

# **Geohydrological consequences associated with the post-mine closure flooding of dewatered dolomitic karst aquifers in the Far West Rand, South Africa**

**A Schrader  
22957723**

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Promoter: Prof F Winde

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## ABSTRACT (ENGLISH AND AFRIKAANS)

**English** The thesis presents a hydrologic investigation into the effects of deep-level gold mining on the hydrogeological conditions of a fractured-karst aquifer system in the Far West Rand (FWR) goldfield, South Africa. The goldfield, located some 50 km south-west of Johannesburg, hosts some of the deepest mines worldwide. In contrast to most other goldfields mining here takes place below up to 1.2-km-thick karstified dolomite in which large volumes of groundwater are stored. Nearly impermeable vertical dykes subdivide this dolomitic karst aquifer into several individual 'groundwater compartments' displaying distinct differences in water table elevation between them. In an attempt to reduce the large influx of dolomitic groundwater into the underlying mine void, three of the compartments were dewatered by the mines through active pumping. These compartments are investigated.

For the foreseeable future, when mining and the associated pumping stops and the mine void and overlying compartments will gradually fill-up with naturally infiltrating groundwater (here termed 're-watering'), predictions were made that a total of four compartments will be hydraulically linked through artificial holings in previously impermeable dykes created by mining. With water now flowing across the dykes that used to hydraulically separate adjacent compartments a so called 'mega-compartment' may form in which a single groundwater table spans across all four joined compartments.

The main objective of this study is to test the validity of this hypothesis and investigate whether or not the predicted scenario is likely to occur. This is of significant practical importance for future water and land use as a 'mega-compartment' scenario would leave the final groundwater table far below its original elevation over large parts of the aquifer thus preventing that formerly strong yielding karst springs that dried up due to dewatering will ever flow again. It has also repercussions for the future water availability as well as the quality of ground- and surface water and ground-stability aspects. The results of the study are therefore of crucial importance for designing adequate water management and land-use strategies that proactively address the hydraulic effects of the inevitable mine closure.

The prediction of the final post re-watering groundwater levels and groundwater flow directions and rates relies largely on historical data predominantly gathered during the active dewatering of the compartments. The spatial scale covered by the data is exceptionally large compared to

similar activities elsewhere with the vertical groundwater drawdown approaching nearly a kilometre in depth affecting surrounding areas over distances of up to several kilometres. The data were analysed by a Darcy-based falling-head approach in order to predict the groundwater flow between compartments, termed inter-compartmental groundwater flow (IGF). Determining the IGF was a critical parameter, as its ratio to groundwater recharge was determined as the key factor for the establishment of the final groundwater levels of all the compartments. Groundwater recharge for re-watered compartments was assessed from a conceptual and semi-quantitative groundwater balance study. The results revealed that the IGF (between 0.7-5.4 Ml/d) will most likely be too low to hydraulically merge together the individual compartments as a mega-compartment. Recharge in re-watered compartments will probably be higher than in pre-mining times due to irreversible hydrogeological changes in the study area (e.g. sinkholes). However, to a large degree it will also depend on the manner of water usage and thus on management decisions.

Furthermore the thesis showed that in principle it is possible to analyse the historical data originating from the large-scale dewatering of the dolomitic compartments in the same way as an ultra-large pumping test using ordinary analytical methods (e.g. Theis). The obtained values were 2468 m<sup>2</sup>/s for the average horizontal transmissivity and 0.67% for the storativity of the dolomitic aquifer.

The methods used in the thesis to determine the hydraulic parameters and the groundwater flow are exclusively based on Darcy's law, initially designed for the saturated flow in porous media, whose applicability to karst aquifers was tested. It turned out that methods generally delivered realistic results. However, persuasive evidence of their applicability exists only from the analysis of the vertical groundwater flow (IGF), whereas in the case of the pumping test analysis it was not possible to finally validate the methods.

**Keywords** *Far West Rand, Karst aquifer, Deep-level mining, Dewatering, Re-watering of dolomitic compartments, Karst springs, Hydrogeology, Darcy's law, Pumping test analysis, Mine closure*

**Afrikaans** Hierdie tesis bied 'n omvattende hidrologiese ondersoek na die gevolge van diepgoudmyn-mynbou op die grondwater-hidrologie van 'n dolomitiese karst-akwifer in die Verre Wes-Rand (VWR), Suid-Afrika.

Die goudveld, geleë sowat 50 km wes van Johannesburg, huisves sommige van die diepste myne wêreldwyd. 'n Besondere kenmerk van die VWR-goudveld is die feit dat die mynbou plaasvind onder 'n tot 1,2 km dik dolomietlaag wat groot hoeveelhede grondwater berg. Die akwifer is onderverdeel deur ondeurdringbare vertikale gange in verskeie individuele grondwater-kompartemente, elk met 'n unieke grondwater-tafelvlak. Om die groot volumes grondwater wat permanent van die dolomiete in die myne invloei te verminder, is drie van die kompartemente waarop hierdie studie fokus in die verlede ontwater. In die afsienbare toekoms, wanneer die myne uitgemyn is en die huidige ontwatering van die kompartemente gevolglik eindig, sal die dolomitiese akwifer opvul met natuurlike infiltrerende grondwater (in hierdie studie genoem herbewatering), en is dit moontlik dat vier van die kompartemente hidroulies sal saamsmelt wat die totstandkoming van 'n enkele grondwater-tafel tot gevolg kan hê. Hierdie moontlikheid bestaan, omrede die gange op mynvlak deurgemyn is, wat die water kompartemente hidroulies verbind.

Die hoofdoel van die studie was om te ondersoek of só 'n enkele watertafel wel sou vorm om 'n megakompartement te vorm. In só 'n megakompartement-scenario word verwag dat die vlak van die grondwater-tafel ver onder die oorspronklike watervlakke van die akwifere sal stabiliseer. Dit is belangrik, want dit raak die heraktivering van die huidige opgedroogde karst-fonteine en gevolglik die beskikbaarheid van oppervlak-water, die gehalte daarvan, sowel as grondstabiliteitsaspekte. Dit sal gevolge inhou vir waterbestuur en grondgebruik-strategieë tydens en ná die toekomstige sluiting van die myne.

Vir die voorspelling van die aard van na-herbewaterde grondwater-vlakke en grondwater-vloei, het die tesis staat gemaak op historiese data wat oorwegend tydens die ontwatering van die kompartemente ingewin was. Die ruimtelike skaal gedek deur die data was uitsonderlik weens die ontwatering-verwante water-aftrekking in die dolomiete van 'n paar honderd meter oor 'n vertikale afstand van 'n paar kilometer.

Die data is deur 'n Darcy-gebaseerde vallende-watertafelbenadering (falling head) ontleed ten einde die grondwater-vloei tussen kompartemente te voorspel, bekend as inter-kompartementele grondwater-vloei (IGV). Die bepaling van die IGV is beskou as 'n kritieke parameter weens die verhouding daarvan tot herbewatering-volumes en gevolglik as die belangrikste faktor vir die vestiging van die finale grondwater-vlakke van al die kompartemente. Grondwater-

herbewatering van die kompartemente is beoordeel vanuit 'n konseptuele en semi-kwantitatiewe grondwater-balansstudie. Die resultate het getoon dat die IGV (tussen 0,7-5,4 M / d) waarskynlik te laag sal wees vir die hidrouliese samesmelting van die individuele kompartemente as 'n megakompartement. Herbewatering-volumes in die herbewaterde kompartemente sal waarskynlik hoër wees as in die voor-mynbouperiode weens die onomkeerbare hidrogeologiese veranderinge in die studiearea, byvoorbeeld sinkgate. Dit sal in 'n groot mate egter ook afhang van water-gebruikspraktyke en gevolglik water-bestuursbesluite.

Verder het die tesis uitgewys dat dit in beginsel moontlik is om historiese data wat afkomstig is van die grootskaalse ontwatering van dolomitiese kompartemente op dieselfde manier as 'n ultra-groot pomp-toets met behulp van gewone analitiese metodes, byvoorbeeld THEIS, te ontleed. Die waardes verkry was  $2468 \text{ m}^2 / \text{s}$  vir die gemiddelde horisontale transmissiviteit en 0,67% vir die waterbergingsvermoë (storativity) van die dolomitiese waterdraer.

Die metodes wat gebruik is in die tesis om die hidrouliese parameters en grondwater-vloeirigtings te bepaal, is eksklusief op Darcy se wet gebaseer wat aanvanklik ontwerp is vir die versadigde vloei in poreuse media. Die toepaslikheid van die gebruik daarvan op karst-waterdraers is gevolglik getoets. In die algemeen het die metodes realistiese resultate gelewer. Oortuigende bewyse van hul toepaslikheid bestaan egter net vir die ontleding van die vertikale grondwater-vloei (IGV). In die geval van die pomptoets-analise was dit nie moontlik om die geldigheid van die metodes met sekerheid te bepaal nie.

**Sleutelwoorde** *Verre Wes-Rand, karst-waterdraer, diepvlak-mynbou, ontwatering, herbewatering van dolomitiese kompartemente, karst-fonteine, hidrogeologie, Darcy se wet, pomptoets-analise, mynsluiting*

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# 1 Introduction

The abstraction of groundwater accounts for about one quarter of the total global water withdrawal. This equals only ca. 8% of the annual global groundwater recharge, which illustrates the future potential of groundwater resources to contribute to meet the water demand worldwide (WWAP 2012). Much of the groundwater is stored in karstified carbonate rocks occupying an estimated 10-15% of the continental area (Ford and Williams 2007). From the wide distribution of carbonate lithologies it was inferred that karstified rock formations may be amongst the most important aquifer formations in the world (Bakalowicz 2005). Exploring these resources is particularly important in arid and semi-arid areas, characterised by low quantities and high variability of rainfall (WWAP 2012). This applies to major parts of South Africa prone to be affected by water shortages around 2025 (UNEP 1999).

Despite this future threat and the fact that many communities in rural areas of South Africa largely rely on groundwater, many aquifers had been neglected and poorly managed in the past (DWA 2010). Indeed, the renewable groundwater resources, approximately equalling the volume of stored surface water, offer an opportunity to meet the projected water demand of the country (Middleton and Bailey 2009, DWA 2010). In this context the National Water Act of 1998 can be considered a milestone. Recognising groundwater as a public resource that can no longer be privately owned and stipulating its development, utilisation, protection and management, it constitutes a legislative framework for recent national water development projects such as 'Water Resources of South Africa 2005 (WR2005)' (Middleton and Bailey 2009) or the 'National Water Resource Strategy' (DWA 2013).

While exploring the possibilities of sustainable utilisation and management of aquifers, special attention is frequently paid to the dolomitic karst aquifers of South Africa (e.g. DWAF 2006, Leyland et al. 2008). Characterised by concentrated groundwater flow in an underground network of solution conduits of varying size, karst aquifers naturally yield high volumes of good quality water. In South Africa, like elsewhere in the world, they possess an important ecological value, e.g. by supporting rare aquatic ecosystems that developed in and around karst springs as only perennial surface water source in dry semi-arid landscapes (Colvin et al. 2007, Leyland et al. 2008). Despite representing highly sensitive and vulnerable aquatic ecosystems, karst aquifers, unlike many other aquifers in South Africa, were extensively used for industrial and domestic water supply, agriculture and mining purposes (DWA 2010).

Especially in the greater metropolitan area of Johannesburg, i.e. in the East, West and Far West Rand regions, karst aquifers had been severely impacted on by deep-level mining for decades. Owing to its significant economic value, mining was often given priority to the disadvantage of sustainable ways of utilisation and management of karst aquifers in the past (e.g. Jordaan et al. 1960). The tremendous impacts of mining - for example described by Winde (2011) - affected the environment as a whole and in particular some major karst aquifers. This includes the deliberate dewatering of dolomitic karst aquifers on unprecedented large-scale and the associated extensive formation of sinkholes as well as groundwater pollution caused e.g. by uraniferous seepage from mine waste deposits on surface and acid mine drainage (AMD) from flooded underground mine workings. Since many mines in the region have meanwhile reached the end of their productive life and more are to follow over the next decades, pro-active and science-based mine closure strategies are needed for those areas in order to cope with the environmental consequences. Yet, currently for most areas those strategies are lacking as the uncontrolled flooding of abandoned deep-level mine voids in and around Johannesburg illustrates (Winde et al. 2011).

The need to develop post-mine closure strategies, the threat of water shortages as well as the general need for sustainable long-term groundwater management, all necessitate a comprehensive understanding of karst aquifers. However, dealing with the hydrology of karst aquifers often poses a challenge, due to specific flow conditions (including turbulent flow in conduits) that fundamentally distinguish them from porous and fractured aquifers for example. As a result a comprehensive understanding of karst hydrology often requires special methodological approaches as well as detailed geological background knowledge and large sets of suitable data. As a consequence the reliable predication of water flow in karst systems remains a challenge, not only in South Africa, but worldwide in spite of the increasing international focus on karst hydrology and the progress made in recent years. In view of the existing gaps in research and scientific understanding of karst systems that contrast sharply with the economic importance of these aquifers further progress is needed in this exceptionally challenging field of geohydrology.

### **1.1 Statement of the problem and research objective**

Within the broad context provided above, this study investigates the impacts of deep-level gold mining on a dolomitic fractured-karst aquifer in the Far West Rand (FWR) goldfield, also known as the 'West Wits Line' or 'Carletonville goldfield'. Located approximately 50 km southwest of Johannesburg, the area encompasses some of South Africa's most important groundwater resources as well as some of the worldwide deepest operating mines.

The main focus of the thesis is the prediction of groundwater table elevations in currently dewatered groundwater compartments after mining ceased in the area. Ever since the draining of the compartments commenced, there has been an on-going discussion, whether original water tables in the compartments would ever re-establish once the aquifer is allowed to fill-up again with infiltrating groundwater (a process also known as 're-watering'). This is because the groundwater compartments, originally separated from each another by impermeable vertical dykes, had been hydraulically linked by deep-level mines piercing the dykes below the water filled dolomites. After the re-watering this could result in hydraulically merging the four linked compartments into a single large 'mega-compartment'. Should this happen, the natural, pre-mining water tables in the affected compartments would not rebound but remain up to almost a 100 meters below its original levels. This, in turn, would prevent several originally high-yielding karst springs that dried up when the compartments were drained, from ever flowing again with far-reaching consequences for the hydrologic system as well as prospective water management strategies and the granting of permissions to close the mines. The latter is of particular concern as the re-activation of springs was made an original pre-condition by Government when permission for dewatering was granted.

Although the issue was first mentioned in the Jordaan report (Jordaan et al. 1960) some 54 years ago, uncertainties endure regarding the consequences of altering the hydrogeologic setting, i.e. the piercing of dykes. This is also due to the fact that amongst the vast amount of relevant literature so far only a single study, Swart et al. (2003), addressed the question in detail. With this thesis it is hoped to fill the remaining gaps by assessing the impacts of deep-level mining on the groundwater hydrology in currently dewatered compartments as a first objective of the study.

The prediction of groundwater flow and groundwater levels in re-watered compartments is almost exclusively done through utilising methods based on Darcy's law initially developed for the water flow in homogeneous porous media, e.g. sand aquifers. Because the flow conditions in karst aquifers in many ways do not obey the requirements of Darcy's law, it is controversially discussed amongst the scientific community, whether those methods can be meaningfully applied to heterogeneous karst systems. By testing the application of those methods, it is hoped to contribute to this discussion, a second objective of the study.

## **1.2 Structure of the thesis**

Chapter 2 represents an introductory chapter reproducing general concepts of karst hydrology focussing also on the scientific discussion about the application of porous-media approaches

based on Darcy's law to karst systems. This chapter further provides a comprehensive literature review in the form of an article manuscript that summarises major findings of six decades of hydrogeologic research in the study area. A general description of the hydrogeologic setting of the study area is not part of this chapter as this is done in Chapters 3-5, which consists of three individual articles published in peer-reviewed scientific journals that represent the main body of the study and contain the actual research work.

Chapter 3 introduces a pumping test analysis of three different hydrological data sets collected in the Bank Compartment, including data from the large-scale dewatering of the compartment. This data in many ways comply with data from an ultra-large and long-term pumping test. Accordingly a set of analytical methods for pumping test analysis were applied (i.e. Thiem 1906, Theis 1935, Stallman as quoted in Ferris et al. 1962) as well as the software tool MLU (Hemker and Post 2012). The methods, actually developed for porous aquifers, were evaluated with special reference to their possible application to karst aquifers. With respect to the overall objective of the thesis Chapter 3 provides a general characterisation of the aquifer providing information on the horizontal groundwater flow and the water volume stored in the aquifer.

Chapter 4 presents several water balance studies of the dolomitic compartments that were set-up in order to approach possible post-mining (re-watering) water table scenarios. Key factors impacting on the water tables are identified, which are groundwater recharge and the inter-compartmental groundwater flow on mine void level (IGF). The latter will most likely adjust in magnitude between the compartments after re-watering of the dolomite. Furthermore, processes involved in groundwater recharge are identified followed by a semi-quantitative assessment of recharge in re-watered compartments.

Chapter 5 forecasts the IGF for a post-mine closure re-watering scenario applying a (modified) Darcy-based method similar to a falling head approach, which in the local context was introduced by Swart et al. (2003). The results directly respond to the overall objective of the thesis, i.e. the determination of finally adjusting water table elevations in currently dewatered compartments. The approach is further evaluated as to its applicability in karst aquifers.

Chapter 6 presents a summary of the thesis and provide a synoptic discussion of the results as well as recommendations for future research.

### **1.3 References**

Bakalowicz M (2005) Karst groundwater: a challenge for new resources. *Hydrogeol J* 13(1):148–160

- Colvin C, le Maitre D, Saayman I, Hughes S (2007) Introduction to aquifer dependent ecosystems in South Africa. WRC Report No. TT 301/07. Water Research Commission, Pretoria. 74 pp
- DWAF (Department of Water Affairs and Forestry) (2006) Vaal River system: Large bulk water supply reconciliation strategy: Groundwater assessment: Dolomitic aquifers. Prepared by DMM Development Consultants, Golder Associates Africa, SRK, WRP Consulting Engineers and Zitholele Consulting. DWAF Report Number: P RSA C000/00/4406/06. Department of Water Affairs, Pretoria. 96 pp
- DWA (Department of Water Affairs) (2010) Groundwater Strategy 2010. Department of Water Affairs, Pretoria. 64 pp
- DWA (Department of Water Affairs) (2013) National Water Resource Strategy 2013. Department of Water Affairs, Pretoria. 115 pp
- Ferris JG, Knowles DB, Brown, Stallman RW (1962): Theory of aquifer tests. U.S. Geological Survey Water-Supply Paper 1536-E. United States Government Printing Office, Washington. 174 pp
- Ford D, Williams P (2007) Karst hydrogeology and geomorphology. West Sussex, England. 576 pp
- Hemker K, Post V (2012) MLU for Windows. Well flow modeling in multilayer aquifer systems. Amsterdam. 30 pp. <http://www.microfem.com/download/mlu-user.pdf> (Cited 7 Nov. 2013)
- Jordaan JM, Enslin JF, Kriel J, Havemann A, Kent LE, Cable WH (1960) Final report of the Interdepartmental Committee on Dolomitic Mine Water: Far West Rand. Department of Water Affairs and Forestry, Pretoria. 38 pp
- Leyland RC, Witthüser KT, van Rooy JL (2008) Vulnerability mapping in karst terrains, exemplified in the wider Cradle of Humankind World Heritage Site. WRC Report No. KV 208/08. Water Research Commission, Pretoria. 64 pp
- Middleton BJ, Bailey AK (2009) Water resources of South Africa, 2005 Study (WR2005). WRC Report No. TT380/08. Water Research Commission, Pretoria. 26 pp
- Swart CJU, James AR, Kleywegt RJ, Stoch EJ (2003) The future of the dolomitic springs after mine closure on the Far West Rand, Gauteng, RSA. *Environ Geol* 44(7):751–770
- Theis CV (1935) The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage. *Trans Am Geophys Union* 16(2):519–524
- Thiem G (1906) *Hydrologische Methoden*. Gebhardt, Leipzig. 56 pp
- UNEP (United Nations Environment Programme) (1999) *Geo-2000 Global environmental outlook, overview*. UNEP, Nairobi, Kenya. 16 pp
- Winde F (2011) Karst, uranium, gold and water – lessons from South Africa for reconciling mining activities and sustainable water use in semi-arid karst areas: a case study. In: Jones, JAA (ed) *Sustaining groundwater resources. A critical element in the global water crisis*. International Year of Planet Earth. Springer Science+Business Media, Dordrecht. pp 35–53
- Winde F, Stoch EJ, Erasmus E (2011) Desktop assessment of the risk for basement structures of buildings of Standard Bank and ABSA in Central Johannesburg to be affected by rising mine water levels in the Central Basin. Final Report (Volume I of III). Mine Water Re-search Group, North-West University, Potchefstroom (unpublished). 265 pp
- WWAP (World Water Assessment Program) (2012) *The United Nations World Water Development Report 4: Managing Water under Uncertainty and Risk*. UNESCO, Paris. 380 pp

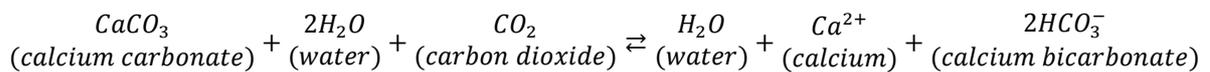


## 2 Literature review

### 2.1 Essentials of karst hydrology

#### 2.1.1 Hydrology of karst aquifers

Ford and Williams (2007) define karst as a ‘*terrain with distinctive hydrology and landforms arising from a combination of high rock solubility and well developed secondary porosity*’. Karst systems develop on the basis of a karstification process, which describes the solution of carbonate rocks in contact with the weak carbonic acid that forms when surface water percolates downwards and is enriched with CO<sub>2</sub> from the soil layer. The chemical formula of the solution of carbonate rock is:



The process stops when the water becomes saturated with calcium bicarbonate. Therefore, moving water is required that removes the dissolved minerals from the reactive surface and re-introduces unsaturated fresh water. As a consequence of continuous corrosion, initial tectonically induced fractures in the carbonate bedrock are enhanced to a network of inter-connected large solution slots, conduits and voids. Fig. 2.1 shows a characteristic carbonate karst system.

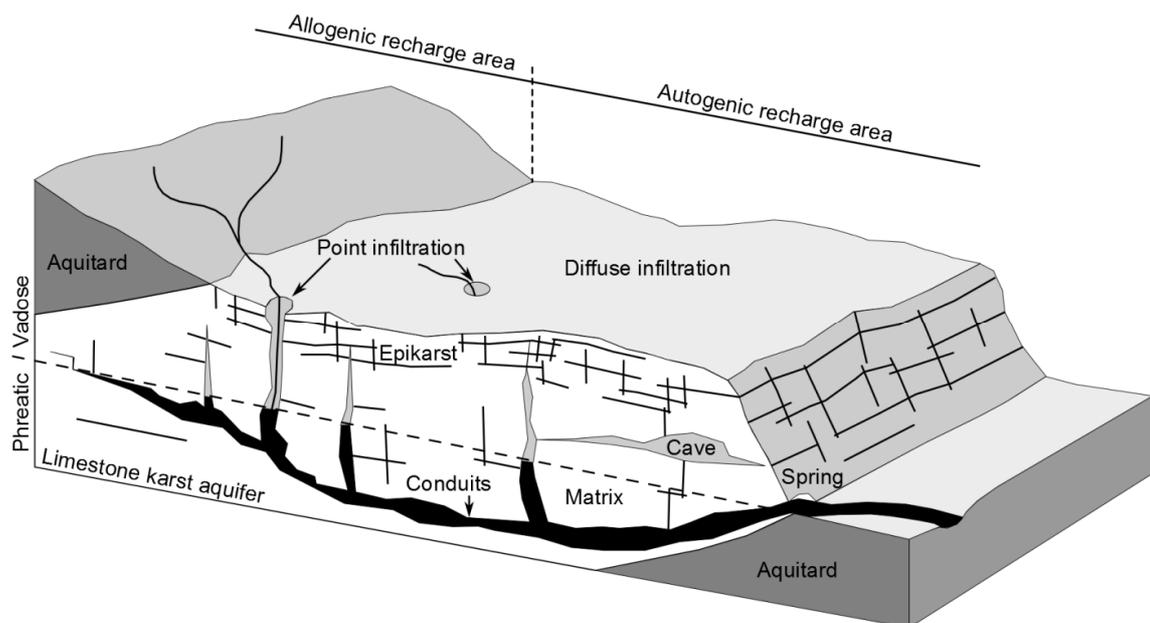


Fig. 2.1 Schematic illustration of hydrologic features in a karst system (Goldscheider et al. 2007, modified)

Karst features predominantly occur in carbonate rocks such as limestone and dolomite, which is considered true karst, but may also occur in other evaporites and sometimes in quartzites, whereas in case of the latter different chemical processes prevail (Bakalowicz 2005).

