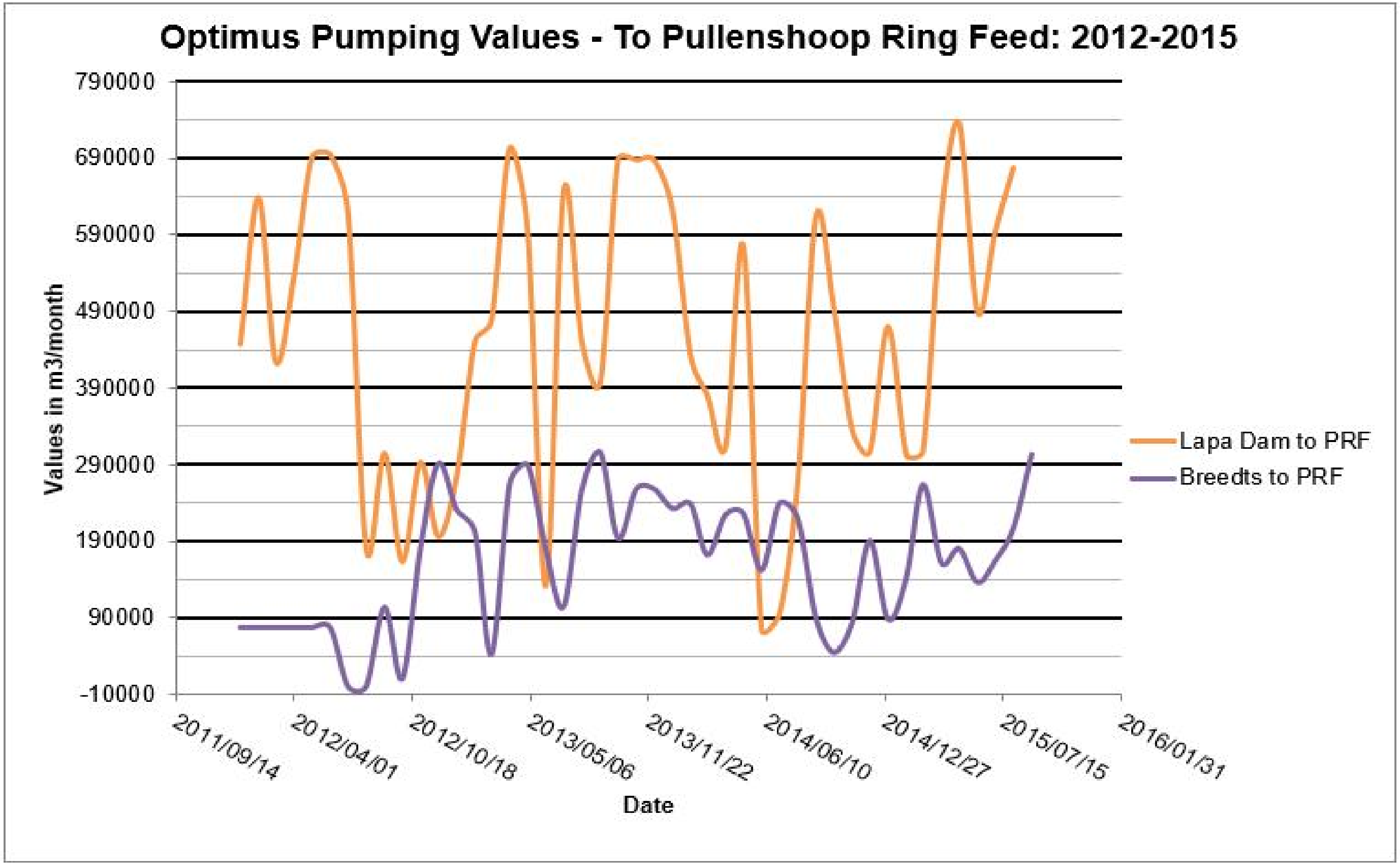
The Optimus opencast pit (Figure 7.16) is the main and largest operation at 23 500 481 m^2 with a connected Bothashoek operation at 7 074 287 m^2 to the west, which brings the total size to 30 574 768 m^2. The whole area has a series of pumping points and water control dams as seen in Figure 6.5 which serves as connector pipelines to the Pullenshoop ring feed system from where the water is pumped to either the water control dams or to the HMS gravity areas for use in mining, dust suppression or artificial recharge.

The Lapa Dam (Figure 7.19) which is centrally located in the Optimus pit, is the largest in the area and consequently the largest amount of water is pumped from there each month (Figure 7.17). The Optimus mining area freely drains towards the Lapa Dam from which water is pumped to the Pullenshoop ring feed system. Also, in the near vicinity pumping takes place at the Breedt Dam to the Pullenshoop ring feed system which can also affect the immediate groundwater table. On average 460 000 m^3/month is pumped from the Lapa Dam and 170 000 m^3/month from the Breedt Dam to the Pullenshoop ring feed system (Figure 7.17). For the Lapa Dam, we can conclude that there is no correlation between the pumping rates and the dam water levels, which means that the inflow into the dam nearly equals that of the pumping rate with external factors like run-off and direct rainfall producing the water level fluctuations. The Optimus area shows the same trend in water level fluctuations over the whole area with only their static water levels not matching (Figure 7.20).



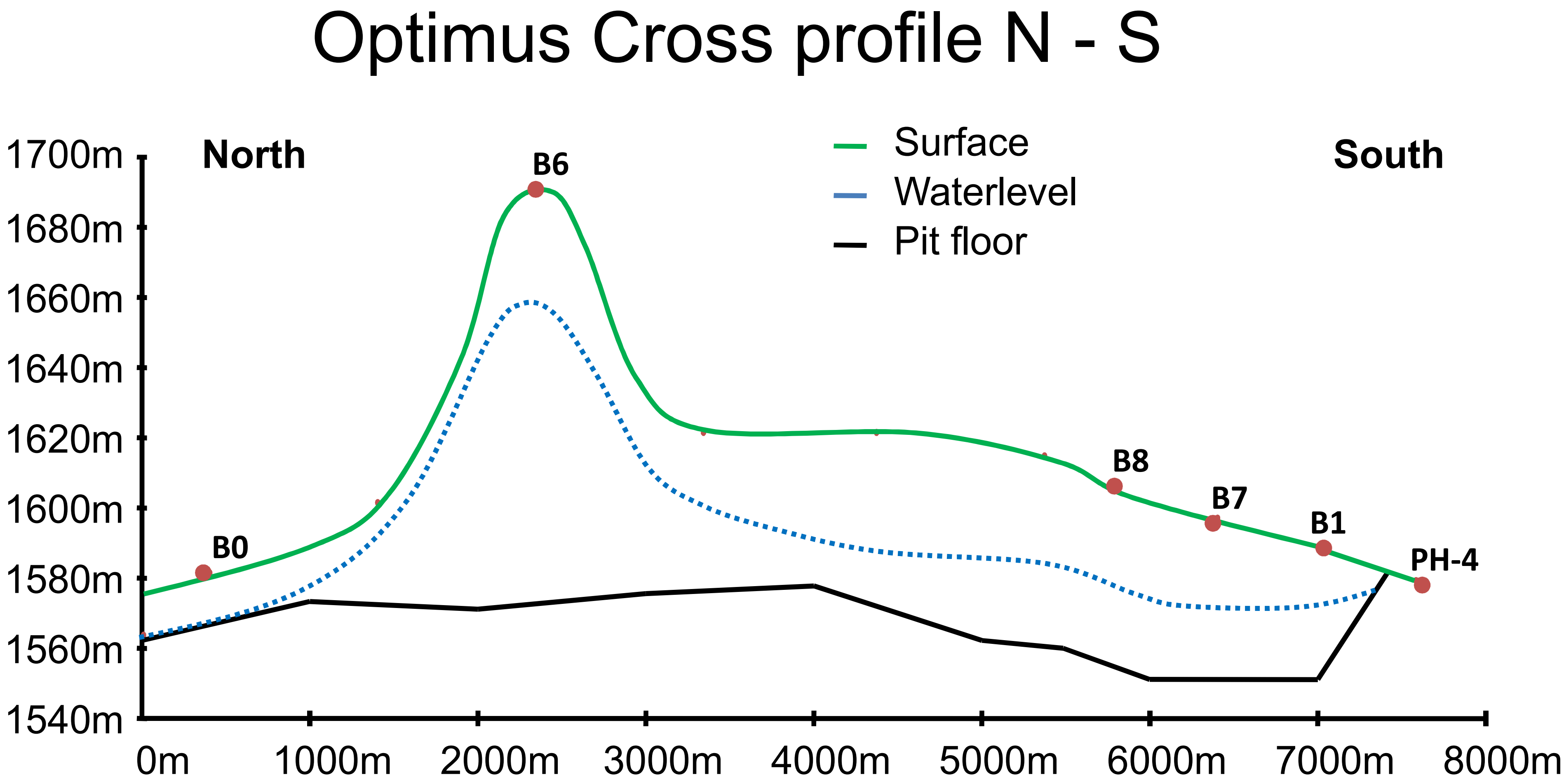
Source: Research results (2017)

Figure 7.16: Optimus mining area layout



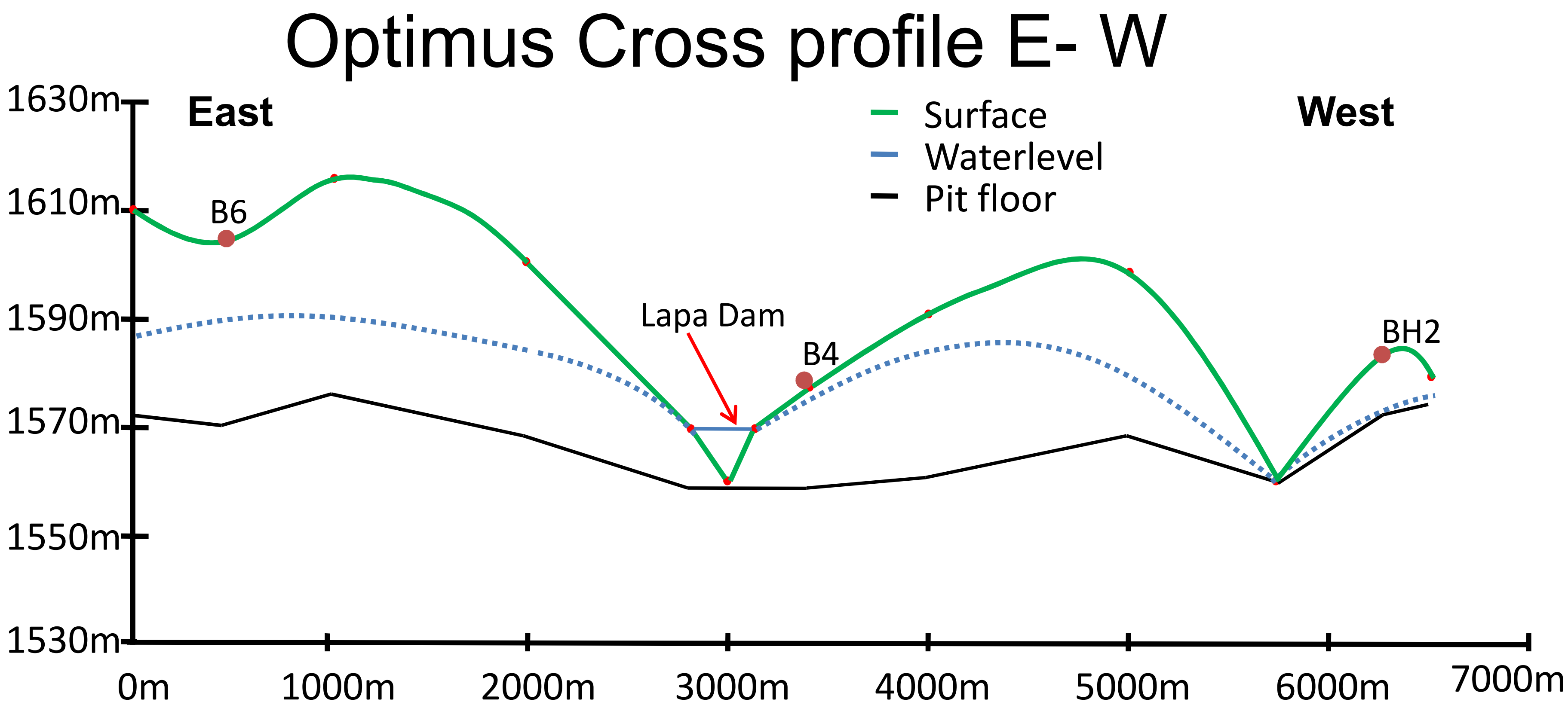
Source: Research results (2017)

Figure 7.17: Optimus pumping values to Pullenshoop ring feed system: 2012−2015



Source: Author's own (2017)

Figure 7.18: Optimus north–south cross profile



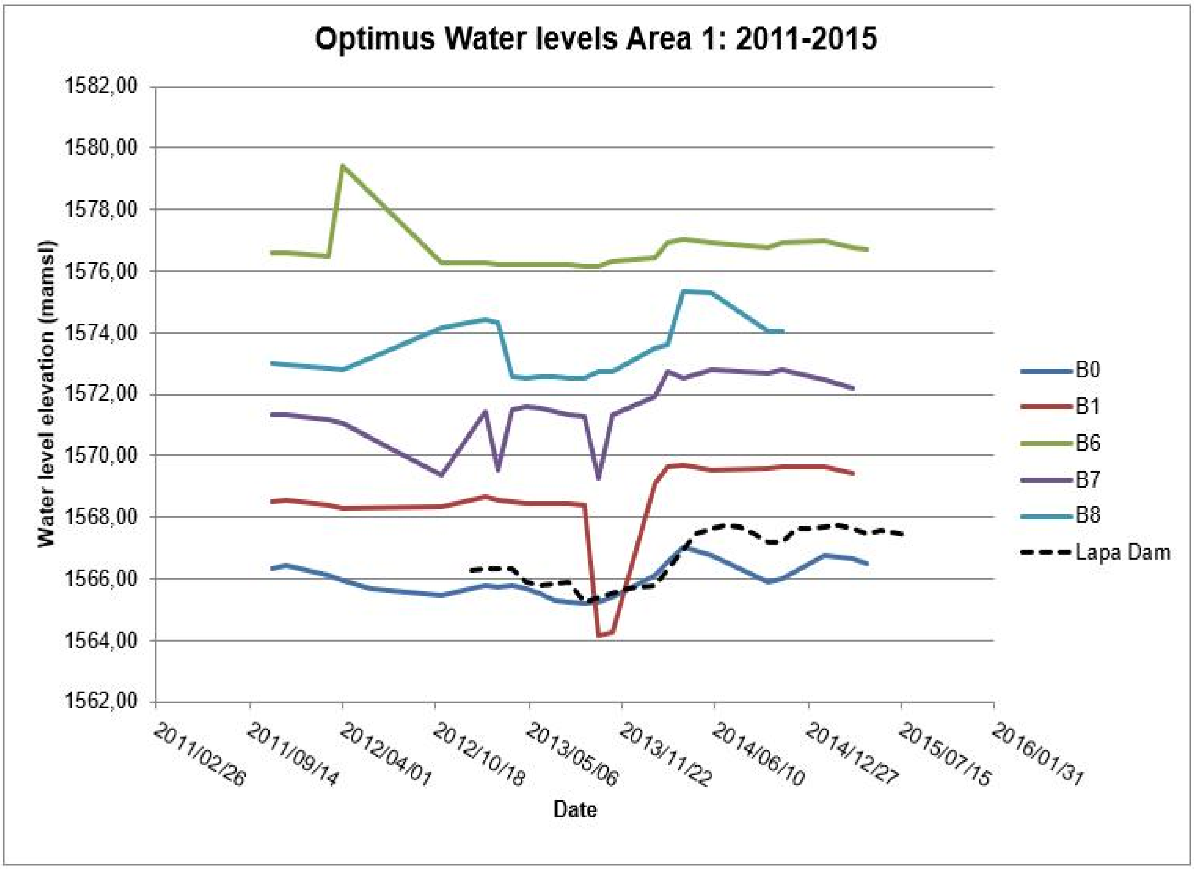
Source: Author's own (20017)

Figure 7.19: Optimus east–west cross profile

7.5.1.1 Area 1: Optimus

The borehole water levels in the opencast pit (Figure 7.20) show only small fluctuations in comparison to the large pumping rates seen in Figure 7.17. There is also no significant correlation between the borehole water levels and the pumping rates for this area. This might be due to the fact that water is pumped directly from the Lapa Dam and not directly from the boreholes which means that there is no immediate or apparent change in water levels

In conclusion,it can be said that all the water from this area freely drains into the Lapa Damand that pumping from this area slightly influences the water levels in the surrounding area but to no apparent comparison.



Source: Research results (2017)

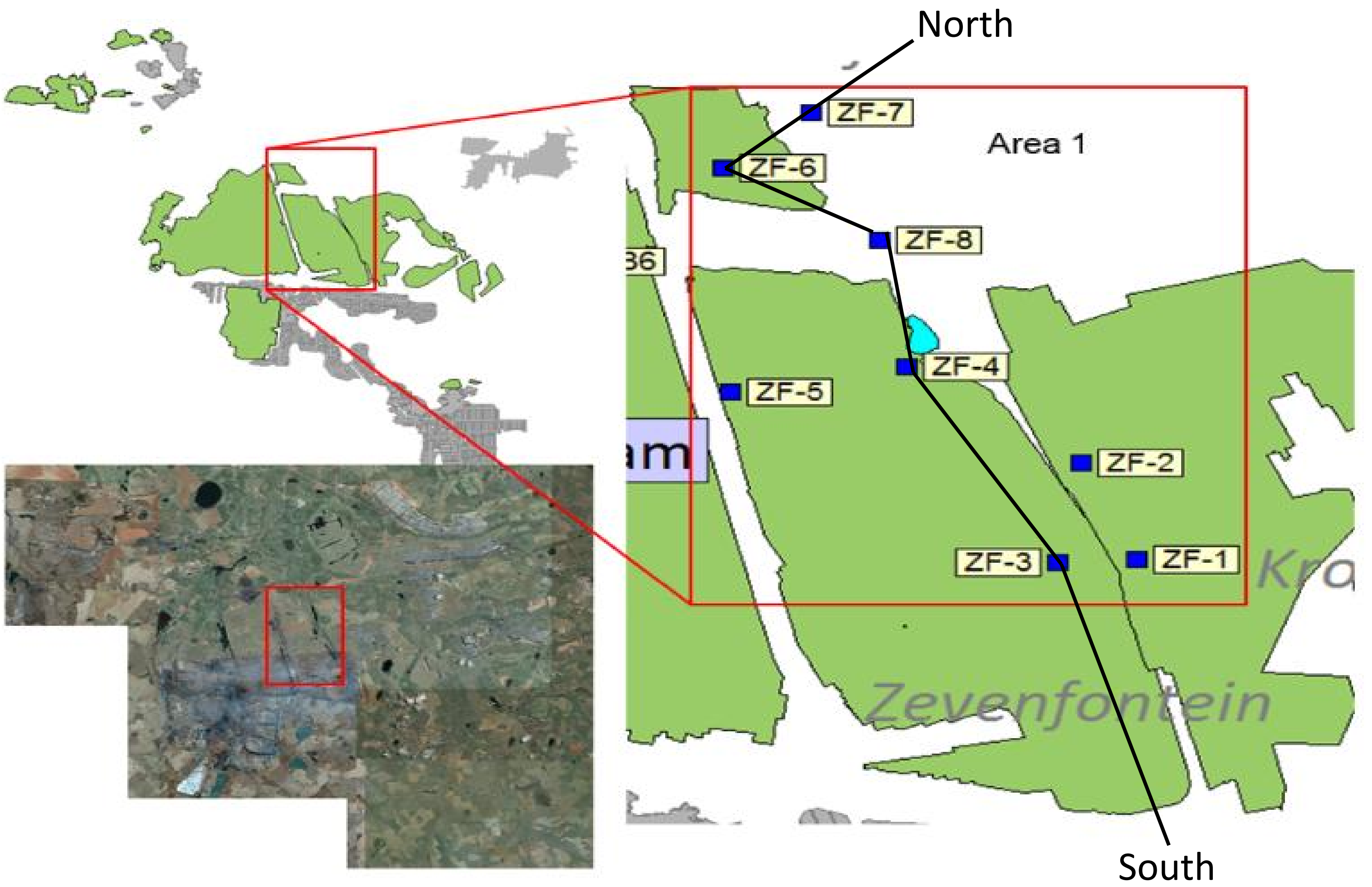
Figure 7.20: Optimus water levels Area 1: 2011−2015

7.6 Zevenfontein

7.6.1 Site location, water levels, pumping rates and dam water levels

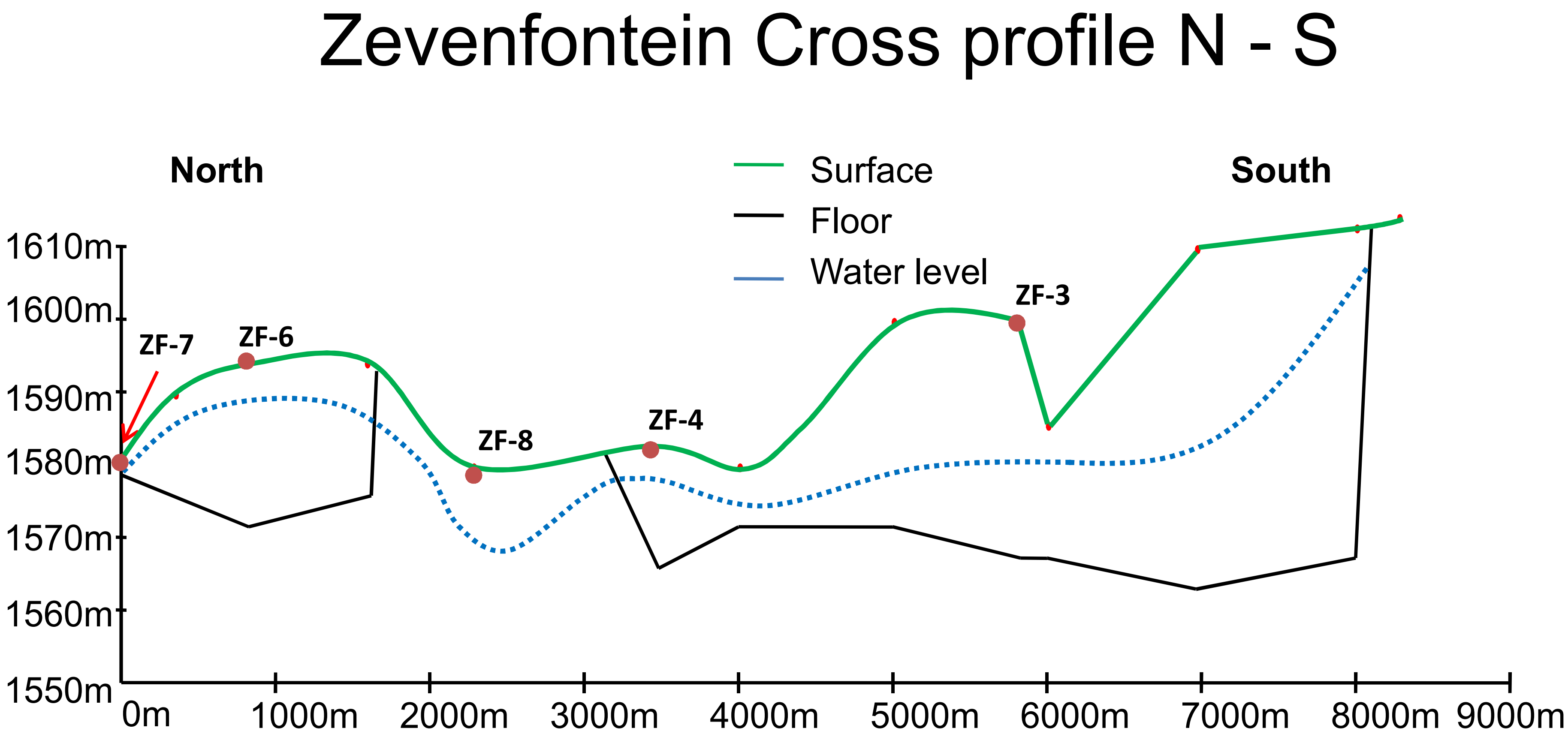
The Zevenfontein operation sits adjacent to the Optimus operation to the east at a total area of 16837 998 m^2 and is in the process of being completely rehabilitated (7.21). This area contains only the Coastal Dam as a surface water body, and is located in the centre of the Zevenfontein opencast area to where water drains freely under gravity. As for the Coastal Dam, the pumping rates (Figure 7.23) which undulate rapidly, has a direct effect on the Coastal Dam water level (Figure 7.24) which also undulates rapidly according to the amount of pumping that takes place.

The Zevenfontein area shows some slight fluctuations in water level when pumping takes place directly from the coastal dam (7.24). This means that the pumping rates do affect the water levels in the area although the water moves under gravity to the coastal dam (7.24). Due to the fact that pumping at one location (Coastal Dam) affects the entire water table for that area, it can be assumed that all the water levels taken at the ZF-series boreholes are interconnected. This assumption is confirmed by the water levels in the boreholes that are at different elevations to each other, but their trend and fluctuations match each other when pumping takes place.



