Investigation into depressurisation of highwalls at Mogalakwena Mine, Limpopo Province, South Africa

Itumeleng Mogatusi

Student Number 2013179094

Supervisor: Dr Eelco Lukas

University of the Free State

UNIVERSITY OF THE FREE STATE
UNIVERSITEIT VAN DIE VRYSTAAT
YUNIVESITHI YA FREISTATA

Declaration

I declare that this research report is my own, unaided work. The content covers work done at Mogalakwena Mine Anglo Platinum open-pit mining operation, by the author as well as fellow staff and consultants. It is being submitted for the Degree of Master of Science in Geohydrology in the School of Groundwater Studies at the University of the Free State. It has not been submitted before by the author for any degree or examination in any other university.

Itumeleng Mogatusi

Abstract

As the magnitude of open pit mines like Mogalakwena Mine, gets bigger and deeper, the assessment and management water in the pits and particularly in the high walls is becomingly increasingly important for water and rock engineers. For over the years, Mogalakwena mine in its older pits has been employing a general mine dewatering method. The popular method involves pumping from vertical wells to reduce groundwater levels and groundwater inflows to the pits. The newer pits use sump pumping programs that target the removal of groundwater collected at the bottom of the pit using mobile pumps in sumps.

Groundwater on the slopes also results in low calculations for Factor of Safety (FoS), increasing the number of geotechnical high-risk zones. This means fewer mining areas to excess ore. Loss of mining due to loss of excess is not good for any profitable mine operation because valuable ore will be left behind. The need for depressurisation is then considered to improve slope stability performance and increase Factor of Safety.

The most applied method of dewatering in open pit mines is usually by drilling vertical boreholes outside the pit and pumping out the groundwater. This technique for Mogalakwena have been investigated to be ineffective for the mine because of the low permeability of the hanging walls rock mass made up of Norites. This hinders efficient and successful pumping using the classic dewatering techniques. Dewatering programs aim to achieve lower levels of the groundwater table in the mining area, ideally to be below the level of the working pit floor. The current water control taking place in the mine is operational dewatering, which pumps out groundwater seepage and rainfall water that collects at the bottom of the pits in sumps. This water is then pumped out from the sump. In a fractured aquifer setting such as that in Mogalakwena another method such as depressurisation to manage saturated slopes is needed.

The dissertation through a hydrogeological and geotechnical analysis of the hydrogeological setting shows a mixed low to moderate hydraulic conductivity (K) system of low storage and moderate precipitation (mean annual precipitation of approximately 700 mm). Very low K occurs in the strong rock mass Hanging Wall (HW) and Foot Wall (FW) slopes and moderate to high K occurs in the Platreef and shear zone generating seepages and discrete inflows into the open-pits. No relevant recharge locations have been identified from nearby aquifers and groundwater inflows during pit development will occur along strikes within the Platreef and along potentially permeable regional structures. The drainable porosity of all rock units are low and the groundwater system has assumed the low overall storativity. Thus, showing that significant reduction in water levels and inflows could be achieved through slope depressurisation and draining of the slopes and not classic dewatering from vertical wells.

The need for a slope depressurisation program for Mogalakwena mine highwalls was established through the investigation outlined in this dissertation. The need and timing was determined by applying the Slope Depressurisation Action Trigger Response Questionnaire (SDATRQ). While the timing of a slope depressurisation program requires further investigation and therefore the timing was not fully determined by SDATRQ. The relationship between dewatering and slope depressurisation was established to be incompatible for Mogalakwena Mine, dewatering the slopes did not depressurise the pore pressures on the highwalls. This was established also through the Read and Stacey (2009) dewatering and depressurisation broad categorization.

Although the dissertation largely focuses on the depressurisation of highwalls of Mogalakwena Mine, it is important to note that the topic of highwall depressurisation is an important discussion point at several open pit mines in the world. The development and further testing use of the Slope Depressurisation Action Trigger Response Questionnaire can prove to be of value to other open pit mines, experiencing the build-up of pore pressure behind the highwalls and mining advancing deeper.

The dissertation demonstrated through an investigation of Mogalakwena Mine highwalls that the need for a slope depressurisation program can be determined by using SDATRQ. Hence proving the dissertation statement to be true and further investigation on the timing needs to be completed.

Acknowledgements

This dissertation is a great illustration of what teamwork can do. Many thanks must go to the following for their contribution to the work at Mogalakwena Mine.

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- Dr Eelco Lukas, my supervisor for his continued patience, support, and encouragement to think differently.

Dedications

I dedicate this master’s dissertation to my family, the Mogatusi Family. Especially my parents Rothman Mogatusi and Mary Mogatusi. This is to thank them for all their sacrifices to ensure that I have a good education and can be the first in my family to have the opportunity to study for a master’s degree. May this dissertation be a reminder of the great work you have done as parents for me and my sister. Thank you, mom and dad.

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FoS	Factor of Safety
FW	Foot wall
HW	Hanging Wall
K	Hydraulic Conductivity
km	Kilometre
m	Metre
mm	Millimeters
m^3/hr	Cubic Metre Per Hour
mamsl	Metres above mean sea level
mH_20	Metre water column
PGM	Platinum Group Metal
SDATRQ	Slope Depressurisation Action Trigger Response Questionnaire
TARP	Trigger Action Response Plan
GMWL	Global Meteoric Water Line
$\delta^{18}O$	(oxygen-18)
$\delta^{2}H$	deuterium
GMWL	the Global Meteoric Water Line
BIC	Banded Iron Complex
m/day	Meters per day
m/yr	Meters per year
mm/ yr	Millimeters per year
Q	Flow abbreviation

"If your only tool is a hammer, you will see every problem as a nail"-African Proverb

1. Introduction and background

1.1 Problem statement

Mogalakwena Platinum mine is located 30 kilometres (km) northwest of Mokopane in the Limpopo Province, South Africa. The mine is in an area of low elevation and is bounded by ridges 10 km to the east and west. The ground-surface elevation in the mine area is approximately 1,100 metres above mean sea level (mamsl). Mogalakwena (previously known as Potgietersrus Platinum Limited) is situated in the centre of the northern limb of the Bushveld Complex (see Figure 1). The northern limb hosts the Platreef orebody, which is about a 100 m thick tabular body that strikes north-south, dips 45° to the west and reaches a depth of at least 2000 m. The Platreef is a Platinum Group Metal (PGM) deposit and contains economic quantities of platinum, palladium, rhodium, gold, copper and nickel, which are extracted and processed by Anglo Platinum.

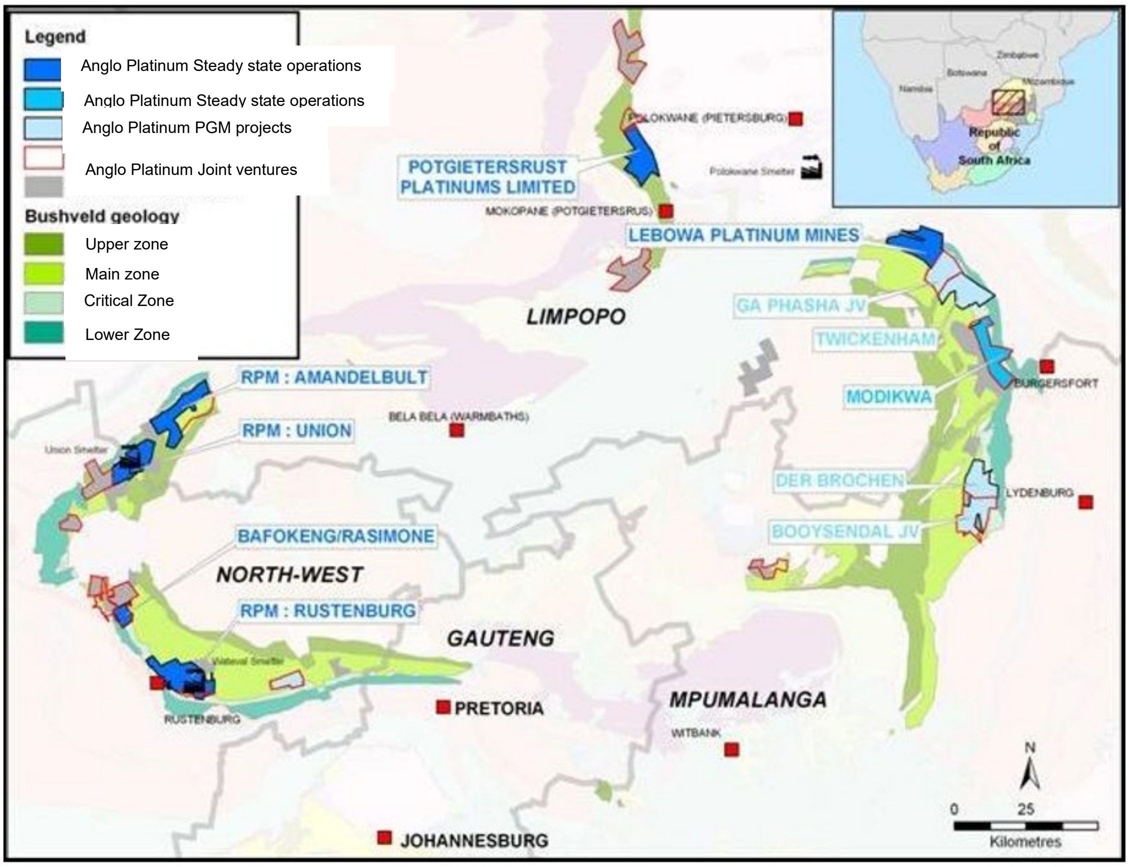


Figure 1: Location map of the Bushveld complex and the Mogalakwena Mine previous known as Potgietersrus Platinum Limited (Little, 2006).

As the size of open-pit mines gets bigger and deeper, the assessment and management of groundwater in the pits and particularly in the highwalls becomes increasingly important for hydrogeologists and geotechnical engineers (commonly known as rock engineers). Over the years, Mogalakwena mine in its older pits has been employing a general mine dewatering program. The program involves pumping from vertical wells to reduce groundwater levels and groundwater inflows to the pits. For the newer pits, however general mine dewatering of pumping from boreholes around the pits, does not seem to be the best method to lower groundwater levels in the pit highwalls. The current method used to manage groundwater is to pump from sumps dug at the bottom of the pit floor. The sumps also target the removal of surface water runoff using mobile pumps.

Groundwater can create saturated conditions in highwalls of pits therefore changing the effective stress of a rock mass. This may result in the following consequences:

- an increase in the probability for slope failures;
- groundwater seepages along the highwalls;
- slope stability analysis resulting in low Factor of Safety (FoS), thus increasing the number of geotechnical high-risk zones which results in fewer mining areas to access ore and;
- high water pore pressures on the pit highwalls thus increasing slope instability.

There is a need for a slope depressurisation program to reduce the negative impacts of groundwater on the highwalls. To date, there has not been any pit highwall depressurisation methods applied in any of the newer pits. There have been several highwalls sections that have failed due to the presence of groundwater and this impacted the operation’s production and mining targets negatively. If this situation is not addressed the problem will become worse as the pits deepen and the slope steepen. Therefore, there is a need to investigate whether the highwalls at Mogalakwena require depressurisation in order to reduce the potential impact of groundwater on the safety and economic performance of the mine.

1.2 Research objectives

The objectives of this dissertation are:

1. To determine the need for slope depressurisation for Mogalakwena mine highwalls.
2. To determine the timing for a slope depressurisation program by applying the Slope Depressurisation Action Trigger Response Questionnaire (SDATRQ) tool.
3. To demonstrate that the presence of groundwater can impact the stability of the slope and cause a decrease in the Factor of Safety (FoS);
4. To analysis pore pressure behaviour focusing on the hanging wall of the slopes;
5. Apply the Read and Stacey (2009) category method to determine the relationship between pit dewatering and slope depressurisation at Mogalakwena; and finally
6. To estimate the recharge rate factor using rainfall data.

1.3 Dissertation statement

The timing and need for a slope depressurisation program for Mogalakwena mine highwalls can be determined by applying Slope Depressurisation Action Trigger Response Questionnaire SDATRQ

Considering the above, the dissertation will demonstrate through an investigation of Mogalakwena Mine highwalls that the timing and need for a slope depressurisation program can be determined by using SDATRQ. The five (5) step questionnaire is dependent on hydrogeological and geotechnical studies and will illustrate how the results of the studies can help determine the timing and need for a slope depressurisation program for sections of highwall. Slope and highwall will be used interchangeably throughout the dissertation.

1.4 Key Assumptions

This dissertation assumes that the general slope depressurization technique will be applied which uses horizontal drainage holes drilled on the highwall and allowed to drain over time. This technique and others commonly used will be explained in detail in the chapters to follow.

1.5 Dissertation Significance and rational

In the experience of the author working in different open pit mines in South Africa and abroad. The author has observed that the timing and need for slope depressurisation is done as a reactive response to groundwater seepage on active slopes. That no proper planning and investigation goes into ensuring that the mine is prepared to start a depressurization program with the timely information that is required. Information such as trigger pore pressures generally do not inform a depressurization program Although the need may be obvious because of the groundwater seepage and the failures associated with those saturated slopes.

The question of when to start depressurization a slope has also not been answered and is an important factor to be determined that will allow adequate time for slope drainage. Since groundwater moves very slowly, depressurisation takes time. Time plays a critical role in mining, when the rate of mining advance is quicker than slope drainage, production is directly impacted and delayed. Therefore, it is critical to have a timely designed programmes that will mitigate the risk of saturated slopes impacting mining. With proper planning and setting of triggers, necessary action can be taken and scheduled with the mine plan. Once the pit becomes too deep, implementing measures for depressurisation may not be practically possible.

Thus, the significance of this work to unable timely planning for slope depressurization to allow mining to advance without negative impact from groundwater seepages.

“You will never know where you are going, unless you know where you come from” –African Proverb

2. Literature review

2.1 Consequences of mining below the water table

As open-pit mine development increases in size and depth, the assessment and management of groundwater in the pits and on the slopes is becoming increasingly important for hydrogeologists and geotechnical engineers to manage. According to Read and Beale, (2013), there are several consequences that come with mining below the water table. These can affect open-pit mine excavations in the following two ways:

A. Groundwater can create “wet mining” -the combination of poor surface runoff control can lead to standing water within the pits. This may result in the following:
   - loss of access to all or parts of the working mine; leaving economic ore behind;
   - an increase in the moisture content in shipped ore, which may be problematic for processing;
   - wet blasting, that causes an increase in blast hole failures, and further resulting in increased operational costs due to re-drills;
   - and an increase in equipment wear (mainly damage of tyres), which may lead to inefficient and unsafe loading and hailing practices, creating unsafe mining environments.

B. Groundwater can leave saturated conditions in highwalls of the pits therefore change the effective stress of the rock mass, Read and Beale, (2013). This may result in the following:
   - an increase in the probability for slope failures;
   - groundwater seepages along the highwalls;
   - slope stability analysis resulting in low Factor of Safety (FoS), increasing the number of geotechnical high-risk zones. This results in fewer mining areas to access economic ore;
   - and high-water pore pressure distribution towards pit highwalls.

In his work Fortin, (2015) shows how “wet mining” negatively impacted three active pits in the Highland Valley Copper mine, the largest open pit copper mine in Canada, located near Logan

Lake, British Columbia. These impacts included increased costs for drilling and blasting activities due to wet holes, inefficiencies for truck haulage because of wet ore and these inefficiency lead to increased diesel fuel consumption by the haulage trucks, and increased maintenance costs associated with tyres and equipment wear. Fortin, (2015) concluded that the cumulative annual costs incurred by “wet mining” were estimated at over $USD8M/year for Highland Valley Copper mine. Once the groundwater is excessive in the pit fit floors, designing an effective groundwater control program will be a reactive approach that will take time and requires heavy investment largely in pumping and piping.

Another reason that influences saturated conditions on slopes, is poor surface runoff control. The runoff water can recharge the weathered rock mass and areas around the slopes. If the weathered rock profile around the pit is significantly thick and saturated, this can create unstable hanging walls that constantly impact mining negatively. These, together with the consequences outlined in B, set the basis of the theory for this dissertation. This dissertation will focus mainly on the consequences of saturated conditions of open-pit highwalls. The approach proposed in this dissertation is a proactive method to design a slope depressurisation program that can inform and possibly prevent slope instabilities caused by saturated slopes with timely recommendations to drain the slopes.

2.2 Stormwater and recharge within pits

As mentioned, other factors that influence the saturation of slopes in open-pits are poor surface, stormwater runoff control and high groundwater recharge rates. According to Douglas et al, (2009), in-pit surface water management must be assessed to consider the impacts from rainfall events and to manage localised seepages. Depending on the size of the pit footprint, the frequency for intense storms and major rainfall events at the mine, will impose significant disruptions to mining operations. In support of this, a study by Dowling et al, (2011) that investigated the key factors affecting mine dewatering and slope depressurisation, showed that prevailing climatic conditions that cause runoff was a top factor if the runoff was not controlled. The study further concluded that the amount of rainfall in the mine area is an important controlling factor that must be included in the design of a groundwater and slope depressurisation control program. Many tropical mining operations require considerable surface water runoff control, even those located in a rock masses that have low permeability. The required pumping rates at these operations can be thousands of m^3/hr.

The groundwater system within many open-pit mine is mainly recharged via infiltration of precipitation (Dowling et al, 2011). To relate and understand the percentage of precipitation that becomes recharged into a groundwater system, several methods exist to estimate recharge from rainfall. Although determining recharge is the most important part of understanding a hydrological system it is also the most difficult to determine. Several methods exist and they are, the use of groundwater numerical modelling, the use of the chloride-mass balance, the use of environmental isotopic tracers, the use of soil moisture balance and using water table fluctuations.

Numerical modelling when used to estimate recharge from rainfall involves the estimation of travel time by using of numerical simulations of transient water flow, in a computer program such as SWAP. The daily precipitation data for a set period is used as boundary conditions. The chloride mass-balance method is convenient and inexpensive because of its simple data input requirements. Recharge can be estimated by: using the equation $R = P \times CL_p/CL_{gw}$, where R is recharge (mm/year); P is rainfall (mm/year); CL_p is weighted average chloride concentration in rainfall (mg/L); and CL_{gw} is average chloride concentration in groundwater (mg/L), (Phillips, 1994). The use of environmental tracers to estimate recharge from rainfall been more successful for recharge estimation because of the natural tracers used for recharge estimation. Environmental tracers are defined as ions, isotopes or gases that move with water that can be detected in atmosphere, surface waters, precipitation and groundwater. Environmental isotopes of $\delta^{18}O$ (oxygen-18) and $\delta^{2}H$ (deuterium) are the most frequently used in recharge studies. The difference in water vapor pressure of the isotopically lighter water ($_1H_2\ ^{16}O$) is higher than for isotopically heavier water (^2H and ^{18}O). The cumulative content of ^{18}O and ^2H in rainfall has been observed for decades and has been established as the Global Meteoric Water Line (GMWL). The GMWL provides reference by which different isotopic compositions of water can be plotted against ^{18}O and ^2H relationship. If samples have been subjected to evaporation or interaction with rock mass (groundwater) the ^{18}O and ^2H relationship will not plot on the GMWL and if samples are of rainfall composition it will plot on the GMWL (Craig,1961). Therefore, this plot can help distinguish if the source sample is of rainfall origin.

Water table fluctuation method is considered a physical method as compared to the chemical methods mentioned above. The method links the change in groundwater storage with resulting water table fluctuations through the storage parameter (Varni et al., 2013). Although the method is low cost, it is considered to involve large amount of errors, since the variation of groundwater storage is estimated from the calculation of the difference of other terms. The water table fluctuation method calculates the ratio of water table rise to total rainfall for all precipitation data available over the period. The water table fluctuation method is based on the premises that the rise in the groundwater levels is due to recharge water arriving at the water table, with the assumption that the amount of available water in a column of unit area is equal to specific yield times the height of water in the column (Varni et al., 2013).this statement by Varni et al,2013 is another base theory for this dissertation.

Subyani, (2004), in his study showed how groundwater recharge estimation is an important parameter to be understood especially in humid and arid regions, like Saudi Arabia. Such regions have precipitation variations over space and time and are influenced by topography and seasonality. Since an open-pit acts as a hydraulic sink that captures rain and groundwater flows from all directions. For successful runoff management especially in the slopes, is important to determine the percentage yield of an aquifer, that is recharged from rainfall.

Subyani, (2004) used isotopic tracers and chloride mass balance to estimate recharge from rainfall as an input of successful management of the hydrologic system. Subyani, (2004) used isotopic compositions of Hydrogen and Oxygen in the groundwater to show that the groundwater recharge resources are mainly from meteoric water (rainfall). The chloride-mass balance method was refined to estimate the amount of recharge, and it estimated 11% of the annual rainfall. Subyani, (2004) also showed how the random distribution of the lighter and heavy isotopes in the Wadi River course indicates that the Wadi Alluvial is also a most productive aquifer system. The chloride-mass balance method Subyani, (2004) applied to estimate the recharge flux for Wadi Tharad aquifers, considered values of the three measured components: rainfall (the total rainfall minus runoff, minus evaporation and minus recharge), chloride concentrations in rainfalls, and groundwater. Rainfall was highly variable in space and time in the study area. Monthly rainfall values correlated with monthly chloride concentration and the groundwater samples from the recharge. This value represented about 11% of rainfall, which is acceptable for arid and semi-arid regions. The aquifer recharge in these areas is mainly from rainfall-runoff in the form of winter and spring storms in the adjacent Baha Escarpment Mountains.

In conclusion, Subyani, (2004) was able to demonstrate that groundwater recharge near the pit is depended on the geometry of the local surface topography relative to the pit. As a result of local rainfall and storm events that cause runoff, when runoff is uncontrolled can contribute to the overall recharge of the groundwater in the pit and on the highwalls. The local surface topography, rainfall and uncontrolled stormwater conditions in this study are similar to the mine that is investigated in this dissertation. Therefore, methods used to estimate recharge percentage from rainfall in this study can provide a better understanding of the percentage of groundwater seepage on the highwalls when applied to Mogalakwena Mine. If the percentage recharge from Mogalakwena Mine is significantly from rainfall, this will then inform necessary interventions and recommendations such as seasonal depressurisation or plan adequate stormwater management measures.

2.3 Dewatering and slope depressurisation

To further understand the role of groundwater on open-pit mines and slopes, this part of the literature review will focus on techniques applied in open-pit mines to minimize the impact of groundwater namely, mine dewatering and slope depressurisation.

The focus of a general mine dewatering program is the first step in reducing the impact of groundwater on any operational conditions and mining schedules (Read and Beale, 2013). Mine dewatering techniques aim to lower the levels of the water table in the mining area. An effective mine dewatering technique can successfully lower the water table below the pit floor. The technique involves high-volume pumping, from vertical wells of different radiuses (mostly 10 inch), drilled and scattered in and/or around the pits (see Figure 2). Based on the surrounding geology these vertical pumping wells can dewater the pit while also draining (depressurise) the slopes (Read and Beale, 2013).

