DEVELOPMENT OF A GROUNDWATER MODEL FOR NEW VAAL COLLIERY

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DECLARATION

I, Matshitane Eva Masemola, hereby declare that the present dissertation, submitted to the Institute for Groundwater Studies in the Faculty of Natural and Agricultural Sciences at the University of the Free State, in fulfilment of the degree of Magister Scientiae, is my own work. It has not previously been submitted by me to any other institution of higher education. In addition, I declare that all sources cited have been acknowledged by means of a list of references.

I furthermore cede copyright of the dissertation and its contents in favour of the University of the Free State.

Matshitane Eva Masemola

January 2018

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Only God knows what it took for me to finish this dissertation…

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CHAPTER 1: INTRODUCTION

Whether it is surface or groundwater, water is an integral component of mining that is encountered throughout an operation's life cycle (Gunson *et al.*, 2012). Water is either needed for processing of minerals and/or has to be removed from the mining face before operations can take place. As a result, mining companies need to manage water used and the volumes abstracted to allow operations to continue and manage potential impacts. The best practice guideline A5 for water management at surface mines by the Department of Water Affairs and Forestry (DWAF) (2008) requires that opencast mines build groundwater models for quantifying the potential total water make for the life of mine (LoM) operations. Consider the questions below that could be posed by a mine's management team:

- How can water management options be optimized?
- What abstraction rates are needed for dewatering to maintain dry pit conditions?
- Will the abstraction rates need to be adapted during life of mine?
- Will plume migration impact on quality of groundwater used by surrounding stakeholders?
- What actions must be taken to minimise water ingress into the mine?

It will be a challenge to provide quantifiable answers to the above questions without the knowledge and understanding of the hydrogeological conditions specific to the scenario. Mining companies need to ensure effective water management, especially since it is an essential component of successful mining operations that could determine the feasibility of a project (Idrysy and Connelly, 2012). Simply put, management of water in mining is a necessity. Key challenges such as tailings dam seepage, mine dewatering and risk of mine flooding are parameters that must be investigated to minimise risk to business, project cost and risk of failure (Idrysy and Connelly, 2012). When water management is not one of the critical components to be considered in mine planning, mining operations can experience significant constraints. Constraints may centre around limited pollution control facility capacity, optimization of machine haulage (dragline walks) and geological losses. Idrysy and Connelly (2012) pointed out that problems involving water often occur when added focus on mineral resource planning and mine planning results in lack of attention on water management. Water management optimisation needs a shift from the traditional water infrastructure focussed approach to a management improvement approach (Gao *et al.*, 2014). The mining industry's own sustainability goals call for improvement in the management of water (Gao *et al.*, 2014 after DRET, 2008). To arrive at a point of sustainable water management, the suggestion made by Gunson *et al.* (2012) that a comprehensive understanding of dynamics governing water systems is essential would have to be heeded. This means that companies need to understand and monitor dynamics influencing the efficient management of water.

It can then be argued that for water management decisions to be effective, the dynamics controlling water need to be well understood. Decisions that have to be made, whether it be with regards to quality or quantity of groundwater that is to be managed, require a tool that can provide information about the behaviour of the system as a result of management actions (Bear *et al.*, 1992). Barnett *et al.* (2012) argued that policy decision and groundwater management must be founded on previous and current behaviour of the groundwater system, the potential response to changes and the knowledge of uncertainty related to those responses. Groundwater systems are complex in nature and a single management decision could trigger multiple responses in the system or result in no noticeable impact. The system response, dependent on the management objectives and project constraints, could be spatially distributed, localised or a water level change (Bear *et al.*, 1992). The question remains, how can the impacts of these responses be understood and managed to the advantage of a mining operation? Bear *et al.* (1992) suggested that a model is needed in order to understand groundwater system response. More specifically, a groundwater conceptual model is needed. A groundwater model can be defined as a simplified representation of a groundwater system. Often, natural systems cannot be directly analysed due to their complexity and as a result, models are used to describe and analyse these systems (Gorrelick, 1997). Gorrelick (1997) rightly noted that conceptualisation is the first step in modelling where the major components of the system are summarised. An appropriately designed groundwater model provides conceptual understanding and insight into an otherwise complex system (Barnett *et al.*, 2012). Barnett *et al.* (2012) further noted that once a model illustrates, within reasonable accuracy, the ability to reproduce past system behaviour, it can be used for predictive modelling of groundwater responses, support decision making process and consideration of multiple management tactics. The basis of following a modelling approach is that once the basic laws of physics and description of a specific system are understood, then an accurate quantitative understanding of the cause and effect follows (Reilly, 2001). Certainly, then the capabilities associated with groundwater models are invaluable for effective and efficient water management decision making. According to Bear *et al.* (1992), knowing the potential behaviour of a system as a result of envisioned actions before implementation is essential for effective decision making progress.

A number of studies have been conducted where groundwater modelling was used as a tool for identifying and quantifying responses triggered by interactions with groundwater systems. Nyende *et al.* (2013) developed a conceptual and numerical model with the objective of the model being used as a tool for understanding the regional subsurface flow in the Ugandan catchments. Martinez *et al.* (2010) highlighted different predictive modelling scenarios that can be simulated using groundwater models. While Shephard *et al.* (2007) used the modelling approach to characterise groundwater quality. As Martinez *et al.* (2010) pointed out, groundwater models are now common tools used for predictive modelling scenarios, particularly in the mining industry. However, their use as a tool is dependent on the assumption that the model is representative of the area under investigation. Documents such as the “Australian groundwater modelling guidelines” by Barnett *et al.* (2012) and

“Guidelines for Groundwater modelling to assess impacts of proposed natural resource development activities” by Wels *et al.* (2012) offer direction on how best to approach the modelling process. Both guidelines highlight the different components of a model and the need to form site specific objectives as well as the use of data to develop an initial conceptual model of an appropriate complexity. However, in as much as there are guidelines for modelling, it is also understood that there are inherent limitations and uncertainties associated with groundwater models. Uncertainties come from the inability to measure, understand and represent all the features of the system (Gorrelick, 1997). Limitations on the other hand, are centred around the lack of data or resources to allow for filling of data gaps. According to Martinez *et al.* (2010), the lack of data is the most frequent restriction to the modelling process that could lead to the model not being build. At the same time, it must be understood that there is a limit on the value of information that can be abstracted from the available data as illustrated by Vivier and Van Der Walt (2011). However, if the uncertainties and limitation are well defined and understood, a model can be used as a management decision making tool.

1.1 BACKGROUND AND VALIDATION

New Vaal Colliery is an opencast mine in the northern Free State surrounded by the Vaal river and underlain by the Transvaal Supergroup dolomitic aquifer. One of the biggest risks and limiting factors for production, the surrounding environment and safety of the employees is the excess high sulphate water on-site. The mine was previously mined by the underground method of bord and pillar. These underground workings were filled with water at the time opencast operations begun. As a result, dewatering of the workings has to take place first before mining can continue.

Water pumped from the pit is stored in three transfer water dams, three evaporation dams and one main pollution control dam called Maccauvlei dam. Most of these dams, including Maccauvlei dam, are not lined. Figure 1.1 shows an illustration of water reticulation on site. Extreme rainfall events over the 2009-2010 rainfall seasons amplified the risks associated with water and the need for pit dewatering. During the same period, the available capacity in the Maccauvlei dam was declining fast.

The mine explored different options to reduce the volume of water that needed to be stored on site. Some of the options explored included providing the water to other water users, optimising mine water use in the coal washing plant and optimisation of dust suppression. However, the quality of the water was and is a limitation with regards to providing it to other users and using in the destoning plant. Mine water was already being used for dust suppression and volumes removed from the system by dust suppression were not significant enough to reduce the risk.

The Department of Water Affair (DWA), now (2017) known as Department of Water and Sanitation (DWS), was approached with a request for a controlled release permit to discharge the water into the Vaal river. The response from the DWS indicated that only water treated to a specified quality would be authorised to be discharged into the Vaal river.

A water management options study conducted in the year 2009 indicated that water treatment would be the most feasible mitigation option of the increasing water levels in Maccauvlei dam. As a result, two mobile reverse osmosis (RO) water treatment plants were commissioned in 2010 as a fast track solution to comply with the DWA legal requirements and mitigate the risks associated with the excess water on site. Brine produced from the RO water treatment process was discharged back into Maccauvlei dam. The DWA, in a form of a directive, authorised the discharge of treated water into the Vaal river and the discharge of brine into Maccauvlei dam with the condition that alternative solutions/management options for disposal of the brine must be investigated by 31st of March 2011. Subsequently, an exemption on the condition to discontinue the discharge of brine into Maccauvlei dam was requested by the mine on the basis that there was no significant impact on the environment external to the mine. DWA challenged the basis of the request stating that the mine had no indisputable study showing that water in the unlined Maccauvlei dam would not impact on receptors, in particular the dolomitic aquifer underlying the mine. The mine was then requested to provide information that would support the “no impact” stance on the dolomitic aquifer. During the process, New Vaal Colliery was issued a water use license (WUL) which had conditions requiring the mine to line all the dams on site. The DWA’s concerns around the brine being discharge back into Maccauvlei dam brought added focus on the fact that the dam is not lined and therefore not compliant to the WUL conditions. The practicality of the conditions was limited by the fact that dewatering of the pit forms an integral part of operation and all the dams were in use and filled with water. Moreover, the mine did not have alternative storage facilities to use should the conditions be enforced.

A re-evaluation of the water management strategy was necessary to ensure the risks associated with the water management on site were addressed. The main objective for the new strategy was and is to reduce the volume of water that is pumped to the Maccauvlei dam and consequently brine produced from treating the water. To achieve the set objective, the mine needed to understand the dynamics controlling and contributing to the groundwater balance onsite. This included understanding and quantifying:

- The interaction between the mine, Vaal river, shallow aquifer and the dolomitic aquifer.
- The interaction between New Vaal Colliery and the adjacent closed underground mine, Cornelia Colliery.
- All sources (inputs) and sinks (outputs) contributing to the groundwater balance

In order to understand the abovementioned, it was decided that a high confidence conceptual site model was to be developed to build a numerical groundwater flow model. The model would then be used as management tools on the mine to ensure proactive water management. Given that the site has been collecting groundwater data since the mine's initiation, it was assumed that there is sufficient data to support a high confidence groundwater model.

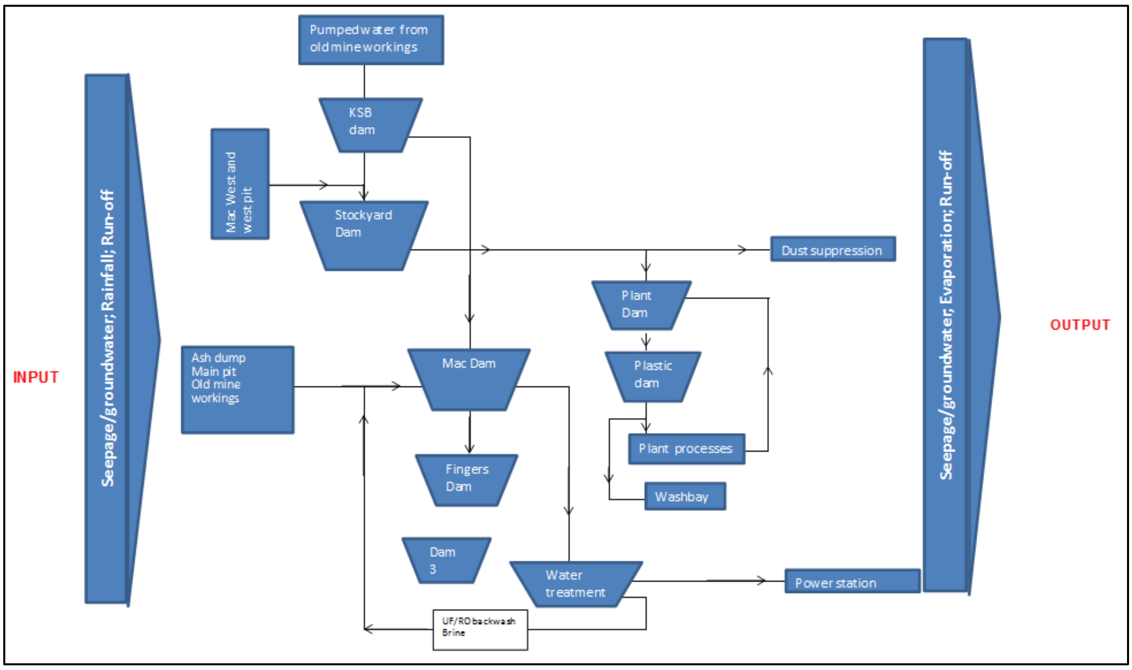

Figure 1.1: Water reticulation at New Vaal Colliery

1.2 AIMS AND OBJECTIVES

This study aims to develop a conceptual groundwater model, given the available data, as a high confidence water management tool. In order to achieve the aim of the study, the following objectives will be met:

- Develop a conceptual site model for New Vaal Colliery.
- Assess the confidence with which the controlling mechanisms and paths for groundwater flow into the mine can be quantified.
- Rate the current water monitoring data on whether it provides sufficient information to support high confidence model.

Available data and information from hydrogeological studies conducted for the New Vaal Colliery as well as newly aquired data will be used to develop and describe the conceptual groundwater model For the purposes of this study, the modelling process will only be described upto the conceptualisation point.

CHAPTER 2: LITERATURE REVIEW

A conceptual groundwater model can be defined as a simplified presentation of the main components controlling hydraulic and hydrogeological behaviour of a system. A more scientific description of a conceptual model, according to Wels *et al.* (2012), is that it is a hypothesis developed based on the available data, knowledge and professional judgement of the modeller. Leon and Ferre (2003) defined a groundwater conceptual model as a foundational framework from which subsurface hydrology data can be analysed.

Development of a conceptual model forms a critical step within the modelling process before the construction of a numerical model (Wels *et al.*, 2012; Leon and Ferre, 2003). The process is iterative in nature where the modeller's understanding of the system can be showcased and critical factors as well as processes influencing groundwater flow can be presented (Wels *et al.*, 2012). Wels *et al.* (2012) advised that a principle of simplicity be used as an approach to the modelling process. The complexity of real-world systems dictates the need for simplification of said systems since a complete reconstruction of field conditions is impractical and planning and making management decisions needs simplicity (Bear *et al.,* 1992; Wels *et al.*, 2012). The model is simplified by introducing assumptions. The assumptions describe the nature of the system and features such as geometry of the domain, heterogeneities, fluid properties and type of flow regime under investigation that are applicable to the study (Bear *et al.,* 1992).

Besides the impracticability of completely reconstructing the field conditions, Wels *et al.* (2012) pointed out that there is rarely enough data to provide a complete description of a groundwater system. This means that the conceptual model should remain as simple as possible while maintaining sufficient complexity to a) represent the physical features of the system, b) simulate the system behaviour should it be converted into a numerical model and c) contribute to answering the question under investigation (Wels *et al.*, 2012). A balance between model complexity and simplification is needed. There is always potential that a model could be imperfect or even wrong. This could be as a result of using incomplete information to define the problem, incorrect assumptions made, key processes controlling conditions that are to be simulated not being taken into consideration and poor understanding of physical and chemical processes (Wels *et al.*, 2012). Regardless of the limitation of modelling, conceptual models are viewed as a tool for identifying data and knowledge gaps ahead of the development of a qualitative model such as a numerical model (Leon and Ferre, 2003). From a conceptual model, generalised conclusions on the immediate impacts of the hydrogeological system can be made (Leon and Ferre, 2003). The model can be taken as a management tool provided the it has sufficient data to answer the modelling questions and meet stated objectives (Wels *et al.*, 2012).

2.1 MODELING PROCESS

Groundwater modelling consists of a number of stages and process activities that lead to the objectives being determined, model conceptualisation, numerical model development and final predictions as well as analysis (Figure 2.1). Barnett *et al.* (2012) stated that the process starts with planning. The point of the planning phase being to gain clarity of the proposed use of the model and type of model necessary to achieve project objectives (Barnett *et al.*, 2012).

There is an implied end to the modelling process however, this should not be the case. Wels *et al.* (2012) suggested that modelling should be viewed as a representation of a time within the process of improving a system conceptualisation that is to be reviewed and refined on a continual basis. As data collection takes place throughout the process, changes may need to be made to the model. Therefore, a model is never to be viewed as final. This view is shared by Wels *et al.* (2012), Bear *et al.* (1992) and Barnett *et al.* (2012). Bear *et al.* (1992) mentioned that the activity of choosing an appropriate conceptual model for an identified problem is not necessarily conclusive. Opportunity to revisit assumptions made presents itself with ongoing investigations and changes to the model domain. According to Wels *et al.* (2012) and Barnett *et al.* (2012), even at the stage of numerical modelling, uncertainty and sensitivity analysis in predictive modelling could highlight areas and data types needed to reduce conceptual model uncertainties which lead to can significant changes in the conceptualisation of the model. According to Wels *et al.* (2012) and Barnett *et al.* (2012), numerical modelling can be used for uncertainty and sensitivity analysis in predictive modelling. At this stage, the model could be used to highlight areas and data types needed to reduce conceptual uncertainties which lead to significant changes in the conceptualisation of the model.

2.1.1 Modelling objectives

According to Wels *et al.* (2012), defining the model objectives is the first important step in the modelling process. The set objectives must be defined in such a manner that the overall project objectives can be met within the allocated budget and time constrains while taking into consideration data availability (Wels *et al.*, 2012). Barnett *et al.* (2012) further added that the objectives should specify how the model will contribute to completion of the overall project.

According to Wels *et al.* (2012), modelling objectives such as “determine groundwater flow” should generally be avoided. Modelling objectives must be as specific as possible. An example of a specific modelling objective given by Wels *et al.* (2012) is determining the volumetric flow seepage from tailings dam during active operation. Bear *et al.* (1992) suggested that a model objective can be assessing if a model is fit for purpose and gives answers to the proposed questions it was developed to address. Wels *et al.* (2012) further stated that, if the model objective is an assessment of environmental impact then, source, pathway and receptor relationship have to be quantified. By setting specific modelling objectives, the modeller can determine the required modelling approach and model complexity (Wels *et al.*, 2012). The objectives determine which features must be presented and to what level of accuracy (Bear *et al.*, 1992)

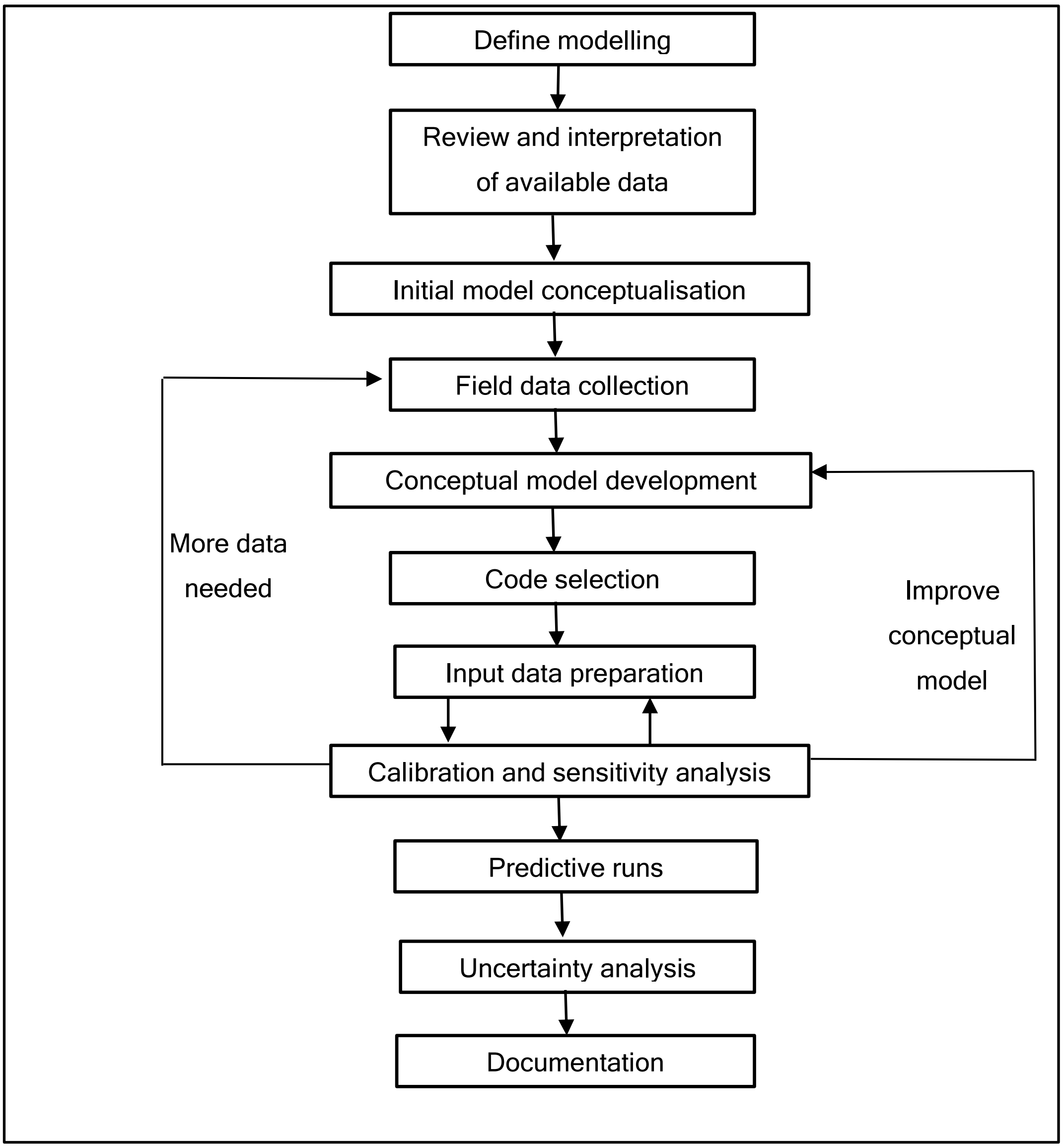

Figure 2.1: An illustration of the iterative nature of groundwater modelling (Bear *et al.*, 1992)

2.1.2 Review and interpretation of available data

Conceptual modelling starts with the compilation and review of available data. Taking the objectives into consideration, the available data will form the basis of the first model conceptualisation from which major gaps that are identified. According to Wels *et al.* (2012), there are two steps involved in the initial data review which include 1) compilation data and 2) analysis of data to improve fundamental understanding of the system dynamics. The initial review includes information on the regional geology, hydrogeology and results of relevant studies done for the area under investigation.

According to Wels *et al.* (2012), initial assumptions about the system can be made from analysing the first dataset. Below are elements that may be of relevance to the system that should be included in the analysis:

- Spatial and temporal distribution of groundwater levels, flow directions
- Spatial distribution of hydraulic properties
- Groundwater recharge rates
- Recharge and discharge zones
- Stream base-flow
- Transport parameters where appropriate

The data review process will provide a database from which a preliminary conceptual model and identification of significant data gaps can be developed. It should however be noted that, the baseline data might not meet the requirements of the model objectives. Nonetheless, data review is needed to identify gaps. Based on the review of existing information and data, it may be necessary to review the model objectives or adjust model objectives to reflect data limitations. Bear *et al.* (1992) stressed the point that available field data for estimating parameters and calibration determine the type of conceptual model to be developed and extent of accuracy needed.

Surinaidu *et al.* (2014) recognised three phases for evaluating groundwater inflow impact on a mine that focus mainly on data acquisition. The identified phases include first, collection of information related to hydrology and hydrogeology which include aquifer parameters and geological structures. The second phase includes the evaluation of potential impacts of mining on groundwater flow through collection of monitoring data such as groundwater levels and seepage information into the pits. Surinaidu *et al.* (2014) noted that together, mapping of geological structures and inflow estimation gives invaluable information when determining groundwater occurrence and controlling the associated volumes. Lastly, the third phase, which will not be covered in this study, involves the estimation of inflows through analysis of dewatering data and numerical modelling.

2.1.3 Model conceptualisation

Model conceptualisation is a critical step in groundwater modelling (Leon and Ferre, 2003). Bear *et al.* (1992), who shares this view also stated that if the conceptual model is wrong in terms of representing the relevant flow and transport mechanism, then follow up modelling efforts are time and money wasted. The aim is to provide a simplified characterisation of the flow and transport mechanisms in a manner that can be translated into a numerical model. Model conceptualisation is a simplification of a system's important hydrogeological features and hydraulic behaviour to an acceptable standard. Figure 2.2 shows two examples of conceptual models. According to Barnett *et al.* (2012), the process forms the foundation for the model design and illustrates how the systems works to varied audiences. Wels *et al*. (2012) identified two phases where conceptualising is critical. The first important conceptualisation phase involves the initial conceptual model developed based on desktop study and the second important phase is the development of a detailed model after field data collection. According to Barnett *et al*. (2012), the conceptualisation of the region of interest is done using the available data and knowledge of that area. Bear *et al*. (1992) further stated that assumption made are used to describe the system's characteristics, transport processes and mechanism controlling them and the associated medium properties. The initial model is commonly more general and used to identify data gaps and design data collection process. As data gaps are filled, the second model that contains more detail and is quantified can be developed (Wels *et al*., 2012). This is not to say that once the first two phases are completed, conceptualisation of the model is completed or ceases to be important. Conceptualisation of a system is an ongoing process within the modelling process. The need to update the conceptual model with time must be recognized. Especially after issues encountered with calibration of the model as this could trigger need to review concept model and need for further data collection. Or after more data has been collected. Furthermore, the scope and model complexity must be indicative of the model objectives (Wels *et al*., 2012). Sufficient detail should be provided to achieve model objectives. Model objectives need to remain within the limits of the conceptual model or model details.