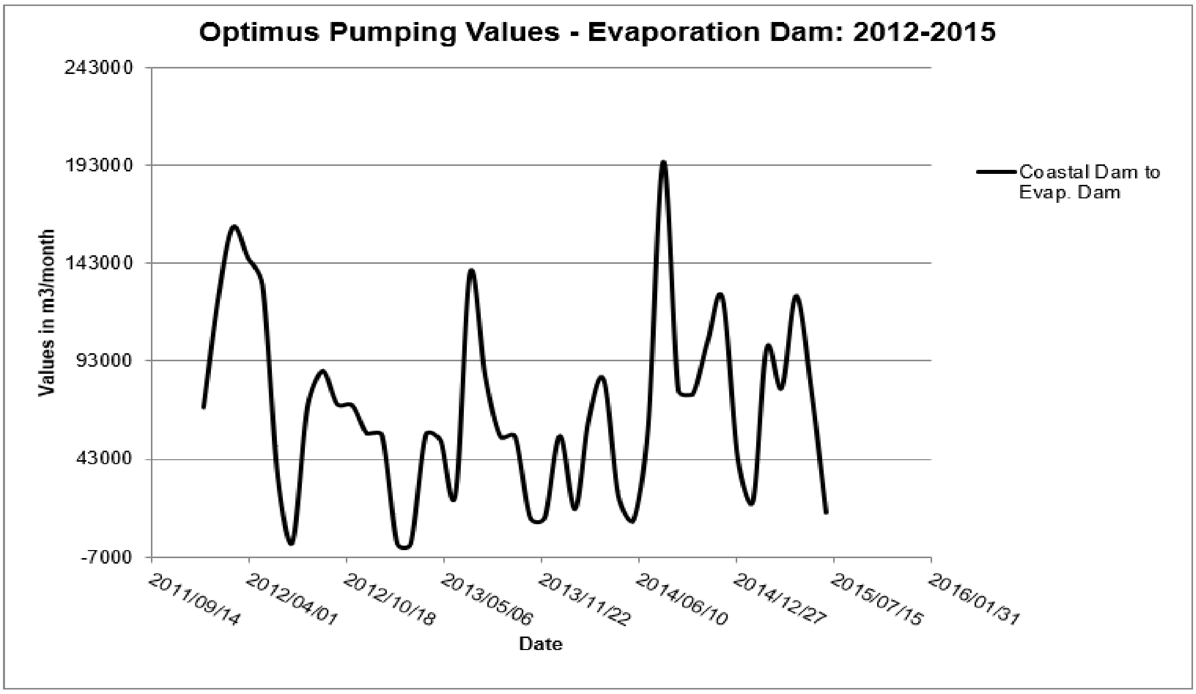
Source: Research results (2017)

Figure 7.21: Zevenfontein layout



Source: Author's own (2017)

Figure7.22: Zevenfontein north–south cross profile



Source: Research results (2017)

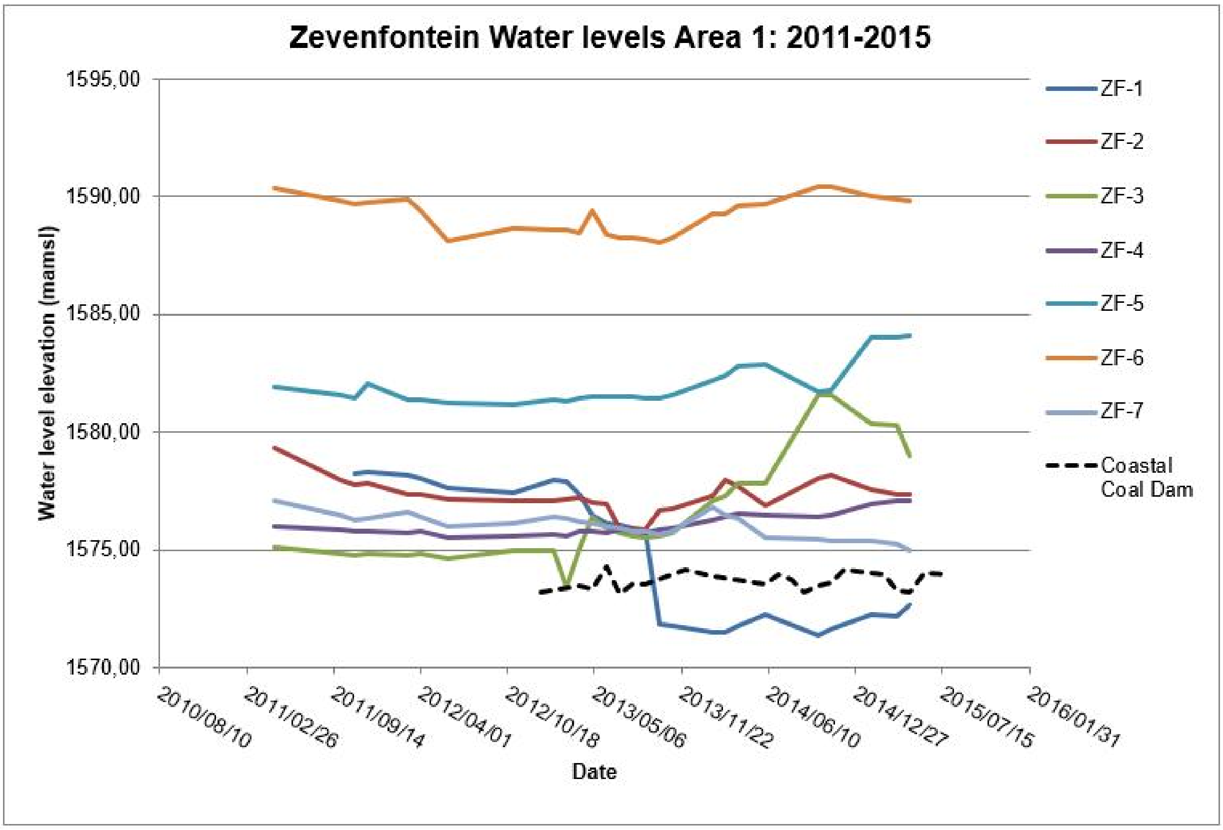
Figure 7.23: Optimus pumping values – Evaporation Dam: 2012−2015

7.6.1.1 Area 1: Zevenfontein

When referring to Figure 7.24, there is a clear indication that the water levels in the Zevenfontein area (Area 1) stay constant with little to no fluctuations in the water levels. Although the depth of the water levels varies greatly, the pattern of the borehole water levels stay the same. This is mainly due to the fact that the water moves underground and as surface run-off, to the lowest point, which in this case is the Coastal Dam situated to the northern part of the Zevenfontein opencast mining area. The Coastal Dam is also where all the pumping for this area takes place. Thus, pumping from the Coastal Dam might not affect the water levels as much as directly pumping from the boreholes although some correlation was found. The pumping from the Coastal Dam also stays constant, although there are large fluctuations in the pumping rates, the average trend stays at 450 000 m^3/month (Figure 7.23).

Thus, it can be deduced that pumping from the dam, and not directly from boreholes, as well as a constant pumping rate, is the result of constant water levels as seen in Figure 7.24.

As for the Coastal Dam, the pumping rates have a direct effect on the Coastal Dam water level which also undulates rapidly according to the amount of pumping taking place.



Source: Research results (2017)

Figure 7.24: Zevenfontein water levels Area 1: 2011−2015

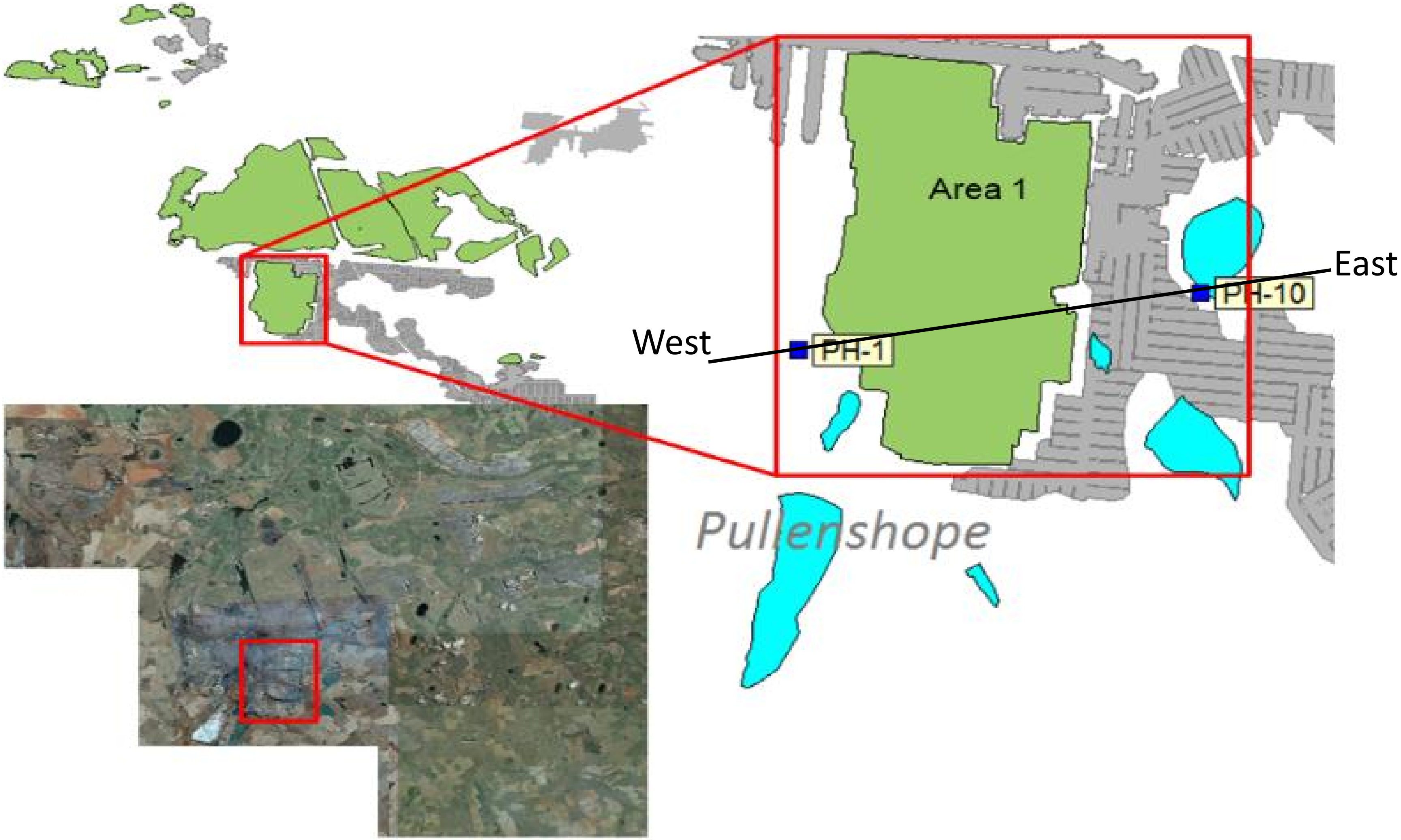
7.7 Pullenshoop

7.7.1 Site location, water levels, pumping rates and dam water levels

The Pullenshoop operation, which is primarily an opencast mining area, sits directly south of Optimus and covers a total area of 15 066 412 m^2 with another 19 281 860 m^2 of new underground operations with plans to extend the underground operation with the Boschmanspoort underground operation by the year 2024.

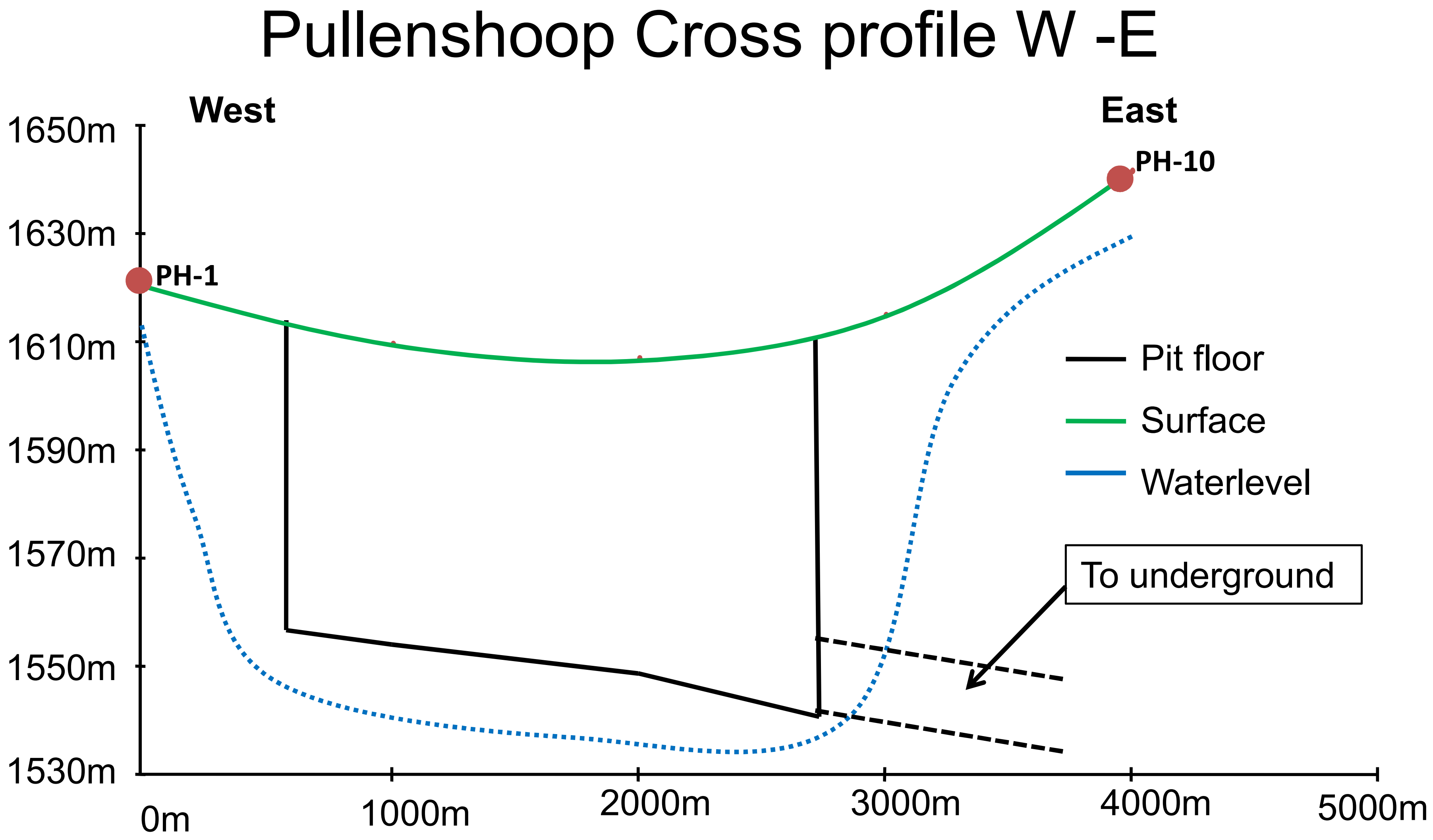
The Pullenshoop water levels (Figure 7.28) are located in the same aquifer and show exactly the same water level fluctuations, although no correlation could be found between the pumping rates and water level fluctuations. The Tollie Dams and North Dam water levels (Figure 7.28) show some small correlation in conjunction with the Pullenshoop pumping rates (Figure 7.27). These correlations are small when referring to the amount of water level fluctuations and all three dam water levels seem to respond in some small manner to pumping rates in the area with an average lag time of around two months. The rest of the dam are located around the Pullenshoop opencast operation were the Boschmanskop Dam 1, 2 and 3 serves as water storage dams. The Tollie Dam 2, 3 and North Dam also serves as temporary water storage as pumping from these dams takes place. The final Evaporation Dam serves as storage for the excess water not used in the mining process and where the water waits to be evaporated.

Over a period of three years the Evaporation Dam water level rose 3 m, which can be explained by the decrease in mining activity as most of the opencast coal has been mined out and underground operations start. Also, a 3 m rise in water level, when looking at the full scale of the dam, is nearly an insignificant rise in the water level. There is also no correlation between the pumping rates and the evaporation dam water levels since the dam is merely there for storage of excess water and not a source of water for mining activities.



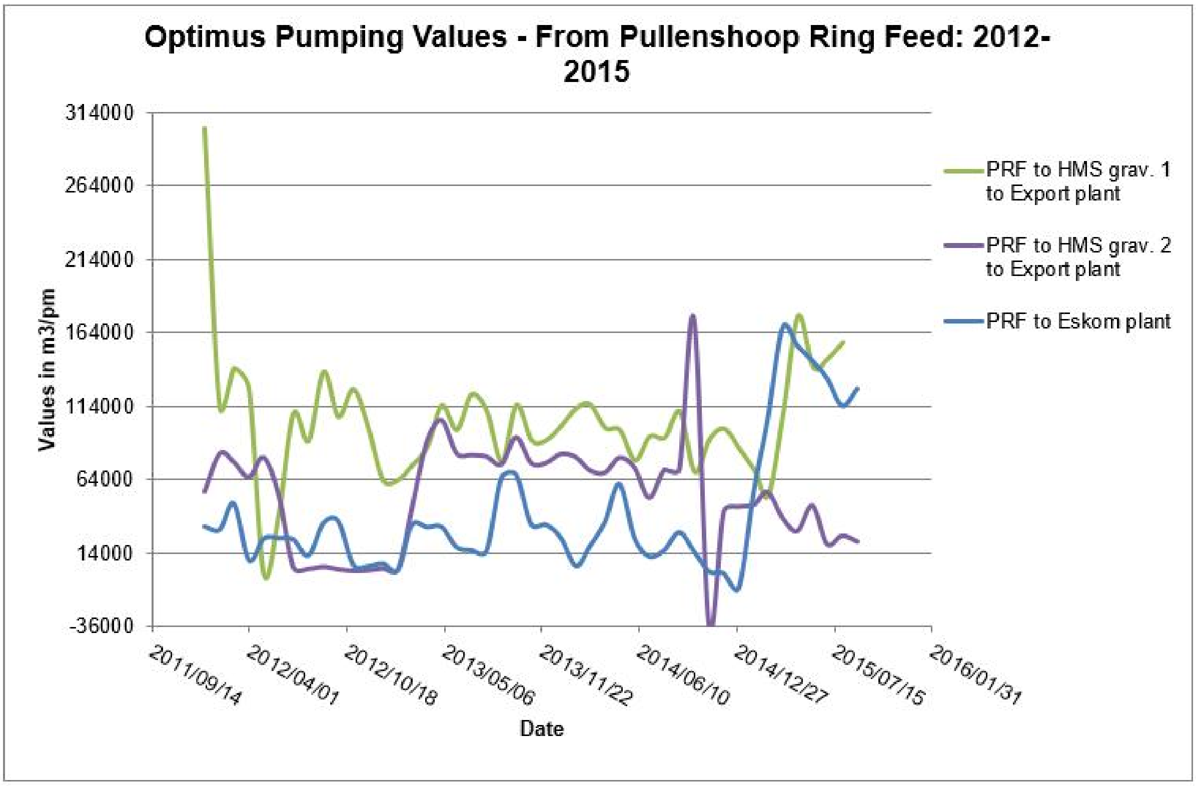
Source: Research results (2017)

Figure 7.25: Pullenshoop layout



Source: Author's own (2017)

Figure 7.26: Pullenshoop west–east cross profile



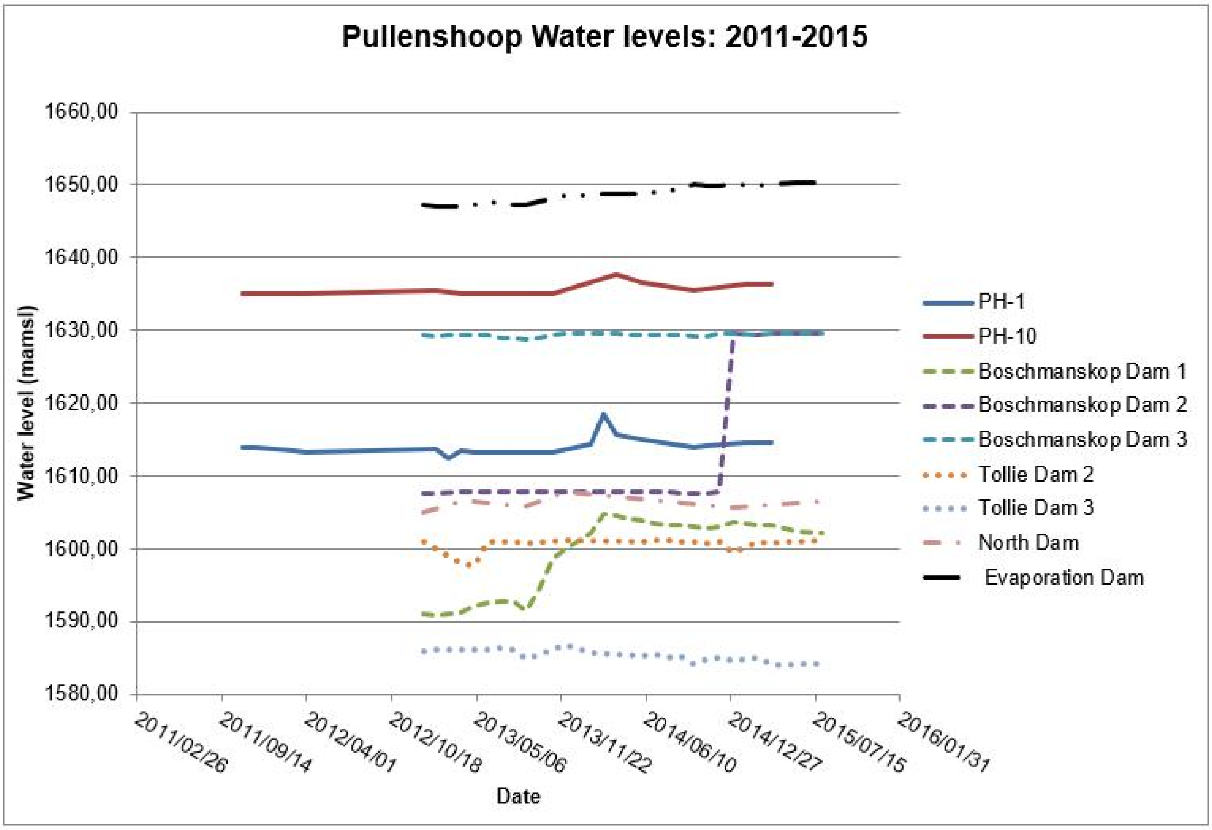
Source: Research results (2017)

Figure 7.27: Optimus pumping values from Pullenshoop ring feed system: 2012−2015

7.7.1.1 Area 1: Pullenshoop

Boreholes PH1 and PH10 are located on opposite sides of the Pullenshoop opencast mine. Both have water levels close to the surface, as the east side of the pit is higher than that of the west side, and show the same trend in water level fluctuations (Figure 7.28). Due to the large volume and large fluctuations for these pumping rates seen in Figure 7.27, it is difficult to determine whether the consistency of the pumping volumes or recharge and other natural factors influences the water levels. Therefore, it is difficult to determine whether the pumping in this area has any effect on the water levels.

The Pullenshoop water levels are located in the same aquifer and show the same water level fluctuations although no correlation could be found between the pumping rates and water level fluctuations. There is also no correlation between the pumping rates and the evaporation dam water levels since the dam is merely there for storage of excess water and not a source of water for mining activities.



Source: Research results (2017)

Figure 7.28: Pullenshoop water levels: 2011−2015

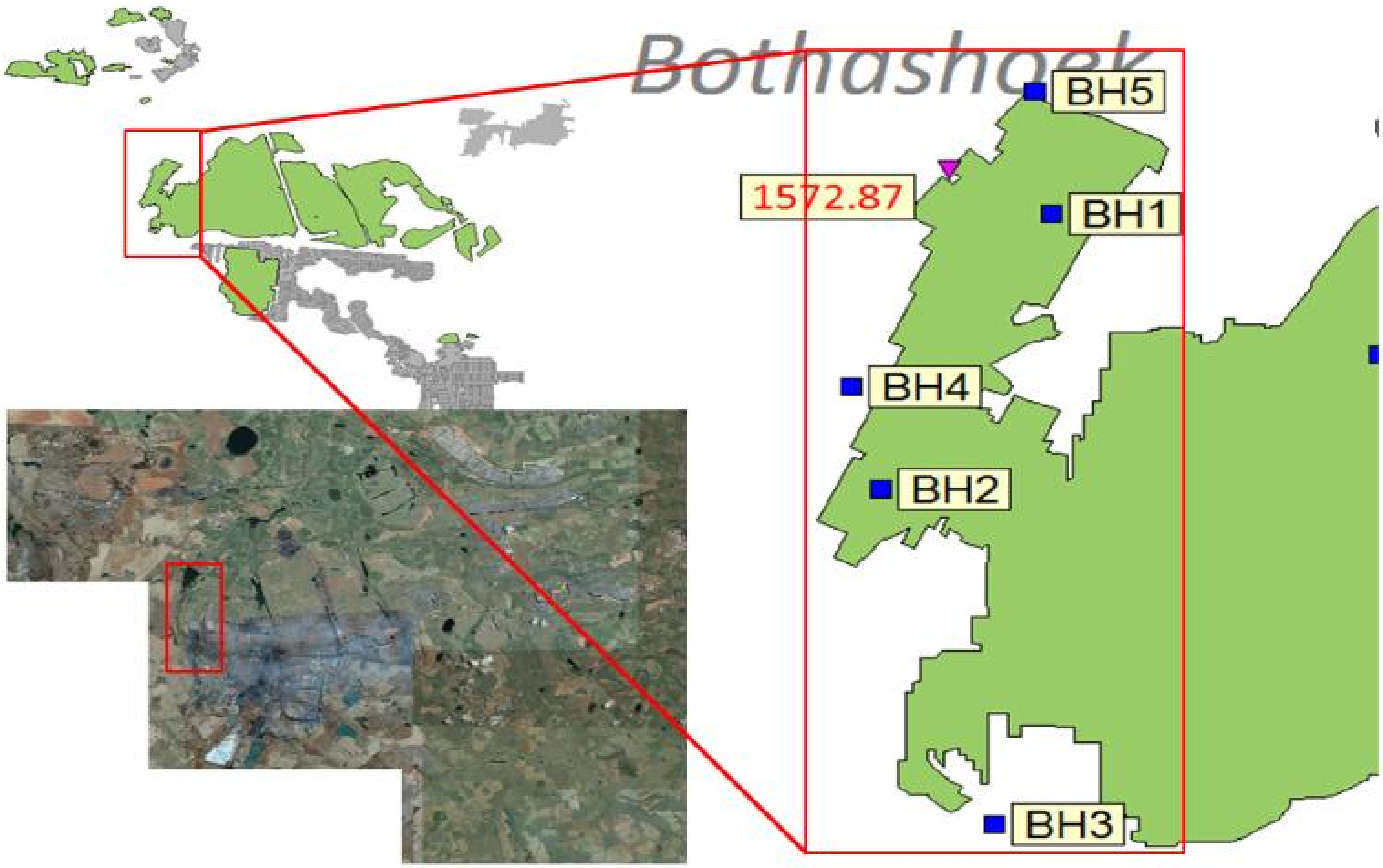
7.8 Bothashoek

7.8.1.1 Site location, water levels, pumping rates and dam water levels

The Bothashoek opencast operation (7 074 287 m^2) is adjacent to the main Optimus opencast mining operation and forms part of the same opencast pit (Figure 7.29).

There is no pumping that takes place in or near the opencast pit, but the water levels (1–13 mbgl) do show fluctuations (Figure 7.30), and may be due to the adjacent Optimus and Pullenshoop pumping rates and although no correlation could be found there is the lag time to be considered which may take up to three to five months.

In the Bothashoek mining area, there is no pumping that takes place in or near the opencast pit, but the water levels do show fluctuations, and may be due to the adjacent Optimus and Pullenshoop pumping rates.



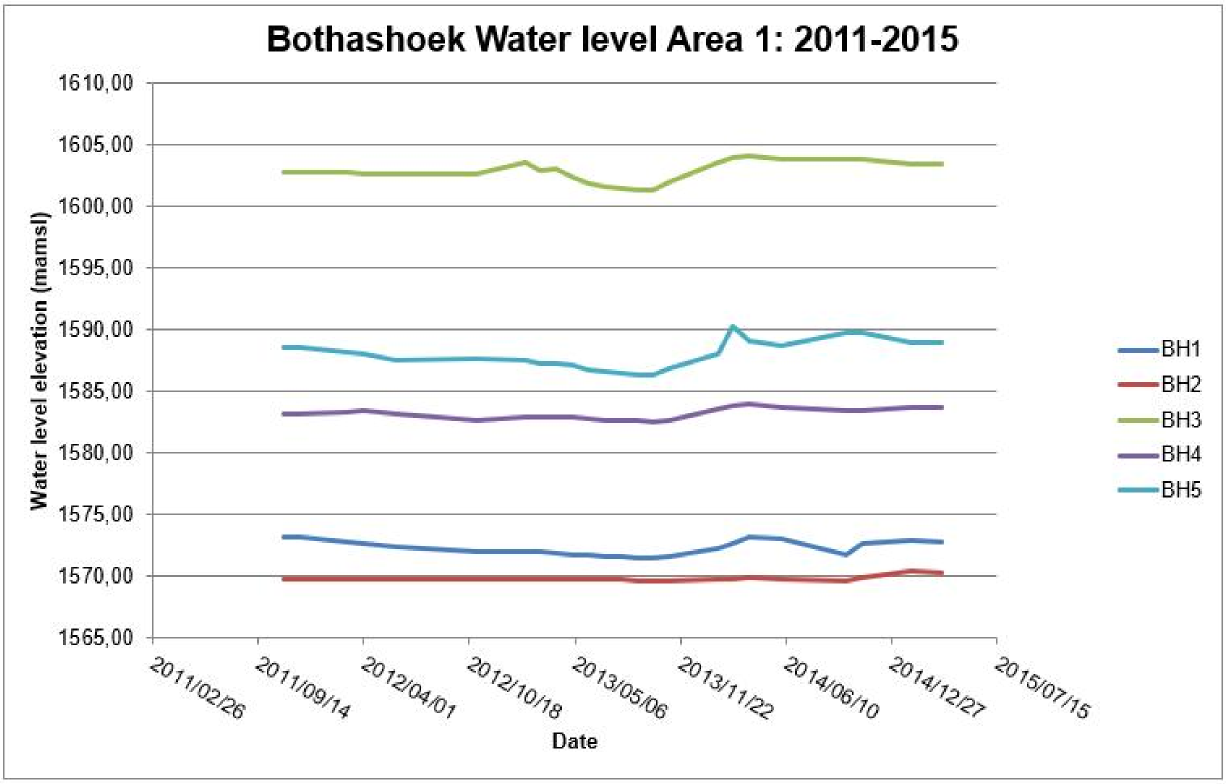
Source: Research results (2017)

Figure 7.29: Bothashoek layout

7.8.1.2 *Area 1: Bothashoek*

All the boreholes seen in Figure 7.30 show the same trend in their water level fluctuations although each borehole's water level is stationary at different metres below ground level. Although no pumping takes place in or close to the Bothashoek opencast pit, water level fluctuations can be influenced by the large amount of pumping that takes place in the adjacent Optimus opencast pit as well as artificial recharge and rainfall recharge.