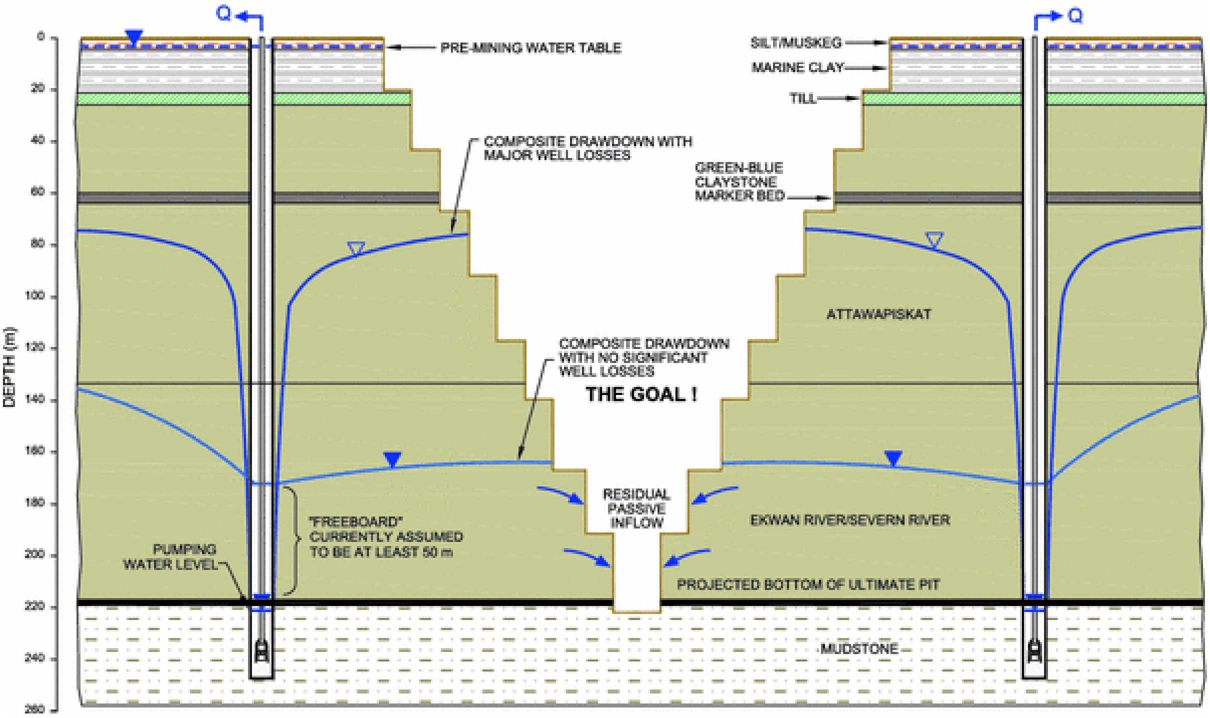


Figure 2: Impacts of pit dewatering using vertical wells equipped with submersible pumps to drain groundwater, Victor Mine Canada (Atkinson at el, 2010).

The difference in radiuses is because of the different phases of a dewatering investigation program. The first phase involves drilling groundwater exploration boreholes, and this mainly uses 8-inch drill bit radii of a percussion drilling machine. When a borehole has successfully found groundwater in a borehole with pumping rates greater than 8 l/s then a 10-inch radii borehole is drilled and then followed by the installation of a submersible pump. The pumping system is then monitored monthly to see if it is lowering the water table to levels below the pit floor (see Figure 2). Water level elevation measurements are taken monthly to understand the elevation of the cone of depression verses the actual water level elevation. This monitoring is often integrated into the mine water balance system paired with piezometers and automatically takes the reading for record keeping. Although determining the targets for a mine dewatering program is easy because the targets are related to the elevations of the working pit floors over time. Achieving the desired targets through pumping is the challenging part and that requires time, careful investigation, and capital investment. The groundwater challenges, on the pit floor, may pose significant disruptions and affect the safety and production of the mining operations.

Open-pit mines that have an evolved (matured) dewatering pumping program that has been running over a few years is most likely more effective in reducing the water table faster. It is better understood because a lot of data has been collected and analysed over time to allow iteration and reconfigured to achieve the required water level drawdown per month. Overtime this results in lowered water tables below the mine pit floor. This makes it easier for the mine to advance deeper with an available buffer of unsaturated conditions for mining (Douglas et al, 2009). The maturity of the dewatering system can also contribute to depressurise (draining) of the slopes in localized areas around the pit, but this is highly depended on the geological setting. For instances where the dewatering program is not able to lower the water table in the slopes, both dewatering and depressurisation techniques are applied to achieve the desired slope performance.

The common slope depressurisation technique applied in open pit mines with the aim to improve slope performance and stability is the use of horizontal drainage holes. The program is designed with high consideration of structural geology and geotechnical investigations. As shown in Figure 3 A, numerous 8-inch (depends on objectives) holes are drilled Pit slope horizontally drill sides of the highwalls, in the targeted lithology. The length of the hole depends to the groundwater investigation showing where the current water table elevations. Once the desired geological structure is hit or the water table is intercepted. The holes will be left to stand and drain to allow slope to naturally drain hence depressurise, the slope. The groundwater from the drains is then collected at the bench toe of the slope and pumped out using surface pumps. Figure 3B shows an instance where some mining operations can have both techniques applied at the same time to achieve maximum drawdown results

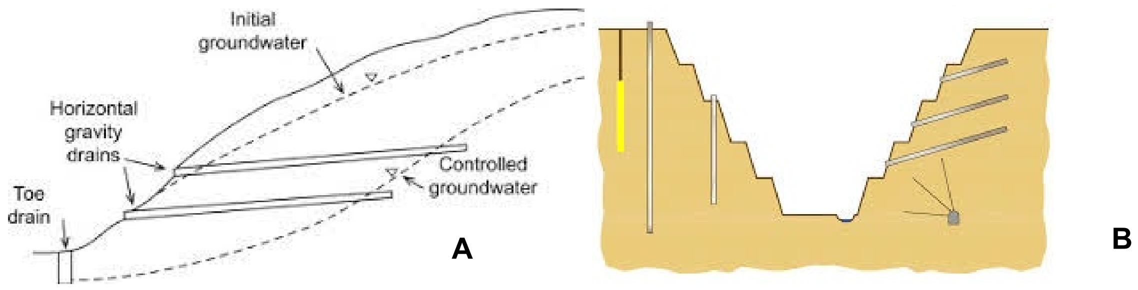


Figure 3A& B: Illustration of horizontal drainage as a common technique applied in open pit mines to depressurize slopes.

The water volumes from a depressurisation system are usually lower compared to the volumes produced by the dewatering system. With a pit slope depressurisation technique discussed above, determining the targets is more complex than the targets for a dewatering program. The design process requires an in-depth understanding of the interrelated geotechnical behaviour of the rock mass to the different geological units and local scale hydrogeological conditions, such as pore pressures distribution (which will be explored further in the literature review), (Douglas et al, 2009).

Unsaturated slopes create more stable highwalls thus increasing the Factor of safety (FoS) of the section of the highwall (Read and Stacey, 2009). If the FoS increases, it provides the opportunity to increase in the slope design angles, which means that the open pit can be designed more optimally, and more ore can be mined safely out of the same pit in the last cut without the need to enlarging the pits' surface outline. This not only increases the economic recovery for the mine but saves lots of money and time by avoiding unnecessary stripping of waste material.

The decision of the timing to apply the slope depressurisation technique mentioned in this chapter is an important one for any open pit mine. The objective of a pit slope depressurisation program is to reduce the water pressure acting on the rock and dissipate groundwater pressures in sectors of the mine (Read and Beale, 2013). The presence of groundwater on slopes is an important controlling factor in slope design and its performance. Therefore, it becomes even more important to reduce the impacts of groundwater on highwall performance.

To further explain the interrelation of mine dewatering and slope depressurisation, Read and Stacey (2009) have summarised five (5) broad categories to explain the dependencies. The authors considered the hydrogeological setting as a controlling factor in their categorization. Table 1 summaries the five (5) relationship categories of dewatering and depressurisation for different open-pit mines settings. These different settings are critical to understand before designing a depressurisation program.

Table 1: Summary describing the categories to define the relationship between dewatering and depressurisation taken from Read and Stacey, 2009.

Category	**Description**
Category1: *Mines excavated below the water table and occur within permeable rock masses that are hydraulically connected.*	• Mine dewatering program can decrease pressure in all pits slopes, as it lowers the water table. • No additional efforts of localised depressurisation are required.
Category 2: *Mines excavated below the water table that occur within lower-permeability rocks occurring in some sections of the pit.*	• Mine dewatering may not completely drain the rock mass in some sections of the pit as the water table is lowered. • Most of the rock mass is drained but not possible in sections of lower permeability rocks. • In these zones' groundwater will move slow and the pressures will not dissipate easily without targeted, localised depressurisation programs.
Category 3: Mines excavated below the water table but has perched aquifer zones on some sections around the pit.	• Mines with perched aquifer conditions mainly occur at a higher elevation, although the main water table is lowered. • These perched aquifers may be related to permeable structure, bedding or alteration that prevent vertical groundwater movement and result in pore pressures that are

	decoupled from the dewatered system.
Category 4: *Mines excavated in a fractured rock mass below the water table and geological structures form barriers to groundwater flow.*	- The rock mass may not drain because of geological structures such as dykes. These structures as impermeable flow barriers, creating compartments of trapped water with high pore pressures. - Most large open-pit mines in hard rock settings have structural compartments that influence groundwater levels and movements. For this category, the rock mass may not drain because geological structures act as impediments to groundwater flow, creating compartments of trapped water with unchanged (and therefore high) pore pressure. - The general mine dewatering program does not dissipate pressure in all pit slope sectors. As the excavation is extended and approaches the structural compartments, localized measures become necessary to penetrate the structures and drain the water behind them.
Category 5 *Mines excavated above the water table where seasonal rainfall leads to high recharge of groundwater heads in the upper stratigraphic units.*	- The control of groundwater is required to support the slope stability and performance, even though the mine excavation is above the water table.

	• Localised infiltration of precipitation can build upon low –permeability units and form high level zones of perched groundwater. • This may lead to localized high pore pressures in the pit slopes. Control of groundwater pressure may be required to support slope performance, even though the open pit is entirely above the water table. • Localized infiltration of precipitation can build up on low-permeability layers and form perched zones of groundwater, leading to locally elevated pore pressures in the pit slopes. • An example is where an open pit is excavated through a paleochannel or active stream deposits.

This considerable amount of work by Read and Stacey (2009) on the relationship between dewatering and slope depressurisation is the base theory of the methods applied in this dissertation. The open pit study area (Mogalakwena Mine) in this dissertation will be categorized according to the categories by Read and Stacey (2009). Although Read and Stacey (2009) attempted to answer the question on determining the need for a slope depressurisation program, they have failed to consider the advancement of mine planning in their categorization. Although the controlling factor in their categorization was hydrogeological setting. They did not address the marriage between the hydrogeological setting and the geotechnical analysis for slope design and slope management. They failed to show the timing of applying a depressurisation program as open pits mines expand and advance deeper. This dissertation will attempt to fill this gap, thus the significance of the work

2.4 Slope stability

The overall management of slopes created during the development of an open pit mine requires an ongoing assessment and analysis of the stability of its slopes. This assessment depends on several factors that go into the design process that include, geological, geotechnical engineering and hydrogeological inputs. A lack of understanding and assessment of all these factors may increase the risks of slope instability, which may lead to slope failures and have detrimental economic consequences and potential loss of life (Read and Stacey, 2009). In open pit mining, the slope must be steep enough to allow maximum productivity and extraction and gentle enough to allow safe mining conditions. The overall slope angle of a pit has a direct influence on the cost of a mining. The steeper the pit slope angle, the cheaper the operational costs, but also means a higher probability of slope failures (Little, 2006).

In the process of slope angle design for open pits, a few steps and levels of analyses are required. According to Carvalho, (2007) the process starts from individual bench design to overall stability of the highwalls, to the evaluation of the design performance and finally the calibration of parameters is done through back-analysis. This process requires the use of a variety of methods of analysis and software ranging from limit equilibrium methods to more involved numerical analyses methods such as distinct element method. The goal is to implement feasible ways to reduce the probability of failure by improving the stability of the slopes during the life of the mine.

As pits progress and advance to greater depth such as the Bingham Canyon near Salt Lake City, Utah, United States. It is 1.2 km deep and 4km wide and is the one of the world's biggest man-made excavation, open pit copper mine and the largest copper operation in the world. The mine pit floor has reached the water table and the rock behaviour has change because of the relaxing of the high stress-zones close to the slope face. This causes movement in the rock mass and has led to slope failures (Duncan & Wright, 2005). Limit-equilibrium methods have been used to analyse slope stability and changes in rock mass behaviour for a long time for the life of a mine as it undergoes expansion and deepening (Duncan & Wright, 1980; Yu et al., 1998; Duncan & Wright, 2005, Zhang et al., 2009). These methods have been unchanged for decades according to Griffiths and Lane, (1999).

In the earlier grounding work by Duncan and Wright, (1980), they emphasized that all equilibrium methods for slope stability analysis have some characteristics in common and one important characteristic is the Factor of Safety (FoS). The FoS is defined as the ratio between the shear strength, and the shear stress required for equilibrium (see Figure 4). Figure 4 shows the most popular theorem of failure criteria for any surface. The theorem is based on the relationship between shear stress and normal stress acting on a failure plane.

The Mohr–Coulomb failure criterion is a set of linear equations in principal stress space describing the conditions for which an isotropic material (example rock mass) will fail, with any effect from the intermediate principal stress σ^2 being neglected. Mohr–Coulomb can be written as a function of (1) major σ^1 and minor σ^3 principal stresses, or (2) normal stress σ and shear stress τ on the failure plane (Jaeger and Cook 1979) (see Figure 4). Mohr's condition assumes that failure depends only on $\sigma^1$and σ^3, and the shape of the failure envelope, the loci of σ, τ acting on a failure plane, can be linear or nonlinear. Coulomb's condition is based on a linear failure envelope to determine the critical combination of σ, τ that will cause failure on some plane (Jaeger and Cook 1979).

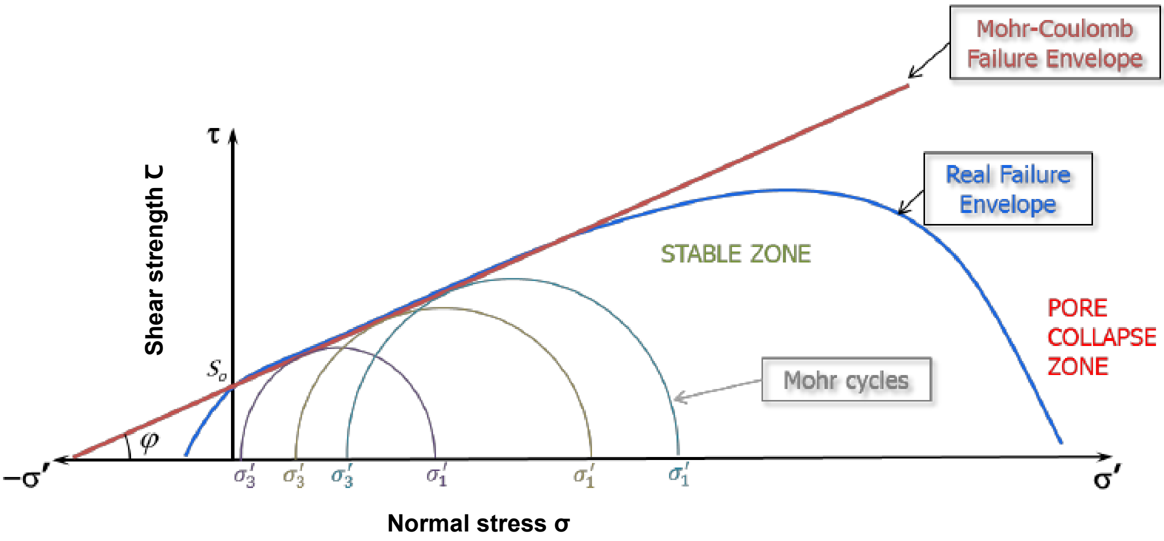


Figure 4: Mohr-Coulomb failure envelope

For slopes, the FoS is defined as the ratio of the actual shear strength to the minimum shear strength required to prevent slope failure (Zienkiewicz et al 1975). A logical way to compute the FoS is with a finite element or finite difference programs that will gradually reduce the shear strength until collapse occurs (Soren et al, 2014). Years after Zienkiewicz et al (1975) work, Soren et al (2014) rewrote the definition and explained that the FoS is the ratio of the total force available to resist sliding, to the total force tending to induce sliding along any discontinuity surfaces. The slopes of open pit fail because the material shear strength on the sliding surface is insufficient to resist the actual shear stresses. FoS values from the finite element programs greater than 1 means the slope is stable, while values less than 1 means slope is unstable (Soren et al, 2014). Therefore, elements such as the presence of water on the rock material can reduce the ability for a rock mass to resist shear stresses and induce sliding along slip surface. (Soren et al, 2014). Thus, further reducing the FoS the stability (equilibrium) state of slopes.

Johnson, (2014) conducted a comprehensive study that was aimed at identifying potential impacts on waterfront slopes subjected to water-level fluctuations. The author also included evaluation of methods for slope stability analysis and the impact to water on the FoS. The results of his study showed that lower FoS values were obtained when using the limit equilibrium approach that assumed saturated conditions below the water-level and dry conditions above. This study concluded that the changes in water pore pressure induced lower FoS and thus resulting in unstable slopes. Soren et al, (2014) in his work analysed the mechanical behaviour of pit slope stability using the finite difference method.

Figure 5 is a popular slope design process established by Read and Stacey, (2009). The diagram illustrates all the critical inputs that go into the design process of a stability analysis that will give the resulting FoS. Figure 5 shows how the fundamental basis of any slope design is the geotechnical model, which is in turn comprised of four models, namely:

1. Geological model
    - Presents rock type and alteration distribution, characterised different lithological and structural domains in the pit.
2. Structural model,
    - encompassing both the major structures and joint sets.
    - Structural mapping data of the different domains and rock types for both bench design and overall stability.
    - This includes both joint sets data and major geological features such as dykes, faults; Since a rock mass is not a continuum, its behaviour is dominated by discontinuities such as bedding planes and faults.
    - Alteration zones data within the pit. Alteration affects rock strength, therefore, different alterations within the same rock type should be grouped.
    - Spacing and condition of discontinuities
3. Material properties model
    - Including both basic properties (strength, elastic properties and potential changes on exposure).
    - Laboratory testing results of the different rock types with the results grouped by alteration for each rock type and; Rock quality designation, (RQD)
4. Hydrogeological model,

- pore pressure distribution data, water level elevation data, pumping system data, planned mining elevation data and storm water drainage data and numerical models. properties that control the drainage and depressurisation characteristics.

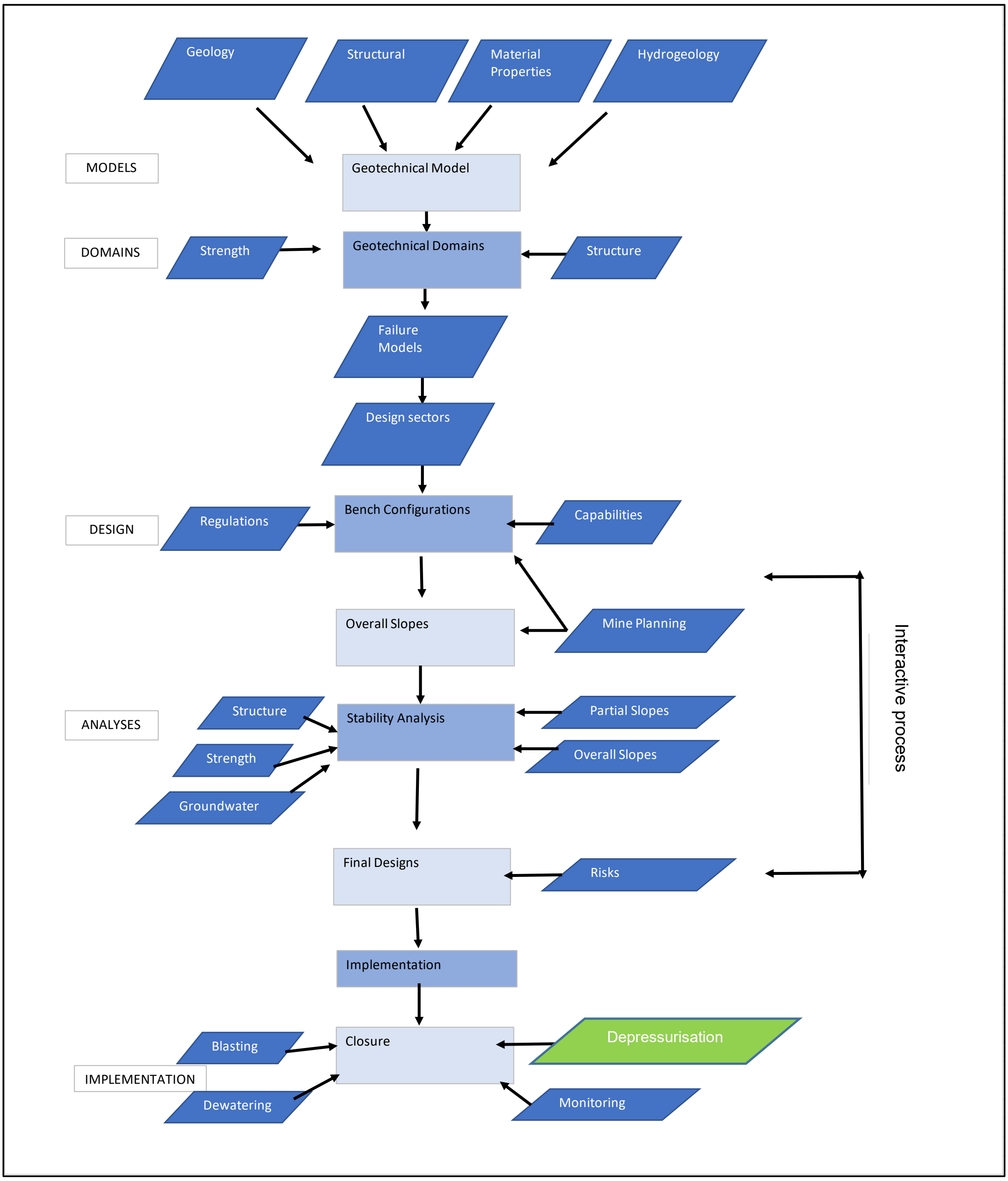
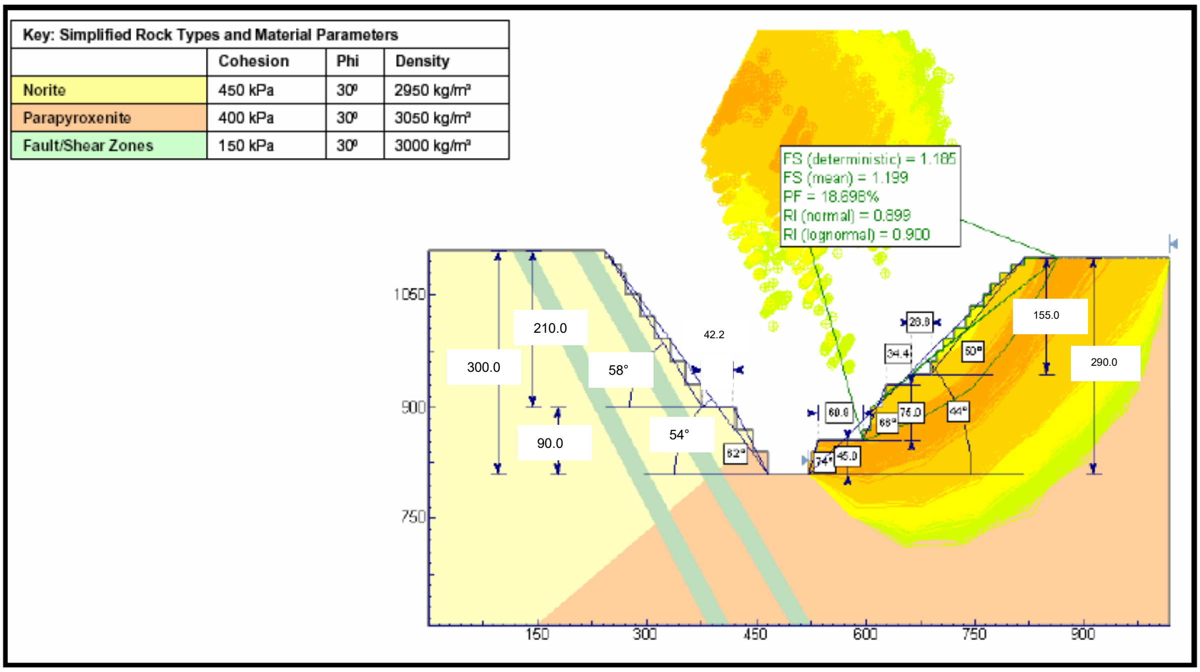


Figure 5: Slope Design process modified from Read and Stacey, (2009)

The analysis that happens in the slope design process involves the use of different softwares, ranging from limit equilibrium methods to more detailed numerical analyses methods such as the finite difference methods. The finite difference geotechnical analysis method involves the analysis of the following data inputs using Slide Software (widely used by rock engineers (see Figure 6). Figure 6 shows three different rock units with their respective densities, namely Norite in yellow, Pyroxenite in orange and shear zone in green. The results of this slide analysis for this highwall show the factor of safety for the slope for the pyroxenite unit is 1.1. this is the rock unit that is not sheared with geological faults. This analysis did not consider the presence of groundwater.