Most karst aquifers show a typical vertical zonation consisting of the epikarst, the vadose (unsaturated) and the phreatic (saturated) zone. The vadose zone between the water table and the ground surface is only partially water filled after heavy rainfall events. In the epikarst forming in the upper part of the vadose zone, percolating rainwater leads to strong corrosion and enhanced permeability that allow for the fast infiltration of surface water. Where vertically transmitted water encounters less permeable layers ponding produces localised saturated zones (perched aquifer) above the main water table (Ford and Williams 2007).

In the phreatic or saturated zone groundwater storage and movement may occur in three types of porosity, namely in the intergranular pore space (primary or matrix porosity), in geologic fractures (fracture or fissure porosity) and in a network of large solution-widened conduits (conduit porosity) (e.g. Teutsch and Sauter 1991, White 1999, Worthington 1999). The conduit system is often connected to one or more karst springs draining the aquifer (Fig. 2.1).

Groundwater flow may occur as laminar flow in the porous and fractured matrix and as concentrated laminar or turbulent flow in the conduit system (Atkinson 1977, White 1988). Usually, laminar groundwater flow in the porous matrix plays only a minor role and is often negligible. The porous matrix, however, is of primary importance for the aquifer storage. In turn, the conduit network greatly enhances the permeability of the aquifer, while it adds little to the aquifer porosity (Worthington 1999). Between the conduit network and the porous matrix groundwater is exchanged as a function of pressure gradients establishing as a result of the different velocities in the respective porosity types. The groundwater exchange between different porosity types on the basis of head differences (double-porosity concept) was initially described by Barenblatt et al. (1960) for fractured rock aquifers.

Recharge of karst aquifers may either be autogenic coming from the karstified area itself; or it may be allogenic if originating from adjacent non-karstic areas. Water infiltrates from surface either diffusely into the porous and fractured matrix or in a concentrated manner into dolines or sinkholes feeding directly into the associated conduit network (point recharge) (Fig. 2.1). In respect of the described components of groundwater flow (laminar and turbulent), recharge (autogenic and allogenic) and infiltration (diffuse and point recharge), Kiraly (2002) pointed out a general duality of karst aquifers.

Due to the unequal distribution of fractures and conduits, karst aquifers are heterogenic and anisotropic systems. This means that hydraulic parameters vary throughout the aquifer. As a consequence, when assessing aquifer parameters the volume of the affected aquifer needs to be considered. As a result, parameters for a single karst aquifer vary according to the spatial scale of the investigation. This scale-dependency of parameters was reported for hydraulic conductivity in various studies e.g. by Kiraly (1975), Sauter (1991) and Noushabadi et al. (2011) (Fig. 2.2).

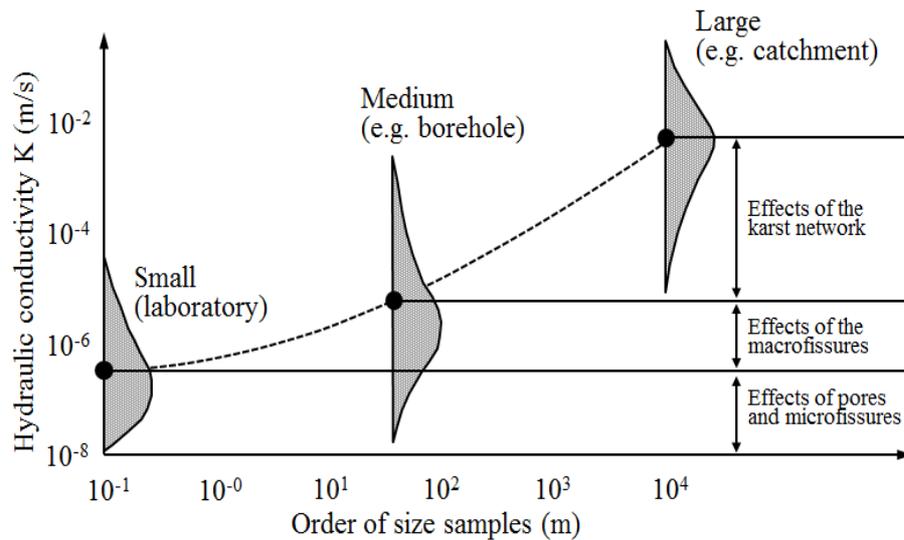


Fig. 2.2 Scale effects on the hydraulic conductivity in karst aquifers (Kiraly 1975, modified)

The hydraulic conductivity is lowest at small-scale investigations (laboratory), which represent predominately the properties of the porous matrix but not of (macro-)fissures and the conduit network. On an intermediate scale with a spatial resolution of several meters to few hundred meters (assessed by slug- and pumping tests of boreholes) hydraulic parameters incorporate effects of interconnected macro-fissures. The global response of the karst system, which includes the influence of the conduit system, only appears on regional or catchment scale investigations (e.g. spring flow analysis, large-scale pumping tests) comprising of study areas of over 10,000 m<sup>2</sup> (Fig. 2.2).

### 2.1.2 Analysing karst aquifers

A variety of methods exist for analysing karst systems including speleological, hydrological, hydraulic, hydrochemical, isotopic and geophysical methods as well as tracer and modelling techniques. A general overview of those methods is presented by Goldscheider and Drew (2007). According to Goldscheider et al. (2007) most methods are not limited to karst systems but can also be applied to other aquifer types except for speleological techniques. However, many meth-

ods may need modification when applied to karst aquifers. This is mainly due to the conduit network, which is a characteristic feature present in karst aquifers only. The turbulent flow in the conduits generally excludes the application of Darcy's law, which is a fundamental law in groundwater hydrology. Designed for the laminar flow in a saturated homogeneous porous medium, Darcy's law states that the flow rate ( $Q$ ) per cross sectional area ( $A$ ) is in direct proportion to the hydraulic gradient ( $i$ ). Darcy's law can be written as:

$$Q = kAi$$

$Q$      *Flow rate discharged per unit of time*

$k$      *hydraulic conductivity of the porous medium*

$A$      *cross sectional area at right angle to the direction of flow*

$i$      *Hydraulic gradient (dimensionless) determined by the hydraulic head difference between two points and the respective length of the flow path*

In a karst aquifer, however, only the diffuse flow in the rock matrix obeys Darcy's law, but not the vast and concentrated flow in the conduits that account for most of the water transported in the system. Conduit flow, if laminar, can be described by the Hagen-Poiseuille and, if turbulent, by the Darcy-Weisbach law initially developed for the flow in pipes. However, the application of the latter two equations requires a good knowledge of the geometry of fractures and/or conduits which is nearly always impossible to obtain at reasonable accuracy for larger karst areas. Furthermore, the flow regime in each conduit needs to be known (laminar or turbulent), which may vary over time and space as a function of the diameter of the conduit, the flow velocity and the dynamic viscosity of the fluid. The latter, in turn, changes as a function of the ambient air and water temperatures (Ford and Williams 2007, Kresic 2007). With these information lacking in many real world cases, the application of those flow laws is often not practicable. Consequently, the choice of the appropriate method is often case-specific and depends on multiple factors such as data availability, the hydrologic behaviour of the particular aquifer system, the investigated part of the aquifer (porosity type), the scale of the investigation (laboratory, local, regional) and the nature of the investigated problem (relating for example to the required degree of accuracy). Depending on those factors the deployment of fundamentally different methodological approaches can be justified. The groundwater flow of the conduit network or in single conduits, for example, can be assessed by tracer tests. The response of karst springs to single recharge events or the analysis of spring flow hydrographs represents the behaviour of the system on catchment scale and can be used to assess either the diffuse flow in the fissured matrix or the flow in the conduit network (Groves 2007). Slug tests and small to medium scale pumping tests can be employed in order to assess the groundwater flow in the fissured matrix in the vicinity of the

pumping well, but do not incorporate the influence of the conduit system, as boreholes are often situated in the rock matrix between conduits (Kresic 2007) .

For the quantitative simulation of spatial and temporal variations of hydraulic parameters and/or groundwater flow, distributive models are frequently deployed. These models require the subdivision (discretisation) of the hydrogeological system into homogenous sub-units (Kovács and Sauter 2008). Each sub-unit has its own characteristic hydraulic parameters and the flow within each sub-unit can be described by equations derived from basic physical laws (Kovács and Sauter 2008). In order to factor in the different flow regimes and/or porosity types, concepts of double porosity (e.g. Sauter 1993, Maréchal et al. 2008) and triple porosity (e.g. Worthington 1999, Lu et al. 2013) were applied. Teutsch and Sauter (1991) identified five approaches of distributive modelling theoretically applicable to karst, that either uses a so-called ‘discrete concept’ considering flow in individual fractures or conduits, a ‘continuum concept’ or a mixture of both.

The disadvantage of such distributive models is the great demand of required information about the hydraulic parameter field, the aquifer geometry and the aquifer recharge (Kovács and Sauter 2008). This is all the more true the more accurate the hydrogeologic features, i.e. for example the geometry and position of conduits, of an aquifer are represented in a model. This limits the practical application of such models. Further criteria influencing the selection of suitable models for a given problem are the capability of the model to simulate karst conditions as well as the required degree of accuracy (Teutsch and Sauter 1991).

### ***2.1.3 Applying Darcian-based methods in karst aquifers***

To circumvent the difficulties arising from specific karst methods that explicitly consider the conduit network, an equivalent porous medium approach based on Darcy’s law is frequently applied, even though this is controversially discussed. Darcy’s law, by implication, presupposes that the rock is considered as a homogenous continuum of open voids and solid matter that can be characterised by certain generalised parameters that, to some extent, describe the real microscopic behaviour of the groundwater flow (Ford & Williams 2007). Transferring the continuum approach of Darcy to a karst aquifer is not straight forward as the hydraulic parameters in karst systems vary with the position in the aquifer as a function of the different types of porosity (matrix, fracture, conduit) seemingly contravening the required homogeneity of the rock. The justification for still applying Darcy’s law to karst aquifers is based on the assumption that, at a sufficiently large scale, effects of different flow velocities smooth out to such extent that the

overall response of all three porosity types is similar to a homogeneous porous medium. In other words, the approach assumes that it is possible to describe the hydraulic behaviour based on average (lumped) hydraulic parameters. This, in turn, requires a rock volume large enough to be representative for the entire system termed ‘representative elementary volume’ (REV) (Bear 1972). Otherwise the determined average parameters would change dependent on the considered part of the aquifer. However, because of the extensively developed conduit systems that may range for many kilometres, for karst systems determining a REV is not always possible.

Despite these approaches it is still a fundamental discussion whether methods based on Darcy’s law should be applied to karst aquifers at all. Some authors point at the inadequacies of equivalent porous-media approaches when dealing with karst (Huntoon 1995, Bakalowics 2005) or emphasise the importance to recognise the triple-porosity nature of karst aquifers (Palmer 1999). Scanlon et al. (2003), however, point out the importance to distinguish between applications of porous media-based approaches in *flow* models (e.g. hydraulic head, groundwater flux, spring discharge) versus *transport* models (e.g. flow direction, destination, velocity) stating that most criticism is only attracted by the latter. This explains why many case studies exist that successfully used porous-media approaches in flow models, for example, simulating spring hydrographs (Scanlon et al. 2003, Sepúlveda 2009), recharge (Martinez-Santos and Andreu 2010) and groundwater flow (Teutsch 1989, Larocque et al. 1999, González-Herrera et al. 2002) in karst aquifers. When porous media methods are applied to karst aquifers most authors agree that the scale of investigation is a key factor with best chance of success pertaining to large-scale (regional) studies (Eagon et al. 1972, Huntoon 1995, Noushabadi et al. 2011). Following this line of argument and the various demonstrations of successful applications in this study Darcy-based approaches to karst hydrology are applied.

### **2.1.4 References**

- Atkinson TC (1977) Diffuse flow and conduit flow in limestone terrain in the Mendip Hills, Somerset (Great Britain). *J Hydrol* 35:93–110
- Bakalowicz M (2005) Karst groundwater: a challenge for new resources. *Hydrogeol J* 13(1):148–160
- Barenblatt GI, Zheltov IP, Kochina IN (1960) Basic concepts in the theory of seepage of homogeneous liquids in fissured rocks (strata). *J Appl Math Mech* 24:1286–1303
- Bear J (1972) *Dynamics of fluids in porous media*. American Elsevier, New York. 764 pp
- Eagon HB (Jr), Johe DE (1972) Practical solutions for pumping tests in carbonate-rock aquifers. *Ground Water* 10(4):6–13
- Ford D, Williams P (2007) *Karst hydrogeology and geomorphology*. John Wiley & Sons, West Sussex. 576 pp
- Goldscheider N, Drew D, Worthington S (2007) Introduction, Chapter 1. In: Goldscheider N, Drew D (eds) *Methods in karst hydrogeology*. Taylor & Francis/Balkema, Leiden, Netherlands. pp 1–8

- Goldscheider N, Drew D (eds) (2007) *Methods in karst hydrogeology*. Taylor & Francis/Balkema, Leiden, Netherlands. pp 264
- González-Herrera R, Sánchez-y-Pinto I, Gamboa-Vargas J (2002) Groundwater-flow modeling in the Yucatan karstic aquifer, Mexico. *Hydrogeol J* 10(5):539–552
- Groves C (2007) Hydrological methods, Chapter 4. In: Goldscheider N, Drew D (eds) *Methods in karst hydrogeology*. Taylor & Francis/Balkema, Leiden, Netherlands. pp 45–64
- Huntoon PW (1995) Is it appropriate to apply porous media groundwater circulation models to karstic aquifers? In: El-Kadi AI (ed): *Groundwater models for resources analysis and management*. CRC Lewis Publishers, Boca Raton, Florida. pp 339–358
- Kiraly L (1975): Rapport sur l' état actuel des connaissances dans le domaine des caracterizationères physiques des roches karstiques. In: Burger A, Dubertret L (eds): *Hydrogeology of karstic terrains*. International Union of Geological Sciences, Series B:53–67
- Kiraly L (2002) Karstification and groundwater flow. In: Gabrovšek F. (ed), *Evolution of karst: from prekarst to cessation*. Založba ZRC, Ljubijana, Slovenia. pp 155–190
- Kovács A, Sauter M (2008) Modelling karst hydrodynamics. In: Martin JB, White WB (eds) *Frontiers of karst research*. Special Publication 13. Karst Waters Institute, Leesburg, Virginia. pp 13–26
- Kresic N (2007) Hydraulic methods, Chapter 5. In: Goldscheider N, Drew D (eds) *Methods in karst hydrogeology*. Taylor & Francis/Balkema, Leiden, Netherlands. pp 65–92
- Larocque M, Banton O, Ackere P, Razack M (1999) Determining karst transmissivities with inverse modeling and an equivalent porous media. *Ground Water* 37(6):897–903
- Lu C, Shu L, Wen Z, Chen X (2013) Interpretation of a short-duration pumping test in the mixed flow karst system using a three-reservoir model. *Carbonates Evaporites* 18(1-2):149–158
- Maréchal JC, Ladouche B, Dörfliker N, Lachassagne P (2008) Interpretation of pumping tests in a mixed flow karst system. *Water Resour Res* 44(5):1–18
- Martínez-Santos P, Andreu JM (2010) Lumped and distributed approaches to model natural recharge in semiarid karst aquifers. *J Hydrol* 388(3-4):389–398
- Noushabadi MRJ, Jourde H, Massonnat G (2011) Influence of the observation scale on permeability estimation at local and regional scales through well tests in a fractured and karstic aquifer (Lez aquifer, Southern France). *J Hydrol* 403(3):321–336
- Palmer AN (1999) Introduction. In: Palmer AN, Palmer MV, Sasowsky ID (eds) *Karst Modeling*. Special Publication 5. Karst Waters Institute, Leesburg, Virginia. pp 1–9
- Sauter M (1991) Assessment of hydraulic conductivity in a karst aquifer at local and regional scale. *Proceedings of the third conference on hydrogeology, ecology, monitoring and management of ground water in karst terranes*, Nashville, USA. *Ground Water Management*, Book 10:39–56
- Sauter M (1993) Double porosity models in karstified limestone aquifers: Field validation and data provision. *Hydrogeological processes in karst terrains*. IAHS Publ 207:261–279
- Scanlon BR, Mace RE, Barrett ME, Smith B (2003) Can we simulate regional groundwater flow in a karst system using equivalent porous media models? Case study, Barton Springs Edwards Aquifer, USA. *J Hydrol* 276(5):137–158
- Sepúlveda N (2009) Analysis of methods to estimate spring flows in a karst aquifer. *Ground Water* 47(3):337–349
- Teutsch G (1989) Groundwater models in karstified terrains - two practical examples from the Swabian Alb, S. Germany. *Proceedings of the 4<sup>th</sup> conference - solving groundwater problems with models*, Indianapolis, USA, Feb. 7-9, 1989. National Water Well Association, Dublin. pp 929–953

- Teutsch G, Sauter M (1991) Groundwater modeling in karst terranes: scale effects, data acquisition and field validation. Proceedings of the 3<sup>rd</sup> conference on hydrogeology, ecology, monitoring and management of ground water in karst terranes, Nashville, USA. Ground Water Management, Book 10:17–35
- White WB (1988) Geomorphology and hydrology of karst terrains. Oxford University Press, New York. 464 pp
- White WB (1999) Conceptual models for karstic aquifers. In: Palmer AN, Palmer MV, Sasowsky ID (eds) Karst Modeling. Special Publication 5. Karst Waters Institute, Leesburg, Virginia. pp 11–16
- Worthington SRH (1999) A comprehensive strategy for understanding flow in carbonate aquifers. In: Palmer AN, Palmer MV, Sasowsky ID (eds) Karst Modeling. Special Publication 5. Karst Waters Institute, Leesburg, Virginia. pp 30–37

## 2.2 Unearthing a hidden treasure: 60 years of karst research in the Far West Rand

Aljoscha Schrader<sup>1,2</sup>, Frank Winde<sup>2</sup>

<sup>1</sup> Faculty of Natural Sciences, North-West University, Potchefstroom, South Africa, <sup>2</sup> Mine Water Re-Search Group, North-West University, Vanderbijlpark, South Africa

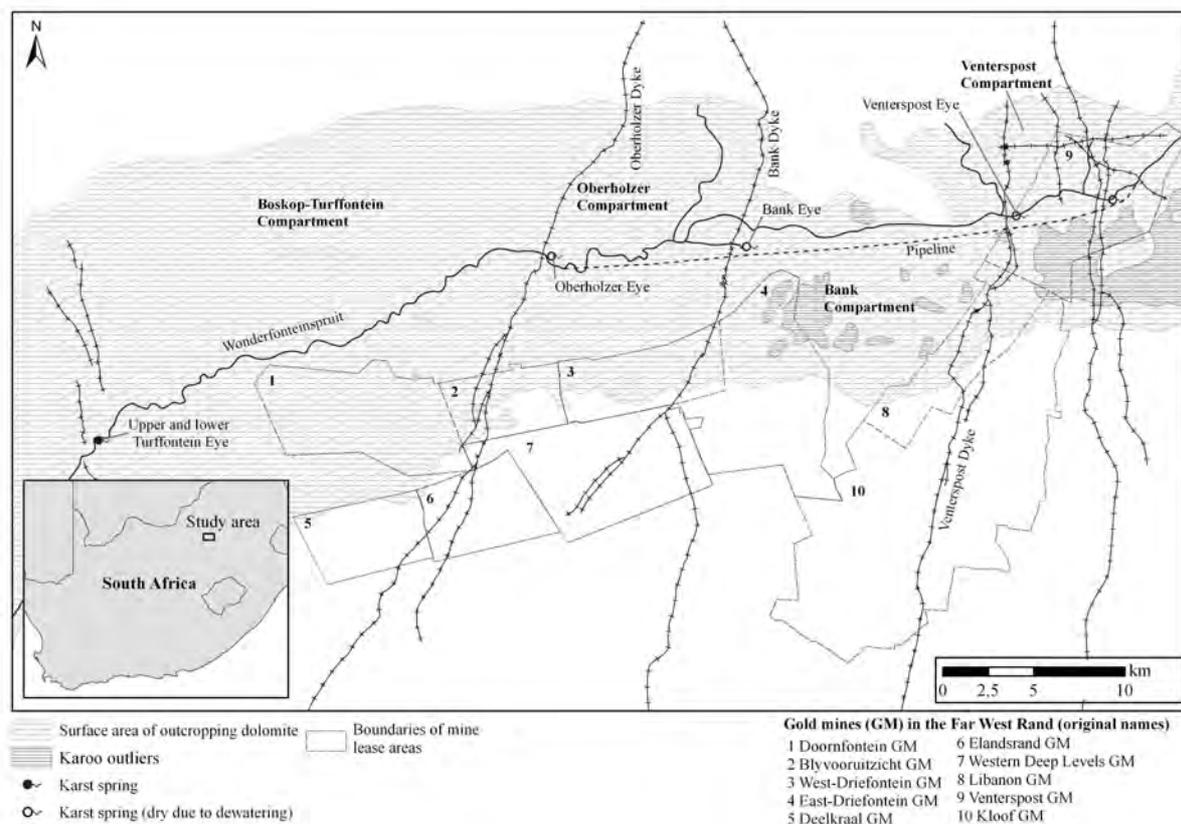
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**Abstract** Karstified dolomitic formations situated in the Far West Rand (FWR) goldfield of the Witwatersrand Basin constitute a significant groundwater resource in semi-arid South Africa and would be of strategic importance for alleviating the increasing water stress in nearby metropolitan areas. The deep-level gold mines operating below the dolomites have suffered from large volumes of dolomitic groundwater flowing into the mine voids, rendering mining both expensive and hazardous. In order to secure the safe and economic mining, the overlying dolomites were dewatered. This review paper covers research over 60 years, conducted in three of the four major dolomitic compartments affected by dewatering. After more than six decades of research these aquifers are arguably the best investigated karst systems in South Africa and possibly worldwide. The data generated are, in many respects, unique, as many measurements can never be repeated, covering stochastic events such as a major water inrush into mine workings and some of the most catastrophic sinkhole developments ever recorded. Given their potential value for improving the understanding of general and local karst hydrogeology, it is the main aim of this paper to alert the scientific community to the existence of this resource of mostly unpublished data and research. A no less important aim is to support a systematic collation of these studies which are in danger of being irretrievably lost as mines increasingly close down. Ecologic and economic impacts of the flooding of mines in and around Johannesburg have recently highlighted the lack of reliable historic mine data to optimally address the matter. This paper provides a first comprehensive, yet not exhaustive, overview on the existing studies briefly discussing scientific content as well as obstacles for utilising the scattered, and often non-peer reviewed information sources.

**Keywords** *karst hydrogeology, dolomitic aquifers, groundwater, deep-level gold mining, dewatering, Far West Rand, grey literature, data preservation / GIS database*

### 2.2.1 Introduction

The goldfield of the Far West Rand (FWR) is a major deep-level mining area of South Africa, located approximately 50 km southwest of Johannesburg (Fig. 1). The gold-bearing reefs are covered, amongst other, by thick karstified dolomites, which host some of the largest groundwater resources in South Africa, supporting a range of high yielding karst springs. Deep-level gold mining in the FWR started in 1934 and soon affected the hydrological and hydrogeological environment.<sup>1</sup> Mining related impacts included the dewatering of the dolomitic aquifers that caused several karst springs to dry up (Fig. 1) and the diversion of stream flow from a river into a nearly 30-km-long pipeline to name a few.



**Fig. 2.3** Locality plan and map of the central part of the Far West Rand goldfield showing the surface area of outcropping water-bearing dolomite, position of dykes and the boundaries of mine lease areas

The impacts of mining have not only initiated numerous water-related studies, but have also created the necessity for on-going research to develop environmentally acceptable mine closure strategies and sustainable long-term water management options. Given the large volumes of water involved and their proximity to water-stressed metropolitan areas affected by increasing water scarcity<sup>2</sup> we believe that the systematic compilation and evaluation of existing relevant

information will be crucial to understanding long-term impacts of historical mining and successfully utilising these valuable water resources in the future.

More than six decades of water-related research in the FWR have generated an enormous amount of knowledge, expertise and data with great potential for developing sustainable post-mine closure strategies in the FWR. The current uncontrolled rise of acidic mine water in the West-, Central- and East Rand regions poses severe threats to the environment, which will cause significant cost to the taxpayers. This illustrates the dire consequences of haphazard and unprepared mine closure, exacerbated by a lack of access to historical data and information. It is therefore imperative to prevent a similar loss of data and expertise in the FWR as the largest of the remaining active goldfields of the Witwatersrand basin. It is necessary to pro-actively collate all the available relevant data whilst access to underground structures is still possible and operational mining companies are still in a position to address potential gaps in order to avoid the negative consequences of closure.

Collating the large amount of knowledge proves, however, to be difficult, as much of it is spread across many role players, including the various mining companies / houses, government departments, municipalities, consultants and research institutions. Information held by dedicated archives and structured data bases is often unavailable, whilst tracing the location of specific reports can be challenging. These difficulties are exacerbated by changes in Government personnel as well as in the structure of the mining industry, which often results in existing reports and data no longer being retrievable as is the knowledge and insight of experts, who are no longer working in the field. This phenomenon is termed the ‘loss of institutional memory’,<sup>1</sup> which leads to repetition of research in the best case and loss of irreplaceable unique information in the worst case.