Although there is no clear correlation between the pumping rates seen in Figures 7.29 and 7.30 it does not necessarily mean it has no effect on the water levels, as lag time and aquifer properties can influence the effect of pumping further away.



Source: Research results (2017)

Figure 7.30: Bothashoek water level area 1: 2011−2015

7.9 Summary

In conclusion it can be said that the waterlevels in and around the Optimum mining area are very shallow: between 0 and 10 mbgl on average. Strong groundwater flow can be expected in the area when taking the previously mentioned waterlevels and the large amount of pumping in the area into consideration. The rainfall pattern suggests a definite wet and dry season with the area receiving on average 450 mm rain per annum.

The Boschmanspoort area has a shallow groundwater table (2–10 mbgl) which is quick to react to any water extraction form the area. Since this area has been established as having a circulatory pumping system the waterlevels are only kept in check. The pumping rate average is established to be at 20 000 m^3/m and the water levels shows that a 18 000 m^3/m extraction rate, will subsequently lower the water table.

From the Eikeboom area waterlevels it could be deduced that they all reside in the same aquifer system as their fluctuations and static water level are more or less the same. Although the whole area contains a shallow water table (0−11 mbgl), it was noticed that a comparison between the waterlevels and the pumping rates suggested a lag time of one to two months.

The Optimus area has the low-laying centrally located Lapa Dam to where all the water freely drains and eventually decants. Pumping is done directly for the Lapa Dam itself, and together with the Breedt dam, all the extracted water is fed to the Pullenshoop ring feed system. No significant water level fluctuation within each separate borehole was noticed and is directly due to the fact that water is only pumped from the Lapa Dam and as a result no comparison could be made between the pumping rates and the waterlevels.

As with the Optimus pit the Zevenfontein area contains a centrally low laying dam (Coastal Dam) to where water freely drains under gravity and where the only extraction of water takes place. In contrast to the Optimus area, the Zevenfontein area does show a positive correlation between the pumping rates and the corresponding water levels. This leads to the conclusion that the water levels, which show the same fluctuations in static water level for the Zevenfontein area, are situated in the same aquifer system.

The Pullenshoop water levels show the same trend and fluctuations in static water level, although no correlation could be made between the water levels and the pumping rates due to a lack of data in this area. The same conclusion can be made for the Bothashoek area.

Chapter 8
New Recharge Calculations

8.1 Introduction

A water balance composes of various factors, and as with most recharge calculations, the more data and parameters there are the more accurate the result will be. For Optimum Mine, only the opencast mining areas were chosen which included the Optimus and Zevenfontein mining areas, as they are completely mined out and already rehabilitated or in the process of rehabilitation. The Pullenshoop, Eikeboom, Kwaggafontein and Boschmanspoort mining areas are either underground operations or are currently being mined. Although most of the data was available to do the recharge calculations, factors such as the way the pit rehabilitation was done, also plays a crucial role in the accuracy of the recharge methods, as will be seen later in this chapter.

Considering that crucial data on the porosity and void space values of the spoils were absent, they had to be calculated in order to produce a recharge value for the selected areas. The water balance methods used on the Optimus and Zevenfontein mining areas consisted of the RIV method, Stage Curve Volume Calculations, dry and wet calculations. The RIV is used as a water balance method to correlate the water infiltrated with the water being pumped out. When this balance is calculated the Stage Curve Volume calculations can be done, which in conjunction with the estimate void space, can yield porosity values for the spoils. After the porosities have been calculated the dry and wet calculations can be done. The dry calculations are also used to calculate porosities which can be compared to the porosities calculated in the stage curve volume method. The wet calculation uses these porosities to calculate a recharge value for the entire opencast pit over a selected period of time.

8.2 Rainfall infiltrated volume method

The RIV method works on the concept that the rainfall that infiltrates every month is influenced by the amount and type of rehabilitation at that specific time. This method can be used to see if the water infiltrated from rainfall matches that of the pumping rates produced by the mining operation over a period of time. The equation is as follows:

$$\textit{Rainfall Infiltrated Volume } (m^3) = \textit{Rainfall (mm)} * \textit{Rehabilitation area (ha)} * \textit{Recharge Factor (\%)} * \textit{Porosity (\%)} \qquad \text{Equation 10}$$

8.2.1 Zevenfontein

The Zevenfontein opencast mining area is nearly completely rehabilitated with small areas that cannot be grassed such as the final voids, cuts and ramps (Table 8-1). In Table 8-1 the recharge factors and porosities are given for each type of spoil within the opencast pit area and were chosen to best suit the area. These recharge percentages chosen, are a combination of numerous works done on recharge in a mining environment and from Hodgson and Krantz (1998) (Table 5-1). The RIV calculations were done over a period of three years stretching from 2011 to 2014.

TABLE 8-1: RAINFALL INFILTRATED VOLUME CALCULATIONS FOR ZEVENFONTEIN

Parameters used for rainfall infiltrated volume calculations						
	Cuts and ramps	**Two rows of spoil**	**Opencast spoils**	**Levelled spoils**	**Top-soiled spoils**	**Grassed spoils**
Areas (ha)	228,64	64,58	234,99	298,89	66,21	1 134,44
Recharge factor (%)	70	60	60	20	17	14
Porosity (%)	100	10	10	10	10	10

Source: Research results (2017)

The mining operation at Zevenfontein does not actively pump water from boreholes to prevent decanting. Instead the water that decants is captured and pumped away for treatment. This means that the water that decants should be equal to that of the pumping rates to prevent any spillage and flooding.

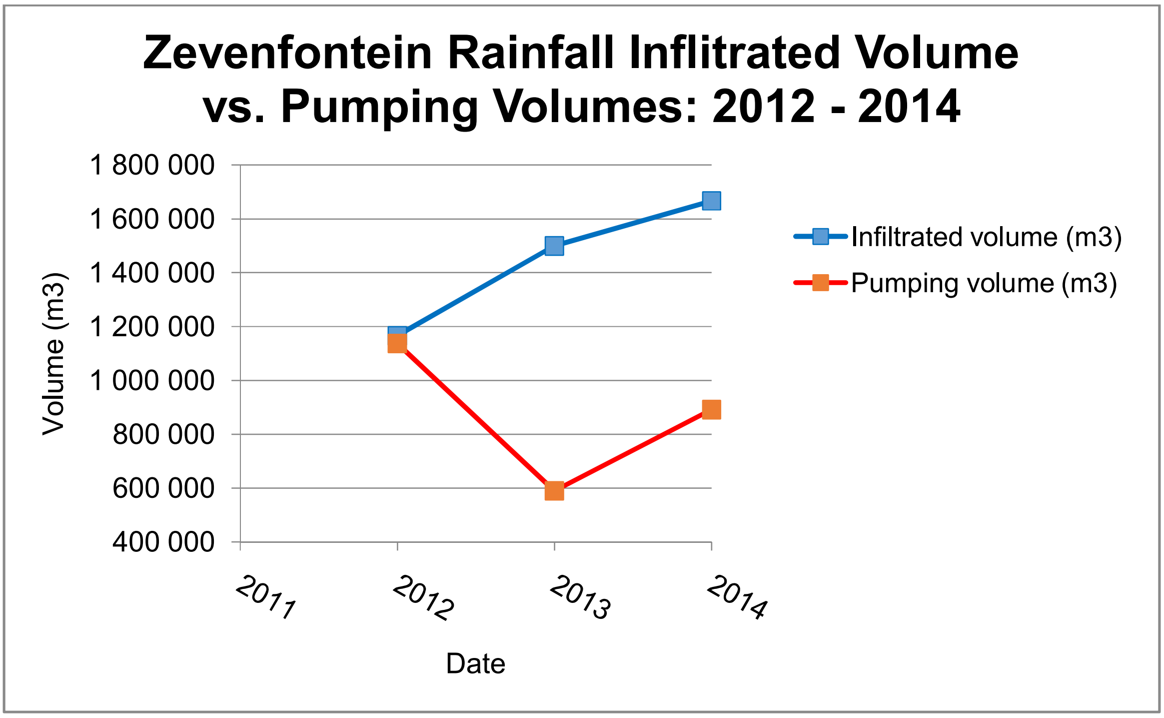
Thus, the water that decants near the Coastal Dam (lowest point) is as a result of excess water entering the system through water infiltrated by rainfall, run-off and inflows. It can then be safely assumed that the pumping values are representative of decanting and that the decanting volumes are representative of the excess water entering the system. That is why the water infiltrated through rainfall (excess water) can be compared to the amount of water being pumped away (decanting water) and that the difference can be attributed to inflows, outflows, run-off to the Coastal Dam or simply the mine adjusted their pumping rates.

When examining Table 8-2 there is a clear correlation between the RIV and pumping volume for 2012. As for 2013 and 2014 they do not show the same correlation. There are numerous factors which could explain the difference seen between the infiltrated volume and the pumping volume. The possible explanations for this can be that although the RIV method suggests higher volumes for decanting, only a fraction of that water decants and that the rest of the water infiltrated is lost to the groundwater system. This explains why the pumping volume values are lower than what the RIV method suggests.

TABLE 8-2: RAINFALL INFILTRATED METHOD

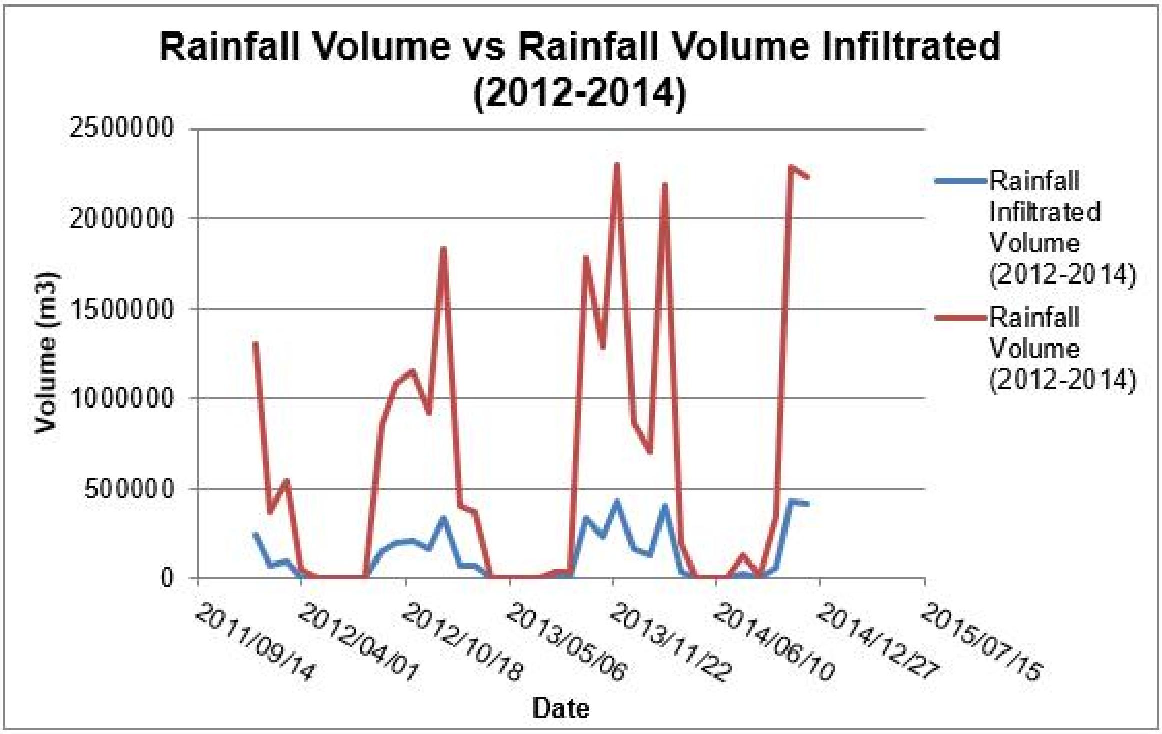
Date	Infiltrated volume (m^3)	Pumping volume (m^3)
2012	1 166 425	1137444
2013	1 500 264	590098
2014	1 667 183	891944

Source: Research results (2017)



Source: Research results (2017)

Figure 8.1: Zevenfontein rainfall infiltrated volume versus pumping volumes: 2012−2014



Source: Research results (2017)

Figure 8.2: Rainfall volume versus rainfall volume infiltrated: 2012−2014

As the final step the RIV can be compared to the rainfall volume for that area over the period 2012 to 2014 as seen in Figure 8.2. Furthermore, the recharge percentage can now be calculated for the whole combined rehabilitated area. This is done by dividing the calculated rainfall that infiltrated by the amount of rainfall for the area. This brought the recharge value from 2012 until 2014 to 18.6%. This recharge value might be considered high for unspoiled virgin ground, but considering the uncovered spoils and the fact that the spoils have higher void space percentage and porosities this value can even be in the vicinity of 30%. Thus, considering all the parameters, 18.6% recharge factor is what is to be expected from the Zevenfontein mining area.

8.2.2 Optimus

The Optimus opencast mining area consists of the largest area and is also in the stages of being completely rehabilitated. As with the Zevenfontein opencast area, the Optimus opencast area is mostly grassed and levelled spoils (Table 8-3). In Table 8-3 a summary of the recharge factors and porosities of each rehabilitated spoil area is given. The RIV calculations were done over a period ofthree years stretching from 2011 to 2014.

TABLE 8-3: RAINFALL INFILTRATED VOLUME CALCULATIONS FOR OPTIMUS

	Cuts and ramps	Two rows of spoil	Opencast spoils	Levelled spoils	Top soilspoils	Grassed spoils
Areas (ha)	84,59	0	125,2	318,69	19,79	1905,2
Recharge factor (%)	70	60	60	20	17	14
Porosity (%)	100	10	10	10	10	10

Source: Research results (2017)

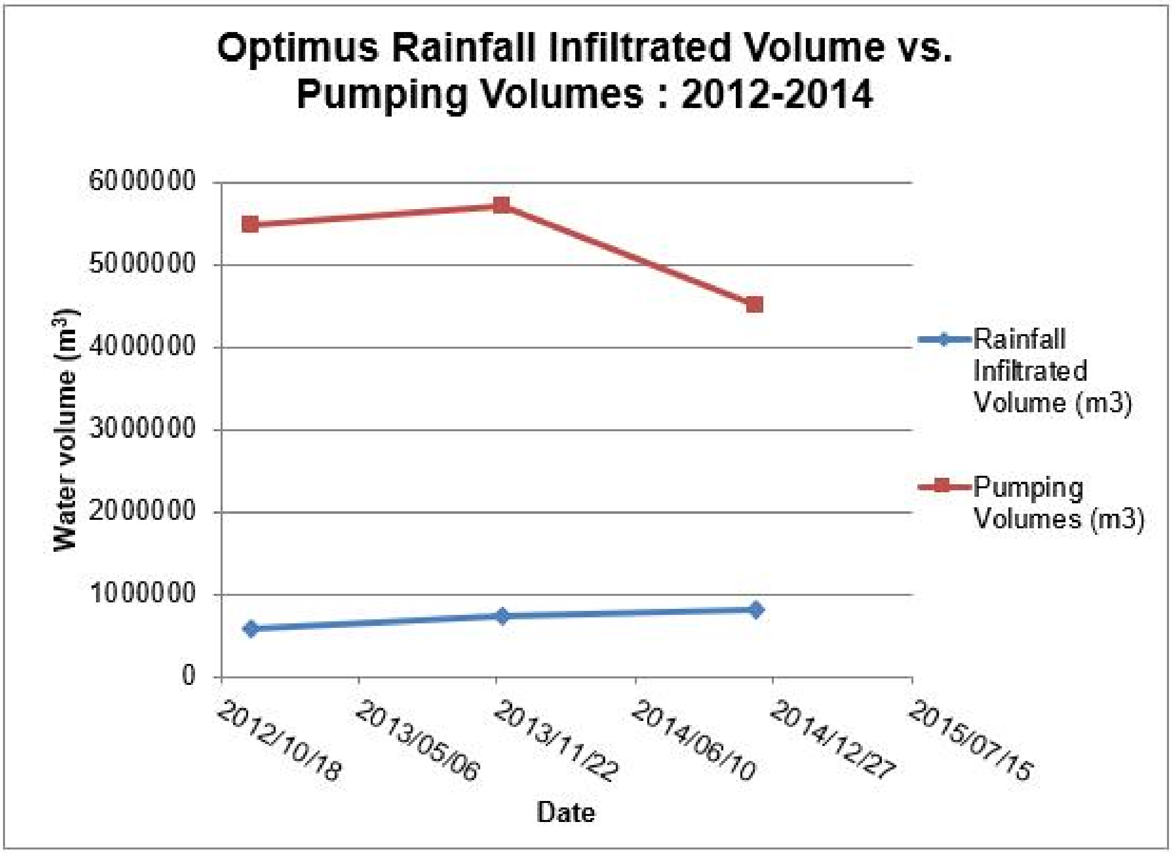
As with Zevenfontein, pumping only takes place when decanting starts, which in this case is near the Lapa dam. It can be assumed that the infiltrated rainfall together with the inflow raises the water level within the opencast pit. Since there is a permanent dam (Lapa Dam) in the centre of the Optimus pit it can be assumed that the natural state of the water level within the opencast pit is already above ground and at the stage of decanting. Thus, any surplus rainfall that infiltrates the spoils within the pit can be regarded as excess water when decanting. This is why the pumping and the RIV can be compared with each other since pumping only takes place due to decanting.

When examining Table 8-4 and Figure 8.3 there is no correlation between the RIV and pumping for 2012, 2013 and 2014. Although no correlation is found there is a good explanation for the values observed in Table 8-4 and Figure 8.3. The large difference between pumping volume and the infiltrated volume can be explained by the design of the rehabilitated pit and the inflows of different water sources. Firstly, due to the design of the Optimus rehabilitated pit all the water from rainfall flows to the centre of the pit to the Lapa Dam, which in turns raises the potential for recharge through natural flow (under gravity) and run-off into the Lapa Dam. Secondly, the river to the north of the Lapa Dam feeds the system with additional water from an outside source, which also raises the recharge potential to the groundwater table. Although the RIV method suggests a much lower pumping rate, the mining operation knows that this is not the only source of recharge and thus increases its pumping volume to accommodate the additional water from the outside sources.

TABLE 8-4: RAINFALL INFILTRATED METHOD

Date	Rainfall infiltrated volume (m^3)	Pumping volume (m^3)
2012	580 626	5464395
2013	746 805	5707010
2014	829 895	4513410

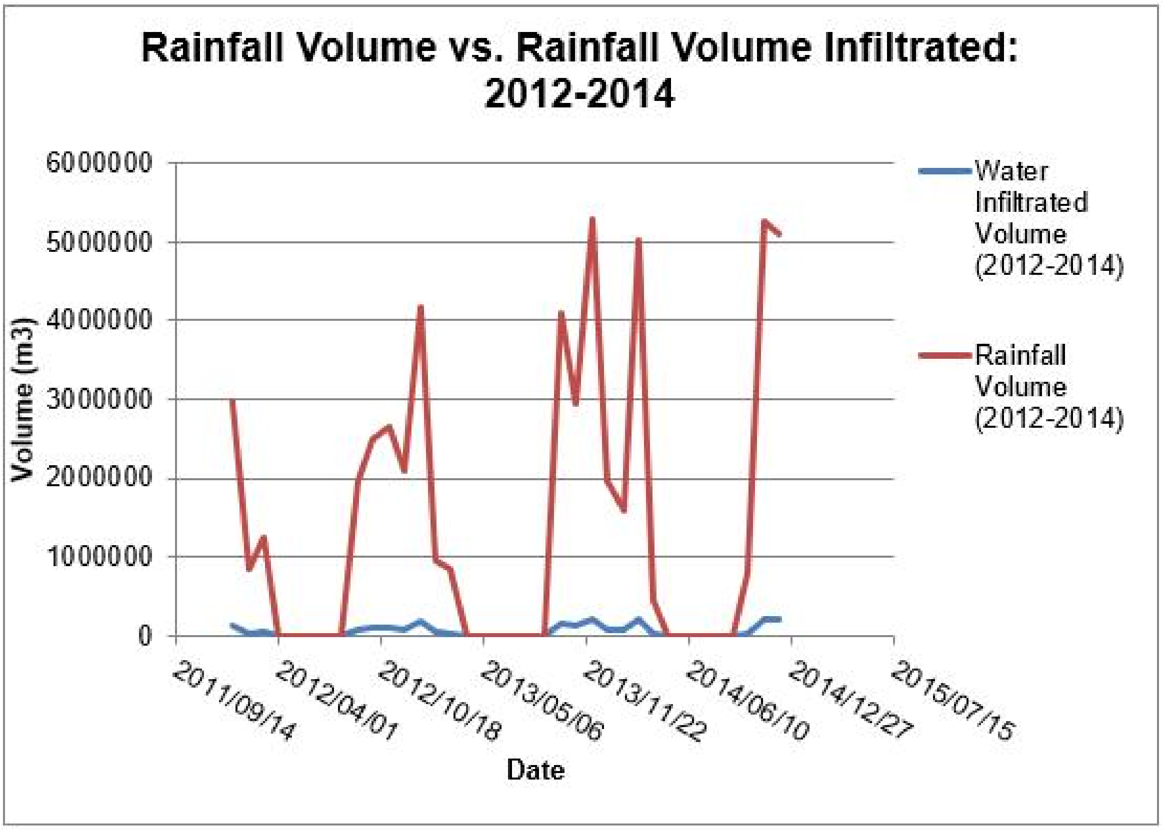
Source: Research results (2017)



Source: Research results (2017)

Figure 8.3: Optimus rainfall infiltrated volume versus pumping volumes: 2012−2014

The recharge percentage for the Optimus was calculated at 4% (Figure 8.4). This is a very low value and close to what is expected of virgin ground. For this opencast pit values close to 30% was expected, but due to the design of the opencast pit and the pumping volumes the recharge percentage was lowered. Since the Optimus pit does not allow free drainage away from the centre and instead guides the water towards the Lapa Dam, as well as a river that feeds an additional amount to the dam, the water inflows into the pit are raised. This means that the difference between the pumping volume and RIV (Figure 8.4) are the additional excess water from external sources.



Source: Research results (2017)

Figure 8.4: Rainfall volume versus rainfall volume infiltrated: 2012−2014

8.2.3 Summary

This method is essentially a water balance between the pumping volumes and the calculated RIV and consequently compared with each other. The pits are assumed to be filled to capacity, any water (recharged) entering the pit must decant or be pumped away. If the water decants, which it is for all two opencast pits, the excess water that decants can be attributed to rainfall, run-off and external water sources whereby the mining operation can either lower or raise their pumping volumes to accommodate for these changes in volume when the water starts to decant.

As a further precaution the exact area of the rehabilitated spoils, carefully chosen recharge factors and porosities are crucial in calculating a reasonable recharge percentage, as only a small change in one of the parameters could have large effects on the final value. It is also advised that longer periods of time are chosen to do the calculations over, between one year and onwards, since monthly calculations can yield either over- or under-estimate recharge values due to large changes in rainfall volume or pumping rates for those months.

Both the Zevenfontein and Optimus areas are passively pumped and that decanting volumes can be directly linked to pumping volumes. Both show that although this is true, outside factors can still influence the values, and thus pumping volumes are either lower (Zevenfontein) or higher (Optimus) that what is suggested by the RIV method.

As seen with the Optimus rehabilitated pit, the manner in which the rehabilitation is done, also plays a large role in determining the recharge percentage. It can be concluded that the Water Infiltrated Method does not work on a non-traditional rehabilitated pit (Optimus) where free flow is absent and ponding (Lapa Dam) takes place inside the pit. This means that recharge is enhanced by a multitude of external water sources which is not included within the RIV method. On the other hand, were pumping volumes and RIVs closely match and the pit is traditionally rehabilitated (Zevenfontein), great results can be obtained, since there are no external water sources which influences the recharge and pumping values.

8.3 Stage curve volume method

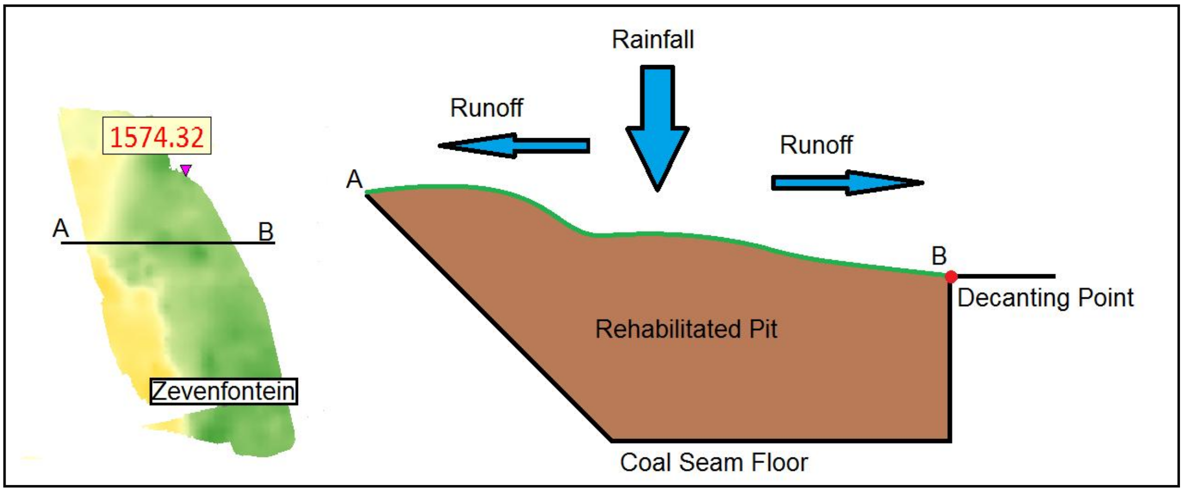
The stage curve volume calculation works on the concept that the total volume of water inside the rehabilitated opencast mine is directly affected by the change in water level over a period. For this method to work effectively parameters such as rainfall, pumping volume, void space at a minimum and maximum allowable value set at 10% and 25% are needed as dictated by the pit calculations (Chapter 5). The void space mentioned is the open spaces between the boulders and the fine-grained spoils which fill up with water after a rainfall event (Figure 5.9). An important effect of void spaces in boulders must be kept in mind, such as when the water level recedes, the fine-grained spoils drain much faster than that of the boulders which keep their void spaces filled long after the water level has drop below them, in a phenomenon called water retention. This phenomenon causes some problems in calculating the true porosity of the spoils since the period between the first and second drop and rise in water levels will differ in volume keeping in mind that the boulders are already saturated. Thus, a void space of 10% and 25% is used as a minimum and maximum allowable value for the spoils. As mentioned before the difference in volume over a period divided by the pumping volumes should produce a close enough estimate of the porosity for the spoils in the opencast pit. The equation is as follows:

$$\boldsymbol{Porosity(n)} = \frac{\boldsymbol{Stage\ Curve\ Vol\ 1_{(month\ 1)} - Stage\ Curve\ Vol\ 2_{(month\ 2)}}}{\boldsymbol{Sum\ of\ pumping\ over\ period}} \qquad \text{Equation 11}$$

8.3.1 Application of stage curve volume calculations on the Zevenfontein and Optimus opencast mines

8.3.1.1 Zevenfontein

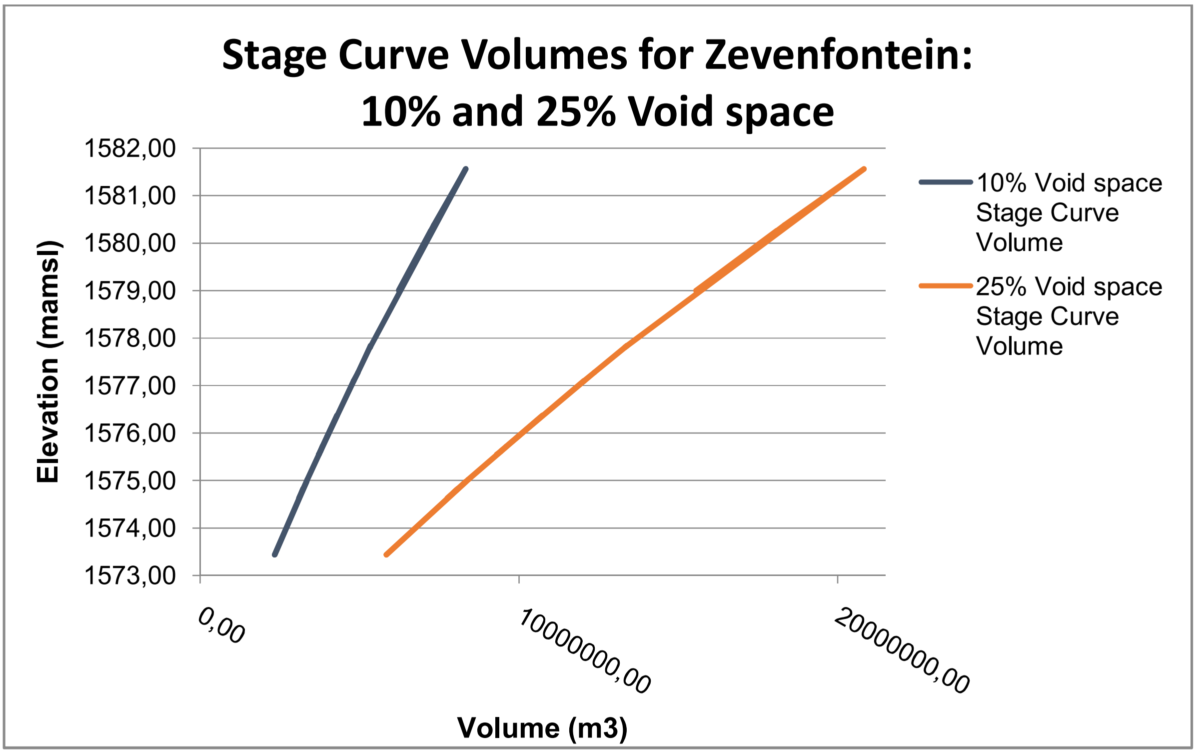
The Zevenfontein opencast pit is rectangular in shape with a rather flat coal seam floor. The rehabilitation, as expected, is not uniformly levelled which aids run-off when rainfall ponds on the spoils (Figure 8.5).