Key: Simplified Rock Types and Material Parameters

	Cohesion	Phi	Density
Norite	450 kPa	30º	2950 kg/m³
Parapyroxenite	400 kPa	30º	3050 kg/m³
Fault/Shear Zones	150 kPa	30º	3000 kg/m³

FS (deterministic) = 1.185
FS (mean) = 1.199
PF = 18.698%
RI (normal) = 0.899
RI (lognormal) = 0.900

Figure 6: Example of Slide analysis done at Mogalakwena by SRK (Section A, East, Sandsloot) Taken after Little, 2006

In the work of Soren et al, (2014) they were able to show the impacts varying water levels could have on lowering the FoS values. The modelling results were derived from modelling three different geological layers of a typical open pit mine, with variations in water level saturation and pore pressure conditions. The results of the FoS obtained was (FoS= 0.33), indicating unstable slopes, also because the zone modelled had may

Another method that is commonly used for slope analysis and determining an accurate FoS is the finite element method using various programs such as Flac3D. Matthews et al (2014) explored the use the finite element method. A study that has been carried out in collaboration with Arup engineers and Oasys developers, also comparing the results from limit equilibrium and finite element methods. Although this was initially intended to be a validation exercise it had some useful results which may provide guidance on when to consider using Finite Element analysis and concludes that circumstances of simpler conditions, Limit Equilibrium method is likely to be more adequate. Finite Element method models slopes with an intended higher degree of realism (complex geometry, sequences of rock material loading, presence of material for reinforcement, action of water, laws for complex soil behaviour) and to better visualize the deformations of soils in place. Due to this higher level of complexity and more data input requirements of the Finite Element method, the limit equilibrium method is still highly favoured because of its simpler requirements for modelling and minimum modelling assumptions. Therefore, a better representation of modelling environment, thus a base theory method for the work presented in this dissertation in producing the FoS values used in this dissertation.

Thus far literature review has successfully established that factors causing reduced shear strength of rock mass in highwalls (reduced stability of slopes) do not only depends on the geometry of slope, rock mass characteristics and shear strength behaviour of the joints but also, on the presence increased water pore pressures profiles caused by the presence of water on the slopes. Therefore, the presence of water on the slopes can have a detrimental effect on slope stability of highwalls within open pit mines.

In summary Duncan & Wright, (2005); Johnson (2014) and Soren et al (2014) were able to show that through finite difference and shear strength reduction modelling. The impacts of groundwater greatly reduced the FoS and impacted the stability of slopes.

2.5 Water pore pressures in highwalls and effects on slope stability

Pore pressure is defined as the pressure of the groundwater occurring within the pore spaces of the rock mass (Read and Stacey, 2009). Pore pressure is normally zero at the water table, positive below the water table, and negative above the water table defined as meter of water column (mH_2O) (Lui et al, 2019). In any given hydrogeological setting, the pore pressure distribution will vary laterally following changes in the water table elevation. The pore pressure occurs in the interstitial spaces between porous strata, or open fractures, discontinuities and joint sets of some competent rock masses. Groundwater can form a pressure head within the rock mass. This can cause a reduction in the normal stress acting on discontinuities found within the rock. The overall effect is a reduction in the shear strength of the discontinuity which may lead to rock and slope failure (Lui et al, 2019). Lui et al (2019), together with Read and Stacey (2009) agree that, for in-pit slope management, the assessment of pore pressures heads along the pit slopes should be an important input into the pit slope design process.

Read and Stacey (2009) make an important statement on the role of pore pressures data input in overall slope stability management. This statement not only sets the tone for the work explored in this dissertation but forms part of the base theories. The statement says, "although groundwater pore pressure and surface water flow are aspects of hydrogeology that may have a negative effect on slope stability, these aspects are usually the only elements in slope design process that can be readily influenced or changed by artificial intervention." Artificial intervention such as applying a depressurisation technique can drain the slope and decrease pore pressures and thus increase the factor of safety without changing any other factors. This means that although factors like the geology, geotechnical conditions of rock mass may not be changed (through artificial intervention), to result in a lower factor of safety, the only other factor that can be changed (through artificial intervention) to result in lower factor safety is pore pressure. Therefore, unstable slopes prone to failure as a result of increased pore pressures can be managed through interventions of reducing pore pressure either through dewatering or depressurisation (Mandzic,1992).

As it stands Mandzic explored in his work principals in 1992 that was written and popularly accepted 17 years later by Read and Stacey. Mandzic (1992) directly correlates negative effects on slope stability due to pore pressures increases and proposes that the presence of water causes a reduction in the stability of slopes because of the high-water pressure within the discontinuities and pore spaces in the rock mass. This reduces the effective stress together with a reduction in the shear strength of the rock mass. In his work he shows that the effect of water pressure, creates an uplift force on the potential of the failure surface area and thus reduce the resistance along the slip surface. To remove that factor, it is important to eliminate or decrease pore pressure by adequate highwall drainage or depressurisation.

By drainage or slope depressurisation, the pore pressure regime can be used to reduce the capacity to produce slope instabilities in open pit slopes, this agrees with the statement that pore pressure is the only element in slope design process that can be readily modified by artificial intervention, thus increasing the FoS without changing any other factors (Read and Stacey, 2009). Mandzic, (1992) comprehensively shows how to determine pore pressures for open pit mines from phreatic surfaces using different equations and correlate the results to the FoS. His study was based on three open-pit mines, Sikulje Coal mine, Bracan Bauxite Mine and Smreka Iron Ore Mine. The method to determine pore pressure ratio he favours uses the Archimedes principle. It states that pore pressure ratio (r_u), is the ratio between the total upward force due to water pressure and the total downward force due to the weight or overburden pressure. Mandzic, (1992) explains pore pressure ratio further by stating that the upward force is equal to the weight of the water displaced or the volume of the sliding mass under water, multiplied by the unit weight under water. The downward force is equal to the weight of the sliding mass. He then used pore pressure ratio to determine the effective stress along the failure surface by a factor of (1- r_u). This theory for pore pressure and effective stress calculation is another base theory that the work in this dissertation is based upon. By understanding the pore pressure ratios and cumulative increases, this then gives insight on the need to reduce or drain excessive pore pressure within the slopes.

Figure 7 illustrates the different forces at play when groundwater influences slope stability. According to Mandzic (1992) some conditions for high pore pressures to affect slope stability are:

I. water pressure which reduces the shear strength along failure surface (Force F);
II. water pressure as an uplift force along the failure surface (Force U);
III. force of gravity as the downward force (W), and,
IV. water pressure in tension cracks (Force V).

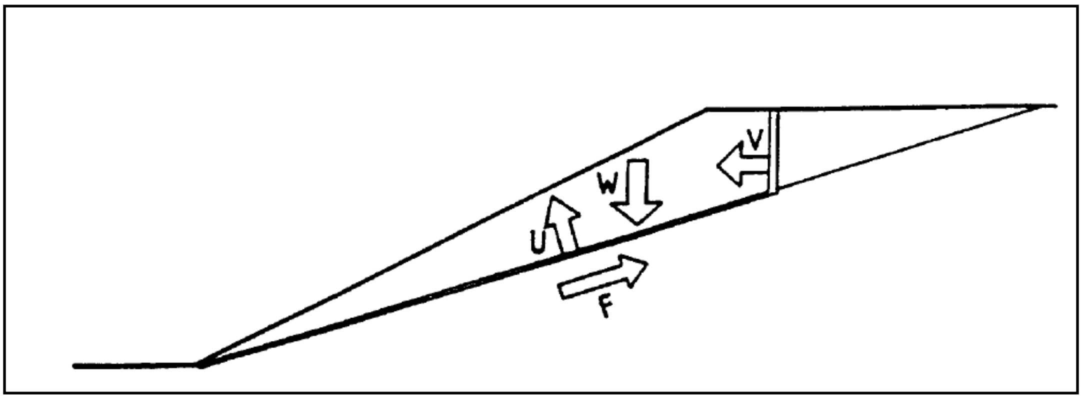


Figure 7: General view of water aspect on slope stability, (Mandzic, 1992)

Through the practical and analytic study of Mandzic (1992), he was able to successfully relate pore pressure values to slope displacement velocities and determine the impact of high pore pressures on the factor of safety. He concludes his findings by stating that the factor of safety can be reduced from 1.3 to 1 if the water level increases and the pore pressures are not controlled through drainage. The methods of analysing groundwater conditions on the slope, for pit slope design preparations must analyse water pore pressure for the assumed phreatic surface and the field water pressure readings from piezometer levels.

In conclusion, authors like Mandzic (1992) and Read and Stacey (2009) agree that to prevent slope failures, pore pressure drainage systems can be installed and will positively increase the FoS without changing any other factor in the slope design analysis. Furthermore, Mandzic, (1992) work address critical components of water in highwalls and their impact on slope stability which help open-pit mines determine the need for slope depressurisation program, which other studies failed to address. A systematic analysis to follow the one by Mandzic, (1992) is an analysis that integrates slope stability results with pore pressures, Factor of Safety and mine planning estimations. This systematic analysis will help open-pit mine planners, hydrogeologist and geotechnical engineers be able to determine the timing of when to start a slope depressurisation program. This dissertation will also attempt to address the timing of depressurisation in terms of mine plan advancement and pit deepening, which Mandzic, 919920 and other authors are lacking so far in the literature review.

According to Morton et al (2008), until recently, very little pore pressure data were available as inputs to slope design and key assumptions had to be used in geotechnical designs calculations despite the need for good information on pore pressure. The study by Morton et al (2008), addresses this gap in pore pressure data availability, by investigating a method that uses piezometers to measure in situ pore pressure.

In their study of Orapa Mine, an open-pit mine situated in the Central Kalahari of Botswana, that had a total of five (5) open hole piezometers and sixteen (16) sealed vibrating wire piezometers installed around the pit in different locations, in different geological units, in between pumping boreholes, and others at distance from the pit. Morton et al (2008) measured the hydraulic head (see Figure 8), by measuring the water table on the open wells and sealed boreholes. The data collected from piezometers was then used for plotting hydraulic heads and piezometric surfaces around the open-pit in space and over time. Piezometric data was represented as hydrographs, which are graphic representations of piezometric head vs. time in one observation point, from four (4) sealed piezometers.

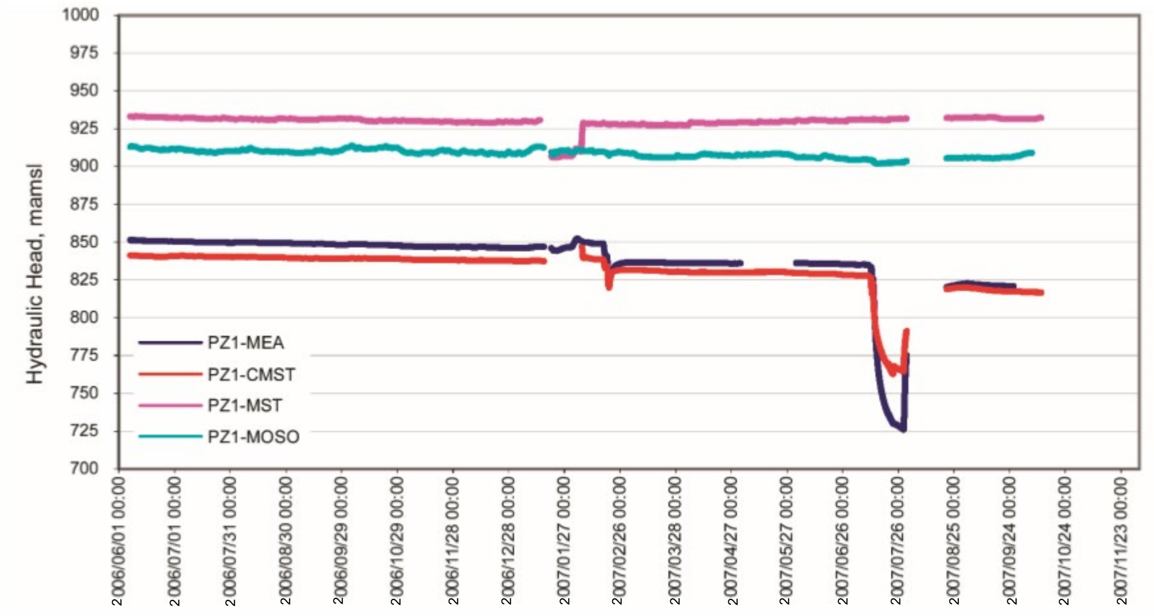


Figure 8: Hydrograph showing hydraulic head vs. time for four sealed piezometers taken after (Morton et al, 2008) Orapa Mine.

From the hydrograph above, Morton et al (2008) was able to deduce the position of the water table, the pressure head and illustrate the effectiveness of a dewatering system. The pore pressure distribution in the highwalls was calculated from water table fluctuations and modelled from the connection Morton et al, (2008) makes with the work of Francois (1974), that, in any given hydrogeological setting, the pore pressure distribution will vary laterally following changes in the water table elevation. Figure 9 taken from Morton et al, (2008) shows a design section of the Orapa pit, simulated in a groundwater flow model, in which pore pressures have been predicted for different years of mine planning. The plot also shows the position of the water table or pressure head and the pore pressure distribution in the highwalls.

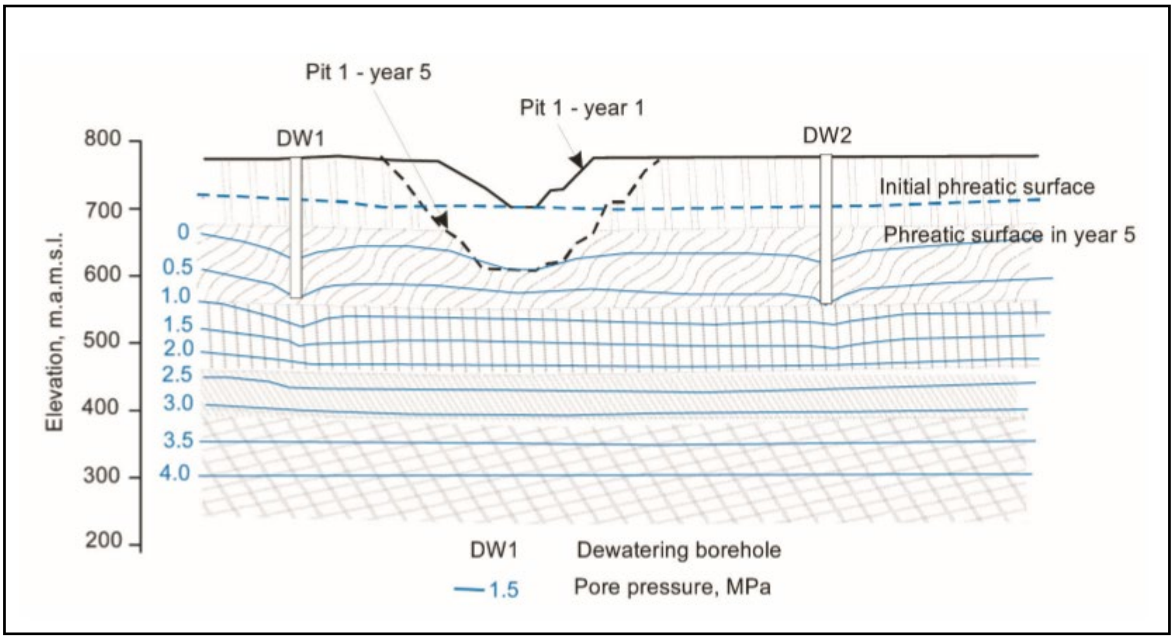


Figure 9 :Simulated pore pressure distribution on a section at Orapa Mine taken after (Morton et al 2008)

In conclusion Morton et al, (2008) was able to address the critical gap of pore pressure data availability. They showed how monitoring of pore pressures and groundwater gradient can be done using either open hole or sealed point piezometers or a combination of both. Also, that it was important that the piezometers are located with a representative lithology. Orapa mine through a detailed monitoring network, has been able to plot and predict the water table and pore pressures to understand the impact of increasing pore pressures. This then ensures information is available for use in the slope design. Like the work by, Morton et al, (2008) this dissertation will analyse piezometer data in the study area in order to derive pore pressure data distribution along highwall in order to validate the need and timing for depressurisation requirements in real time.

Although Morton et al, (2008) was able to demonstrate how to use the sensitive point piezometers to measure in situ pore pressures distribution in real time the others failed to demonstrate how to use this information to determine when to start the timing of a depressurisation program that will reduce high pore pressures (above 0 mH2O although not all positive pore pressures mean high pore pressure, context depend) throughout life of mine. Price et al (2000) attempts to fill this gap in their literature review as a follow up to the work of Morton et al, 2008.

Abosso Goldfields Limited at the time of the study by Price et al, (2000) was in the process of developing an expansion of their Damang Open-pit gold mine in Ghana. The proposed pit expansion was devised following the results of a 2004 deep drilling program that identified a significant extension to the ore resource. The geotechnical design focused on the optimization of the bench face angle and recommended a “Steep Slope Strategy”, involving 24 m high near vertical benches.

Among the many geotechnical challenges in the slope design, dewatering and depressurisation of the pit walls was a major consideration in this tropical environment. Furthermore, the literature review explains the complexity of the site groundwater and hydrogeological regime. The groundwater is recharged by the Ayaasu river system, sediments appear as saturated local aquifers within the saprolitic weathered profile which forms a flat lying aquitard. The saprolite in the lower expression is influenced by the steep easterly-dipping bedding. The orientation of the structure and the fine-grained sedimentology have the effect of restricting flow towards the pit and therefore maintaining locally elevated hydraulic gradients. This study relates very closely to the work covered in this dissertation that have tight rock masses with structurally controlled flow.

Groundwater entering the Damang Open-pit is pumped from a sump at the pit floor. Surface water is currently intercepted by a diversion drain that runs along the pit perimeter. There are no active dewatering measures in place for the pit slopes. Groundwater drains from the base of weathered material in the middle of the east wall. The geotechnical analysis criteria focused on the development of groundwater management plan including slope depressurisation strategy for fresh and weathered rocks. The stability analysis showed that to achieve the designed FoS the natural groundwater profile must be modified by the use of horizontal drains to reduce the magnitude of the pore pressures that can build within the slope. This is demonstrated in Figure 10 taken from Price et al, (2000).

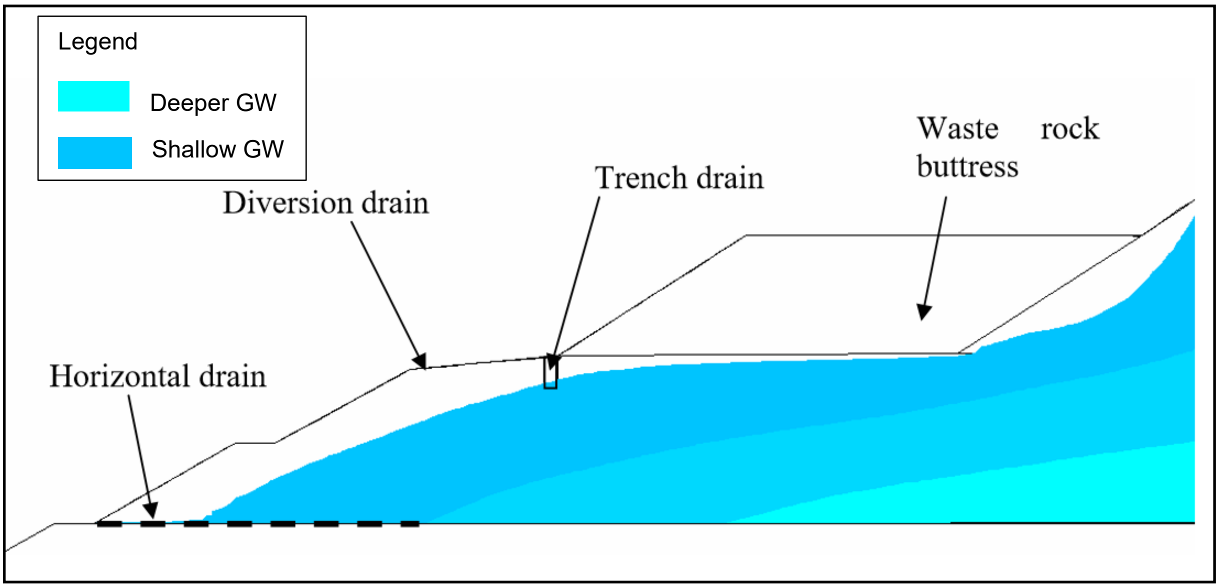


Figure 10: Pore pressure contours and phreatic surface from FEFLOW analysis of Eastern Wall showing influence of horizontal drain and interceptor trench on Saprolite layer. Deeper groundwater and associated pore pressures within the oxides is

represented by the lighter blue and will be drained by the drilling of shallow 30 m long horizontal drains at the base of the oxidised zone. Taken after Price et al (2000).

Price et al (2000) demonstrated how the use of the Triggered Action Response Plan (TARP) approach can be used in determining when to start a slope depressurisation program. By triggering and tagging certain pore pressure levels and gradients in the saprolite lithology and using the effectiveness of finite element modelling using FEFLOW software (Figure 10). Price et al, (2000) was able to demonstrate how to determine the timing of when to start draining the slopes, therefore reducing the pore pressures. The effectiveness of the timing of the horizontal depressurisation drains in the saprolite was studied and the hydraulic conductivity was monitored in the existing piezometers. This drain reduced the eastern development of the groundwater profile. Deeper groundwater and associated pore pressures within the saprolite were drained by the drilling of shallow 30 m long horizontal drains at the base of the saprolite zone, (see Figure 10) The construction and installation of pit drainage and depressurisation technique enabled the management of the site groundwater conditions on the highwalls. The flows and pore pressures were monitored to assess the response of hydrogeological field conditions to the artificial intervention of depressurisation (Price et al, 2000).

In conclusion Price et al, (2000) showed how the pit slope drainage and depressurisation are important in the maintenance of stable slopes, and that the TARP based approach is most reliable to determine the timing for a slope depressurisation program. The TARP approach will be demonstrated in detail in work covered in this dissertation.

2.6 Collaboration between Hydrogeologists and Geotechnical engineers

Geotechnical engineers and hydrogeologists often interact to resolve common problems, particularly on projects in areas were open-pit expansion plans are in place and there is a need for re-design of the slopes. In these cases, the geotechnical engineer requires assistance from the hydrogeologist, in the hydrogeological characterization of the groundwater regime and to provide specific parameters for phreatic surfaces and pore pressure distribution. This is then used in the geotechnical analyses to determine the FoS of a slope section. If the determined FoS is above the required for safe slope, the hydrogeologist then puts artificial measures in place such as dewatering and depressurisation to reduce the hydrogeological inputs until the desired FoS is obtained.

This collaboration was perfectly displayed in the literature review by Price et al, (2000). The hydrogeologist and the geotechnical engineer have a joint responsibility in the management of slopes and groundwater on highwalls. Unfortunately, from the work experienced by the author of this dissertation, who has worked in various open-pit mines in South Africa and Chile, she observed that geotechnical engineers and hydrogeologists are trained to approach and address groundwater problems differently and the interaction between the two disciplines can be a source of frustration for both if they do not realise that slope management and stability is a joint responsibility. Although the literature review has shown how critical hydrogeological data input is for the slope design process, authors like Fowler et al, (1980) and many others, agree that groundwater monitoring especially in highwalls is still not considered critical monitoring by geotechnical engineers.

The literature review has also has briefly addressed the lack of data availability as a point of frustrations by hydrogeologists. In summary, the dissertation will later propose recommendations for better collaboration between hydrogeologists and rock engineers on slope design processes and management of groundwater in slopes.