Another obstacle to utilising the accumulated knowledge results from the fact that much of it was generated without exposure to peer-reviews, or other methods of quality assurance. A large proportion of the literature produced over the last six decades consists of reports drafted by private consultants, governmental officials and technical mine personnel. Generally driven by matters affecting day-to-day operations, some urgent and case specific, these studies have in common a strong focus on practical applicability rather than scientific rigor. Moreover, many reports are of limited circulation as they are contained in internal, unpublished or confidential documents, severely limiting public access. As a consequence, whilst undoubtedly containing particularly unique data and information, many reports hardly satisfy strict scientific standards in terms of objectivity, quality assurance and referencing. The lack of proper referencing, in partic-

ular, frustrates tracing and verifying the sources of information. Dedicated sections explaining the used methodology for generating the presented data are commonly absent. All this limits the possibilities of researchers to assess the reliability and quality of provided data and information thus reducing their scientific value. Consequently many reports have to be approached with caution in order to avoid compromising the quality of follow-up studies. Unfortunately this applies to the bulk of available consulting reports which often liberally use information and data from third parties without quoting the original sources.

Apart from raising awareness to these challenges, this review aims, for the first time, to provide a structured overview on the scope and extent of existing literature. To this end each available study is allocated to one of six topical categories. Geographically, the review focuses predominantly on literature pertaining to the three currently dewatered groundwater compartments (Venterspost, Bank, Oberholzer) to which the overwhelming majority of studies refers. As the number of documents concerned with hydrological issues in the FWR runs into the thousands, this overview does not claim to be exhaustive. Ideally it should be followed by systematically archiving the available sources preferably in digitized format to allow for collation in a singly centrally managed and searchable electronic data base.

### ***2.2.2 Topical categories of research in the FWR***

This review covers hydrogeologic research in the FWR from the mid-20<sup>th</sup> century, when industrial-scale deep level mining as well as large-scale dewatering of the dolomitic compartments commenced to the present (2012). Excellent overviews on the course of events related to deep-level mining in the FWR and associated hydrogeologic impacts are provided by Swart et al.<sup>3</sup> as well as Winde<sup>4</sup>. Based on these and other sources six major research themes have been identified into which the available studies are categorised:

- a) General geology of the study area*
- b) Groundwater-related problems faced by the mines*
- c) Ground-instabilities and sinkholes following the dewatering*
- d) Hydrogeologic characterisation of dolomitic compartments*
- e) Mining-related water quality issues*
- f) Closure of mines*

These categories are briefly discussed focussing on some of the most prominent sources.

### **a) General Geology of the study area**

First published reports of geophysical investigations in the FWR<sup>5-6</sup> date back to the 1930's.<sup>7</sup> De Kock<sup>7</sup> compiled those findings as well as numerous company reports from gold mines, comprehensively addressing the geology of the FWR, describing the major geologic formations as well as structural geologic features such as the major faults and intrusive and impermeable dykes. Trending roughly north to south, the latter form the eastern and western boundary of the groundwater compartments and thus are essential for understanding the hydrogeology of the FWR. The work of de Kock<sup>7</sup> provided the basis for later and more detailed studies of the area. Subsequent geologic descriptions supplementing his work include Brink<sup>8</sup>, the South African Committee for Stratigraphy<sup>9</sup>, Engelbrecht<sup>10</sup>, Rob and Rob<sup>11</sup> and McCarthy<sup>12</sup>.

### **b) Groundwater-related problems faced by the mines**

In many instances the ingress of large volumes of groundwater from the overlying karst aquifers into the mine void initiated hydrological research. In 1957 a tracer test was conducted in the area at Blyvooruitzicht Goldmine in the Oberholzer Compartment (Fig. 1) that aimed to determine the rate of recirculation of water pumped from the underground mine void to surface followed by ingress into the mine void.<sup>13</sup> From this test, conclusions were drawn on the groundwater flow velocity as well as on the volume of groundwater stored in the dolomite and possible leakage through dykes. In respect to the groundwater problem of the mines, several unpublished reports discussed the consequences, practicability and economic viability of dewatering the groundwater compartments.<sup>14-17</sup>

The most significant study on this topic was performed by the Inter-Departmental Committee of Dolomitic Mine Water between 1956 and 1960 under the authority of the Minister of Water Affairs. This study thoroughly examined a range of aspects associated with the ever-increasing ingress of groundwater into the growing mine voids. The resultant 'Jordaan Final Report'<sup>18</sup> compiled findings from several detailed studies (e.g. Enslin and Kriel<sup>19</sup>) that, *inter alia*, also investigated environmental and economic consequences of the dewatering of the two dolomitic compartments under investigation. Many hydrological data (e.g. spring flow volumes) that appear in later studies originate from the Jordaan Report, even though the source is not indicated in many instances. Following the recommendations of the report, legal permission to dewater the Oberholzer compartment – as defined by Wolmarans<sup>20</sup> – was granted to the Chamber of Mines by Government after the 4-year investigation was concluded. Two of the three mines involved had already started this process well before the permission was granted, as two springs had already ceased to flow.<sup>21</sup>

In 1968 a massive inrush of groundwater occurred at the West-Driefontein mine (Fig. 1). The event that eventually led to the dewatering of the Bank Compartment was described in detail by Cartwright<sup>22</sup> and Cousens and Garrett<sup>23</sup>. Valuable facts relating to inrush volumes during and prior to the event are to be found in an unpublished report from the Acting Secretary for Water Affairs<sup>24</sup>.

After official dewatering of the compartments commenced, numerous studies (see following sections) were carried out, aiming to characterise the aquifer system and adjacent geologic formations, in order to respond to the various hydrogeologic consequences of dewatering and resulting problems encountered during daily operations.

### **c) Ground-instabilities and sinkholes following dewatering**

After dewatering commenced, ground-instability in form of subsidences and often dramatic sinkholes rapidly developed. The consequence of lowering the water table demanded scientific attention. Early descriptions of the phenomenon exist.<sup>25-26</sup> Later, the processes were described comprehensively by Brink<sup>8</sup>, Bezuidenhouth and Enslin<sup>26</sup>, Kleywegt and Enslin<sup>27</sup> and Kleywegt and Pike<sup>28</sup> evaluated data from gravimetric surveys carried out in order to delineate high risk areas of sinkhole formation. In accordance with the serious consequences of sinkholes for the local population and infrastructure and the associated public and political attention given to the matter, these surveys were unprecedented in terms of the level of detail and spatial scale. The findings of these surveys indicated that the formation of sinkholes depends on specific geologic and hydrologic conditions relating to the depth and shape of the bedrock surface,<sup>26,27,28</sup> the nature and thickness of the (weathered) overburden,<sup>28</sup> the original depth of the groundwater table<sup>26,27,28</sup> as well as the presence or absence of surface (stream) water.<sup>26,27,28</sup> Most sinkholes formed in the outcrop area of the chert-rich dolomitic formations (i.e. Monte Christo and Eccles formations) often associated with fault zones, fractures and dyke edges as well as in the stream bed of the Wonderfonteinspruit. Beukes<sup>29</sup> found a possible effect of rising water tables (termed 'rewatering') on the rate at which new sinkholes develop. Swart<sup>30</sup>, Swart et al.<sup>3</sup> and Winde and Stoch<sup>1</sup> outlined the possible impact of sinkholes on the recharge rate of the dolomitic compartments based on historical heavy rainfall events. Although desirable in order to assess groundwater recharge of compartments under the present conditions, reliable long-term data indicating the impacts of sinkholes on recharge rates do not exist. More recent studies reviewing the history and extent of sinkhole development in the FWR, without necessarily introducing new aspects or concepts, exist from de Bruyn and Bell<sup>31</sup> and van Niekerk and van der Walt<sup>32</sup>. A vast quantity of unpublished data tracked dewatering related ground movements from 1964 to 2007, comprising

some 2500 documents, has been assembled by the State Coordinating Technical Committee (SCTC). This work was and is complemented by work at the Geobasecamp of Gold Fields Ltd. in Oberholzer, where many data relating to sinkholes and ground subsidence are captured in a dedicated Geographical Information System (GIS).

#### **d) Hydrogeological characterisation of dolomitic compartments**

The hydrogeology of the dolomitic compartments, focussing on the structural geology, groundwater storage and recharge as well as the determination of hydraulic parameters, has been assessed by a range of comprehensive and detailed studies. In an early seminal study, Enslin and Kriel<sup>19</sup> delineated surface catchment boundaries of the dolomitic compartments and assessed monthly and annual water balances including artificial sources of re- and discharge. Subsequent comprehensive hydrologic studies exist from Brink<sup>8</sup>, Jordaan et al.<sup>18</sup>, Enslin<sup>33</sup>, Enslin and Kriel<sup>34</sup>, Fleisher<sup>35</sup>, Vegter<sup>36</sup> and Foster<sup>37</sup>.

Martini and Kavalieris<sup>38</sup> described the general genesis and morphology of the Transvaal dolomites and especially the caves. Processes involved in the weathering and karstification of the dolomites in the FWR were taken up by Morgan and Brink<sup>39</sup>, who outlined three vertical zones distinguished by their degree of karstification; a highly weathered nearly porous zone followed by a cavernous zone as well as weakly fractured to solid dolomite. The hydraulic characteristics of vertical fissures in the dolomite were described by Wolmarans and Guise-Brown<sup>40</sup> and Wolmarans<sup>41</sup>. Cross-cutting through all geologic formations, these fissures transport groundwater from the dolomite into the mine voids. According to the authors, the hydraulic properties as well as ability to conduct groundwater down to the mine voids largely depends on the large-scale folding of the dolomite, whereas fissures in areas of synclinal folding (tension zones) generally generate more ingress water than fissure in areas of anticlinal folding (compression zones). Descriptions of the petrography, thickness and distribution as well as the hydrology of non-dolomitic rock formations associated with the dolomitic aquifer system can be found in de Freitas<sup>42</sup>.

For the hydraulic characterisation of the dolomite various pumping tests have been analysed. Schwartz and Midgely<sup>43</sup> derived values of transmissivity and the storage coefficient of the Bank Compartment by applying the method of Theis<sup>44</sup> to data recorded during the inrush event that flooded West-Driefontein in 1968. Fleisher<sup>35</sup>, de Freitas<sup>42</sup> and Bredenkamp et al.<sup>45</sup> describe further pumping tests evaluated by a range of methods. Results indicate a high heterogeneity of the dolomite with transmissivities ranging from few hundred to several thousand m<sup>2</sup>/d. Geo Hydro Technologies<sup>46</sup> conducted slug tests in the Pretoria Group rocks covering the dolomite at

the southern edge of the outcrop area. Values of hydraulic conductivity thus obtained were generally lower compared to hydraulic conductivities found in the upper dolomite.

Most pumping test analyses quoted above, as well as those conducted in similar aquifers in South Africa (e.g. van Tonder et al.<sup>47</sup>), found that the determination of the storage coefficient is problematic, as values in many cases showed a so-called distance-dependency (referring to the distance between the observation and pumping well). A possible explanation for this observation was provided by Neuman (1994, personal communication quoted in Kirchner and van Tonder<sup>48</sup>).

The (effective) porosity, which was found to decline with depths, have been assessed by Enslin and Kriel<sup>19</sup>, Enslin and Kriel<sup>34</sup>, Fleisher<sup>35</sup> and Foster (unpublished data, quoted in Foster<sup>49</sup>). Applied methods include pumping tests as well as borehole and mine shaft log evaluation, spring flow analysis and water balance studies.

On the basis of spring flow hydrographs, groundwater recharge of compartments was described by Fleisher<sup>35</sup> as a two-phase system with an immediate and a delayed component. The long-term average recharge volume of compartments, often quoted as percentage of rainfall, was estimated from natural spring flow volumes,<sup>18</sup> the Hill-method<sup>35</sup> and (long-term) pumping rates of mines.<sup>50-51</sup> Bredekamp<sup>52-53</sup> estimated recharge in similar dolomitic compartments using chloride profiles and a <sup>14</sup>C model, respectively. The possibility of artificially recharging the aquifer via boreholes has been investigated by Enslin et al.<sup>54</sup>, who identified possible recharge areas on the basis of data from the gravimetric survey quoted above.

#### **e) Mining-related water quality issues**

Groundwater quality issues relating to the problem of acid mine drainage (AMD) have been addressed.<sup>55</sup> Pyrite, occurring in mined ore reefs, produces iron hydroxide and sulphuric acid when it comes in contact with water and oxygen. This highly toxic acidic solution may decant on surface after flooding of abandoned mine voids. As stated by Pulles et al.<sup>56</sup>, decanting of mine water is likely to occur to some degree in the FWR after mining ceases. Although the environmental threats linked to AMD were recently under discussion for other mining areas of South Africa,<sup>57</sup> detailed studies of these aspects are largely lacking in the FWR.

In a study jointly funded by the Water Research Commission (WRC) and the Far West Rand Dolomitic Water Association (FWRDWA), Dill et al.<sup>58</sup> investigated the effects on the quality of below groundwater resources of the common practice of using tailings materials for the filling of sinkholes. Dill et al.<sup>58</sup> suggested that uranium levels of up to 300 mg/l (0.3 g/l) are to be expected

in leachate from such fillings. This renders tailings-filled sinkholes a major risk for polluting groundwater.

Pollution of the environment caused by the water- and airborne transport of uranium originating to large extents from large slimes dams has been addressed by Wade et al.<sup>59</sup>, Coetzee et al.<sup>60</sup>, Winde<sup>61-63</sup>, NECSA<sup>64</sup>, Barthel<sup>65</sup> and IWQS<sup>66</sup>. These studies report on elevated concentrations of uranium in ground- and surface water,<sup>60,61,63,66,67</sup> riverine sediments,<sup>59,60,65</sup> soil,<sup>60,65</sup> fish<sup>63,64</sup> and livestock.<sup>64</sup> Current research focuses on possibly associated health risks, including concentrations of uranium and processes and pathways involved in the spreading of uranium. As a major issue in this regard, Winde<sup>67</sup> pointed out the general lack of reliable scientific knowledge about long-term health-effects of uranium, which is also reflected by the wide range of uranium limits for drinking water given by different organisations and countries.

#### **f) Closure of mines**

In recent years, as mining in the FWR has passed its zenith, research has shifted towards the challenges of sustainable mine closure and associated hazards. Winde and Stoch<sup>1</sup>, Usher and Scott<sup>68</sup> and Winde et al.<sup>69</sup> comprehensively address the environmental impacts of mining with special reference to mine closure strategies. A report of the Department of Water Affairs and Forestry<sup>70</sup> briefly assesses the future (post-mining) water supply potential of the dolomitic compartments. Winde and Stoch<sup>71</sup> were the first to examining the opportunities associated with mine closure by exploring the potential of the area for beneficial post-closure use of mining residuals and infrastructure.

The water quality issues mentioned above as well as the availability of water will be influenced by the post-mine closure management of rewatering of the compartments. Different authors have estimated the time it will take for compartments to fill up with infiltrating groundwater once the mines stop pumping. Estimates for the period for the mine void and the dewatered compartment to re-fill range from 15 years<sup>69</sup> to 30 years.<sup>51</sup> Usher and Scott<sup>68</sup> estimated the time it will take for the rewatering of the dolomites (but not the mine void) from groundwater balance studies at maximum 30 years and from numerical modelling at 21 years (only Bank Compartment). The time it takes for the rewatering of the Gembokfontein West compartment was estimated to be 7.5 years<sup>72</sup> and between 5.8–46 years,<sup>73</sup> respectively.

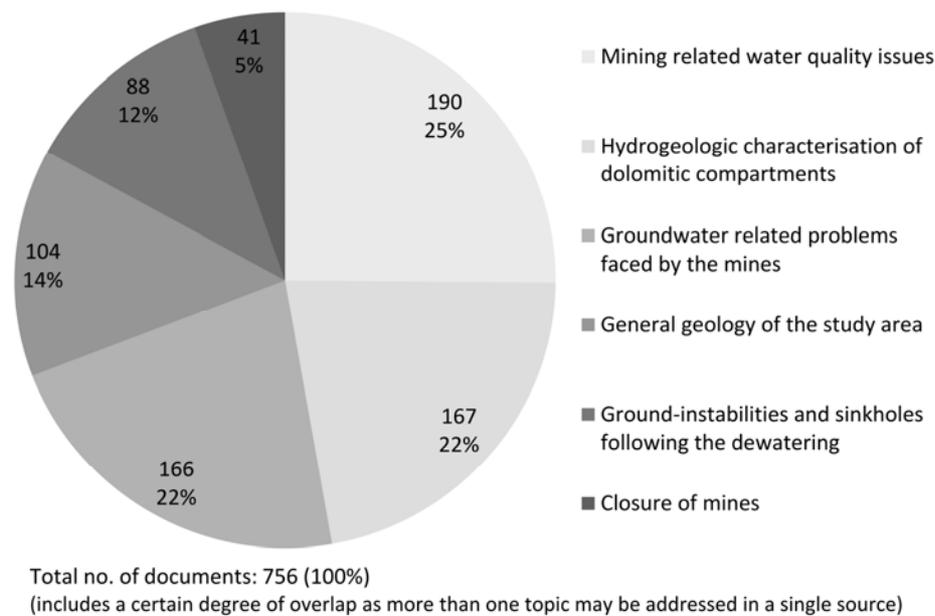
The processes of rewatering may be influenced by the formation of a mega-compartment, which could result from hydraulic linking of the previously discrete groundwater compartments of the FWR.<sup>18</sup> This is likely to have serious implications for many features of the hydrologic system

such as spring flow, the rate of groundwater recharge and the resultant groundwater quality. Although the issue was already mentioned in the Jordaan Report<sup>18</sup> in 1960, the matter has not yet been resolved. The existing uncertainties complicate the assessment of post-mine closure scenarios with regard to aquifer conditions and the associated environmental aspects. As a result, even studies that actually investigated other aspects had in some way or another make assumptions about the hydrogeologic future by either settling for one of the two opposing scenarios<sup>58,74</sup> (i.e. reactivation of spring flow vs. formation of a mega-compartment where springs remain dry) or advancing their arguments taking both possibilities into account.<sup>70</sup>

The mega-compartment concept has recently been subject to opposing views. The concept has been highlighted by Scott<sup>75</sup> and Usher and Scott<sup>68</sup>, the latter proposing the possibility of preventing the formation of a mega-compartment by artificially sealing the tunnels that inter-connect compartments. Investigations by Gold Fields in correspondence with the Department of Water Affairs showed that this was not an economically feasible option (Stoch 2014, personal communication). The mega-compartment concept was rejected by Dill et al.<sup>58</sup> and Swart et al.<sup>51</sup>. Whilst the mega-compartment concept has largely been addressed exclusively on a speculative basis, Swart et al. have provided the only existing study employing a scientific methodological approach (based on Darcy's law) in order to approach the issue on a hydraulic basis. Consequently Van Niekerk and van der Walt<sup>32</sup> and Winde and Erasmus<sup>74</sup> propose that the existing research on the topic (i.e. hydraulic consequences of piercing of dykes) is insufficient to reach any firm conclusions.

### **2.2.3 Conclusions and recommendations**

The FWR is a major deep-level gold mining area in South Africa and hosts significant groundwater resources. The present study identifies some particularities and issues related to the literature relevant to hydrologic research in the FWR. Related literature over the past six decades has produced a large volume of literature, which is difficult to evaluate systematically owing to a lack of a coherent and central archiving facility and a marked lack of quality assurance procedures. By subdividing the many complex and overlapping studies into six major topical categories, an overview is provided which reduces the overwhelming complexity of the collection of relevant studies to manageable proportions. The identification of relevant studies for future researchers is hereby simplified. The number of obtained documents (amounting to a total of 765 entities) is listed in each topical category discussed in this review in Fig. 2.



**Fig. 2.4** Number of documents per category considered in this review ranked in descending order

Water quality issues related to mining is the single largest category of the six topics covered in this review with a quarter of all documents relating to this aspect (Fig. 2). Next largest is the two groundwater-related aspects addressing the hydrogeological properties of dolomite and related water flow. The closure of mines ranks last in terms of number of relevant documents, since many mines are still active. This study highlights the need to address this aspect in more detail in future. The relatively modest number of documents relating to ground stability reflects the short-term nature of scientific attention. Once the causes of sudden appearance of sinkholes and ground subsidence had been understood, the number of dedicated studies on this aspect decreased. However, documents relating to routine observations of ground movement by the SCTC alone are currently estimated to number 2500, which would render this aspect by far the best covered.

The fact that much hydrologic knowledge is contained in unpublished documents such as internal and confidential reports of companies is a major issue that hampers the effective utilization of available data. Furthermore, many documents do not meet scientific standards it is often difficult to evaluate the reliability and quality of provided information. However, by putting individual studies into the context of related studies and through inter-comparisons this obstacle can often be overcome allowing the use of unique and often unreproducible data and studies.

In an effort to ameliorate the problems relating to the literature describing the FWR, an initiative by the Mine Water Re-search Group (MWRG) of the North-West University (Vaal Triangle

Campus) is currently underway. This initiative involves the systematic compilation of all available relevant documents into a single archive approaching some 6 000 hard copies. These documents are in the process of being digitized and collated in an electronic catalogue. It is envisaged that all contained relevant numerical data will be ultimately extracted georeferenced and transformed into electronic formats for the subsequent incorporation into a central GIS-supported database.

**Acknowledgement** With sadness we learned that Dr. Eliezer Joshua (Leslie) Stoch passed away on 24 August 2014. As a long-term resident he was passionate about the study area and much of what is reported in this paper is based on his vast and comprehensive collection of historic documents and inspired by his contagious enthusiasm for this unique region. We dedicate this paper to him.

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## **2.2.4 References**

1. Winde F, Stoch EJ. Threats and opportunities for post-closure development in dolomitic gold mining areas of the West Rand and Far West Rand (South Africa) - a hydraulic view. Part 1: Mining legacy and future threats. *Water SA* 36. 2010(1):69–74.
2. United Nations Environment Programme. *Geo-2000 global environmental outlook, overview*. Nairobi: United Nations Environmental Programme; 1999.
3. Swart CJU, Stoch EJ, van Jaarsveld CF, Brink ABA. The lower Wonderfontein Spruit: an exposé. *Environ Geol.* 2003;43(6):635–653.
4. Winde F. Karst, Uranium, Gold and Water – Lessons from South Africa for Reconciling Mining Activities and Sustainable Water Use in Semi-arid Karst Areas: A Case Study. In: Jones JAA, editor. *Sustaining groundwater resources*. Dordrecht: Springer Science+Business Media; 2011. p. 35–53.
5. Krahmman R. The geophysical magnetometric investigations on the West Witwatersrand areas between Randfontein and Potchefstroom, Transvaal. *Trans Geol Soc S Afr.* 1936;39:1–44.
6. Pelletier RA. Contributions to the geology of the Far West Rand. *Trans Geol Soc S Afr.* 1937;40:127–162.
7. De Kock WP. The geology and economic significance of the West Wits Line. In: Houghton SH, editor. *The Geology of some ore deposits in Southern Africa, volume 1*. Johannesburg: Geological Society of South Africa; 1964. p. 323–386.
8. Brink ABA. *Engineering Geology of South Africa, volume. 1*. Pretoria: Building Publications; 1979.
9. South African Committee for Stratigraphy. *Stratigraphy of South Africa. Part 1*. Pretoria: Department of Mineral and Energy Affairs, Geological Survey; 1980.
10. Engelbrecht CJ (1986) The West Wits Line. In: Antrobus ESA, editor. *Witwatersrand Gold - 100 Years*. Johannesburg: Geological Society of South Africa; 1986. p. 199–223.
11. Robb LJ, Robb VM. Gold in the Witwatersrand Basin. In: Wilson MGC, Anhaeusser CR, editors. *The mineral resources of South Africa [6th edition]*. Silverton: Council for Geosciences. 1998; Handbook 16:294–349.
12. McCarthy TS. The Witwatersrand Supergroup. In: Johnson MR, Anhaeusser CR, Thomas RJ, editors. *The Geology of South Africa*. Johannesburg: Geological Society of South Africa, Council for Geosciences; 2006. p. 155–186.
13. National Mechanical Engineering Research Institute. *Water Problem at West Driefontein G.M. CO*. Pretoria: New Consolidated Gold Fields Ltd. Report No 2; 1957 (unpublished).