Source: Author's own (2017)

Figure 8.5: Zevenfontein opencast pit design

An area of 10 810 661 m^2 was calculated for the Zevenfontein opencast mine which is used to calculate the volume rainfall and the stage curve volumes with the pit. In Table 8-5 there is a comparison between the minimum and maximum water levels and their associated stage curve volumes (Figure 8.6). Boreholes ZF-4 and ZF-5 do not show large fluctuations between the minimum and maximum water levels whereas ZF-3 shows a large fluctuation of nearly 7 m in water level and more than double the volume water within the pit between the minimum and maximum values.



Source: Research results (2017)

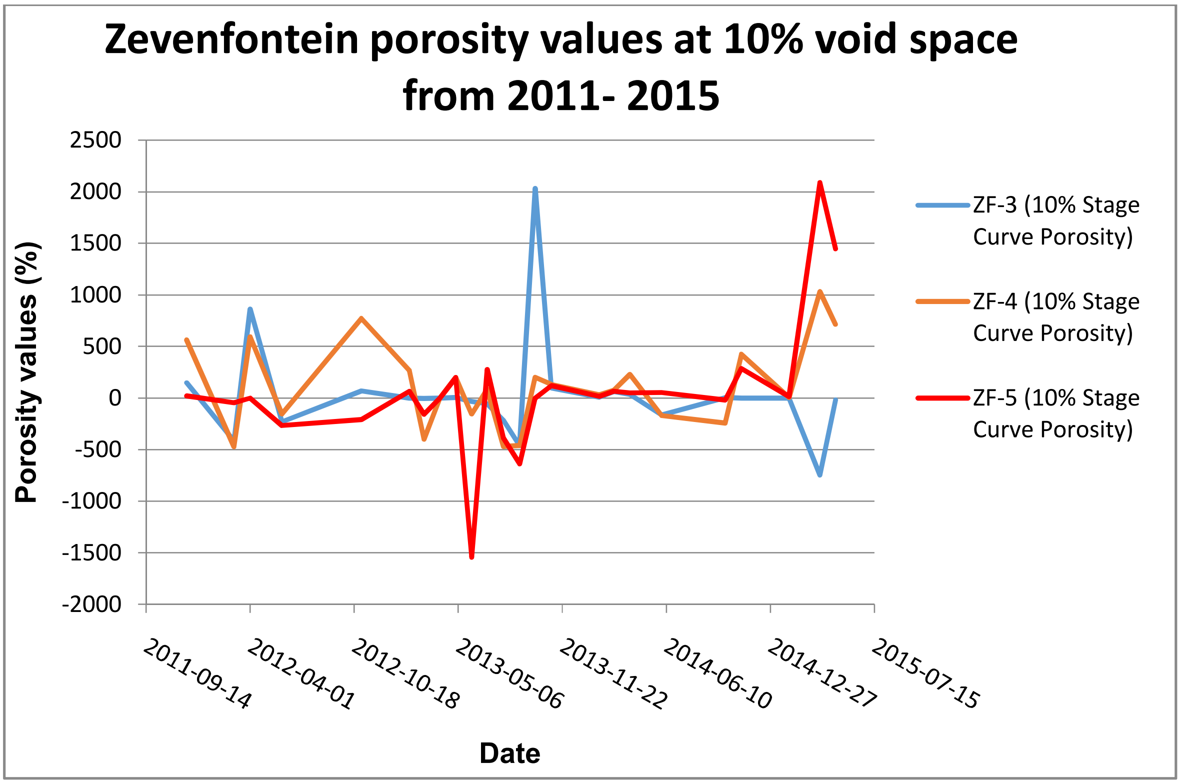
Figure 8.6: Stage curve for boreholes ZF-3, ZF-4 and ZF-5 at 10% and25% void space

TABLE 8-5: STAGE CURVE VOLUMES AT MINIMUM AND MAXIMUM WATER LEVELS AT 10% VOID SPACE

ZF-3		ZF-4		ZF-5	
Water level	Stage Curve Volume (m^3)	Water level	Stage Curve Volume (m^3)	Water level	Stage Curve Volume (m^3)
1 574.63	3099837	1575.55	3 722490	1 581,14	6 242004
1 581.56	8 328784	1577.10	4814658	1 582,86	7 465556

Source: Research results (2017)

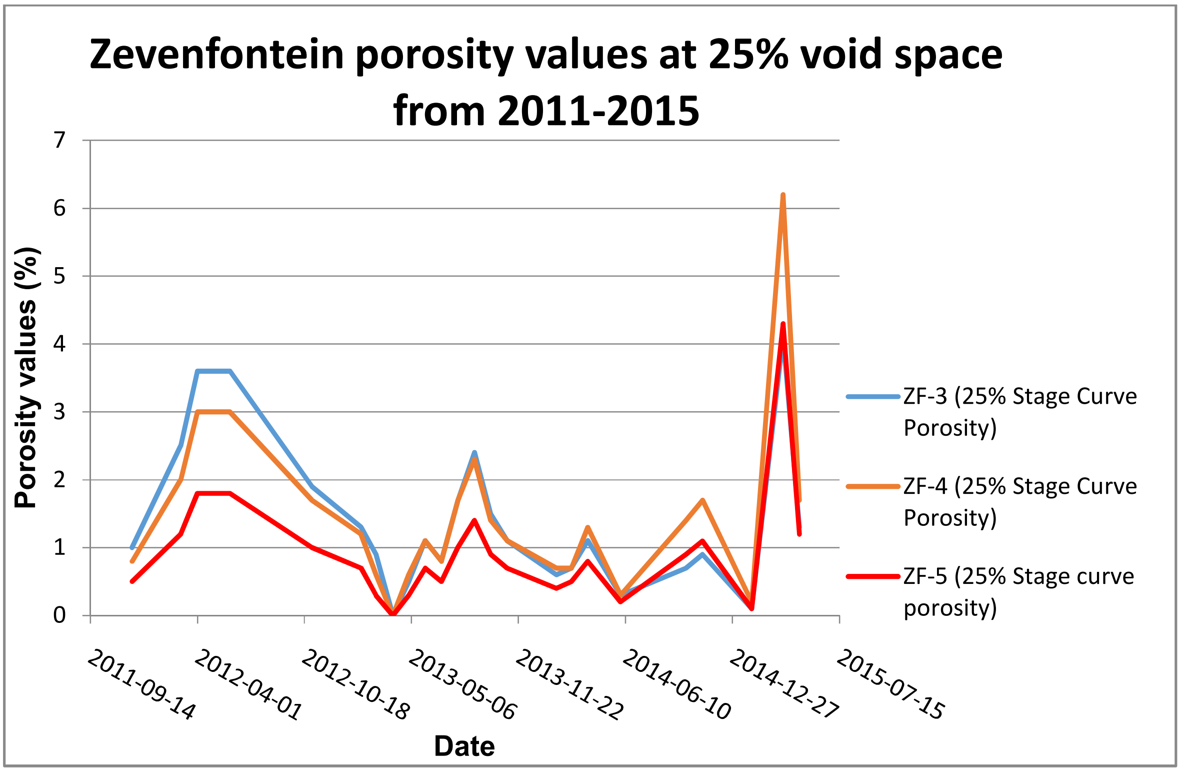
When the calculations were done over a two-month consecutive period for the 10% and 25% void space, the results can be seen in Figure 8.7 and 8.8. In Figure 8.7 there is no correlation between the 10% void space and porosity calculated. Gross over- and under-estimations were achieved, ranging both into the thousand values. Although the chosen void space of 10% was not close enough to the real value to calculate the correct porosity and the data produced had gross over- and under-estimations, the average over a three-year period had more acceptable values as supposed to individual values.



Source: Research results (2017)

Figure 8.7: Zevenfontein porosity values at 10% void space from 2011−2015

In Figure 8.8 a void space of 25% was chosen to calculate the porosity for the Zevenfontein rehabilitatedopencast pit. A 25% void space produced more believable porosity values, ranging between 0% and7%. When looking at Figure 8.9, there is also a correlation in the porosity trend seen for all the boreholes. The average porosity over a period of three years also produced very acceptable values. These values can be considered the true porosity for the rehabilitated opencast pit since the water retention in the larger boulders keep their water locked inside and thus the true porosity is calculated for the fine-grained spoils.

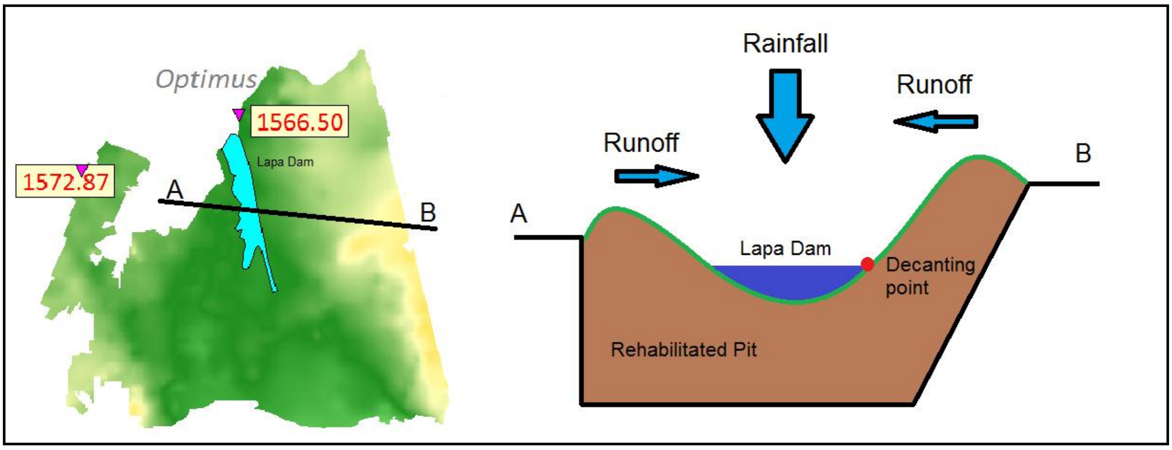


Source: Research results (2017)

Figure 8.8: Zevenfontein porosity values at 25% void space from 2011−2015

8.3.1.2 Optimus

The Optimus opencast pit is an oval shape and encompasses an area of 24 794 131 m^2 with the remainder of Bothashoek connected to the main Optimus pit, to the west of the opencast operation. The coal seam floor is uniformly flat and dips towards the Lapa Dam as well as to the southern border of the pit. The rehabilitation of the Optimus opencast operation is an excellent example of the problems faced when a river runs straight through the opencast pit (Figure 8.9). As a result of the river, the rehabilitation cannot commence in the traditional way as seen with the Zevenfontein rehabilitated pit (Figure 8.5). The result is a sloping rehabilitated pit which dips from the east and west towards the Lapa Dam, and as seen in Table 8-6 causes errors in the calculation of porosities as well as recharge.

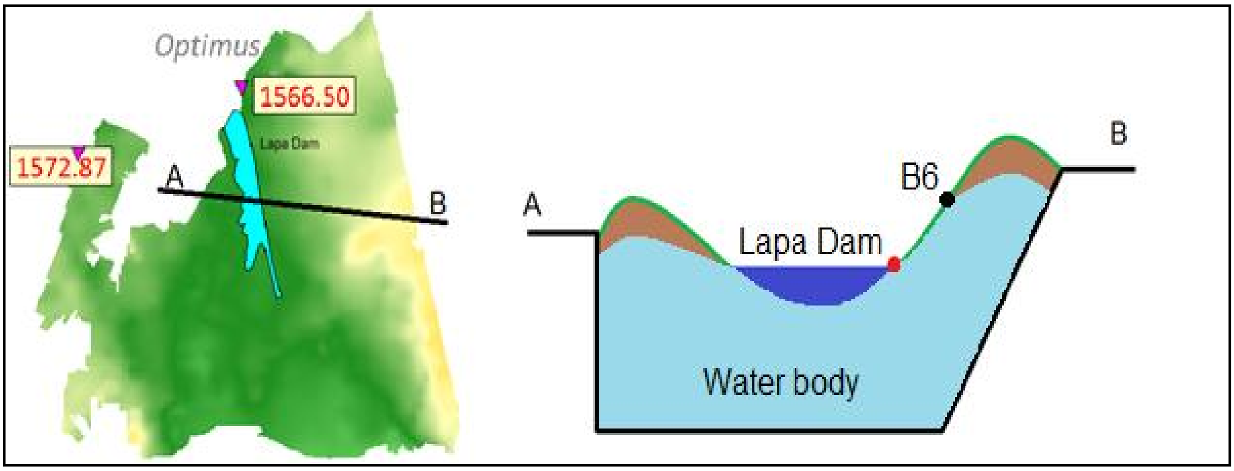


Source: Author's own (2017)

Figure 8.9: Optimus rehabilitation design

Since the rehabilitation of the Optimus opencast pit was done in an unusual way the stage curve volume method cannot be successfully applied to this opencast pit. The reasons for this are as follows:

- As seen in Figure 8.10, the rehabilitation is not uniform, and thus, as a result of higher elevated spoils at both the east and west side of the Optimus opencast pit, the stage curve could only be calculated for the water body at specific water levels (Figure 8.11) instead of the opencast pit as a whole, as was done with the Zevenfontein opencast pit.
- The highest decanting level found at Borehole B6 is still below the highest elevation of the rehabilitated spoils and thus the water body stage curve volumes was only extrapolated to an elevation of 1 577 masl and not for the whole pit area, as decanting would not allow water levels to go higher than that (Figure 8.10).
- Due to the spoils sloping towards the centre of the rehabilitated pit the run-off is increased as well as the amount of water infiltrated since the run-off runs directly into the Lapa Dam within the Optimus pit (Figure 8.9). This is confirmed by the large negative errors for this pit and seen in Table 8-6.



Source: Author's own (2017)

Figure 8.10: Highest elevation of the Optimus water body

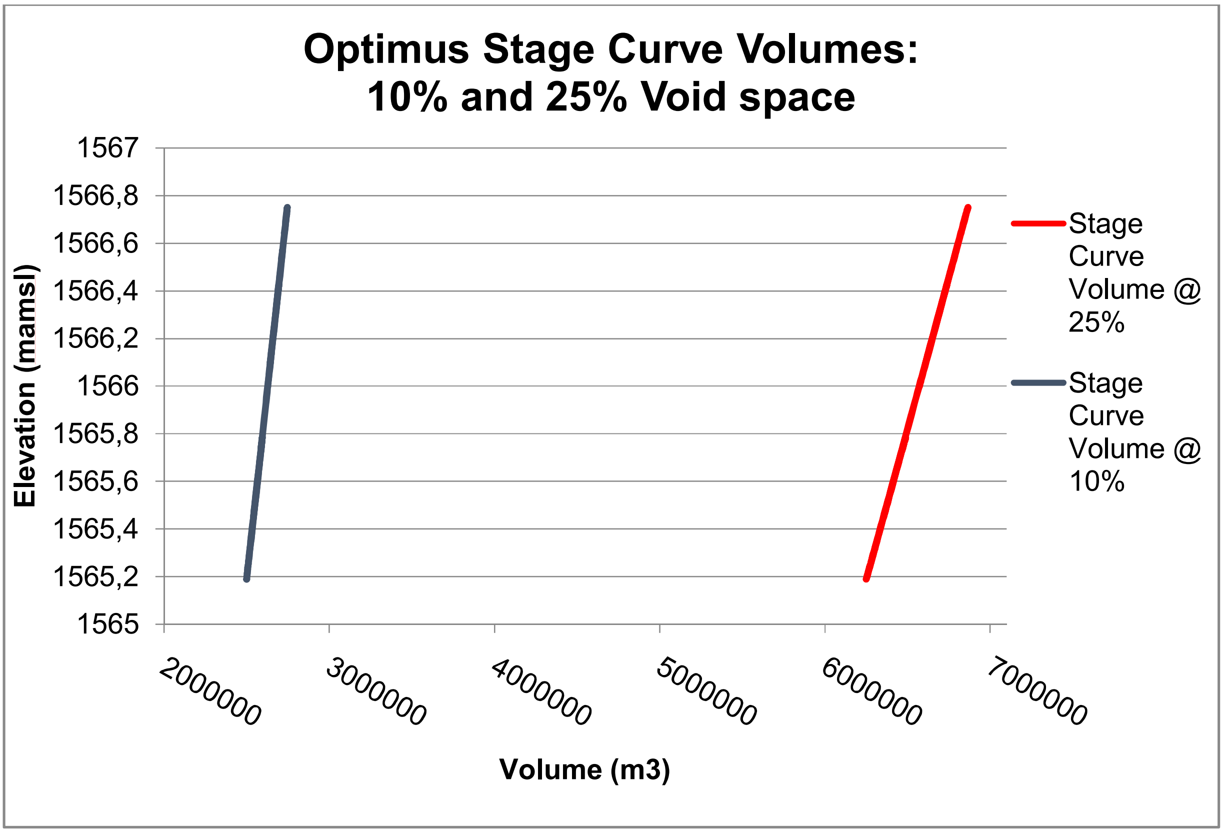


Figure 8.11: Stage curve for boreholes B0, B1, B6, B7 andB8

TABLE 8-6: CALCULATED STAGE CURVE POROSITIES FOR THE OPTIMUS OPENCAST PIT FROM 2011TO 2015

Borehole	10% Stage curve porosity	15% Stage curve porosity	20% Stage curve porosity	25% Stage curve porosity
B0	−103,9	−155,9	−207,8	-259,8
B1	−177,8	−266,7	−355,7	-444,6
B6	−325,6	−488,4	−651,2	-813,9
B7	−232,7	−349,0	-465,3	−581,7
B8	−277,7	−416,6	-555,5	−694,3

Source: Research results (2017)

Even when the gross under- and over-estimated values are removed as seen in Table 8-7, the porosities calculated are still too high to be considered for any useable data.

TABLE 8-7: CALCULATED STAGE CURVE POROSITIES FOR THE OPTIMUS OPENCAST PIT FROM 2011 TO 2015 (EDITED)

Borehole	10% Stage curve porosity	15% Stage curve porosity	20% Stage curve porosity	25% Stage curve porosity
B0	13,6	20,4	27,2	34,1
B1	13,0	19,6	26,1	32,6
B6	29,3	44,0	58,6	73,3
B7	16,3	24,5	32,7	40,8
B8	36,8	55,2	73,5	91,9

Source: Research results (2017)

8.3.2 Summary

The SCV method can be applied successfully to determine the porosity of the rehabilitated spoils but only if the pit has been rehabilitated in such a manner that free draining can take place away from the rehabilitated opencast mine. This is demonstrated by the porosities calculated for the Zevenfontein and Optimus opencast rehabilitated mine. Zevenfontein was traditionally rehabilitated (Figure 8.5) and gave excellent data concerning the porosities. Optimus on the other hand was not traditionally rehabilitated (Figure 8.9), due to the natural river running through the opencast pit, and thus gave gross under- and over porosity values which could not be used.

8.4 Dry and wet calculationsusing stage curve volumes

The dry and wet calculation works on the principal of a basic water balance which calculates the porosity of the spoils between 10% and 25% void space during dry periods which can then be used to calculate the porosity during the rainy seasons. The equation is as follows:

$$\Delta_{Stage\ Curve\ Vol.} \times \boldsymbol{Area}\ (\boldsymbol{m^2}) \times (\boldsymbol{Porosity}\ \%) = \boldsymbol{Pumping} + \boldsymbol{Recharge}$$ Equation 12

Since this method requires that the dry calculation be done first the recharge parameter can be ignored since no rainfall or infiltration has occurred. The equations for the dry periods are as follows:

$$\Delta_{Stage\ Curve\ Vol} \times (\boldsymbol{Porosity}\%) = \boldsymbol{Pumping}$$ Equation 13

And since the parameter that is unknown is the void space the equation can be rewritten into the following:

$$\boldsymbol{Porosity}\ \% = \frac{\boldsymbol{Pumping}\ (\boldsymbol{m^3})}{\Delta_{Stage\ Curve\ Volume\ (m^3)}} * \mathbf{100}$$ Equation 14

After the porosities have been calculated for the dry season, the values can be substituted into equation 12 for the wet season, to calculated recharge.

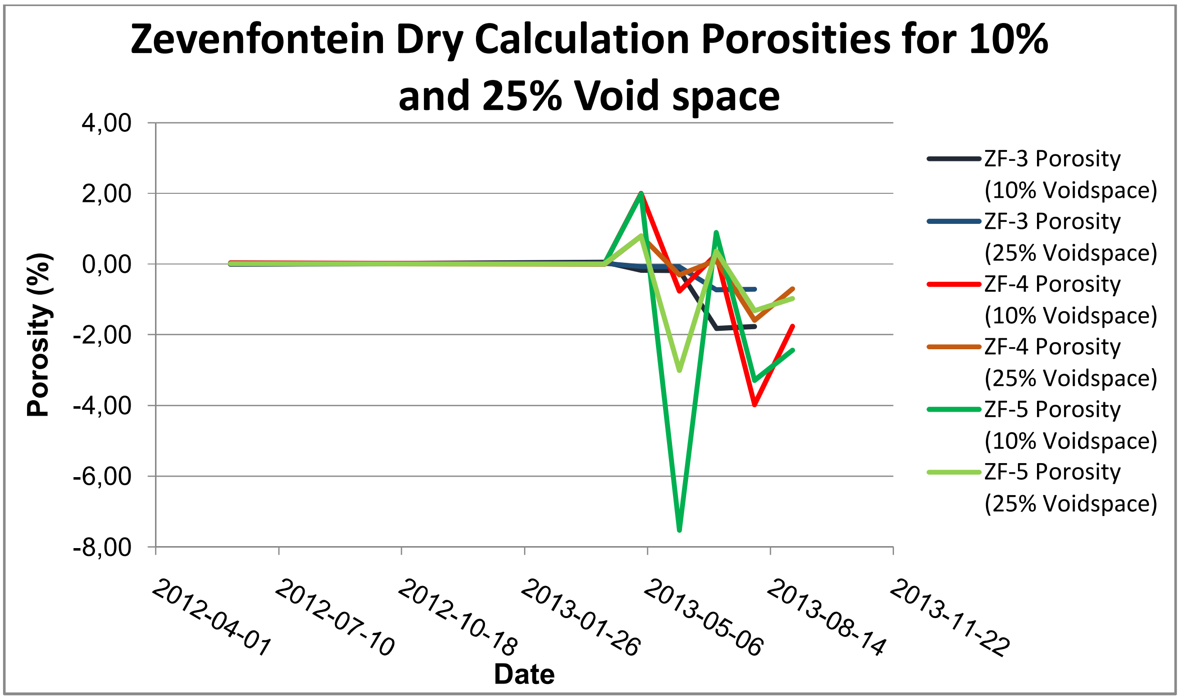
For these calculations to work, it is essential that the correct pumping volumes and rainfall volumes are collected since even a small error can change a value up to the power of 10. In this case some water levels as well as pumping values were incorrect due to either incorrectly measuring the water levels and the water flow meter being broken. These suspicious values can be corrected and are easily recognised when calculating the final recharge value.

8.4.1 Dry and wet calculations for the Zevenfontein rehabilitated opencastpit

8.4.1.1 Dry calculationsusing stage curve volumes

As explained in 8.3.1, the porosities for boreholes ZF-3, ZF-4 and ZF-5 were calculated for the dry months from 2012 until 2013, using the minimum and maximum void space allowable which was set between 10% and 25%. As seen in Table 8-8 and Figure 8.12 the porosities calculated are acceptable and are close to what is expected in a natural environment.

In Table 8-8 only the positive values are used to calculate the average porosity since the negative values represent the natural phenomena called water retention. The negative porosity values are represented by the larger boulders which still hold a large percentage of their water even after the water level has dropped well below their elevation. Thus, the positive values give a more accurate representation of the finer more abundant spoils with inside the pit.