“Only a fool tests the depth of a river with both feet’’- African Proverb

3. Methodology

The dissertation statement for the bases of the work covered in this dissertation states that, “The timing and need for a slope depressurisation program for a section on the Mogalakwena mine highwalls, can be determined by applying Slope Depressurisation Action Trigger Response Questionnaire (SDATRQ). The combination of the quantitative and qualitative nature of the Slope Depressurisation Action Trigger Response Questionnaire (SDATRQ) will attempt to test the dissertation statement and determine when a section of the highwall at Mogalakwena can be depressurised as the mine advances deeper. The following paragraphs will be explaining the details of the Slope Depressurisation Action Trigger Response Questionnaire (SDATRQ).

3.1 Research design

The research method design approach for this dissertation is an experimental design. The experimental design will test the dissertation statement and observe the effects of the given intervention namely: Slope Depressurisation Action Trigger Response Questionnaire (SDATRQ) will work to determine the timing and the need for a slope depressurisation program for Mogalakwena Mine.

This experimental approach will provide insight to whether the application of SDATRQ method can be easily replicated at other open-pit mines, with similar questions on the timing and need for slope depressurisation. The experimental design approach will use both quantitative and qualitative analysis of the data. The results of the quantitative analysis will provide results that will be critical answering the descriptive quantitative analysis of the SDATRQ method. SDATRQ method is a qualitative analysis that describes certain actions that can trigger the need for a slope depressurisation program for Mogalakwena Mine. Another analysis that will be applied is a comparative analysis, this will be done to compare the results of the FoS with varying pore pressure data conditions and observe how that will trigger action for a slope depressurisation program.

3.2 Data

The data presented and analysed in the dissertation was obtained from the Mogalakwena mine between 2013 to 2017. This includes geology (geological setting model and structural and country rock model) and geotechnical (studies on FoS) data taken from varies sections in the mine. The measured water level data is taken from seven (7) vibrating wire piezometers around the pit of focus and standpipe monitoring boreholes. These are therefore representative of the groundwater behaviour in the mine operation. Measured pumping data used in this dissertation is used in total wellfield pumping rates estimations. Other data is the measured is groundwater seepage data in the summer and winter months observed during pit wall inspection on certain locations within the pits.

There was lack of data availability on surface water data such as reservoir water-level data, pit lake water levels and runoff estimates data. This data was not available because the data collection of this data is inconsistent, or only taken when bi-annually update of the hydrogeological models by the responsible consultants. Rainfall data used for the recharge estimation is taken over a 10-year period between 2007 to 2017. Other data used is the mine expansion elevation data taken from 2018 which includes 2018 pit elevations and planned pit elevations until 2022. Pore pressure data was taken from 2018 groundwater simulation model from the pit in focus in this dissertation.

3.3 Slope Depressurisation Action Trigger Response Questionnaire (SDATRQ)

The analysis of the data will be done in such a way as to test the experimental quantitative design of the Slope Depressurisation Action Trigger Response Questionnaire (SDATRQ) shown in Figure 11. This approach will analyse the data and the qualitative results using SDATRQ and conclude if it can be used in determining the timing and need for depressurisation at Mogalakwena Mine.

SDATRQ asks five (5) critical questions (in grey) in order to establish whether or not, slope depressurisation is triggered and needs to happen in the highwalls of Mogalakwena Mine. The questions are answered by a simple yes or no (in dark grey) to determine the next steps. It is important to note that the SDATRQ is a tool only applicable at the end a thorough data analysis that will be shown in chapters to follow. Without the data results SDATRQ tool will not work as intended.

Question one (1) starts by asking if there is visible groundwater seepage observed on the highwall and if there has been a record of highwall failure on that highwall because of presence of water. This data is mainly recorded qualitatively in the daily highwall monitoring inspection sheet. Question two (2) then seeks to understand the results of the desktop quantitative analysis of the same section of the highwall in the slope design process, using the limit equilibrium methods in software applications. Whether the results of the slope design process yielded a FoS less or greater than one (1). A FoS less than one (1), indicates that the highwall is unstable therefore unsafe, in rock engineering terms. If the FoS is greater than one (1), then the highwall section is classified as stable and safe, mining can continue uninterrupted. Question three (3) is divided into two questions, the first question seeks to establish whether active dewatering is taken place close to the section of the highwall. Question 3.2 seeks to understand if a potential recharge rock layer close to the highwall section could be the reason water seepage is observed on the highwall section.

The purple boxes give the potential high-level outcomes, depending on the answer given. If question 3.1 is a yes, there is a possibility that the current active dewatering is not depressurising the slopes. If question 3.2 is a no, there is a possibility that the water seepage on the highwall is a perched aquifer that is recharged from a water body, depending on its type. The black box then suggests a potential solution to question 3.2 which is effective recharge management. The black box suggestions are mitigation control measures to consider before deciding not to depressurise the slope. Question 4 asks if the water levels data is increasing through time in monitoring wells close to the highwall. If seasonal water levels increases are observed this should also be considered in the depressurization plan if depressurization is considered. Finally, question 5 seeks to understand if the pore pressures from monitoring data are increasing through time from piezometer monitoring wells. This final step will support the decision to depressurise the section of the highwall. The second black consideration provides a suggestion for determining the timing of depressurization. It provides an opportunity to set trigger pore pressures that will trigger the need to depressurise if not immediate depressurisation is recommended based on the answers provided.

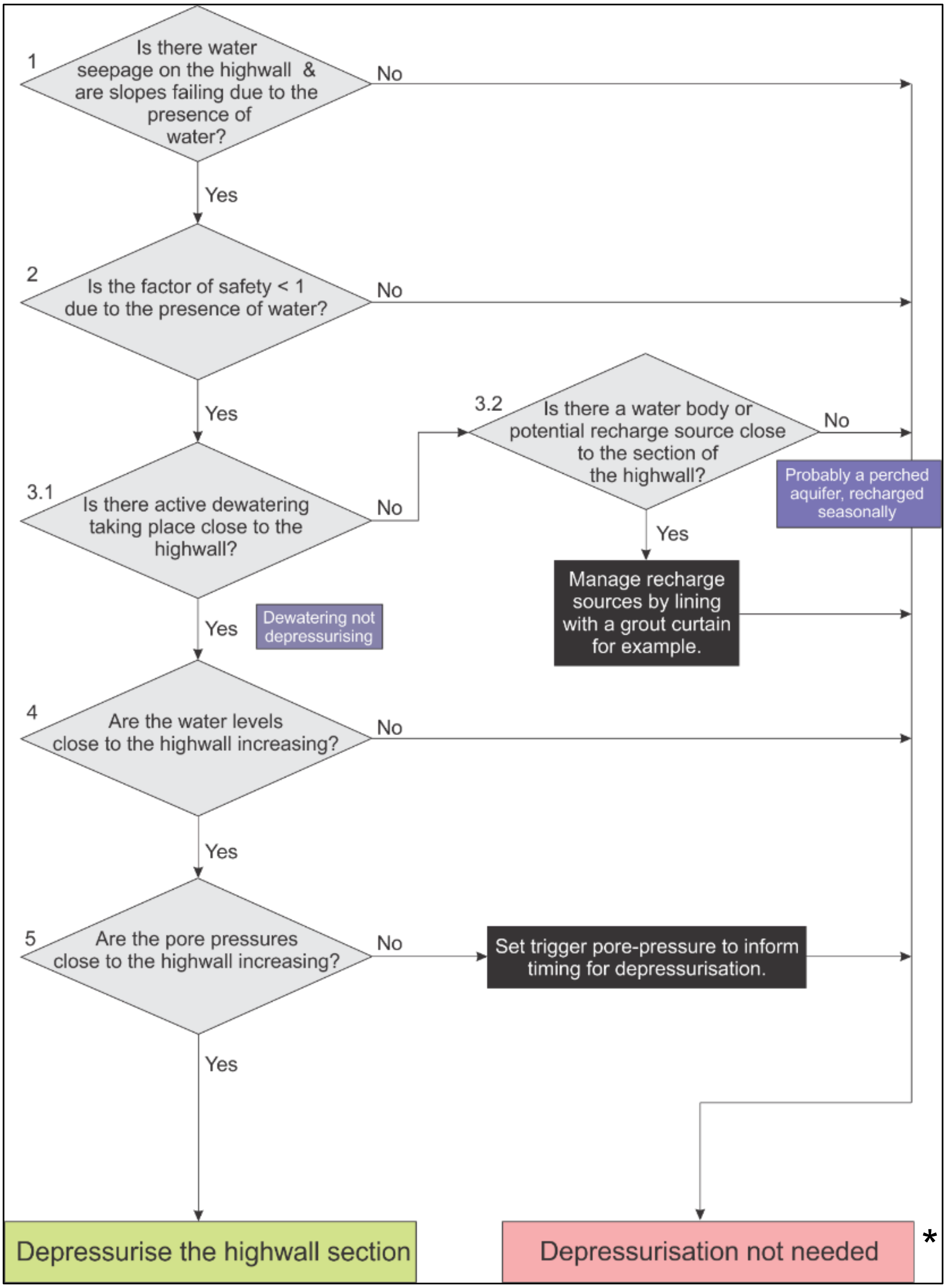


Figure 11: Slope Depressurisation Action Trigger Response Questionnaire

* ***Note all five (5) the questions need to be answered, even if one may answer no. Before making the final decision to depressurise or not.***

3.4 Slope Depressurisation Action Trigger Response Model (SDATRQ) limitations

It is important that all the questions are to be answered if even one question answers no. So that all the important elements of the questionnaire are taken into account. Slope Depressurisation Action Trigger Response Questionnaire (SDATRQ) tool may be limited because the questionnaire assumes that a thorough geological, hydrogeological modelling analysis has been incorporated into the geotechnical slope design process at a high level of accuracy. The questionnaire does not ask any trigger questions related to a deeper understanding of the geology and that may influence the need to depressurise the section of the slope, such as the identifying the type of lithology in if it has been determined to be a known aquifer. Another limitation is that the questionnaire is set up to be used as a decision-making tool, asking high level questions which may be limited if a thorough hydrogeological understanding of the pit is not known. A final limitation is that SDATRQ was only tested at Mogalakwena, to expand usefulness it could be applied at other open it operations.

3.5 Method conclusion

In summary, the SDATRQ tool will be tested in detail in the chapters to follow. The data mentioned in section 3.2 will be analysed and through experimental design, the results of the analysis be used to answer the questions from SDATRQ. This will then inform the outcome of the dissertation and evaluate if the dissertation statement, which states “The timing and need for a slope depressurisation program for sections on the Mogalakwena mine highwalls, can be determined by applying Slope Depressurisation Action Trigger Response Questionnaire (SDATRQ) is true or false.

‘Between true friends, even water drank together is sweet enough’’- African Proverb

4.Discussion

4.1 Geological and pit layout of Mogalakwena Mine

This chapter will discuss how the local geology and structural geology of the mine controls the groundwater flow at Mogalakwena Mine. According to Little (2006) the groundwater flow at Mogalakwena Mine is fracture and fault controlled and has contributed to destabilising of slopes, causing some failures.

Mogalakwena Mine (previously Potgietersrust Platinum Limited) is located 35 km north of the town of Mokopane (previously known as Potgietersrus), in the Limpopo Province of South Africa, Figure 12. The mine was established in 1993, is the largest open pit platinum mine in the world and is 100% owned by Anglo American. It is situated in the centre of the northern limb of the Bushveld Complex, a saucer-shaped layered igneous intrusion. The northern limb hosts the Platreef orebody, which is a ~100 m thick tabular body that strikes north-south, dips 45° to the west and reaches a depth of at least 2000 m. The Platreef is a PGM deposit and contains economic quantities of platinum, palladium, rhodium, gold, copper and nickel, which are extracted and processed by Anglo American Platinum.

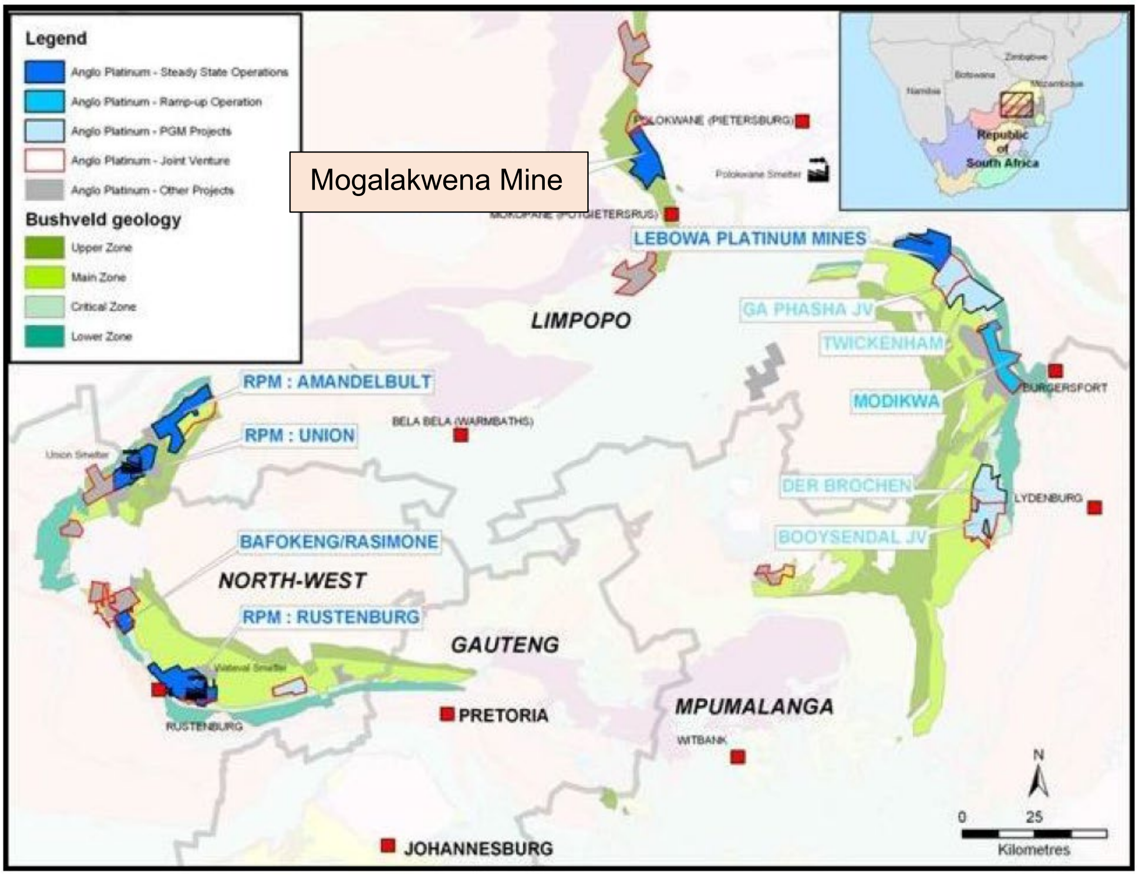


Figure 12: Location map Mogalakwena Mine, Bushveld Complex outcrop, After (Little, 2006).

Famously known, the Bushveld Igneous Complex is the largest layered intrusion in the world and was emplaced 2060 – 2054 Ma ago (Walvaren et al., 1990). Several models have been proposed for the emplacement of the Rustenburg Layered Suite, a mafic to ultramafic unit of rocks followed by an acidic phase of granites. The Rustenburg Layered Suite intruded the Transvaal Supergroup and consists of the five famous compartments or limbs, namely, the Far Western, the Western, the Eastern, the (covered) Bethal and the Northern Limb in the north.

The Rustenburg Layered Suite is divided into five zones, namely the marginal, lower, critical, main and upper zones, in order of decreasing age and depth, which relate to separate magma injections (Ainsworth, 1994). In the northern limb, the older Marginal Zone is absent, and the poorly developed Lower and Critical Zones only appear south of Mokopane. The Platreef lies at the base of the Main Zone and is overlain by gabbronorites which are in turn overlain by Upper Zone ferrogabbros. Figure 13 shows the lease farm area together with the associated geology. The farm names correspond to the pit names and major structures while others have changed over time. The Platreef orebody strikes roughly north-south in a sinuous outcrop pattern and dips roughly 45° to the west. It steepens to 75° to the south at Tweefontein Hill where the footwall rocks display a synformal structure (Ainsworth, 1994), (see Figure 13).

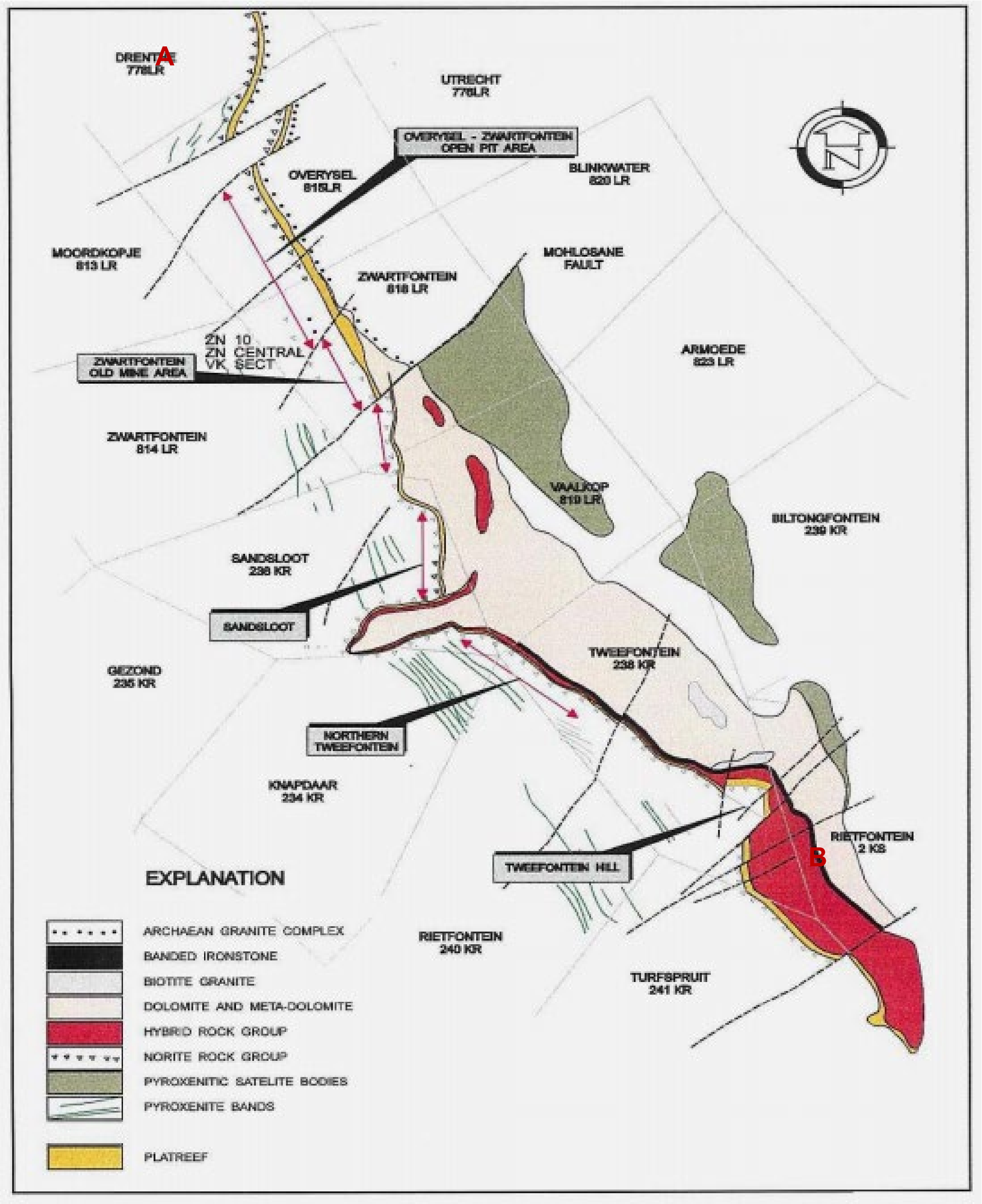


Figure 13: Geology outcrop plan across the Northern limb in the Mogalakwena Mine lease area (After PPrust, 2005)

A cross section showing the underlying geology taken from point Overysel farm (A) to Tweefontein Hill (B) in Figure 13 can be seen in Figure 14. According to (PPrust,2005), the Platreef is divided into a C-Reef (medium grained feldspathic pyroxenite), a B-Reef (coarse grained pyroxenite) and the A-Reef (pegmatoidal feldspathic pyroxenite) which forms the base of the reef (Figure 11). The C-Reef is often unmineralised and the A-Reef varies greatly in width and grade. Serpentinisation is pronounced at Zwartfontein South and three geological zones have been identified by production geologists. A large calc-silicate xenolith is present in the south-east. At Mogalakwena North (Overysel), the Platreef intruded above Archaean granite and this has resulted in a granofels footwall. At Tweefontein, banded iron formation and shales form the country rock and the interaction with the Platreef formed a hornfels footwall. Mogalakwena Mine currently has five (5) pits developed across the mine lease area. Overysel Farm is made up of the North, Central pit and South pit, then Zwartfontein pit and finally Sandsloot pit, (see Figure 15).

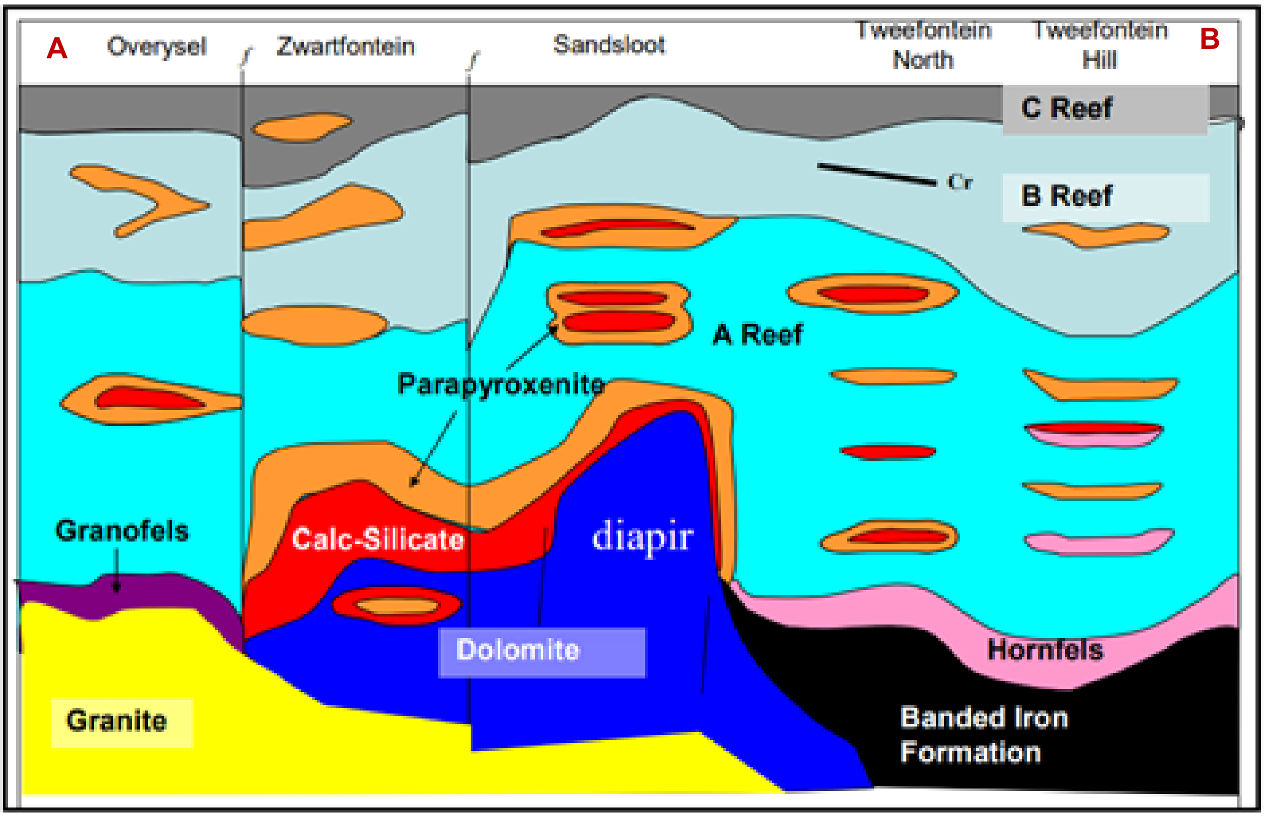


Figure 14: Schematic map of geological layout across mine lease area (PPRust,2005)

The testing of the Slope Depressurisation Action Trigger Response Questionnaire covered in this dissertation will focus on sections of the highwall of the North pit and Sandsloot respectively.