The conceptual model forms the basis on which a mathematical model design is built. While a mathematical model provides a solution for a flow system of a given conceptual model. Components included in the mathematical model should be the same as those identified in the conceptual model. That is, a mathematical model cannot be an improvement of the conceptual model used to develop it.

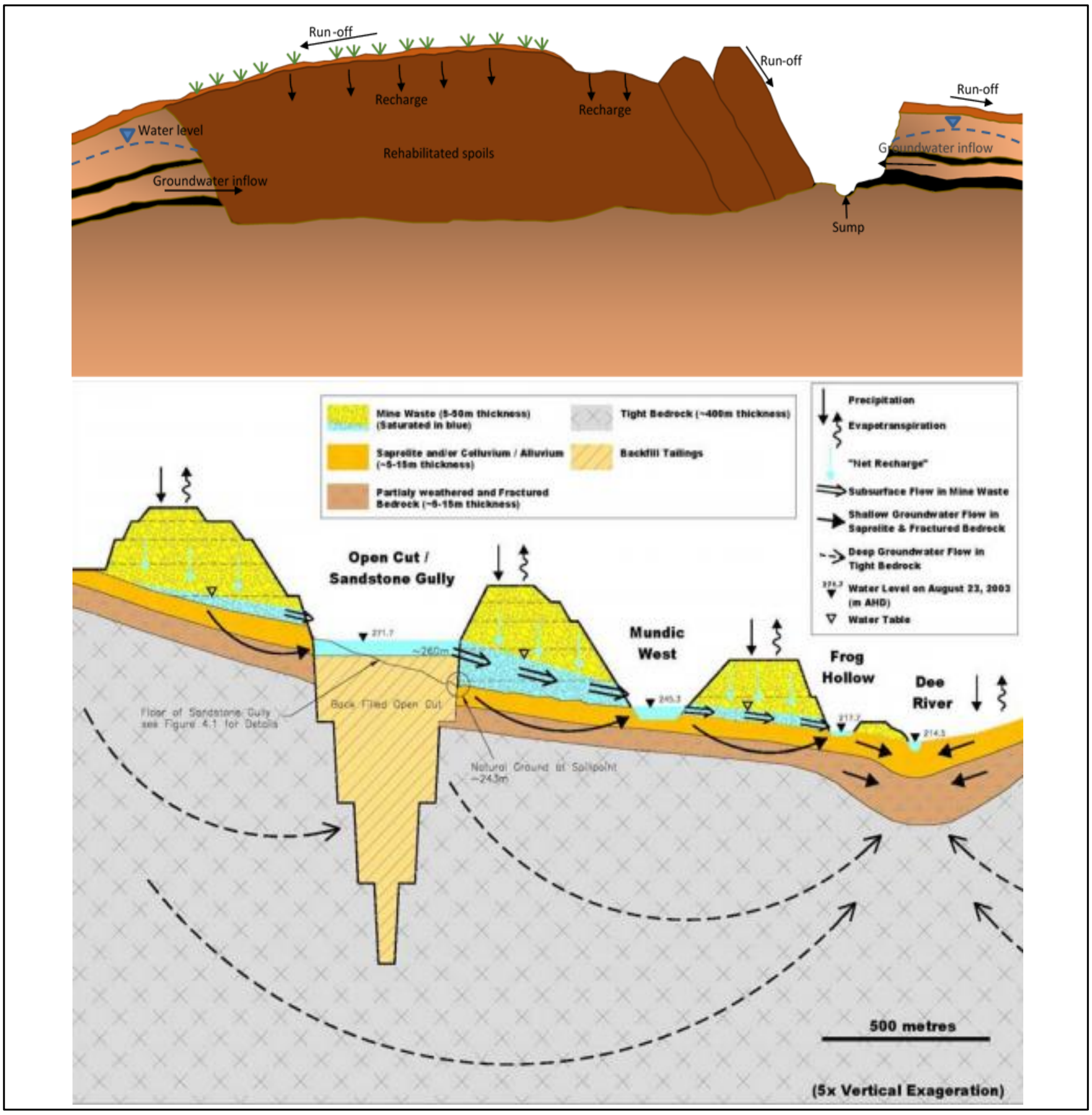

Figure 2.2 Examples of illustrated conceptual groundwater model.

2.1.4 Model complexity

A model's complexity will vary depending on the model objectives, potential impacts, hydrogeological framework and data availability (Wels *et al.*, 2012). The model objectives will by far dictate the required model complexity with a further influence from available data, time, budget and regulatory requirements. Bear *et al.* (1992) suggested that selecting the relevant conceptual model and the extend of simplification depends on, the objectives, the available data and resources as well as the legal and regulatory framework that is applicable. This is in line with the views shared by Wels *et al.* (2012). Complexity, according to Wels *et al.* (2012) after MDBC (2001), can be defined as the degree to which the "model application resembles or is designed to resemble the hydrogeological systems". Characterisation of complexity is completed during the model conceptualisation stage (Barnett *et al.*, 2012). The model complexity can apply to the conceptual and mathematical model and further linked to the model extend. According to Hill (2006), the number of parameters such as boundary conditions and hydraulic conductivity used to describe the model represent the model complexity. It is from this perspective that Hills (2006) reviewed the benefits of the use of detailed data in models. Hill (2006) applied the number of parameters used to define a model as measure of model complexity where fewer parameters show a simple model.

The level of a model complexity is flexible for any given objective but this is accompanied by impacts on the level of confidence for the required model output. Hills (2006) stated that the principle of parsimony (that is, simplicity) should be used when developing groundwater models. In their study, Hills (2006) pointed out that the principle of parsimony required that the model be kept as simple as possible while taking cognisance of processes and characteristics made from observations and predictions that are to be made. There is danger of oversimplification which may result in not being able to accurately simulate the observed system behaviour (Wels *et al.*, 2012). Hill (2006) as well as Zhou and Li (2011) cautioned that neither simplicity or complexity equate to accuracy. Conceptual model oversimplification as Bear *et al.* (1992) also pointed out, can produce a model that lacks the required information. Conversely, too much complexity can result in non-transparency (Wels *et al.*, 2012) or insufficient data for model calibration and parameter estimation (Bear *et al.*, 1992) should the conceptual model be translated into a numerical model. To safeguard against either scenario, it is suggested by Wels *et al.* (2012) that the model should be tested by converting it to a numerical model that can be calibrated. At the same time, it should be noted that conceptual models often do not explain all field observations. The required standard of complexity should be decided in combination with the envisioned final use of the model results. Data used for modelling needs to be consistent with the assumptions made and complexity of the model. Wels *et al.* (2012) highlighted that a complex model founded on limited data is no better than an appropriately formulated basic model that is difficult to justify.

Taking the above mentioned into consideration, it was noted by Hill (2006) that the modeller can better understand the system dynamics by starting with a simple conceptual model. Complexity can then be added to the model as justified by supporting data (Hill, 2006). Hill (2006) argued that this approach allows for model refutability and transparency. Refutability defined as ability to test assumptions made and transparency as the extend that the model dynamics can be understood.

2.1.5 Exclusions and assumptions

A model is a simplified representation of a real-world system and as such, there is not one unique model for a given groundwater system (Bear *et al.*, 1992). The varied simplifying assumptions produce different models (Bear *et al.*, 1992) and reduce level of complexity. The need to make assumptions cannot be avoided. Bear *et al.* (1992) suggested that the following assumptions are often included in model conceptualisation:

- Defined boundary geometry for the aquifer domain.
- Boundary conditions, which define how the aquifer domain interacts with the surrounding environment.
- Extend of homogeneity and isotropy of the structures and fractures.
- Dimension within which flow occurs in the aquifer.
- The existence of sharp fluid boundaries such as the phreatic surface.

Beyond the commonly included assumptions are fundamental assumptions that, according to Bear *et al.* (1992), are always made when modelling groundwater flow and contaminant transport. The assumption that the porous medium is continuous in its extent and replaces the real, complex system characterised by solids and void filled with fluid (Bear *et al.*, 1992). Lack of detailed data on the void space configuration in groundwater systems is the reason water flow and contaminant transport problems cannot be solved. Consequently, the porous medium is represented as a being continuous. Another fundamental simplifying assumption made is that groundwater flow at a regional scale is essentially horizontal (Beat *et al.*, 1992; Barnett et al., 2012). This assumption is supported by the commonly observed ratio between aquifer thickness and horizontal length which indicates a horizontal flow of water (Bear *et al.*, 1992). In further support of this assumption, Barnett *et al.* (2012) also stated that the horizontal head gradients are commonly much higher than vertical gradients. According to Bear *et al.* (1992), the assumption of horizontal flow can also be applied to in leaky aquifers. Barnett *et al.* (2012) stated that exclusions can be applicable for areas with insufficient reliable data and to limit model application for generating or predicting system responses. Due to the impact that exclusion can have model application, Barnett *et al.* (2012) stressed the need for the modeller to explicitly state exclusions to ensure that the inappropriate use of the conceptual model can be avoided.

2.2 COMPONENTS OF A GROUNDWATER FLOW MODEL

A groundwater flow model consists of a number of components, which together, are representative of the real system. The elements that contribute water to the region, outflow of water from the region, physical boundaries of the region and the spread of hydraulic properties all form the basic components of a conceptual model (Leon and Ferre, 2003).

2.2.1 Hydrostratigraphic units and hydraulic properties

Geological units characterised by similar hydraulic properties form the basis for identifying different major hydrogeological units. Barnett *et al.* (2012) support this notion that the subsurface can be divided into different hydrostratigraphic units according to similar properties they share such as storage and groundwater transmission. Given sufficient justification, geological units can be grouped into different hydrogeological units. A description of the properties requires supporting information as to how each parameter was determined for each hydrogeological unit (Wels *et al.*, 2012). Although it is acceptable to use literature based data, it is preferable that they are based on site specific testing. In describing the conceptual model, the source data and degree of uncertainty of the available field data must be considered (Wels et al., 2012). Wels *et al.* (2012) identified water storage and transmission parameters below as important aspects when describing hydrogeological units:

- Porosity: describes the volumes of pores space as percentage of the total aquifer volume. It is a measure of the maximum amount of water that can be stored in an aquifer.
- Specific yield: Only applicable in unconfined units, specific yield describes the volume of water released when a unit of water table drops per unit surface area of the aquifer. Specific yield does not exceed porosity as some water remains within the aquifer matrix against gravitational force.
- Storativity: describes the volume of water released per unit drop in hydraulic head per surface area of the aquifer as a result of the compressibility of water and aquifer matrix deformation.

When grouping geological strata into different hydrogeological units, a certain amount of homogeneity and anisotropy within the unit is assumed. However, it is well understood that the assumed homogeneity is not an accurate representation of the system. Nature is known to have very strong variation of hydraulic properties that can have directional preference (Barnette *et al.,* 2012). The extend of heterogeneity and anisotropy may have little to significant influence of on the system flow dynamics. For these reasons, heterogeneity and anisotropy have to be considered in model conceptualisation. Wels *et al.* (2012), defined heterogeneity as the variation of main parameters such as hydraulic conductivity within a hydrogeological unit. An area characterised by a big range of hydraulic properties with no apparent spatial pattern is classified as heterogeneous. Anisotropy is defined as the preferred spatial orientation of hydraulic properties that result in a preferred flow path. Together, anisotropy and heterogeneity can have a significant effect on flow paths and interaction between sources, sinks and boundary conditions subject to scale of investigation. This view was validated by Leone and Ferre (2003) who stated that heterogeneities have great impact on contaminant movement and water flow. The impact that heterogeneities and anisotropy have are even more significant at small scales (Wels *et al.*, 2012). During model conceptualisation, both heterogeneity and anisotropy should be accounted for, accompanied by supporting geological data. Ardito *et al.* (2004), argued that when heterogeneity is included into a model properly, there is a potential for increasing the model accuracy. According to

Ardito *et al.* (2004), Zimmerman *et al.* (1998) discovered that models which incorporated geology with heterogeneous properties were better able to reproduce the studied system than those without this incorporation.

Areas characterised by natural porous material and fracture rock aquifers can be expected to have significant anisotropy and heterogeneity with respect to aquifer properties (Wels *et al.*, 2012). In fractured rock aquifer, variations in hydraulic properties may be a consequence of different fracture connections while in porous aquifers, hydraulic properties are influenced by variation in size of particles (Wels *et al.*, 2012). Surinaidu *et al.* (2014) after Surinaidu *et al.* (2013) stated that heterogeneity and anisotropy in both fractured and weathered aquifer system can be reduced at a large scale using an equivalent porous medium approach.

2.2.2 Model domain

A modelling domain should be defined taking into consideration the area of interest, area of influence, available data and scale of the project. Wels *et al.* (2012) support this approach for defining the model domain. According to Wels *et al.* (2012), the scale of the project, that is, whether it is regional, local or intermediate, and expected spatial impact can be used to define the model domain. There are common factors used to define model domains such as a) the known spatial extent of the aquifer of interest b) watershed model within which the site is situated and c) site specific components of the local model.

2.2.3 Model boundaries

Since groundwater system are continuous, deciding on the domain will need judgement on what should represent the boundaries of the system (Reilly, 2001). Model boundary conditions form a key component of conceptualising a groundwater flow system (Reilly and Pollock, 1993); Surinaidu *et al.*,2014). The model boundaries should be selected based on justifiable data. Similar to defining the model domain, Wels *et al.* (2012) stated that watersheds, watercourses such as streams, large water bodies and geological features such as bedrock contact or faults as well as no flow boundaries perpendicular to streamlines are used as model boundaries. A decision on the type and location of model boundaries should be supported by monitoring data. However, there may be instances where data is not available to motivate for selecting specified boundary conditions. In these cases where data is not available, Wels *et al.* (2012) advise that the rational used selecting boundary conditions and implications thereof should be stated. Modelling objectives should be used to guide the spatial extend of the conceptualisation of a system. According to Reilly (2001), study objectives will influence the depth of concern and how the boundary conditions of the model domain are represented. Boundary condition essentially represent the source and sinks of water within the groundwater system (Reilly, 2001).

There are three different types of boundary conditions that can be assigned:

- Dirichlet (first type) boundary – the hydraulic head is specified.
- Neumann (second type) boundary – flux/flow is specified.
- Cauchy (third type) boundary – head dependent boundary, also referred to as a leaky boundary.

The different types of boundaries can be represented by physical feature or artificial boundaries. Physical boundary typically include recharge as a specified flow at the top of the model while lateral extend boundaries can be represented as streams, lake features (Reilly, 2001) or even geological structures such as faults and dykes. Although Reilly (2001) does not discuss geological features as boundary conditions, he does discuss how streams can be used to represent boundaries in a model. Streams can be included in the model as constant head boundary with the implication that there is no head loss between groundwater system and surface water body (Reilly, 2001). This approach is commonly appropriate for large streams or stream that are well connected to the groundwater system and the stage will change. Alternatively, streams can be assigned as a flux boundary if the loss or gain is known or represented as a leaky boundary with constant specified stage and restrictive layer of material between the stream and groundwater (Reilly, 2001). The assumption is that the river and groundwater are in constant connection and water flow to or from the river is directly proportional to the gradient between the river stage and water level in the groundwater system. This suggests that the Vaal river could be assigned either of the boundary conditions provided all requirements are met. However, there are no data or literature available on flux (loss or gain) along the Vaal river bed therefore only a first and third type boundary can be assigned to the Vaal river. The same applies to the surface water bodies at New Vaal Colliery. Despite the number of groundwater studies conducted, quantifying surface water leakage factor has not been a focus.

Artificial boundaries can assist with limiting the size of the model for an extensive, continuous, permeable groundwater system (Reilly, 2001). Reilly (2001) mentioned that the key to selecting an artificial boundary is ensuring that the impact on the analysis on the system is minimised. However, according to Reilly (2001), by definition they cannot accurately represent the response of the actual groundwater system. To get around this limitation, artificial boundaries should be tested at the numerical modelling stage to ensure a system response aligned with the conceptual model.

2.2.4 Groundwater – surface water interaction

The interaction of groundwater and surface water is a common natural occurrence controlled by geology and hydraulic gradients between the water table and surface water elevation. Barnett *et al.* (2012) stated that water movement between surface and aquifers function in a similar way as it does in groundwater bodies, from sites of high head to those of low head. Where the water level in a stream is higher than groundwater elevation, the stream can be considered to be a losing stream. A water table higher than a stream elevation is indicative of a gaining stream. Where the water table is below the streambed, the stream is commonly classified as detached. Interaction between streams and groundwater can be highly influenced by seasonal run-off and storm events. Other influencers on groundwater and surface water interaction, according to Wels *et al.* (2012), are the stream morphology, hydraulic gradients, water quality and stream flow. The type of interaction in any setting can vary along a stream from gaining to losing depending on aforementioned influencers (Barnett *et al.*, 2012). Wels *et al.* (2012) stated that this interaction is considered to be critical for environmental impact assessments on groundwater in resource projects.

2.2.5 Groundwater recharge

Healy (2010) defined recharge as the infiltrating water that reaches the water table, expressed as volume per time unit (recharge rate). Two methods of recharge mentioned by Healy (2010) include focused and diffuse recharge.

- Diffuse recharge, also known as local or direct recharge, is defined as precipitation over a large area that reaches the water table via infiltration (Healy, 2010).
- Focused recharge, also known as indirect recharge or leakage, on the other hand is defined by flow from canals, streams or lakes.

Recharge is an important parameter in groundwater modelling. It is also one of the most difficult variables to account for in the modelling process. According to Healy (2010) and Wels *et al.* (2012), because it cannot be measured directly, recharge is one of the biggest uncertainties in modelling. Factors such as slope, vegetation, rainfall and ground conditions impact on the rate of recharge over an area. In the case of a mining environment, type of mining, rate of extraction and methods of extraction also impact on recharge rates (Vermeulen and Usher, 2006). Vermeulen and Usher (2006) suggested different recharge rates for the Witbank Coalfields mines (Table 2.1). Hodgson and Krantz (1998) suggested recharge values specific to an opencast mine. Since the values provided are given as a percentage of rainfall for the stage of mining, that is open pit or spoils or rehabilitated land, they can be applied to different catchments. However, the wide range provided means the selected recharge rate becomes subjective.

Table 2.1: Recharge as a percentage of rainfall for different Underground mining methods (Vermeulen and Usher, 2006).

Sources which contribute water	Water sources into mine
Shallow bord and pillar	5 – 10% of rainfall
Deep bord and pillar with no subsidence	3 – 4 of rainfall
Stooping	5 -12% of rainfall, or as high as 20% in some abnormal cases
Longwall	6 – 15% of rainfall

Table 2.2: Recharge rates estimation for the South African opencast mines (Hodgson and Krantz 1998).

Sources which contribute water	Water sources into opencast pits	Suggested average value
Rain onto ramps and voids	20 - 100% of rainfall	70% of rainfall
Rain onto unrehabilitated spoils (run-off and seepage)	30 - 80% of rainfall	60% of rainfall
Rain onto levelled spoils (run-off))	3 - 7% of rainfall	5% of rainfall
Rain onto levelled spoils (seepage)	15 - 30% of rainfall	20% of rainfall
Rain onto rehabilitated spoils (run-off))	5 - 15% of rainfall	10% of rainfall
Rain onto rehabilitated spoils (seepage)	5 - 10% of rainfall	8% of rainfall
Surface run-off from pit surroundings into pits	5 - 15% of total pit water	6% of total pit water
Groundwater seepage	2 - 15% of total pit water	10% of total pit water

Changes in rainfall due to seasonal variations can be expected to impact on groundwater recharge rates (Wels *et al.*, 2012). For this reason, the seasonal behaviour of rainfall must be considered in the modelling process Wels *et al.* (2012).

2.2.6 Groundwater discharge

Unlike recharge, discharge can be quantified directly by flow or seepage meter as well as calculated indirectly based on hydraulic head gradients (provided the K-value is site specific). Discharge is expressed as volumetric flow out of the model domain. Modes of discharge and their seasonal variation should be identified and further linked to the influence they have on the groundwater system dynamics (Wels *et al.*, 2012). There are different areas of discharge such as pipeline, seeps, springs to surface, discharge to surface water bodies, flow into mine workings, evaporation and human withdrawal (Leon and Ferre, 2003). Evapotranspiration can be especially significant for areas with a negative net water balance (Wels *et al.*, 2012). The process controlling discharge and the factors controlling them should be noted (Wels *et al.*, 2012).

2.2.7 Groundwater flow regime

A representation of the groundwater flow regime is one of the expected outputs of the model. One of the methods for representing groundwater flow is through pictorial representation (Figure 2.2) accompanied by supporting qualitative data (recommends a trend analysis of a full year's rainfall data in relation to groundwater levels (Wels *et al.*, 2012). A representation of the groundwater flow will indicate the main groundwater flow paths from recharge points to discharge area, water table location, flow fields (both vertical and horizontal hydraulic gradients) and potentiometric field (Wels *et al.*, 2012). According to Barnett *et al.* (2012), water level also referred to as the hydraulic or piezometric head is the most important quantity in assessing groundwater flow. Because the water level expresses the potential energy of the groundwater per unit weight, it influences the groundwater flow direction from areas of high hydraulic head to areas of low hydraulic head (Barnett *et al.*, 2012). Therefore, groundwater the travel time or resident time can be estimated from the hydraulic gradient for simplified scenarios.

2.3 FACTORS THAT MAKE MODELLING COMPLEX

By nature, groundwater systems are characterised by complex flow patterns that are continuously changing with time and within space (Barnett *et al.*, 2012; Taylor and Alley, 2001). The systems are dynamic as they respond to both influences from natural and anthropogenic influences over short-term and long-term periods (Taylor and Alley, 2001). These factors make the modelling process complex. As a result, during model development, simplification of the system is needed (Barnett *et al.*, 2012). According to Barnett *et al.* (2012), the capacity to replicate the real-world complexity in a model is limited and as such the conceptual model itself is a source of uncertainty (Krom and Lane, 2009), largely due to the information constraints from which models are built. Bear *et al.* (1992), stated that the extent of uncertainty in models is worsened, in most cases, by insufficient data for parameter estimation and model validation. Another contributing factor according to Bear *et al.* (1992), Barnett *et al.* (2012) and Neumann and Wierenga (2003) is the fact that there is imperfect knowledge of the processes controlling groundwater systems. Neumann and Wierenga (2003) further point out that this limited knowledge of the systems imposes the use of assumptions when considering what processes are to be included in the model.

Although a conceptual knowledge of groundwater systems can be developed from borehole observation and hydrologic response, the level of understanding remains limited and uncertain due to scarce temporal and spatial observational data (Barnett *et al.*, 2012). Furthermore, there is often a lack of data for a full description of the model from the defined geology, geophysical data interpretation and geochemical data therefore making a substantial interpretation from an expert necessary (Krom and Lane, 2009). According to Neumann and Wierenga (2003) both the conceptual and parameter uncertainties would be reflected in the in-built knowledge gaps. Some of these knowledge gaps stem from uncertainty with regards to (Bear *et al.*, 1992):

- the location of domain boundaries and the conditions prevailing on them
- initial conditions

- the meaning of measured data;
- the various sink/source phenomena for the considered extensive quantity
- the transport mechanisms
- the ability of the model to cope with a problem in which the solid matrix heterogeneity spans a range of scales, sometimes orders of magnitude apart

Further to this, the features included in the model can exacerbate the level of uncertainty. Such features include conceptualising several watersheds, steep topography, heterogenous fracture systems and their hydraulic significance, complex geology and changing mine designs or mine site conditions during modelling process (Wels *et al.*, 2012). Options to measure the extent that the parameters add to complexity of modelling are limited (Wels *et al.*, 2012). Barnett *et al.* (2012) pointed out that illustrating the inherent uncertainty in all model predictions would be beneficial especially when taking into consideration that the available data can provide a variety of plausible outputs. This is similar to the suggestion by Mclaughlin (1984) who mentioned that the best way to examine the role of uncertainty in modelling study is to review the technical decisions which must be made when a model is formulated. That is, is the uncertainty significant enough that the objective for which the model is being built cannot be achieved?

2.4 GROUNDWATER MODEL AS A WATER MANAGEMENT TOOL

Despite the inherent uncertainties in groundwater models, they remain the main tools for prediction of groundwater system behaviour. Both Bear *et al*. (1992) and Leon and Ferre (2003) agree that even with the lack of description of hydraulic parameters, models can be regarded as reliable tools for guiding management decisions. According to Leon and Ferre (2003), this holds true particularly in regions where the hydraulic conductivity is relatively homogeneous. Barnett *et al.* (2012) added that although groundwater modelling is complex and characterised by subjective decisions of the modeller, the resulting models have proven to be valuable in addressing groundwater management issues and supporting management decision making process over several decades.