Source: Research results (2017)

Figure 8.12: Zevenfontein dry calculation porosities for 10% and 25% void space

TABLE 8-8: DRY CALCULATIONS FOR ZEVENFONTEIN

		Void space %			Void space %			Void space %	
		10%	25%		10%	25%		10%	25%
BH Name	Date	Porosity %		BH Name	Porosity %		BH Name	Porosity %	
ZF-3	2012-06-01			ZF-4	0,04	0,01	ZF-5	0,02	0,01
	2013-04-01	0,00	0,00		0,00	0,00		0,00	0,00
	2013-05-01	0,06	0,02		2,00	0,80		1,98	0,79
	2013-06-01	-0,17	-0,07		-0,76	-0,30		-7,52	-3,01
	2013-07-01	-0,18	-0,07		0,28	0,11		0,90	0,36
	2013-08-01	-1,82	-0,73		-3,98	-1,59		-3,29	-1,32
	2013-09-01	-1,77	-0,71		-1,76	-0,70		-2,44	-0,97
Average when positive values are taken:		0,03	0,01		0,58	0,23		0,73	0,29

Source: Research results (2017)

8.4.1.2 Wet calculations using stage curve volumes

The wet calculation uses equation 12, since the rainfall is now a parameter to consider and the porosity values calculated for the dry periods are now substituted into equation 15. Which are as follows:

$$\Delta_{Stage\ Curve\ Vol.} \times \boldsymbol{Dry\ Porosity}(\%) = \boldsymbol{Rainfall} \times \boldsymbol{Recharge}\ \% - \boldsymbol{Pumping}(\boldsymbol{m^3}) \qquad \text{Equation 15}$$

Since the recharge needs to be calculate the equation can be rewritten as:

$$\frac{\Delta_{Stage\ curve\ Vol.}(\boldsymbol{m^3}) \times \boldsymbol{Dry\ Porosity} + \boldsymbol{Pumping}(\boldsymbol{m^3})}{\boldsymbol{Rainfall\ Vol}(\boldsymbol{m^3})} \boldsymbol{Recharge} = \qquad \text{Equation 16}$$

As seen in Table 8-9 the recharge values for Zevenfontein at 10% and 25% void space are exactly the same. This is due to the fact that although the porosity has an influence on the amount of water the given spoils can hold at one time, it does not affect the amount of water that infiltrates at one time, and thus the excess infiltrated water within the system will drain to the lowest point, or in this case the decanting point. The low recharge percentage can be attributed to the way pumping takes place at the Zevenfontein rehabilitated opencast pit. Pumping only takes place when water starts to decant and thus the pumping matches the water infiltrated which decants a couple of days later. Thus, the equation in this circumstance can be written as only pumping divided by rainfall over the area * 100.

TABLE 8-9: RECHARGE FOR ZEVENFONTEN

		Void space %			Void space %			Void space %	
		10%	25%		10%	25%		10%	25%
BH Name	**Date**	**Recharge %**		**BH Name**	**Recharge %**		**BH Name**	**Recharge %**	
ZF-3	2013-02-01	0,08	0,08	ZF-4	0,09	0,09	ZF-5	0,16	0,16
	2013-03-01	0,03	0,03		0,06	0,06		0,04	0,04
	2013-08-01	0,50	0,50		0,57	0,57		0,58	0,58
	2013-09-01	2,57	2,57		2,26	2,26		2,29	2,29
	2013-10-01	0,08	0,08		0,1	0,1		0,07	0,07
	2013-11-01	0,04	0,04		0,05	0,05		0,06	0,06
	2014-02-01	0,05	0,05		0,10	0,10		0,20	0,20
	2014-03-01	0,03	0,03		0,05	0,05		0,058	0,058
	2014-04-01	0,07	0,07		0,08	0,08		0,15	0,15

Source: Research results (2017)

8.4.2 Dry and wet calculations for the Optimus rehabilitated opencast pit

8.4.2.1 Dry calculations using stage curve volumes

As in Chapter 8.3.1, the porosities for boreholes B0, B1, B6, B7 and B8 were calculated for the dry months for 2013, using the minimum and maximum void space allowable which was set between 10% and 25%. As seen in Table 8-10 the porosities calculated are mostly negative which can be explained by the way the Optimus pit was rehabilitated and also explained in 8.3.1 and Figure 8.9. The negative values represent the water retention by the bigger boulders which were also recognised during the Zevenfontein dry calculations. Since the rainfall infiltrated and run-off drains directly into the centre (Lapa Dam) of the Optimus rehabilitated pit the boulders as well as the fine-grained spoils stayed saturated during 2013 and no positive porosity values could be calculated.

8.4.2.2 Wet calculations using stage curve volumes

The wet calculations for the Optimus rehabilitated pit is the same method and equation (Equation 17) used in the Zevenfontein wet calculations. The porosity values calculated for the dry periods in Chapter 8.4.2 and Table 8-10 are now substituted into Equation 18 Which are as follows:

$$\Delta_{Stage\ Curve\ Vol.} \times \boldsymbol{Dry\ Porosity} = \boldsymbol{Rainfall} \times \boldsymbol{Recharge} - \boldsymbol{Pumping}(\boldsymbol{m^3}) \qquad \text{Equation 17}$$

Since the recharge needs to be calculated the equation can be rewritten as:

$$\boldsymbol{Recharge} = \frac{\Delta_{Stage\ curve\ Vol.}(\boldsymbol{m^3}) \times \boldsymbol{Dry\ Porosity} + \boldsymbol{Pumping}(\boldsymbol{m^3})}{\boldsymbol{Rainfall\ Vol}(\boldsymbol{m^3})} \qquad \text{Equation 18}$$

TABLE 8-10: DRY CALCULATIONS FOR OPTIMUS

		Void space %			Void space %			Void space %			Void space %			Void space %	
		10%	25%		10%	25%		10%	25%		10%	25%		10%	25%
BH	Date	Porosity		BH	Porosity		BH	Porosity		BH	Porosity		BH	Porosity	
B0	13-05-01	-5,5	-2,2	B1	-6,7	-2,7	B6	N/A	N/A	B7	3,5	1,4	B8	-11	-4,5
	13-06-01	-2,5	-1,0		-11	-4,5		-12	-4,9		-5,0	-2,0		3,6	1,4
	13-07-01	-0,5	-0,2		-7,5	-3,0		N/A	N/A		-0,8	-0,3		-3,2	-1,3
	13-08-01	-5,9	-2,4		N/A	N/A		N/A	N/A		-2,7	-1,1		-5,2	-2,1
	13-09-01	-6,6	-2,7		-13	-5,1		-4,6	-1,9		-5,7	-2,3		N/A	N/A
Average:		-4,2	-1,7		-9,6	-3,8		-8,4	-3,4		-2,2	-0,9		-4,0	-1,6

Source: Research results (2017)

As seen in Table 8-10, the recharge values for Optimus at 10% and 25% void space are exactly the same and are the same effects experienced during the Zevenfontein calculations. The only difference between the Zevenfontein and Optimus pit is that the decanting water moves outside the pit for Zevenfontein and the decanting water for the Optimus pit moves inside towards the centre of the pit to the Lapa dam. The high recharge percentage calculated for the Optimus pit compared to that of the Zevenfontein pit (Table 8-9) can also be attributed to the way the Optimus pit channels the rainfall towards the Lapa dam. Another factor that differs from the Zevenfontein pit is that the pumping at Optimus takes place directly from the Lapa Dam and not the point of decanting.Thus, the equation in this circumstance can be written as only pumping divided by rainfall over the area * 100.

TABLE 8-11: OPTIMUS RECHARGE PERCENTAGE

Borehole name	From	To	Average recharge %
B0	2011/11/01	2015/02/01	2,00
B1	2011/11/01	2015/02/01	2,70
B6	2011/11/01	2015/02/01	2,40
B7	2011/11/01	2015/02/01	0,90
B8	2011/11/01	2015/02/01	1,30

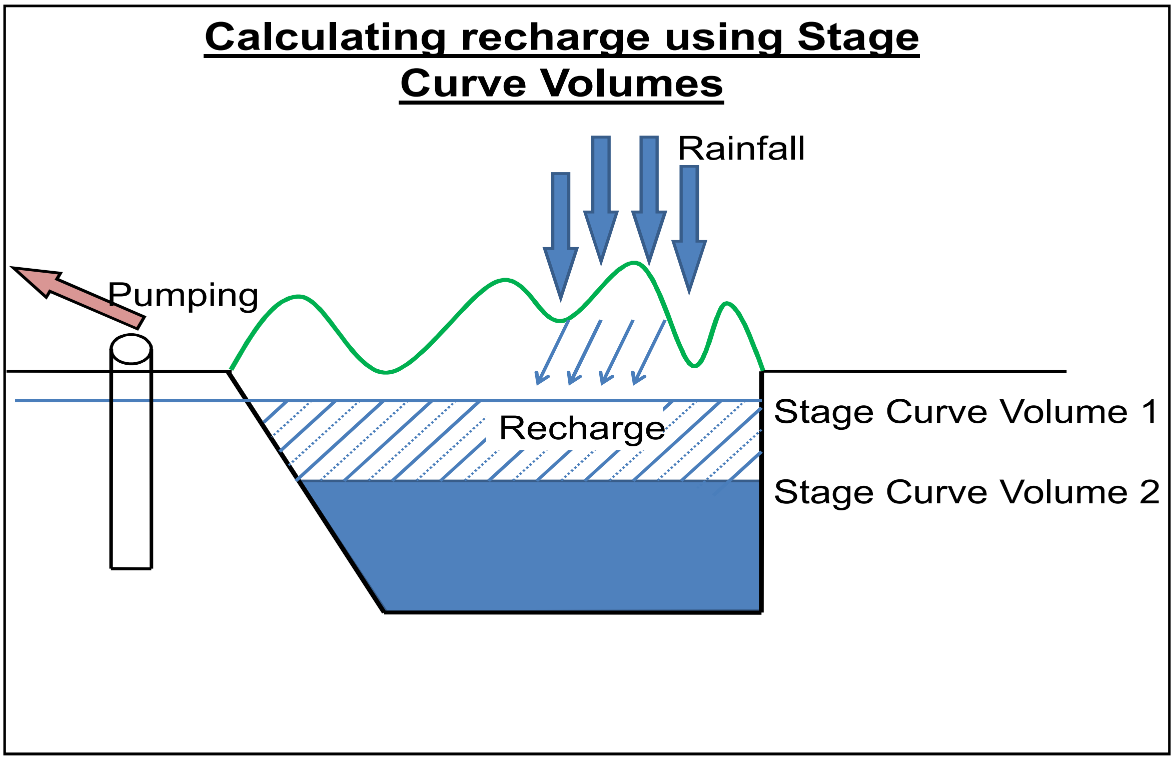
Source: Research results (2017)

8.4.2.3 Summary

Although the dry calculation porosity values for the Optimus pit were al negative the porosities calculated are all believable considering the way the rehabilitation occurred, and that pumping takes place from the Lapa dam and not the decanting point. This means that run-off is also part of the pumping values and will consequently increase the recharge values calculated. This can be seen in the wet calculations where the recharge percentage is up to the power of a 100 more than that of the Zevenfontein recharge values. It was also concluded that the porosity does not affect the recharge percentages calculated for Zevenfontein and Optimus and thus the equation for recharge is only the pumping (m^3) divided by rainfall over the area and multiplied by a hundred. In summary, the dry and wet stage curve volume calculations are inconclusive, for both the porosity and recharge calculations and further research needs to be done concerning this method.

8.5 Calculating recharge using stage curve volumes

This method of recharge calculation goes back to the most basic of assumptions that the change in water level, from stage curve volume 1 to volume 2, is as a result of the rainfall that infiltrated (recharge) minus the pumping that took place during that period (Figure 8.13), and thus the equation is as follows:



Source: Author's own (2017)

Figure 8.13: Recharge calculated using curve volumes

$$\boldsymbol{SC\ Volume\ 2(m^3) = SC\ Volume\ 1(m^3) + Recharge - Pumping(m^3)}$$ Equation 19

Since the recharge is the unknown and desired value the equation can be rewritten as:

$$\boldsymbol{Recharge = SC\ Volume\ 2(m^3) - SC\ Volume\ 1(m^3) + pumping}$$ Equation 20

As seen in Chapter 7 the pumping that occurs is only as a result decanting that needs to be removed from the system and seeing that the decanting is a result of the recharge from rainfall they closely match each other in regard to the inflow and outflow. Thus, in Chapter 8 the porosity does not play a major role in the calculation of recharge if the water level of the rehabilitated has already reached its maximum capacity.Thus Equation 20 can be used to calculate recharge for both the Zevenfontein and Optimus Rehabilitated pits.

When the calculations were done for the Zevenfontein and Optimus areas it was noticed that the large changes to pumping and rainfall within a period of a month over several months gave either under- or over-estimated values. The best results came from using extended periods of time betweenfour and twelve months, which gave improved averages for the rainfall and pumping values, and resulted in more realistic and credible values.

8.5.1 Zevenfontein

As seen in Table 8-12, the recharge values for the period of months are very reasonable and correlate with the RIV method about recharge in opencast rehabilitated spoils. Firstly, as with the RIV method a 25% void space to calculate a stage curve volume yielded the best results with an average recharge of between 12% and 35%. There are, however, some values that are higher than 30% recharge from rainfall. This can be attributed to a decrease in pumping or an increase in rainfall or rather a combination of the two parameters mentioned.

TABLE 8-12: RECHARGE PERCENTAGE FOR THE ZEVENFONTEIN PIT

ZF-3			
From	**To**	**Recharge @ 10% void space**	**Recharge @ 25% void space**
2011-11-01	2012-03-01	13,91	14,22
2012-04-01	2012-11-01	25,95	31,40
2012-12-01	2013-06-01	26,70	54,42
2013-07-01	2013-10-01	9,93	0,53
2013-11-01	2014-04-01	23,89	54,03
2014-05-01	2015-05-01	34,94	53,97
Average:		22,56	34,76

ZF-4			
From	**To**	**Recharge @ 10% void space**	**Recharge @ 25% void space**
2011-11-01	2012-03-01	12,85	11,57
2012-04-01	2012-11-01	17,26	9,69
2012-12-01	2013-06-01	9,79	12,14
2013-07-01	2013-10-01	15,46	14,35
2013-11-01	2014-04-01	9,12	17,10
2014-05-01	2015-05-01	28,45	37,75
Average:		15,48	17,09

ZF-5			
From	**To**	**Recharge @ 10% Void space**	**Recharge @ 25% void space**
2011-11-01	2012-03-01	12,84	11,54
2012-04-01	2012-11-01	16,57	7,95
2012-12-01	2013-06-01	10,60	14,17
2013-07-01	2013-10-01	12,09	5,92
2013-11-01	2014-04-01	15,28	32,50
2014-05-01	2015-05-01	14,13	1,94
Average:		13,58	12,34

Source: Research results (2017)

8.5.2 Optimus

Table 8-13 shows elevated recharge values which was also noticed and discussed in the RIV method. As mentioned in this chapter, the reason for the elevated recharge values lies in the design and rehabilitation of the Optimus pit which guides the infiltrated water and surface run-off towards the Lapa Dam in the centre of the Optimus pit. This increase in water and the fact that pumping takes place directly from the dam and not the decanting point is reason enough to account for the high recharge values seen in Table 8-13.

TABLE 8-13: RECHARGE PERCENTAGE FOR THE OPTIMUS PIT

		B0		B1	
From	**To**	**Recharge @ 10% Void space**	**Recharge @ 25% Void space**	**Recharge @ 10% Void space**	**Recharge @ 25% Void space**
2011-11-01	2012-03-01	28,4	20,9	30,5	26,2
2012-04-01	2013-03-01	29,4	26,0	34,8	39,6
2013-04-01	2013-10-01	62,4	36,6	65,8	44,9
2013-11-01	2014-03-01	26,8	41,9	31,7	54,0
2014-04-01	2014-10-01	46,1	-116,6	138,3	113,7
2014-11-01	2015-05-01	25,6	33,1	18,0	14,1
Average:		36,5	31,7	36,2	35,8
		B6		B7	
2011-11-01	2012-03-01	29,7	24,2	29,9	24,8
2012-04-01	2013-03-01	28,4	23,6	37,5	46,4
2013-04-01	2013-10-01	76,2	71,1	70,5	56,6
2013-11-01	2014-03-01	25,5	38,6	21,8	29,4
2014-04-01	2014-10-01	115,4	56,7	173,6	202,0
2014-11-01	2015-05-01	17,3	12,3	12,9	1,3
Average:		35,4	37,8	34,5	31,7
		B8			
2011-11-01	2012-03-01	28,8	22,0		
2012-04-01	2013-03-01	25,2	15,7		
2013-04-01	2013-10-01	89,4	104,0		
2013-11-01	2014-03-01	27,6	43,9		
2014-04-01	2014-11-01	64,1	99,5		
Average:		36,5	27,2		

Source: Research results (2017)

8.5.3 Summary

Calculating recharge by using stage curve volumes for the Optimus and Zevenfontein area, the pumping rate volumes have to be considered equal to the decanting volumes and that the decanting volumes are as a result recharge. Secondly, it is advisable that these calculations are done over longer time periods (four months or more) to average out the sudden changes in rainfall and pumping rates, otherwise under- or over-estimated recharge values can be expected.

For Zevenfontein a 25% void space yielded the best results between 12% and 35% recharge from rainfall which was expected for the spoils. For the Optimus area all the recharge values calculated were above 30%. This was expected since the rehabilitation design forces all the water to run towards the centre of the pit and thus increases the amount of water that infiltrates.

Chapter 9
KnownRecharge Methods

9.1 Introduction

For this chapter, the methods discussed in the literature review will be applied to the data received from the Optimum Mine to ultimately compare to the recharge values calculated for the Rainfall Infiltrated Volume method, Stage Curve Volume Method, Dry and Wet Calculations and Calculating Recharge using Stage Curve Volumes. The recharge methods that will be discussed are as follows: Saturated Volume Fluctuation (SVF)method, Cumulative Rainfall Departure (CRD) method and the Water Table Fluctuation (WTF) method. For the CRD and SVF methods an Excel-based program was used that was developed by G. van Tonder and Y. Xu in 2000,*Program to Estimate Groundwater Recharge and the GW Reserve*. The WTF method was calculated manually using Excel as the basis of the calculations.

9.2 Saturated Volume Fluctuation method

For the SVF method abstraction, water level and rainfall data were needed to meet the requirements to calculate recharge. When the data is read into the program, a chart appears whereby the water level needs to match the fit so that an accurate value can be deduced for the recharge, specific yield, inflows and outflows. What follows are the values calculated for the Zevenfontein and Optimus mining areas.

9.2.1 Zevenfontein

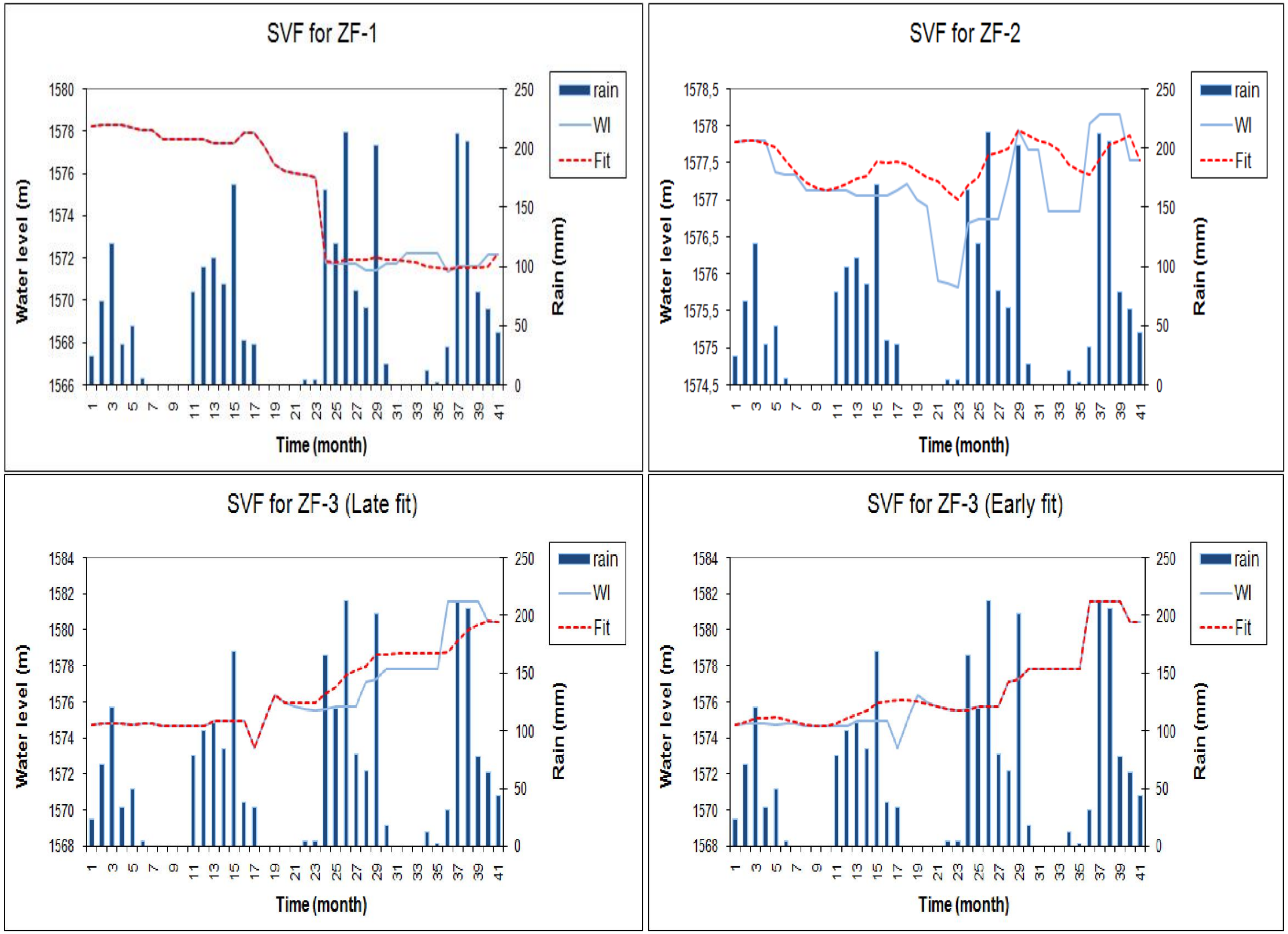
The values calculated by the Excel program can be seen in Table 9-1 together with the fitted charts for each borehole form ZF-1 until ZF-7 (Figure 9.1 and 9.2).

Keeping in mind that these recharge values are representative of virgin ground and not that of spoils, the recharge values will be on average lower than that calculated with the methods in Chapter 8.

TABLE 9-1: ZEVENFONTEIN SATURATED VOLUME FLUCTUATION METHOD RECHARGE CALCULATIONS

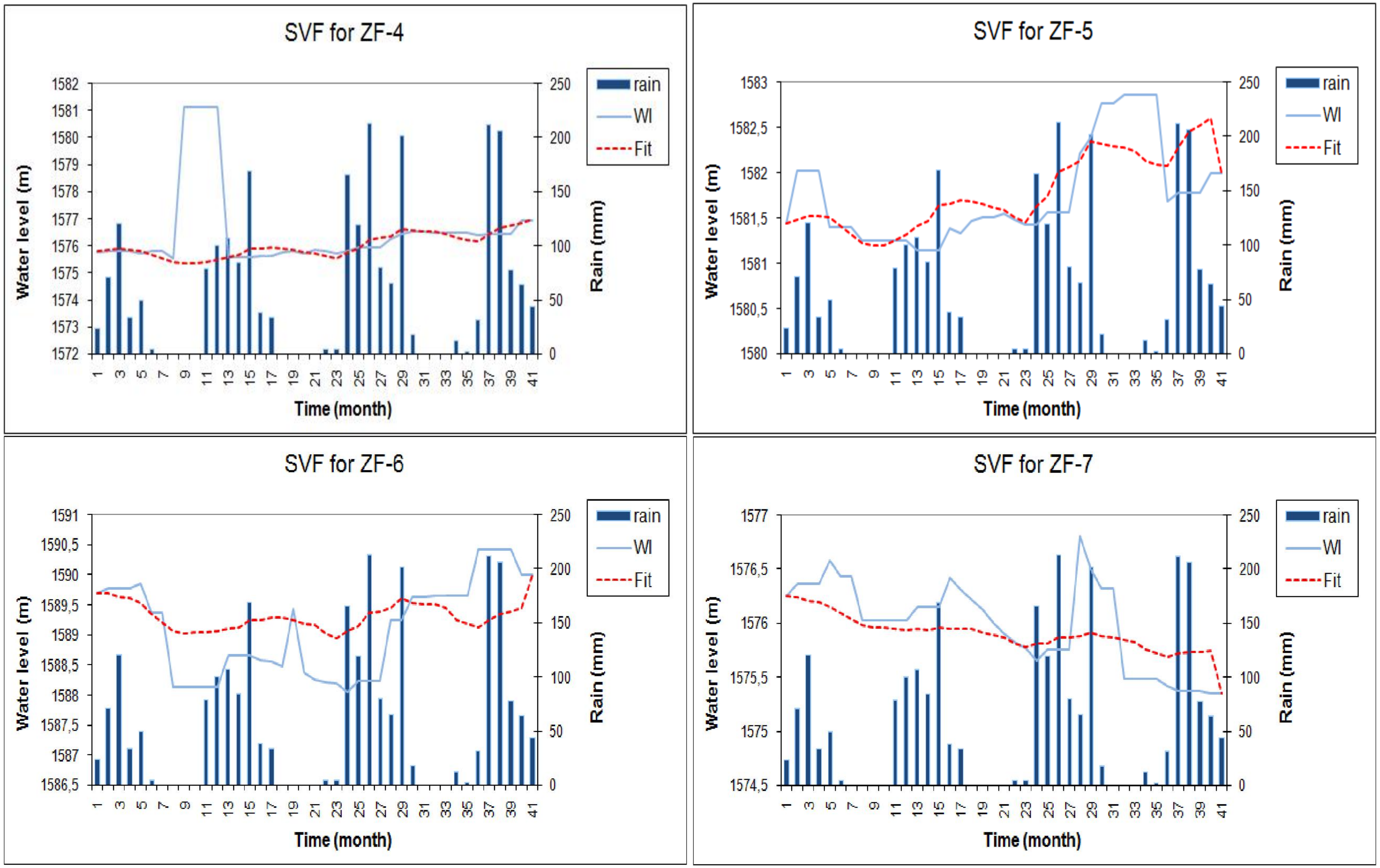
Saturated Volume Fluctuation Method						
Zevenfontein						
Borehole No.	**Lag time (month)**	**Recharge %**	**S value**	**Inflow (m3/d)**	**Outflow (m3/d)**	**Error**
ZF 1 (late fit)	0	5,7	0,074	0	800	0,036
ZF 2	0	12	0,0725	0	1450	0,083
ZF 3 (early fit)	0	23,7	0,0745	0	850	0,190
ZF 3 (late fit)	0	39,4	0,1295	3550	1150	0,140
ZF 4	0	13,1	0,078	0	800	0,028
ZF 5	0	13	0,1015	650	900	0,061
ZF 6	0	5,9	0,055	1750	1500	0,109
ZF 7	0	5,9	0,1855	1450	2300	0,047

Source: Research results (2017)



Source: Research result (2017)

Figure 9.1: Rainfall, water level and fit for the ZF-1, ZF-2 and ZF-3 SVF method



Source: Research results (2017)

Figure 9.2: Rainfall, water level and fit for ZF-4, ZF-5, ZF-6 and ZF-7 SVF method

When examining the values generated for the Zevenfontein mining area the values are relatively stable, between 5% and 13% recharge from rainfall (Table 9-1). There are some outliers for the ZF-3 early fit and ZF-3 late fit at 23.7% and 39.4%, respectively (also see Figure 9.1). This can be explained by the unusual response the water level fluctuated in comparison to the rainfall and abstraction rates. An early and late fit had to be implemented between the 0 and 20th time point and the 20th and 41st time pointto make the fitting line follow the fluctuations of the water levels which yielded these high recharge results. Overall an average of 9.3% recharge was calculated for the entire Zevenfontein, excluding the ZF-3 borehole values which were the outliers. At an average of 9.3% recharge from rainfall, it is safe to assume that this value can be considered accurate for the whole Zevenfontein area when calculating recharge for virgin ground. Some of the water levels in Figures 9.1 to 9.2, show large fluctuations, which in this case can be attributed to a decrease in pumping rates or a mistake made during the actual data collection and data capture.