14. Enslin JF. Report on the groundwater in the mining areas of Blyvooruitzicht, West Driefontein, Doornfontein and Venterspost mines and its relation to the supplies of the Oberholzer and Venterspost loop irrigation boards. Pretoria: Geological Survey; 1954 (unpublished).
15. Interdepartmental Committee on Dolomitic Water Pumped by Mines. Depletion of water stored in Oberholzer Compartment. Interdepartmental Committee on Dolomitic Water Pumped by Mines; 1958 (unpublished).
16. Knight K. An estimate of the total quantity of water abstracted from the Oberholzer Dolomitic compartment up to the end of 1964, the possible rate of replacing the water and the feasibility of so doing. Report to Rand Mines Ltd; 1964 (unpublished).
17. Irving CJ. Comment on the dewatering of the Oberholzer Dolomitic Compartment. Blyvooruitzicht Gold Mining Co Ltd; 1964 (unpublished).
18. Jordaan JM, Enslin JF, Kriel J, Havemann A, Kent LE, Cable WH. Final report of the Interdepartmental Committee on Dolomitic Mine Water: Far West Rand. Pretoria: Department of Water Affairs and Forestry; 1960 (unpublished).
19. Enslin JF, Kriel JP. Some results obtained from a hydrological study of a dolomitic catchment area in the Transvaal, Union of South Africa. Pretoria: Department of Water Affairs, Division of Hydrological Research; 1959.
20. Wolmarans JF. The least unsafe route, volume. 1. Carletonville: Webb and Partners; 1982.
21. Stoch EJ, Winde F. Threats and opportunities for post-closure development in dolomitic gold mining areas of the West Rand and Far West Rand (South Africa) - a hydraulic view. Part 3: Planning and uncertainty – lessons from history. *Water SA*. 2010;36(1)83–88.
22. Cartwright AP. West Driefontein - ordeal by water. Johannesburg: Gold Fields of South Africa Ltd., JG Ince & Son Ltd.; 1969.
23. Cousens RRM, Garrett WS. The flooding at the West Driefontein Mine. *S Afr Inst Min Metall*. 1969;69(9):421–463.
24. Acting Secretary For Water Affairs. Far West Rand: De-watering Bank Compartment: Through West Driefontein Gold Mine: Effects on farming community: Application for urgent decision re purchase of properties and/or water rights. Pretoria: Department of Water Affairs; 1968 (unpublished).
25. Foose RM. Sinkhole formation by groundwater withdrawal: Far West Rand, South Africa. *Sci*. 1967;157(3792):1045–1048.
26. Bezuidenhout CA, Enslin JF. Surface subsidence and sinkholes in the dolomitic areas of the Far West Rand, Transvaal, Republic of South Africa. In: *Land Subsidence 1969. Proceedings of the Tokyo Symposium*; 1969 Sep; Tokyo. Gentbrugge: Unesco/IAHS; 1970. p. 482–495.
27. Kleywegt RJ, Enslin JF. The application of the gravity method to the problem of ground settlement and sinkhole formation in dolomite on the Far West Rand, South Africa. In: *IAEG 1973. Proceedings of the International Association of Engineering Geologists Symposium on sinkholes and subsidence – Engineering Geological Problems Associated with Soluble Rocks*; 1973; Hannover. Essen: Deutsche Gesellschaft für Erd- und Grundbau; 1973. p. 301–315.
28. Kleywegt RJ, Pike DR. Surface subsidence and sinkholes caused by lowering of the dolomitic water-table on the Far West Rand Gold Field of South Africa. *Ann Geol Surv (S Afr)*. 1982;16:77–105.
29. Beukes JHT. Ground movement and the formation of sinkholes due to the partial rewatering of Venterspost Compartment 1975-1978]. In: *Geological Survey (South Africa). Proceedings of the Seminar on the Engineering Geological Evaluation of Sites on Dolomite*. Pretoria: Geological Survey. 1987. p. 86–95.
30. Swart CJU. Storm water infiltration into dewatered dolomitic compartments via sinkholes in river beds. Gold Fields Ground Stability Group. Memorandum No GF/GSG/2000/19. 2000 (unpublished).
31. De Bruyn IA, Bell FG. The occurrence of sinkholes and subsidence depressions in the Far West Rand and Gauteng Province, South Africa, and their engineering implications. *Environ Eng Geosci*. 2001;7(3):281–295.

32. Van Niekerk HJ, van der Walt IJ. Dewatering of the West Rand dolomitic area by gold mining activities and subsequent ground instability. *Land Degrad Dev.* 2006;17(4):441–452.
33. Enslin JF. Dolomitic water supplies in the Transvaal, Republic of South Africa. *Memoirs Internat Assoc Hydrogeol.* 1967;8:433–476.
34. Enslin JF, Kriel JP. The assessment and possible future use of the dolomitic ground water resources of the Far West Rand, Transvaal, Republic of South Africa. In: *Papers of the International Conference on Water for Peace; 1967 May 23-31; Washington DC, volume 2.* Washington DC: US Government Printing Office; 1968. p. 908–918.
35. Fleisher JNE. The geohydrology of the dolomitic aquifers of the Malmani subgroup in the South-Western Transvaal Republic of South Africa. Pretoria: Department of Water Affairs and Forestry. DWAFF Technical Report No GH 3169; 1981 (unpublished).
36. Vegter JR. Dolomitic water supplies with special reference to southern and western Transvaal. Pretoria: Department of Water Affairs and Forestry. DWAFF Technical Report No GH 3353; 1984 (unpublished).
37. Foster MBJ. The hydrogeology of dolomitic formations in the southern and western Transvaal. Pretoria: Department of Water Affairs and Forestry. DWAFF Technical Report No. GH 3643; 1989 (unpublished).
38. Martini JEJ, Kavalieris I. The Karst of the Transvaal (South Africa). *Int J Speleol.* 1976;8(3):229–251.
39. Morgan DJT, Brink ABA. The Far West Rand dolomites. In: National Water Well Association, editor. *Proceedings of the International Conference on Ground Water Technology; 1984 Nov 14-17; Johannesburg, volume 2.* National Water Well Association; 1984. p. 554–573.
40. Wolmarans JF, Guise-brown FH. The water hazard in deep gold mining of the Far West Witwatersrand - South Africa. In: *Asociacion Nacional de Ingenieros de Minas, Consejo Superior de Colegios de Ingenieros de Minas. Proceedings, World Congress on Water in Mining and Underground Works (SIAMOS-78); 1978 Sept 18–22; Granada, Spain, volume 1.* Granada: Asociacion Nacional De Ingenieros De Minas; 1978. p. 329–346.
41. Wolmarans JF. Ontwikkeling van die dolomietgebied aan die verre Wes Rand: gebeurte in perspektief [Dewatering of the dolomitic area on the Far West Rand: events in perspective] [dissertation] Pretoria: University of Pretoria; 1984.
42. De Freitas MH. The effect of non-dolomitic rocks upon the flow of water in the Bank Compartment. London: Geology Department, Imperial College. 1974 (unpublished).
43. Schwartz HI, Midgley DC. Evaluation of geo-hydrologic constants for the Far West Rand dolomitic formations. *Civ Eng S Afr.* 1975;17(2):31–36.
44. Theis CV. The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage. *Trans Am Geophys Union.* 1935;16(2):519–524.
45. Bredenkamp DB, Fayazi M, Botha LJ. Interpretation of pumping test in the Gembokfontein East Compartment - A typical heterogeneous karst system. Pretoria: Department of Water Affairs and Forestry, Directorate of Geohydrology. DWAFF Technical Report No GH 3727; 1991 (unpublished).
46. Geo Hydro Technologies (1998) Geohydrological investigation of the groundwater conditions at West Driefontein a division of Driefontein Consolidated Ltd. Pretoria: Geo Hydro Technologies. Report No. WES97\103; 1998 (unpublished).
47. Van Tonder G, Bardenhagen I, Riemann K, van Bosch J, Dzanga P, Xu Y. Manual on pumping test analysis in fractured-rock aquifers. Pretoria: Water Research Commission. WRC Report No 1116/1/02; 2002.
48. Kirchner J, van Tonder GJ. Proposed guidelines for the execution, evaluation and interpretation of pumping tests in fractured-rock formations. *Water SA.* 1995;21(3):187–200.
49. Foster MBJ. First revision of the geohydrology of the Zuurbekom and Gembokfontein Compartments. Pretoria: Department of Water Affairs and Forestry. DWAFF Technical Report No GH 3542; 1987 (unpublished).

50. Foster MBJ. The groundwater resources of the Far West Rand dolomitic compartments. Pretoria: Department of Water Affairs and Forestry DWAF Technical Report No. GH 3607; 1988 (unpublished).
51. Swart CJU, James AR, Kleywegt RJ, Stoch EJ. The future of the dolomitic springs after mine closure on the Far West Rand, Gauteng, RSA. *Environ Geol.* 2003;44(7):751–770.
52. Bredenkamp DB. Recharge estimation based on chloride profiles. Pretoria: Department of Water Affairs and Forestry, Directorate of Geohydrology. DWAF Technical Report No GH 3804; 1993 (unpublished).
53. Bredenkamp DB. Use of natural isotopes and groundwater quality for improved recharge and flow estimates in dolomitic aquifers. *Water SA.* 2007;33(1):87–94.
54. Enslin JF, Kleywegt RJ, Buekes JHT, Gordon-Welsh JF. Artificial recharge of dolomitic ground-water compartments in the Far West Rand Gold Fields of South Africa. In: International Association of Hydrological Sciences, editor. *Proceedings of the second International Symposium on Land Subsidence*; 1976 Dec 13-17; Anaheim, California. Michigan: International Association of Hydrological Sciences; 1977. p. 495–506.
55. Durand JF. The impact of gold mining on the Witwatersrand on the rivers and karst system of Gauteng and North West Province. *J Afr Earth Sci.* 2012;68:24–43
56. Pulles W, Banister S, van Biljon M. The development of appropriate procedures towards and after closure of underground gold mines from a water management perspective. Pretoria: Water Research Commission. WRC Report No 1215/01/05; 2005.
57. Winde F, Stoch EJ, Erasmus E. Desktop assessment of the risk for basement structures of buildings of Standard Bank and ABSA in Central Johannesburg to be affected by rising mine water levels in the Central Basin. Potchefstroom: Mine Water Re-search Group, North-West University. Final Report (Volume I of III); 2011 (unpublished).
58. Dill S, Boer RH, Boshoff HJJ, James AR, Stobart BI. An Assessment of the impacts on groundwater quality associated with the backfilling of dolomitic cavities with gold mine tailings. Pretoria: Water Research Commission. WRC Report No 1122/1/07; 2007.
59. Wade PW, Woodborne S, Morris WM, Vos P, Jarvis NV. Tier 1 risk assessment of selected radionuclides in sediments of the Mooi River catchment. Pretoria: Water Research Commission. WRC Report No 1095/1/02; 2002.
60. Coetzee H, Winde F, Wade PW. An assessment of sources, pathways, mechanisms and risks of current and potential future pollution of water and sediments in gold-mining areas of the Wonderfonteinspruit catchment. Pretoria: Water Research Commission. WRC Report No 1214/1/06; 2006.
61. Winde F. Challenges for sustainable water use in dolomitic mining regions of South Africa – A case study of uranium pollution. Part I: Sources and pathways. *Phys Geogr.* 2006;27(4):333–347.
62. Winde F. Uranium pollution of the Wonderfonteinspruit, 1997-2008 Part 1: Uranium toxicity, regional background and mining-related sources of uranium pollution. *Water SA.* 2010;36(3):239–256.
63. Winde F. Uranium pollution of the Wonderfonteinspruit, 1997-2008 Part 2: Uranium in water – concentrations, loads and associated risks. *Water SA.* 2010;36(3):257–278.
64. NECSA (South African Nuclear Energy Corporation). Report of radioactivity analysis of fish and chicken. Pretoria: South African Nuclear Energy Corporation. Job code RA 08190, 28 Aug. 2007, for Driefontein GM; 2007 (unpublished).
65. Barthel R. Radiological impact assessment of mining activities in the Wonderfonteinspruit catchment area, South Africa. In: Merkel BJ, Schipek M, editors. *The new uranium mining boom, challenge and lessons learned.* 6th International Conference. Freiberg: Springer; 2011. p. 517–527.
66. IWQS (Institute for Water Quality Studies of the Department of Water Affairs and Forestry, South Africa). Report on the radioactivity monitoring programme in the Mooi River (Wonderfonteinspruit) catchment. Pretoria: Department of Water Affairs and Forestry. Report No. N/C200/00/RPQ/2399; 1999.

67. Winde F. Uranium pollution of water resources in mined-out and active goldfields of South Africa – A case study in the Wonderfonteinspruit catchment on extent and sources of U-pollution and associated health risks. In: Water Institute of Southern Africa, International Mine Water Association. International Mine Water Conference [CD ROM]. Pretoria: Document Transformation Technologies; 2009. p. 772–781.
68. Usher BH, Scott R. Post mining impacts of gold mining on the West Rand and West Wits Line. In: Hodgson FDI, Usher BH, Scott R, Zeelie S, Cruywagen LM, de Necker E, editors. Prediction techniques and preventative measures relating to the post-operational impact of underground mines on the quality and quantity of groundwater resources. Pretoria: Water Research Commission. WRC Report No 699/1/01; 2001. p. 5.1–5.117.
69. Winde F, Stoch EJ and Erasmus E. Identification and quantification of water ingress into mine voids of the West Rand and Far West Rand goldfields (Witwatersrand basin) with a view to long-term sustainable reduction thereof. Pretoria: Council for Geoscience. Final report, Project No 5512; 2006 (unpublished).
70. Department of Water Affairs and Forestry. Vaal River System: Large bulk water supply reconciliation strategy. Groundwater assessment: Dolomitic aquifers. Prepared by DMM Development Consultants, Golder Associates Africa, SRK, WRP Consulting Engineers and Zitholele Consulting. Pretoria: Department of Water Affairs and Forestry, Directorate National Water Resource Planning. DWAF Report No P RSA C000/00/4406/06; 2006.
71. Winde F, Stoch EJ. Threats and opportunities for post-closure development in dolomitic gold mining areas of the West Rand and Far West Rand (South Africa) - a hydraulic view. Part 2: Opportunities. *Water SA*. 2010;36(1):75–82.
72. Van Biljon M, Krantz R. Predicted rate of rewatering the Gembokfontein West groundwater compartment. Rivonia: Rison Consulting. Report to Harmony Gold Mining Limited; 2001 (unpublished).
73. De Roer K. Hydrologic Impact of Rewatering of the Gembokfontein Dolomitic Western Subcompartment on the Wonderfonteinspruit, South Africa [thesis]. Potchefstroom: North-West University; 2004.
74. Winde F, Erasmus E. Peatlands as filters for polluted mine water? - A case study from an uranium-contaminated karst system in South Africa. Part I: Hydrogeological setting and U fluxes. *Water*. 2011;3(1):291–322.
75. Scott R. Investigation of the post mining impact on groundwater in the West Rand and West Wits Line mining areas. Pretoria: Water Research Commission. Third interim progress report to the Water Research Commission. 1997 (unpublished).

### **3 Determining hydraulic parameters of a karst aquifer using unique historical data from large-scale dewatering by deep level mining – a case study from South Africa**

Aljoscha Schrader<sup>1,2</sup>, Ewald Erasmus<sup>1</sup>, Frank Winde<sup>1</sup>

<sup>1</sup> Faculty of Natural Sciences, Potchefstroom Campus, North-West University, Private Bag X6001, Potchefstroom 2520, South Africa, <sup>2</sup> Mine Water Research Group, Vaal Campus, North-West University, South Africa

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**Abstract** Although karst aquifers constitute some of the most important water resources worldwide, generally accepted methods for reliably characterising their hydraulic properties are still elusive. This paper aims at contributing to the discussion by a first-ever attempt to utilise various sets of unique historical data derived from draining a large dolomitic karst aquifer by deep-level gold mines in South Africa. In contrast to conventional pumping tests which only penetrate thick aquifers to a limited extent from surface, this draining took place at the very bottom of the aquifer offering the rare opportunity to capture its entire thickness of nearly a kilometre. The datasets have been treated as analogies to conventional pumping tests applying various types of analytical methods designed for porous media. In order to increase the robustness of the results and to account for specific local conditions a total of four different analytical methods were applied to calculate (horizontal) transmissivity and storage coefficients. The obtained values, in general, compare favourably to previous studies in the area and values reported in literature for similar aquifer types confirming earlier findings that Darcy-based methods can be successfully applied to karst aquifers if the scale of investigation is large enough. Apart from improving the understanding of local karst hydrology the present study also aimed at retrieving and preserving valuable and unique historical datasets that otherwise would have been lost for scientific evaluation and the proactive preparation for mine closure.

**Keywords** *Karst, Dewatering, Deep level mining, Porous medium analytical methods, Transmissivity, Storage coefficient, Far West Rand*

### 3.1 Introduction

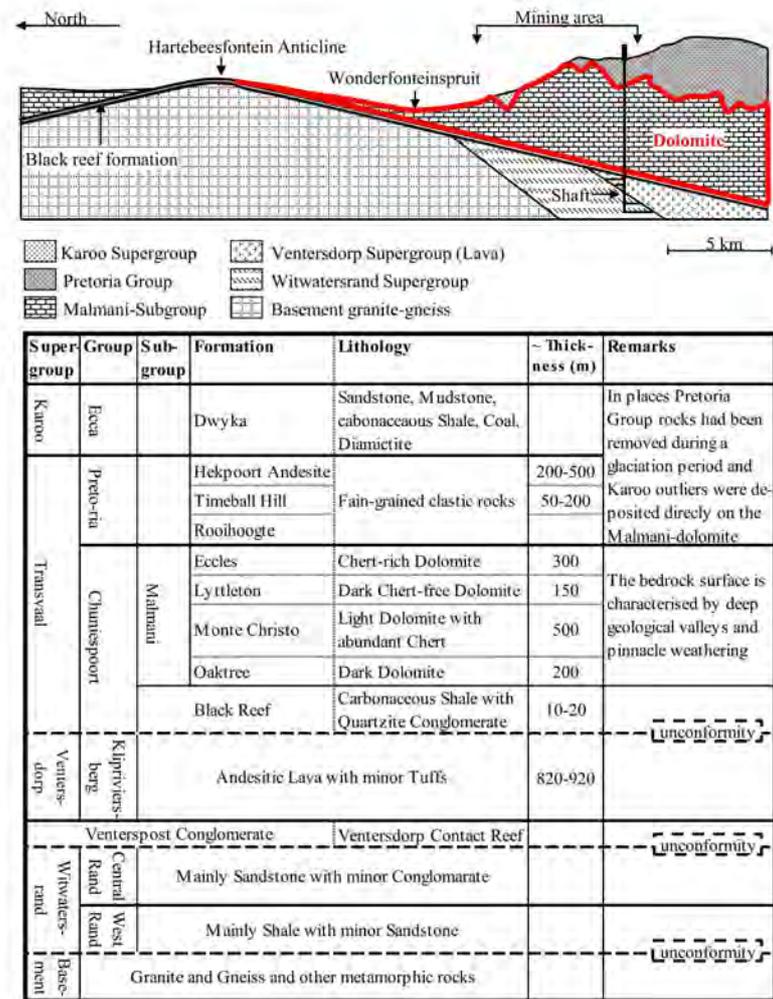
The main purpose of this paper is to explore the usability of historical data gathered over 4 decades of deep-level gold mines dewatering an overlying dolomitic karst aquifer in the Far West Rand (FWR), South Africa, in order to determine hydrological parameters. Based on the conceptual understanding that the set-up under which these data were generated resembles an ultra-large pumping test covering the thickness of the entire karst aquifer, standard analytical methods typically used in pumping tests were applied. At the same time the study attempts to preserve large sets of unique data that are regarded as most valuable for predicting hydraulic conditions after future mine closure. The latter is particularly important as mining-induced modifications of the natural hydrogeological setting in the FWR will, in all likelihood, have profound impacts on post-mining land use as well as on the long-term availability of surface and groundwater resources.

### 3.2 Hydrogeological conditions of the study area

**Geological setting** The karstified dolomites of the FWR goldfield, southwest of Johannesburg, host some of the largest groundwater resources in South Africa, as well as a range of strong associated karst springs. Gold-bearing reefs below the dolomite have been subject to extensive deep-level mining for many decades. Following a sudden and nearly catastrophic inrush of dolomitic groundwater to the Driefontein Mine in October 1968, it was found necessary to dewater the dolomitic aquifer above the mine void. Owing to the large-scale lowering of the regional groundwater table many of the karst springs dried up. Simultaneously, large quantities of hydrologic data were recorded, some of which are used in this study. The historical and hydrogeological context of the latter data is briefly outlined in this section.

The overall geological situation is depicted in Fig. 3.1, indicating a north to south cross-section in the FWR as well as the associated stratigraphy. The areal extent of the investigated area in plane view is depicted in Fig. 3.2.

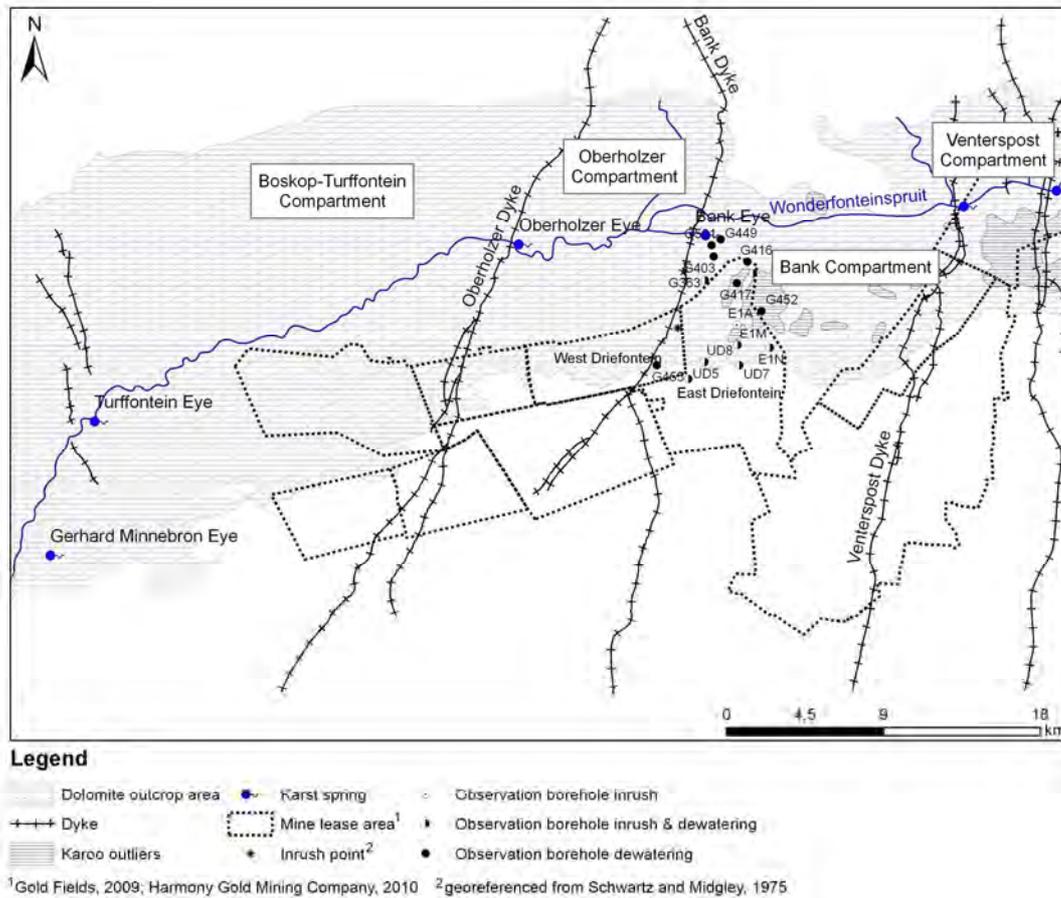
The dolomite is subdivided into several so called ‘groundwater compartments’ by approximately north to south–trending intrusive, nearly-vertical dykes, which act as groundwater flow barriers (De Kock, 1964; Brink, 1979). Compartments in the area concerned are the Venterspost, Bank, Oberholzer and, lastly, Boskop-Turffontein Compartments. Data analysed in this study exclusively refer to the Bank Compartment. The northern aquifer boundary is set by granites of the Hartebeesfontein Anticline (Fig. 3.1).