A conceptual model is limited in its use as a predictive modelling tool but it forms the basis on which mathematical models are build. It is the most critical step in modelling (Surinaidu *et al.*, 2014). Should the conceptual model be wrong in representing the relevant groundwater flow or transport system, then the translation of the model into a numerical/mathematical model and subsequent use as predictive tool would be a waste of time and money (Surinaidu *et al.*, 2014). Models are particularly useful as a management tool for the mining industry for example, to determine the types of dewatering diversions and sealing prevent the interference of water in production (Surinaidu *et al.*, 2014). Knowing which method to use at the most cost efficient rate requires identification of the source of groundwater flow into the mining face (Surinaidu *et al.*, 2014).

Surinaidu *et al.* (2014) conducted a study where the main objective was to predict and estimate the groundwater inflows into an underground coal mine that was to be converted into an opencast mine in order to develop optimal groundwater dewatering plans. From their study, Surinaidu *et al.* (2014) illustrated how a groundwater model can be used to understand the controlling mechanism and path for groundwater flow and further quantify volumes associated with dynamic mining conditions. Surinaidu *et al.* (2014) used the staged wise mining plan to divide the model into sections representing the different mine development stages. The study noted a dynamic variation in groundwater conditions during mine development as a result of changes in extent and depth of the area and floor respectively as well as the practices used of internal dumping of overburden material which would take place adjacent to the active mine floor depending on available mine void space (Surinaidu e*t al*., 2014). At different mine plan stages, associated groundwater mine floors were simulated by including the pit area, changes in depth and extend of the internal dump (Surinaidu e*t al*., 2014). Hydraulic parameters were adjusted to fit the changes in the pit at different mine stages (Surinaidu e*t al*., 2014). The results from the study showed that volumes of water that would need to be managed had a general increase with progressive mining. According to Surinaidu *et al.* (2014), inflows into the mine ranged from 5 877 m^3/day to 22 617 m^3/day. These changes were, according to Surinaidu *et al.* (2014), a function of the pit floor elevation and surrounding groundwater elevation. Furthermore, it was noted that majority of the flow in the entire sub-basin took place along faults zones (Surinaidu *et al*., 2014). With this knowledge in-hand, the mine can plan for the required pumping infrastructure with progressive development by updating the model with relevant data. A major limitation to the study is the uncertainty brought about by model parameter used which Surinaidu *et al.* (2014) did acknowledge.

2.5 ASSESSING CONCEPTUAL MODEL CONFIDENCE LEVEL

Whether a model's prediction output can be relied on is dependent on the model confidence level. According to Barnett *et al.* (2012), the level of confidence placed in predictive modelling outputs can be critical during groundwater modelling. The envisioned model confidence should be determined and documented at the beginning of a project in order to manage expectations (Barnett *et al.*, 2012). Barnett *et al.* (2012) pointed out that availability of data, time and budget allocated for a project are often limitations for the model's confidence level. Regardless of this, model application should be defensible (Ardito *et al.*, 2004). According to Ardito *et al.* (2004), there exist a need for a process to prevent the misapplication and misuse of groundwater models which includes the selection of the most appropriate tools and application of those tools for model development and an especial evaluation of the used field data. As it stands, there are no industry standards for groundwater modelling development and application requirements. And according to Ardito *et al.* (2004) developing such standards would be a monumental task due to the complexity and controversial nature of the subject not to mention the diverse applications and users of highly variable background and expertise (Ardito *et al.*, 2004). Ardito *et al.* (2004) suggested a process of self-regulation similar to that used by the engineering discipline as a means to enhance defensibility and reliability of using groundwater models for decision making.

The model confidence can, according to Barnett *et al.* (2012), be approximated using a semi quantitative assessment of the available data used for model conceptualisation and calibration of the model, the method of calibration and how predictions are formulated. A subsequent judgement can then be made based on whether the model outputs are fit for purpose (Barnett *et al.*, 2012). In their publication "Australian groundwater modelling guidelines", Barnett *et al.* (2012) identified three model confidence classification levels each with factors (relevant to model conceptualisation) that must be considered when determining model confidence classification level (Table 2.3). This concept provides a way of ranking the relative confidence with which a model can be utilised for predictive modelling (Barnett *et al.*, 2012). The available data and accuracy of that data used for model conceptualisation, design and construction will influence the model confidence level (Barnett *et al.,* 2012). An assessment of the spatial and temporal distribution of the dataset should be conducted (Barnett *et al.*, 2012). Additionally, it should be assessed whether the dataset is sufficient for fully characterising the aquifer and the noted historic groundwater responses that could be used for model calibration (Barnett *et al.*, 2012).

Table 2.3: Summary of model confidence level classification adapted from Barnett *et al.*, (2012)

Confidence level	Class 1	Class 2	Class 3
Data	There are a few poorly distributed boreholes to get water level and geological information	Groundwater head measurements and borehole logs are available however do not provide sufficient coverage for the model domain	There are sufficient spatial and temporal groundwater levels to define groundwater behaviour in the area of interest
	There is no record of groundwater abstraction or injection readings	Groundwater abstraction flow meter data is available however, temporal coverage is not extensive	Reliable groundwater abstraction or injection flow meter readings are available
	Limited to no useful land use, soil or river flows and stage elevation data	Stream flow data and baseflow estimates are available for a few points along the river	Stream flow, stage measurements and reliable baseflow estimates are available for multiple points along the river of interest
	Observations and measurements are not available or they are sparsely distributed in the area of interest		There are aquifer testing data to define key parameters
	The available climate data is from relatively remote locations		Rainfall and evaporation data is available

			Land use and soil mapping data is available

Another factor that influences the model confidence level classification is the calibration procedures used during the model development (Barnett *et al*., 2012). Barnett *et al*. (2012) considered the types and quality of data included in the calibration to be of significance. This implies that it should be clear at the model conceptualisation stage the confidence classification into which the model will fit. Depending on the assessment of the confidence level of the model output, it may be necessary that the expectations are reviewed. Some scenarios may require the modelling objectives to be revised and/or updated (Barnett *et al*. (2012). Refsgaard and Henriksen (2004) on the other hand suggested that the appropriate method of analysing model performance is to compare it with uncertainties associated with the available field data. If the model produced results within the expected range of uncertainty, then it would be considered adequate. The approach by Refsgaard and Henriksen (2004), may appear vague but they point out that it brings into question what the acceptable confidence range for the uncertainty related to field data is. Therefore, they suggest that determining the appropriateness of a model should be based on context within which the mode will be used (Refsgaard and Henriksen, 2004). In contrast, Ardito *et al*. (2004) argued that an industry standard is needed for selecting and developing appropriate models along with a review of how the hydrogeological data was included in the model.

2.5.1 Data adequacy evaluation

For the purposes of this study, model confidence will be determined based on whether the available data is sufficient for building and calibrating a numerical model, as a numerical model will not be developed.

Models are not built with the aim of illustrating all the details of a field site and it may not be necessarily desirable to do so (Hill, 2006). However, the goals set for models need to be achieved within the context of the data that is available, the system processes and characteristics about which the data gives information (Hill, 2006). There is no doubt that groundwater modelling relies on hydrogeological information and such data is critical for constructing simplified and useful models (Hill, 2006).

It would be expected that with the addition of more detailed field data the model output would be improved to better reflect the real system and reduce model uncertainty. However, Scheibe and Chien (2003) proved this concept to be incorrect. Scheibe and Chien (2003) conducted a study where an extensive groundwater data set of multiple hydraulic conductivity flowmeter readings were used to simulate transport with different levels of details. The study findings indicated that the use of localised point source data, even hundreds of such data, does not provide much benefit and may even contribute to misleading results. According to their study, a homogeneous assignment of hydraulic parameter produced better results (Scheibe and Chien, 2003). In contrasts, McLaughlin (1984) highlighted a scenario where the lack of field data compounded by poor data collection and interpretation of said data would lead to a useless model. This is in alignment with the EU (2003) who stated that new monitoring data can contribute to better understanding of a groundwater system and subsequently improve the confidence in the conceptual model.

Vivier and Van Der Walt (2011) conducted a study investing the point at which the collection of new data no longer adds value. On the basis that information is the collection and arrangement of data, that is, a picture and data is an equivalent collection and arrangement of pixels which form the picture (information) (Vivier and Van Der Walt, 2011). Using this analogy, Vivier and Van Der Walt (2011) investigated the limit at which data stops being useful. The argument presented by Vivier and Van Der Walt (2011) was that at some point, a decision has to be made regardless of whether there is sufficient data to make an informed decision. As such, will more data equate to more information for decision making? Will the "picture" be clearer with more "pixels"? Using a case study in Middelburg, Eastern Cape, South Africa, Vivier and Van Der Walt (2011) used water level data from 715 boreholes with a density of 2.86 km^2/ borehole to answer the aforementioned questions. The data indicated that the cumulative change in the average and standard deviation of the measured water levels converges as the data points increase (Vivier and Van Der Walt, 2011). Vivier and Van Der Walt (2011) concluded that additional data reaches a point at which it does not significantly change the average groundwater level or standard deviation. At this point, the information is considered to be sufficient. However, it should be noted that a project decision should be made on the acceptable convergence value as the data will approach zero but never reach the limit of zero (Vivier and Van Der Walt, 2011).

2.5.2 Data distribution and representativeness

In order to understand the information on hydrologic stresses influencing aquifers and how these stresses impact factors such as groundwater recharge, storage and discharge, water levels from observation boreholes are used (Taylor and Alley, 2001). These observations serve as the principal source of information about subsurface water dynamics (Taylor and Alley, 2001). According to Taylor and Alley (2001), long term, methodical measurements of groundwater levels give vital data required to assess changes in the resource over time, construct groundwater models and forecast trends. For these reasons, monitoring programs dependent on observations boreholes that are setup to collect water level data in one or more specified aquifers (Taylor and Alley, 2001). Taylor and Alley (2001) stated that choices made about the number and location of monitoring boreholes are important to water level data collection program. It is preferable that the borehole network is representative of the different topographic, geological, climatic and land use environments (Taylor and Alley, 2001). Representativeness dictates that the spatial and temporal scale of the data used stay within the boundaries of the decision-making scale (Nielsen, 1996). Therefore, the design of a monitoring program should provide the data needed to verify model objectives (EU, 2003). The spatial distribution and depth of completion of boreholes needs to also consider the physical boundaries and geological complexity of the aquifers under investigation (Taylor and Alley, 2001). In areas characterised by complex, multilayer aquifer systems, wells may need to be developed (drilled) at multiple depths in various geological units (Taylor and Alley, 2001). Ideally, the data collected needs to be representative of the aquifers considered in the study. Nielsen (2006) stated that representativeness is of paramount importance to data quality. It is a qualitative parameter that is dependent on the proper design of a sampling program (Nielsen 2006 after Jenkins 1996) The sampling program must be setup in such a manner that data can be confidently extended to a larger volume of material.

CHAPTER 3: GENERAL SETTING

New Vaal is an opencast coal mine in the northern Free State, South Africa, located along the meandering Vaal river. It is the sole provider of coal to the Lethabo Power Station located immediately east of the mine. The towns of Vereeniging, Vanderbijlpark and Salsolburg are located north, west and south west of the mine respectively (Figure 2.3). The area falls under the Upper Vaal catchment C22F and has a history of coal mining going back to the 19th century. Underground mining took place north and south of the Vaal river with a number of shafts going underneath the river.

Table 2.4: A summary of Upper Vaal catchment hydrology

Quaternary catchment	Area (Km2)	Mean Annual Precipitation (mm/a)	Mean Annual Runoff (mm/a)	Mean Annual Recharge	
				mm/a	% of MAP
C22F	440	655	24.3	34.8	5.3

Figure 2.3: Locality map of New Vaal Colliery

3.1 MINING HISTORY

Mining operations in the area started in 1880 with underground operations at the now defunct Bedworth Colliery on the Transvaal side (now Gauteng Province) north of the Vaal river with the shaft located on the Free State side (Figure 2.4). As better coal seams were discovered south of the Vaal River, coal mining moved to the Free State side of the Vaal. The discovery led to opening of the underground mine Cornelia Colliery in 1894 (Figure 2.4). According to Hancox and Götz (2014), the mined seam at Cornelia Colliery is highly intruded with dykes which lead to the flooding and eventual abandonment of the mine. However, mining operations at Cornelia Colliery commenced again closer to the Vaal River where production carried on for 33 years (Hancox and Götz, 2014). Closure of the mine in1969 resulted in the flooding of the workings. Furthermore, records from Orpen and Wiegmans (1983) indicate that between 1975 and 1984, Randwater board disposed of water treatment sludge into the mine workings. Mining operation commenced again in 1985 as part of the New Vaal Colliery opencast.

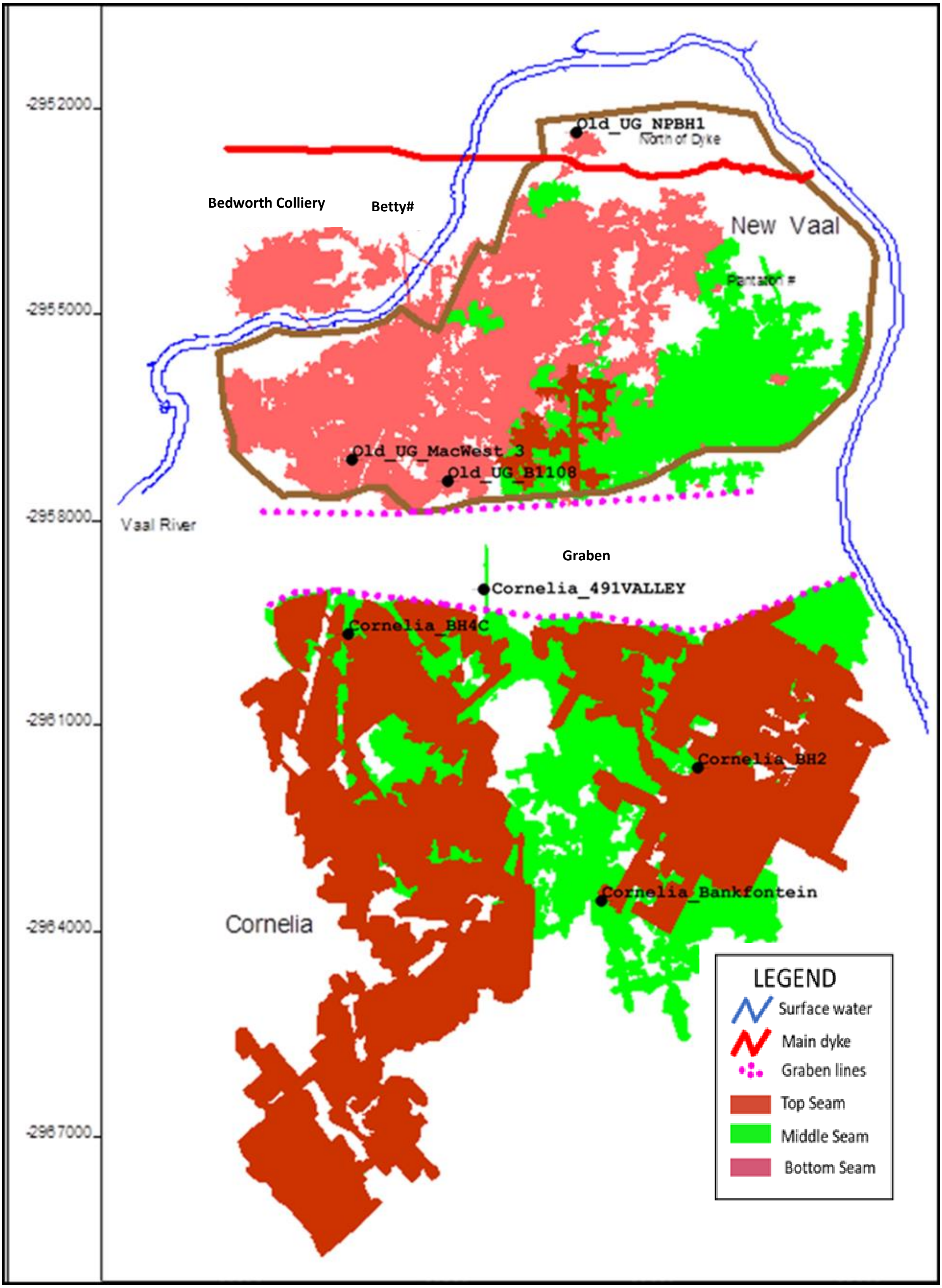

Figure 2.4: Illustration of old underground mine areas in the Cornelia Coalfield sub-basin (Hodgson, 2010)

The site is divided into what is known as Maccauvlei West and Maccauvlei East (Figure 2.5). The sites are connected through drives beneath a national road. Current assumption is that the drives where closed when mining ceased. There are three pits being mined at Maccauvlei East, namely, West pit, Main pit also known as South pit and North pit (Figure 2.5). The North pit and Main pit are differentiated by an east west striking swarm of dykes (Figure 2.4). Direction of mining in the Main pit and North pit is from east to the west and mining direction is from the west to the east in the West pit. Progressive rehabilitation by backfilling with spoil and discard material takes place as mining advances. The land rehabilitation process includes backfilling, levelling and compacting, dressing with alluvium sand and seeding. Sections of old underground mine workings still remain to be mined (Figure 2.5).

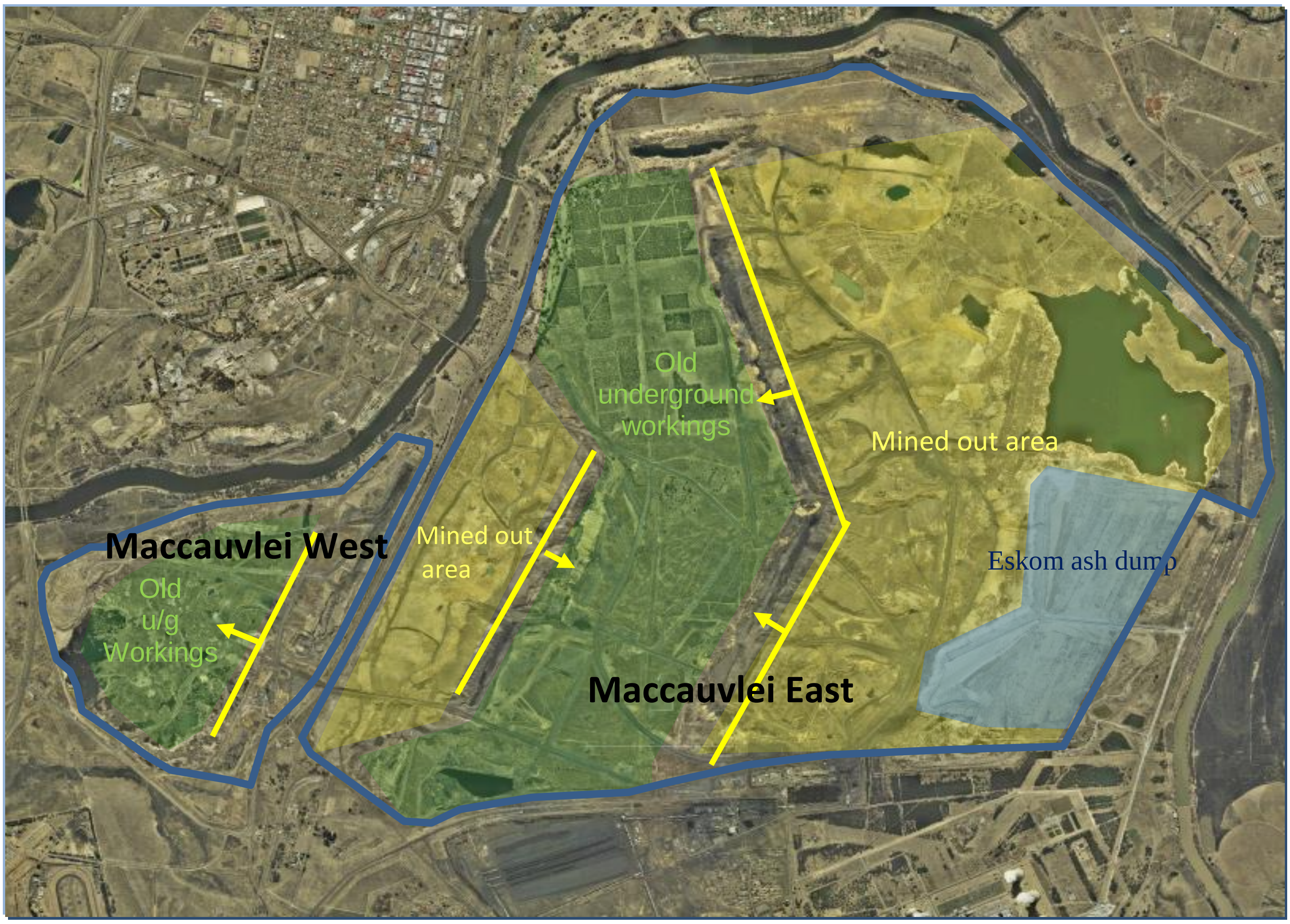

Figure 2.5: Illustration of the old underground mine areas in the Cornelia Coalfield sub-basin

3.2 RAINFALL

The study area has a climate typical of the Highveld region with notable rainfall and temperature seasonality. The mine's Environmental Management Plan Report (EMPR) (2010) reports a mean annual rainfall of ±650 mm which predominantly falls during the summer months. Site specific rainfall records collected over 25 years show that January, December and February have highest rainfall while July, June and August have the lowest recorded of rainfall. On Average, New Vaal Colliery receives 710 mm of rainfall.

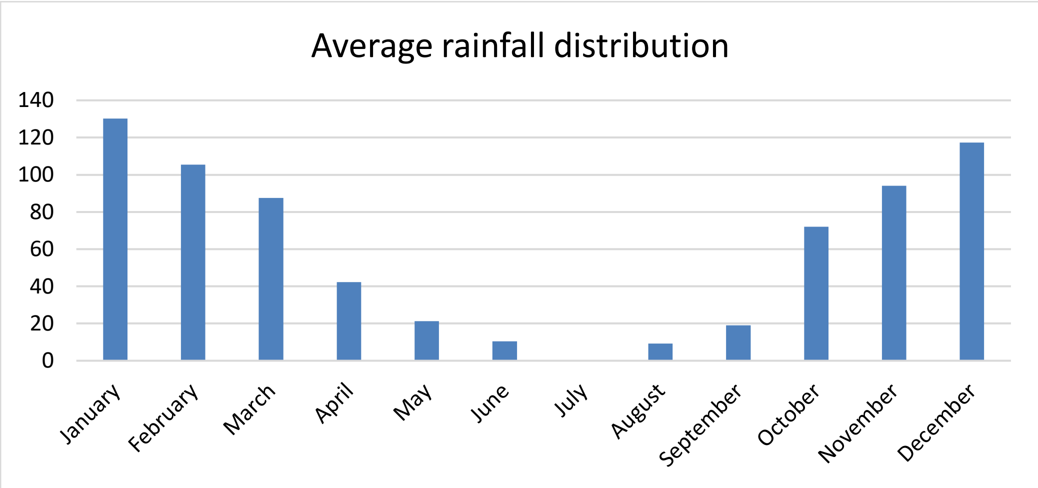

Figure 2.6: Monthly rainfall (mm) for New Vaal Colliery.

3.3 GEOLOGY

3.3.1 Regional geology

The regional geology comprises lithologies from the Witwatersrand, Ventersdorp, Transvaal, and Karoo Supergroups (Figure 2.7). The Witwatersrand Supergroup is characterised by shales, quartzites, and conglomerates. The Witwatersrand Supergroup is unconformably overlain by the volcano-sedimentary lithostratigraphic units of the Ventersdorp Supergroup which contains largest and most widespread sequence of volcanic rock (Johnson *et al.*, 2006). The Kliprivierberg Group of the Ventersdorp Supergroup, found in the region, hosts a sequence of flood basalts averaging a thickness of 1500 to 2000 meters (Johnson *et al.*, 2006).

The Witwatersrand and Ventersdorp Supergroups are unconformably overlain by the Transvaal Supergroup rocks. The Transvaal Supergroup rocks consists of relatively mature quartz arenite, conglomerates and subordinate mudrocks of the Black reef formation (Johnson *et al.*, 2006). Outcrop of the Black reef formation lie unconformably over the lavas of the Ventersdorp Supergroup, north to north east of New Vaal Colliery (Hodgson, 1983). The transitional siliciclastic sedimentation to platform carbonates, carbonaceous shales, stromatolitic dolomites of the Malmani Sub group also present in the area, outcrop along the Klip river and the Three Rivers area (Hodgson, 1983). The Pretoria Group, also present in the regional geology, consists of alternating mudrock with quarzitic sandstones, interbedded basaltic-andesitic lavas and subordinate conglomerates, diamictite and carbonates (Johnson *et al.*, 2006). The area is predominantly made up of the sedimentary rocks from the Vryheid Formation of the Ecca Group that represent the Karoo Supergroup. The Vryheid formation is characterised by coarsening upwards sequence of mudstone, siltstones, shale and sandstones interbedded with coal seams (Johnson *et al.*, 2006). The Ecca Group is underlain by Dwyka Group. The Dwyka Group comprised predominantly of clastic, massive to stratified diamictite (tillite). Subordinate sandstones, mudstones and conglomerates facies are also present with the Group (Johnson *et al.*, 2006).