9.2.2 Optimus

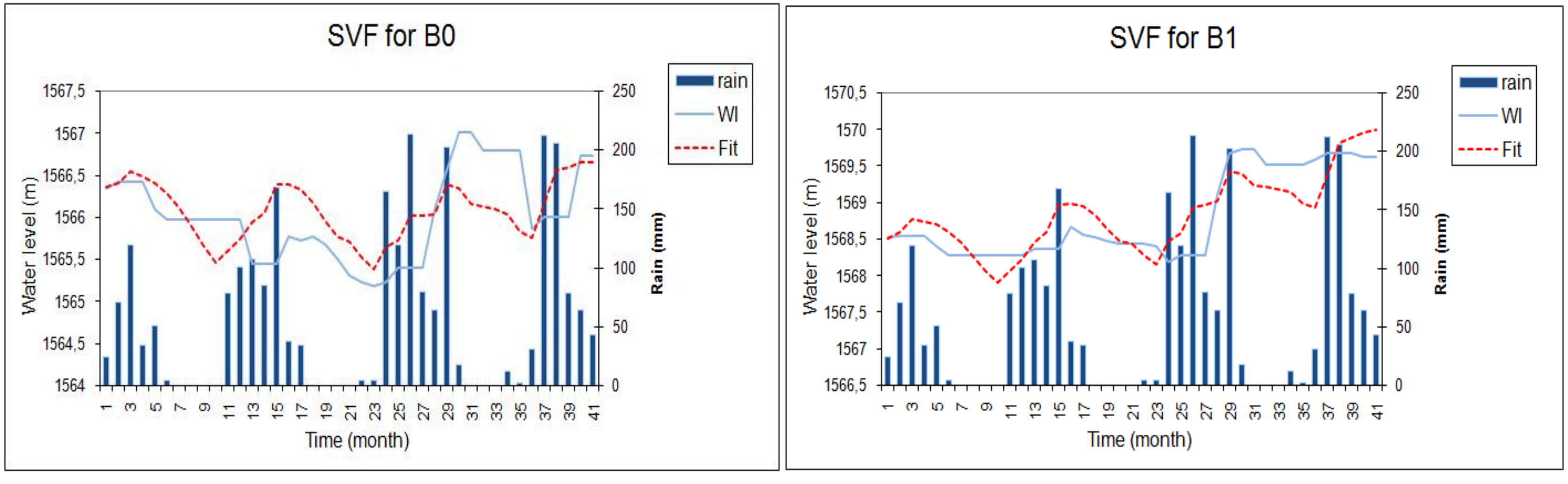
The values calculated by the Excel program can be seen in Table 9-2, together with the fitted charts for each borehole from B0 until B8 (Figure 9.3 and 9.4).

As discussed in Chapter 8, the Optimus opencast mining area is unconventionally rehabilitated with the spoils that slope inward towards the middle of the operation. This means that more water will be retained within the mine workings and as a result recharge values will be higher than what is expected from the area.

TABLE 9-2: OPTIMUS SATURATED VOLUME FLUCTUATION METHOD RECHARGE CALCULATIONS

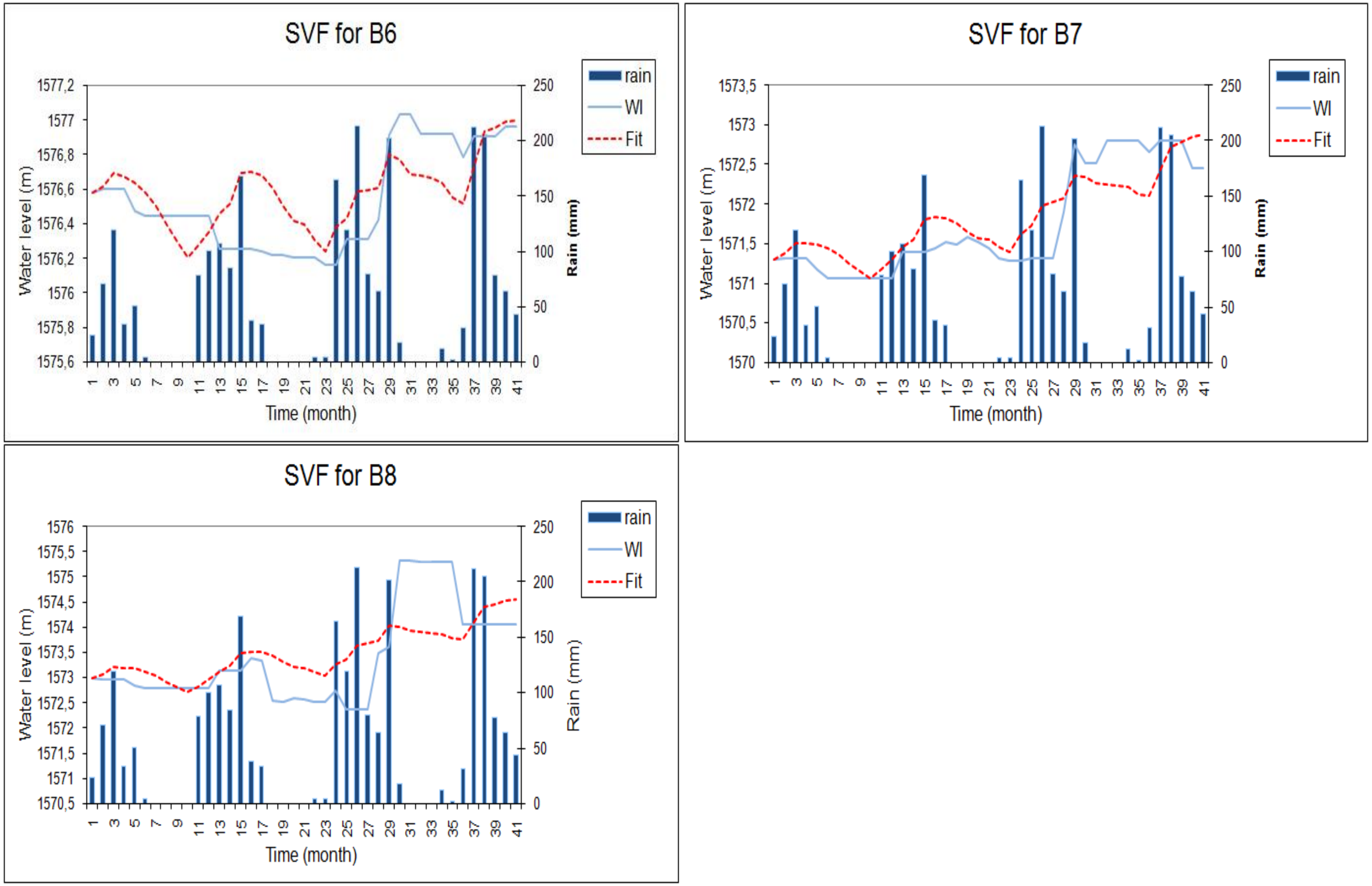
Saturated Volume Fluctuation Method						
Optimus						
Borehole No.	**Lag time**	**Recharge %**	**S value**	**Inflow**	**Outflow**	**Error**
B0	0	13,1	0,0540	0	700	0,0730
B1	0	15,9	0,0625	450	700	0,0514
B6	0	13,8	0,1135	700	700	0,0354
B7	0	19,4	0,1140	600	700	0,0534
B8	0	19,4	0,1085	0	700	0,1119

Source: Research results (2017)



Source: Research results (2017)

Figure 9.3: Rainfall, water level and fit for B0 and B1 SVF method



Source: Research Results (2017)

Figure 9.4: Rainfall, water level and fit for B6, B7 and B8 SVF method

The recharge values calculated for the Optimus pit using the Excel-based program estimates the recharge to between 13 and 19% for the opencast pit. These recharge estimates are in correlation to what is expected from the area ranging between the minimum and maximum calculated at 7% and 30%, respectively. The SVF method calculates recharge for virgin ground and not the spoils for the opencast pit and considering the already high recharge percentages calculated for the Optimus area using the RIV and SCV method, the recharge percentages can be assumed to be correct.

9.3 Cumulative Rainfall Departure method

The CRD method used to calculate recharge for the Zevenfontein and Optimusareas uses the rainfall (mm), abstraction (m^3), water levels (mbgl or mamsl) and the area (m^2) to calculate a preliminary recharge estimate for the area. The lag time (months), specific yield (S_y), threshold for rainfall, inflow (m^3) and outflow (m^3) are all parameters used to calibrate the 'fit' with the water levels so that a more accurate estimation of recharge can be calculated. The Zevenfontein and Optimus data were all used in G. van Tonder and Y. Xu's Excel-based program,*Program to Estimate Groundwater Recharge and the GW Reserve* (2000).

9.3.1 Zevenfontein

When comparing the water level with that of the rainfall events in Figures 9.5 and 9.6,there is a clear relationship between the above-mentioned parameters, in that the amount of rainfall correlates with the fluctuations in water levels. There are, however, some errors when examining borehole ZF-4 (Figure 9.5) and ZF-6 (Figure 9.6). ZF-4 has a positive peak in water level which does not correspond to any rainfall event and can be classified as an error made during the initial data collection or capture thereof.

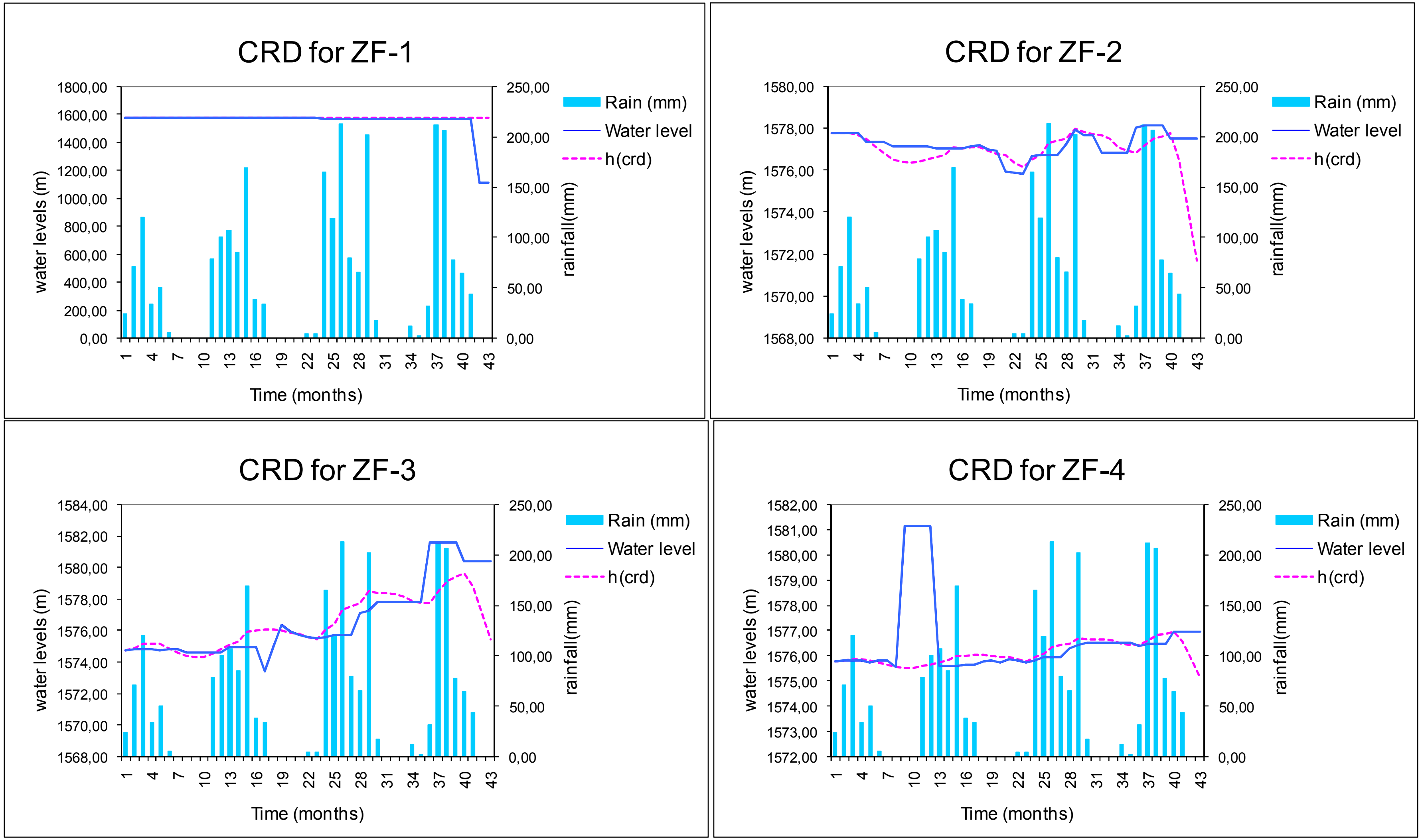
ZF-6 has a positive peak in water level at month 19 during the dry season where no rainfall occurred and can also be attributed to errors in data collection or capture.After taking all of the errors mentioned above into consideration the ‘fit’ (h(CRD)) needs to be matched to the water level as closely as possible to estimate recharge correctly and accurately. In the case of the Zevenfontein area the CRD ‘fit’ closely matched most of the boreholes’ water levels which gave consistent data concerning recharge when referring to Table 9-3. The CRD method calculates between 9% and 17% recharge from rainfall for the opencast mining area. Keeping in mind that this method is not specifically designed to calculate recharge within spoils and is lower than which was calculated for the RIV and stage curve methods, it still gives an indication that recharge is significantly higher than what is expected for the surrounding virgin ground. An anomalous recharge and subsequent ‘fit’ was encountered for the ZF-6 borehole where the water level was unusually low for the rainfall that precipitated. (This might be due to more pumping taking place from that specific area during that time.) This meant the ‘fit’ had to be averaged and gave the lowest recharge value of 7.71%. This value does not correlate with the other recharge values and can thus be ignored and classified as being suspect. The rest of the area’s parameter specified by Table 9-3 states that the average specific yield is 0.08, the average inflow stands at 450 m^3/day and the outflow at 900 m^3/day. This means that the average difference between the inflow and outflow comes to 450 m^3/day in the favour of outflow and can be attributed to excess pumping or decanting. Also, the specific yield values generated by the CRD method indicate that the spoils can be classified as a fine to medium sand, as well as medium to coarse gravel (ground types selected on minimum specific yield values).

TABLE 9-3: RECHARGE FOR ZEVENFONTEIN USING THE CRD METHOD

Cumulative Rainfall Departure Method							
Zevenfontein							
Borehole no.	**Lag time**	*** Re% > C**	**Sy**	**Cut-off C**	**Inflow(m3/d)**	**Outflow(m3/d)**	**Recharge in terms of rainfall**
ZF 1	0	10,2	0,0410	5,00	450,00	800,00	9,59
ZF 2	0	9.0	0,0290	5,00	450,00	850,00	8,46
ZF 3	0	18.0	0,0410	5,00	550,00	950,00	16,93
ZF 4	0	12,6	0,0950	5,00	0,00	0,00	11,85
ZF 5	0	14,2	0,1510	5,00	0,00	0,00	13,35
ZF 6	0	8,2	0,0855	5,00	500,00	350,00	7,71
ZF 7	0	9,9	0,1070	5,00	450,00	1550,00	9,31

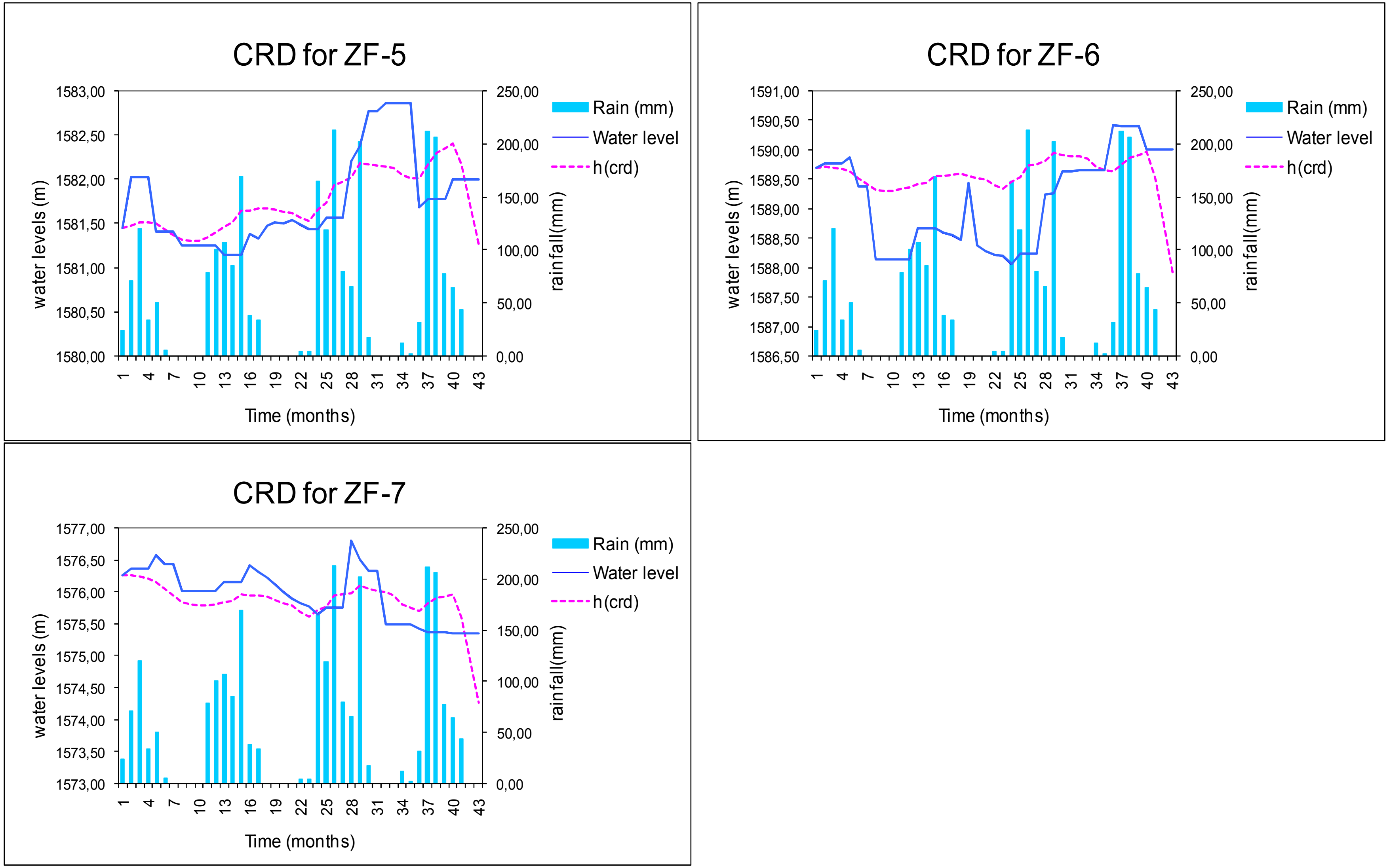
* Recharge must be higher than rainfall infiltration cut-off for any recharge to occur

Source: Research results (2017)



Source: Research results (2017)

Figure 9.5: Rainfall, water level and h(CRD) for ZF-1, ZF-2, ZF-3 and ZF-4 CRD method



Source: Research results (2017)

Figure 9.6: Rainfall, water level and h(CRD) for ZF-5, ZF-6 and ZF-7 CRD method

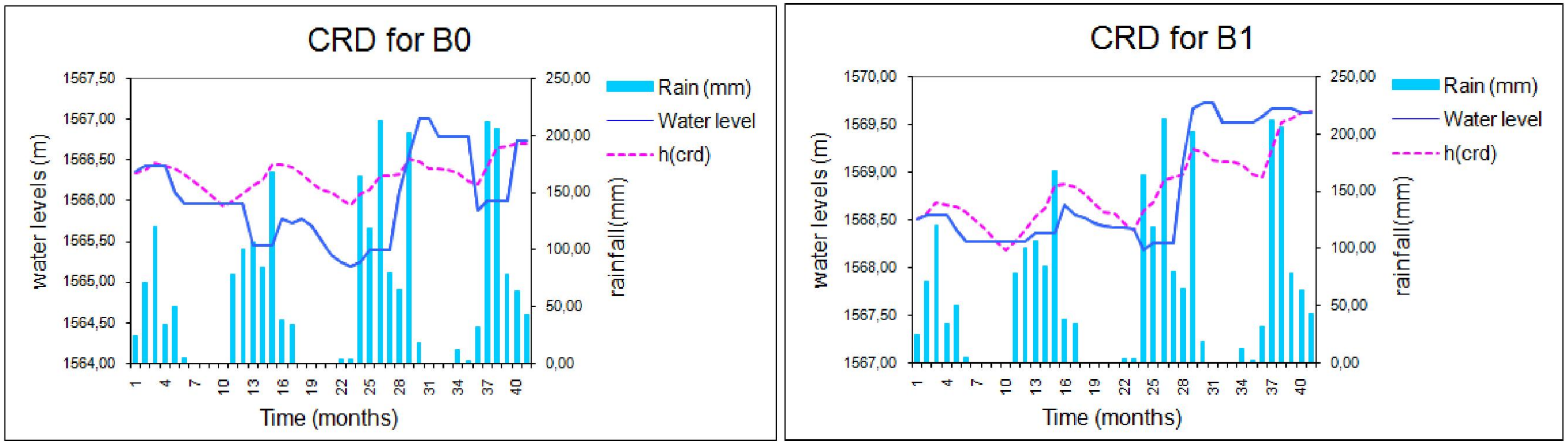
9.3.2 Optimus

When comparing the rainfall amount and fluctuation in water levels for the Optimus area, a positive correlation can be made between an increase and decrease in rainfall amount with that of the water level response. When time came to 'fit' the water level to the predicted h(CRD) some problems were encountered. One of the major problems encountered was that of the large positive and negative changes in water level observed in Figures 9.7 and 9.8. These changes in water level are directly due to the large amount of pumping taking place at the Optimus mining area. As a result of these sudden changes in water levels over the entire area, it is near impossible to find a perfect 'fit' for the h(CRD). The best fit for this area and its water levels was to use and average 'fit' which intersects the average of the negative and positive peaks through the entire range. The results are tabulated in Table 9-4. The CRD method for the Optimus rehabilitated opencast yielded a recharge for rainfall of between 13% and 19%. As with the previously discussed Zevenfontein CRD values, this method is not designed to work specifically well in spoil material, but the higher recharge percentage that was calculated for the Optimus CRD method confirms that recharge is significantly higher for spoils than that of the surrounding virgin ground and adds value to the recharge values calculated in the RIV and Stage Curve Volume Methods. The rest of the data revealed that the area has an average of 0.14 for the specific yield, 600 m^3/day inflow and 600 m^3/day for the outflow. The specific yields for the Optimus area indicate that the spoils can be classified as either fine to coarse sand as well as fine to coarse gravel.

TABLE 9-4: RECHARGE FOR ZEVENFONTEIN USING THE CRD METHOD

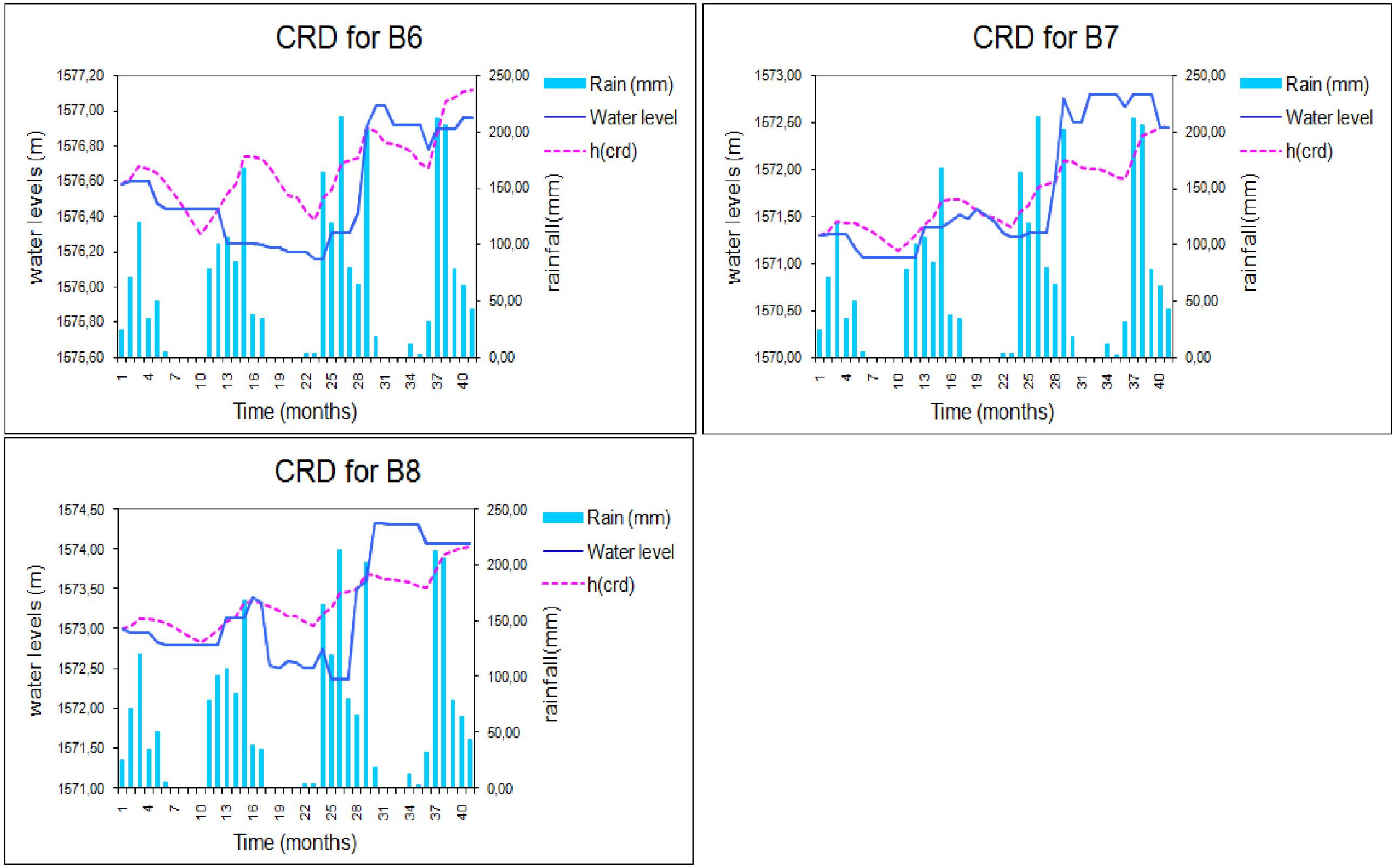
Cumulative Rainfall Departure Method							
Optimus							
Borehole no.	**Lag time**	**Re% > C**	**Sy**	**Cut-off C**	**Inflow(m3/d)**	**Outflow(m3/d)**	**Recharge in terms of rainfall**
B0	0	14,3	0,1075	5,00	150,00	200,00	13,45
B1	0	18.0	0,1095	5,00	600,00	600,00	16,93
B6	0	16.0	0,1455	5,00	600,00	600,00	15,05
B7	0	21,2	0,1685	5,00	600,00	600,00	19,94
B8	0	20,6	0,1755	5,00	600,00	600,00	19,37

Source: Research results (2017)



Source: Research results (2017)

Figure 9.7: Rainfall, water level and h(CRD) for B0 and B1 CRD method



Source: Research results (2017)

Figure 9.8: Rainfall, water level and h(CRD) B6, B7 and B8 CRD method

9.4 Water Table Fluctuation method

This method provides an estimate of groundwater recharge by analysingwater level fluctuations in boreholes and is based on the assumption that a rise in water table elevation is caused by the addition of recharge across the water table.