**Fig. 3.1** North-south cross section showing the geologic setting of the FWR (modified after Brink, 1979) and, below, the associated stratigraphic column (after Els, 1987, 2000). The areal extent of the investigated area in plane view is depicted in Fig. 3.2

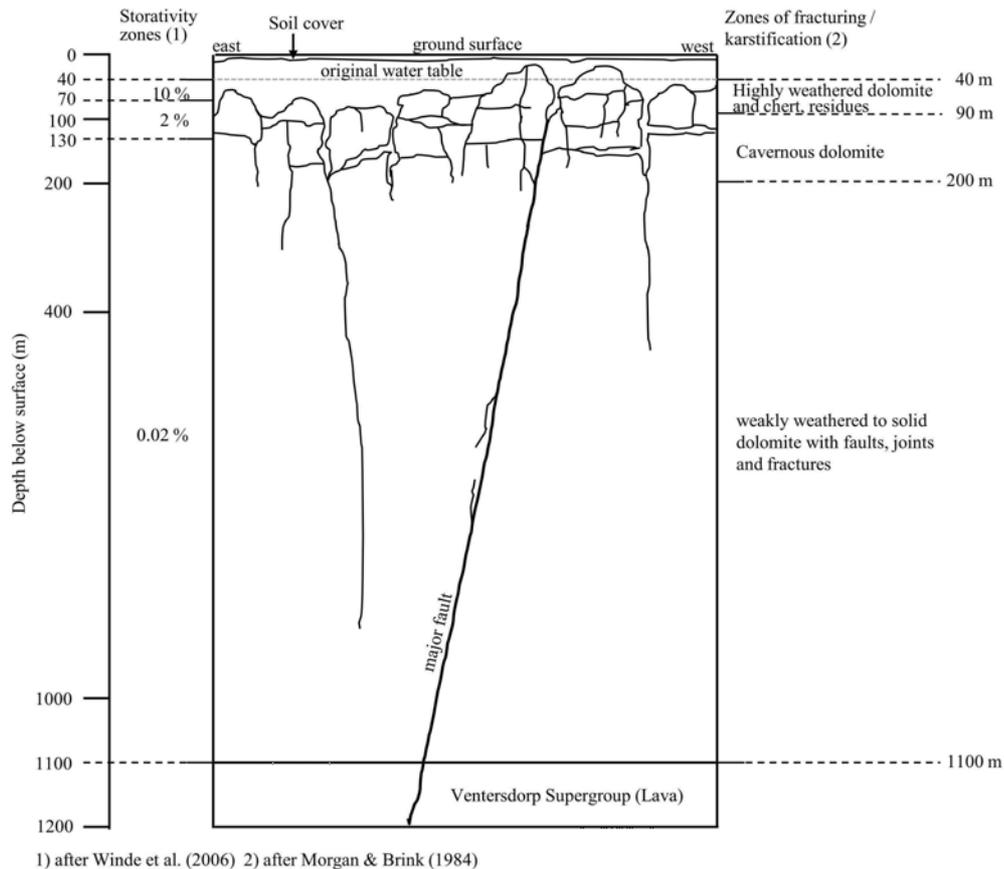
To the south a gradual boundary forms where rocks of the Pretoria Group increasingly overlie the dolomite, preventing pronounced karstification through shielding the underlying dolomite from infiltrating rainfall (Enslin and Kriel, 1968; Brink, 1979). According to Swart et al. (2003), the shielding effect creates a boundary where the thickness of the Pretoria Rocks is at least 150 m. The Ventersdorp Supergroup Lava and Witwatersrand Supergroup Quartzites do not store significant volumes of groundwater (De Kock, 1964), and therefore constitute the lower flow boundary of the overlying dolomite. The storativity and transmissivity of the dolomites decrease with depth. Figure 3.3 depicts the vertical zonation provided by Morgan and Brink (1984) and zones of storativity as listed by Winde et al. (2006). The zone just below the original water table (OWT) extends to a depth of about 70–90 m below surface (mbs) and has a thickness of up to 50 m. It consists mainly of the residues of leached and highly weathered dolomite (wad) as well as of chert and insoluble residues. Owing to the fine-grained nature of wad and the other sediments

this zone resembles a porous layer. Below this zone water is stored in a network of large cavities, solution conduits and solution-widened fractures. This zone of ‘cavernous dolomite’ extends to depth of maximal 200 mbs. This is followed by a zone of weakly weathered to solid dolomite with intersecting vertical tectonic faults, joints and fractures that may in cases be widened by solution (Morgan and Brink, 1984).



**Fig. 3.2** Map of the FWR showing the surface area of outcropping Malmani-dolomite, surface positions of intrusive dykes and the associated dolomitic compartments and springs as well as the mine lease areas. Furthermore, the locations of 15 observation boreholes used for monitoring the various ingress events that are analysed in this study are depicted

Based on estimates from various authors, Winde et al. (2006) identified 3 zones of storativity, as shown in Fig. 3.3. In accordance with the storativity of the various zones, the total volume of groundwater stored in the Bank Compartment has been estimated to be between 663 (derived from Winde et al., 2006) and 2 200 Mm<sup>3</sup> (million m<sup>3</sup>) (Schwartz and Midgley, 1975). Values for the transmissivity of the dolomite differ within a broad range, which is typical for karst. Values between 1 000 and 25 000 m<sup>2</sup>/d have been recorded (Enslin and Kriel, 1959; Schwartz and Midgley, 1975; Bredenkamp et al., 1991).

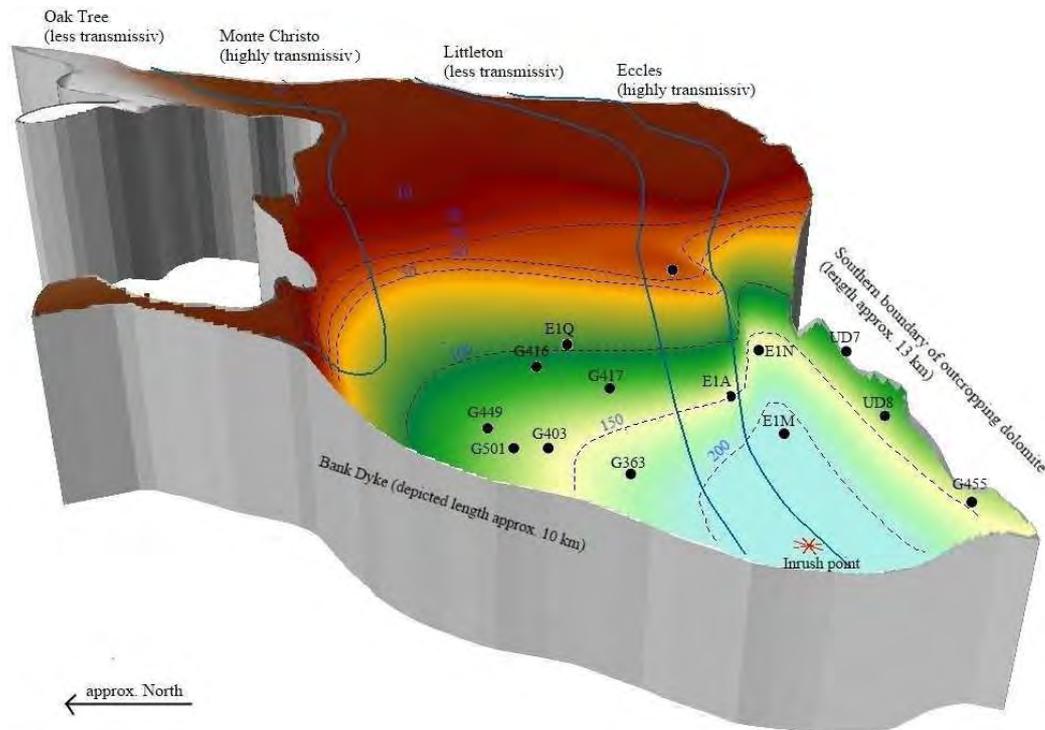


**Fig. 3.3** Schematic depiction of the vertical zonation of the dolomite in the FWR based on the degree of karstification/ fracturing and storativity (according to Winde et al. (2006) and Morgan and Brink (1984))

**Dewatering of the Bank Compartment** Dewatering of the Bank Compartment was implemented by West-Driefontein Mine from June 1969 onwards, after a hazardous inrush in October 1968, which occurred after mining operations encountered a major fault, namely, the so-called ‘Big Boy fault’ (Swart et al., 2003a). In this context the term ‘dewatering’ refers to the process of pumping ingress water from the mine void to surface and then discharging it outside the compartment boundaries at a rate that exceeds the natural groundwater recharge rate (Wolmarans, 1982). This results in gradual lowering of the water table reducing the water pressure above the mine void and thus the associated ingress volume. Dewatering is completed when the falling water table reaches a level at which the ingress rate equals the rate of the natural recharge of that particular compartment. Although the water table is lowered by several hundreds of meters in places, the compartment is not ‘dewatered’ in the true sense of the word but still contains significant volumes of groundwater (Wolmarans, 1982).

Most of the active drawdown of the groundwater table, which as a matter of policy commenced soon after the inrush, had been completed by 1974. By then the sustained groundwater abstraction through the former inrush point had created a steep depression cone in the south-western

corner of the Bank Compartment (Fig. 3.4). Swart et al. (2003) estimate that about 90% of all water pumped by West- and East Driefontein together still enters the mine void via the Big Boy fault.



**Fig. 3.4** 3D-model (created with ArcMap®) showing the water table surface (vertically exaggerated) and groundwater draw-down contours (in meters below the OWT) of the Bank Compartment in May 1971 (based on a scanned image of a drawdown contour map (Geological Survey of South Africa, undated)). Blue lines mark the outcrop area of dolomitic formations (e.g. Oak Tree) indicating the influence of different hydraulic properties of the formations on the shape of the depression cone. Black dots mark the position and code of boreholes used in this study

### 3.3 Characterisation of the used historical data

The data used in this study consist of a variety of formats including diagrams, unpublished reports, maps at various scales, formats and age, pumping and drilling data from mine operators and water-level observations that were scattered over a multitude of sources including private collections, archives, mining companies, governmental departments, and academic institutions (Fig. 3.5). The data had been collected over decades by Professor EJ Stoch (Mine Water Research Group, North-West University), who prevented many of them from being irretrievably lost.

After retrieving the original data, most had to be converted manually into usable electronic formats for their subsequent compilation and collation in a dedicated database. Given the large amounts of funds spent at the time on generating these datasets and their uniqueness in terms of

the scale and nature of associated events, which can never be repeated, their preservation was deemed imperative. Apart from possibly contributing to an improved understanding of karst hydrology in general, these data are also regarded to be of crucial importance for the proactive preparation for future mine closure in the FWR, as the largest and by far most water-rich active goldfield in South Africa. Preserving the data for future scientific use also counteracts the widespread ‘loss of institutional memory’ in South Africa where changing structures in Government as well as the mining industry often result in the loss of existing data, information, knowledge and expertise (Stoch and Winde, 2010).

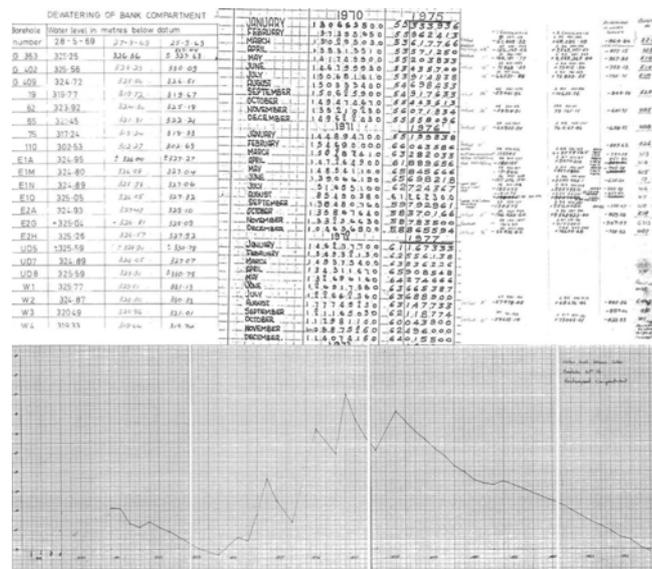


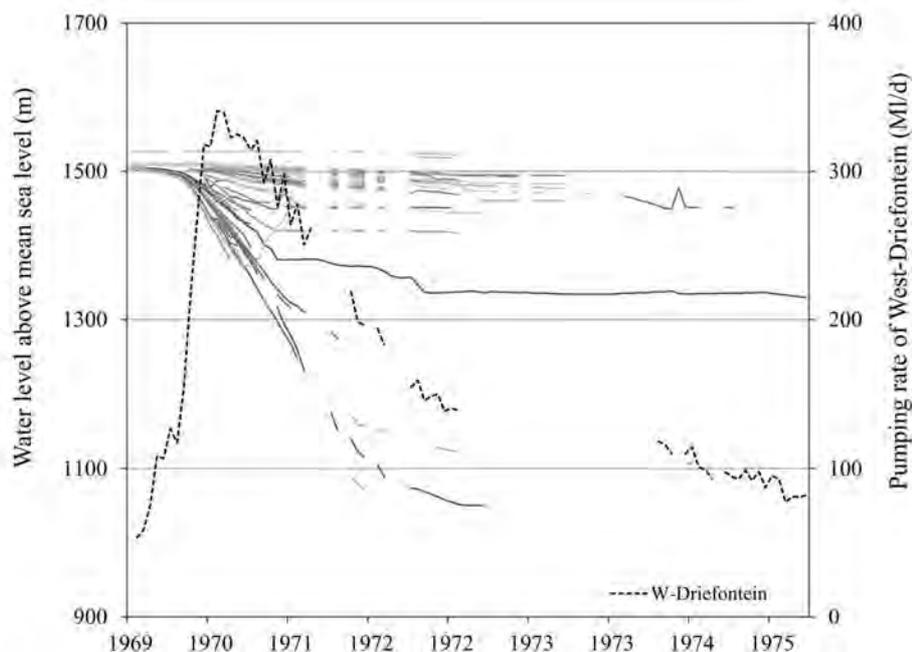
Fig. 3.5 Example of a typical source of historical pumping data used in this study

This paper focuses exclusively on drawdown data and pumping figures associated with the Bank Compartment (Fig. 3.2). The total dataset can be subdivided into 3 distinctly different datasets which are briefly characterised.

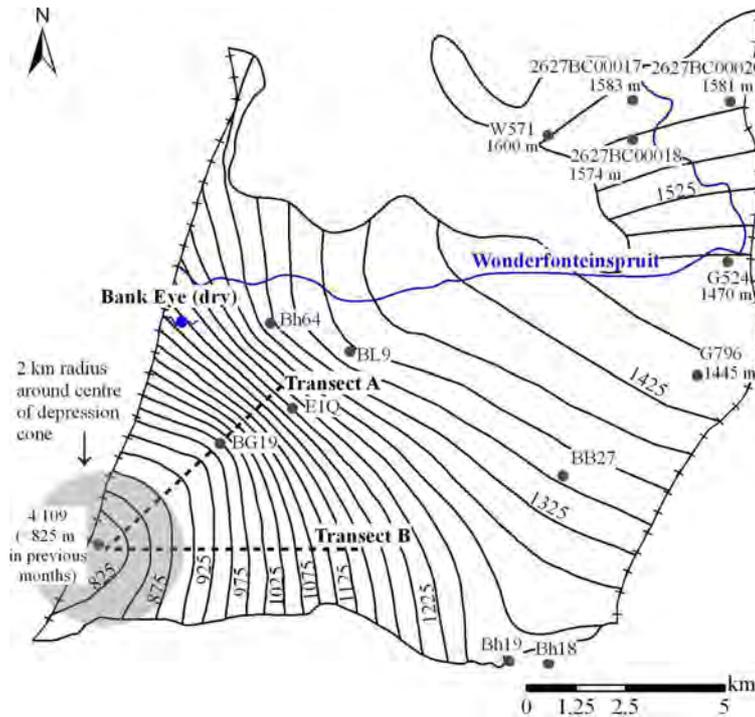
- **Dataset 1 (‘drawdown dewatering’)** originates from the dewatering of the Bank Compartment from 1969 to 1974, when the water table was actively lowered by mines pumping out up to 4 times more water than what naturally could be replenished. The pumping rate of West-Driefontein Mine that dewatered the compartment at the time is shown in Fig. 3.6. Also shown are drawdown observations as available for a total of 66 boreholes located in the Bank Compartment, mostly drilled by the gold mines for this specific purpose. For reasons discussed later, this study uses only observations from 14 boreholes within a distinct radius from the centre of the depression cone and a time period of 24 months, as listed in the Appendix. The geographical location of the used boreholes is shown in Figs 3.2 and 3.4.

- **Dataset 2 ('inrush event')** originates from the accidental inrush of large volumes of dolomitic groundwater into the West-Driefontein Mine over a period of 4 weeks in October–November 1968. The event caused a water-level drawdown of up to 50 m in places, which was monitored by the mine in a total of 15 boreholes and led to the temporary drying up of the Bank Eye within a few days after the inrush started. This study uses drawdown data from 8 boreholes within the defined radius from the centre of the depression cone (see Appendix). The inrush volume was estimated at between 228 and 386 Mℓ/d (Anonymous, 2005, cited in Winde et al., 2006; Enslin et al., 1977). The latter volume, estimated 3 days after the beginning of the event (quoted in Cousens and Garrett, 1969) appears to be the most cited and more reliable one and is thus used in this study.
- **Dataset 3 ('steady-state dewatering')** consists of a snapshot of water-level data for the dewatered Bank Compartment from June 1996, representing the prevailing conditions after the active drawdown of the water table was achieved. Water level data (see Appendix) were digitised from the groundwater contour map shown in Fig. 3.7.

The data represent quasi steady-state conditions of the aquifer, which is characterised by a stable water table that is maintained by a constant pumping rate. Table 3.1 gives a condensed overview on the characteristics of the three datasets.



**Fig. 3.6** Development of the water level in the Bank Compartment and the pumping rate of West-Driefontein during active (drawdown) dewatering



**Fig. 3.7** Groundwater contour map of the Bank Compartment in June 1996 (Based on data from Gold Fields Ltd, undated; DWA, 2013). Values of maximum drawdown ( $s_m$ ) as well as the distance to the centre of the depression cone were derived from the intersected water level contour lines along the two transects A and B

**Table 3.1** Metadata of the three datasets

Data-set	Cause of water level drop	Period	Duration	No. of boreholes (total/used)	Range of water levels*	Corresponding zones of karstification (Fig.3.3)**	No. of water level data points	Ave. pumping rates (ME/d)
1	Active dewatering	27.08.1969 – 28.07.1971	24 months	66/ 14	0.5–194.2	Weakly weathered to solid (>200 mbs to inrush point at 863 mbs*)	161	252 (75–341)
2	Accidental inrush	26.10.1968 – 23.11.1968	4 weeks	15/ 8	0–43.59	All zones (elevation of original water table to inrush point at 863 mbs)	120	386
3	Steady-state dewatering	26.06.1996	1 day	unknown	278–603	mostly solid dolomite (>600 mbs to inrush point at 863 mbs)	25 (14: Transect A, 11: Transect B)	61

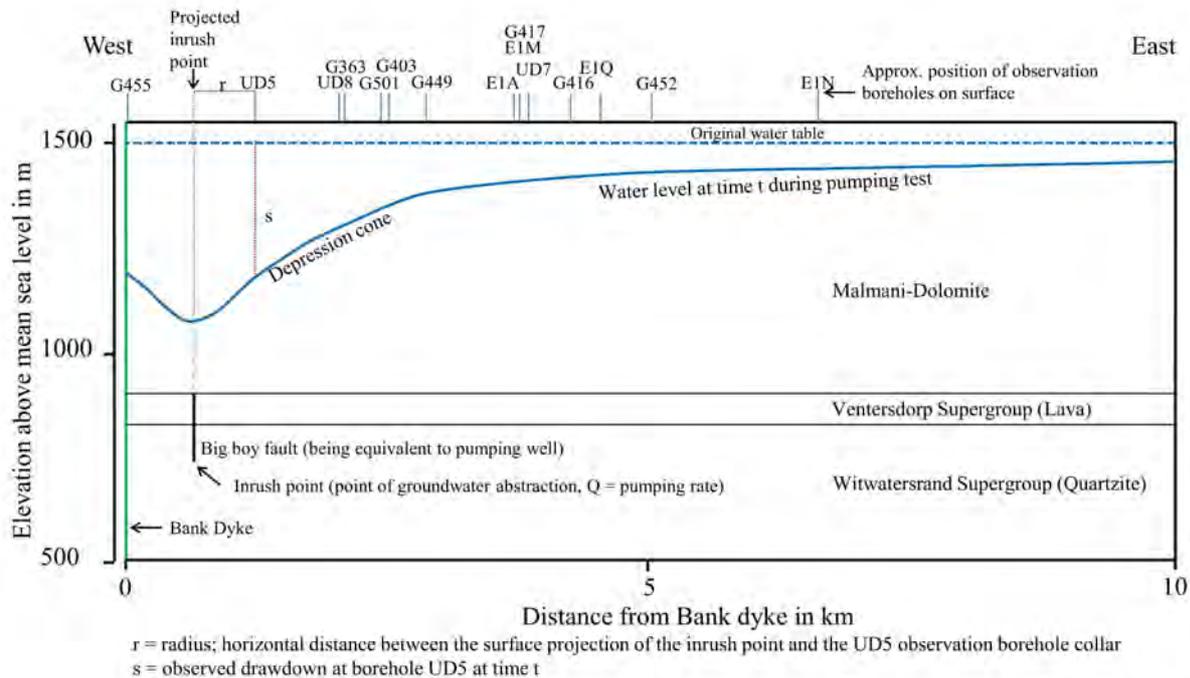
\* in meters below original water table

\*\* refers to the thickness of the water-saturated rock column at the end of the drawdown below the maximum water level depth recorded (mbs = meters below surface)

### 3.4 Pumping tests as an analogy to analyse historical data

As can be seen in Fig. 3.8, the hydrologic setting during dewatering of the Bank Compartment was very similar to a common pumping test setting except that the associated drawdown is much larger than commonly achieved. The pumping well in the Bank Compartment is represented by the Big Boy fault, which in the following is called ‘inrush point’ (approx. coordinates:

27.477774, -26.361681; Fig. 3.8). Thus the above situation resembles an ultra-large pumping test, which allows the application of generalised analytical methods developed for pumping test analysis. Descriptions of these methods can, amongst others, be found in McWhorter and Sunada (1977) or Langguth and Voigt (2004).



**Fig. 3.8** East–west section through the Bank Compartment schematically showing the depression cone developed as a result of dewatering as well as positions of boreholes on ground surface

### 3.4.1 Selecting appropriate analytical methods for the Bank Compartment

The first analytical method for the evaluation of (transient) pumping test data was developed by Theis (1935) for an aquifer with very specific conditions, as listed in Table 3.2. Today a wide range of those analytical methods exist, each applying to very specific aquifer conditions. Table 3.2 lists the methods applied in this study including required aquifer conditions in relation to conditions found in the Bank Compartment.

Given the large scale of the karst aquifer investigated in this study, it was found appropriate to apply porous-media analytical methods. While applying simple analytical methods comes with a number of limitations, this was regarded as acceptable given that the study aims at a first evaluation of the aquifer rather than developing a comprehensive (numerical) model. Consequently, 3 different porous-media analytical methods were applied as well as the analytical software tool MLU for Windows (Hemker and Post, 2012).

**Table 3.2** Analytical methods used in this study related to aquifer conditions required. Specific adaptations made by the methods applied (deviating from the Theis method) are shaded grey

Setting	Method	Thiem, 1906	Theis, 1935	Stallman, 1962	MLU <sup>5</sup> Hemker and Post, 2012	Bank Compartment
Water table	Confined	x	x	x	x	x
	Unconfined	(x) <sup>1</sup>	(x) <sup>1</sup>	(x) <sup>1</sup>	x	x
	Leaky				x	
Aquifer type	Porous	x	x	x	x	x <sup>2</sup>
	Fractured				x	x <sup>2</sup>
	Karst					x <sup>2</sup>
Aquifer texture	Homogeneous	x	x	x	x	
	Heterogeneous					x
Pump. rate	Constant rate	x	x	x	x	x <sup>3</sup>
	Variable rate				x	x <sup>4</sup>
Flow to well	Transient		x	x	x	x
	Steady-state	x			x	x
Areal aquifer extent	Infinite	x	x		x	
	Boundary effects			x	x	x
Thickness	Uniform	x	x	x	x	
	Wedge-shaped					x
Isotropy	Isotropic	x	x	x	x	
	Anisotropic				(x)	x
Well radius	Small	x	x	x	x	not known
	Large diameter well				x	
Aquifer layer	Single layer	x	x	x	x	
	Multi-(two)-layer				x	x

<sup>1</sup> drawdown data from an unconfined aquifer can be adjusted to be analysed with this method

<sup>2</sup> the aquifer involve zones of porous rock as well as fractures and large solution conduits

<sup>3</sup> dataset 2 (inrush data)

<sup>4</sup> dataset 1 (dewatering data)

<sup>5</sup> Software tool that combines analytical solution techniques with numeric methods

Treating the aquifer like a homogeneous porous medium is based on the assumption that the large area considered here represents a representative elementary volume (REV). The REV is defined as the smallest volume over which microscopic fluctuating parameters can be statistically meaningfully described by averaged parameters representative of the whole (Bear, 1972), i.e., that over a certain volume an average hydraulic conductivity can be determined that adequately describes the flow discharged from the block, despite the fact that the microscopic (local) hydraulic conductivity fluctuates within the block (due to different porosity types, i.e., porous matrix, fracture and conduit porosity).

Even though the aquifer shows characteristics of all major aquifer types (porous, fractured and karst), analytical methods for double-porosity (for fractured rocks) were deliberately ignored since assumptions underlying those methods hardly comply with the complex geological setting found in the Bank Compartment. Moreover, the application of double porosity methods is more complex and often requires rather detailed hydrogeological information that is not always avail-

able. The unusual drawdown curves as well as the uncertainty associated with the gathering of the data – this refers, for example, to the constantly changing pumping rate, dewatering of fractures and the fact that measurements in boreholes only started some time after the abstraction of water commenced – render the application of double-porosity methods problematic (e.g., obtaining a unique fit of drawdown and type curves) and would even hamper the interpretation of results by adding further vagueness.