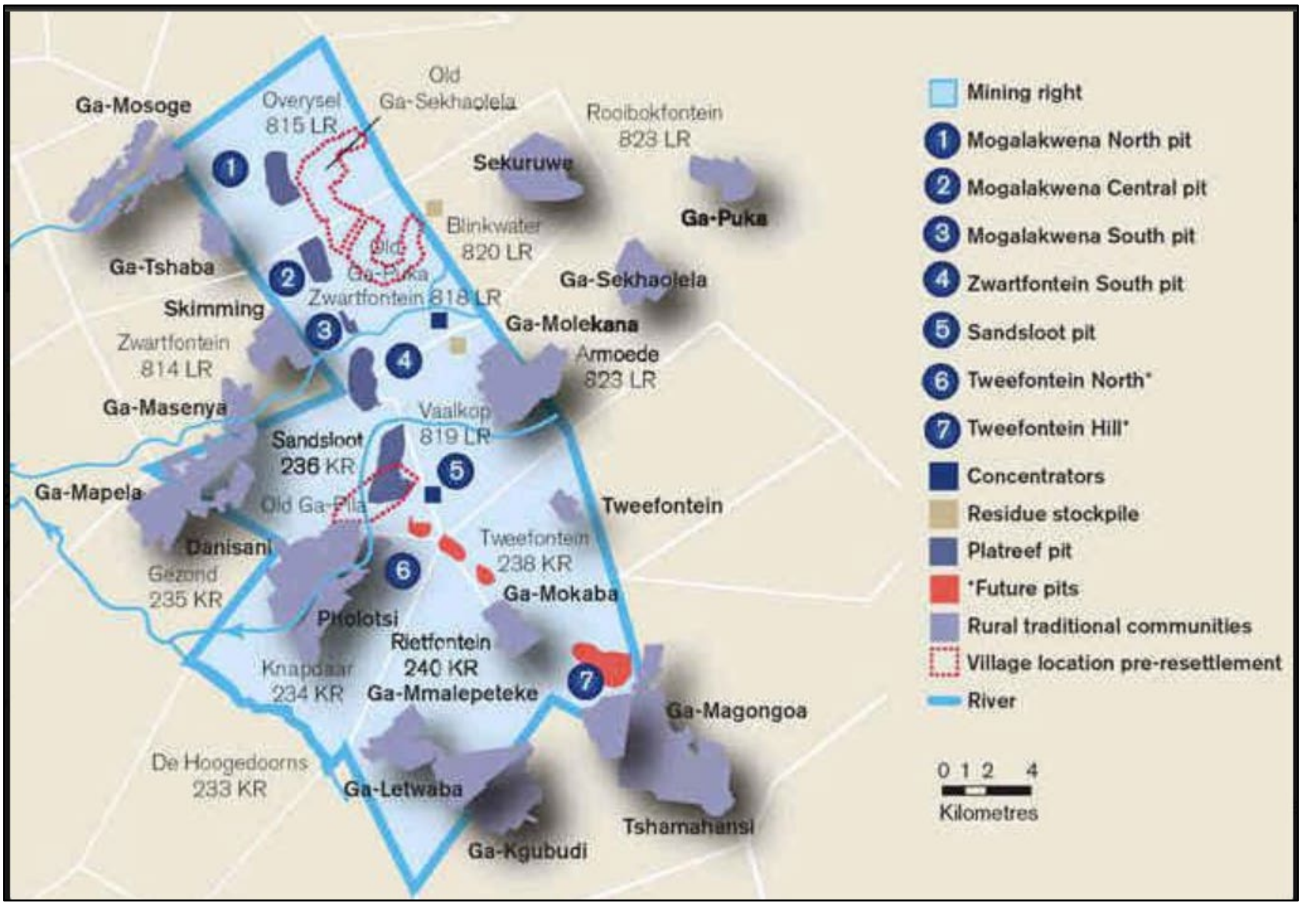


Figure 15: Pit layout in mining lease area with surrounding villages (Little,2006).

4.2 Structural Analysis of Mogalakwena Mine

Many detailed structural studies have been completed for the mine which show evidence that ground water flow movement is controlled by geological structures and major faults. The best work is by Friese (2004); which shows detailed geological structural mapping that highlights and groups the major faults with their associated joints sets as listed below, from oldest to youngest. Figures 16 and 18 show an example of the detailed structural mapping by Friese (2004) for Sandsloot and Zwartfontein pit respectively.

1. Shallow northwest dipping thrusts/thrust zones and associated east-northeast trending, sub-horizontal, low-amplitude regional folds within Archaean basement and Transvaal Supergroup.
2. Northwest to west-northwest trending, moderate to steeply dipping extensional faults/fault zones (Sandsloot Fault, Figure 16) that formed within the Transvaal Supergroup and Banded Iron Complex (BIC) . These may be reactivated in a dextral shear sense.

3. East-northeast to northeast striking, steep to sub-vertical predominantly southeast dipping first-order fault zones (Mohlosane Fault zone, Figure 18), with northeast to north-northeast trending second-order interlinking faults (the pattern is illustrated in Figure 18) in an interpreted dextral strike-slip shear system (reactivated first with normal sense, then sinistral). Also associated southwest dipping layer/bedding-parallel thrusts/thrust zones.
4. North-south striking, moderately west dipping extensional fault zones, with typical undulating gross geometry and an imbricate fan of combined normal dip-slip and sinistral strike-slip duplexes in their immediate hanging wall.
5. West-northwest to west-southwest trending extensional fracture zones cross-cutting all other structural discontinuities.

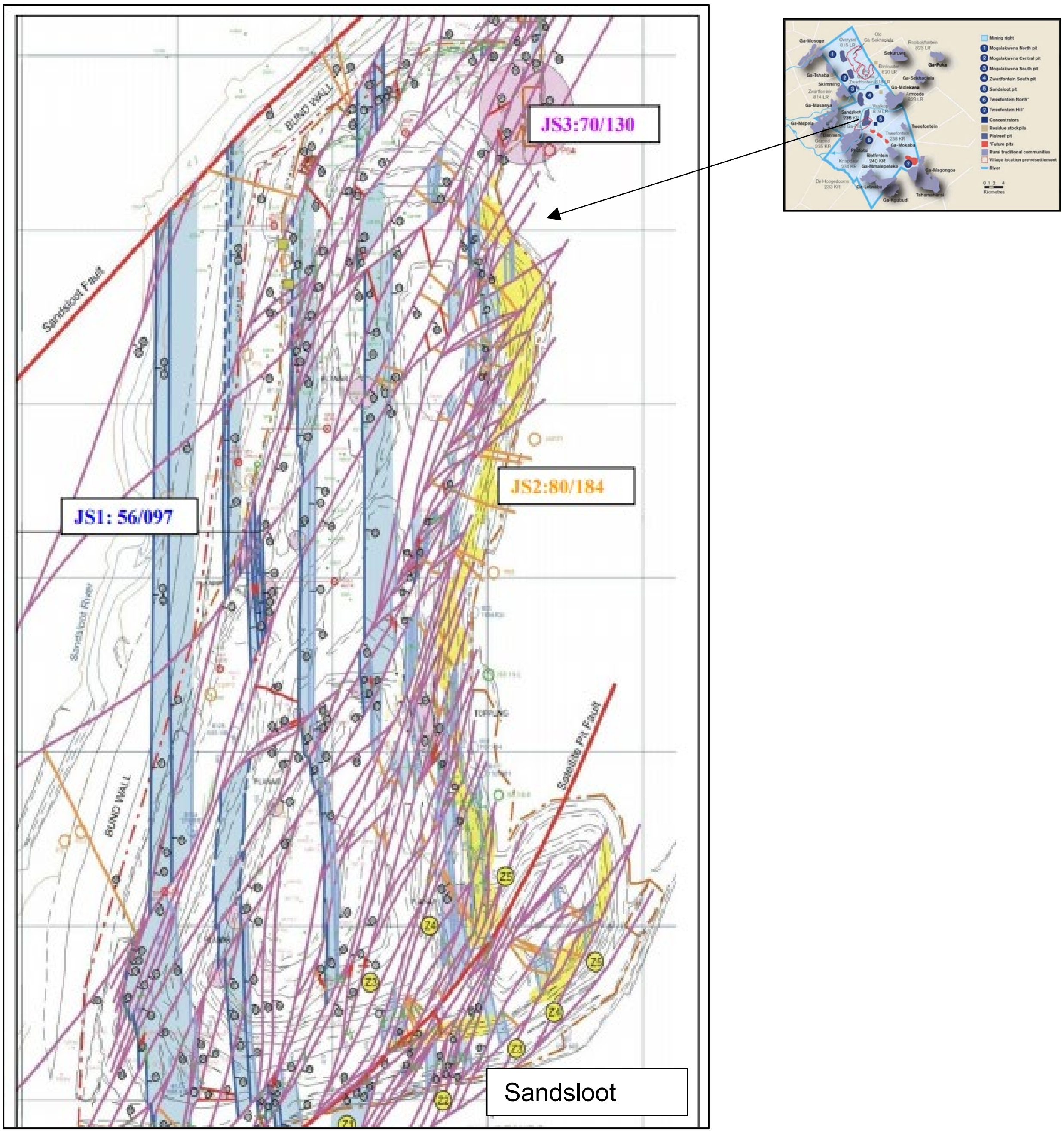


Figure 16: Structures interpreted by Friese (2004) from mapping and remote sensing data modified from Friese (2004).Sandsloot: Joint Set (JS) JS1: Strike N-S, dip 72° , dip direction 088°. JS2: Strike E-W dip 78°, dip direction 357°, JS3 Strike NW-SE dip 70°, dip direction 310°.

A photo taken in January 2015 of Sandsloot North pit (see Figure 1) shows the impact of groundwater on the slope as groundwater seepage is observed on the highwalls. This seepage resulted in mining being halted in the northern section of the highwall and mining was only concentrated in the South. The groundwater seepage here is associated with Sandsloot fault, a shear zone and the Platreef.

Figure 17: Sandsloot pit , Highwall / north wall view from the east. Seepages associated to Platreef / shear zone, Highwall dry Photo taken from mine gallery archives.

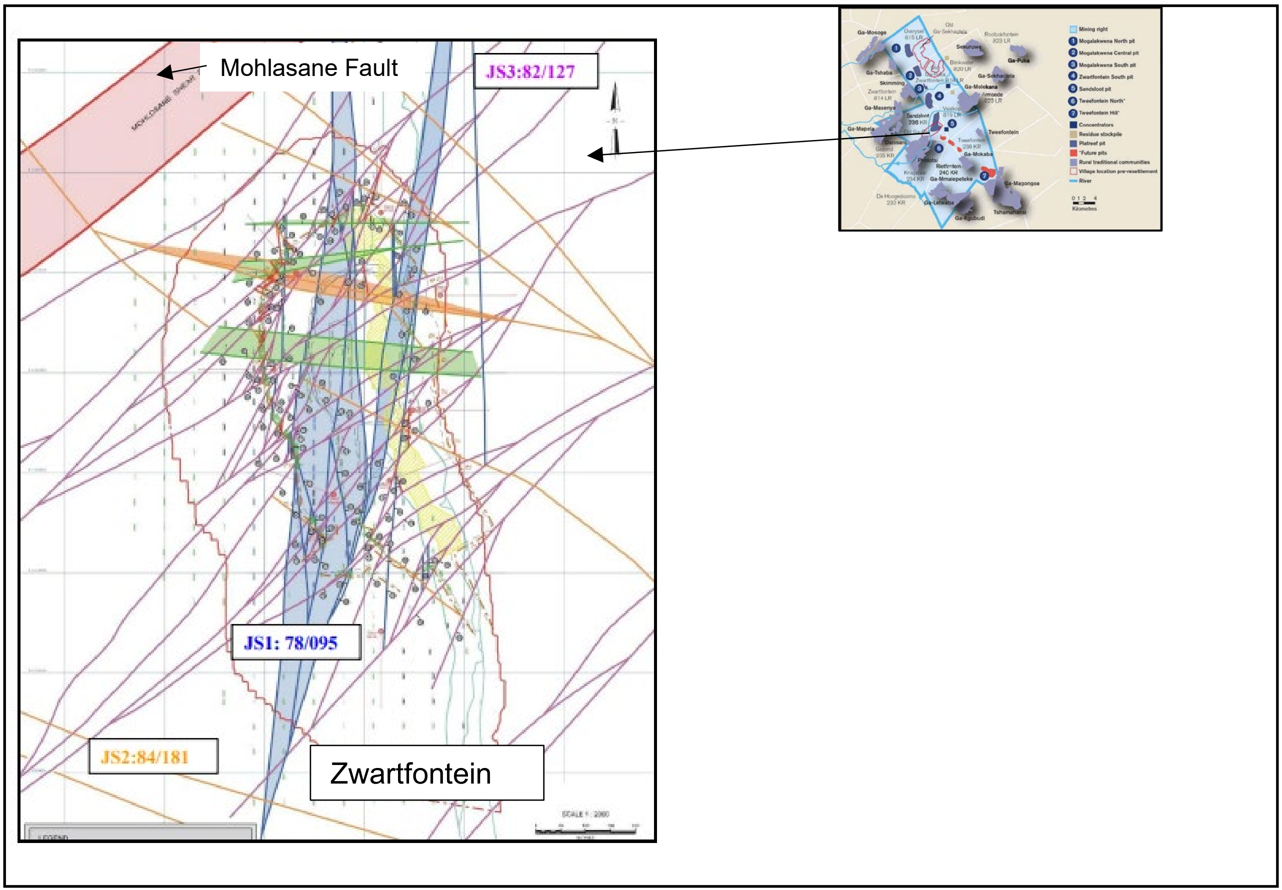


Figure 18: Zwarfontein JS1 Strike N-S, dip 84° dip direction 270°, JS2 strike E-W, dip 84° dip direction 181°, JS3 strike NE-SW dip 82° dip direction 127°.

Field observations from across the mine show that most of the fault zone of the Pit Fault in the North pit is in the southern wall. The fault zone strikes northeast, dipping approximately 60 degrees to the southeast. The core of the fault zone is variable in width and is comprised of strong chloritized breccia (increased permeability and transmissivity) 10 to 15 m wide in current exposures with gradational strain-gradient contacts (SRK, 2016). Figure 19A shows the Pit Fault zone that acts as a conduit for groundwater to flow and seepage is observed and therefore the slope on the south of North Pit is saturated, thus could impact and increase slope instability.

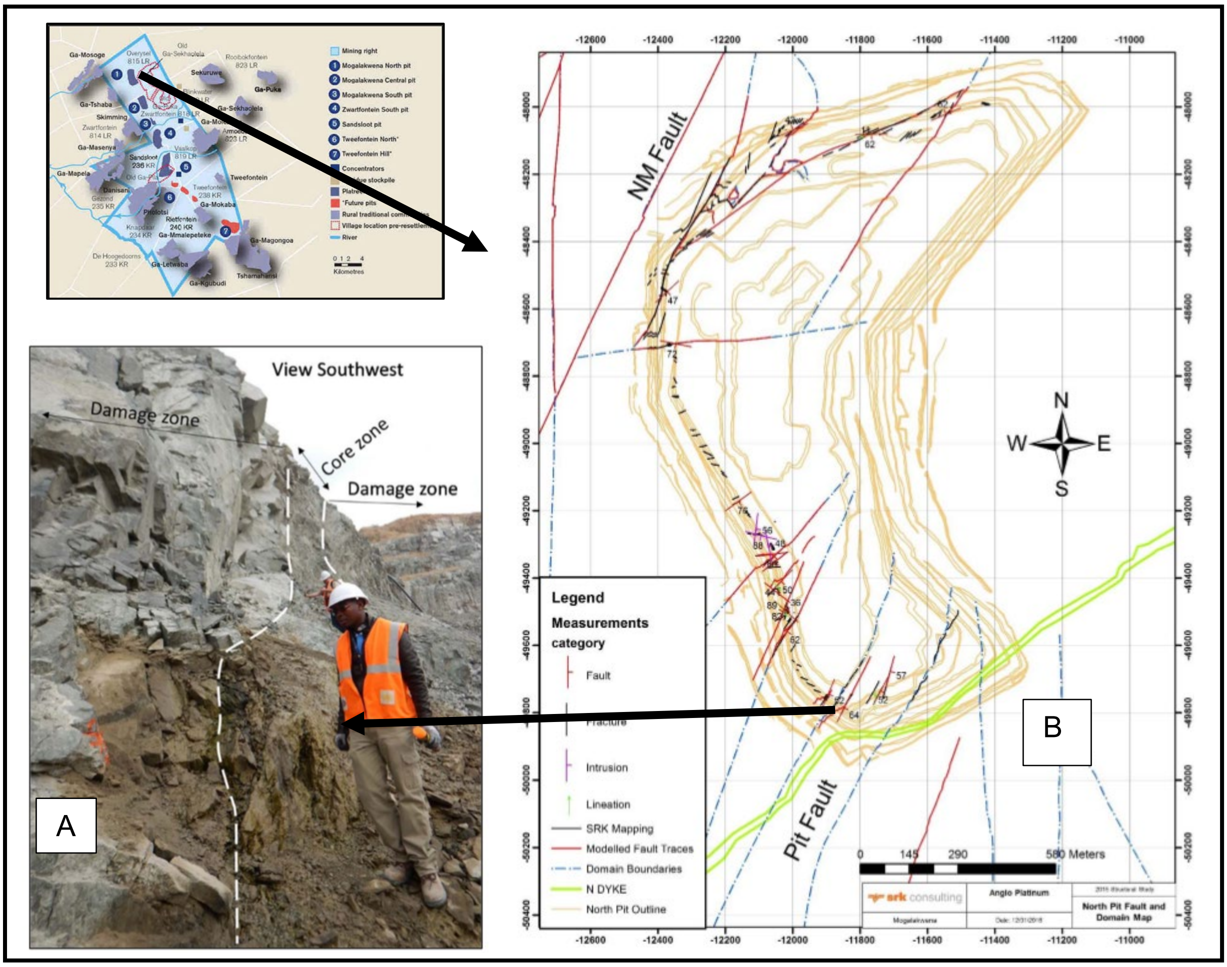


Figure 19: A: Pit Fait core zone composed of saturated breccia on south slope of north pit, Emmanuel for scale. B: Summary map of the structures and domains mapped in the North pit taken after (SRK ,2016).

A further view from the northwest of North Pit a thrust fault domain is seen, shown in Figure 20. The domain is characterised by a 65-degree southeast dipping fracture-fault system. This observed fault is continuous over multiple benches and the parallel fractures are impacting the bench profiles. Groundwater seeps through the open joints and thrust faults domain and has been a part of historical bench and stack failures.

Figure 20: Shallow to intermediate northwest dipping (42 degrees) fault zone, interpreted as a thrust fault. Rory for scale taken after (SRK, 2016).

The South Pit is smaller, and the structural geology is less complex than the other pits. There are about five demarcated domains in the south pit and a dolerite dyke known as the Southern Dyke shown as the green line in Figure 19B. However, part of the Mohlosane Fault zone is exposed in the southern slopes. During site investigations by SRK (2016) it is observed a fault zone 6 to 8 m wide, with well-developed slickenlines showing normal displacement (Figure 19A). This fault dips steeply to the north in contrast to the modelled southward dip of the Mohlosane fault zone. The rock mass immediately to the south of the fault is heavily fractured, saturated and interpreted as part of the Mohlosane fault damage zone. This zone of the pit was classified as high risk geotechnical zone because of the combination of factors such as structural complexity and the presence of groundwater. Groundwater seepage is visible in the rock face.

In the mine there are three main dykes, namely Southern Dyke-S Dyke (Figure 19B), the Central Dolerite Dyke, and the Northern Dolerite Dyke (Figure 21B). The dykes are observed to be filled with quartz-plagioclase by the structural work completed by (SRK, 2016) and are therefore sealed. The sealed nature of the dykes can lead to the creation of groundwater barriers, preventing the interconnected movement of groundwater between the different pits. This can lead to compartmentalization along the mine traverse (Itasca, 2016).

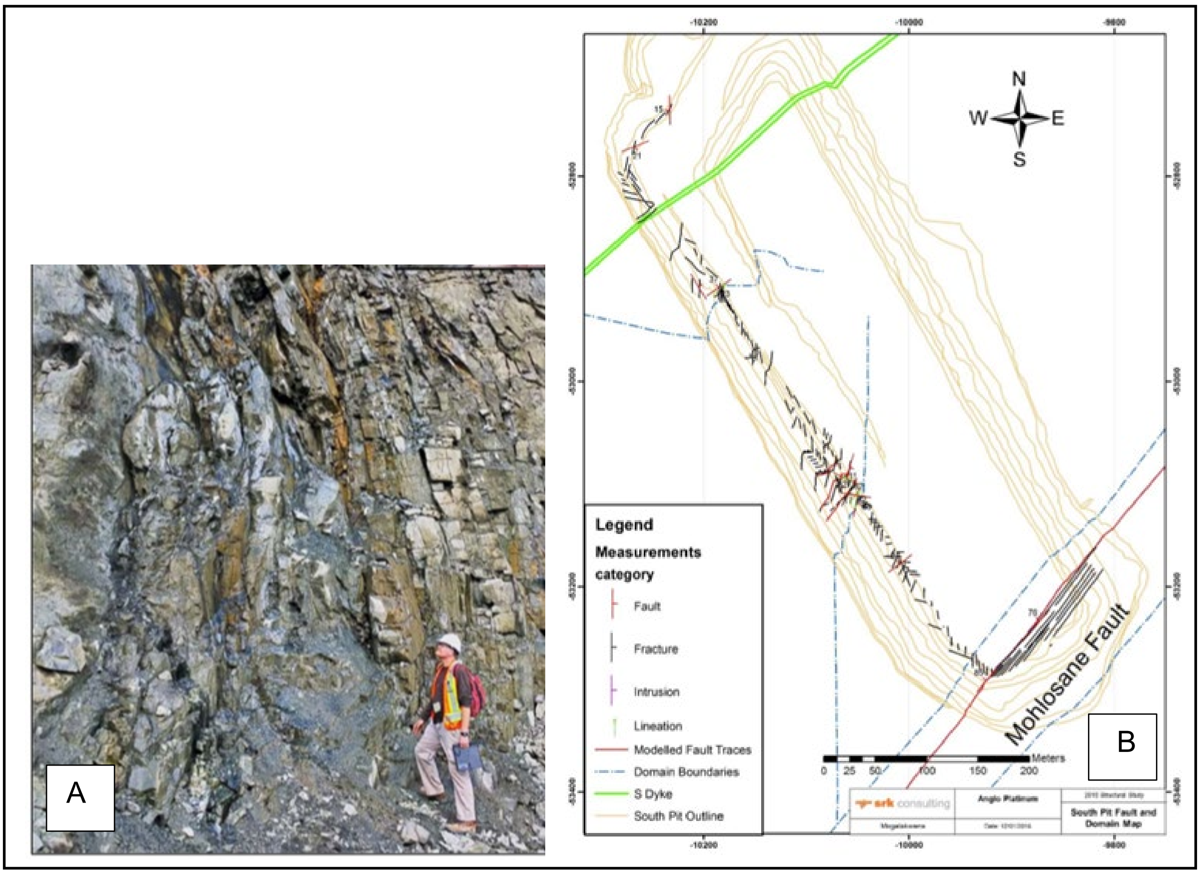


Figure 21: A Fault zone about 6-8m wide in the southern face of the south Pit associated with Mohlosane Fault zone, large volumes of water seepage observed. Barnett (1.8m)for scale. B: Summary map of the structures and domains mapped in the South pit (SRK, 2016).