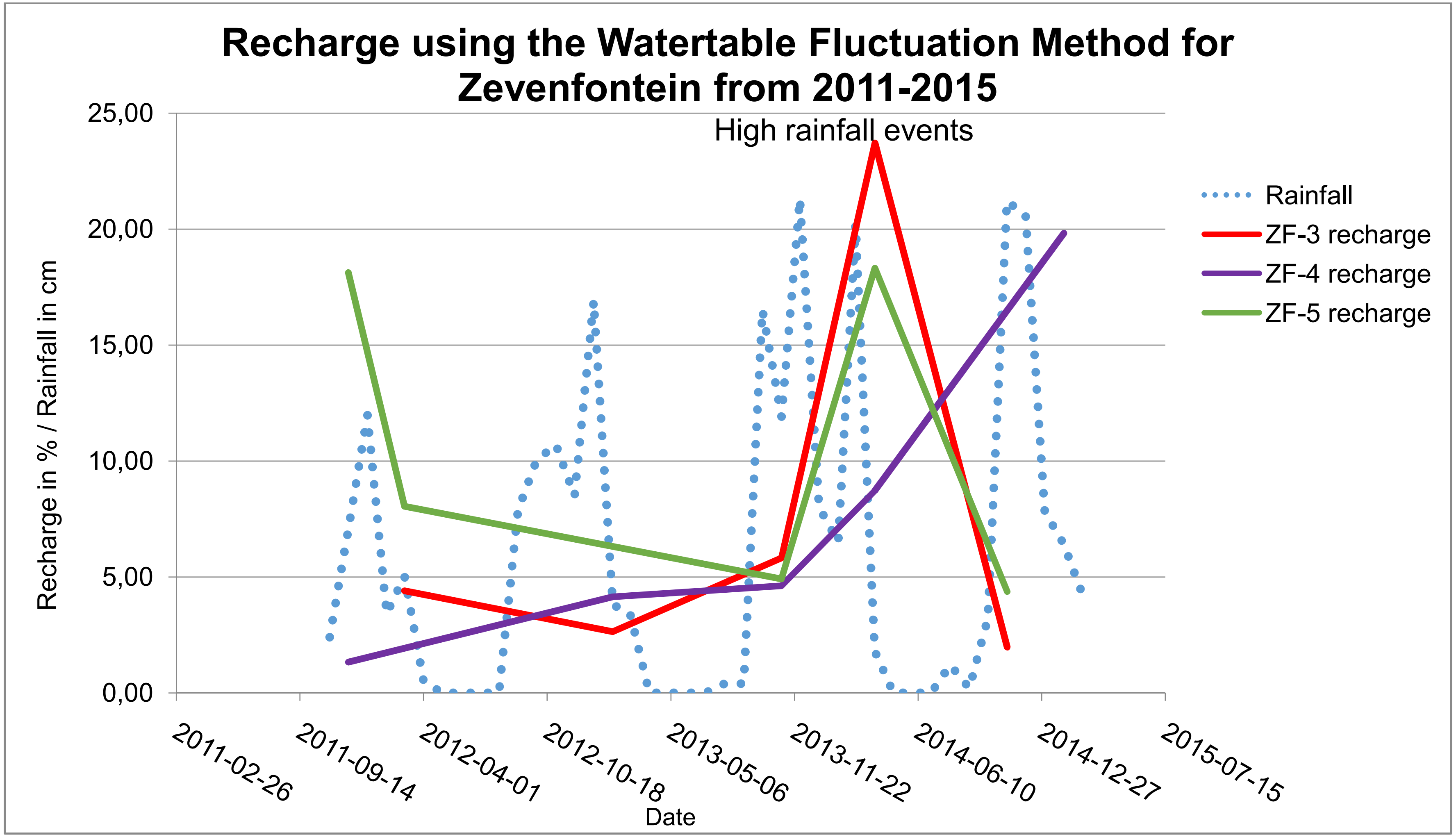
9.4.1 Zevenfontein

For this method all the parameters were known except that of specific yield (S_y). From previous studies in the area and calculations done using stage curve volumes a specific yield of 0.3 was chosen. The results of the WTF method are shown in Table 9-5. The results concerning the recharge values calculated, showed that there was a definite dry period from 2011 until mid-2013 (Figure 9.9), which reflects in the low recharge percentages from that period. From mid-2013 the rainfall suddenly increases and reflects in the higher recharge percentages calculated until the start of 2015. Although ZF-5 shows higher recharge values right at the start of 2011, and can be considered an outlier, ZF-3 and ZF-4 starts off with a 1–8% recharge percentage (Figure 9.9). When the rainfall increases from mid- 2013 and thus the infiltration percentage increases, the water levels will subsequently increase as well. There is a clear correlation between the rainfall increase and recharge percentage increase in ZF-3, ZF-4 and ZF-5 until the start of 2015, as seen in Figure 9.9. Although this method does not deliver a clear estimate of recharge for the area, there is, however, a clear correlation between the increase and decrease in rainfall and the amount fluctuation in the recharge percentages calculated. As a secondary observation the amount of rainfall in a single event affects the recharge percentage more than the same amount over a period of months.

TABLE 9-5: RECHARGE VALUES CALCULATED FOR ZEVENFONTEIN USING THE WTF METHOD

Water Table Fluctuation Method				
Zevenfontein				
Borehole no.	Date	Rainfall (mm)	Specific Yield	Recharge %
ZF-3	2012-03-01	452	0,3	4,4
	2013-02-01	361	0,3	2,6
	2013-11-01	165	0,3	5,8
	2014-04-01	267	0,3	23,7
	2014-11-01	32	0,3	1,9
ZF-4	2011-12-01	91	0,3	1,3
	2013-02-01	361	0,3	4,1
	2013-11-01	165	0,3	4,6
	2014-04-01	267	0,3	8,7
	2015-02-01	450	0,3	19,8
ZF-5	2011-12-01	24	0,3	18,1
	2012-03-01	399	0,3	8,0
	2013-11-01	165	0,3	4,9
	2014-04-01	267	0,3	18,3
	2014-11-01	32	0,3	4,0

Source: Research results (2017)



Source: Research results (2017)

Figure 9.9: Diagram illustrating the recharge values calculated from 2011 to 2015 for the Zevenfontein pit

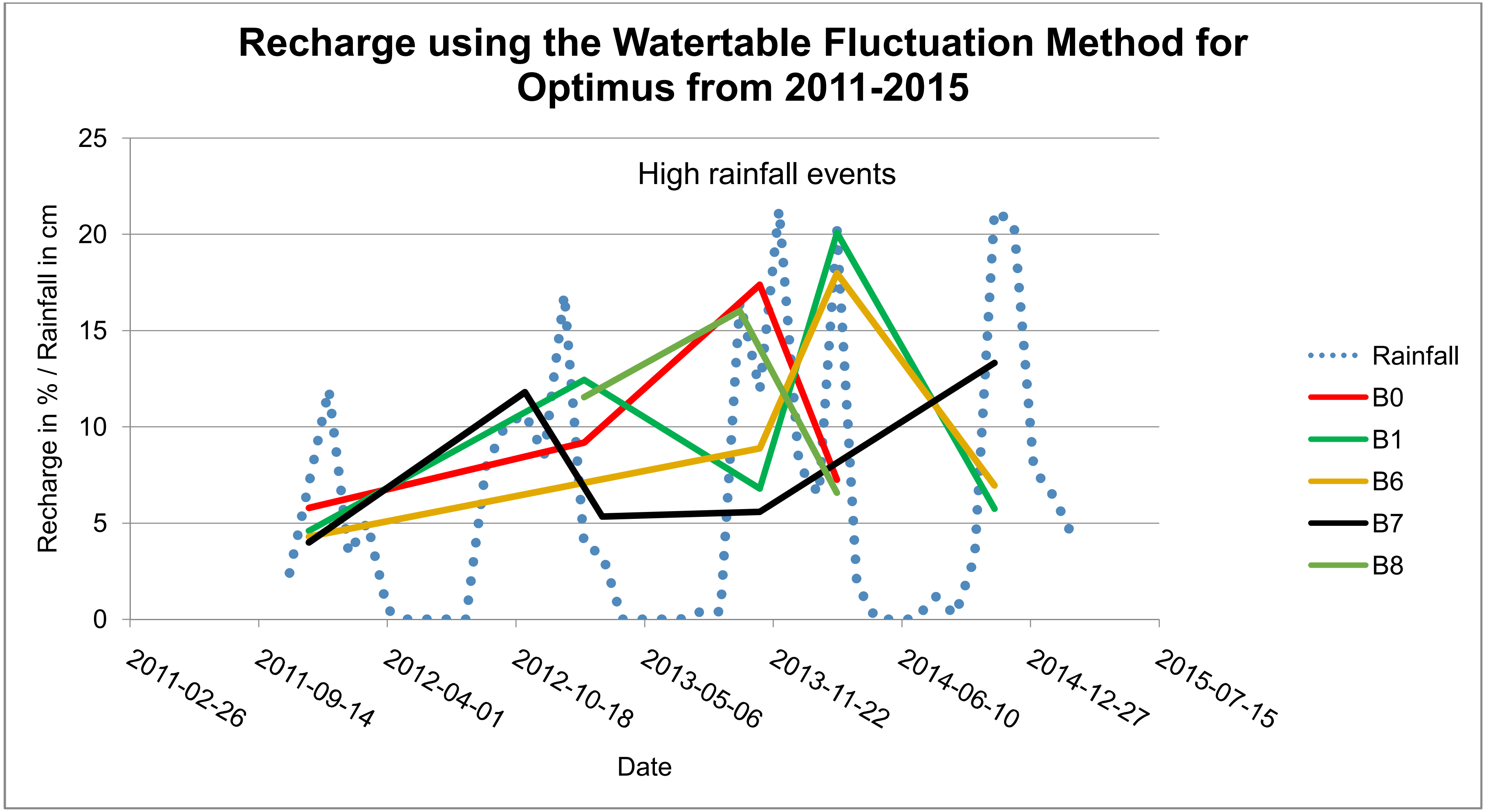
9.4.2 Optimus

As with the Zevenfontein calculations the specific yield was not known and since this unknown parameter was calculated to be 0.3 for the spoils in the pit, it is assumed that the specific yield for the spoils in the Optimus opencast is the same. For the Optimus pit the WTF method calculates low recharge values in the vicinity of 4–5% recharge of rainfall. As with Zevenfontein the conclusion is definite, that there was an exceptionally dry period from 2011 to mid-2013. From mid-2013 and onwards to the beginning of 2015 there was a sudden increase in rainfall which in turn caused more rainfall to penetrate the spoils and thus caused a larger fluctuation in water levels as seen in Figure 9.10. The recharge values calculated with the WTF method again confirms the statement that single high rainfall events cause more recharge to take place than the same rainfall amount over a period of months, and can be seen in Table 9-6. Although boreholes B0 and B8, as well as B1 and B6, show the same trend in recharge percentage, they cannot be connected in any way to each other due to the large distance between them.

TABLE 9-6: RECHARGE VALUES CALCULATED FOR ZEVENFONTEIN USING THE WTF METHOD

Water Table Fluctuation Method				
Optimus				
Borehole no.	Date	Rainfall (mm)	Specific Yield	Recharge %
B0	2011-12-01	24	0,3	5,8
	2013-11-01	165	0,3	9,2
	2014-03-01	65	0,3	17,4
	2014-11-01	32	0,3	7,3
B1	2011-12-01	24	0,3	4,6
	2013-02-01	192	0,3	12,4
	2013-11-01	165	0,3	6,8
	2014-03-01	65	0,3	20,1
	2014-11-01	32	0,3	5,8
B6	2011-12-01	24	0,3	4,3
	2013-11-01	165	0,3	8,9
	2014-03-01	65	0,3	18,0
	2014-11-01	32	0,3	7,0
B7	2011-12-01	24	0,3	4,0
	2012-11-01	234,5	0,3	11,8
	2013-03-01	169	0,3	5,3
	2013-11-01	165	0,3	5,6
	2014-11-01	64	0,3	13,3
B8	2013-02-01	214	0,3	11,5
	2013-10-01	42	0,3	16,0
	2014-03-01	65	0,3	6,6

Source: Research results (2017)



Source: Research results (2017)

Figure 9.10: Diagram illustrating the recharge values calculated from 2011 to 2015 for the Optimus pit

Chapter 10
Conclusion

10.1 Introduction

In conclusion it can be said that the Optimum mine is an area that has been researched thoroughly concerning its water. Their objectives are to keep the clean water from the surrounding groundwater table clean and to re-use the mine water and later on fully treat the water for irrigation. The Optimum area has numerous water control dams and evaporation dams so that the intricate system of pumping works to keep the mine water separate from that of the environment. The Pullenshoop area also has undergone a major upgrade concerning the stream diversion project which aims to further separate natural clean water from the mine water. It can be said that the decanting that happens at the Optimus and Zevenfontein areas are under control, for when an overflow happens the excess water flows directly to their respective dams which are regulated and separated from the surrounding areas.

The Zevenfontein and Optimus areas are almost completely rehabilitated, and the spoils thrown back into the opencast pit will subsequently have the potential for more infiltration from rainfall to occur. The Optimum mine has the infrastructure to deal with this excess water that has been predicted together with their close monitoring, and no future problems can be foreseen concerning environmental water contamination or a lack of storage for excess water.

10.2 Methods

It was determined early on that selection of the right methods for recharge calculations within spoils was crucial. In this case, waterbalance methods were selected as the data provided for these waterbalance parameters was abundant and stretching over a period of five years. As with many recharge methods, some parameters were not available or even possible to acquire and thus steps had to be taken to fill this void in the data correctly for the recharge method to yield conclusive results.

Another conclusion made during the dissertation is that a combination of water balance methods will ultimately yield better results when they are compared to each other. They compensate for the disadvantages that one method displays by taking into account the advantages of the other methods to eventually come to a combined recharge value. As further precautionary methods that the Optimum mine used, methods using stage curve volumes were also implemented and calculated to compare with that of the known methods used to calculate recharge.

10.3 Study area

For this dissertation, only the Optimus and Zevenfontein areas were chosen to do the recharge calculations on as they were rehabilitated and had no underground mining components, or was actively being mined.

The rainfall statistics from 2010 to 2015 suggest that the average rainfall is around 700 mm per annum, whereas the literature prescribesa 450 mm rainfall average. When the years are compared with each other, there are distinct six months dry and wet seasons with 2011 and 2012 being drought years.

The whole area is situated in the Karoo Supergroup with the Ecca Group being the main geology where the Vryheid Formation (East succession) is the coal-bearing horizon being mined. The area contains two aquifer systems called the weathered aquifer system and the fractured aquifer system. Both havean effect on the mining as well as the water, but the weathered aquifer located close to the surface plays the more important role as water levels in the area are exceptionally shallow. This shallow water level explains the existence of numerous man-made and natural dams in the area and causes the recharge potential from rainfall to increase as little infiltration needs to occur for the rain water to percolate through the ground profile to reach the groundwater table.

10.4 Research conclusions

10.4.1 Pit volume calculations

It was concluded that pit calculations were applicable to the Optimus opencast pit and satisfactory void space percentages were calculated for the spoils. There were,however, certain assumptions that need to be made for pit calculations to yield a conclusive result. Firstly, enough data on the different topographies are a must for accurate volume calculations and, secondly, uneven undulating topographies need to be averaged and levelled for accurate in-pit volumes. It is also advisable to understand all the parameters that affect the spoil volume, otherwise an under- or over-calculated spoil volume will result.

The void space for the Optimus spoil volume was calculated to be between minimum 10% and maximum 24% void space throughout the effects of erosion, shrinkage and mechanical compaction. In conclusion, for the pit calculations attempted on the Optimus opencast pit, the void space values calculated are what was expected from the spoils, but on the other hand, more accurate data on the parameters can narrow down the value between 10% and 24% voidspace.

10.4.2 Pumping cycles

It is clear from the pumping that takes place in and around the Optimum area that the areas where pumping occurs, are strategically placed to remove excess water from active mining areas as well as to keep waterlevels in check so that minimal decanting occurs. It was concluded from the pumping rates and the direction in which the extracted water is pumped that the objectives of the Optimum coal mining operation are to keep the mine water in circulation and the rest is treated or evaporated, doing all of this while keeping the contaminated runoff and decanting water clear of clean groundwater.

For the areas themselves it was found that the following is in effect:

- The **Boschmanspoort** area is an underground mining operation, which utilises a circulatory pumping system which effectively contains mine water from contaminating the surrounding aquifer system.
- The **Eikeboom and Kwaggafontein** areas make use of a direct pumping system which pumps the water directly away from the mining area to where it can be controlled and treated. For the Eikeboom area the water is pumped to water control dams, whereas the Kwaggafontein area uses final voids left over from previous mining activities to store the water for evaporation.
- The **Optimus and Pullenshoop** area is centrally located and serves as a junction point for the water pumped from around the area. The Pullenshoop ring feed serves as this junction point for the Optimus, Pullenshoop and **Zevenfontein** areas, where all the excess water is pumped to. From there on the water will either be evaporated at the Evaporation Dam or pumped to the HMS Gravity 1 and 2 for treatment or any other use thereof.

10.4.3 Borehole water levels and rainfall

In conclusion it can be said that the waterlevels in and around the Optimum mining area are very shallow between 0 mbgl and 10 mbgl on average. Strong groundwater flow can be expected in the area when taking the previously mentioned waterlevels and the large amount of pumping in the area into consideration. The rainfall pattern suggests a definite wet and dry season with the area receiving on average 700 mm per annum.

The following deductions were made concerning each mining area of the Optimum mining operation:

- The **Boschmanspoort** area has an aquifer that is quick to respond to any extraction from and addition to the groundwater table due to the fact that the water level is between 2 mbgl and 10 mbgl. Pumping here only takes place to keep the water levels static and it was concluded that on average the pumping rates are around 20 000 m^3/pm, while the waterlevels suggest that an 18 000 m^3/pmextraction rate will subsequently lower the water table.

- The **Eikeboom** area contains an even shallower water table than that of the Boschmanspoort area and the same fluctuations and trends in the water levels indicate that they all reside in the same aquifer system. When comparing the pumping rate fluctuations with that of the water levels a lag time of one to two months can be expected.
- The **Optimus and Zevenfontein** areas are located just beside each other and both contain a centrally low-laying dam (Lapa Dam and Coastal Dam, respectively) to which water can freely drains or decant in. Also, all the water pumped from these two dams are directly fed into the Pullenshoop ring feed system for further distribution, either towards the evaporation dam for evaporation or to the HMS Gravity 1 and 2 for treatment. The key difference is that the water levels at Optimus stay unchanged and no correlation could be found between the water levels and the pumping rates, whereas the Zevenfontein showsa correlation between these two parameters. This suggests that the Optimus area or Lapa Dam has no connection to the borehole water levels and thus it can be concluded that the boreholes do not reside in the same aquifer. The Zevenfontein borehole water levels do show a correlation between water pumped directly from the Coastal Dam and between each other which suggest one aquifer system.
- The **Pullenshoop** water levels show the same trend and fluctuations in static water level, although no correlation could be made between the water levels and the pumping rates due to a lack of data in this area. The same conclusion can be made for the **Bothashoek** area.

10.5 New recharge methods

10.5.1 Rainfall Infiltrated Volume method

This method is essentially a water balance between the pumping volumes and the calculated RIV and consequently compared with each other. In the research it was concluded that if the water decants, which it is for all two opencast pits, the excess water that decants can be attributed to rainfall, runoff and external water sources, whereby the mining operation can either lower or raise their pumping volumes to accommodate for these changes in volume when the water starts to decant. When selecting an area to calculate the RIV on the exact area of the rehabilitated spoils, carefully chosen recharge factors and porosities are crucial in calculating a reasonable recharge percentage, as only a small change in one of the parameters could have large effects on the final value. It is also advised that longer periods of time are chosen to do the calculations over, between one year and onwards, since monthly calculations can yield either over- or under-estimate recharge values due to large changes in rainfall volume or pumping rates for those months.

Both the Zevenfontein and Optimus areas are passively pumped and the decanting volumes stand equal to that of the pumping volumes. Both show that although this is true, outside factors can still influence the values, and thus pumping volumes are either lower (Zevenfontein) or higher (Optimus) than what is suggested by the RIV method.

As seen with the Optimus rehabilitated pit, the way the rehabilitation is done, also plays a large role in determining the recharge percentage. It can be concluded that the water infiltrated method does not work on a non-traditional rehabilitated pit (Optimus) where free flow is absent and ponding (Lapa Dam) takes place inside the pit. As a result, the increase in pumping at the Optimus opencast severely decreases the amount of recharge calculated at only 4%, when a realistic recharge value of 30% was expected (Figure 10.1). On the other hand, where pumping volumes and RIVs closely match each other and the pit is traditionally rehabilitated (Zevenfontein), great results can be obtained since there are no external water sources which influence the recharge and pumping values. Zevenfontein showed a RIV recharge value of 18.6% which was close to the expected value of 20% for the spoils.

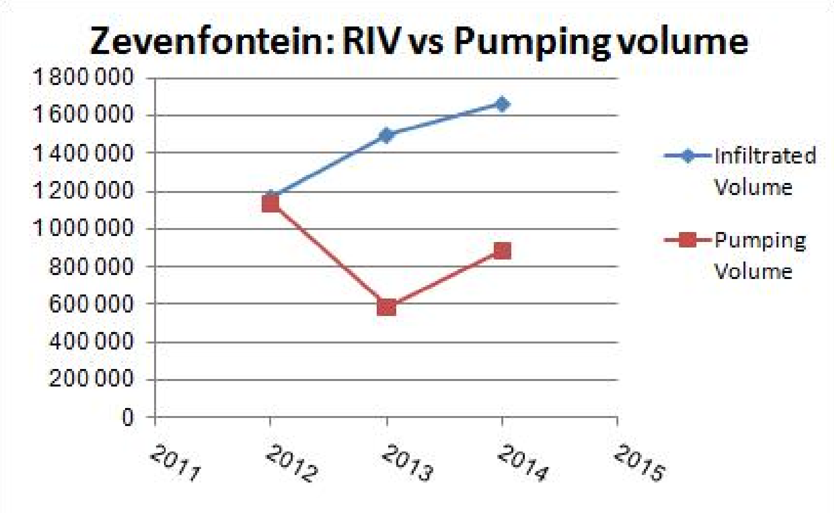
In conclusion, the RIV method works well on rehabilitated areas which show consistent pumping rates and one or two sources of recharge. Thus, Zevenfontein's recharge from rainfall value at 18.6% can be considered close to what is expected from the spoils.

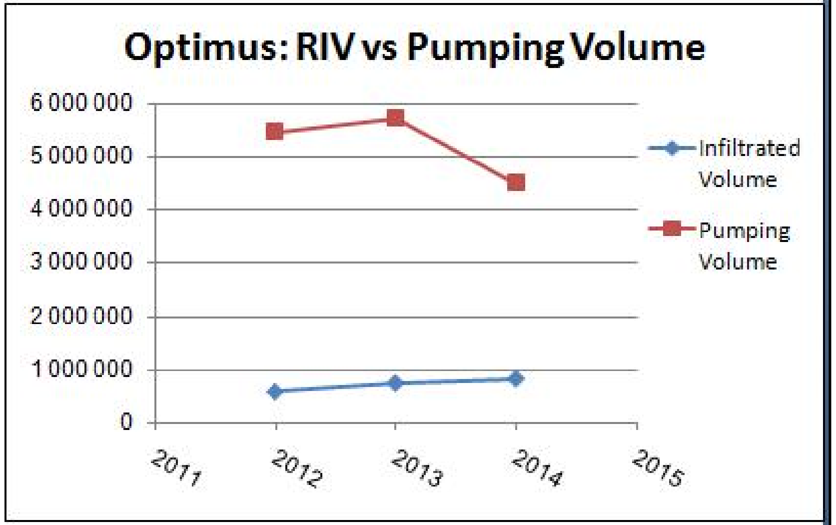
Zevenfontein

Date	Infiltrated volume (m^3)	Pumping volume (m^3)
2012	1 166 425	1137444
2013	1 500 264	590098
2014	1 667 183	891944

Optimus

Date	Infiltrated volume (m^3)	Pumping volume (m^3)
2012	580 626	5464395
2013	746 805	5707010
2014	829 895	4513410





Recharge Calculated at 18,6%

Recharge Calculated at 4%

Source: Research Results (2017)

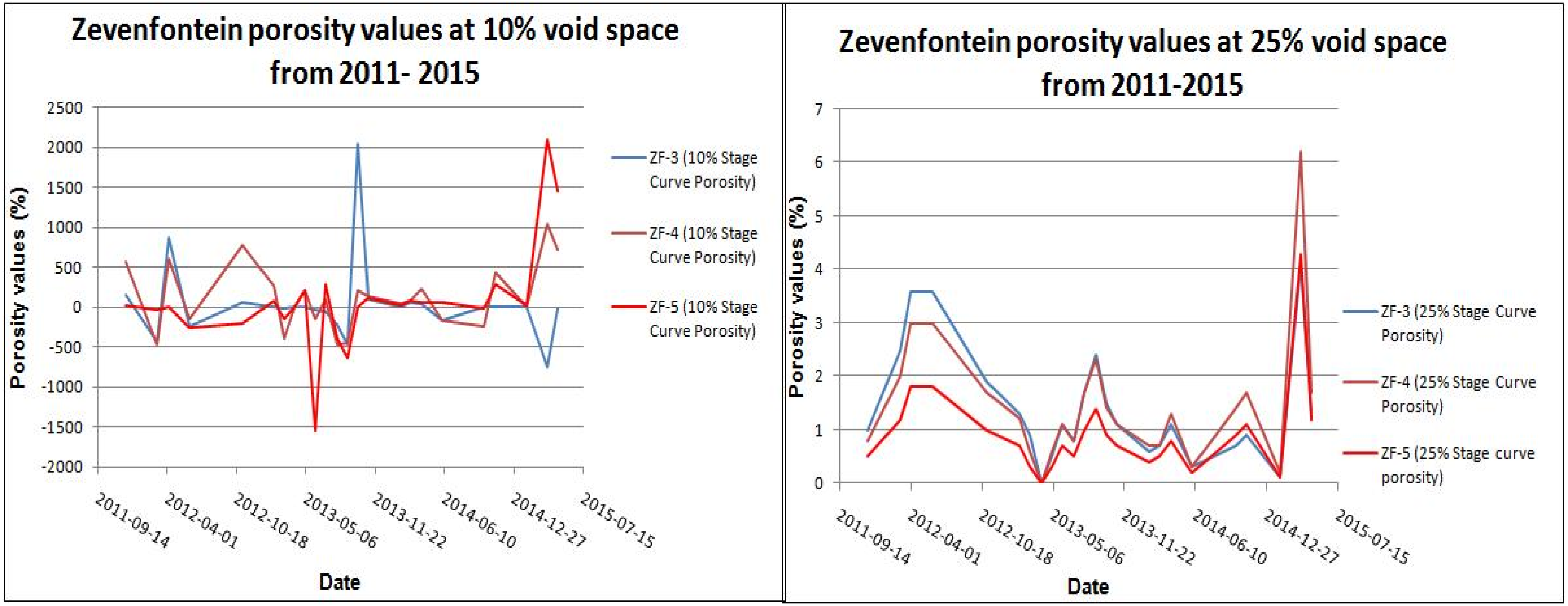
Figure 10.1: Combination of the Optimus and Zevenfontein RIV method values

10.5.2 Stage Curve Volume method

The SCV method calculates the porosity of the spoils by assuming that a change in waterlevel volume is as a direct effect of pumping over the same period of time in which the change in water volume occurred. The Pit Volume Calculation's void space percentages were used to calculate a volume for the Zevenfontein and Optimus opencasts and were set at a 10% and 25% void space in between the spoils.

This method only aims to confirm that the void space chosen for the spoil material is correct, as seen when Zevenfontein's porosity was calculated at a 25% voidspace which yielded porosity values of between 0% and 7% (Figure 10.2). This method can only work if all the sources of water which contribute to recharge are known, as in the case of Zevenfontein. Optimus yielded mostly negative porosity values and the positive values were much too high. This was because not all the sources of water which contribute to recharge was known and that the subsequent pumping values were much too high.

In conclusion, the Zevenfontein porosity values at between 0% and 7% confirm that the spoil material has a void space of 25% which was calculated during the pit calculations.



Source: Research results (2017)

Figure 10.2: Difference in porosity values calculated for the Zevenfontein area at 10% and 25% void space

10.5.3 Stage Curve Volume method

The dry and wet calculations for both the Zevenfontein and Optimus were unsuccessful in calculating recharge from rainfall. The Zevenfontein area had exceptionally low recharge values between 0.1% and 3%, whereas the Optimus area yielded only negative results for the porosities and around 2% recharge values (Figure 10.3).