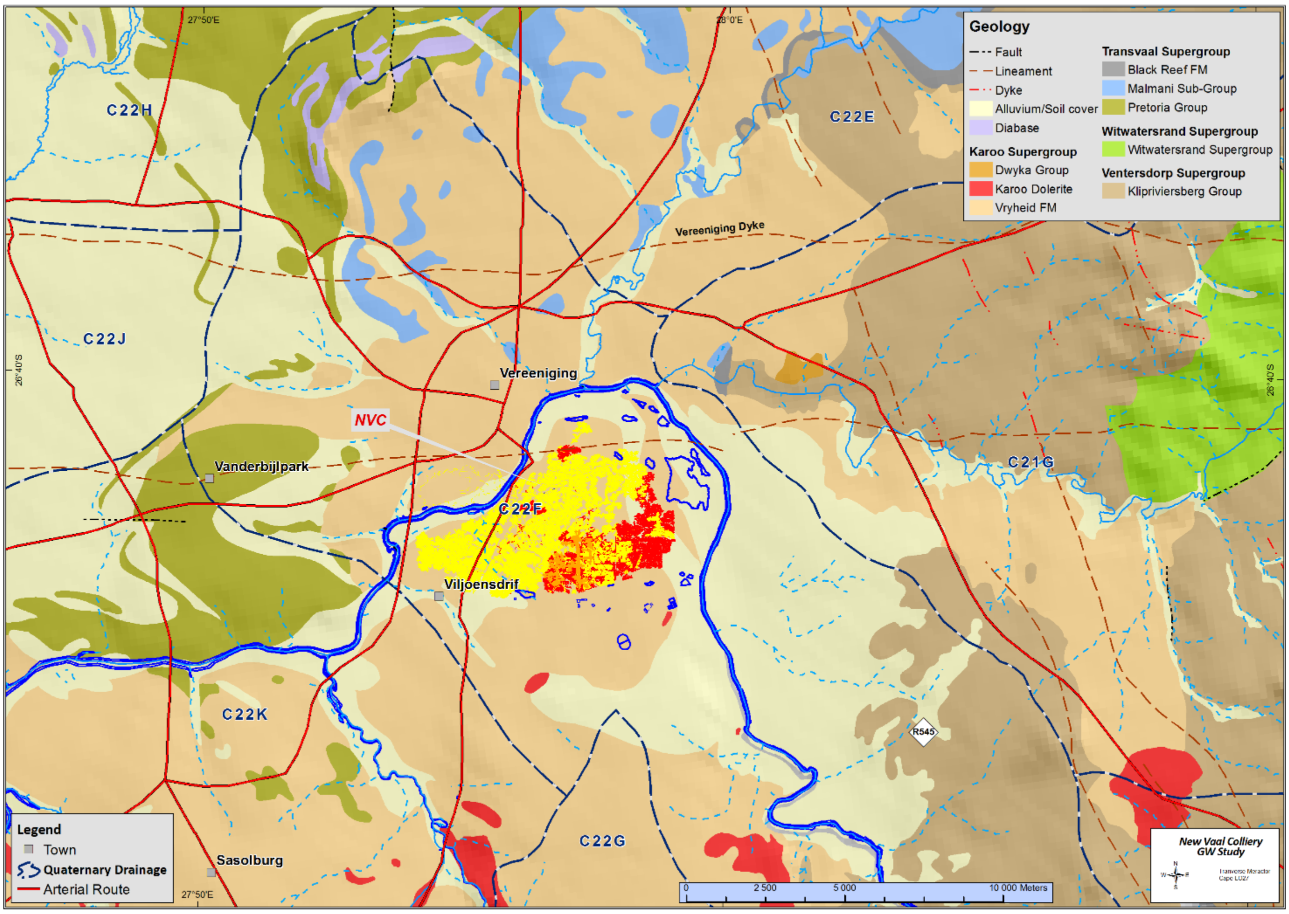

Figure 2.7: Regional geology for New Vaal Colliery

3.3.2 New Vaal Stratigraphy

New Vaal Colliery is located in the Sasolburg-Vereeniging coalfields in the northern Free State. The coalfield extends from the south of Vereeniging to roughly 20 km north of Heilbron in the south of the Free State and from west in Sasolburg and to the east in Deneysville (Hancox and Götz, 2014). The coalfield is further subdivided into three sub-basins namely the Cornelia sub-basin, Sigma sub-basin and the Coalbrook sub-basin (Hancox and Götz, 2014). The Cornelia sub-basin is confined within the pre-Karoo ridges of which, the Vereeniging dome is the most noticeable. The Colliery sits within the Cornelia sub-basin.

Figure 2.8 shows a typical borehole log for New Vaal. The entire site is covered by clayey river alluvium sand that averages 20 meters in thickness (New Vaal Colliery, 2013). The sand is characterised by very fine sediments, thin layer of clay bands and in some instances boulder beds (Hodgson 2005). Underlying the alluvium sand is the weathered Karoo Supergroup's fine grained sandstone and together they form the soft overburden. Below the weathered Karoo sandstone is the hard overburden characterised by shales and sandstones/siltstones. The hard overburden averages a thickness of 7.5 meters; however, thicknesses can vary from zero meters to 37 meters in the southernmost part of the mine (New Vaal Colliery, 2013).

Top Seam coal underlies the hard overburden and in some portions where the coal seam is weathered, it is directly below the soft overburden. Top Seam coal averages a thickness of 8.7 meters although thicknesses can reach 13 meters in certain places (New Vaal Colliery, 2013). Separating Top Seam coal from Middle Seam coal is the 11.6 meters average thick interburden. The interburden consists of a variation of upward coarsening sequence of carbonaceous mudstone, shale, siltstone and fine grained micaceous sandstone. The Middle Seam coal has an average thickness of 7.4 meters and maximum thickness of 23 meters. The coal seam has been noted as sub-outcropping below the soft overburden in some portions of the mine. Between Middle Seam coal and Bottom Seam coal is a parting characterised by a thin layer of grit stone underlain by a carbonaceous, silty to gritty mudstone. The parting varies in thickness from zero meters to six meters but generally averages a thickness of two meters. Bottom Seam coal has an average thickness of 5.9 meters. Thickness of the seam can reach maximum of 21 meters in the western and north western areas of the mine where Doline features are present. Dwyka Group sediments underlie the Bottom Seam. The sediments consist of a sequence of shale, coal, sandstone, grit, conglomerate and tillite. Two lower Bottom coal seams have also been previously identified as occurring in the Dwyka. Sediment thickness of the Dwyka Group varies between zero meters to over 20 meters. According to Orpen and Wiegmans (1983), tillite makes up most of the Dwyka rocks underlying Bottom Seam but efforts to contour the thickness of the formation was not feasible due to insufficient information. Below the Dwyka is a transitional zone and dolomite. The transitional zone consists of cherty conglomerate characterised by angular chert and quartz pebbles. Both the transitional zone and dolomite are fractured. Towards the north in Three Rivers, the dolomite occur at a shallow depth and are exposed to the surface in some locations (Hodgson, 1983).

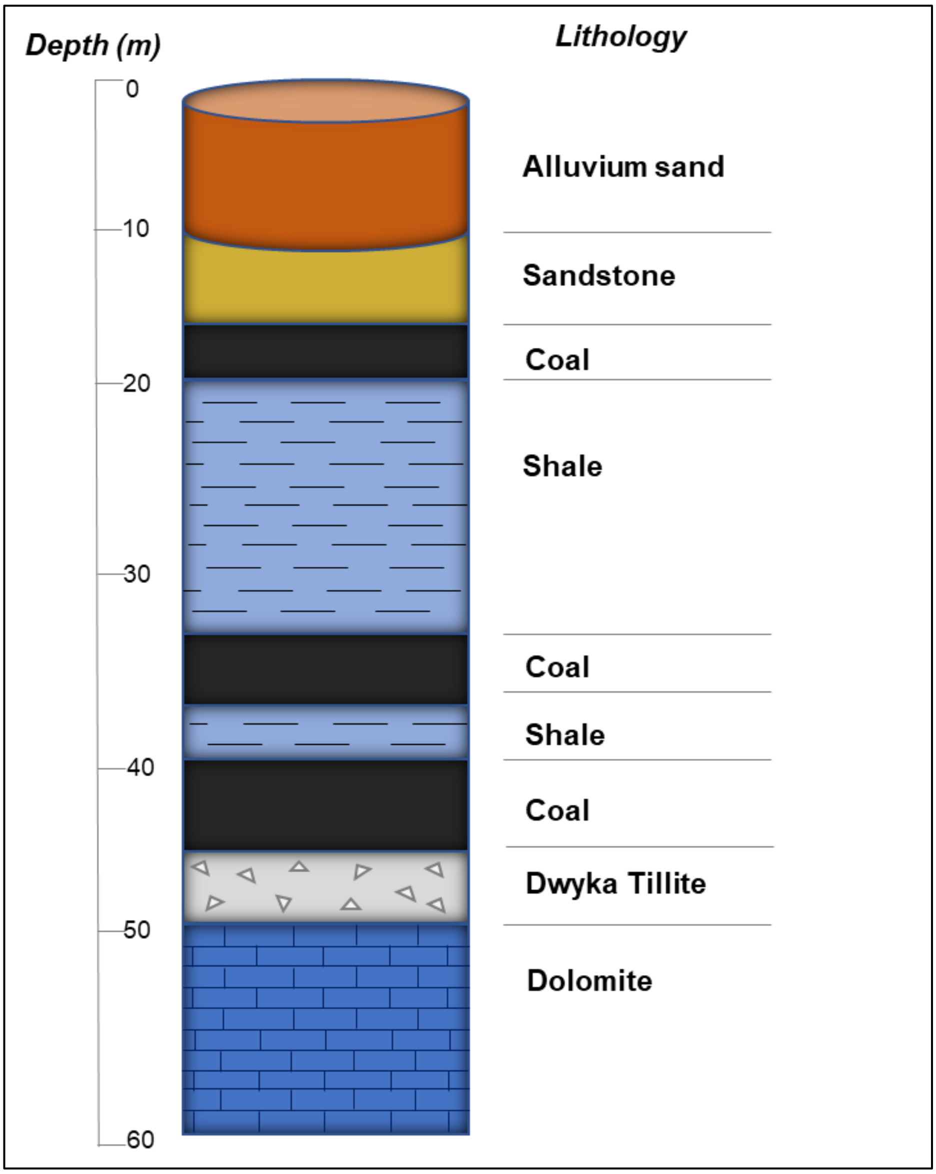

Figure 2.8: Typical borehole log for New Vaal Colliery

3.3.3 Geological structures and features

The geology at New Vaal is characterised by undulations that become significant with depth. General dip direction is towards the south west with east west trending faulting. Faulting ranges from regional scale to a localised faulting. Of significance is the set of faults forming a graben structure (Viljoensdrift trough) north of Cornelia Colliery south of the New Vaal operations. According to Orpen and Wiegmans (1983), downthrows of 50 meters for the south fault and 68 meters for the north fault were noted from borehole data. A regional east west striking dolerite dyke separates the Main pit and the northern pit into two different compartments (Hodgson, 1983). The dyke is associated with a stringer of dyke intrusions and faulting.

CHAPTER 4: COLLECTED DATA

Site specific groundwater data collection has been part of the New Vaal Colliery before the first coal was mined. However, this data was not available for the current study. The studies conducted between1983 and 1985 concentrated on the collection of data in the northern portion of the future mining area where the initial boxcut would be established. While the data collection points from those studies are no longer available, other ground and surface water monitoring points were added as mining progressed. The surface water bodies on site have available data from 2010 and current groundwater sites since 2001.

4.1 SURFACE WATER MONITORING

The Vaal river is the most significant surface water feature in the area (Figure 2.9). Although the water level in the river is regulated from the Vaal dam, it has a history of overflowing its banks. In the event that the river overflows its banks, the mine has constructed a levee along the boundaries bordering the Vaal river as a means of diverting 1:100 year flood waters away from mining operations. Along the Maccauvlei East levee there are remnants of a vlei used as an evaporation dam, referred to onsite as Kingfisher dam (Figure 2.9). Also along the Maccauvlei East levee are the Yellowfish dam and Fingers dam, which are occasionally used as evaporation dams as well (Figure 2.9). Fingers dam is located in close proximity to the Maccauvlei dam. The Maccauvlei dam is a depression that is being used as the mine’s main water holding dam. Both the Maccauvlei and Fingers dam are located on areas that have been previously mined. There are several other depressions located on previously mined areas namely, Wildebeest dam, Kgotso dam and Tshepe dam filled with surface run-off. Only two dams, namely KSB dam and Plastic dam at the site are constructed and with identifiable lining. Plant dam is a constructed facility assumed to be clay lined, however this could not be confirmed during desilting of the dam. For the purpose of this study, all lined dams will be excluded from the study as they do not interact with groundwater system.

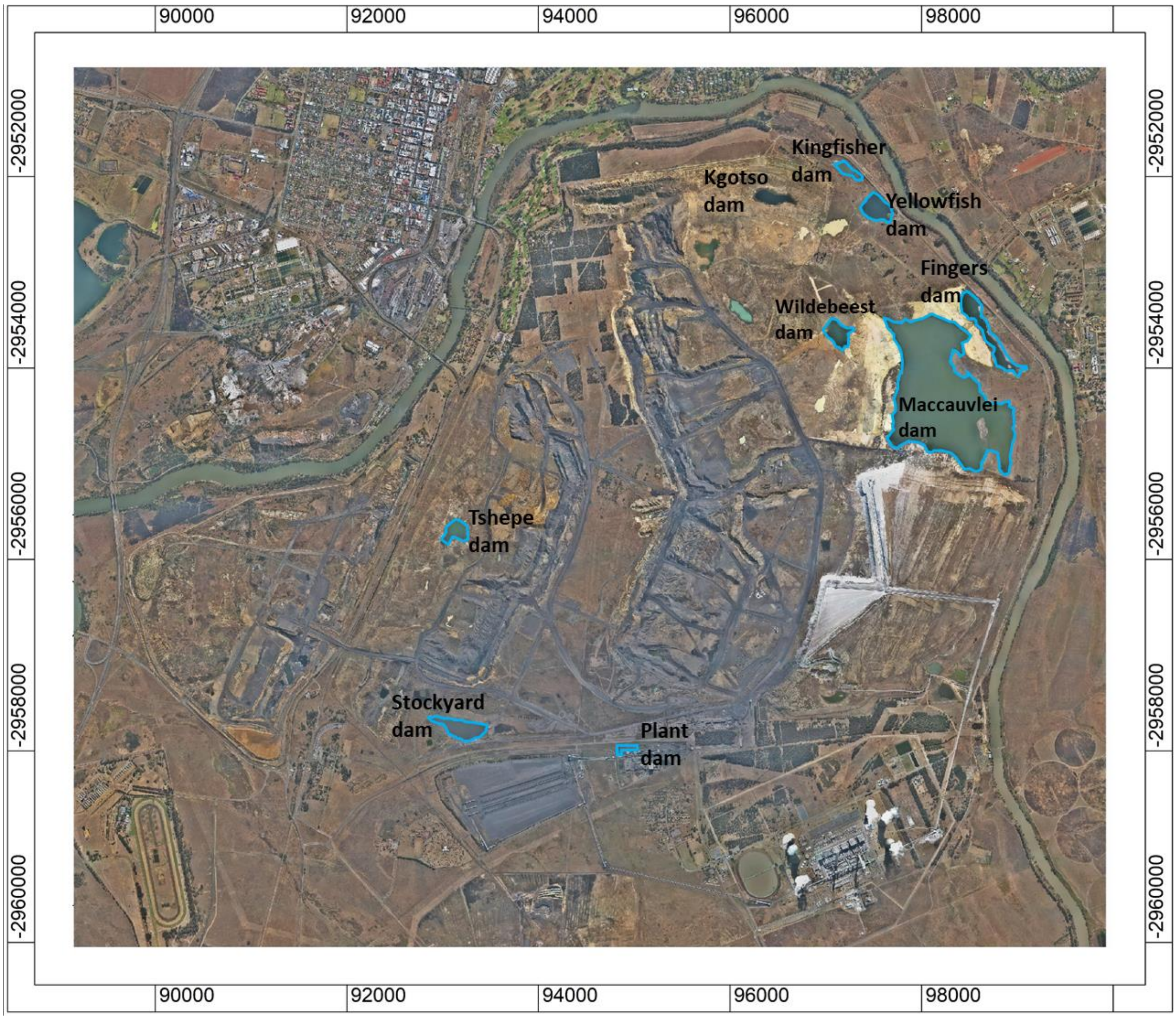

Figure 2.9: Surface water bodies at New Vaal Colliery

Water levels measured in the dams located in close proximity to the levee in the northern portion of the mine are shown in Figure 2.10. Water levels in the Maccauvlei dam have showed a gradual increase between 2007 and mid-2009. From the year 2009, a significant increase in the water levels measured is noted. This significant increase continues until early 2011 at which point the water level began to decline. The trend of water level increase in Maccauvlei dam can be attributed to an increase in water disposed into the dam without significant outflows and higher than average rainfall between 2009 and 2010. Between 2011 and 2012, a significant water level decline of two meters is noted in the dam. This water level decline can be attributed to abstraction of water from the dam by the water treatment plants. Water level data for Fingers dam are available from 2010 to 2013. Water levels during the monitoring period show only minor fluctuations, with a noted gradual decrease towards the end of 2012 possibly due to the lowering of the water level in Maccauvlei dam. This can be expected given that the two dams shared a water elevation between 2010 and 2012. At an elevation of 1425.8 mamsl, water from Maccauvlei dam overflows into Fingers dam, resulting in the two dams forming one surface water body. Water levels in Yellowfish dam show an increase from

2010 onwards until they peaked in 2011. Between 2011 and 2013 the water levels showed a gradual decline similar to Fingers dam. Water levels in Kingfisher dam show generally similar trends to that of Yellowfish dam although a brief increase in 2010 is noted. The levels remain fairly constant in the last quarter of 2010 and first quarter of 2011. Between the second quarter of 2011 and 2013, the water levels showed a gradual decline with minor fluctuation over the monitoring period. Although water levels in the dams are at different elevations, the dams show overall similar trends throughout the monitoring period as driven by rainfall and mine water pumped into the dams. Furthermore, throughout the monitoring period the water levels maintain an elevation above the stage of the Vaal river, indicating (if linked) a hydraulic gradient in the direction of the river.

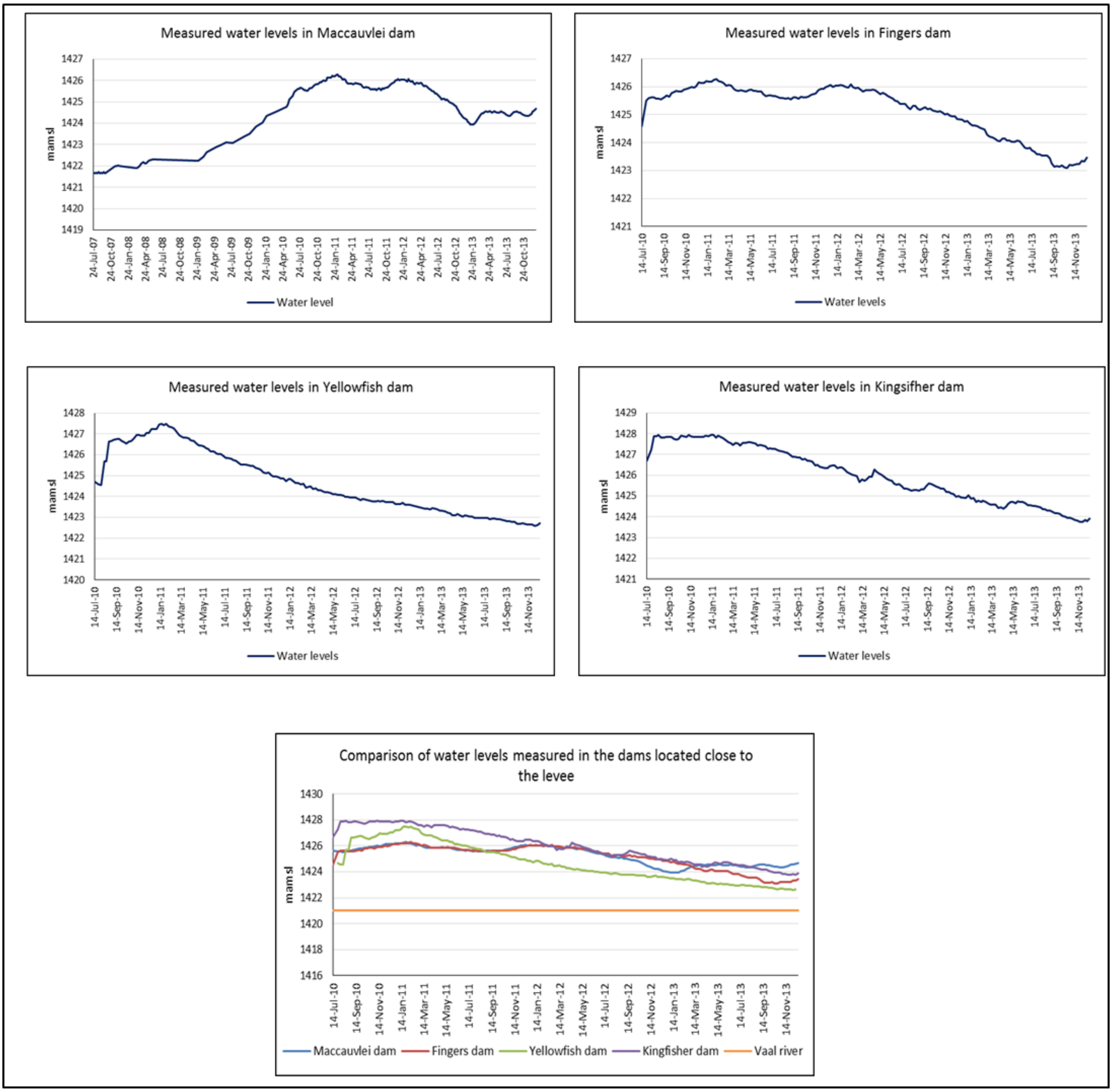

Figure 2.10: Water levels measured in the surface water bodies

4.2 GROUNDWATER MONITORING

Groundwater monitoring sites are as indicated in Figure 2.11. In total, 26 monitoring boreholes were used for the study. With the exception of Ash1 and Ash2, the boreholes can be grouped according to the aquifer that they are monitoring. Four of the boreholes (Spoil 1, Spoil 3, Spoil 6 and Spoil 11) were drilled into the rehabilitated backfill material, six boreholes (Dam3 BH1, Dam3 BH2, Dam4 BH1, Dam4 BH2, Ash 1 and Ash 2) were drilled in close proximity to the evaporation dams and the main pollution control Dam respectively. Seven of the boreholes were drilled into dolomite, that is, boreholes B1680, B1681, B1682, B1683, B1684 and B1094. Cornelia Colliery hosts two boreholes, BH2 and Bankfontein. BH4C which are located between New Vaal Colliery and Cornelia Colliery in the geological graben area.