In summary, the studies above are evidence that groundwater is present in the highwalls around Mogalakwena Mine. Groundwater flow into the mine is structurally controlled and water is known to destabilize the slopes and cause failure. It has been established in the earlier chapters that, saturated conditions on slopes can change the effective stress of the rock mass and can result in an increase in the probability for slope failures and destabilize slopes, as the groundwater flows through the discontinuities, open joints and faults; this can be detrimental considering that some joints and faults cut across benches and can cause stack failures. Groundwater on the slopes also results in low calculations for Factor of safety (FoS less than one), increasing the number of geotechnical high-risk zones which means fewer mining areas to access ore. Loss of mining areas due to lack of access is not good for any profitable mining operation because this means valuable ore will be left behind, therefore not meeting economic projections. The need for depressurisation is then considered to improve slope stability and increase factor of safety calculations by lowering the water stress on the slopes, thus, improving access to areas in the mine with valuable ore to mine and to potentially meet profitability.

4.3 Hydrogeological setting at Mogalakwena Mine

The basis of any hydrogeological analysis begins with understanding the geology, structural behaviour and geotechnical properties. This chapter aims to give a description of the findings of the site geological setting investigations, the geological fault structures and joint set behaviour as they play a large role in slope stability and groundwater flow.

The geologic setting of the Mine is in the Northern Limb of the Bushveld Igneous Complex, which is well known for its large proportion of the world's platinum and palladium resources as discussed earlier in this chapter. The simplified schematic section shown on Figure 22 indicates that the Platreef is overlain by norites of the Main Zone that can have thicknesses up to 2,000 m. The Platreef overlies the granites (Archean Basement) in the north as well as the dolomites and meta dolomites of the Malmani Subgroup in the south. A geologic transition zone or contact zone was assumed to exist on both sides of the Platreef (referenced as a “shear zone”). The extent of the transition zone/ shear zone is not well defined and was assumed to be continuous along the Platreef unit. As shown in Figures 22 the dip angle of the Platreef is generally 45- degrees from east to west, which is followed by various pit-excavation.

All geologic units are weathered near the ground surface, with thicknesses ranging from 50 to 100 m. The blue colour represents the Hanging Wall (HW) Norites in contact with the orange which is the shear zone, this in contact with the Platreef pyroxenite and finally the yellow colour represents the Foot Wall (FW) Granite basement with Dolomite in some areas. The circle within the Platreef is a representation of a lens of parapyroxenite within the reef. The Fault zone cross cuts all the lithologies. The numbers represent the typical borehole log and lithologies one would encounter while logging at Mogalakgwena Mine (SRK, 2016).

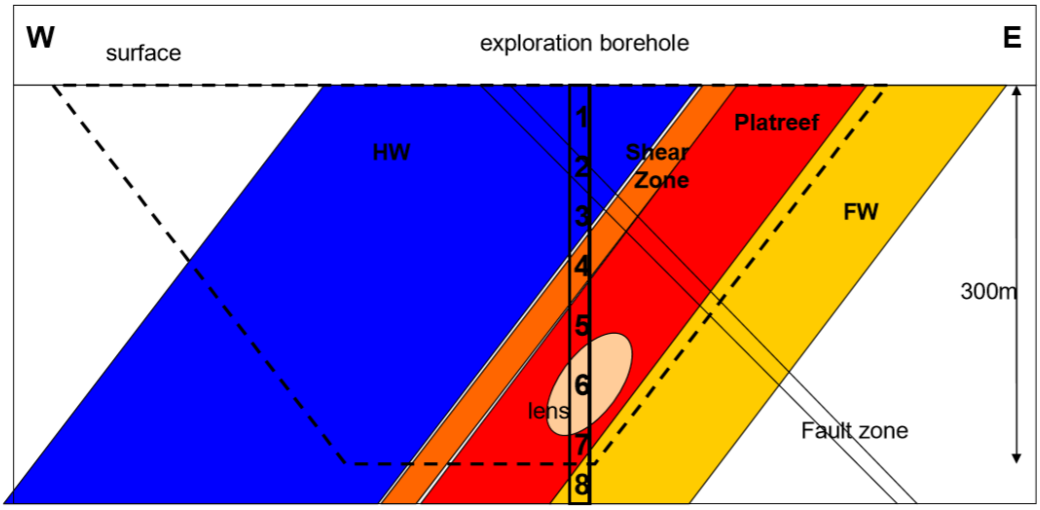


Figure 22:Simplified cross section Sandsloot pit taken from SRK (2016)

4.3.1 Mine Dewatering studies

A groundwater study was conducted by Little (2006) on Sandsloot Pit. Ten (10) boreholes were drilled numbered GW1 to GW10. They were drilled to 250 m in depth and pumps and piezometers were installed. The results of the study showed that pumping produced highly variable results with yields ranging from zero to 30.5 m^3 / hr (see Table 2). This study showed that dewatering by pumping at Sandsloot pit could not effectively dewater the slopes and it was concluded that the same principle applies for the rest of the mine pits based on the hydrogeological conditions. The suggested alternative option was slope depressurisation, using the technique of drilling bench toe drains into water-bearing fractures. According to Little (2006), the ten (10) horizontal drainage holes were drilled on the west wall in Sandsloot on Bench 32. The results of the trial proved that it was difficult to target the correct water-bearing structure and a recommendation was made to conduct more trials to investigate the application of slope depressurisation on the other pits and slopes.

Table 2: Summary of piezometer information at Sandsloot taken from (Little, 2006)

Name	Location	Final Depth	Water Strikes	Yield [m^3/hr]	Final Yield [m^3/hr]	Piezo	Depths [m]
GW1	Bundwall, centre of pit	250 m	Dry	Dry	Dry	1	Open to 250 m
GW2	Bundwall, southern portion of pit	250 m	105-106 m	2.82	2.82	1	106
GW3	W of Bundwall, centre of pit	250 m	19-20 m	0.3	0.8	1	22
			105-106 m	0.78		2	107
GW4	Slightly N of SSPZ1 (E wall)	250 m	20-21 m	0.3	0.9	1	22
			37-38 m	0.5		2	64
			62-63 m	0.7			
			203-204 m	0.9		3	205

Name	Location	Final Depth	Water Strikes	Yield	Final Yield	Piezo	Depths
GW5	N boundary of pit on SSL river	250 m	58-59 m	Seepage (0.0 m^3/hr)	0.4 m3/hr	1	61 m
			135-136 m	0.4 m^3/hr		2	110 m
			98-99 m	0.1 m^3/hr		3	138 m
GW6	Between the 2 seismic houses	250 m	41-42 m	Seepage (0.0 m^3/hr)	2.82 m^3/hr	1	50 m
			49-50 m	1.6 m^3/hr		2	100 m
			99-100 m	2.82 m^3/hr			
GW7	On top of northern bundwall	167 m	165-166 m	30.48 m^3/hr	30.48 m^3/hr	test pump	
GW8	Bundwall, northern tip of pit	250 m	Dry	Dry	Dry	1	40 m
GW9	Outside mine boundary, near small crusher	250 m	19-21 m	1 m^3/hr	2.0 m^3/hr	1	20 m
			87-90 m	1.47 m^3/hr		2	91 m
			117-120 m	1.5 m^3/hr		3	118 m
GW10	SW of Dispatch on haul road	250 m	57-58 m	1 m^3/hr	2.8 m^3/hr	1	66 m
			65-66 m				90 m
			84-90 m				99 m
			98-99 m				

The best method of dewatering is usually by drilling vertical boreholes outside the pit and pumping out the groundwater. This technique for Mogalakwena has been investigated and because groundwater is fracture controlled, this hinders efficient and successful pumping using the classic dewatering techniques. Dewatering programs aim to achieve lower levels of the groundwater table in the mining area for unconfined aquifers, ideally to be below the level of the working pit floor. The current water control taking place in the mine is operational dewatering, which pumps out groundwater seepage and rainfall water that collects at the bottom of the pits in sumps. In a fractured aquifer setting like the one at Mogalakwena, groundwater flows on open joints and faults and has played a role in historic bench and stack failures. The zones or faults with higher permeability seems to be dewatered if they have intercepted the pits excavation or through horizontal drainage boreholes.

4.3.2 Hydraulic conductivity characterization studies

A groundwater and fault characterization study conducted by Rosond in 2016 was aimed at characterizing the hydraulic parameters of the major faults at Mogalakwena Mine and install vibrating wire piezometers. Four (4) major structures were the target of this study, namely Mohlosana Fault (PZ1604), Pit Fault (PZ1601), North Fault (PZ1602NM) and Drenthe Fault (PZ1603), see Figure 23.

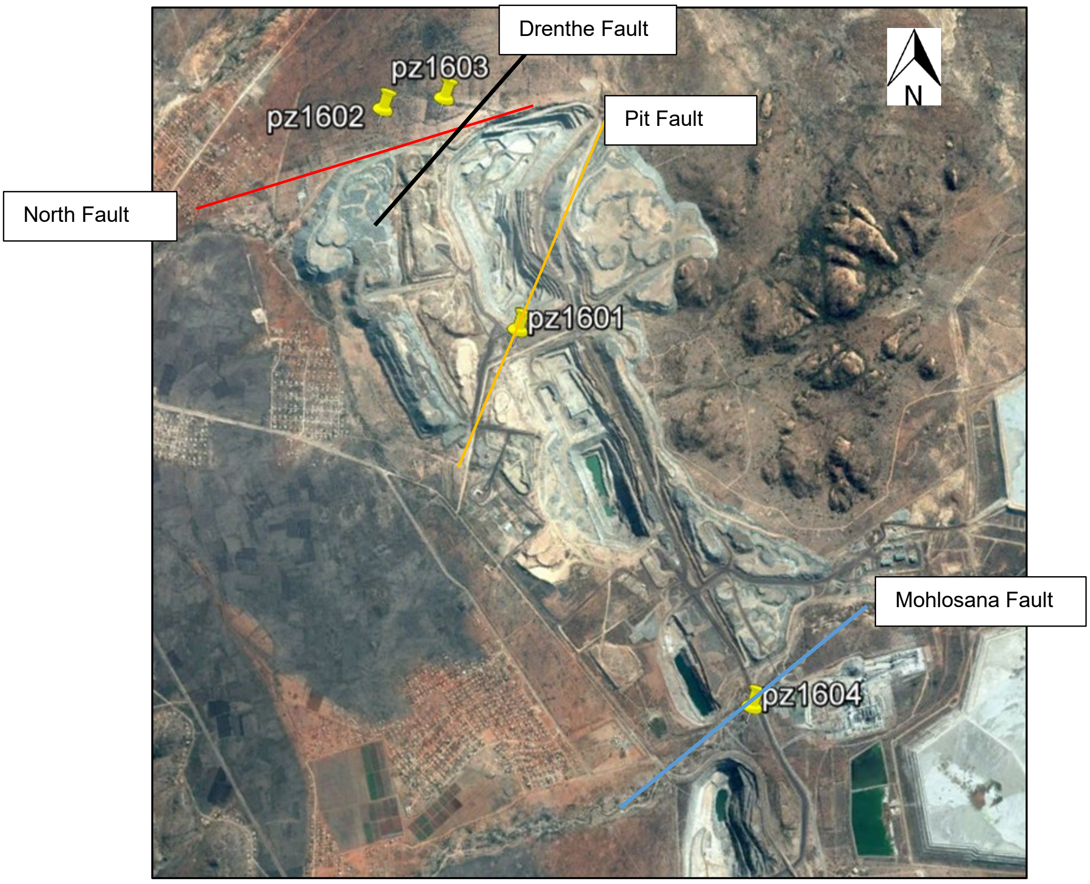


Figure 23 Location map of major structure characterization study (PZ1601-Pit Fault, PZ1602-NM Fault, PZ1603-Drenthe Fault, PZ1604-Mohlasane Fault (Google Earth, 2017)

The summary of the results of the study is captured in Table 3 taken from Rosond (2016). The table also shows the results of the packer test for each borehole at different sections of the borehole in order to determine the hydraulic conductivity of that specific lithology. Packer testing (Also known as Lugeon test) is a method used to assess the hydraulic conductivity of a limited section of a borehole. The Lugeon test is an in- situ testing method widely used to estimate the average hydraulic conductivity (K) in unit of a rock mass. The test is named after Maurice Lugeon, a Swiss geologist who first formulated the test using a packer, thus also named packer test. During packer testing a unit section (in meters) of borehole is installed with packers which act as ‘blocks’, therefore sealing the borehole see Figure 24 and a smaller pipe runs through the packer and brings water from the outside into the borehole at a certain pressure. As the water enters the borehole in the section of interest (mainly fractured rock mass) such as section *2B* in Figure 24, the interaction of the water with that rock unit is measured by the pressure exerted and the volume pumped down over time. The pressure is measured with the pressure gauge and the flow is measured with the water meter at the top of the borehole.

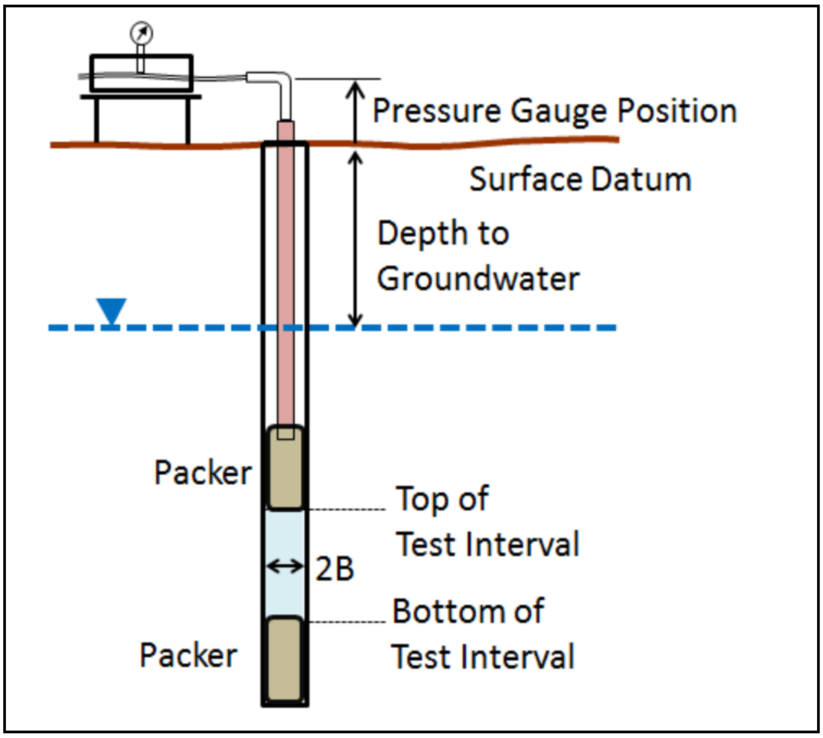


Figure 24:Typical set up of a packer test in a borehole to measure hydraulic conductivity of a section of the borehole (www.geotech.hr.com)

The hydraulic conductivity is then calculated from plotting the results based on the ease with which the water injected moves through the pore spaces or fractures of the unit of rock of interest of the borehole. This is done using Darcy's law for flow (Darcy's equation) $Q = K_{sat} \cdot d H d x$ where Q is the (m^3/s), K_{sat} is the saturated hydraulic conductivity (m/s), d H is the head difference (m), and d x is the distance (m). Dx distance of the unit thickness in meters is an important determining factor in the equation when investigating hydraulic conductivity (section 2B, Figure 24).

The waterflow passing through the rock mass depends on parameters such as: interconnection of rock crack and joints, joint width, joint filling type and filling erosion. These are considerations to resistance during waterflow. The results of the packer tests in the Rosond study for hydraulic conductivity (K), for the Pit Fault were K= 0,00261 m/day. A Hydraulic conductivity value of 0,00261 m/day is less than 1 m/year flow, and this is a low hydraulic conductivity for the fault and therefore indicating a tight rock mass.

Also, In the Rosond study, the unit thickness of 8,84 m was used for the testing of the North Fault, whereas the actual fractured fault thickness observed in core logging was approximately 2 m. This can explain the low value in K for North Fault which was 0,00208 m/day indicating a relatively low hydraulic conductivity for the fault indicating a tight rock mass although the flow regime and physical mapping shows seepage and the presence non–persistent discontinuities.

Table 3: Summary results of Rosond drilling and packer testing from major faults (Rosond 2016)

Borehole ID		Test depths (m) at Top	Test depths (m) at Bottom	Lithology	Stratigraphy	Calculated Hydraulic Conductivity (m/day)
PZ1601	PZ1601	67	68	Norite	HW	0,00027
Azimuth		73	74	Fault	HW	0,00410
260		103	104	Gabbronorite	HW	0,00460
Dip		149	150	Gabbronorite	HW	0,00200
75		235	243	Pit Fault	Platreef	0,02600
Final depth (m)		268	270	Pyroxenite	Platreef	0,00004
264						
PZ1602	PZ1602	135	144	NM Fault	Fault	0,00208
Azimuth						
330						
Azimuth						
85						
Final depth (m)						
283						
PZ1603	PZ1603	124	144	Shear	HW	0,00077
Azimuth		181	182	Anorthosite	HW	0,01210
300		202	203	Gabbronorite	HW	0,02030
Dip		264	270	Drenthe Fault	Platreef	0,05510
60						
Final depth (m)						
292						
PZ1604	PZ1604	196	209	Pyroxenite	Platreef	0,00111
Azimuth		239	242	Mohlosane Fault	Platreef	0,07720
300						
Dip						
60						
Final depth (m)						
329						

The study also found that the Dyke in the North of North Pit has a K value of 5,64 X10 $^{-21}$m/day suggesting very tight rock mass which is expected for an impermeable Dolerite Dyke. Something to note is that the K-values of the Dyke falls way outside the “framework” set out by Freeze and Cherry (1979) which has a limit of 1 E-10 in the relative hydraulic conductivity scale. This may suggest that all the dolerite dykes found in Mogalakwena Mine, are most likely sealed and create a hydrogeology system that is compartmentalized. From field observation, the following was recorded which support the results of the study by Rosond (2016). The Platreef when highly faulted and fractured showed results of moderate to high hydraulic conductivity values ranging from 0,02 to 0,07 m/day.

The zone of relaxation which develops around the pit perimeter due to blasting comprises of concentric and vertical cracks and zones of enhanced weathering which taper with depth. This zone is more permeable than the intact, fresh rock mass. This relaxed zone allows rapid flow along the fault structures due to increased porosity and permeability. Another evidence is seen in the water levels measured closer to the surface of the pit in 2016 monitoring boreholes along the pit perimeter which showed that the weathered zones of the Norite and Granite may have low permeability. It has been assumed through field observations that the fresh Norites, Pyroxenites and the Granites are generally competent rocks with low permeability values although these rock types may exhibit localized higher permeability as a result of faulting and fracturing. Therefore, the efforts of operational dewatering do not dewater or depressurise the permeable fractures or zones. This is a significant finding in support for the rational for the work outlined in this dissertation.

In summary, the hydrogeological setting is characterized by a mixed hydraulic conductivity (K) system of low and high storage. Very low K values occurs in the strong fresh rock mass Hanging Wall (HW) and Foot Wall (FW) slopes and moderate to high K values occurs in the Platreef and shear zone generating seepages and discrete inflows into the open-pits. No relevant recharge sources have been identified from nearby aquifers and groundwater inflows during pit development will occur along the strike within the Platreef and along potentially permeable regional structures. The drainable porosity of all rock units is low and the groundwater system has low overall storativity. It is expected that a significant reduction in water levels and inflows could be achieved through slope depressurisation and draining of the slopes in the Platreef.

4.3.3 Precipitation and recharge studies

The amount of rainfall in the mine area is an important indicative factor that must be included in the understanding of the hydrogeological setting of Mogalakwena Mine. It is important to relate and understand the percentage of precipitation that becomes recharged into a groundwater system. Since the open-pit acts as a hydraulic sink, that captures precipitation and groundwater is flowing in from all directions. it is important to determine the percentage recharge of an aquifer from rainfall (Itasca, 2016).

The mean annual precipitation rate at Mogalakwena Mine is approximately 700 millimetres per year (mm/yr). This is shown in Figure 25 which shows the average precipitation recorded over 10 years from 2007 to 2017. Although not represented in Figure 25, but in the yearly rainfall graphs, the annual rainfall graphs show that most of the rainfall between 350 mm to 700 mm occurs in the summer months of November to March. This already provides a period when to expect recharge in the pit.

Groundwater recharge is a hydrologic process during which precipitation and surface water infiltrate the groundwater system. The direct recharge of groundwater through precipitation primarily occurs during the summer months November to March (Environment Department, 2017). The potential evaporation rate at the mine is considered higher than recharge and is recorded at an average of 130 mm/per month and that the runoff is about 80% of the annual rainfall.

Currently, there is no surface water runoff control into the open-pits, runoff moves into the open-pits / upper highwalls, and a large portion of runoff water is collected at the pit floor sump and pumped from the sumps back out again. It has been assumed through various studies that the recharge rate into the groundwater system as a result of precipitation, is a low percentage of the mean annual rainfall percentage.

Groundwater flow model studies by Golder (2013) and Itasca (2016) estimated recharge percentage rate from precipitation at 0.5% and 0.3% respectively. The studies concluded that the evaporation rate at Mogalakwena exceeds the recharge rate and therefore the low rate of recharge is assumed and applied for these episodic events.

When applying the simplified water balance equation for a basin, it assumes that the annual groundwater recharge is equal to Precipitation (P) (mm/yr) into the basin minus evapo-transpiration (ETR) from the basin (mm/yr) minus direct runoff (R) from the basin (mm/yr) (Golder, 2013).

Annual groundwater recharge=P-ETR-R

Annual groundwater recharge= 700 mm/yr-130 mm/yr-(700 mm/yr x 80%)

=700 mm/yr-130 mm/yr- 560 mm/yr

=10 mm/yr….1.4% of annual rainfall.

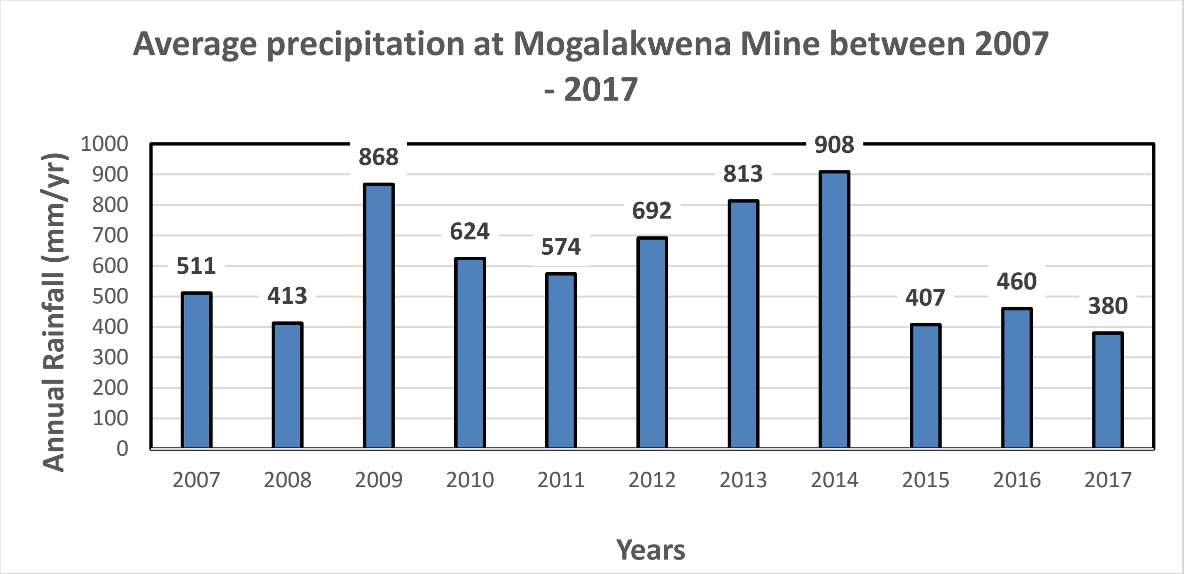


Figure 25:Average annual precipitation rate at Mogalakwena Mine from 2007 to 2017. (Taken from Environment Department at Mogalakwena Mine).