In order to reduce the interference by double-porosity effects, this study considers only observation boreholes with a large distance ( $>2\ 000$  m) from the inrush point. This is based on findings of Bourdet and Gringarten (1980), indicating that double-porosity effects are confined to a limited area surrounding the pumping well and can be neglected outside this area where drawdown is described by the type-curve of Theis. The above distance was determined from carefully observing drawdown data as well as preliminary calculations showing that boreholes closer to the inrush point are characterised by different drawdown behaviour.

For this particular case, a further advantage of porous-media analytical methods over double-porosity methods exists, as they allow for considering no-flow boundaries present in the aquifer (i.e. Bank Dyke). The analytical methods used in the study were that of Thiem (1906), Theis (1935) and Stallman (as quoted in Ferris et al., 1962) together with the software tool MLU (multi-layer unsteady state) for Windows (Hemker and Post, 2012).

The rather rigid requirements of the Theis methods are listed in Table 3.2. All other methods used here are, in essence, variations of the Theis method that try to overcome some of the limitations by introducing certain modifications. The Stallman method, for example, can be used if the depression cone reaches one or more aquifer boundaries, as is the case in the Bank Compartment (Fig. 3.4). The Thiem method, on the other hand, only applies to steady-state groundwater flow conditions in a pumped aquifer and is therefore limited to Dataset 3. MLU for Windows is a software tool for calculating drawdowns and analysing pumping test data. It combines an analytical solution technique with numeric applications (Stehfest's numerical method), the superposition principle and the Levenberg-Marquardt algorithm. Detailed information on the theoretical background is given by Hemker and Maas (1987) and Hemker (1999). Like other analytical methods, MLU assumes simplified aquifer conditions such as homogeneity, isotropy and the infinite horizontal extent of the aquifer (Carlson and Randall, 2012). However, despite making these assumptions MLU allows for analysing more complex aquifer conditions than the other methods applied in this study. For the case study at hand this is of particular importance as MLU is able to account for the variable pumping rate that affects the largest of the three datasets (Da-

taset 1, Fig. 3.6). All other analytical methods theoretically require at least a couple of drawdown observations during a period of stable pumping. MLU can also consider the influence of aquifer boundaries on the drawdown observations (as does the Stallman method) and thus considers the hydrogeologic setting more adequately, compared to the other methods used in this study.

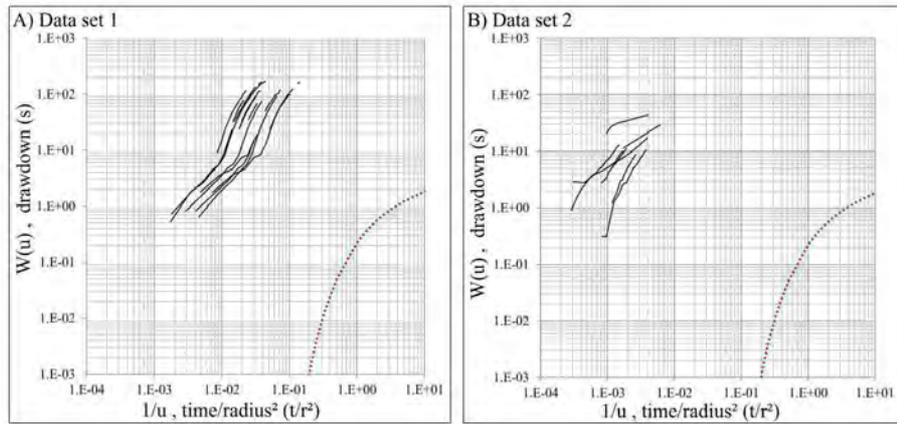
### **3.4.2 Application of the selected analytical methods**

Owing to the large drawdown observed in Datasets 1 and 3, the saturated thickness of the aquifer is significantly reduced, which creates unconfined (phreatic) water table conditions. However, the analytical methods applied require confined aquifer conditions. To overcome this obstacle the observed drawdown data had been adjusted by transferring values of observed drawdown ( $s$ ) into the so-called corrected drawdown ( $s'$ ) data using the method of Jacob (1963).

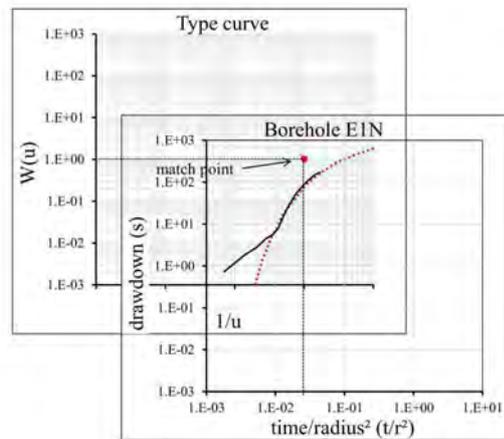
The analytical methods applied in this study are well-established standard methods for analysing pumping test data. Therefore the technical details are only briefly touched on. For more information the original literature may be consulted (e.g. Theis, 1935; Kruseman and De Ridder, 1991).

#### ***Theis method***

Drawdown curves of Datasets 1 and 2 as well as the Theis type curve are depicted in Fig. 3.9. Each data curve was brought to match with the type curve by shifting the curves parallel to the axes as illustrated in Fig. 3.10. Following the advice of Kruseman and De Ridder (1991), more weight was given to data gathered towards the end of the pumping test while matching both curves. According to the authors the late-time data (Dataset 1) would reflect the combined fracture and matrix system and can be described by the Theis equation. The curves at early times show a deviation of the data from the Theis model, which is likely to be due to the ignoring of double porosity effects. A match point was chosen, and corresponding values for  $W(u)$ ,  $1/u$ ,  $t/r^2$  and  $s$  were read from the axis. These values were inserted into the Theis equation ( $T = \frac{Q}{4\pi \cdot s} \cdot W(u)$  and  $S = \frac{4T \cdot t}{r^2} \cdot u$ ) in order to calculate the transmissivity ( $T$ ) and the storage coefficient ( $S$ ). The calculation also requires the pumping rate ( $Q$ ) at which the aquifer was pumped during the observed drawdown. In Dataset 1 the aquifer was pumped at a variable rate that cannot be accommodated in the Theis equation. Therefore an average pumping rate over the 24-month observation period had to be calculated (252 Mℓ/d). For Dataset 2 the pumping volume was 386 Mℓ/d.



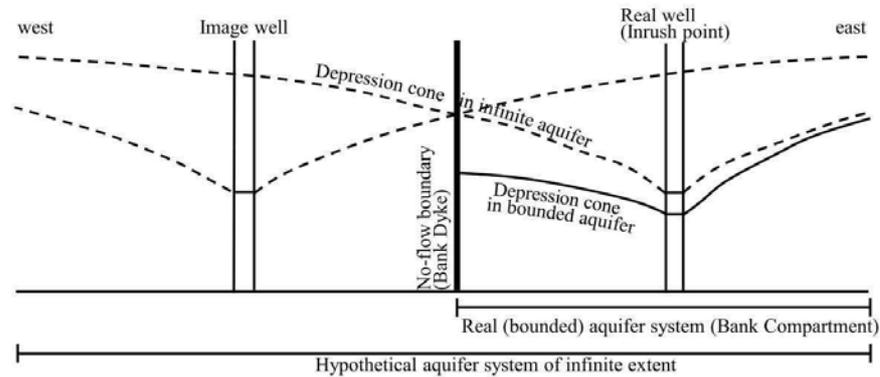
**Fig. 3.9** Diagrams showing data curves of drawdown (s) plotted against time/radius<sup>2</sup> ( $t/r^2$ ) ( $r$ =distance from the observation well to the pumping well) for Datasets 1 and 2. The red line represents the Theis type curve (dimensionless drawdown  $W(u)$  against the dimensionless time parameter  $1/u$ )



**Fig. 3.10** The drawdown curve of Borehole E1N (data curve) is brought to match with the Theis type curve (dotted line)

### ***Stallman method***

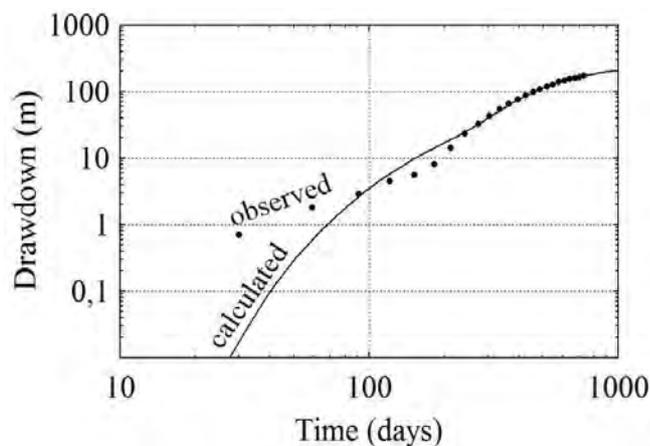
The Stallman method (first quoted in Ferris et al., 1962) is used in the case when a pumping test is conducted close to an aquifer boundary. In such cases the assumption of the Theis method, i.e., the infinite extent of the aquifer, is no longer valid and the drawdown in the observation boreholes will be different from the drawdown that would occur in an (seemingly) infinite aquifer. In order to account for the resulting difference, the Stallman solution uses modified type curves while still employing the principle of curve matching (superposition). The method is based on the theory of ‘image wells’ described by Ferris (1959). The theory replaces the bounded aquifer with one pumping well by assuming a hypothetical infinite aquifer that is pumped at 2 wells as explained for Fig. 3.11.



**Fig. 3.11** Section illustrating the theory of image wells for an aquifer with one no-flow boundary. Instead of a bounded aquifer system with 1 pumping well (real well) the theory assumes a hypothetical aquifer of infinite extent that is pumped at 2 wells (adapted from Ferris et al., 1962). It was decided to only consider the Bank Dyke as a no-flow boundary, and not the southern edge of the dolomite outcrop area as was done previously by Schwartz and Midgley (1975). This is mainly because drawdown contours in Fig. 3. 4 indicate that the southern edge did not truly act as a no-flow boundary since groundwater contours would otherwise intersect the boundary of outcropping dolomite at right angles

### **MLU for Windows**

As a third method, MLU for Windows was applied to Datasets 1 and 2. For detailed information on the mode of operation of MLU the reader is referred to the software manual (i.e., Hemker and Post, 2012). The aquifer was treated as a single-layered aquifer of 810 m thickness. Each observation borehole was evaluated separately. An image well was set in order to account for the Bank dyke as no-flow boundary. MLU requires initial estimates for transmissivity and the storage coefficient. For that purpose values calculated from the Theis method were used. MLU was set to estimate both parameters, i.e., transmissivity and the storage coefficient, simultaneously. In order to optimise both parameters, MLU calculates the drawdown curve that fits the observed drawdown curve the best. Figure 3.12 displays the curve of calculated and observed drawdown of Borehole E1N (Dataset 1) as an example.

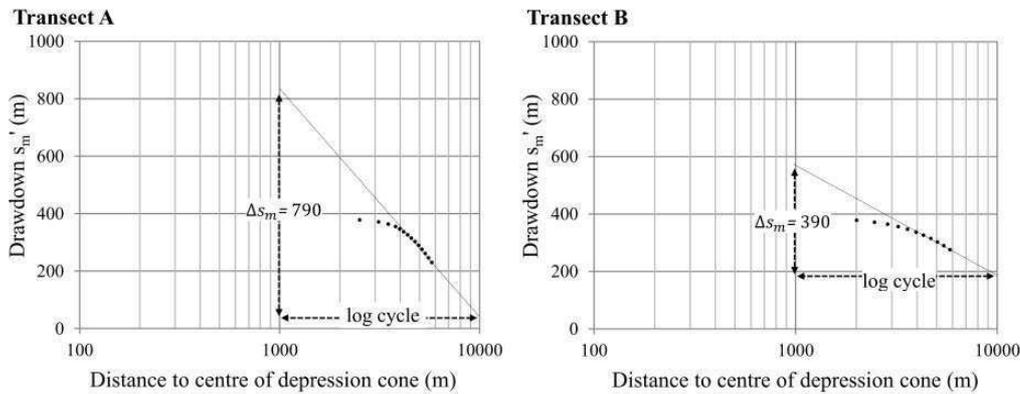


**Fig. 3.12** Observed and calculated drawdown for Borehole E1N (Dataset 1) as obtained from MLU

Similar results were obtained for other boreholes. Figure 3.12 shows a good fit of observed and calculated values except for early time drawdown, which shows that the aquifer behaviour at early times differs from the model presumed by MLU.

### ***Thiem method***

The Thiem (1906) method was used to evaluate Dataset 3. It uses values of maximum drawdown ( $s_m$ ) measured at different distances from the centre of the depression cone to calculate the transmissivity. The pumping rate that maintained the depression cone was 61 Ml/d. Measurements of maximum drawdown were made in 2 directions to representatively cover the aquifer (Transects A and B, Fig. 3.7). Obtained values of maximum drawdown are listed in the Appendix (Dataset 3). For both transects (A and B), values of corrected drawdown  $s_m'$  are plotted against the corresponding distance (log-scale) to the centre of the depression cone (Fig. 3.13).



**Fig. 3.13** Semi-logarithmic plots of the corrected maximum drawdown ( $s'_m$ ) against the distance to the centre of the depression cone. Black dots indicate data of corrected maximum drawdown ( $s'_m$ ) measured along Transects A and B in Fig. 3.7

Then the best-fitting linear regression line and the slope  $\Delta s_m$  (maximum drawdown difference per one logarithmic unit of distance) are determined. The deviation of the observed drawdown from the regression line shows that drawdown towards the centre of the depression cone differs from what the method predicts for a homogeneous and porous aquifer. A reason for this could be that a vertical flow component increasingly impacts on the drawdown with decreasing distance to the inrush point. Therefore the values close to the inrush point were ignored while adjusting the best-fitting linear regression line. Finally the Thiem equation ( $Q = \frac{2\pi * T}{2.30} * \Delta s_m$ ) is used to calculate the transmissivity. It is not possible to determine the storage coefficient from the Thiem method.

### 3.5 Results and Discussion

Values of transmissivity and storage coefficients as derived from the four analytical methods are listed in Table 3.3. Table 3.4 provides a condensed overview of the obtained  $T$ - and  $S$ -values for each analytical method and the associated dataset.

**Table 3.3** Transmissivity ( $T$ ) and the storage coefficient ( $S$ ) calculated from the drawdown measured in boreholes in the Bank Compartment. Listed are results for 4 different analytical methods that were applied to 3 datasets

Borehole	Distance to inrush point (m)	Dataset 1 (dewatering data)						Dataset 2 (inrush data)						Dataset 3
		Theis		MLU		Stallman		Theis		MLU		Stallman		Thiem
		$T$ (m <sup>2</sup> /d)	$S^*$	$T$ (m <sup>2</sup> /d)	$S^*$	$T$ (m <sup>2</sup> /d)	$S^*$	$T$ (m <sup>2</sup> /d)	$S$	$T$ (m <sup>2</sup> /d)	$S$	$T$ (m <sup>2</sup> /d)	$S$	$T$ (m <sup>2</sup> /d)
G449	5 547	37	0.0024	238	0.0063	60	0.0042							
G452	4 403	37	0.0038	272	0.0082	60	0.0062							
G455	2 426	58	0.0138	538	0.0330	78	0.0229							
G417	3 972	50	0.0054	287	0.0107	56	0.0072							
G416	5 201	41	0.0050	457	0.0073	54	0.0042							
G403	4 477	46	0.0042	316	0.0103	70	0.0067							
G501	5 054	60	0.0039	403	0.0093	110	0.0074							
G363	3 069	35	0.0070	174	0.0176	58	0.0124	2 721	0.0040	5418	0.0101	6 143	0.0091	
EIQ	4 979	48	0.0034	232	0.0070	74	0.0056	1 029	0.0028	2783	0.0057	3 072	0.0055	
UD8	2 420	48	0.0125	277	0.0238	66	0.0181	1 700	0.0037	3377	0.0070	3 195	0.0063	
UD7	3 829	38	0.0052	154	0.0098	58	0.0076	618	0.0051	1216	0.0094	1 112	0.0082	
EIN	4 882	52	0.0037	259	0.0069	78	0.0062	737	0.0032	1434	0.0058	1 720	0.0064	
UD5	2 989	55	0.0087	366	0.0189	70	0.0129	2 104	0.0006	4207	0.0015	4 608	0.0010	
EIM	3 231	175	0.0195	241	0.0178	221	0.0262	969	0.0079	1818	0.0133	1 812	0.0132	
EIA	3 031							1 066	0.0083	2027	0.0136	2 119	0.0138	
Transect A														28
Transect B														57
Geo mean		<b>50</b>	<b>0.0058</b>	<b>285</b>	<b>0.0117</b>	<b>73</b>	<b>0.0088</b>	<b>1 214</b>	<b>0.0036</b>	<b>2 468</b>	<b>0.0070</b>	<b>2 593</b>	<b>0.0065</b>	<b>40</b>
Min		35	0.0024	154	0.0063	54	0.0042	618	0.001	1 216	0.0015	1 112	0.0010	
Max		175	0.0195	538	0.0330	221	0.0262	2 721	0.008	5 418	0.0136	6 143	0.0138	
Relative SD		63%	70%	36%	59%	54%	67%	56%	57%	54%	51%	58%	52%	
n		14	14	14	14	14	14	8	8	8	8	8	8	2

\* $S^*$  = storage coefficient derived from the corrected drawdown  $s'$

Values of transmissivity of individual boreholes show a high variability (relative standard deviation (SD) around 50%), which one would expect for a karstified aquifer. This indicates that the REV-concept is only applicable to a certain degree as expanding the investigated area (or adding additional observation boreholes) could significantly change the obtained average value. On the other hand, the fluctuations are small enough for deriving an order of magnitude for the transmissivity.

Sizable differences also exist between the results of the various analytical methods within a particular dataset. For Dataset 1, transmissivities from the Theis and Stallman method are significantly lower than those for MLU. This difference is most probably attributable to the fact that

both analytical methods (Theis and Stallman) do not consider the variable pumping rate, which affects Dataset 1 (Fig. 3.6). In contrast, in Dataset 2 the aquifer was pumped at a stable rate. Hence, values for the Stallman method differ only slightly from MLU. However, the average transmissivity received by the Theis method is still considerably below that of MLU. This is because MLU considers the influence of the no-flow boundary, i.e., the Bank Dyke, which the Theis method does not. Therefore, it is believed that for Dataset 1 MLU yields the most reliable results, while for Dataset 2 this is true for MLU and the Stallman method.

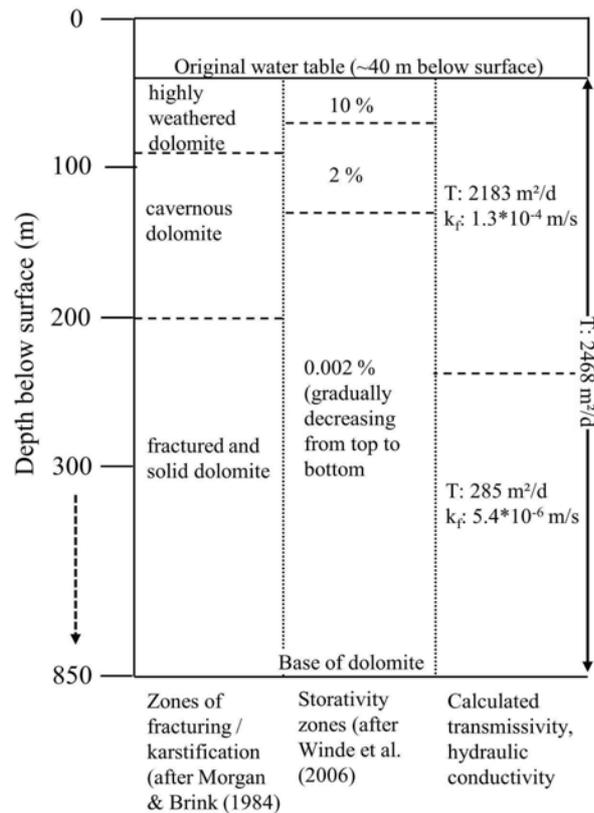
**Table 3.4** Comparison between *T*- and *S*-values calculated for the dolomitic karst aquifer in the Bank Compartment based on 3 different datasets and 4 different analytical methods

Dataset: (no), type, (no. of WL data, observed karst zone (mbs))	Transmissivity (T) (m <sup>2</sup> /s) Geometric mean (min-max)				Storage (S) (%) Geometric mean (min-max)		
	Theis	Stallman	MLU	Thiem	Theis	Stallman	MLU
(1) Active dewatering 1969-71 (n=161, 194-863)	50 (35-175)	73 (54-221)	285 (154-538)	-----	0.58 (0.24-1.95)	0.88 (0.42-2.62)	1.12 (0.63-3.30)
(2) Inrush Oct. 1968 (n= 8; 53-863)	1214 (618-2721)	2593 (1112-6143)	2468 (1216-5418)	-----	0.36 (0.1-0.8)	0.65 (0.1-1.38)	0.70 (0.15-1.36)
(3) Steady state pumping June 1996 (n= 25, 600-863)	-----	-----	-----	40 (28-57)	-----	-----	-----
All data	50-1214 (35-2721)	73-2593 (54-6143)	285-2468 (128-5418)	40 (28-57)	0.36-0.58 (0.1-1.95)	0.65-0.88 (0.1-2.62)	0.70-1.12 (0.15-3.18)
Limitations of applied solution (see also Tab. 3.2)	a, b	a		b	a, b	b	

*a* – does not consider variable pumping rate

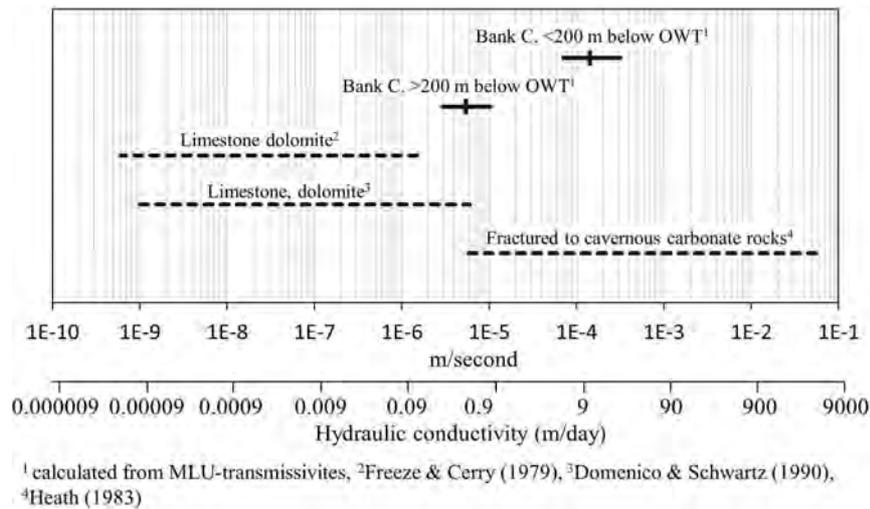
*b* – does not consider flow boundary effects

Results of transmissivity derived from inrush data (2 468 m<sup>2</sup>/d) are, on average, one order of magnitude higher than the dewatering data (285 m<sup>2</sup>/d). One possible explanation for this significant difference is that the two datasets represent very different thicknesses of water-filled (saturated) dolomite. The much higher *T*-value (2 468 m<sup>2</sup>/d) was derived from the completely water-filled aquifer, with all vertical zones of the dolomite being saturated (Fig. 3.3). In contrast, the 10-times lower transmissivity (285 m<sup>2</sup>/d) only represents the aquifer after the upper ~200 m below the OWT have already been dewatered. Therefore this value reflects only the zone of 'fractured and solid dolomite' and does not consider the highly transmissive zone above it. In principle this is also true for the transmissivity obtained from the Thiem method. But since the latter does not take into account the no-flow boundary it is not considered in the following interpretation. Figure 3.14 summarises the calculated average values of hydraulic conductivity in relation to corresponding zones of karstification and storativity. Values of hydraulic conductivity calculated for individual boreholes range from 7.0\*10<sup>-5</sup> to 3.1\*10<sup>-4</sup> m/s for the upper 200 m. For greater depths, values range from 2.9\*10<sup>-6</sup> to 1.0\*10<sup>-5</sup> m/s (Table 3.3).



**Fig. 3.14** Calculated values for transmissivity ( $T$ ) and hydraulic conductivity ( $k_f$ ) in relation to previously identified vertical zones of karstification and porosity

Figure 3.15 displays ranges of hydraulic conductivity in relation to values found in literature for similar aquifers. It can be seen that values from  $>200$  m below the OWT concur with weakly fractured to solid dolomite. Values from above 200 m comply with moderately fractured to cavernous carbonate rocks. Thus values are in general agreement with what one would expect for the respective zones. The transmissivity of 2 468 m<sup>2</sup>/d calculated in this study is consistent with the value of 2 983 m<sup>2</sup>/d that Enslin and Kriel (1959) obtained for the similar nearby compartments (using an unspecified method), and the value of 1 818 m<sup>2</sup>/d that Bredenkamp (1991) obtained for the nearby Gemsbokfontein Compartment using the double-porosity model of Boulton and Streltsova (1977). Thus indications are that results of MLU and the Stallman method (in Dataset 2) have a realistic order of magnitude. To a certain degree this supports the argument that realistic results can be obtained from applying porous-media analytical methods to non-porous aquifers, provided the spatial scale of investigation is large enough (i.e., not considering a single karst channel or fracture, for example, but a large network of inter-connected conduits with varying transmissivities). This, however, should not be seen as proof that those methods are in general applicable to all karst aquifers, given the deviation between the theoretical model of porous-media methods and the actual hydrogeologic situation as discussed in the section above.