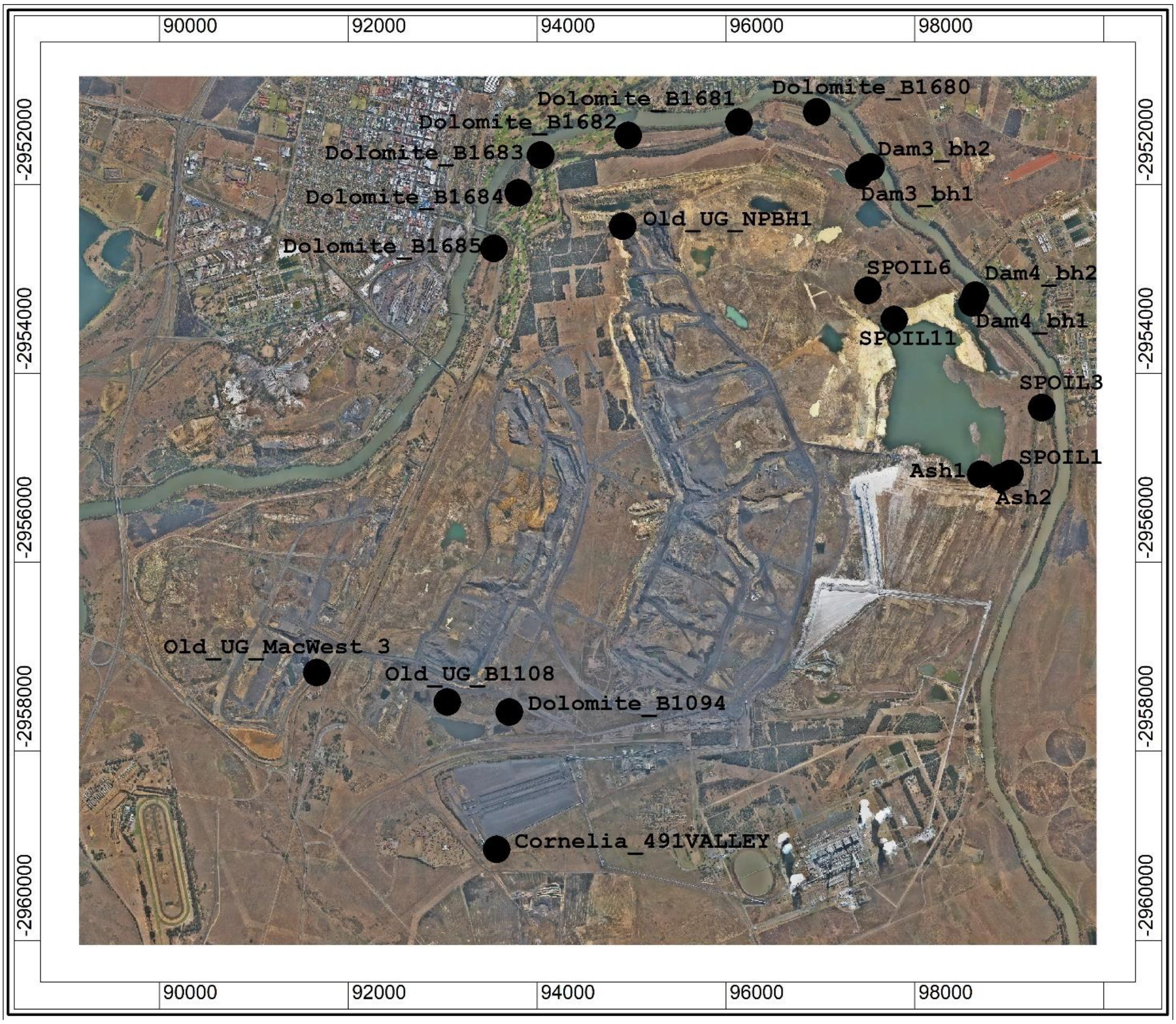

Figure 2.11: Groundwater monitoring boreholes at New Vaal Colliery

4.2.1 Spoils boreholes

All the spoils boreholes show a similar trend of increasing water levels throughout the monitoring period (Figure 2.12). The water levels peaked around an elevation of 1426 mamsl towards the end of 2010 and beginning of 2011, after which a decline of approximately two meters in the levels is noted (from 1426 mamsl to an elevation around 1424 mamsl) between 2011 and 2013. The initial rising water levels are a possible indication of flooding of the backfill material. Water levels remained below the average elevation of the Vaal River until the end of 2008, indicated by the green line in Figure 2.12, after which the water levels in the boreholes started to increase to elevations above that of the Vaal River. Water level spikes/outliers are noted for all the boreholes between May 2004 and July 2004 and again between May 2006 and October 2006. Although the spikes for the individual boreholes are noted in different months, they appear around the same period and suggest that the spikes may be a result of issues with the equipment, a change in personnel or rainfall ingress into the borehole. For all the boreholes, an analysis of the water level trend compared to rainfall does not indicate that rainfall has a significant influence on groundwater levels in the backfill. This suggests that rainfall is not the main mechanism controlling water levels in the backfill material. However, compared to the water levels measured in the Maccauvlei dam, the backfill spoil boreholes water levels show a similar trend to that seen in Maccauvlei dam water levels. This suggests that water in Maccauvlei dam is the main mechanism controlling groundwater levels in the backfill material due to a direct hydraulic connection of the unlined dam to the underlying spoils material.

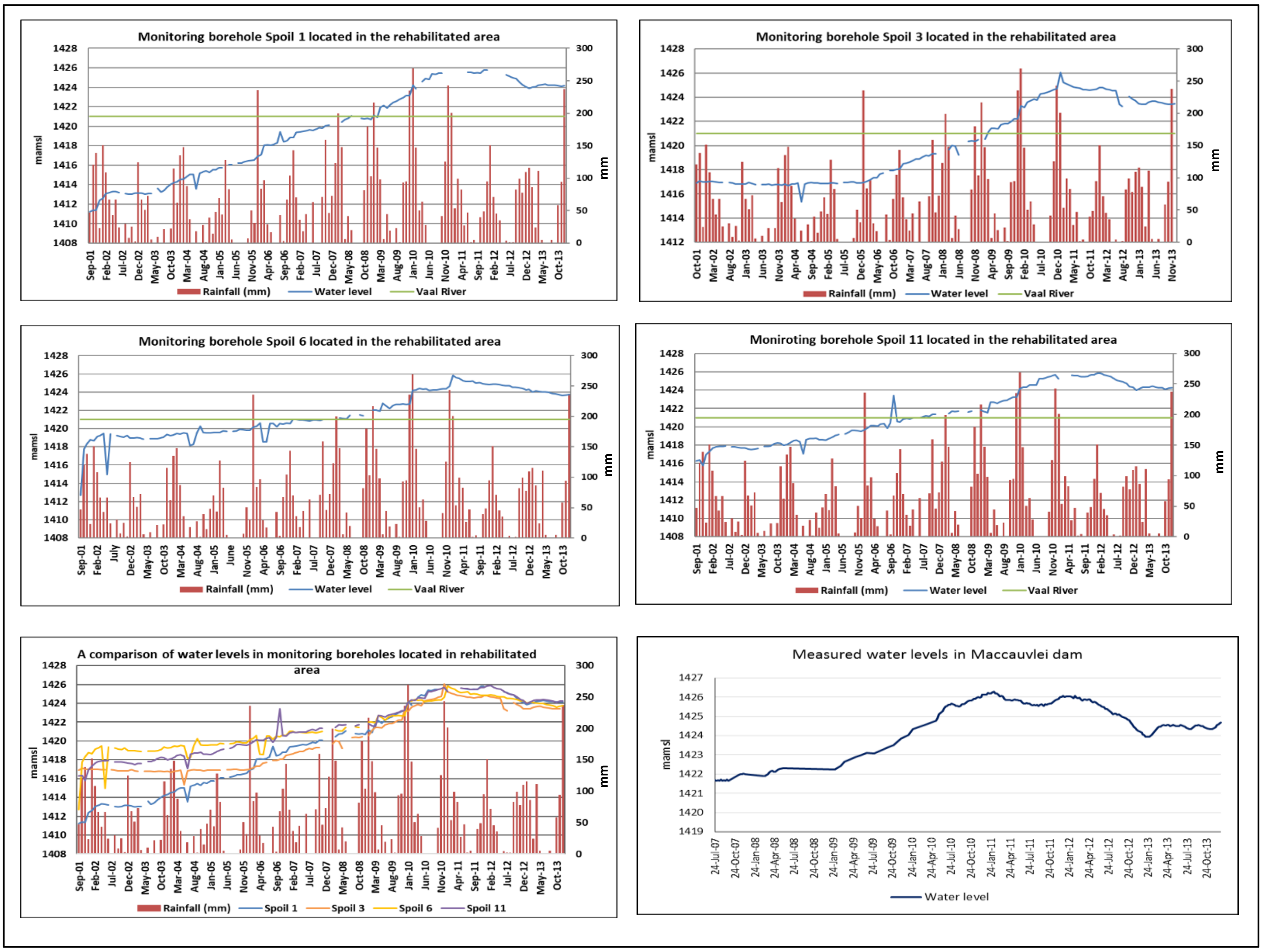

Figure 2.12: Water levels measured in monitoring boreholes located in the main pit rehabilitated area.

4.2.2 Dams boreholes

Boreholes Ash1 and Ash2 are located on the bank of the Maccauvlei dam. Similar to the spoils monitoring boreholes (Section 4.2.1), the two boreholes are drilled in to backfill material. The boreholes show an increasing water level trend similar to that of the Maccauvlei dam water levels (Figure 2.13.). Unexplained dips and spikes are noted between November 2008 and April 2009, again, this is possibly due to equipment or human error. The low collar height and proximity of the boreholes to the dam has in the past resulted in their submergence consequently the groundwater level in those periods can be assumed to the same elevation as the Maccauvlei dam water level (Figure 2.14). This was observed to be the case in the period between May 2010 and April 2013.

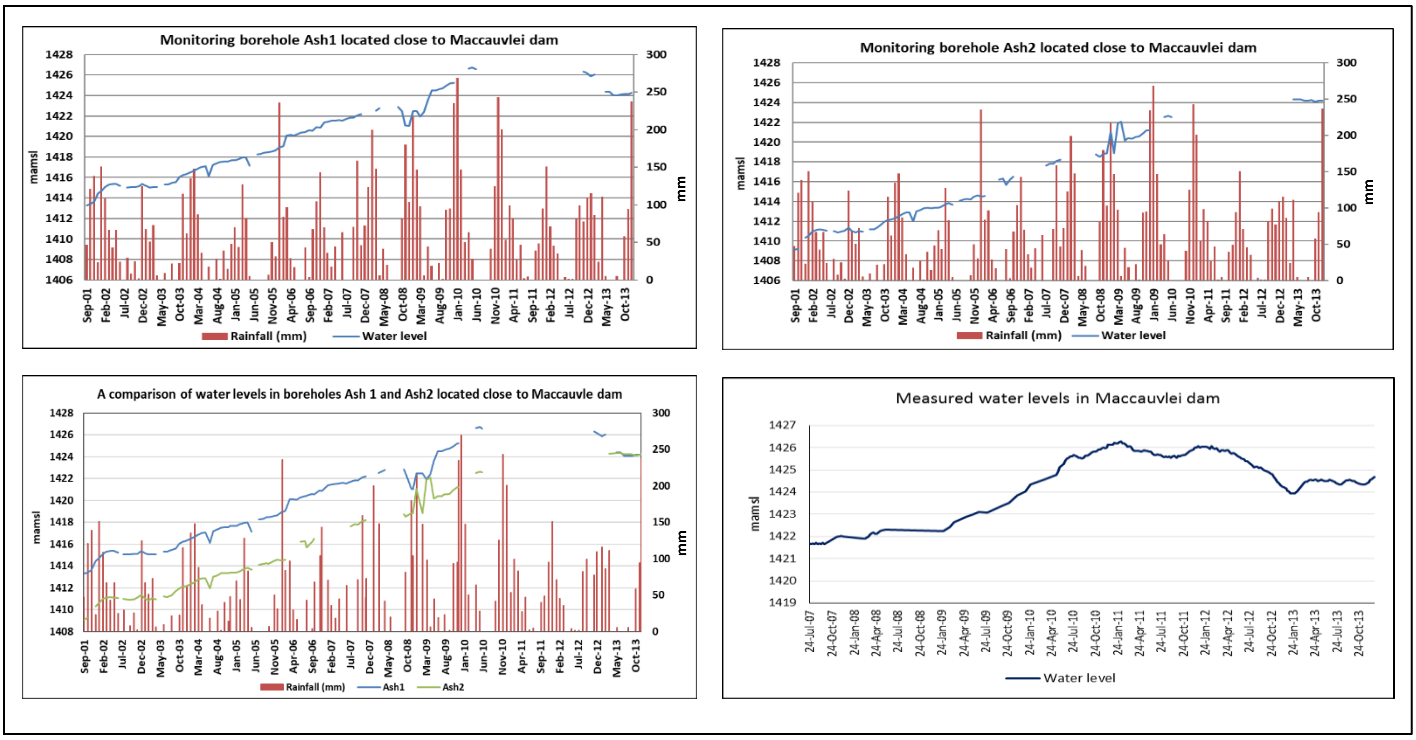

Figure 2.13: Monitoring boreholes in close proximity to the Maccauvlei dam and the ash dump


Borehole submerged in Maccauvlei dam water


Monitoring borehole without a sanitary seal and cap

Figure 2.14: Photo showing condition of some of the monitoring boreholes.

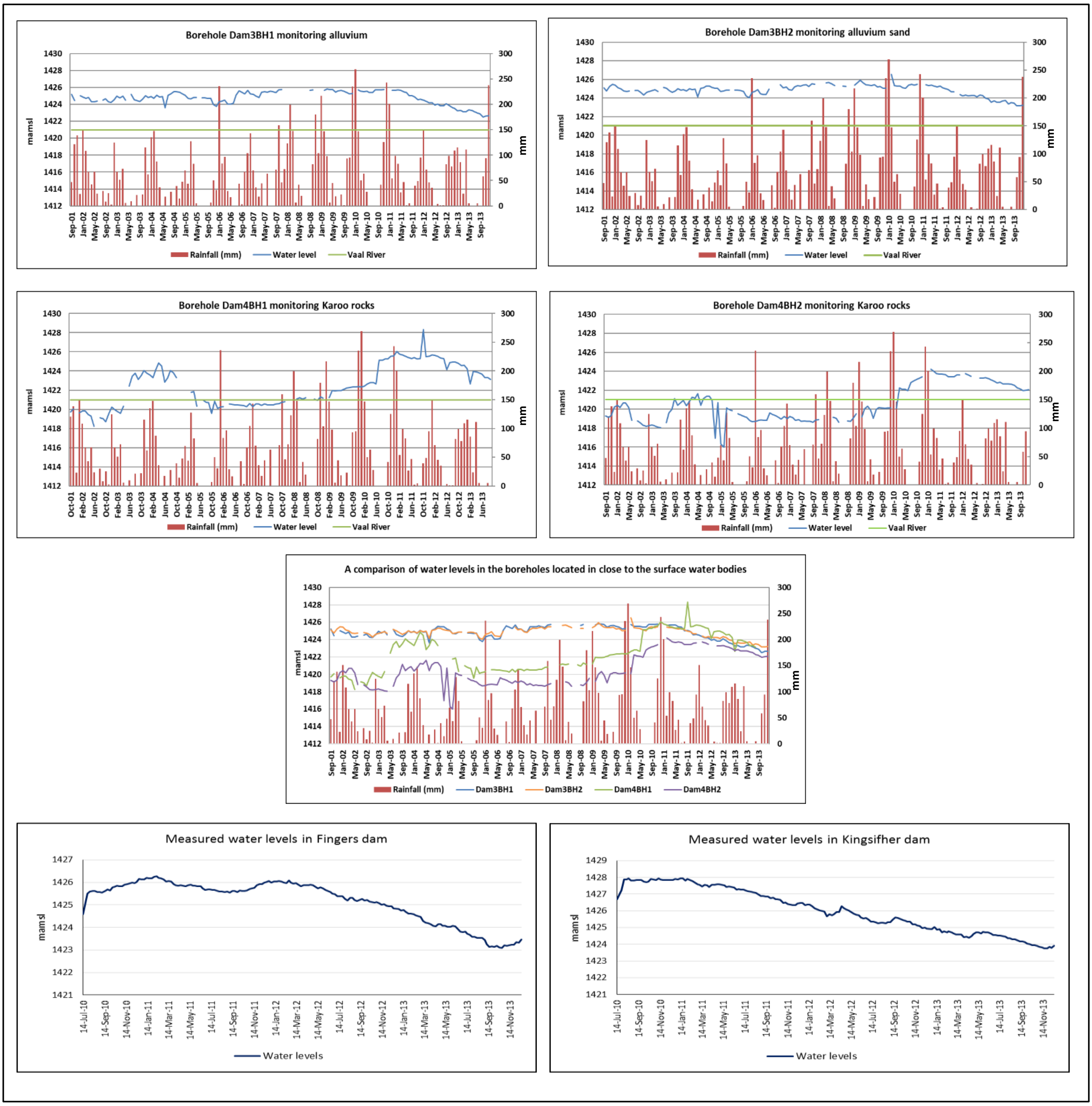

Figure 2.15: Water levels measured in boreholes located close to the surface water bodies

Boreholes Dam3 BH1 and Dam3BH2 show similar measured water level trends throughout the monitoring period (Figure 2.15.). The depth of boreholes, 14 meters for Dam3 BH1 and 11 meters for Dam3 BH2 indicated to the monitoring of the shallow alluvial sand aquifer between the mine and the Vaal river. For both boreholes, the water levels show fluctuations along a central axis until 2010 where after a general declining trend in the water levels is evident. During this period of declining water levels, it is noted that rainfall also shows a decrease, suggesting direct rainfall recharge drives water levels in the dam boreholes. A similar decline in water levels for monitoring period between 2010 and 2013 is noted in the Kingfisher dam (Figure 2.15). that is located in close proximity to the two boreholes. This suggests that there is a hydraulic connection between the dam and the boreholes that is significant enough to also influence groundwater levels in the alluvium sand adjacent to the banks of the Vaal river.

Dam4BH1 and Dam4BH2 generally have water levels below those of boreholes Dam3BH1 and Dam3BH2 (Figure 2.15). This remains true throughout the monitoring period excluding the period between end 2011 to end 2012 where the groundwater levels measured in Dam4BH1 were above those of Dam3BH1 and Dam3BH2. This difference in water levels for the period 2001 and 2011 supports the conclusion that Dam3BH1 and Dam3BH2 are monitoring a different aquifer from Dam4BH1 and Dam4BH2. Generally, the groundwater levels in Dam4BH1 and Dam4BH2 show similar trends with Dam4BH1 consistently having higher measured water elevations. Compared to borehole Dam4BH2, water levels measured in Dam4BH1 are generally above the water elevation at which the Vaal river is managed. This is excluding the monitoring period between end 2001 and the beginning of 2003 and again between mid-2005 and end 2007 during which the levels were below 1421 mamsl. Compared to rainfall, the changes in water levels are not strongly associated with rainfall trends. This suggest that rainfall is not the major mechanism controlling groundwater levels in the system.

4.2.3 Dolomite boreholes

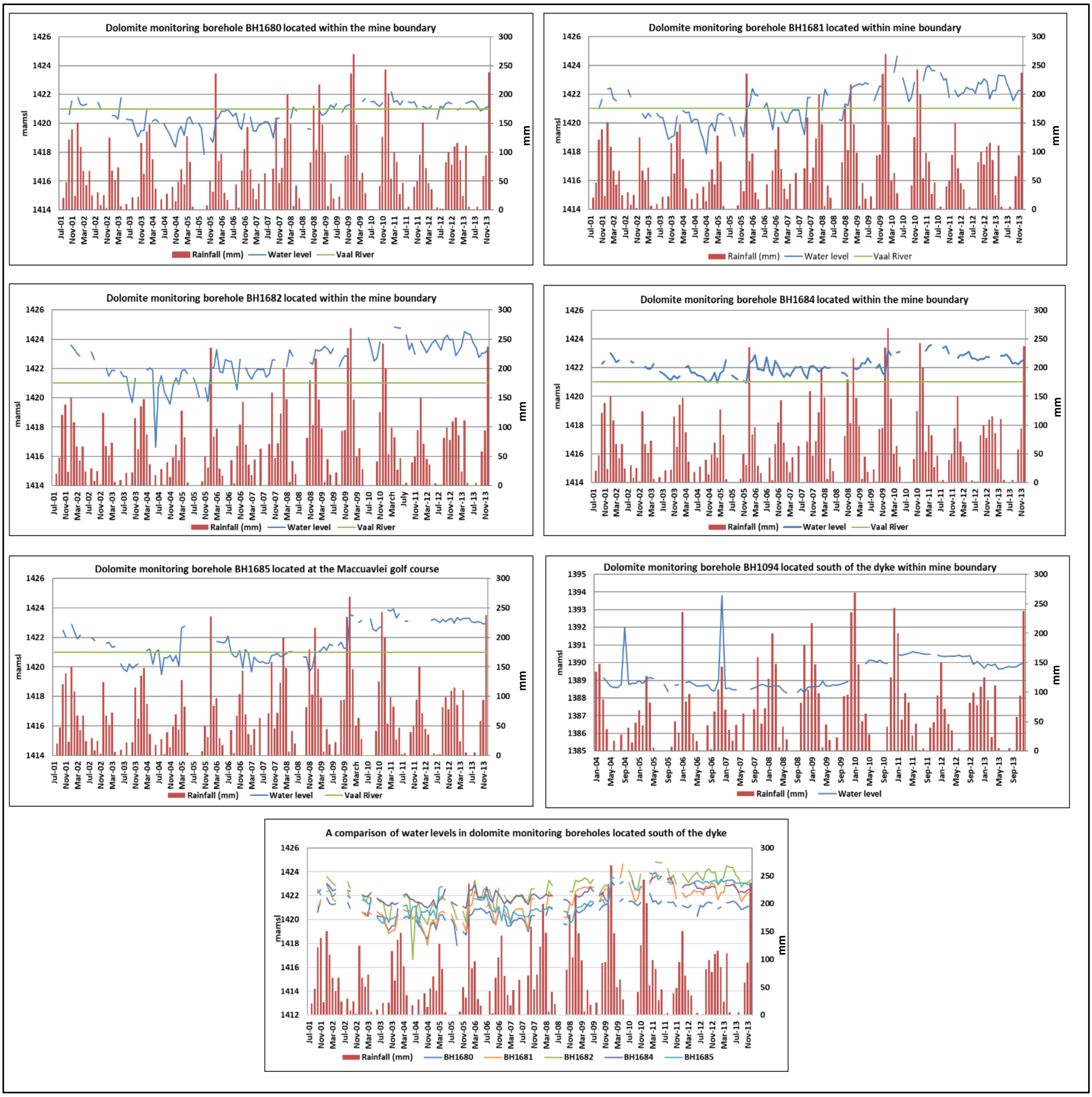

Figure 2.16: Water levels measured in boreholes monitoring the dolomite aquifer

All the dolomite monitoring boreholes show considerable fluctuations throughout the monitoring period. For boreholes BH1680 and BH1681, rainfall appears to have some influence on the water level fluctuations. While for boreholes BH1682, BH1684 and BH1685 there is no obvious pattern of influence from rainfall noted from the water level fluctuations. An overall analysis of the water levels compared to rainfall does not indicate rainfall as significant influencer of water levels within the dolomitic aquifer. Therefore, the influence that rainfall has over the water levels cannot be stated with confidence. The noted trends suggest that there is another factor having a greater influence on groundwater level fluctuations other than rainfall. This is most likely to be groundwater abstraction in the residential areas which is known to be common. The groundwater levels in BH1680 and BH1682 remain above 1421 mamsl, the level at which the Vaal river is managed. This is excluding the period between 2003 and 2009 for BH1680 and the period between 2003 and 2005 for BH1682. In contrast, BH1681 and BH1684 groundwater levels generally oscillate above the 1421 mamsl.

BH1094, unlike the other dolomite monitoring boreholes, is located south of the dyke in an area that has yet to be opencast mined. Groundwater levels in this borehole are significantly lower than the dolomite monitoring borehole levels recorded north of the dyke (Figure 2.16). This further supports the conclusion that the regional dyke is a low permeability to no flow boundary. The water levels in BH1094 generally remains below 1389 mamsl until end 2009. It is also noted that water elevations remain consistently lower than that of the average water level at which the Vaal river is managed. The rise in water levels corresponds with a relatively high rainfall period. However, rainfall does not appear have a significant influence on the fluctuating water levels.

4.2.4 Old underground mine workings boreholes

The New Vaal Colliery's old underground mine workings have areas that are still filled with water. In order to avoid intersecting large volumes of water during the opencast mining operations, dewatering of the underground workings takes place ahead of mining where possible. The Colliery has had a number of dewatering boreholes ahead of mining that have subsequently been destroyed as mining advanced. At the time of the study, dewatering of the old mine workings data was available from two boreholes namely, BH1108 and Mac West 3. The two boreholes have monitoring data records from 2004 to 2013.

4.2.4.1 Groundwater abstraction

At close evaluation, the water levels in both BH1108 and Mac Wes 3 show some correlation to rainfall trends (Figure 2.17). This suggests that rainfall is a significant contributor to the groundwater. Furthermore, compared to the pumping rates, it can be suggested that dewatering was not significant enough to mask the effects that rainfall has on water levels in the underground mine workings. However, the observed trend for Mac West 3 does not show a correlation to rainfall post 2011. This is the same period during which pumping from the workings ceased. The above observation provides an alternative theory that the water levels seemed to mimic rainfall due to pumping being initiated in response to rainfall events. A comparison of water levels between BH1108 and Mac West 3 suggest that the two boreholes are monitoring different compartments of the underground workings. Compared to water levels in the old mine workings pumping well BH1108 located in closed proximity to BH1094, groundwater levels (average of 1389 mamsl) in BH1094 (Figure 2.16) are significantly higher than those in BH1108 (average of 1374 mamsl). The same difference in water elevations is noted between Mac West 3 (average 1368 mamsl) and BH1094. This suggests that the dolomitic aquifer, being monitored by BH1094, is indeed a confined aquifer.