The value of 1.4% is obtained for Mogalakwena for the average recharge is low as expected but slightly higher than the estimations by Golder (2013) and Itasca (2016). The difference could be that the above calculation assumed evaporation also included transpiration. If transpiration was considered it could potentially further decrease the results of the recharge percentage.

According to Itasca (2016), there are two types of recharge to differentiate from, recharge from precipitation and the recharge from surrounding mine facilities such as the return water dam and waste rock dumps. Recharge from precipitation is referenced as "natural recharge", while recharge from the mine/facilities is referenced as "induced recharge". There has not been any estimates done to date to determine the induced recharge percentage and its impact on the seepage observed on highwalls of the pit. Sources of induced recharge include water runoff from the plant, water storage reservoirs, and waste and tailing dumps. Further recommendation is to conduct isotope studies to better understand and characterise the recharge sources. In the study by Itasca (2016) recharge from the mine facilities such as return water dams and waste dumps which are situated only a few meters away from the pit shell, are higher than precipitation-based recharge. But this requires further investigation.

In summary the mean annual precipitation rate at Mogalakwena Mine is approximately 700 (mm/yr) recorded over 10 years from 2007 to 2017. The evaporation rate at the mine is high and is recorded at an average of 130 mm per month. The recharge percentage is 1,4% from precipitation into the groundwater system

4.4 The relationship between depressurisation and dewatering at Mogalakwena

Earlier in the literature review chapter, Read and Stacey (2009) explained the relationship of mine dewatering and slope depressurisation by using five (5) broad categories. They considered the hydrogeological setting as a controlling factor in their categorizing. Since the evidence has been shown that the hydrogeological setting at Mogalakwena is characterized by a low to moderate, and high hydraulic conductivity (K) (mainly Platreef), a system of low storage and moderate precipitation and low recharge. Very low K values occurs in the strong rock mass Hanging HW Norites and FW calc silicates slopes and moderate to high K values occurs in the Platreef, shear zone and faults generating seepages and discrete inflows into the open-pits.

The Hanging Wall is referred to the lithology above the Platreef and the Foot wall is the lithology below the Platreef. This part of the dissertation will focus on categorising Mogalakwena Mine according to the criteria by Read and Stacey (2009) to further establish the relationship between dewatering and slope depressurisation and thus support the need for a slope depressurisation programme.

According to the main classification in Table 2, Table below 4 shows the category Mogalakwena mine falls within. Mogalakwena Mine falls within two (2) categories, namely category 2 and category 4. Category 2 classes those open-pit operations whose pits are excavated below the water table and occur in low permeability rocks and where mine dewatering has been able to completely dewater or drain the rock mass. Although the weathered rock on the top of the Hanging Wall may be drained or dewatered the faulted norites of the hanging wall and footwall with lower permeability, proved impossible to dewater. Groundwater will only be drained and pore pressures dissipated only if there is targeted horizontal drainage along the slope section drilled.

Category 4 classes open-pits whose pits that are excavated in fractured rock mass and geological structures either form barriers or conduits for groundwater to flow. We have seen that the rock mass in Mogalakwena Mine may not drain unless in cases where the pit excavation intercepts faults and highly jointed shear zones that serves as conduits for groundwater to flow. The dykes at the mine have been found to be filled with calc silicate, therefore, acting as barriers for groundwater flow, creating compartments of trapped groundwater between the various pits. The structural compartmentalisation means the depressurisation intervention between the various pits will be different because of this added complexity. The dewatering program does not dissipate pore pressures in all slope sections therefore localised measures become necessary to horizontally drill through the structures and drain the groundwater behind them.

Table 4: Summary describing the two (2) categories that define the relationship between dewatering and depressurisation for Mogalakwena Mine taken from (Read and Stacey, 2009, Table 1).

Category	**Description**
Category 2: *Mines excavated below the water table that occur within lower-permeability rocks occurring in some sections of the pit.*	• Mine dewatering may not completely drain the rock mass in some sections of the pit as the water table is lowered. • Most of the rock mass is drained but not possible in sections of lower permeability rocks. • In these zones groundwater will move slow and the pressures will not dissipate easily without targeted, localised depressurisation programs. • Sleeper mine in Nevada, where in excess of 4543 m$^{3/}$hr was pumped from alluvium and permeable volcanic tuffs using wells, but the drainage of argillaceous rocks in certain sectors of the pit wall was poor and required localized control with in-pit horizontal drain programs.
Category 4:	• The rock mass may not drain because of geological structures

Mines excavated in a fractured rock mass below the water table and geological structures form barriers to groundwater flow.	such as dykes. These structures as impermeable flow barriers, creating compartments of trapped water with high pore pressures. • Most large open-pit mines in hard rock settings have structural compartments that influence groundwater levels and movements. For this category, the rock mass may not drain because geological structures act as impediments to groundwater flow, creating compartments of trapped water with unchanged (and therefore high) pore pressure. • The general mine dewatering program does not dissipate pressure in all pit slope sectors. As the excavation is extended and approaches the structural compartments, localized measures become necessary to penetrate the structures and drain the water behind them. • Examples of mines with structural compartments that require proactive drainage measures to support pit slope performance include the South Wall of the Chino Mine in New Mexico and Rio Tinto-Minerals Boron Operations in California.

4.5 Pore Pressure analysis and factor of safety studies

Earlier in this dissertation, it was discussed that increasing pore pressures over time can have a detrimental impact in overall slope stability. This statement not only sets the tone for the work explored in this dissertation but forms part of the base theories. For the analysis of pore pressure at Mogalakwena Mine the focus is the hanging wall made up of unconsolidated Norites of the Main Zone. The assessment will include the results of the pore pressure in meters of water column (mH_2O) of the fully grouted wire-line piezometers. The analysis will include several boreholes from the fault characterization study mentioned earlier by Rosond (2016) and others from existing fully grouted wire-line piezometers.

The data used was provided by the Geotechnical Engineering department for the period of 2016 to 2017. It is important to note that some of this data some of the data from this period of 2016-2017 was not usable in this study. It was filtered and found to have many boreholes where open standpipe piezometers wells, with and inconsistences in data and no monitoring of pore pressure and only three (3) wells are closed/sealed wells with installed vibrating wireline piezometers with usable data

Figure 26 shows a borehole location map taken from Itasca (2016) that summaries different types of boreholes found across the mine. The orange dots represent sealed boreholes with installed vibrating wireline. The purple squares are the open standpipe piezometer wells, some of which have been destroyed. The green and blue dots represent old boreholes some of which have been destroyed. This limited the amount of data available for the analysis. The focus of pore pressure analysis that will be also used in applying SDATRQ will be from the fully sealed/grouted wireline piezometers that are located closest to the highwalls where the impact of groundwater on slope stability needs to be assessed in consideration of whether to start a slope depressurisation program.

4.5.1 Factor of safety

It is important to note that the FoS for the three highwalls of interest were determined in a 2018 study through Finite Element Modelling method using the Slide software by the Geotechnical Engineering Department. The factor of safety is one index in slope analysis that has been extensively used for determining the stability of slopes. The numerical simulation of a deep highwall slope. Parametric analysis through the software programme has been conducted by changing one parameter at a time and keeping all other parameters fixed in order to understand the influence of various parameters, namely, rock density, angle of internal friction, cohesion, overall pit slope angle and influence of groundwater (groundwater elevations).

It has been observed that all the parameters undertaken in this study have a strong and well-defined influence on the stability of the slopes. Kinematic analysis also through the software illustrate the potential for various modes of highwall slope failures, namely, planar, wedge and toppling failures which may occur due to the presence of unfavourably oriented discontinuities or the presence of groundwater. The analysis revealed that the highwall slope is susceptible to structurally controlled failure and that is amplified if water levels observed on the monitoring close by the slopes are increased.

The corresponding FoS from the 2018 study corresponding highwall sections of North pit, central Pit as a result from the finite element modelling were:

- PZ1603 closest to the Northern highwall of North Pit; (FoS=2.0)
- PZ1601 closest to the southern highwall of North Pit and northern highwall of Central Pit; (FoS=0.8)
- DBH33 closest to the eastern wall of Central Pit; (FoS 2.5).

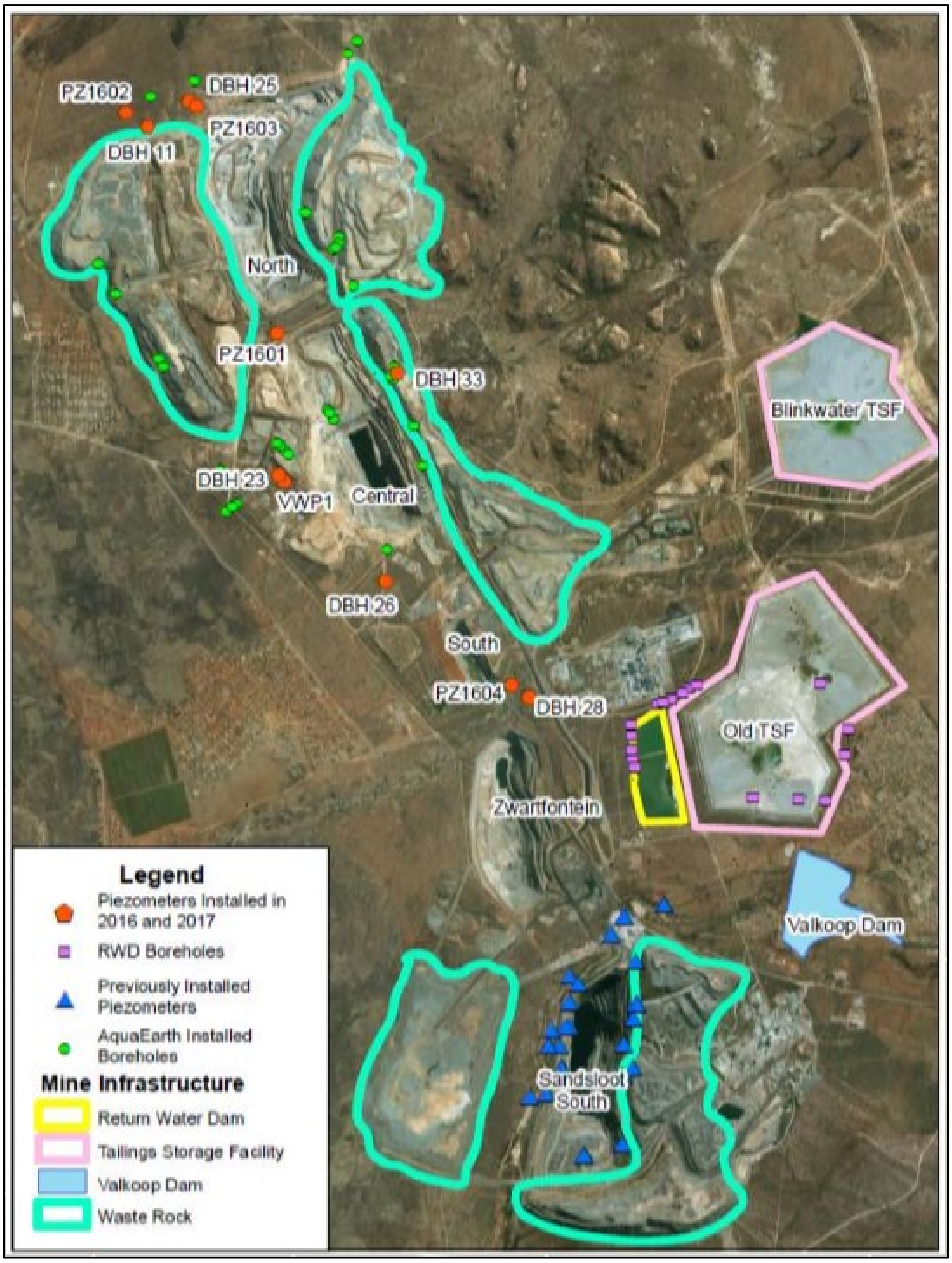


Figure 26: Groundwater monitoring boreholes across Mogalakwena Mine Taken after (Itasca 2016)

4.5.2 Pore pressure analysis

The pressure transducers inside the wire-line piezometers are able to calculate and measure groundwater elevations (mamsl) and pore pressures (mH_2O). A plot of the pore pressures through time will enable the analysis of whether pore pressure behind the chosen highwall is increasing, decreasing or remain the same. Pore pressure (mH_2O) data downloaded from the three grouted wire-line piezometers from 2017 to 2018 is plotted against time and is shown below in Figures 27 to Figure 31. The data was taken from the sensor closest to the ground surface.

PZ1603 wireline piezometer installed at 188 mbgl.

The results of the pore pressure over time show that the pore pressure behind this section of the highwall remained relatively unchanged between June 2017 to January 2018 at 147 mH_2O (1.44MPa) and 146 mH_2O (1.43MPa). From May 2017 to January 2018 the pore pressures were relatively stable at around 145mH_2O (1.42 MPa). Then there was a gap in data collection after that an increase was observed. The increase of pore pressures from January 2018 to June 2018 of about 7 mH_2O (0.06 MPa) in 6 months is observed and this is the same highwall where seepage has been observed on the northern wall of North Pit between January and March 2018, including minor slope failures as well. The increasing pore pressure behind this highwall suggests that there may be a need to depressurise the slope, but more questions need to be answered in order to make this decision using SDATRQ tool. A further investigation will need to be considered to determine if 7 mH_2O (0.06 MPa) is the trigger pore pressure to used in future slope depressurisation program planning.

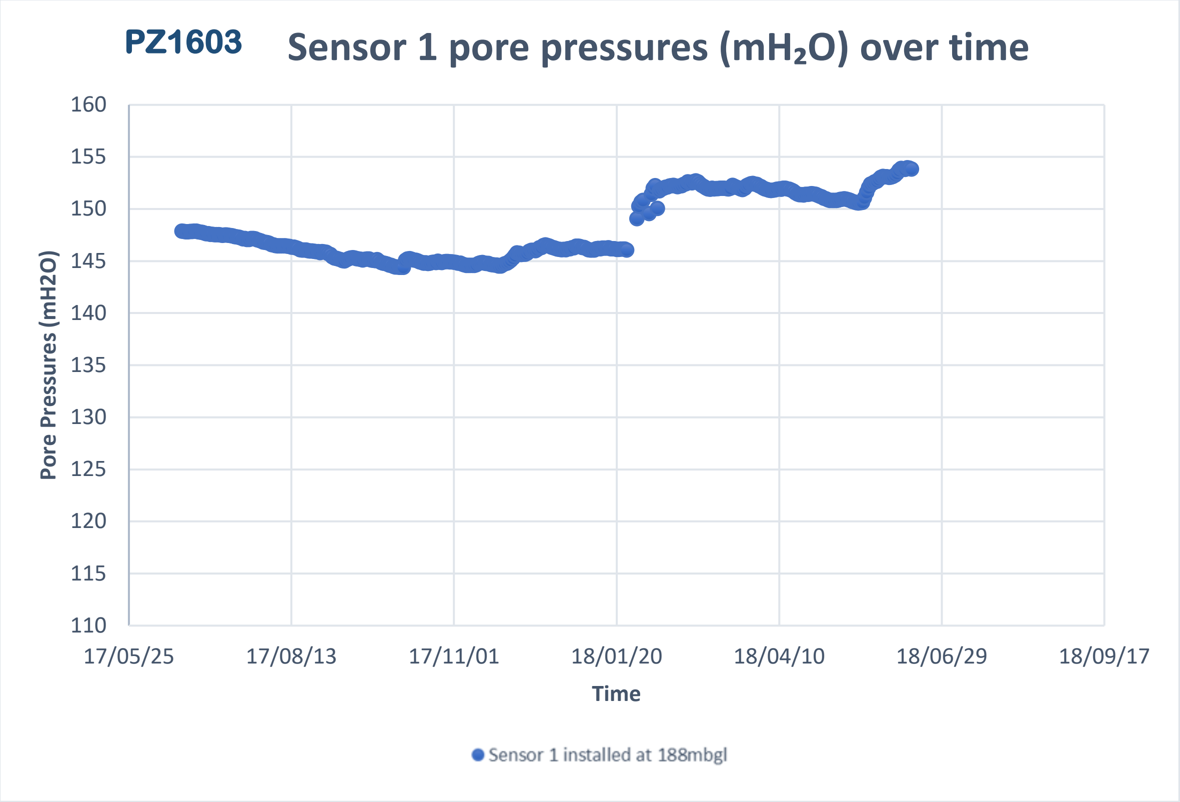


Figure 27: Pore Pressure data in mH_2O PZ1603 over time

PZ1601 wireline piezometer that is installed at 104 mbgl

Figure 28 shows results of PZ1601 and the results of the analysis of pore pressure through time show an overall decrease in pore pressure from 82 mH_2O (0.80 MPa) in October to 81 mH_2O (0.70 MPa) in June 2018, therefore a decrease of 1 mH_2O (0.01 MPa) over 9 months. Although during November 2017 to December 2017 there is an increase in pore pressure of 0.6 mH_2O (0.005 MPa) in the month. The overall decrease over time could be caused by the zone of relaxation that happens through continues pit activities such as blasting. The rock mass on the highwall will over time relax and crack therefore dissipating some of the pore pressure. There is no need to depressurise this slope according to this result because the pore pressures are decreasing thought time at 1 mH2O in 9 months, very little change and suggest a stable slope. But more questions need to be answered in order to make this decision using SDATRQ tool.

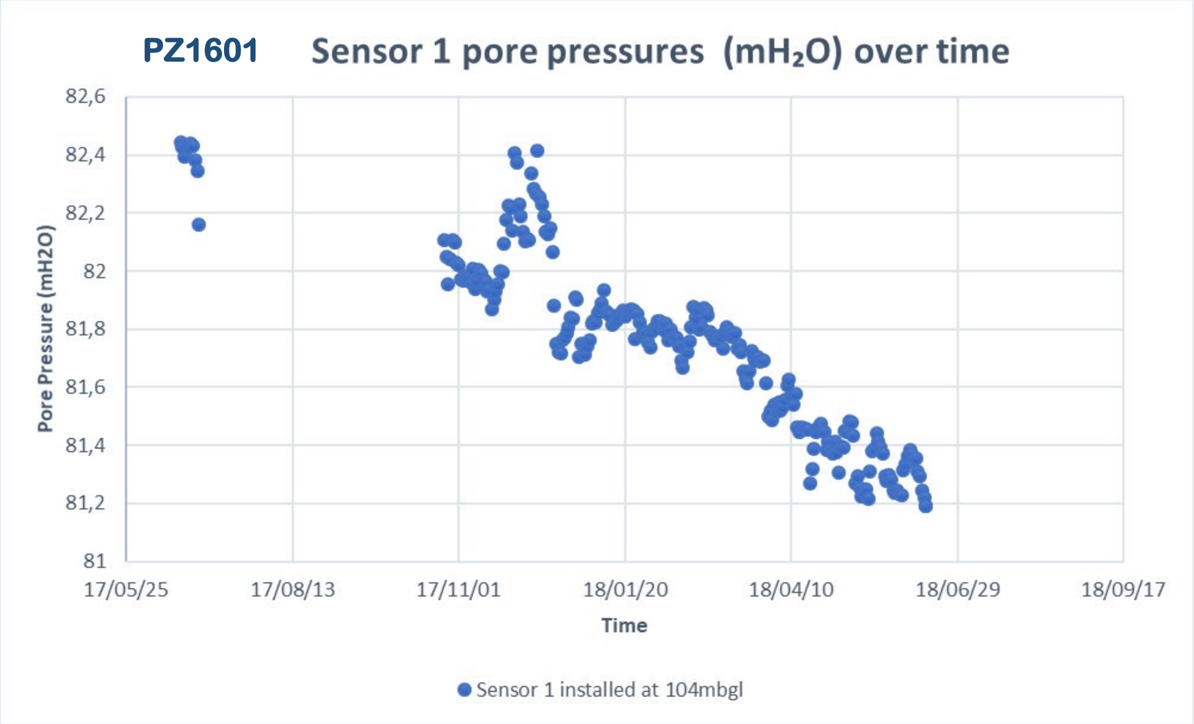


Figure 28: Pore pressure data (mH_2O) PZ1601 over time

DBH33 wire piezometer that is installed at 85 mbgl

Figure 29 shows DBH 33 and the gaps in the data are due to no data collected when the battery of the sensor was depleted and the battery needed to be replaced. The overall slope of the curve of the results shown in Figure 29 is a decrease in pore pressure, a further decrease and stabilization through time. From May 2016 to May 2017 there is a decrease from

75 mH_2O (0.73 MPa) to 23 mH_2O (0.22 MPa) that is a difference of 52 mH_2O (0.5 MPa) one-year period, 4.3 mH_2O per month.

Between November 2017 to June 2018 the pore pressure seems to have stabilized at 14 mH_2O (0.13 MPa). There was a major Platreef zone intercepted through blasting in the pit, that released large volumes of groundwater over many months and drained into the pit. Mining was stopped in this section and the groundwater drained into the sumps and was pumped out. This was near DBH33 and that can explain the decrease in pore pressure over time. Since then, pore pressures have stabilized. There may be a need to depressurise the slope, but more questions need to be answered in order to make this decision using SDATRQ tool.

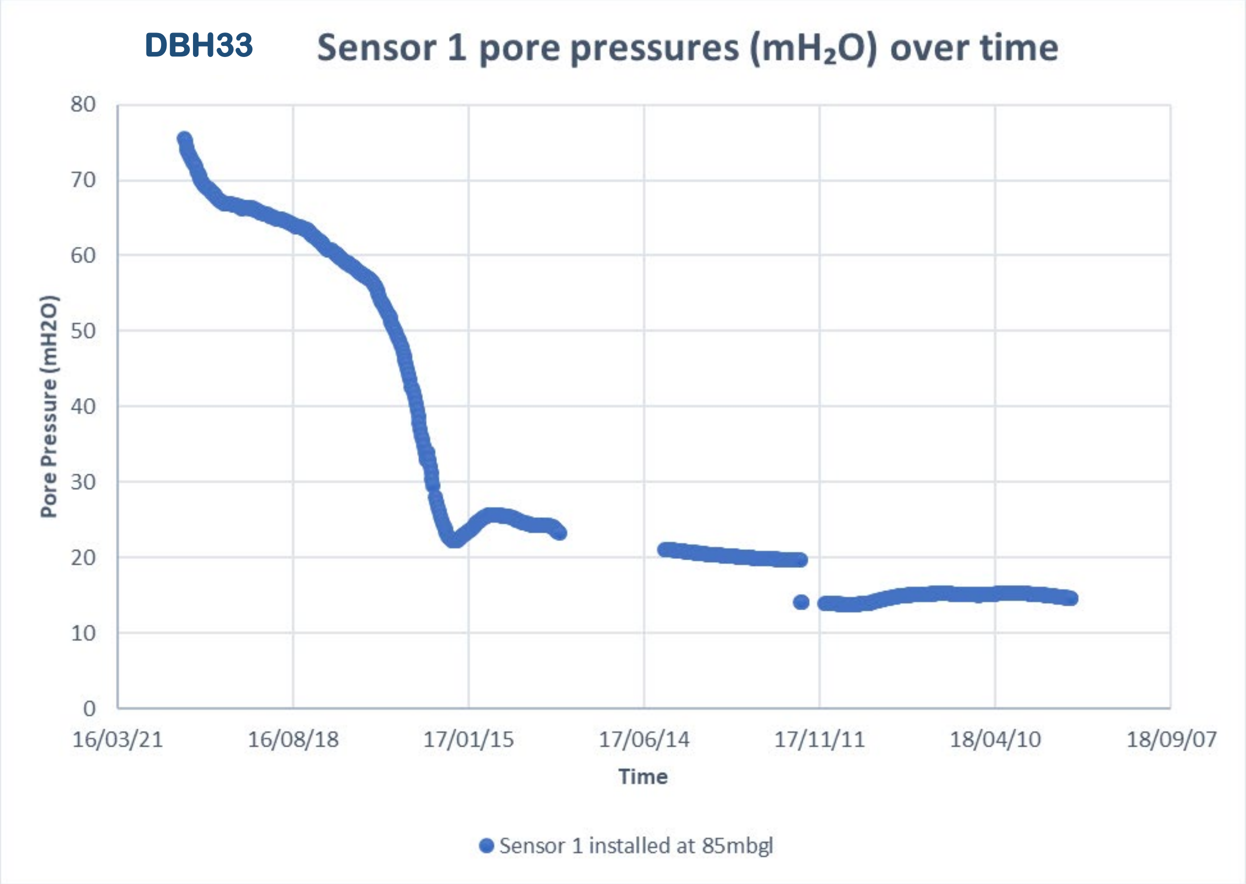


Figure 29: Pore pressure data mH_2O DHB 33 overtime

In summary, the analysis of the results showed that the pore pressure behind the highwall on the north of North Pit (**PZ1603)** increased with 7 mH_2O (0.06 MPa) over 6 months. This highwall has had groundwater seepage and was prone to minor slope failures and rock falls. There is a need to depressurise this slope to manage the slope stability of this section of the highwall but more questions need to be answered in order to make this decision using SDATRQ tool. The analysis in southern North pit **(PZ1601**) and eastern Central pit did not show any need to depressurisation of the slopes as the pore pressure remained relatively unchanged over one year and no slope failures were associated with these slopes although sessional seepage was observed. Also, there may be a need to depressurise the slope, but more questions need to be answered in order to make this decision using SDATRQ tool. The final analysis of the eastern wall of Central Pit (**DBH33**) showed no need to depressurise the slope, but more questions need to be answered to make this decision using SDATRQ tool. The 7 mH_2O (0.06 MPa) (PZ1603) increase may need to be investigated further to establish if it can be used as the baseline trigger pore pressure, to be used in the monitoring to plan for future slope depressurisation programs.