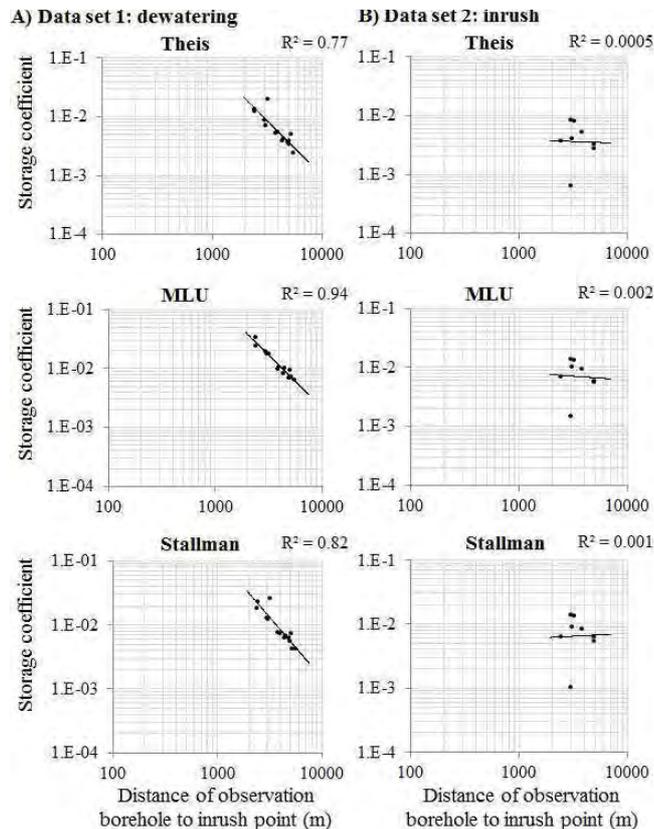
**Fig. 3.15** Values of hydraulic conductivity for carbonate and karstified rock types. Also shown are values of hydraulic conductivity calculated for different depths of the Bank Compartment. Vertical bars represent average values

Less reliable, however, are the calculated storage coefficients. Not much weight at all should be given to the storage coefficients obtained from Dataset 1 as these values display a so-called ‘distance-dependency’, as illustrated in double-logarithmic plots (Fig. 3.16). The plots show that the storage coefficient of individual boreholes increases with decreasing distance of the borehole to the pumping well (here: inrush point). This phenomenon was first recognised in South Africa by Bredenkamp et al. (1991), applying different analytical methods to a similar dolomitic aquifer. Later the same distance-dependency of storativity values was found in numerous fractured and karst aquifers throughout South Africa (Kirchner and Van Tonder, 1995). A possible explanation provided in literature is related to the concept of double-porosity. Porous-media analytical methods do not consider that the groundwater flow in fractured/karst aquifers is governed by different pressure gradients that develop between large fractures/conduits and the pore-matrix/small fractures during drawdown.

The generated pressure gradients are larger in close proximity to the pumping well and decrease with increasing distance, possibly explaining the distance-dependency of the associated storage coefficients (Neuman, 1994, personal communication quoted in Kirchner and Van Tonder, 1995). The problem of distance-dependency, however, is not restricted to porous-media analytical methods, as Van Tonder et al. (2002) showed that it also appears when applying double-porosity analytical methods that claim to account for the very double-porosity effects that are thought to cause the dependency.

For some reason the distance-dependency of the storage coefficient does not appear in values for Dataset 2 (Fig. 3.16), which warrants an interpretation. An average value of 0.0067 is derived

from MLU and the Stallman method. This equals a storativity of 0.67% (uniform over the entire thickness). Values of storativity for different zones quoted in Fig. 3.14 average to 0.5% if the dolomite is treated like a homogenous unit. Thus the value derived from MLU and Stallman is in the same order of magnitude as previous estimates even though it does not consider vertical changes in storativity.



**Fig. 3.16** Log-log plots of the storage coefficient of selected observation boreholes against distance of the observation borehole to the intrush point (for Datasets 1 and 2)

Estimating the total volume of water stored in the dolomite of the Bank Compartment based on a porosity of 0.67% results in some 923 Mm<sup>3</sup>. (For this estimation the dolomite aquifer was assumed to extend approx. 1 070 m south of the southern border of the dolomite outcrop area, where the Pretoria Group rocks (dipping approx. 8°) reach a thickness of 150 m. This results in an areal extent of some 170 Mm<sup>2</sup>. The average depth of the dolomite was assumed to be 810 m. By this means the volume of the dolomite was estimated at  $1.38 \cdot 10^{+11}$  m<sup>3</sup>.) This falls between previous estimates for the Bank Compartment ranging from 663 Mm<sup>3</sup> (following from Winde et al., 2006) to 2 200 Mm<sup>3</sup> (Schwarz and Midgley, 1975), with Brink (1975) suggesting that the latter value probably represents an overestimation.

### 3.6 Summary and Conclusions

In the course of several decades of deep-level gold mining in the FWR, significant amounts of hydrogeological data were gathered relating to accidental as well as deliberate draining of a large overlying and highly karstified dolomitic aquifer. Given the uniqueness of the situation, where an over 800 m-thick aquifer was dewatered literally by ‘pulling the plug’ at its very bottom – something only possible for deep-level mining operations – and the spatial and temporal scale of related events, it was deemed to be of scientific importance to preserve the associated data and prevent their irretrievable loss through diligent compilation in a dedicated database where they are available to scientists for further evaluation.

In total, 3 different datasets are analysed, all consisting of weekly to monthly groundwater-level measurements and associated daily pumping volumes that were generated during an accidental inrush event into the deep-level mine void and the subsequent dewatering of the overlying karst aquifer over the next 40+ years.

This paper is a first-ever attempt to use these data for characterising the hydraulic properties of the drained Bank aquifer, hoping that the unique situation and extreme scale of the associated events will provide new aspects for understanding the still challenging hydrology of karst aquifers in South Africa and perhaps even worldwide. In applying the analogy of a pumping test, the 3 datasets were analysed by 4 porous-media-based analytical methods, differing mainly in the degree to which they are able to account for local conditions. The obtained results are generally in good agreement with each other (exceptions are explained) as well as with previous estimates for the study area and values reported in general literature for similar rocks types. This is interpreted as confirming earlier suggestions that porous-medium analytical methods can indeed be applied to karst aquifers provided the spatial scale of investigation is large enough.

The study also shows that the accuracy of the obtained values was less affected by the fact that the applied analytical methods were actually developed for porous media and more by the degree to which the various requirements of the applied methods (such as constant pumping rates, no-flow boundaries, etc.) were met. Not surprisingly, MLU, as the one method that took most of the local peculiarities into account, yielded the best-fitting results for the largest of the three datasets.

The most pronounced limitations of the applied methods came from the fact that they all ignored vertical variations in permeability of the dolomite. This was revealed by comparing 2 different datasets pertaining to different vertical zones of the dolomitic column. The fact that the highly permeable zones in the dolomite were covered in one dataset, but not in the other, resulted in the

respective transmissivity values differing by an order of magnitude. This, in turn, allowed for the first time quantification of the transmissivity of the different vertical zones of the dolomite in the Bank Compartment.

While obtained storage coefficients are generally less reliable than transmissivity values, their application yielded reasonable storage volumes that compare favourably with existing data and earlier estimates. However, no satisfactory explanation could be found why distance-dependency of the storage coefficients was observed in one dataset but not in the other. Thus storage values are to be interpreted cautiously.

Based on the obtained parameters, it is envisaged to investigate the effects that mining through dykes below the dolomite has on the future elevation of the recovered water table after mining and the associated dewatering ceases in the area. Given the large costs currently incurred by implementing emergency measures to address effects of haphazard mine closure in the East, Central and West Rand, a more pro-active and coordinated approach to mine closure in the FWR, as the most water-rich of all goldfields in South Africa, is deemed to be imperative.

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### 3.7 References

- ANONYMOUS (2005) Salute this special mine. *Ngonyama News* (27) October 2005, 4-5.
- BEAR J (1972) *Dynamics of fluids in porous media*. American Elsevier, New York. 764 pp.
- BOULTON NS and STELTSOVA TD (1977) Unsteady flow to a pumped well in a fissured water-bearing formation. *J. Hydrol.* **35** (3-4) 257-270.
- BOURDET D and GRINGARTEN AC (1980) Determination of fissure volume and block size in fractured reservoirs by type-curve analysis. Paper SPE 9293 presented at the 1980 SPE Annual Fall Technical Conference and Exhibition, Dallas. 20 pp.
- BREDENKAMP DB, FAYAZI M and BOTHA LJ (1991) Interpretation of pumping test in the Gemsbokfontein East Compartment – A typical heterogeneous karst system. DWAF Technical Report No. GH 3727. Department of Water Affairs and Forestry, Directorate of Geohydrology, Pretoria (unpublished). 13 pp.
- BRINK ABA (1975) Discussion on evaluation of geohydrological constants for the Far West Rand dolomitic formations, by H. I. Schwartz and D. C. Midgley. *Trans. S. Afr. Inst. Civ. Eng.* **17** 178-180.
- BRINK ABA (1979) *Engineering Geology of South Africa, Vol. 1*. Building Publications, Pretoria. 319 pp.
- CARLSON F and RANDALL J (2012) MLU: A Windows application for the analysis of aquifer tests and the design of well fields in layered systems. *Ground Water* **50** (4) 504-510.
- CARTWRIGHT AP (1969) *West Driefontein – Ordeal by Water*. Gold Fields of South Africa Ltd., JG Ince & Son Ltd., Johannesburg. 83 pp.

- COUSENS RRM and GARRETT WS (1969) The flooding at the West Driefontein Mine. *J. S. Afr. Inst. Min. Met.* **69** (9) 421–463.
- DE KOCK WP (1964) The geology and economic significance of the West Wits Line. In: Houghton SH (ed.) *The Geology of Some Ore Deposits in Southern Africa, Vol. 1*. The Geological Society of South Africa, Johannesburg. 323–386.
- DWA (DEPARTMENT OF WATER AFFAIRS) (2014) National Groundwater Archive of South Africa. URL: <http://www3.dwa.gov.za/NGANet/Security/WebLoginForm.aspx> (Accessed 13 February 2014).
- DOMENICO PA and SCHWARTZ FW (1990) *Physical and Chemical Hydrogeology*. John Wiley & Sons, New York. 824 pp.
- ELS BG (1987) The auriferous Middelvlei Reef depositional system, West Wits Line, Witwatersrand Supergroup. Ph.D. thesis, Rand Afrikaans University, Johannesburg. 658 pp.
- ELS BG (2000) Unconformities of the auriferous, Neoproterozoic Central Rand Group of South Africa: application to stratigraphy. *J. Afr. Earth Sci.* **30** (1) 47–62.
- ENSLIN JF and KRIEL JP (1959) Some results obtained from a hydrological study of a dolomitic catchment area in the Transvaal, Union of South Africa. DWA Technical Report No. GH 3727. Department of Water Affairs, Division of Hydrological Research, Pretoria (unpublished). 16 pp.
- ENSLIN JF and KRIEL JP (1968): The assessment and possible future use of the dolomitic ground water resources of the Far West Rand, Transvaal, Republic of South Africa. *International Conference on Water for Peace*, Washington. 908–918.
- ENSLIN JF, KLEYWEGT RJ, BEUKES JHT and GORDON-WELSH JF (1977) Artificial recharge of dolomitic ground-water compartments in the Far West Rand Gold Fields of South Africa. *Proceedings of the Second International Symposium on Land Subsidence*, Anaheim, California. *IAHS Publ.* **121** 495–506.
- FERRIS JG (1959) Ground water, Chapter 7. In: Wisler CO and Brater EF (ed.) *Hydrology*. John Wiley & Sons, New York. 198–272.
- FERRIS JG, KNOWLES DB, BROWN RH and STALLMAN RW (1962) Theory of aquifer tests. U.S. Geological Survey Water-Supply Paper 1536-E. United States Government Printing Office, Washington. 174 pp.
- FREEZE RA and CHERRY JA (1979) *Groundwater*. Prentice-Hall, Englewood Cliffs. 604 pp.
- GEOLOGICAL SURVEY OF SOUTH AFRICA (undated) *Drawdown contour map, 15 May 1971*. Geological Survey of South Africa, Pretoria (unpublished).
- GOLD FIELDS (2009) Driefontein Gold Mine technical short form report. Gold Fields Ltd. 11 pp. URL: [https://www.goldfields.co.za/reports/rr\\_2009/pdfs/Driefontein.pdf](https://www.goldfields.co.za/reports/rr_2009/pdfs/Driefontein.pdf) (Accessed 28 March 2011)
- HARMONY GOLD MINING COMPANY (2010) Harmony Annual Report 2010. Harmony Gold Mining Company Ltd. 364 pp. URL: [http://www.harmony.co.za/assets/investors/reporting/annual-reports/2010/f/HAR\\_AR2010.pdf](http://www.harmony.co.za/assets/investors/reporting/annual-reports/2010/f/HAR_AR2010.pdf) (Accessed 18 April 2013)
- HEATH RC (1983) Basic ground-water hydrology. U.S. Geological Survey Water-Supply Paper 2220. United States Government Printing Office, Washington. 83 pp.
- HEMKER CJ and MAAS C (1987) Unsteady flow to wells in layered and fissured aquifer systems. *J. Hydrol.* **90** (3–4) 231–249.
- HEMKER CJ (1999) Transient well flow in layered aquifer systems: the uniform well-face drawdown solution. *J. Hydrol.* **225** (1–2) 19–44.
- HEMKER K and POST V (2012) MLU for Windows. Well flow modeling in multilayer aquifer systems. Amsterdam. 30 pp. URL: [www.microfem.com/download/mlu-user.pdf](http://www.microfem.com/download/mlu-user.pdf) (Accessed 13 February 2014).
- JACOB CE (1963) Determining the permeability of water-table aquifers. In: Bentall R (ed.) *Methods of Determining Permeability, Transmissibility and Drawdown*. U.S. Geological Survey Water-Supply Paper 1536-I. United States Government Printing Office, Washington, 245–271.

- JORDAAN JM, ENSLIN JF, KRIEL J, HAVEMANN A, KENT LE and CABLE WH (1960) Final report of the Interdepartmental Committee on Dolomitic Mine Water: Far West Rand. Department of Water Affairs and Forestry, Pretoria (unpublished). 38 pp.
- KIRCHNER J, and VAN TONDER GJ (1995) Proposed guidelines for the execution, evaluation and interpretation of pumping tests in fractured-rock formations. *Water SA* **21** (3) 187–200.
- KRUSEMAN GP and DE RIDDER NA (1991) Analysis and Evaluation of Pumping Test Data. ILRI Publ. 47. International Institute for Land Reclamation and Improvement, Wageningen. 377 pp.
- LANGGUTH RH and VOIGT R (2004) *Hydrogeologische Methoden*. Springer, Berlin, Heidelberg. 1005 pp.
- McWHORTER DB and SUNADA DK (1977) *Ground Water Hydrology and Hydraulics*. Water Resources Publication, Littleton, Colorado. 290 pp.
- MORGAN DJT and BRINK ABA (1984) The Far West Rand dolomites. *Proc. Int. Conf. Groundwater Technology*, 1984, Johannesburg, South Africa. National Water Well Association, Worthington, Ohio. 554–573.
- SCHWARTZ HI and MIDGLEY DC (1975) Evaluation of geo-hydrologic constants for the Far West Rand dolomitic formations. *Civ. Eng. S. Afr.* **17** (2) 31–36.
- STOCH EJ and WINDE F (2010) Threats and opportunities for post-closure development in dolomitic gold mining areas of the West Rand and Far West Rand (South Africa) – a hydraulic view. Part 3: Planning and uncertainty – lessons from history. *Water SA* **36** (1) 83–88.
- SWART CJU, JAMES AR, KLEYWEGT RJ and STOCH EJ (2003) The future of the dolomitic springs after mine closure on the Far West Rand, Gauteng, RSA. *Environ. Geol.* **44** (7) 751–770.
- SWART CJU, STOCH EJ, VAN JAARSVELD CF and BRINK ABA (2003a) The lower Wonderfontein Spruit: an exposé. *Environ. Geol.* **43** (6) 635–653.
- THEIS CV (1935) The relation between the lowering of the piezometric surface and the rate and duration of discharge of a well using ground-water storage. *Trans. Am. Geophys. Union* **16** (2) 519–524.
- THIEM G (1906) *Hydrologische Methoden*. Gebhardt, Leipzig. 56 pp.
- VAN TONDER G, BARDENHAGEN I, RIEMANN K, VAN BOSCH J, DZANGA P and XU Y (2002) Manual on pumping test analysis in fractured-rock aquifers. WRC Report No. 1116/1/02. Water Research Commission, Pretoria. 157 pp.
- WINDE F, STOCH EJ and ERASMUS E (2006) Identification and quantification of water ingress into mine voids of the West Rand and Far West Rand Goldfields (Witwatersrand basin) with a view to long-term sustainable reduction thereof. Final report, Project No. 5512, Council for Geoscience, Pretoria (unpublished). 261 pp.
- WOLMARANS JF (1982) *The Least Unsafe Route, Vol. 1*. Webb and Partners, Carletonville. 83 pp.

## Appendix

**DATASET 1**

**Drawdown (in meter below OWT) in boreholes in the Bank Compartment from August 1969 to July**

	G449	G452	G455	G417	G416	G403	G501	G363	E1Q	UD8	UD7	E1N	UD5	E1M	Total sum
long.	27.4999	27.5209	27.4669	27.5083	27.5138	27.4962	27.4952	27.4917	27.5165	27.4915	27.5096	27.5252	27.4833	27.5086	
lat.	26.3158	26.3531	26.3813	26.3384	26.3274	26.3247	26.3189	26.3370	26.3334	26.3797	26.3813	26.3723	26.3882	26.3708	
Date	Draw-down (m)*														
27.08.1969								0.6	0.5	1.8	0.8	0.7	1.8	0.8	
25.09.1969								1.7	1.8	3.6	1.8	1.8	3.6	1.8	
27.10.1969								2.8	2.6	4.7	3.0	2.9	4.7	2.9	
26.11.1969								4.2	4.0	7.4	4.6	4.5	7.4	4.5	
27.12.1969								5.5	5.4	8.4	5.7	5.6	8.4	5.6	
27.01.1970	9.1							8.7	8.2	12.9	8.5	8.2	14.8	8.4	
25.02.1970	14.5		24.3					15.2	14.3	22.4	14.3	14.4		14.0	
28.03.1970	25.2	24.2	36.9					24.8	23.7	36.3	23.4	23.5		19.2	
28.04.1970	36.3	34.6	49.9	36.1	33.0	33.8	32.9	35.6		49.8	33.1	33.3	51.7		
28.05.1970	48.0	45.9	64.3	47.7	43.9	44.5	42.4	47.2		65.7	43.7	44.3	66.4		
27.06.1970	59.6	56.1	75.1	58.5	58.0	55.8	53.4	58.0		78.9	55.1	56.4	78.3		
28.07.1970	72.1	70.9	88.0	71.7	69.9	67.4	63.1	71.7	69.5	93.7	67.0	68.4	92.5		
27.08.1970	84.0	82.4	100.4		81.5	79.7	71.9	83.9	81.7	107.1	77.6	79.0	105.9		
26.09.1970	96.8	93.9	104.7			90.5	80.5	96.8	94.3	120.3		91.5	108.6		
27.10.1970	111.0				104.1	102.6	89.4		107.4	133.6		103.5	129.0		
26.11.1970	124.5					121.3	105.6		120.4			116.0			
28.12.1970						121.3	111.3		135.1			127.8			
27.01.1971									147.9	174.5		139.0			
25.02.1971										188.0		152.6			
27.03.1971									169.0			163.1			
28.04.1971									179.5			173.4			
28.05.1971									187.5			181.4			
28.06.1971												186.2			
28.07.1971												194.2			
n	11	7	8	4	6	9	9	14	18	17	13	24	13	8	161

\*Drawdown in meter below original water table

DATASET 2									
Drawdown (m) in boreholes in the Bank Compartment during the accidental inrush event from October 26 - November 23, 1968 (from Schwartz and Midgley, 1975)									
	G363	E1Q	UD8	UD7	E1N	UD5	E1M	E1A	Total sum
long.	27.4917	27.5165	27.4915	27.5096	27.5252	27.4833	27.5086	27.5082	
lat.	26.3370	26.3334	26.3797	26.3813	26.3723	26.3882	26.3708	26.3600	
Date	Draw-down (m)*								
26.10.1968	-1.52								
27.10.1968									
28.10.1968	1.34								
29.10.1968	1.26								
30.10.1968	2.26								
31.10.1968	2.75	0.91					-0.61		
01.11.1968	3.30	1.52				20.73	-0.30	2.74	
02.11.1968	3.83	2.13	11.28			27.43	-0.30	3.05	
03.11.1968	4.54							3.35	
04.11.1968	4.99					32.00	0.61	4.27	
05.11.1968	5.55	3.66				32.92	0.91		
06.11.1968	6.04	3.96				33.83	1.22	5.18	
07.11.1968	6.61	4.27		1.22		34.75	1.83	5.79	
08.11.1968	7.19	4.88		1.52		35.66	2.13	6.10	
09.11.1968	7.78	5.18		1.83		36.58	2.13	6.71	
10.11.1968								7.32	
11.11.1968	8.96	6.40		3.05		38.10	3.35	7.92	
12.11.1968	9.62	7.01		3.05		39.01	3.96		
13.11.1968	10.24	7.32		3.81		39.93	4.57	9.30	
14.11.1968	10.67	7.92		4.27	4.88	40.54	4.88	9.91	
15.11.1968	11.52	8.84		4.88	5.49	41.15	5.33	10.67	
16.11.1968		9.45		5.33	6.10	41.76	5.94	11.13	
17.11.1968									
18.11.1968	13.72	10.97		6.55	7.32	42.98	7.16		
19.11.1968	14.25	11.73	28.80	7.16	7.92	42.98	7.62		
20.11.1968	15.29	12.50	28.96	7.62	8.38	43.59	8.38		
21.11.1968	15.85	12.80		8.23	9.30		9.14		
22.11.1968				8.23	9.60		9.60		
23.11.1968				8.69	9.91		9.91		
n	23	18	3	15	9	17	21	14	120

\*Drawdown in meter below elevation of Bank Eye (1 502 meter above mean sea level)

<b>DATASET 3</b>						
Values of maximum drawdown ( $s_m$ ) and corrected maximum drawdown ( $s_m'$ ) in different distances from the centre of the depression cone in June 1996 (determined by intersected groundwater levels by transects A and B respectively as indicated in Figure 3.7)						
	Transect A			Transect B		
	distance to centre of depression cone (m)	maximum draw-down $s_m$ (m)	corrected maximum drawdown $s_m'$ (m)	distance to centre of depression cone (m)	maximum draw-down $s_m$ (m)	corrected maximum drawdown $s_m'$ (m)
	2511	603	379	2009	603	379
	3123	578	372	2463	578	372
	3485	553	364	2863	553	364
	3793	528	356	3230	528	356
	3984	503	347	3587	503	347
	4169	478	337	3954	478	337
	4355	453	326	4311	453	326
	4548	428	315	4678	428	315
	4748	403	303	5045	403	303
	4943	378	290	5434	378	290
	5136	353	276	5823	353	276
	5337	328	262			
	5547	303	246			
	5764	278	230			
n	14	14	14	11	11	11

## **4 Using impacts of deep-level mining to research karst hydrology—a Darcy-based approach to predict the future of dried-up dolomitic springs in the Far West Rand goldfield (South Africa). Part 1: a conceptual model of recharge and inter-compartmental flow**

Aljoscha Schrader<sup>1</sup>, Frank Winde<sup>2</sup>, Ewald Erasmus<sup>2</sup>

<sup>1</sup> Faculty of Natural Sciences, North-West University, Potchefstroom, South Africa, <sup>2</sup> Mine Water Re-Search Group, North-West University, Vanderbijlpark, South Africa

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**Abstract** Some of the world’s deepest goldmines are located in the Far West Rand (FWR) goldfield operating below of up to 1.2-km-thick dolomites hosting some of the largest karst aquifers in South Africa. Associated impacts include the dewatering of the overlying karst aquifers as well as linking previously disconnected compartments by mining through aquicludes (dykes). The focus of the study is on predicting groundwater balances in re-watered aquifers after mining ceases as this will determine whether or not associated karst springs that dried-up due to dewatering will ever flow again. Critically revisiting, Swart et al. (*Environ Geol* 44:751–770, 2003a) who predict that all springs will flow again, this study uses significantly larger data sets and modified assumptions to increase the robustness of findings as the question is crucial for post-closure development. As a first of two papers, this part develops a conceptual model on the mega-compartment concept that predicts a flat water table across all linked compartments that would leave the springs dry. The model identifies the ratio between inflowing surface water (recharge) and underground water losses to downstream compartments via mined-through dykes (‘inter-compartmental groundwater flow’, IGF) as a key factor governing the elevation of the post-mining water table, creating the base for part 2, where the IGF and the post-mining water tables are determined using unique large data sets that have not been evaluated before.