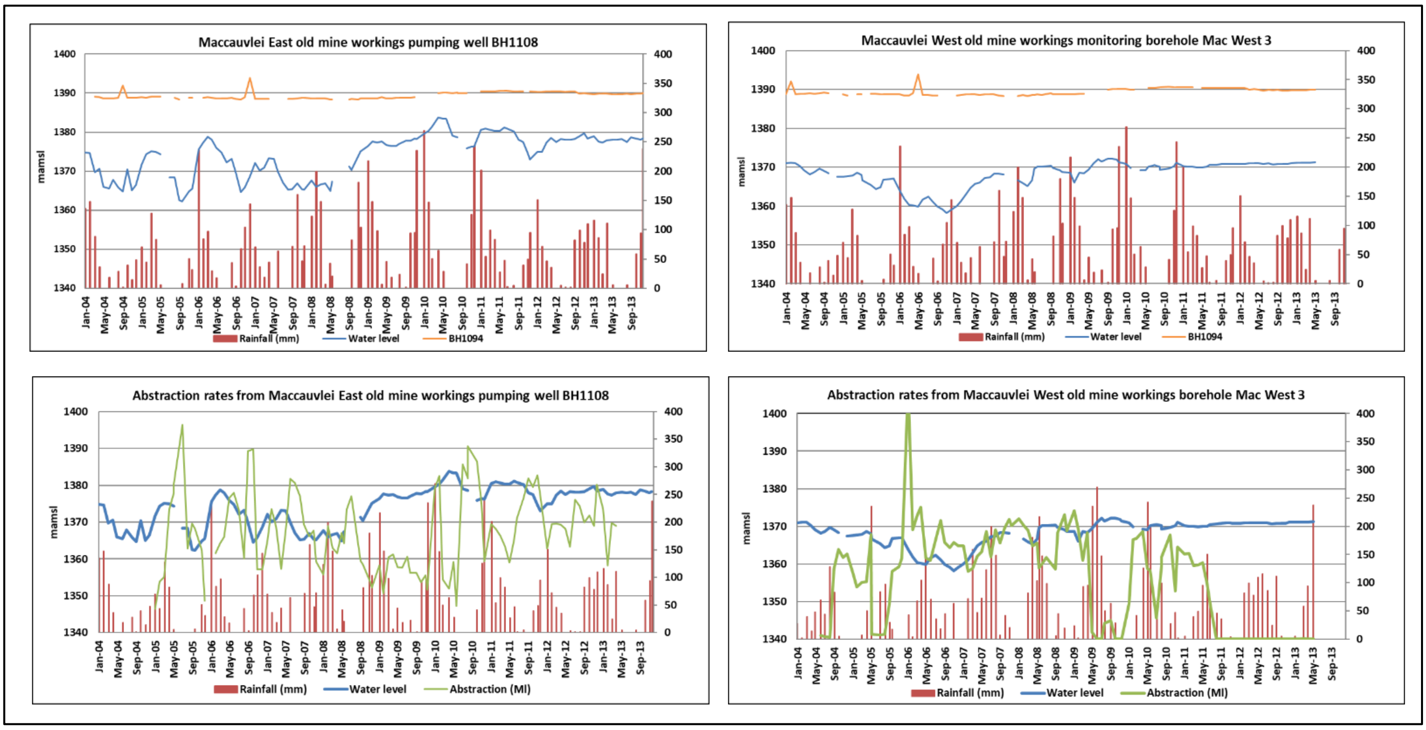

Figure 2.17: Groundwater levels in the old mine workings boreholes compared to rainfall and abstraction rates

4.2.4.2 Cornelia Colliery monitoring boreholes

The New Vaal Colliery's underground mine workings lie north of the Cornelia Colliery's old underground mine workings that are being monitored by boreholes BH2 and Bankfontein. The graben separating the two mines is monitored by a single borehole, BH491 Valley. The borehole water levels are not showing obvious seasonal fluctuation (Figure 2.18). This suggests that rainfall is not a significant influencer of groundwater for the underground workings. From the initial water motoring period towards end 2009, the water levels remained below 1404 and 1408 mamsl for Bankfontein and BH2 respectively, after which the water levels showed a significant increase of six meters by 2012 in both boreholes. Such a trend suggests that the levels are portraying the flooding stages of the mine voids. It is also noted that it was around the same period of high rainfall experienced in the area. Compared to the New Vaal boreholes, the Cornelia Colliery borehole water levels are at higher elevation. Therefore, the groundwater gradient is from Cornelia Colliery towards New Vaal Colliery's mine workings.

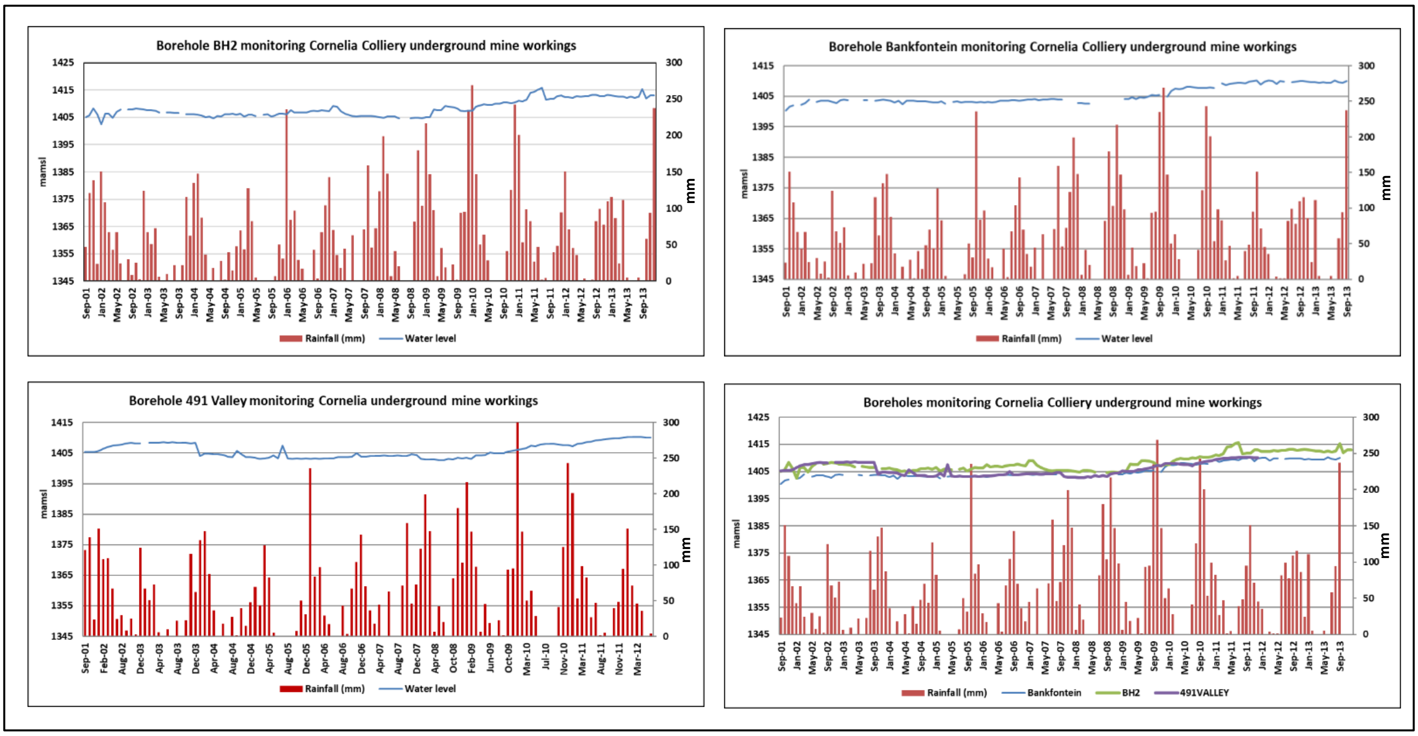

Figure 2.18: Monitoring boreholes targeting Cornelia Colliery's underground mine voids.

CHAPTER 5: CONCEPTUAL MODEL

A number of studies were conducted pre-opencast mining in the New Vaal area to understand the implication of mine dewatering on the availability of groundwater for the Vereeniging community and also to gain better understanding of the hydrogeological conditions in the area. These studies, together with the monitoring data collected over the years will be used to support the conceptual groundwater models presented in the study. The mining history in the area, geological context of the area and proximity to the Vaal River contribute to complexity of the system. As a result, it is important that the principle of simplicity is followed.

5.1 HYDROSTRATIGRAPHY AND HYDRAULIC PROPERTIES

Orpen and Wiegmans (1983) completed one of the first hydrogeological investigation at New Vaal focusing on the potential impacts of mining on groundwater levels in Vereeniging. A survey of private boreholes and exploration boreholes, all of which intersected the dolomitic aquifer, was conducted. In their study, Orpen and Wiegmans (1983) identified two major groundwater systems in the area the first being the Karoo Supergroup rocks coupled with the overlying alluvium sand and the second aquifer system being the Transvaal Supergroup dolomitic aquifer system. Hodgson (1983) however, identified five distinct hydrogeological units. These units included, the alluvium sand, Ecca group of rocks and coal, Dwyka, transitional zone and dolomites of the Transvaal Supergroup. This study follows the classification followed by Witthüser and Holland (2015) who identified three major hydrogeological units namely, the shallow aquifers, Karoo aquifers and aquicludes and the pre-Karoo aquifer and aquiclude. Within the major units are sub-units as described below.

5.1.1 Shallow aquifers

5.1.1.1 Shallow alluvium sand

Both Hodgson (2005) and Witthueser and Holland (2015) identified the shallow alluvium sand and the weathered Karoo aquifer as aquifer system in the study area. However, the mine's geologists maintain that the weathered Karoo zone is not commonly noted in the area as a result, this study will focus only on the alluvium sand. The aquifer is an unconfined to confined predominantly homogeneous fined grained sand. Water is generally intersected at the fresh bedrock (hard overburden) interface as well as in the coarser layers of the alluvial material, particularly at the bottom boulder beds (Witthüser and Holland, 2015). In certain parts of the high wall, seepage can be seen flowing out from the bedding plane between the sand and underlying strata (Figure 2.19).

Figure 2.19: Seepage from the interface between the hard overburden and shallow alluvium sand

The fine grained nature of the material suggest that the aquifer is a low yielding aquifer. This is supported by findings from Hodgson (2005) who reported borehole yields of less 0.1 L /s, excluding areas where boulder beds have been encountered. According to WRC (2005) after Bouwer (1978) and Domenico and Schwartz (1990), fine grained sand can be expected to have hydraulic conductivities that range between 0.106E-06 m/s and 0.706E-06 m/s. The values are in line with pump test conducted on site by Orpen and Wiegmans (1983). According to Orpen and Wiegmans (1983) pump test results, the fine grained material has an estimated hydraulic conductivity of 0.463E-06 m/s with an associated storage coefficient of 0.5E-03. Coarse material intersected had a hydraulic conductivity between 38.2E-03 m/s and a storage coefficient of 0.10E-03. The associated storage coefficients are commonly indicative of unconfined to semi confined aquifer conditions (Orpen and Wiegmans, 1983). Given the storage values, Orpen and Wiegmans (1983) accepted an effective porosity value of 5 percent for the fine sand and 10 percent for coarse sand in their study

5.1.1.2 Shallow perched aquifer

Within the alluvium is a series of perched aquifers formed as a result of infrequently occurring, discontinuous high yielding boulder beds (Hodgson, 2005). Although the boulder beds are noted as being high yielding, their limited spatial extend inhibits long terms yields. Water levels in the aquifers are influenced by rainfall and expected to be shallow due to the low permeability clay layer over which the aquifer is perched. The clay layer is generally at an average depth of 10 meters from the top of the alluvium sand. Subsurface flow is dominated by lateral movement of water as a result of the clay layer (Figure 2.20). Potential impacts of the perched aquifers are viewed as being insignificant and can therefore be excluded from the conceptual model. Witthüser and Holland (2015) also shared this view as they stated that the perched nature of the aquifer disconnects it from mine inflow related hydraulic impacts.

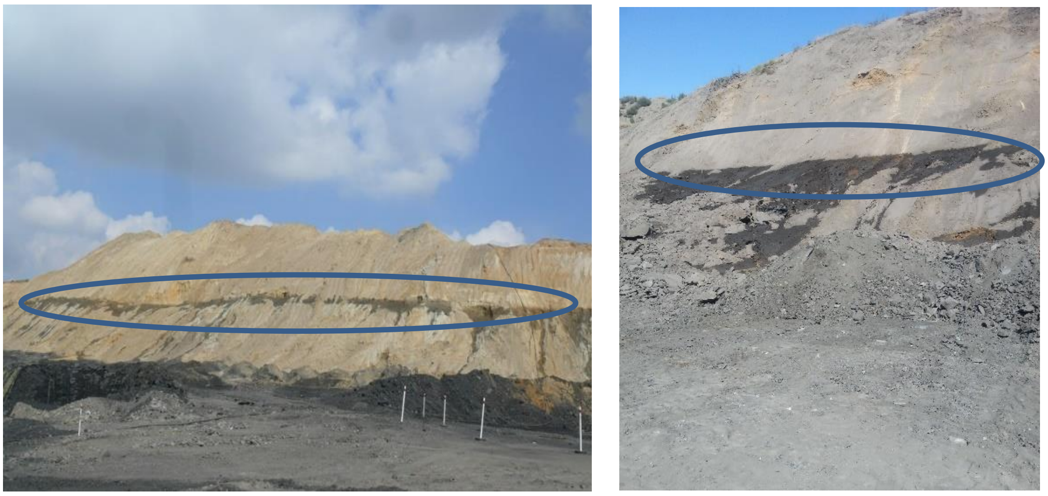

Figure 2.20: Lateral seepage flow from the perched aquifer

5.1.1.3 Artificial mine aquifer (backfill material)

Land rehabilitation takes place concurrently with mining. Mine voids are filled with spoils and discard, compacted, dressed with layer of alluvium sand and seeded. The spoil and discard material form the artificial mine aquifer that comprises unconsolidated, poorly sorted rock material. Consequently, the aquifer can be expected to be heterogeneous in nature on a local scale. Given the spatial extend of the mined-out areas, a new unique artificial mine aquifer with distinctively different hydraulic properties compared to the rest of the study area, can be classified. Despite the aquifer covering a large portion of the mine and potential impact on the water balance of the site, there are no site-specific data of the hydraulic properties such as the aquifer. This is viewed as a major data gap and limitation for the conceptual model.

5.1.2 Karoo aquifers and aquiclude

5.1.2.1 Deep fracture Karoo aquifer

The deep fractured Karoo aquifer lies below the shallow alluvium sand aquifer. The aquifer is classified as confined to semi-confined with fracture flow as the dominant groundwater flow mechanism. It is characterised by sedimentary lithologies of the Vryheid formation of the Ecca Group as described in Chapter 3, 3.3. According to Witthueser and Holland (2015), secondary porosities arising from faults, joints, fractures and bedding planes or other geological contacts control groundwater flow, while the rock matrix, according to Hodgson (2005), remains impermeable to flow. The coal seams are highly fractured (Hodgson,1983) however, majority of fractures have been partially cemented by calcite consequently making the coal seam low yielding in nature. Hodgson (1983) described the fractured Karoo aquifer as having poor to moderate water bearing properties, with yields between 0 and 3 L/s linked to fracture zones and bedding planes. The seepage flow is often observed in exposed sections in the pit along the high-wall strata bedding plane. However, groundwater flow is commonly thought to be along fracture zones which create a hydraulic connection between the different lithologies of the Vryheid Formation. Permeabilities assigned to the coal seams varied between 0.12E-09 m/s and 0.58E-06 m/s (Hodgson, 1984) however, an average permeability of 0.58E-06 m/s and storage coefficient of 1E-03 (Hodgson *et al.*, 1997) have been suggested. Woodford and Chevallier (2002) suggested permeability ranging 0.19E-9 to 19.26E-6 m/s and porosity range between 2 and 10 percent for the fractured Karoo aquifer sandstones and siltstone.

Figure 2.21: Lateral seepage flow from geological contact zone (bedding plane)

5.1.2.2 Artificial mine aquifer (underground mine voids)

Similar to the backfilled areas, the old mine workings form an artificial aquifer. The voids form of high porosity and permeability aquifer superimposed on the natural fractured Karoo aquifer. It comprises of the Top, Middle and Bottom coal seams mined by the bord and pillar method. The extraction rate for all the seams is 65 percent which effectively represents the porosity for the aquifer. Groundwater flow is expected to simulate flow throw a tunnel and as such, a conductivity value of 1 m/s was assigned to the mine voids. Potential influence of subsidence on the porosity and conductivity is noted, however, such occurrences have not been reported for the site. It is noted that within the mine workings, compartments have been created as a result of the undulating nature (paleo-highs) of the geology. This is supported by observations of dry and water filled bords, in some instances still pressurized mine void in different areas (Figure 2.22). Furthermore, there is evidence of constructed compartments which can be a limitation for quantifying the groundwater balance. Since details of their location and extent of compartmentalisation are not known they will therefore be excluded from the study.

Figure 2.22: Photos of different areas of the old mine workings showing areas that are dry, filled with water and an area with a constructed compartment wall.

5.1.2.3 Dwyka aquiclude

The role the Dwyka rocks play as a water barrier to flow was established with the initial hydrogeological studies at New Vaal pre-mining. During the investigation on the dolomites, Hodgson (1983) and Hodgson (1984) found evidence that the Dwyka sediment provide a barrier between the overlying fractured Karoo aquifer and the underlying dolomitic aquifer. Where present and undisturbed by mining, the irregularly developed tillite horizon of the Dwyka Group serves an impermeable barrier to vertical flow separating Bottom Seam floor from the underlying dolomitic aquifer. This conclusion is further supported by recent borehole water levels observed between the dolomitic aquifer and Karoo aquifers. (Chapter 4, 4.2). However, uncertainties with regards to the layer's lateral extend (thickness varies between 1 and 15 meters) and structural integrity bring into question its role as a water barrier throughout the mining area. Findings by Hodgson (1984) highlighted the heterogeneous nature of the aquiclude. Hodgson (1984) found that sections where the Dwyka sediments were predominantly shale, mudstone, sandstone and grit which would be expected to form a less effective barrier to flow. The Colliery has however, never reported incidents of significant groundwater flow into the pit through the Bottom Seam floor. This is despite a record from Hodgson (1984) of rare instances of significant flows and permeability from the aquiclude. Therefore, it is maintained that the Dwyka rocks form a groundwater flow barrier between the fractured Karoo and dolomite aquifer and where flow does occur, it is through fractures and joints. The expected hydraulic conductivities fall within the range of 0 to 0.12E-6 as suggested by Witthueser and Holland (2015). Porosity which is a result of fractures is estimated to range between 0.5 to 1.3 percent (Woodford and Chevallier, 2002).

5.1.3 Pre-Karoo aquifer and aquiclude

5.1.3.1 Dolomite aquifer

The dolomite aquifer includes the transitional zone underlying the Dwyka Group characterised by highly permeable chert pebbles (Hodgson, 1983 and Orpen and Wiegmans, 1983). The aquifer underlies most of the study area apart from the far south west area that Orpen and Wiegmans (1983) stated that the Dwyka lies directly above the Ventersdorp Supergroup lavas. The dolomitic aquifer is confined with a transmissivity range between 10 and 100 m^2/d and a storage coefficient of 0.1E-03 to 0.1E-06 Hodgson *et al*. (1997). Witthueser and Holland (2015) in comparison calculated a transmissivity of 75 m^2/d based on pump test data from Hodgson (1983). According to Hodgson (1983), the rate rapid at which dewatering cone spread showed that the dolomitic aquifer had limited storage.

5.1.3.2 Ventersdorp aquiclude

Ventersdorp aquiclude is made up of the thick succession of lavas of the Klipriviersberg Group of the Ventersdorp Supergroup. Their impermeable nature makes this lithology an ideal lower barrier of flow and marks the lower boundary of the dolomitic aquifer.

Table 2.5: A summary of hydraulic conductivity for the New Vaal aquifers and aquiclude

Rock type	Average conductivity		Conductivity range
	(m/d)	(m/s)	(m/s)
Alluvium sand aquifer		0.463E-06 m/s	0.106E-06 to 0.706E-06
Artificial mine aquifer (Backfilled area)	No data	No data	No data
Fracture Karoo aquifer	5.01 E6	0.58E-06	0.12E-09 m/s and 0.58E-06 m/s 0.19E-9 to 19.26E-6 m/s
Artificial mine aquifer (mine voids)	86400	1	N/A
Dwyka sediments aquiclude	8.6E-04	1E-08	0 to 0.12E-6
Dolomites aquifer	4.32	5E-05	10 to 100 m^2/d
Ventersdorp aquiclude	No flow		

5.1.4 Geological structures

Faulting and dolerite intrusions are the most common geological features at New Vaal. The significance of the faults with regards to groundwater are not well documented and therefore the hydraulic parameters are not known. With that said, Orpen and Wiegmans (1983) suggested that some of the faults and dykes can act as mechanism for groundwater flow into underground workings. When intersected, the faulting and dykes have the potential to yield sudden rushes of water (Orpen and Wiegmans,1983). According to Orpen and Wiegmans (1983), a large volume of water from the dolomites was intersected through the dolerite dyke in Bottom Seam old mine workings. Inspection of the faults in the current opencast operations does not provide evidence of the statements made by Orpen and Wiegmans (1983). This potentially due to the structure being dewatered as dewatering activities takes place ahead of mining. However, occurrences of low impact (on mining) inflows, associated with pinnacles (doline structures) and underground compartments have been experienced (Figure 2.23). These inflows are sporadic and not commonly encountered. However, without further evidence of the water bearing nature of the faults, their significance with regards to groundwater flow cannot be conclusively stated.

In comparison, the regional east west trending dyke in the northern portion of the mine forms a barrier to groundwater flow as confirmed through pump test conducted by Hodgson (1983). The dyke compartmentalises the dolomite aquifer into a northern and southern sections.

Figure 2.23: Water accumulation in the vicinity of a pinnacle (doline structure) and water flowing out of the mine workings.

5.2 SURFACE AND GROUNDWATER INTERACTION

5.2.1 Vaal river and shallow aquifers

Orpen and Wiegmans (1983) indicated that the Vaal River was losing water along the eastern boundary and a portion of the northern boundary of the mine. Therefore, the mine loses water to the Vaal river on the western boundary and along a portion of the northern boundary (Figure 2.24). Applying Darcy's law, the recent monitoring data (Chapter 4) indicate that the groundwater flow that was present pre-opencast mining has been reversed. Borehole water levels in the artificial aquifer have maintained an elevation above that of the Vaal River (1421 mamsl) between 2008 and 2013. The shallow alluvium aquifer boreholes also having recorded water levels above that of the Vaal River support this conclusion as well. Therefore, it can be expected that the Vaal river receives seepage from the mine. This view is further substantiated by water quality data from SRK (2012) (Figure 2.25). SRK (2012) indicated that Vaal river's total dissolved solids (TDS) changed from an average of 189 mg/l (Station Number 177904) upstream of the Vaal (Adjacent the Ash dump) to 577 mg/l upstream of Maccauvlei dam before it decreased to 254 mg/l at the Suikerbos water purification works upstream of the Suikerbosrand river. With the aforementioned it can be concluded that a hydraulic connection exists between the Vaal River and the shallow aquifer systems.

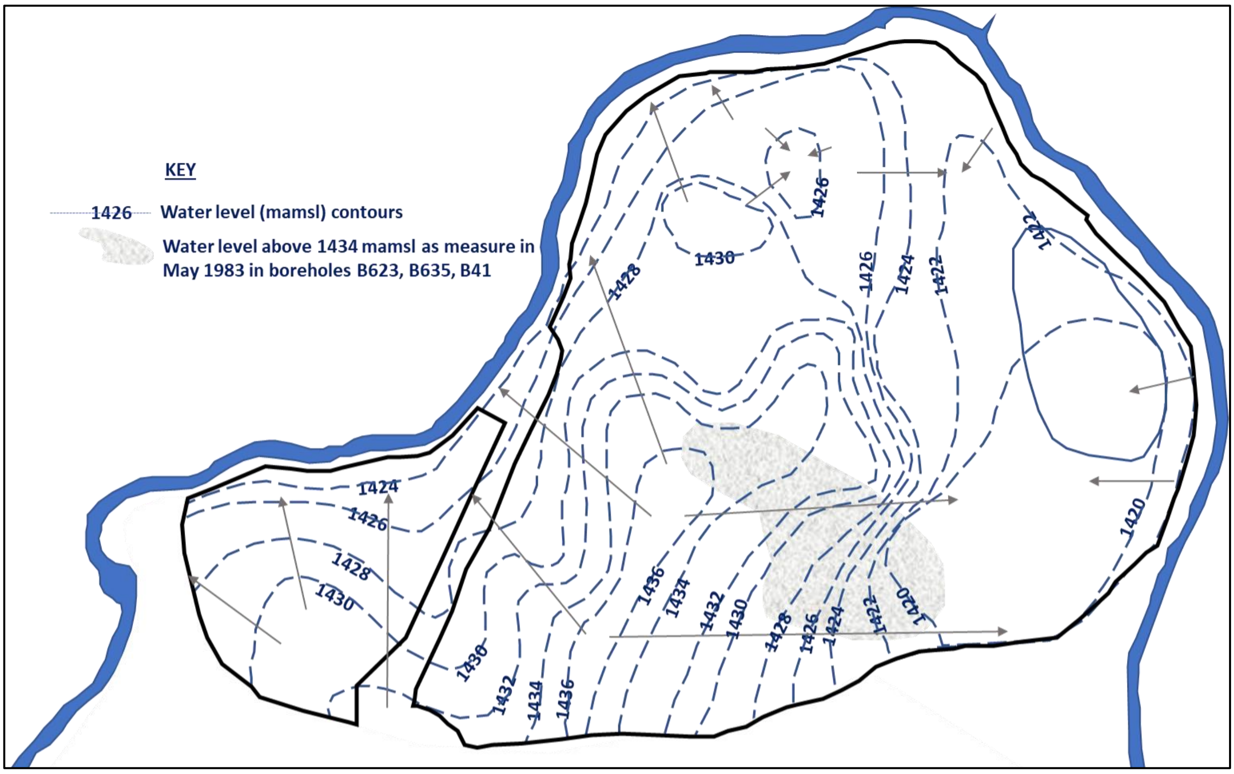

Figure 2.24: Groundwater flow at New Vaal pre- opencast mining (Orpen and Wiegmans, 1983).