4.6 Analysis using Slope Depressurisation Action Trigger Response Questionnaire (SDATRQ)

Now that the data has been analysed for understanding the following components which include:

- the structural and geological setting,
- the hydrogeological setting,
- the hydraulic conductivities,
- annual rainfall and estimates recharge percentage has been established,
- the relationship between dewatering and depressurisation is established and
- the need for depressurisation based on the pore pressure has been established.

The data is ready to be analysed thought SDATRQ too. The following part of this dissertation will seek to answer the questions found in SDATRQ to finally establish if the SDATRQ can be used to determine the timing and need for a slope depressurisation for sections of a highwall at Mogalakwena Mine. It is important that all the questions are answered if even one question answers no. So that all the important elements of the questionnaire are taken into account.

SDATRQ (Figure 30) will be applied to:

- the Northern highwall of North pit (PZ1603), Southern highwall of North Pit (PZ1601), and Eastern highwall of Central pit (DBH33). PZ1603 highwall section showed an increase in pore pressure of 7 mH_2O (0.06 MPa) over 6 months which the pore pressure is not dissipating fast enough, therefore indicated the potential need to depressurise the slope.
- (PZ1601) section of the highwall the results showed an overall decrease in pore pressure from October 2017 82 mH_2O (0.80 MPa) to June 2018, 81 mH_2O (0.70 MPa)

therefore a decrease of 1 mH_2O (0.01 MPa) over 9 months. Therefore, showing the potential to not depressurise the highwall.

- The Eastern highwall section of Central Pit,(DBH 33) results of pore pressure showed a decrease in pore pressure, a further decrease and stabilization through time. From May 2016 to May 2017 there is a decrease from 75 mH_2O (0.73 MPa) to 23 mH_2O (0.22 MPa) that is a significant difference of 52 mH_2O (0.5 MPa) one-year period, 4.3 mH_2O per month. Between November 2017 to June 2018 the pore pressure seems to have stabilized at 14 mH_2O (0.13 MPa) indicating a no need to depressurise this slope.

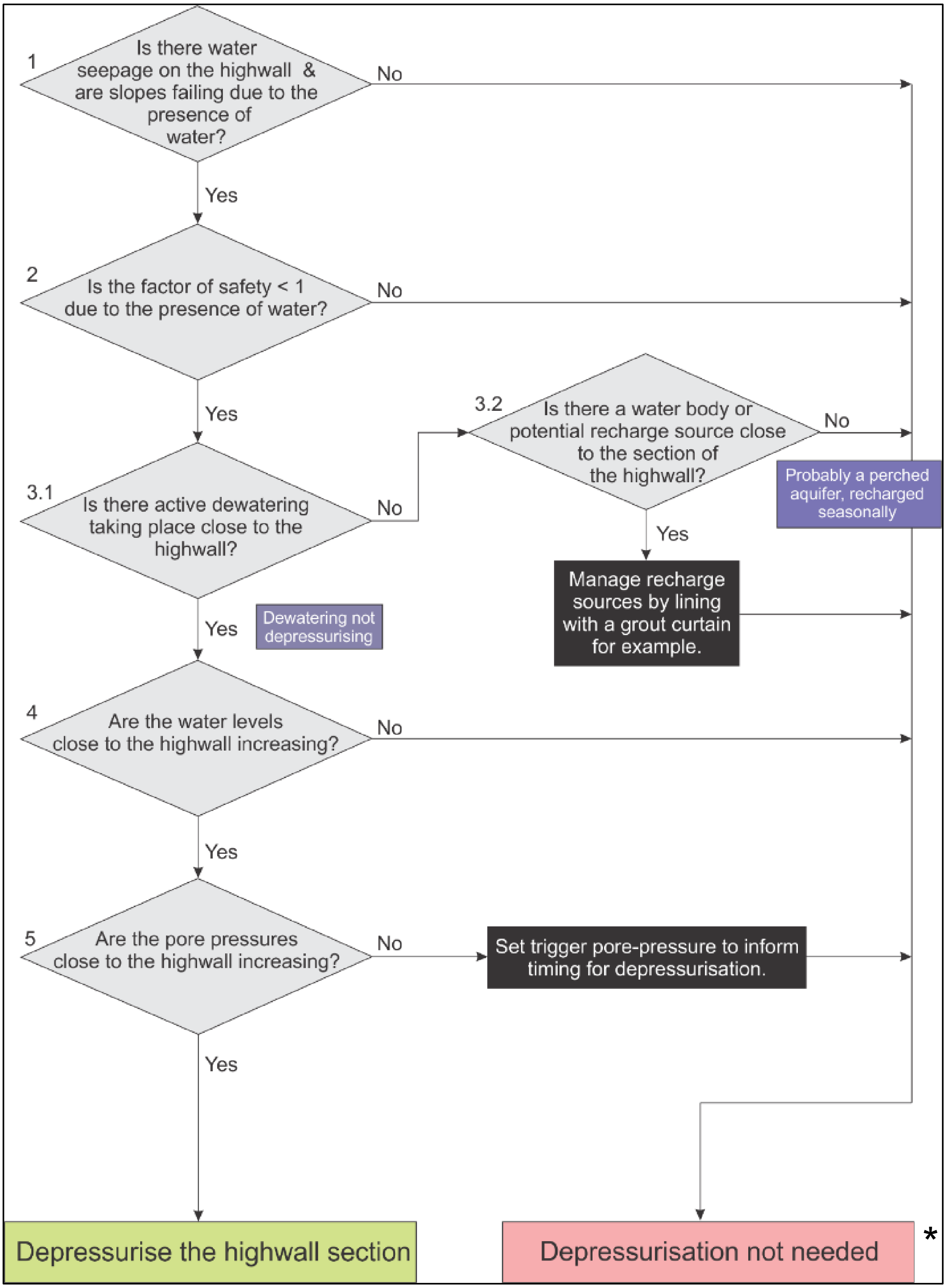


Figure 30: Slope Depressurisation Action Trigger Response Questionnaire

* ***Note, all five (5) the questions need to be answered, even if one may answer no. Before making the final decision to depressurise or not.***

4.6.1 PZ1603- (FoS= 2.0)

Below is a summary of responses for North highwall of North pit (PZ1603) using SDATRQ:

1. Is there water seepage recorded on the highwall and are the slopes failing due to the presence of groundwater?
    a. Yes
2. Is the FoS less than 1 due to the presence of groundwater?
    b. No (FoS=2.0)

    3.1 Is there active dewatering taking place to close to the highwall section?
        c. No

    3.2 Is there a water body or potential recharge source close to the section of the highwall?
        d. Yes

    4. Are the water levels increasing seasonally through time in active monitoring wells close to the highwall section?
        e. Yes

    5. Are the pore pressures increasing through time /seasonally in the monitoring wells close to the highwall section?
        f. Yes

    ACTION: Depressurise this section of the slope

4.6.2 PZ1601 (FoS=0.8)

Below is the summary of the for southern highwall of North pit (PZ1601) using SDATRQ:

1. Is there water seepage recorded on the highwall and are the slopes failing due to the presence of groundwater?

    a. yes

2. Is the FoS less than 1 due to the presence of groundwater?

    b. No (FoS=0.8)

3.1 Is there active dewatering taking place to close to the highwall section?

    c. No

3.2 Is there a water body or potential recharge source close to the section of the wall?

    d. Yes (Close to waste rock dump)

4.Are the water levels increasing seasonally through time in active monitoring wells close to the highwall section?

e. No

5.Are the pore pressures increasing through time /seasonally? In the monitoring wells close to the highwall section

f. No

ACTION: No need to depressurise this section of the slope

4.6.3 DBH33 9 FoS=2.5)

Below is a summary of responses for Eastern highwall of Central pit (DBH33) using SDATRQ:

1. Is there water seepage recorded on the highwall and are the slopes failing due to the presence of groundwater?

d. No

2. Is the FoS less than 1 due to the presence of groundwater?

e. No (FoS=2.5)

3.2 Is there active dewatering taking place to close to the highwall section?

f. No

3.2 Is there a water body or potential recharge source close to the section of the wall?

d. Yes (Close to waste rock dump)

4.Are the water levels increasing seasonally through time in active monitoring wells close to the highwall section?

e. No

5.Are the pore pressures increasing through time /seasonally? In the monitoring wells close to the highwall section

f. No

ACTION: No need to depressurise this section of the slope

4.6.4 Conclusion of SDATRQ analysis

The Slope Depressurisation Action Trigger Response Questionnaire (SDATRQ) was designed to be used as a decision-making tool, asking high level questions to test whether it can be an operation can needs to depressurise a slope and when. This is done once the hydrogeological and geotechnical studies have been completed for the sections of the highwalls of inteest. The questionnaire considered the water level behaviour in the piezometer, pore pressure behaviour, if there is active dewatering close to the monitoring piezometer, the physical inspection of the highwall groundwater seepage, the associated FoS from the highwall section geotechnical analysis and finally if there is a water body present close to the highwall that could act as a potential recharge source.

When applying SDATRQ to north highwall of North Pit (PZ1603) it is seen that majority the questions of the SDATRQ answered Yes, which means depressurisation of this highwall is needed and recommended. Although Question 3.1 answered No because there is no active dewatering close to this section. A further investigation is required to determine whether the trigger pore pressures 0.06 MPa could be used as a baseline pore pressure to inform the future timing for highwall depressurisation for future highwall sections. 0.06 MPa can be set up used in the monitoring of the piezometers to trigger action for depressurisation. This can then be a great example to show how hydrogeologists and geotechnical engineers can proactively collaborate to jointly manage groundwater impact on highwalls. Interestingly the FoS for Pz1603 was 2.0 indicating a stable slope. This shows the importance of going through all five questions and that a geotechnical analysis is not enough to determine the need for depressurisation. Further emphasising the need for a closer collaboration between geotechnical engineers and hydrogeologists.

When applying SDATRQ to south of North Pit (PZ1601), results of this analysis unlike PZ1603 suggested that there is no need for the slope to be depressurised since majority the questions of the SQTARQ answered no. Even though there is a waste rock dump close to this section of the highwall (see Figure 26). The SDATRQ suggests the use of alternative artificial measures of recharge control such as grout curtains can be used to separate the seasonally recharge source from the waste rock dump that ends up as seepage on the highwall.

The concept of using grout curtains to prevent seepage of groundwater is quite popular in the construction industry for seepage control. The premise of design for the grout/ concrete curtain is based on extensive geological drilling, permeability testing and grouting. Then the concrete filling is first conducted to pre-treat the very permeable zones, to seal the clean fissures that may cause permeability. Grout curtaining is very expensive when compared to the cost of setting up a depressurisation program, but a cost benefit study would have to be conducted to understand the best outcome. Grout curtains as a form of recharge control is beyond the scope of the work addressed in this dissertation. When comparing the FoS for PZ1601 it can be observed that the FoS of 0.8 which implies unstable slope is not directly correlated with depressurising the slopes but in this case the overall decision was not to depressurise. Therefore, showing the importance to answer all the questions of SDATRQ tool.

Finally, when applying the SDATRQ to the eastern highwall of central pit (DBH 33). The results of this analysis like (PZ1601) suggest that there is no need for the slope to be depressurised since the majority of l the questions of the SQTARQ answered No. There is a waste rock dump close to this section of the highwall and an unlined water channel that runs alongside this highwall refer to Figure 26. The SDATRQ suggests the use of alternative artificial measures of recharge control such as concrete lining of the water channel can be used to mitigate any seasonally recharge source from the running on the channel.

‘’When the roots are deep there is no need to fear the wind”- African proverb

5. Conclusions

In the investigation into depressurisation of the highwalls at Mogalakwena Mine the objective of the dissertation was to determine the timing and the need for highwall depressurisation for sections of the slope. It has been established that increasing pore pressures over time can have an impact in overall slope stability and impact the FoS if not managed. This dissertation agrees with the work by Soren et al (2014) that the presence of groundwater on the rock material can reduce the ability for a rock mass to resist shear stresses and induce sliding along discontinuity surface. This will then decrease the values for the FoS to be less than 1 and further reduce the stability (equilibrium) state of slopes. Also, by applying hydrogeology data analysis methods to various hydrogeological data the usefulness of the Slope Depressurisation Action Trigger Response Questionnaire was established.

5.1 Accomplishment of research objectives and Implication on base theory

The six (6) research objectives that were outlined at the beginning of this dissertation were:

1. *To determine the need for a slope depressurisation program for Mogalakwena mine highwalls.* This objective was accomplished because through the structural geology analysis it was determined that the presence of groundwater on the highwalls can negatively impact the stability of the slopes at Mogalakwena Mine thus establishing the need. The need to depressurise was determined for north highwall of North Pit (PZ1603).

   Groundwater flow in the mine is structurally controlled and groundwater is known to destabilize the slopes and cause failure. As it has been established that saturated conditions on slopes can change the effective stress of the rock mass and can result in an increase in the probability for slope failures and destabilize slopes. As the groundwater flows through the discontinuities, open joints and faults, this can be detrimental considering that some joints and faults cut across benches and can cause stack failures. Water on the slopes also results in low calculations for Factor of safety (FoS less than one), increasing the number of geotechnical high-risk zones. This means fewer mining areas are available to excess ore. Loss of mining due to loss of excess is not good for any profitable mine operation because valuable ore will be left behind. The need for depressurisation is then considered to improve slope stability and increase factor of safety calculations by lowering the water stress on the slopes. This is important to achieve because the lowering of the total head of water to the pre-determined targets will locally dissipate pore pressures within the highwalls thus promoting stable highwalls and access to mining areas.

2. *To determine the timing for a slope depressurisation program by applying the Slope Depressurisation Action Trigger Response Questionnaire (SDATRQ).* This objective was accomplished once all the data was hydrogeological and geotechnical studies are completed because it is designed as a questionnaire. Without the important data analysis SDATRQ is not useful. SDATRQ suggests that the pore pressure of 0.06 MPa be used as the trigger pore pressures to inform future timing for highwall depressurisation for other sections. This still needs to be investigated further and incorporated into the monitoring routine.
3. *To demonstrate that the presence of groundwater in a form of increasing pore pressures impact on the stability of the slope and cause a decrease in the Factor of Safety (FoS);*

   Before the analysis of the pore pressure the FoS for the three highwalls was determined in a 2018 study by the geotechnical engineering department. The summary of the pore pressure analysis against FoS shows no correlation between stable slopes and decreasing pore pressures. As shown in Table 5, that these two parameters are not interrelated.

Table 5: Summary of results for pore pressure vs Factor of Safety

Highwall section	Factor of Safety	Pore Pressure (Increase/ decrease)
PZ1603 (South, North pit)	2.0 (Stable slope)	Increase
PZ1601 (North, North pit)	0.8 (unstable Slope)	Decrease
DBH33 (East Central Pit)	2.5 (Stable slope)	Decrease

4. *To analysis pore pressure behaviour with a focus on the hanging wall of the slopes.* This objective was accomplished by plotting a series of graphs to analyse pore pressure results from wireline-piezometers boreholes drilled on the hanging wall. PZ1603 showed an increase of 7 mH_2O (0.06 MPa) in the analysis
5. *Apply the Read and Stacey (2009) category method to determine the relationship between dewatering and slope depressurisation at Mogalakwena Mine.*

   This objective was accomplished, Mogalakwena mine is classified within two (2) categories, namely category 2 and category 4. Category 2 classes those open-pit operations whose pits are excavated below the water table and occur in low permeability rocks and where mine dewatering has been seen to not completely dewater or drain the rock mass. Although the weathered rock may be drained or dewatered the compact norites of the hanging wall and footwall with lower permeability proved impossible to dewater. Groundwater and pore pressure will only move or be dissipated only if there is targeted horizontal drainage along the slope section.

Category 4 classes open-pits whose pits are excavated in fractured rock mass and geological structures either form barriers or conduits for groundwater to flow. We have seen that the rock mass in Mogalakwena mine may not drain unless in cases where the pit excavation intercepts faults and highly jointed shear zones that serve as conduits for groundwater to flow. The dykes at the mine have been found to be filled with calc silicate, therefore, acting as barriers for groundwater flow, creating compartments of trapped water between the various pits. The structural compartmentalisation means the intervention between the various pits will be different because of this added complexity. The dewatering program does not dissipate pressures in all slope sections therefore localised measures become necessary to drill through the structures and drain the groundwater behind them.

6. *To estimate the recharge rate factor using rainfall data,*

   This objective was accomplished the mean annual precipitation rate at Mogalakwena Mine is approximately 700 (mm/yr) recorded over 10 years from 2007 to 2017. The evaporation rate at the mine is high and is recorded at an average of 130 mm per month. The recharge calculated estimated percentage is 1,4% from precipitation into the groundwater system using the water balance equations. The value of 1.4% is obtained for Mogalakwena for the average recharge is low as expected but slightly higher than the estimations by Golder (2013) and Itasca (2016). The difference could be that the above calculation assumed evaporation also included transpiration. If transpiration was considered it could potentially further decrease the results of the recharge percentage.

5.2 Summary of findings and Conclusions

Groundwater flow at Mogalakwena Mine is within Platreef and fracture and fault-controlled. Groundwater is present on the highwalls and known to flow through Platreef and the faults to de-stabilize slopes and cause slope failure. It has been established that saturated conditions on slopes can change the effective stress of the rock mass and can result in an increase in the probability for slope failures. As the groundwater flows through the Platreef and discontinuities, open joints and faults, this can be detrimental considering that the Platreef and some joints and faults cut across benches and can cause stack failures.

Groundwater on the slopes also results in low calculations for Factor of Safety (FoS), increasing the number of geotechnical high-risk zones, leaving fewer mining areas to access the ore. Loss of mining due to loss of excess is not good for any profitable mine operation because valuable ore will be left behind. The need for depressurisation is then considered to improve slope stability performance and increase Factor of Safety.

The most applied method of dewatering in open pit mines is usually by drilling vertical boreholes outside the pit and pumping out the groundwater. This technique for Mogalakwena have been investigated to be ineffective for the mine because of the low permeability of the hanging walls rock mass made up of Norites. This hinders efficient and successful pumping using the classic dewatering techniques. Dewatering programs aim to achieve lower levels of the groundwater table in the mining area, ideally to be below the level of the working pit floor. The current water control taking place in the mine is operational dewatering, which pumps out groundwater seepage and rainfall water that collects at the bottom of the pits in sumps. This water is then pumped out from the sump. In a fractured aquifer setting such as that in Mogalakwena another method such as depressurisation to manage saturated slopes is needed.

The summary of the packer test results of hydraulic conductivity showed that the hydrogeological setting is characterized by a mixed low to moderate hydraulic conductivity (K) system of low storage and moderate precipitation (mean annual precipitation of approximately 700 mm). Very low K occurs in the strong rock mass Hanging Wall (HW) and Foot Wall (FW) slopes and moderate to high K occurs in the Platreef and shear zone generating seepages and discrete inflows into the open-pits. No relevant recharge locations have been identified from nearby aquifers and groundwater inflows during pit development will occur along strikes within the Platreef and along potentially permeable regional structures. The drainable porosity of all rock units are low and the groundwater system has assumed the low overall storativity. It shows that significant reduction in water levels and inflows could be achieved through slope depressurisation and draining of the slopes and not classic dewatering from vertical wells.

It has been discussed that increasing pore pressures over time can have a detrimental impact in overall slope stability. This statement not only sets the tone for the work explored in this dissertation but forms part of the base theories. For the analysis of pore pressure at Mogalakwena Mine the focus is the hanging wall made up of unconsolidated Norites of the Main Zone. The assessment will include the results of the pore pressure in meters of water column (mH_2O) of the fully grouted wire-line piezometers. The summary of the pore pressure analysis showed whether there was a need to pressurise or not but still needed further consideration with questions from SDATRQ tool.

The need for a slope depressurisation program for Mogalakwena mine highwalls was established through the investigation outlined in this dissertation. The need a slope depressurisation program as determined by applying the Slope Depressurisation Action Trigger Response Questionnaire (SDATRQ). While the timing of a slope depressurisation program requires further investigation and therefore the timing was not fully determined by SDATRQ. The relationship between dewatering and slope depressurisation was established to be incompatible for Mogalakwena Mine, dewatering the slopes did not depressurise the pore pressures on the highwalls. This was established also through the Read and Stacey (2009) dewatering and depressurisation broad categorization.

Although the dissertation largely focuses on the depressurisation of highwalls of Mogalakwena Mine, it is important to note that the topic of highwall depressurisation is an important discussion point at several open pit mines in the world. The development and further testing use of the Slope Depressurisation Action Trigger Response Questionnaire can prove to be of value to other open pit mines, experiencing the build-up of pore pressure behind the highwalls and mining advancing deeper.

The dissertation demonstrated through an investigation of Mogalakwena Mine highwalls that the need for a slope depressurisation program can be determined by using SDATRQ. Hence proving the dissertation statement to be true and further investigation on the timing needs to be completed.

5.3 Recommendations for further research and research shortcomings.

The following recommendations are made:

- The working relationship between Geotechnical engineers and Hydrogeologist can be improved for better slope management. The data required by the Hydrogeologists directly feeds into the modelling inputs of the geotechnical models. Slope Stability management should be a joint responsibility between both and not only the Geotechnical Engineers. With the same robustness that slope monitoring data is collected daily, the same attention should be given to collecting and analyzing pore pressures on the highwalls.
- To further investigate if the pore pressure 0.06 MPa, should be used to as the trigger pore pressure for north of North Pit. A baseline for determining the timing for future slope depressurisation requirements.

- To apply SDATRQ continuously on highwalls as the life of mine evolves to determine the need and timing of the slope depressurisation. To further add an additional question asking if the trigger pore pressure of 0.06 MPa has been reached.
- Due to the lack of long term (uninterrupted) data (two years and above) availability for the piezometers, the data evaluation and analyze would be more substantial with data extended for several years and SDATRQ could be applied to more sections. It is therefore recommended that if other open pits desire to test the Slope Depressurisation Action Trigger Response Questionnaire for their highwalls, use a longer series of monitoring data.
- To research the recharge estimates from induced recharge in order to further determine the impact of recharge water on the highwalls of the pit. Also, include the analysis of evapo-transpiration on the water balance equation. Investigate sources of induced recharge include water runoff from the plant, water storage reservoirs, waste and tailing dumps and the unlined water channel that run alongside the pit. To specifically use isotopic tracers of isotopic compositions of H and O in the groundwater to show that the groundwater recharge resources are mainly from meteoric water.
- To investigate the pore pressures in the different compartments of Mogalakwena Mine this could further assist to set specific trigger pore pressures in the different compartments for specific slope management measures.
- To test if SDTARM can be applied to other open pit mines by hydrogeologists and geotechnical engineers to determine the need and timing of a slope depressurisation program.

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