In conclusion, this method is mathematically correct, but more parameters need to be added which might change the values calculated, that they are more in line with what is expected. Another reason for the scattered recharge values for both opencasts are the high pumping values compared to the rainfall over the rehabilitated opencast. The researcher believes that this method can successfully be applied to a much larger area seeing that changing the rainfall volume to become more will yield higher, more conclusive values.

Zevenfontein

		Void space %			Void space %			Void space %	
		10%	25%		10%	25%		10%	25%
BH Name	Date	Recharge %		BH Name	Recharge %		BH Name	Recharge %	
ZF-3	2013-02-01	0,08	0,08	ZF-4	0,09	0,09	ZF-5	0,16	0,16
	2013-03-01	0,03	0,03		0,06	0,06		0,04	0,04
	2013-08-01	0,5	0,5		0,57	0,57		0,58	0,58
	2013-09-01	2,57	2,57		2,26	2,26		2,29	2,29
	2013-10-01	0,08	0,08		0,1	0,1		0,07	0,07
	2013-11-01	0,04	0,04		0,05	0,05		0,06	0,06
	2014-02-01	0,05	0,05		0,1	0,1		0,2	0,2
	2014-03-01	0,03	0,03		0,05	0,05		0,058	0,058
	2014-04-01	0,07	0,07		0,08	0,08		0,15	0,15

Optimus

Borehole name	From	To	Average recharge %
B0	2011-11-01	2015-02-01	2
B1	2011-11-01	2015-02-01	2,7
B6	2011-11-01	2015-02-01	2,4
B7	2011-11-01	2015-02-01	0,9
B8	2011-11-01	2015-02-01	1,3

Source: Research results (2017)

Figure 10.3: Recharge values for dry and wet calculations for the Zevenfontein and Optimus opencasts

10.5.4 Stage Curve Volumemethod

Calculating recharge by using stage curve volumes for the Optimus and Zevenfontein areas, the pumping rate volumes must be considered equal to the decanting volumes and that the decanting volumes are as a result recharge. Secondly, it is advisable that these calculations are done over longer time periods (four months or more) to average out the sudden changes in rainfall and pumping rates, otherwise under- or over-estimated recharge values can be expected.

For Zevenfontein, a 25% void space yielded the best results between 12% and 35% recharge from rainfall, which was expected for the spoils. The fact that the 25% void space also yielded the best result for recharge from rainfall, is the second confirmation (first was the SCVmethod) that the Zevenfontein has definitely or close to a 25% void space within the spoil material (Figure 10.4). For the Optimus area, all the recharge values calculated was above 30%. This was expected since the rehabilitation design forces all the water to run towards the centre of the pit and thus increases the amount of water that infiltrates, which shows in the difference between the first water level and second elevated water level.

In conclusion, this method, although the simplest, yielded the best recharge from rainfall values and close to what was expected for the area.

Zevenfontein

ZF-3

From	To	Recharge @ 10% void space	Recharge @ 25% void space
2011-11-01	2012-03-01	13,91	14,22
2012-04-01	2012-11-01	25,95	31,40
2012-12-01	2013-06-01	26,70	54,42
2013-07-01	2013-10-01	9,93	0,53
2013-11-01	2014-04-01	23,89	54,03
2014-05-01	2015-05-01	34,94	53,97
Average:		22,56	34,76

ZF-4

From	To	Recharge @ 10% void space	Recharge @ 25% void space
2011-11-01	2012-03-01	12,85	11,57
2012-04-01	2012-11-01	17,26	9,69
2012-12-01	2013-06-01	9,79	12,14
2013-07-01	2013-10-01	15,46	14,35
2013-11-01	2014-04-01	9,12	17,10
2014-05-01	2015-05-01	28,45	37,75
Average:		15,48	17,09

ZF-5

From	To	Recharge @ 10% Void space	Recharge @ 25% void space
2011-11-01	2012-03-01	12,84	11,54
2012-04-01	2012-11-01	16,57	7,95
2012-12-01	2013-06-01	10,60	14,17
2013-07-01	2013-10-01	12,09	5,92
2013-11-01	2014-04-01	15,28	32,50
2014-05-01	2015-05-01	14,13	1,94
Average:		13,58	12,34

Optimus

		B0		B1	
From	**To**	**Recharge @ 10% Void space**	**Recharge @ 25% Void space**	**Recharge @ 10% Void space**	**Recharge @ 25% Void space**
2011-11-01	2012-03-01	28,4	20,9	30,5	26,2
2012-04-01	2013-03-01	29,4	26,0	34,8	39,6
2013-04-01	2013-10-01	62,4	36,6	65,8	44,9
2013-11-01	2014-03-01	26,8	41,9	31,7	54,0
2014-04-01	2014-10-01	46,1	-116,6	138,3	113,7
2014-11-01	2015-05-01	25,6	33,1	18,0	14,1
Average:		36,5	31,7	36,2	35,8

		B6		B7	
2011-11-01	2012-03-01	29,7	24,2	29,9	24,8
2012-04-01	2013-03-01	28,4	23,6	37,5	46,4
2013-04-01	2013-10-01	76,2	71,1	70,5	56,6
2013-11-01	2014-03-01	25,5	38,6	21,8	29,4
2014-04-01	2014-10-01	115,4	56,7	173,6	202,0
2014-11-01	2015-05-01	17,3	12,3	12,9	1,3
Average:		35,4	37,8	34,5	31,7

		B8	
2011-11-01	2012-03-01	28,8	22,0
2012-04-01	2013-03-01	25,2	15,7
2013-04-01	2013-10-01	89,4	104,0
2013-11-01	2014-03-01	27,6	43,9
2014-04-01	2014-11-01	64,1	99,5
Average:		36,5	27,2

Source: Research results (2017)

Figure 10.4: The combined recharge calculated for the Zevenfontein and Optimus areas using stage curve volumes

10.6 Known recharge methods

10.6.1 Saturated Volume Fluctuation method

From the data provided by the Optimum mine for the Zevenfontein and Optimus opencast areas, the following results came to light (Figure 10.5):

The **Zevenfontein area** shows conclusive recharge values when the SVF method is applied. This method calculates recharge from rainfall to be between 5% and 13%, with an average of 9.3%. Taking into account that this method was designed for use on virgin ground, it is exactly what can be expected for the area.

The **Optimus area** also shows conclusive results when calculating recharge from rainfall. The SVF method estimates recharge to be between 13% and 19%. Keeping in mind the unusual way in which the Optimus area guides the water towards the centre of the opencast and increase infiltration, this factor explains the higher recharge values when compared to that of the Zevenfontein values.

In conclusion, the SVF method can be considered applicable to this area and delivers accurate and satisfactory results in conjunction with the recharge expected for the area and calculated during the RIV and recharge using SCV methods.

Saturated Volume Fluctuation Method						
Zevenfontein						
Borehole No.	Lag time (month)	Recharge %	S value	Inflow (m3/d)	Outflow (m3/d)	Error
ZF 1 (late fit)	0	5,7	0,074	0	800	0,036
ZF 2	0	12	0,0725	0	1450	0,083
ZF 3 (early fit)	0	23,7	0,0745	0	850	0,190
ZF 3 (late fit)	0	39,4	0,1295	3550	1150	0,140
ZF 4	0	13,1	0,078	0	800	0,028
ZF 5	0	13	0,1015	650	900	0,061
ZF 6	0	5,9	0,055	1750	1500	0,109
ZF 7	0	5,9	0,1855	1450	2300	0,047

Saturated Volume Fluctuation Method						
Optimus						
Borehole No.	Lag time	Recharge %	S value	Inflow	Outflow	Error
B0	0	13,1	0,0540	0	700	0,0730
B1	0	15,9	0,0625	450	700	0,0514
B6	0	13,8	0,1135	700	700	0,0354
B7	0	19,4	0,1140	600	700	0,0534
B8	0	19,4	0,1085	0	700	0,1119

Source: Research results (2017)

Figure 10.5: Recharge values calculated using the SVF methodon the Zevenfontein and Optimus opencasts

10.6.2 Cumulative Rainfall Departure method

The CRD method was used to calculate recharge from rainfall using the data previously supplied by the Optimum mine. The following are the conclusions made for the Zevenfontein and Optimus opencasts (Figure 10.6):

For the **Zevenfontein** area, the CRD method calculates between 9% and 17% recharge from rainfall for the opencast mining area. Keeping in mind that this method is not specifically designed to calculate recharge within spoils and is lower than which was calculated for the RIV and stage curve methods, it still gives an indication that recharge is significantly higher than what is expected for the surrounding virgin ground. The parameters for the rest of the area state that the average specific yield is 0.08, the average inflow stands at 450 m^3/day and the outflow at 900 m^3/day. Also, the specific yield values generated by the CRD method indicate that the spoils can be classified as a fine to medium sand, as well as medium to coarse gravel (ground types selected on minimum specific yield values).

For the **Optimus** area, the CRD yielded a recharge from rainfall of between 13% and 19%. As with the other methods a higher recharge from rainfall is noticed for the Optimus area when the same methods are applied to the Zevenfontein area and adds value to the recharge values calculated in the RIV and SCV methods. The rest of the data revealed that the area has an average of 0.14 for the specific yield, 600 m^3/day inflow and 600 m^3/day for the outflow. The specific yields for the Optimus area indicate that the spoils can be classified as either fine to coarse sand, as well as fine to coarse gravel.

In conclusionthe CRD confirms pervious recharge estimates for the virgin ground, but comes up short when trying to calculate recharge from rainfall in spoil material.

Cumulative Rainfall Departure Method							
Zevenfontein							
Borehole no.	**Lag time**	*** Re% > C**	**Sy**	**Cut-off C**	**Inflow(m3/d)**	**Outflow(m3/d)**	**Recharge in terms of rainfall**
ZF 1	0	10,2	0,0410	5,00	450,00	800,00	9,59
ZF 2	0	9.0	0,0290	5,00	450,00	850,00	8,46
ZF 3	0	18.0	0,0410	5,00	550,00	950,00	16,93
ZF 4	0	12,6	0,0950	5,00	0,00	0,00	11,85
ZF 5	0	14,2	0,1510	5,00	0,00	0,00	13,35
ZF 6	0	8,2	0,0855	5,00	500,00	350,00	7,71
ZF 7	0	9,9	0,1070	5,00	450,00	1550,00	9,31

* Recharge must be higher than rainfall infiltration cut-off for any recharge to occur

Cumulative Rainfall Departure Method							
Optimus							
Borehole no.	**Lag time**	**Re% > C**	**Sy**	**Cut-off C**	**Inflow(m3/d)**	**Outflow(m3/d)**	**Recharge in terms of rainfall**
B0	0	14,3	0,1075	5,00	150,00	200,00	13,45
B1	0	18.0	0,1095	5,00	600,00	600,00	16,93
B6	0	16.0	0,1455	5,00	600,00	600,00	15,05
B7	0	21,2	0,1685	5,00	600,00	600,00	19,94
B8	0	20,6	0,1755	5,00	600,00	600,00	19,37

Source: Research results (2017)

Figure 10.6: Combined recharge values calculated for all the boreholes in the Zevenfontein and Optimus opencasts

10.6.3 Water Table Fluctuation method

This method works on the assumption that an increase in water level is the direct result of recharge to the groundwater table. The following observations were made (Figure 10.7):

For the **Zevenfontein** area all the parameters were known, except that of specific yield (S_y), but was previously selected when calculating recharge from stage curve volumes at 0.3. The results showed a definite dry period from 2011 until mid-2013, which reflect in the low recharge percentages from that period. From mid-2013 the rainfall suddenly increases and reflects in the higher recharge percentages calculated until the beginning of 2015.

Thus, it can be concluded that this method for calculating recharge is directly linked to the amount of rainfall over a specific time period. This method can also give a minimum and maximum value for recharge but cannot specifically pin point the exact recharge value. In this case the recharge calculated from rainfall ranges from 2% to 24%, with the average being 8%. As a secondary observation, the amount of rainfall in a single event affects the recharge percentage more than the same amount over a period of months.

For the **Optimus** pit, the WTF method calculates low recharge values in the vicinity of 10% recharge of rainfall. As with Zevenfontein, the conclusion is definite, that there was an exceptionally dry period from 2011 to mid-2013. From mid-2013 and onwards to the beginning of 2015 there was a sudden increase in rainfall which, in turn, caused more rainfall to penetrate the spoils and thus caused a larger fluctuation in water levels. The recharge values calculated with the WTF method again confirms the statement that single, high rainfall events cause more recharge to take place than the same rainfall amount over a period of months.

Water Table Fluctuation Method				
Zevenfontein				
Borehole no.	**Date**	**Rainfall (mm)**	**Specific Yield**	**Recharge %**
ZF-3	2012-03-01	452	0,3	4,4
	2013-02-01	361	0,3	2,6
	2013-11-01	165	0,3	5,8
	2014-04-01	267	0,3	23,7
	2014-11-01	32	0,3	1,9
ZF-4	2011-12-01	91	0,3	1,3
	2013-02-01	361	0,3	4,1
	2013-11-01	165	0,3	4,6
	2014-04-01	267	0,3	8,7
	2015-02-01	450	0,3	19,8
ZF-5	2011-12-01	24	0,3	18,1
	2012-03-01	399	0,3	8,
	2013-11-01	165	0,3	4,9
	2014-04-01	267	0,3	18,3
	2014-11-01	32	0,3	4,

Water Table Fluctuation Method				
Optimus				
Borehole no.	**Date**	**Rainfall (mm)**	**Specific Yield**	**Recharge %**
B0	2011-12-01	24	0,3	5,8
	2013-11-01	165	0,3	9,2
	2014-03-01	65	0,3	17,4
	2014-11-01	32	0,3	7,3
B1	2011-12-01	24	0,3	4,6
	2013-02-01	192	0,3	12,4
	2013-11-01	165	0,3	6,8
	2014-03-01	65	0,3	20,1
	2014-11-01	32	0,3	5,8
B6	2011-12-01	24	0,3	4,3
	2013-11-01	165	0,3	8,9
	2014-03-01	65	0,3	18,0
	2014-11-01	32	0,3	7,0
B7	2011-12-01	24	0,3	4,0
	2012-11-01	234,5	0,3	11,8
	2013-03-01	169	0,3	5,3
	2013-11-01	165	0,3	5,6
	2014-11-01	64	0,3	13,3
B8	2013-02-01	214	0,3	11,5
	2013-10-01	42	0,3	16,0
	2014-03-01	65	0,3	6,6

Source: Research results (2017)

Figure 10.7: The rainfall and recharge for the Zevenfontein and Optimus opencasts

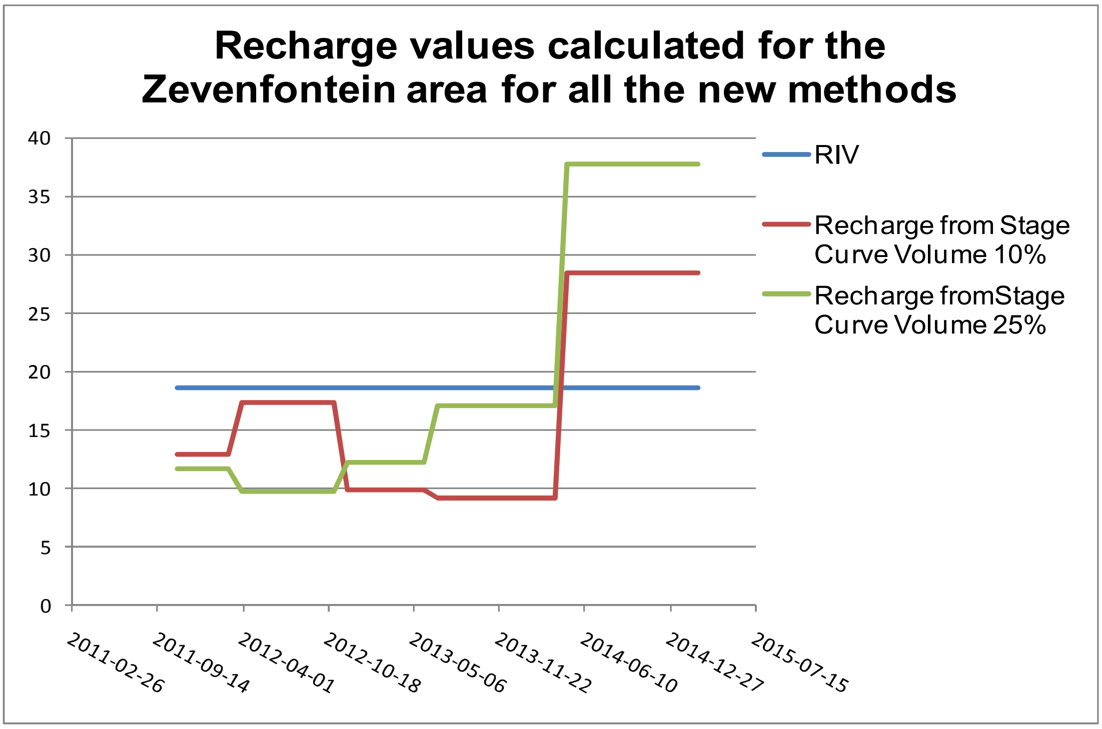
10.7 Final conclusion

10.7.1 Zevenfontein

In conclusion it can be said that the Zevenfontein area is the perfect example of a rehabilitated opencast to do recharge from rainfall calculations on. Most of the methods yielded good results or close to what was initially expected from the spoils of the area:

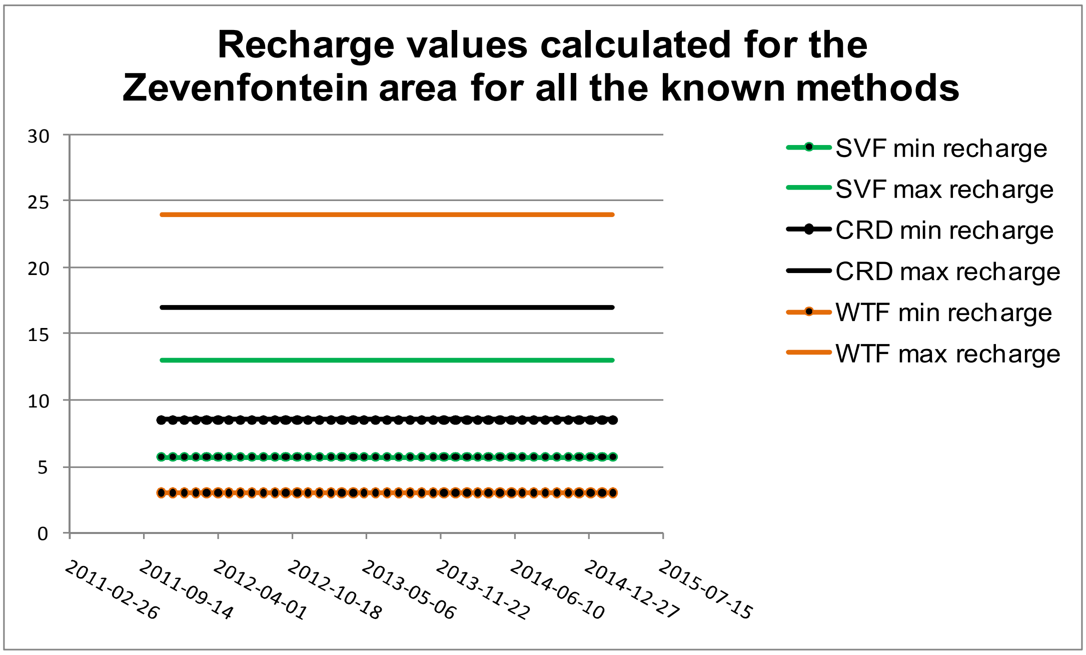
Rainfall Infiltrated Volume method	: 18.6%
Recharge using Stage Curve Volumes 10%	: 15.4%
Recharge using Stage Curve Volumes 25%	: 17.6%
Saturated Volume Fluctuation method minimum	: 5.7%
Saturated Volume Fluctuation method maximum	: 13.0%
Cumulative Rainfall Departure method minimum	: 8.5%
Cumulative Rainfall Departure method maximum	: 17%
Water Table Fluctuation method minimum	: 3%
Water Table Fluctuation method maximum	: 24%

Thus, it can be concluded that the Zevenfontein area is traditionally rehabilitated and that pumping only takes place from the Coastal Dam at 45 000 m^3/pm on average. The boreholes are in the same aquifer and the water levels fluctuate in accordance with the pumping rates. Taking all the parameters received and calculated into consideration, the Zevenfontein recharge from rainfall percentage for the new calculated methods stands at 18–20% (Figure 10.8) and for the known methods at 15–17% (Figure 10.9).



Source: Research results (2017)

Figure 10.8: Recharge from 2011 to 2015 for the RIV and calculating recharge from SCV methods for the Zevenfontein area



Source: Research results (2017)

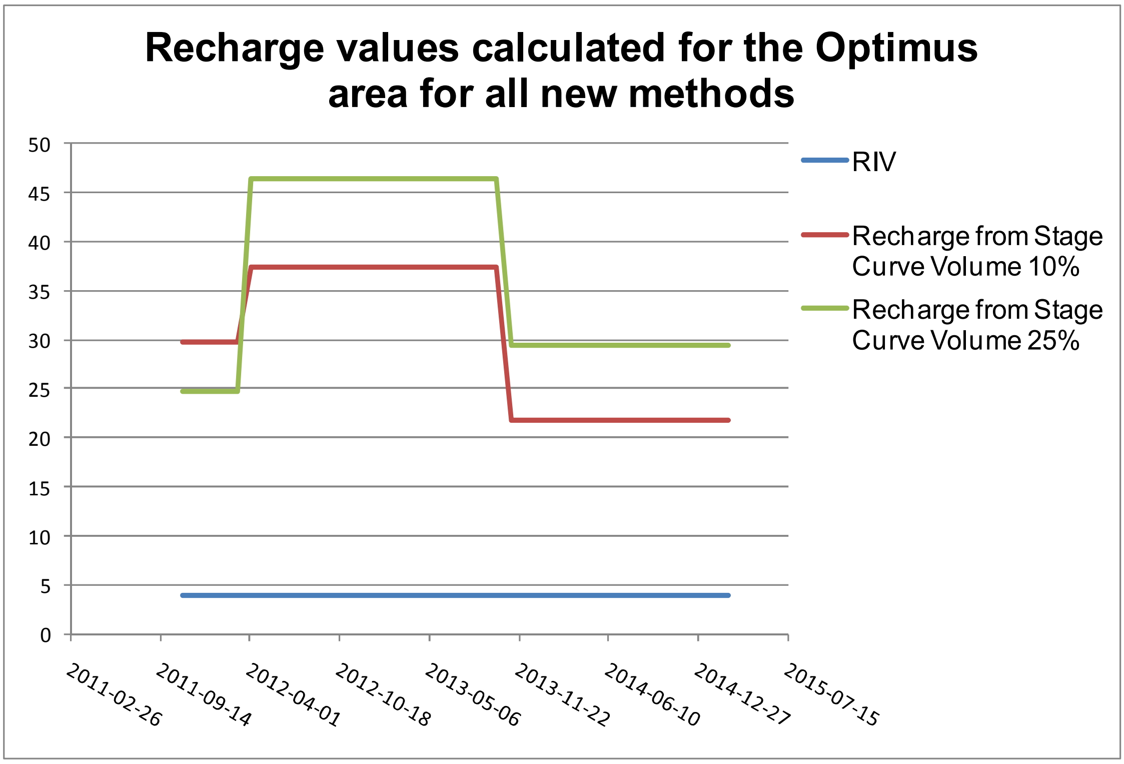
Figure 10.9: Recharge from 2011 to 2015 for Zevenfontein using the SVF, CRD and WTF methods

10.7.2 Optimus

The Optimus mining area had numerous environmental factors which was not ideal for recharge calculations. These included the way in which rehabilitation was done so that water runs towards the opencast instead of away from the spoils, and most importantly, due to the previously mentioned problem, higher pumping rates are needed which does not correspond with only one source of recharge (rainfall). This causes errors in recharge calculations when pumping volumes and rainfall are used. Nevertheless, there were certain methods that did work which are as follows:

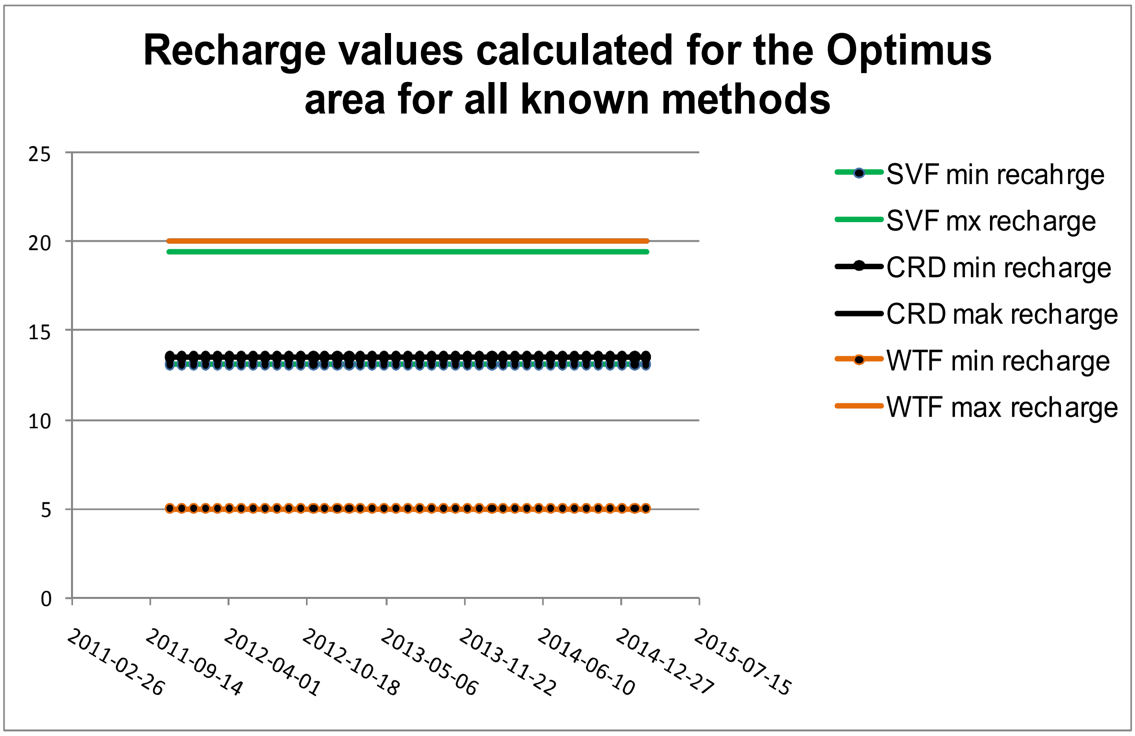
Recharge using Stage Curve Volumes 10%	: 30.0%
Recharge using Stage Curve Volumes 25%	: 34.0%
Saturated Volume Fluctuation method minimum	: 13.1%
Saturated Volume Fluctuation method maximum	: 19.4%
Cumulative Rainfall Departure method minimum	: 13.5%
Cumulative Rainfall Departure method maximum	: 20.0%
Water Table Fluctuation method minimum	: 5.0%
Water Table Fluctuation method maximum	: 20.0%

In conclusion, it can be said that the Optimus area is rehabilitated in an unconventional manner and that pumping only takes place from the Lapa Dam at 460 000 m^3/pm. Due to the size and manner of rehabilitation, no borehole water levels can be compared to either among themselves or, as a matter of fact, that of the pumping rates. Considering everything that was wrong with the Optimus opencast for recharge from rainfall calculations, the following values were calculatedfor the new calculated methods the recharge percentage stands at 25–30% (Figure 10.10) and for the known methods at 15–20% (Figure 10.11).



Source: Research results (2017)

Figure 10.10: Recharge from 2011 to 2015 for the RIV and calculating recharge from the SCV methods for the Optimus area



Source: Research results (2017)

Figure 10.11: Recharge from 2011 to 2015 for Optimus using the SVF, CRD and WTF methods

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