Figure 2.25: Total dissolved solids (TDS) of surface water at New Vaal and the Vaal River (SRK, 2012).

5.2.2 Dolomite aquifer

The water elevations (average of 1422 mamsl) in the dolomite boreholes are generally above the Vaal river water level (1421mamsl) as a result of the confining Dwyka tillite layer. According to Witthueser and Holland (2015) the dolomitic aquifer water level would have equilibrated with the Vaal river level if the two systems had a significant hydraulically connected. The current data indicates that there is little to no connection between the Vaal River and dolomite aquifer.

5.2.3 Shallow aquifers and Storage dams

Spoil borehole water levels indicate that rainfall is not the main source controlling the shallow artificial mine aquifer levels. Instead, Maccauvlei dam water levels show a strong influence on the water levels in all boreholes monitoring the artificial shallow primary aquifer. The trends noted suggest a significant hydraulic connection between Maccauvlei dam and the artificial aquifer. Similarly, boreholes located between the dams and the Vaal River do not show rainfall as significant influencer on the groundwater levels. Instead, the water level fluctuation corresponds significantly with changes in water levels in the dams. Therefore, all the unlined dams onsite can confidently be assumed to be the main controlling factor of groundwater levels by means of losing water to the aquifer systems.

5.3 GROUNDWATER RECHARGE AND DISCHARGE

5.3.1 Recharge

The main source of recharge is rainfall infiltration into the shallow primary aquifers. Recharge to the deep Karoo aquifer is through the fracture system that hydraulically connects it to the shallow aquifer. The fracture system is heterogenous in nature and does not have preferential spatial orientation. This limits the controlling mechanism of recharge to the deep Karoo aquifer to the preferential flow paths. However, since mining can induce fracturing due to blasting, preferential flow paths for recharge can be created. Additional recharge sources include the dams, depressions and potential intermine flow where the prevailing groundwater gradient is from the dams/Cornelia Colliery towards the aquifer (that is, the dams and depressions lose water to the aquifer).

Groundwater recharge estimation studies have been conducted for different catchments in South Africa. Vegter (1995) and the water research commission (WRC) GRAII 2005 report are examples of commonly cited recharge estimates studies. For the C22F (Upper Vaal catchment), the recharge value estimated by Vegter (1995) is 47 mm/a which is 7 percent of MAP of 655 mm and the GRAII estimated recharge value of 35 mm/a which is 5.3 percent of MAP of 655 mm for the undisturbed weathered Karoo aquifer. However, these studies are at a catchment scale and not necessarily applicable to a highly-altered mining environment. The estimated values suggested by Hodgson and Krantz (1998) for an opencast environment can be used for New Vaal's conceptual model in the absence of site specific data (Section 2.2.5, Table 2.2). Recharge estimates for the old underground mine sections are also expected to vary according to the mining method used. According to Vermeulen and Usher (2006) based on the underground mining method used the recharge values in (Section 2.2.5, Table 2.1) are applicable. In the case of New Vaal's old underground mine workings, recharge would be expected to range between 3 and 10 percent of the MAP. However, the nature of the permeable thick sand aquifer suggests that a higher recharge value should be considered. Hodgson (2010) suggested recharge values ranging between 20 and 30 percent (approximately 131 to 197 mm/a) of MAP. Recharge of the alluvium sand aquifer was previously estimated to be 20 percent of the annual rainfall by both Hodgson (2005) and Orpen and Wiegmans (1983). The high recharge value was attributed to vegetation clearing which subsequently reduced the rate of evapotranspiration losses and increased infiltration. Based on Hodgson and Krantz (1998) and Vermeulen and Usher (2006) the range of recharge values at New Vaal can be expected to be as follows (Table 2.6):

Table 2.6: Recharge estimates for New Vaal Colliery based on recommendations from Hodgson and Krantz (1998).

Unit	Mean Annual Recharge	
	(% of MAP)	(mm/a)
Alluvium Sand	20	131
Ramps and open mine voids	60	393
Spoils (still to be levelled)	70	458.5
Rehabilitated spoils	15	98

5.3.2 Discharge

Groundwater leaves the model domain as part of regional groundwater flow. This flow is from the north east to the south west. Dewatering from the pit is by far the most significant groundwater discharge mechanism within the model domain. The 2013 data shows that on average, 31 ML/d (370 L/s) of water was dewatered from the pit. The effect that the abstraction has on the groundwater levels fluctuation in the backfilled material can only be assumed due to the absence of monitoring boreholes close to the pit. However, the groundwater gradient is obviously towards the pit. And since Maccauvlei dam appears to be the main control of water levels in the backfill, then there is a certain amount of water recirculation within the system.

Figure 2.26: Groundwater levels for New Vaal Colliery

Groundwater gradient indicates that discharge also occurs from the mine into the Vaal River, making it a gaining stream along the north eastern boundary whereas it is a losing stream along the western boundary. The operational phase groundwater gradients contradict the pre-mining conceptualisation by Orpen and Wiegmans (1983) which showed groundwater flow from where the pits would be today to a vlei as well as from the Vaal River towards the vlei on the eastern boundary of the mine. That is, the Vaal River was a losing stream whereas on the western boundary, the groundwater gradient was towards the Vaal river making it a gaining stream along the north east boundary (Figure 2.24).

5.4 MODEL BOUNDARIES AND DOMAIN

5.4.1 Model domain and boundaries

New Vaal colliery's groundwater modelling objectives are focused on understanding the dynamics controlling groundwater flow within the mine and by effect, influencing the overall mine water balance. Therefore, it is necessary to ensure that boundary conditions defining the model extremes are defined such that impact that water sources and sink have on the water balance are well represented. In the absence of physical boundaries, the model domain is dependent on data availability and probable influence of the boundary on the model output.

A similar approach used by Witthueser and Holland (2015) was employed to define the model boundaries and consequently, the model domain. Although the shallow aquifers extend beyond the Vaal River, their hydraulic properties together with the Vaal River limit potential propagation of the dewatering cone beyond the Vaal River. The same is applicable for the Karoo aquifers whose hydraulic properties limit the dewatering cone within the immediate area of the colliery. Consequently, the artificial mine aquifer’s influence is limited by the deep fractured Karoo aquifer within which it is superimposed. As a result, limiting the model domain to the Vaal River is acceptable. These views are aligned with those proposed by Orpen and Wiegmans (1983). Orpen and Wiegmans (1983) stated that the likelihood that the dewatering cone would extend across the Vaal River was relatively low.

It is however noted that the dolomite aquifer extents further north beyond the Vaal river and southwards towards Cornelia Colliery. With respect to the inclusion of northward extension of the dolomites, groundwater abstraction within the town of Vereeniging would have to be taken into consideration. The abstraction boreholes would constitute a well filed conceptualisation which is not within the scope of the study and further introduce unknown parameters associated with the abstraction. Furthermore, Hodgson (1984) illustrated that the impacts on the dolomitic aquifer in Vereeniging due to mine dewatering would be insignificant. It is therefore deemed sufficient to maintain the East, North and West boundaries along the Vaal River and utilise current borehole monitoring data to assign a boundary condition. The southern boundary is marked by southernmost fault that forms part of the prominent geological graben. Selection of the southernmost fault allows for the incorporation of BH491 located in the graben.

Cornelia Colliery, located adjacent to the graben, potentially has a significant influence on groundwater flow at New Vaal Colliery due to prevailing gradient. However, it is excluded from the model domain as inclusion would require a simultaneous flooding model for the mine for which there are limited data is available. The closed Colliery cannot however, be completely excluded from the model conceptualisation. Therefore, borehole water levels targeting the underground mine workings of Cornelia will be used to assign a boundary condition to account for its influence on the New Vaal Colliery groundwater balance.

5.4.2 Model boundaries

All three types of boundary conditions, Dirichlet (first type boundary) where a hydraulic head is specified, Neumann (second type boundary) where a flux or flow is specified and a head dependent boundary known as Cauchy (third type boundary) can be assigned to the New Vaal model domain. The following boundaries were assigned:

- The dolomite aquifer and Cornelia Colliery were assigned a first type boundary based on a full hydrological year's average water levels of 1423 mamsl and 1411 mamsl respectively. Assigning a constant head boundary to the dolomite aquifer and Cornelia has the disadvantage of infinite water flow into the model. However, it does have the advantage of including both aquifers without the introduction of new uncertainties and minimising the model complexity.
- The second type boundary (recharge) was assigned to the surface of the model. Recharge values are assigned based on the aquifer type as outlined in Section 5.3.
- The third type (leakage) boundary was assigned to the Vaal River and all the dams on site. However, leakage rate from the surface water bodies is unknown and therefore a limitation in terms of model conceptualisation. This limitation can be overcome through future field work or by translating the conceptual model into a numerical or mathematical model.

5.5 IDENTIFIED GAPS

New Vaal Colliery has a substantial groundwater monitoring dataset however, a number of gaps have been identified. The following are data gaps identified:

- There are no site specific hydraulic parameters for the individual aquifers that can be used for groundwater flow modelling purposes with the exception of the dolomite aquifer. Specifically, for the rehabilitated backfilled areas which cover an extensive area and are likely to have a significant impact on the groundwater balance.
- The borehole spatial distribution is skewed to the northern section of the mine. The southern portion has only two underground mine void monitoring boreholes and a single dolomite monitoring borehole. There are no boreholes in the backfilled areas of the West pit and alluvial sand aquifer.
- Furthermore, there are insufficient boreholes targeting the different aquifers. Boreholes monitoring the fractured Karoo Aquifer are limited to the two boreholes Dam4 BH1 and Dam4 BH2 and there are no boreholes into the Main pit underground mine workings. Consequently, the groundwater gradient between the Vaal River and the mine as well as the graben and mine cannot be determined with certainty.
- Previous studies have assumed that there is no interaction between the mine and the Vaal River. The basis for this conclusion is not recorded and there have been no follow-up studies confirming the detached nature of the Vaal River. Studies conducted in the past by Hodgson (1985), focused on understanding the interaction between the dolomite and the artificial mine aquifer (mine voids) as well as the Vaal river and the dolomite aquifer.

- Borehole construction for majority of the boreholes is not well documented and a number of the boreholes do not have caps and/or collars.

Closing of the gaps was limited by costs and time constraints. As a result, drilling new boreholes in order to get a better representative spatial monitoring distribution for each aquifer was excluded. The following gaps were targeted as part of this study:

- Determining the hydraulic conductivity and specific yield for the rehabilitated backfilled area.
- Determining the groundwater gradient between New Vaal's southern boundary and Cornelia Colliery's northern boundary.
- Surface and groundwater interaction

5.5.1 Newly drilled boreholes

5.5.1.1 Graben and Maccauvlei West boreholes

One borehole, Mac West 5, targeting the fractured Karoo aquifer was drilled between the Maccauvlei West old underground mine workings and the Vaal River. The borehole was drilled to a depth of 52 meters and a solid case installed to exclude the shallow alluvium sand. The measured water elevation in the borehole was 1413 mamsl (or 17.88 mbgl). The borehole water level indicates that the groundwater elevation is lower than that of the Vaal River in the western boundary of the mine. That is, the prevailing gradient is from the New Vaal towards the River. The River is likely to gain water along the eastern boundary (and a portion of the northern boundary) and lose water along the western boundary of the Mine.

Two additional boreholes, namely Graben 1 and Graben 2, where drilled in the graben area between New Vaal Colliery and Cornelia Colliery. The two boreholes were drilled in order to calculate the water gradient between the two mines and determine the direction of groundwater flow. The locations of the boreholes were limited by access to the drilling site and proximity to the existing borehole, Bh49C. Both boreholes were constructed to allow for monitoring of the Karoo aquifer while excluding the overlying alluvium sand. Drilling stopped once the characteristic whitish coarse grained material of the Dwyka Group was intersected. Graben 1 was drilled to 170 meters and Graben 2 to 120 meters. The measured water level was 1427 mamsl (or 19.68 mbgl) for Graben 1 and 1432 mamsl (or 12.87 mbgl) for Graben 2.

5.5.1.2 Slug test

Slug tests were conducted on two of the boreholes drilled into the aquifer to provide preliminary hydraulic properties. The resulting conductivity values between the boreholes differ by an order of magnitude possibly due to the poorly sorted nature of the backfill material or potentially different compaction rates. In addition to the slug test, a pump test was conducted to provide a better indication of both hydraulic conductivity and specific yield.

The slug test conducted targeting the alluvial sand indicated a hydraulic conductivity range between 0.52E-09 m/s and 0.590E-06 m/s. According to Witthüser and Holland (2015), the slug test results are typical of silty-clayey to sandy material.

Table 2.7: Estimated hydraulic conductivity from slug tests (Witthueser and Holland, 2015)

Borehole name	BH depth (mbgl)	Water level (mbgl)	Water level (mamsl)	Hydraulic conductivity	
				(m/d)	(m/s)
Spoil 1	27.95	0.68	1425	0.128	1.5E-06
Spoil 11	28.84	4.27	1425	2.582	3.0E-05
Dam3 BH1	13.11	3.77	1423	0.005	5.2E-08
Dam3 BH2	10.37	5.75	1422	5.105	5.9E-05
Dam4 BH2	11.30	8.40	1420	0.022	2.6E-07

5.5.1.3 Spoil boreholes

The last two boreholes, namely Spoil 14 and Spoil 15, were drilled into spoil material. The boreholes were drilled using ODEX with the intention of conducting a pump test on both boreholes. Spoil 14 was drilled approximately 20 meters from spoil 6 in order to used Spoil 6 as an observation borehole. Spoil 15 was drilled between the ash dump and the Maccauvlei East's main pit. The location of Spoil 15 was selected in order to get a water level closer to the pit however, this was limited by access for the drilling rig to the desired location. Drilled depth of Spoil 14 is 31 meters and Spoil 15 is 47 meters deep and a perforated casing installed in both boreholes. The water elevation in Spoil 14 was 1424 mamsl (or 3.42 mbgl) and the elevation in Spoil 15 was 1388 mamsl (or 43.35 mbgl).

A pumping test was conducted only on Spoil 14 as Spoil 15 did not have sufficient water to complete a pump test that would provide useful results. In order to get site specific hydraulic parameters for the shallow artificial mine aquifer, a pump test was conducted on Spoil 14 with spoil 6 serving as an observation borehole. A three-step test of 60 minutes per step was conducted. The first step was at a discharge rate of 3 l/s, followed by a discharge rate of 6 l/s and a final step of 9 l/s. A 24-hour constant discharge test was then conducted at a rate of 3.3 l/s. Water levels were measured in both boreholes Spoil 14 and Spoil 6. The pump test achieved a total drawdown of 8.56 mbgl in the pumping borehole and 0.13 mbgl in the observation borehole.

Renard *et al*. (2009) highlighted that there are often multiple solutions that can be used for the interpretation of field observations. Therefore, knowledge of the site's hydrogeological setting should be used as well. Based on knowledge of the site and the Kruseman and de Ridder (2000) and Renard *et al*. (2009) diagnostic plot guidelines (Figure 2.27 and Figure 2.28), the aquifer falls under a leaky unconfined aquifer. Based on the shape of the drawdown curves, the diagnostic graphs can be used to determine the aquifer type and solution(s) to use for data analyses. Figure 2.27 shows log-log and semi-log time-drawdown diagnostic plots for three types of unconsolidated aquifers, namely confined, unconfined and leaky aquifers. The solutions are valid for ideal conditions, for a homogeneous and isotropic aquifer pumped at a constant rate by a fully penetrating well (Kruseman and de Ridder, 2000). Since the time drawdown relationship is only linear at late pumping time in graph A' (Figure 5.9), then the late time pumping data should be used to calculate hydraulic characteristics. This is because matching field data plots with the curve of graph A' will be more accurate than matching field data plots with the curve graph A (Kruseman and de Ridder, 2000). Graph B and B' show diagnostic curves of unconfined, homogenous, isotropic aquifer of infinite extent. Graph B follows the curve for a confined aquifer similar to graph A at early pumping time (Kruseman and de Ridder, 2000). At medium pumping time the curve flattens, reflecting recharge from the less permeable overlying aquifer which consequently stabilises the drawdown (Kruseman and de Ridder, 2000). Furthermore, the curve follows a section of graph A at late times. In comparison, graph B' shows two early and late time pumping lines that are parallel which are characteristic for the type of aquifer (Kruseman and de Ridder, 2000). Graph C and C' are characteristic of a leaky aquifer (Figure 2.27). The graphs follow those of graph A and A' at early pumping times. According to Kruseman and de Ridder (2000) at medium time water from the aquitard reaches the aquifer. Ultimately, at late time the water pumped will be leakage from the aquitard. At this stage flow towards the well reaches steady state condition. Renard *et al.* (2009) presented similar diagnostic plots as shown in Figure 2.28. The shape of the derivative of the drawdown curve as indicated by the dashed lines is used together with the drawdown data curve represented by the solid line to determine the type of aquifer. According to Renard *et al.* (2009), the curves in Figure 2.28 describe the following types of aquifers: a) two-dimensional confined aquifer b) double porosity or unconfined aquifer c) infinite linear no-flow boundary d) infinite linear constant head boundary e) leaky boundary f) skin effect and borehole storage g) unlimited conductivity vertical fracture h) overall radial flow for non-integer flow dimension smaller than two i) overall radial flow with non-integer dimension greater than 2 and j) shows a effects of borehole storage and unlimited linear constant head boundary.

The pumping test data was plotted on a displacement versus time log-log graph from which the conceptual model used to determine the hydraulic properties was selected (Figure 5.10). The data was analysed using AQTESOLV 4.5 software package and the Neuman and Theis solution were used to estimate the aquifer parameters. Both solutions are valid for unconfined aquifers however, the Neuman solution is applicable for leaky aquifers while the Theis solution is applicable for nonleaky aquifers. The Theis solution is included for comparison purposes. Analysis indicated a specific yield (Sy) of 0.18 and transmissivity of 55 m^2/day.

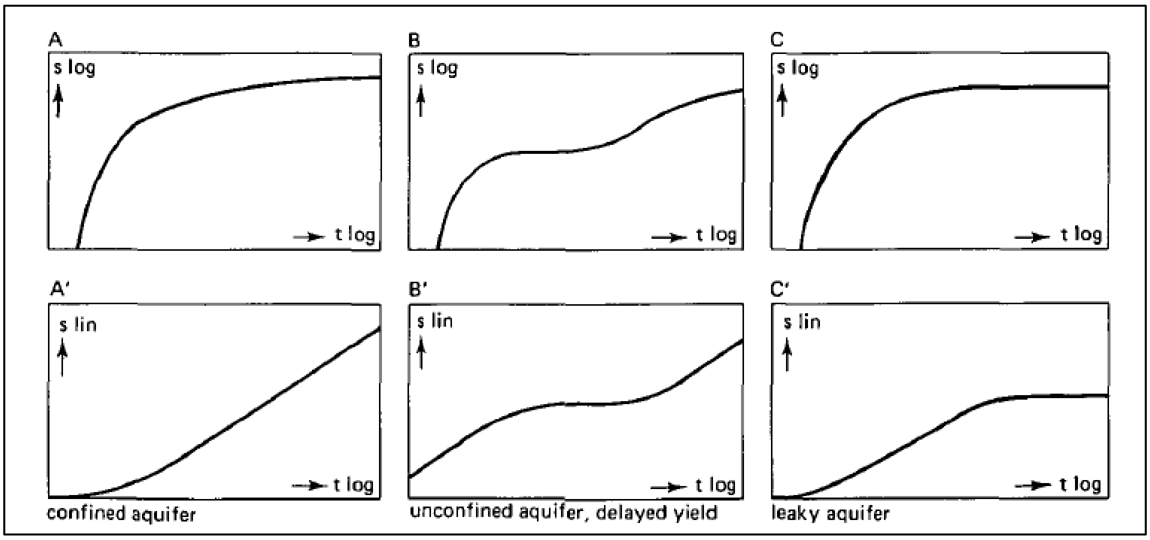

Figure 2.27: Diagnostic plots for a theoretical time-drawdown relationship for consolidated aquifers (Kruseman and de Ridder, 2000)

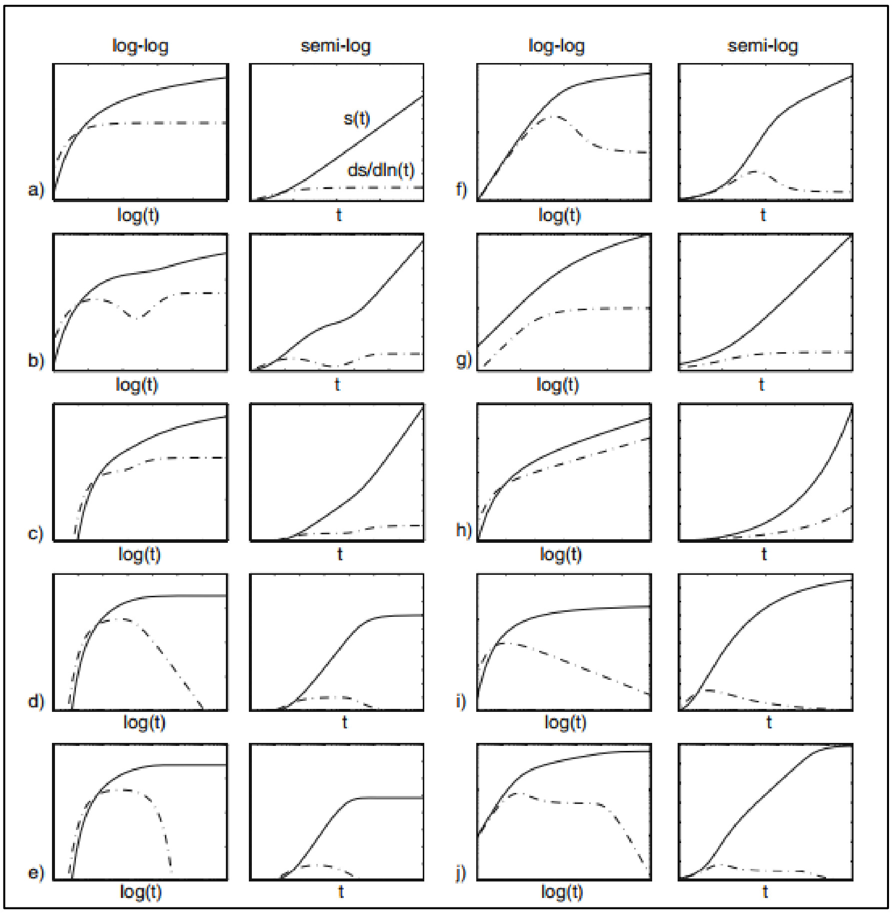

Figure 2.28: Common hydrogeological diagnostic plots (Renard *et al.*, 2009).

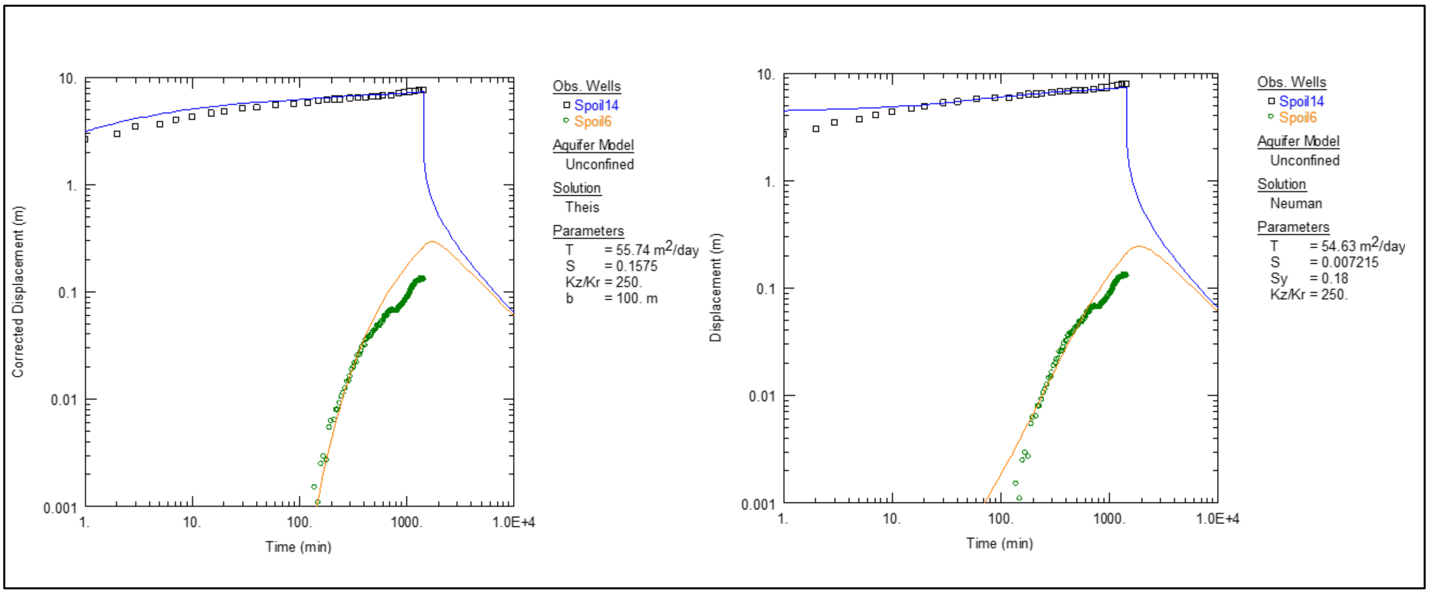

Figure 2.29: Diagnostic plots and hydraulic characteristics for Spoil 14 and Spoil 6.

5.5.2 Isotope analysis

Different isotopic signatures in water samples are a result of different processes through which the water has undergone. The New Vaal samples can be grouped into two groups, those associated with surface water and groundwater samples. Samples associated with surface water include a sample taken from Maccauvlei dam (Mac Dam), DVASCOT sample taken from the Vaal river at the Ascot on Vaal road bridge and Lethabo taken from the Vaal river adjacent Lethabo Power station, boreholes Ash1 and Dam 3 BH2. These samples show a significant deviation from the local meteoric water line (LMWL), an indication that the water has undergone evaporation and therefore is enriched in heavier isotopes. The fact that boreholes Ash1 and Dam 3 BH2 are enriched in heavy isotopes further support the suggestion that there is a hydraulic link between surface water bodies and the dams as well as the Karoo aquifers as discussed in sections 4.2.1 and 4.2.2. In comparison, samples associated with groundwater namely, Ramp 16, Ramp 20, MCWBH4, MCWBH5, BH2 and B1680 show less isotopic depletion. These samples have a signature closely related to rainfall, suggesting that groundwater recharge is mainly by rainfall.

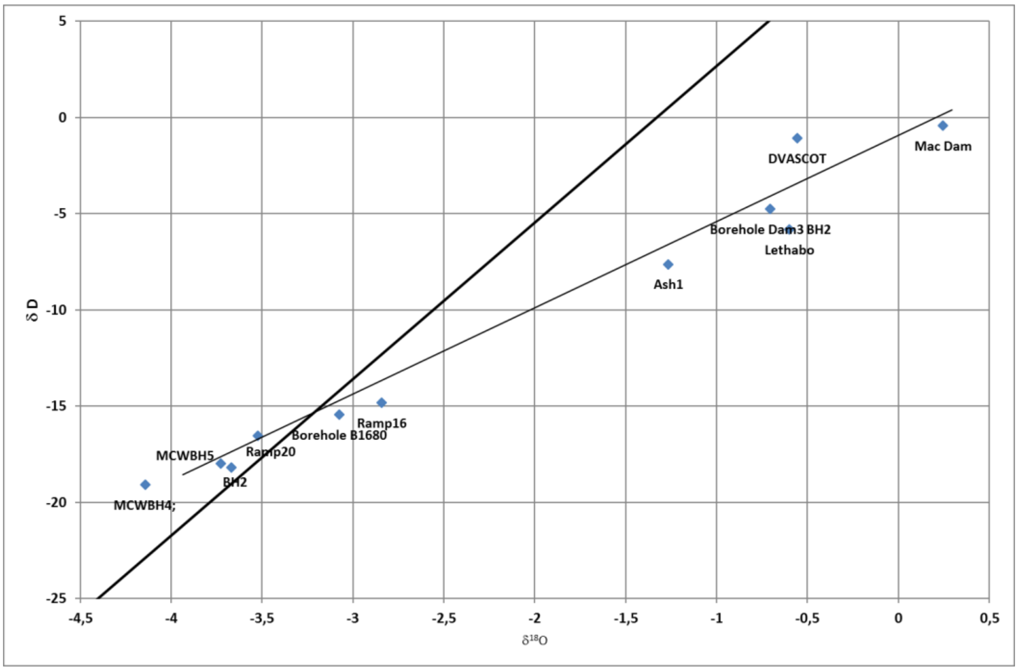

Figure 5.12: Isotope analyses results

5.6 GROUNDWATER FLOW REGIME

It is well understood that there is no one unique solution where models are concerned. The study area presents a complex system consisting of multiple aquifers and components influencing groundwater flow. As stated by Reilly (2001), the representation of sites where water originates as well as where and how the water leaves the groundwater system is critical to the development of an accurate model. A number of possible dynamic interactions between the different aquifers can be concluded. This section summarises a conceptual groundwater flow regime based on the available data (Figure 2.30)

- The regional groundwater flows from the north, north east towards the south west.
- There is hydraulic connection between the Vaal River and the deep Karoo system and the shallow aquifers. Groundwater is discharged as seepage towards the Vaal River from the artificial shallow mine aquifer on the eastern section of the mine as supported by monitoring data (Section 4.2.1). Water seeps towards the mine from Vaal River along the western boundary. This hydraulic connection limits the propagation of the dewatering cone past the Vaal River.
- The dolomitic aquifer discharges water into the New Vaal operations although this is limited by the Dwyka tillite. The water enters the mine through hydraulically limited fractures and joints of the tillite.
- The groundwater gradient in the graben and Cornelia Colliery is towards New Vaal Colliery. Seepage from these areas contributes to the mine operations total water make with the seepage rate expected to increase with increasing mining depth.

- A significant portion of the groundwater is derived from the old underground mine workings. A portion of which is intersected in the pit as mining advances the other is abstracted through a pumping (abstraction) borehole in Maccauvlei East. This water is pumped to surface water dams and eventually into Maccauvlei dam where a groundwater mound is created below the dam. The groundwater flows from Maccauvlei dam towards the pits as well as towards the Vaal River according to the prevalent the gradient.
- The regional dyke prevents water flow from the northern section to the south of the model domain. Fracture flow through the faults is limited making it insignificant in terms of serving as conduits for groundwater flow.
- Rainfall recharge is expected to be the main source of water and discharge is limited to abstraction from the pit and borehole.

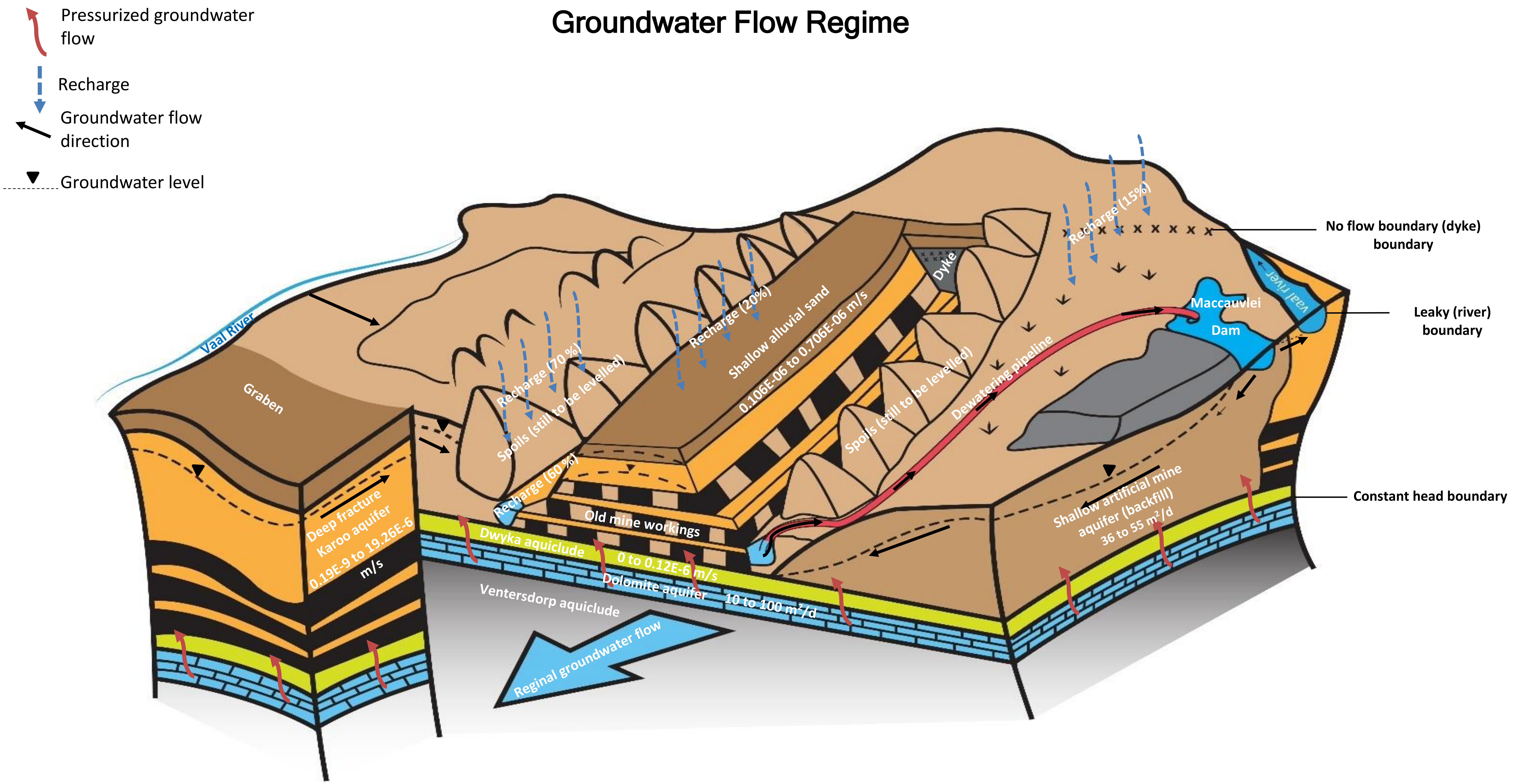

Figure 2.30: Conceptual groundwater flow regime for New Vaal Colliery

5.7 ASSUMPTIONS AND EXCLUSION

An understanding exists that not all aspects of the groundwater system can be represented when conceptualising the system. Assumptions and certain exclusions need to be made in order to present a simplified model according to the available data and model objectives. The following exclusions and assumptions were made for the New Vaal conceptual mode:

- It is assumed that the boundary conditions are representative of the real system. The model domain is limited to the immediate area of interest with the model boundaries adjusted to fit the available data and scope of the study. This allows for reduced complexity and limits introduction of unknown parameters.
- As a continuation of the above-mentioned assumption, assigning a constant head boundary to Cornelia Colliery and the dolomite aquifer allows for simplicity and reduces the introduction of unknown parameters. There is currently not sufficient data to develop a flood model for Cornelia Colliery or develop a well-field model for the dolomitic aquifer. The addition of both would unnecessarily add to the complexity and uncertainty of the model.
- Hydraulic parameters within an aquifer can vary spatially depending on the scale which a study is being conducted. However, given the relatively regional scale of the New Vaal model, assuming a homogeneous distribution of parameters and horizontal isotropic groundwater flow for all aquifers is viewed as reasonable. Furthermore, the hydraulic conductivity is given as a range since site specific data proven to be applicable to New Vaal is not available. A numerical model would have to be built where the hydraulic parameters can be calibrated against the water levels.
- Leaky boundaries are assigned to the Vaal River and the dams, the leakage factor however, is not known and therefore was not included in the model. The leakage factor can be estimated in future field investigations or through a numerical model which is not part of this study.
- A sensitivity analysis, often performed using a mathematical model, would be required to test the significance of faults' hydraulic properties on groundwater system. This study is study is limited to conceptualisation of the system and therefore cannot conduct an analysis to test the validity of the assumption. The observations made in the pit with respect to the faults are considered effective for the conceptual model. The faults are insignificant in terms of groundwater flow, including the fault system that forms the graben.
- The regional dyke has remained impermeable to groundwater flow despite blasting activities at the mine.

CHAPTER 6: DATA GAP ANALYSIS

According to the EC (2003), monitoring data should be proportional to the complexity of the groundwater system, presence of trends and implications of errors in judgement. New Vaal Colliery intended to use the groundwater model as an indicator of potential impacts on receptors and as a water management tool from which a groundwater balance can be developed to be integrated into the sites overall water balance. Therefore, it would be expected that data distribution for the model development would reflect the needs of management. Reilly (2001), stated that an accurate description of the system being studied will allow for accurate quantitative understanding of the cause and effect relationships which would allow scenario planning for decision making.

6.1 DATA DISTRIBUTION

6.1.1 Boreholes

Alley *et al.* (2002) and Taylor and Alley (2001) stated that, regular and long-term water level measurements from boreholes are the main source of information used for understanding aquifer water flow, behaviour and the factors that influence them. Groundwater levels from observation boreholes give the best indication of water flow and change in storage, whether as a result of natural or anthropogenic influences. Consequently, an extensive, accurate and continuous head measurement dataset is an important prerequisite for the understanding and management of groundwater. The EC (2003) further stated that the water monitoring network design should support and assist in the testing of the conceptual understanding of the system. As it stands, New Vaal Colliery has extensive data sets, but the boreholes are predominantly clustered in the north eastern rehabilitated section of the mine, which limits the extent to which the conceptual model can be tested. The interpretation of groundwater levels for the artificial mine aquifer (voids), alluvial sand aquifer and fractured Karoo aquifer south of the dyke realise significantly on limited data taking the extend of mining area into consideration. Even with these challenges, the current borehole observations, including those from the newly drilled boreholes, provide sufficient data to understand the general groundwater flow regime. The data provides sufficient information to support the conclusion that the mine has little to no impact on the dolomitic aquifer. An iterative process should be continued to fill the identified data gaps to improve the conceptual understanding of the site. Because the areas of interest are close to the pits and mine voids, the mine should consider new boreholes in these areas to quantify the gradient between the pits and backfilled spoils as well as to determine the water volumes stored in the old underground mine voids for the groundwater balance calculation. It is especially important that boreholes targeting the old underground mine voids are drilled due to the complexities and uncertainty associated with these voids (5.1.2.2). For a holistic conceptual model, data gaps surrounding the interaction between the mine and Vaal River should also be filled.

6.1.2 Recharge and hydraulic parameters

Recharge values from Hodgson and Krantz (1998) are widely used in groundwater modelling for mines. The values based on a single study conducted in the Witbank coalfields in 1998 and a follow up validation study has yet to be conducted. In the absence of other sources, the recharge values have become accepted as the standard for groundwater recharge for mining environments. In the absence of data, these recharge values were used for the New Vaal Conceptual model taking into consideration the site's geology to constrain the range. A study by Surinaidu *et al.* (2014) demonstrated that in the absence of site specific data, literature data is sufficient for developing a model. In their study, Surinaidu *et al.* (2014) used the groundwater resource estimation committee (GEC) recommended climate and geology based recharge estimates determined for different terrains in India. The hydraulic properties of the strata determine along with the head gradients the rate at which water will flow and therefore have an impact on the groundwater balance and the source - receptor pathway (SRP). Hodgson (1983, 1984) provided insightful data for the dolomitic aquifer, the dyke and the Dwyka tillite. These studies represent all hydrogeological studies conducted at the site in order to estimate the hydraulic properties of the aquifers. Despite the environment having been highly altered (e.g. extensive sections of mined out and backfilled areas) and therefore the hydraulic properties, no further hydraulic tests were conducted before this study. As a result, literature data had to be used extensively which adds a level of uncertainty into the conceptual model.

6.1.3 Groundwater abstraction

The abstraction from boreholes and the pit is well documented for each pit. Presumably, the dewatering rates reflect the volumes that need to be abstracted to keep the pit dry. However, this is not always the case, particularly in Ramp 0 and 14 where mining is often limited by the presence of water. The abstraction rates do however provide initial seepage rates towards the pit. On average 15, 5 and 3 ML/d of water were abstracted from the Main Pit, West pit and Maccauvlei west in 2013 respectively.

The disadvantage of using the abstraction rates to estimate seepage rates is that the in-rush of water associated with old mine working or doline structures is not accounted for which can result in an overestimation for some areas. Because such occurrences are rare and the problematic ramps are limited two areas (Ramp 0 and Ramp14), the data is viewed as being sufficient for conceptualising the groundwater flow for the site.

6.2 GROUNDWATER FLOW PATH AND CONTROLLING MECHANISM

The water levels observed for majority of the boreholes did not show seasonal variations, suggesting that rainfall is not the predominant mechanism controlling groundwater fluctuations. Further statistical analysis of the water levels substantiates the conclusion (Table 6.1). The lack of variability in the data as noted by the standard deviation and coefficient of variance indicates the presence of overriding processes controlling water levels in the different aquifers (Table 6.1). For the dolomites boreholes, groundwater abstractions in Vereeniging are the overriding factor, while the boreholes targeting the backfill and dams are heavily influenced by the dam water levels and lastly, the underground workings boreholes are influenced by mining activities (dewatering).

Table 6.1: Statistical analysis of the borehole groundwater levels

Borehole	Mean water level (mamsl)	Standard deviation	Coefficient of variance (%)
BHSpoil 1	1419.3	4.48	0.32
BHSpoil3	1420.2	3.22	0.23
BHSpoil 6	1421.8	2.49	0.17
BHSpoil 11	1421.7	2.94	0.21
Ash1	1420.4	3.83	0.27
Ash2	1416	4.64	0.33
Dam3BH1	1424.8	0.81	0.06
Dam3BH2	1424.6	0.81	0.06
Dam4BH1	1422.4	2.14	0.15
Dam4BH2	1420.6	1.83	0.13
B1094	1389.4	0.896	0.06
BH1680	1420.5	0.855	0.06
BH1681	1421.4	1.320	0.09
BH1682	1422.4	1.307	0.09
BH1683	1424	1.144	0.08
BH1684	1422.1	0.643	0.05
BH1685	1421.7	1.2	0.09
B1108BH	1374.1	5.44	0.40
Mac West 3	1368.2	3.48	0.25
NPBH1	1393.3	7.64	0.55
Bankfontein	1405.4	2.79	0.20
BH2	1408.3	3.00	0.21

491VALLEY	1405.79	2.37	0.17

If the view shared by Beale and Read (2013), that the fundamental control of groundwater is geology, is to be taken into consideration, then the Colliery's groundwater system can be assumed to be well understood. The extensive faulting and facture zones as well as the continuity of the Dwyka tillites introduce a level of uncertainty into the model. However, the implications for groundwater flow are predominantly based on observations in the pit or anecdotal evidence. This takes on the approach that as long as there is no sign of unacceptable impact on the mine operations, it is not necessary to characterise the faults in terms of groundwater flow.

The probability of quantifying groundwater flow and factors driving groundwater flow for these areas is limited and create in the absence of field data a reliance on models for their quantification. The suspicion that the Graben faults could serve as preferential flow paths can therefore not be confirmed currently. Understanding the role the Graben plays in intermine flow from Cornelia Colliery to New Vaal is vital. Hodgson (2010) estimated seepage rate of 10 ML/d (split between Cornelia and the dolomitic aquifer) into the New Vaal operations. The estimated rate is likely to increase as mining progresses southwards resulting in a steeper gradient causing an increase in inflow.

CHAPTER 7: CONCLUSIONS

Water forms an integral component to operating a mine and will remain an important, if not the most important aspect long after closure. The successful management of a mine requires an understanding of the hydrogeological factors that are likely to impact on operations. Often, a mine will need to quantify its life of mine water make in order to manage and mitigate risks to business as well as the environment. For South African mines, this is a legal requirement and a best practice guideline is available to assist mines in ensuring that they comply with regulations. New Vaal Colliery, a historical underground mine now an opencast mine, is not an exception to the legal and water management requirements. The legal requirements concerning the water treatment plants on site and the need to prove that the mine has little to no impact on the underlying dolomitic aquifer were the catalysts that directed the Colliery to review the existing water strategy. Consequently, New Vaal set out to build a high confidence groundwater model to be used to identify receptors of mine impacts and to quantify the groundwater balance for the site. The process of building a groundwater model begins with conceptualisation of the site. Using the existing data and literature, an initial conceptual groundwater model can be developed and further used to identify data and information gaps. In the case of New Vaal, previously conducted studies and the available data were used to develop a conceptual groundwater model.

The study identified three main hydrostratigraphic units namely shallow aquifers, Karoo aquifers and aquiclude and the pre-Karoo aquifer and aquiclude that were partially characterised. The shallow aquifers include the alluvial sand aquifer and an artificial mine aquifer formed as a result of rehabilitated backfill. The deep fractured aquifer and the artificial mine aquifer formed as a result of the old underground mine voids superimposed on the fracture aquifer form part of the Karoo aquifers. These aquifers are underlain by the Dwyka aquiclude that forms an impermeable layer separating the Karoo aquifers from the Pre-Karoo dolomitic aquifer and Ventersdorp aquiclude. Borehole water levels, bias to northern portion of the mine, were used to understand the groundwater flow dynamics between the aquifer systems. Water levels confirmed the confined to semi confine nature of the dolomitic aquifer consequently the mine is likely to be receiving water inflow from the dolomites. While water levels in the shallow artificial aquifer indicated a significant hydraulic connection between the main pollution control dam and the aquifer as well as a groundwater gradient from the mine towards the Vaal River along the northern and eastern boundary. Although northern section could be relatively well conceptualised, two major gaps were identified for the western and southern boundaries. The western section required that a borehole should be drilled to determine the groundwater gradient between the mine and the Vaal River. Groundwater gradients along the southern boundary showed that New Vaal was likely to be receiving intermine flow from the defunct Cornelia Colliery. In order to understanding the significance of the flow it would require boreholes to be drilled into the graben and site specific hydraulic data which are not available. One borehole drilled along the western boundary to determine the hydraulic head and the two boreholes drilled into the graben filled two major gaps. The western boundary borehole suggested that the mine is gaining water from the River, while the graben boreholes validated the steep gradient between the two mines. An interpretation of groundwater level monitoring data provided the basis on which the sources and sinks contributing to the groundwater balance could be identified and the flow regime conceptualised. This is in spite of the skewed distribution of monitoring boreholes and lack of site specific hydraulic parameters on site. Due to the site not having site specific hydraulic parameter for the majority of the aquifers, the ability to quantify the contribution of each source and sink to the groundwater balance is inadequate for a high confidence model. The literature parameters used, although valuable, are given as ranges that differ in orders of magnitude and introduce a high level of uncertainty to the quantification of flow rates. A difference between 5 and 20 percent recharge for an area can have a significant impact on the water balance. Furthermore, the uncertainty surrounding the continuity of the Dwyka tillites or faults acting as preferential groundwater flow paths reduce the model confidence. The Colliery should therefore drill new boreholes representative of the different aquifers and determine their site specific hydraulic parameters.

The site's long mining history and the interaction between the different aquifers and surface waters introduce complexities and uncertainties in the conceptualization of the groundwater flow. However, the combination of historical hydrogeological studies and current monitoring data provides New Vaal with sufficient information to build a conceptual model from which the groundwater flow regime could be defined. Despite the limitations associated with the available data, New Vaal can state with relative confidence the relatively low impacts the mine has on the underlying dolomitic aquifer. Quantifying the impacts on all potential receptors like the Vaal River is limited by lack of site specific data. These data gaps that still need to be filled form part of an iterative process of building a higher confidence conceptual site model. They do not negate the usability of the current conceptual model, but simply emphasize the iterative nature of CSM development. The model should therefore not be viewed as final, especially in a mining environment where hydrogeological changes are common throughout the life of mine and post mine closure. It is imperative that the mine management understands that the use of the model should be aligned with the objectives for which it was built. As more data become available and the needs of mine water management change, the model development/update should be aligned accordingly to avoid misrepresentation or unreasonable use.

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ABSTRACT

New Vaal Colliery, is an open cast mine in the northern Free State along the meandering Vaal River. The Colliery is a historically bord and pillar underground mine and the sole provider of coal to the Lethabo Power Station. The underground mine voids were flooded by water prior to open cast operations starting in 1985 as a result, dewatering forms an integral part of the mining activities. In 2011, the mine received its approved water use license which contained the condition that the all the dams on site had to be lined, including the main pollution control dam, the Maccauvlei dam. A combination of a high rainfall season, declining capacity in the Maccauvlei dam and limited options for the disposal of the mine impacted water resulted in mobile reverse osmosis water treatment plants being installed to treat water from Maccauvlei dam and the brine discharged back into the dam. Discussions with the DWA triggered the need to re-evaluate the water management strategy on site in order to illustrate that the mine was not impacting on the underlying dolomitic aquifer.

Given that the site has been collecting groundwater data since the mine's initiation, it was assumed that there are sufficient data to develop a conceptual groundwater flow model. The process of developing a groundwater conceptual model was used to understand subsurface flow dynamics at the mine. Water levels in the shallow artificial mine indicated a synchronous connection between the aquifer and the main pollution control dam, Maccauvlei dam. Furthermore, the water levels indicated that the groundwater gradient is from the mine towards the Vaal River. Water levels in the dolomitic aquifer confirmed findings from previous studies conducted at the site. The dolomitic monitoring borehole water levels remained generally above the elevation at which the Vaal River is being managed therefore confirming the confined to semi-confined nature of the aquifer. A single dolomite monitoring borehole located south of the mine also confirmed the confined nature of the aquifer. Water levels in the borehole are consistently above those of the boreholes monitoring the underground mine voids. It is therefore more likely that the dolomite aquifer is contributing water into the mine rather than the mine discharging water into the aquifer. A comparison of groundwater levels between the New Vaal Colliery and Cornelia Colliery indicated a groundwater water gradient from Cornelia towards New Vaal.

The conceptual model is able to illustrate that the mine is not likely to have an impact on the dolomitic aquifer. This is in spite of the identified data limitations which include the skewed distribution of the boreholes and lack of site specific hydraulic parameters provide a basis on which further studies can be conducted.