**Keywords** *Dolomitic compartments, Dewatering, Mega-compartment concept, Re-watering, Post-mining spring flow*

## 4.1 Introduction

Karst aquifers are amongst the richest groundwater resources worldwide often displaying a complex hydrology that frequently defies simple applications of known groundwater models. Despite their importance, especially for semi-arid countries such as South Africa, karst aquifers are often difficult to manage and methods adequately describing their hydrology are still scarce. This, in many respects, also applies to the dolomite aquifer system of the Far West Rand (FWR), a gold mining area in South Africa.

Storing an estimated volume of some 3,390 mega cubic metres (Mm<sup>3</sup>) groundwater (Schwartz and Midgley 1975; Vegter 1984), the karstified dolomites represent one of the country's largest aquifers. Nonetheless, crucial parts of its hydrology, heavily affected by deep-level gold mining, are still not fully understood despite pertinent research spanning more than six decades. As a result, the aquifer was poorly managed ever since mining started in the beginning of the last century. Authorities granted mines permission to partly dewater the aquifer shortly after the mining commenced to secure mining operations below the aquifer causing a range of adverse consequences, such as extensive ground instability in the form of sinkholes and dolines and the drying up of high-yielding karst springs (Swart et al. 2003b).

Most important in the context of this paper, is the fact that the generated mine void below the dolomite soon physically connected formerly separated so-called 'groundwater compartments'. This connection will become hydraulically relevant after the mines reach the end of their life span and the aquifer will fill-up with groundwater again in a few decades from now. It was predicted that, as a result of such hydraulic links, the formerly separated compartments would be merged into a 'mega-compartment' whose water table would remain well below its original level (nearly 100 m below in some compartments) leaving the high-yielding karst springs that dried-up due to dewatering dry forever. This, in turn, will have severe implications for post-mining water availability and land-use options as well as for natural ecosystems as these springs originally contributed to the flow of a major perennial stream, the Wonderfonteinsspruit (Jordaan et al. 1960; Usher and Scott 2001).

The final elevation of the water table after the re-watering (flooding) of the drained (dewatered) karst aquifers will also determine if and where potentially acidic and toxic mine water may decant on surface (Usher and Scott 2001). This process, known as acid mine drainage (AMD), currently poses large problems in several abandoned mining areas in South Africa including the central business district area of Johannesburg (Winde et al. 2011).

Given the importance of reliably predicting the final water table elevation for developing sustainable land-use concepts and aquifer management strategies after mine closure, this study investigates the question whether a mega-compartment is going to form once the mining ceases. A first approach to this question was provided by Swart et al. (2003a), who presented a conceptual model, which identified the inter-compartmental groundwater flow on mine void level (IGF) and the corresponding groundwater recharge of each compartment as key factors for the possible formation of a mega-compartment. However, the study largely lacks reliable quantitative estimates for both the IGF and the post-mine closure groundwater recharge. It is a main objective of this paper to fill these gaps by providing an improved conceptual model on the basis of which the second part of the series quantifies the two abovementioned key factors. For this purpose, a historic water balance of the FWR is proposed and subsequently used to derive an improved conceptual model for the current groundwater recharge. Based on this, semi-quantitative estimates for recharge rates are derived for different post-mining scenarios when compartments will be re-watered.

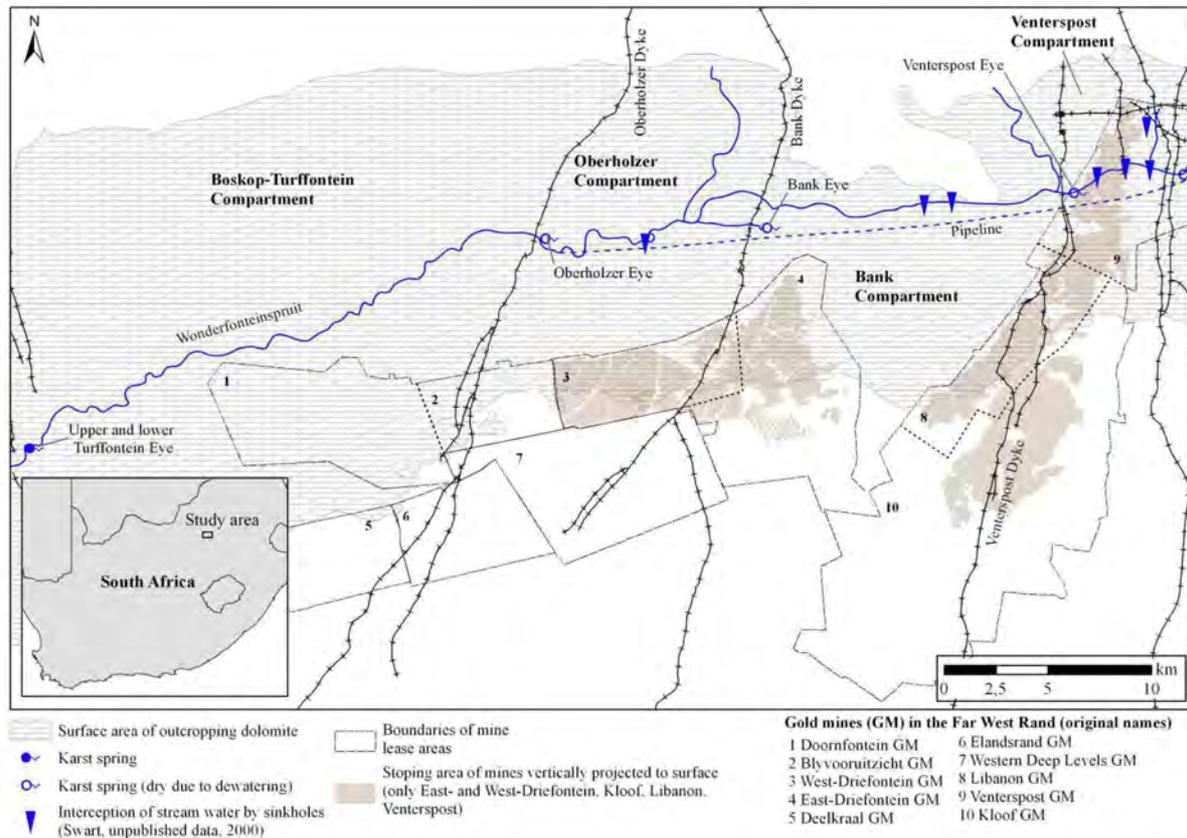
With regard to the IGF this study adapts the basic model of Swart et al. (2003a). However, an unrealistic assumption regarding a governing factor for the IGF of Swart et al. (2003a) is revised, and an alternative mathematical model presented that allows better quantification of the IGF using more realistic data.

## 4.2 Study area

**Hydrogeologic setting:** Figure 4.1 shows a map of the study area, which comprises the central and western part of the FWR goldfield, also known as the Carletonville goldfield or West Wits Line, approximately 50 km southwest of Johannesburg. As indicated in the map most mining takes place below the up to 1,200-m-thick dolomite, which is in part highly karstified, forming an aquifer that stores large quantities of groundwater (Fig. 4.1). Figure 4.2 depicts a north to south cross section of the geologic setting in the FWR with the associated stratigraphy as the geological strata related to the underground mine void is of relevance to the ingress and flow of groundwater.

Quartzites of the Witwatersrand Supergroup as well as the Ventersdorp Supergroup Lava are low in storativity and transmissivity, therefore acting as aquifer boundaries below the dolomite (de Kock 1964). The northern aquifer boundary is formed by granite-gneiss of the Hartbeesfontein Anticline. To the south, a gradual boundary is formed by rocks of the Pretoria Group overlying the dolomite with an increasing thickness, and thus preventing the development of significant

karstification by shielding the dolomite from infiltrating surface water (Enslin and Kriel 1968; Brink 1979). The previously mentioned groundwater compartments are formed by approximately north–south trending intrusive dykes acting as aquicludes.



**Fig. 4.1** Locality plan and map of the study area showing the surface area of outcropping dolomite, surface projection of dykes and the boundaries of lease areas and the stoping area of (relevant) mines

The elevation of the water table in each compartment is controlled by the associated karst spring, located just upstream of the western dyke of each compartment commonly in small depressions of the micro relief near the valley bottom and stream channel of the Wonderfonteinspruit (Brink 1979). The elevation difference between springs of adjacent compartments is in the order of several tens of metres (de Kock 1964) indicating that dykes indeed serve as barriers to groundwater flow forcing the water table to intersect with the surface and as such creating springs (Enslin and Kriel 1959, 1968). Compartments of importance to this study, following the main direction of groundwater flow from east to west (Enslin and Kriel 1968), are the Venterspost, Bank, Oberholzer and Boskop-Turffontein Compartment (Fig. 4.1). Springs, locally referred to as ‘dolomitic eyes’, are responsible for nearly all the groundwater discharge from the compartments, thus reflecting the amount of natural recharge (Enslin and Kriel 1968).

The near-surface bedrock consists of highly weathered dolomite, large cavities and solution-widened fractures (de Kock 1964; Bezuidenhout and Enslin 1970; Enslin et al. 1977; Morgan and Brink 1984). It was estimated that as much as 75 % of the groundwater is stored in this upper zone of the dolomite (Jordaan et al. 1960).

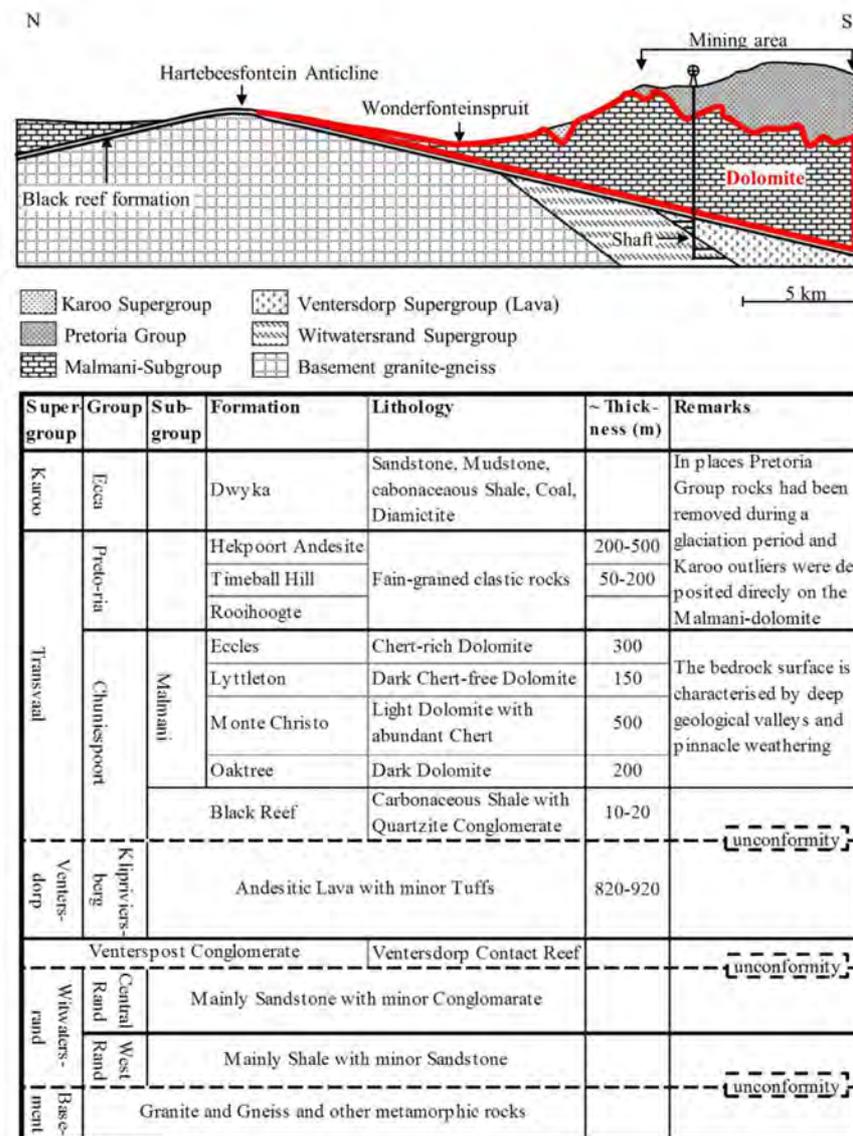


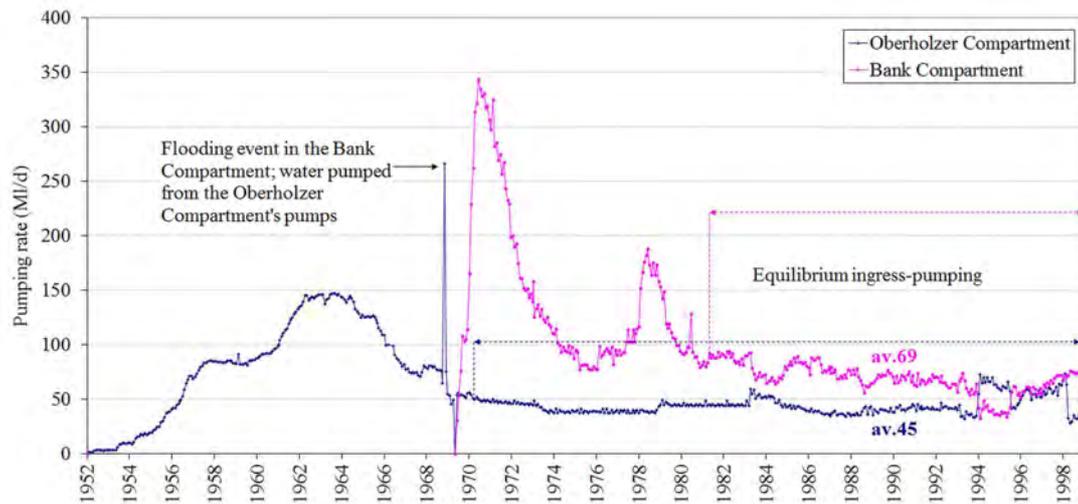
Fig. 4.2 North-south cross section showing the geologic setting of the FWR (after Brink 1979, modified) and below the associated stratigraphic column (after Els 1987 and Els 2000)

**Dewatering of dolomitic compartments:** Deep-level mining in the FWR started in the 1930s (Engelbrecht 1986). The mined gold reefs appear within the upper strata of the Witwatersrand Supergroup at the contact zone to the Ventersdorp Supergroup (Brink 1979, Fig. 4.2). Thus, most gold mining took place underneath a column of several hundreds of metres of water-filled cavities and fissures in the overlying dolomitic. Major fault zones and anticlinal buckling in the

dolomite associated with joints and fissures penetrating through the un-weathered dolomite bedrock provide pathways for groundwater from the high-permeable cavernous zones in the upper dolomite to the underground mine workings. As a result, mines had to pump large quantities of ingress water to surface to keep mine voids dry. As the stoping area extended horizontally along the quartzite–dolomite interface, progressively more water-bearing fissures and fractures were intersected. This resulted in a constantly growing ingress volume that soon exceeded the natural recharge of the overlying compartments (Wolmarans 1982). The pumped water was initially discharged within compartments in bore- and sinkholes, nearby caves or directly into the Wonderfonteinspruit (Knight, unpublished data 1964; Enslin et al. 1977). With such discharged water circulating back into mine voids within a few days, this practice was soon recognised as being uneconomic. It was also believed at the time that the continuously growing mine voids would lead to ever increasing ingress volumes, which would eventually exceed the capacity of the mines to manage the ingressing water volumes.

Attempts to reduce ingress by technical solutions, such as cementation of hanging walls of stopes or the adding of sawdust into cover boreholes that intersected fissures to eventually clog fissures, proved to be not feasible in the long-term (Wolmarans 1982). In order to secure mining operations as well as to reduce the continuously increasing pumping costs, the dewatering of compartments was considered a possible solution and subsequently proposed by the mines to Government (Jordaan et al. 1960). Dewatering, in this context, refers to the process of pumping ingress water to surface but discharging it outside the boundaries of the compartment from where it originated. Since ingress into the mine void exceeded the natural recharge, this leads to the gradual lowering of the groundwater table in the compartment concerned. Through the associated reduction of the hydraulic head that drives the water into the mine void (several hundreds of metres above the main ingress zones), ingress rates also gradually decrease. The active draw-down is completed when the hydraulic head is reduced to a level where the associated ingress rate equals the natural recharge rate of the overlying compartment, resulting in a more or less stable water table elevation (Wolmarans 1982). Therefore, in contrast to what the term literally suggests, ‘dewatered’ compartments still contain significant volumes of groundwater whose volume and water table are controlled by the dynamic equilibrium between influx from surface via natural recharge and the ingress into the mine void in the form of fissure water. From this point in time onwards, the pumping rate is a direct reflection of the natural recharge and should, as a long-term average, be equal to the pre-mining spring flow (provided that the natural recharge remains constant). Oberholzer Compartment, pumping rates in other compartments (e.g., Gembokfontein, Bank) exceeded pre-mining spring flow, in some cases significantly. A range

of possible factors explaining this phenomenon is discussed in Winde et al. (2006). The typical dewatering pumping chart (pumping rate vs. time) looks similar to a flood hydrograph consisting of a rising and falling limb tapering out to a constant low-level rate (Fig. 4.3).



**Fig. 4.3** Pumping rates for the Bank and Oberholzer Compartments with indications from when on pumping rates reflected natural recharge (termed: 'ingress-pumping') as well as the associated average (av.) pumping rate in megalitre/day (ML/d)

The rising limb reflects the increase in ingress through intersecting additional water-bearing fissures until a culmination point is reached where ingress and thus pumping volumes are at a maximum. At this point, ingress increase due to void expansion is still higher than ingress decrease due to lowering of the hydraulic head. This changes around after the culmination point is passed when ingress reduction through dropping water levels overcompensates the ingress increase through stoping area expansion. Finally, the curve flattens out marking a situation where simply all naturally generated groundwater eventually flows into the mine void. This assumes that the connections between the cavernous zone and the mine void (i.e. fissures, faults, fractures) are large enough to accommodate the totality of naturally recharged groundwater since otherwise the groundwater table would rise again. The latter did happen in the Bank Compartment following a period of 4 years of average and 2 years of above-average rainfall between 1971 and 1977. According to Swart et al. (2003b), the groundwater table recovered considerably by several hundreds of metres in places during this wet period, and the increasing hydraulic head was subsequently reflected by rising pumping rates in the Bank Compartment between 1977 and 1979 (Fig. 4.3). That no such increase was observed in the Oberholzer Compartment may be due to the fact that many sinkholes, which developed in or near the stream channel of the Wonderfonteinspruit probably intercepted most if not all the stream water before it could reach the Oberholzer Compartment.

The first compartment to be dewatered was the Venterspost Compartment in the late 1940s. The associated karst spring known as the Venterspost Eye dried-up in 1947 (Enslin and Kriel 1959). Dewatering of the Oberholzer Compartment, which is separated from the Venterspost Compartment by the initially full Bank Compartment, started around the mid-1950s. Dewatering was conducted by the West Driefontein mine<sup>1</sup> and from 1964 onwards also by the Blyvooruitzicht mine. The Oberholzer Eye ceased flowing in September 1959 (Knight, unpublished data, 1964).

Eventually, dewatering of the Bank Compartment commenced after an accidental water inrush into West Driefontein mine on October 26th, 1968. Mines involved in the pumping from the Bank Compartment were West and East Driefontein and Libanon mines.

The lowering of the water table caused the drying up of three of the major karst springs, which used to maintain the stream flow of the Wonderfonteinspruit throughout the year rendering the stream perennial, despite the strongly seasonal rainfall in the area (Bezuidenhout and Enslin 1970, Swart et al. 2003b). In 1977, the Wonderfonteinspruit had been diverted from the natural stream bed into a 30-km-long pipeline (of 1 m in diameter) that carried the water across the dewatered compartments. This was implemented to minimise aquifer recharge through stream water lost to the underlying aquifer via sinkholes and other conduits (termed ‘stream loss’ or ‘bed loss’). Dewatering also caused ground instabilities in the form of the development of more than a 1,000 sinkholes, which permanently and in many cases irreversibly changed the hydrologic conditions through significantly increasing the aquifer recharge at the expense of surface run off and stream flow (Swart et al. 2003b, Winde and Stoch 2010).

***Mining through dykes:*** In order to re-establish pre-mining groundwater flow conditions, the Jordaan report (Jordaan et al. 1960) recommended sealing (reclosing) the parts of the dykes that had been mined through. This was later picked up by Usher and Scott (2001) as an option to prevent the formation of a mega-compartment. However, dykes were penetrated by haulage tunnels, intermittent thoroughfares and stoping areas on a horizontal length of several kilometres (Swart et al. 2003a; Winde et al. 2006) (Table 4.1).

Therefore, the sealing of mined-through dykes from an economic point of view is not an option to prevent the formation of a mega-compartment, not least because accessing mined-through parts of the dykes in many cases is no longer possible.

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<sup>1</sup> This study uses old names of mines in order to simplify cross referencing to historical data.

**Table 4.1** Horizontal length of dykes that is mined through by gold mines (estimated from map provided by Swart et al. 2003a)

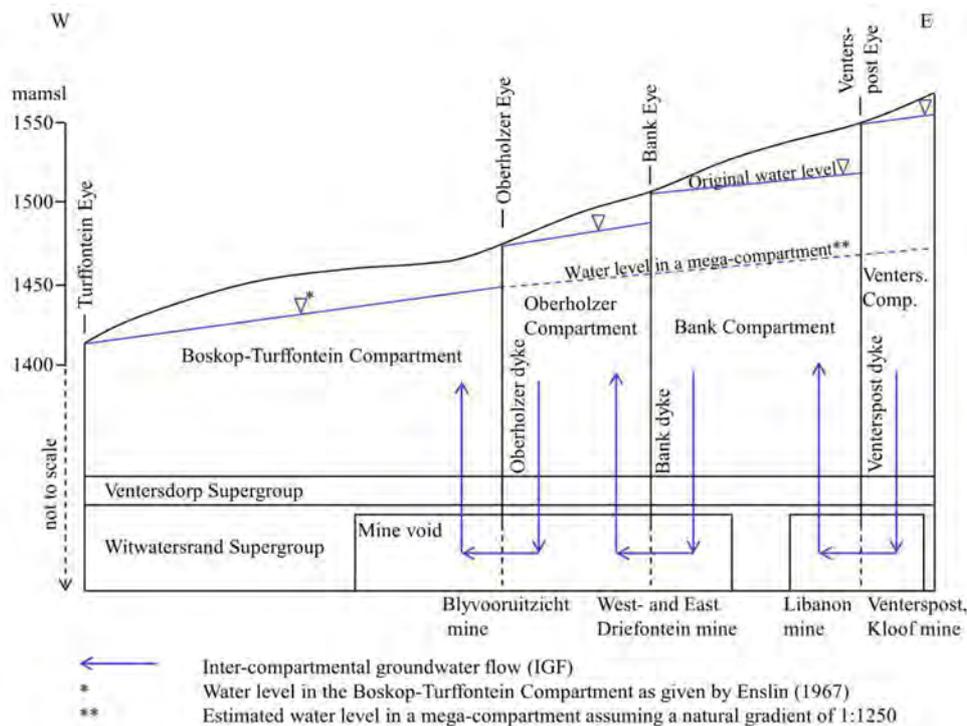
Dyke	Mines that are mined through the dyke	Length of mined-through dyke (km)
Venterspost Dyke	Libanon, Kloof	15
Bank Dyke	West-Driefontein	5
Oberholzer Dyke	Blyvooruitzicht	4

The table considers only mines relevant for the mega-compartment concept

### 4.3 The Mega-compartment concept

The most significant change of the aquifer hydrology was predicted to be the possible formation of a so-called ‘mega-compartment’ (e.g. Jordaan et al. 1960; Usher and Scott 2001; Dill and James 2003; Swart et al. 2003a; van Niekerk and van der Walt 2006). The concept is based on the fact that mining pierced through the watertight dykes separating the dolomitic compartments at mine void level. When mining ceases, mine voids as well as the overlying aquifer will fill-up with naturally infiltrating groundwater. This will then flow across compartments via the pieced dykes hydraulically linking previously separated aquifers. As a result, four of the compartments may be merged into a single large ‘mega-compartment’ with a single water table cutting across all compartments, the elevation of which would be controlled by the lowest-lying karst spring (Turffontein Eye). The conceptual model of the mega-compartment is illustrated in Fig. 4.4.

As Fig. 4.4 depicts, the dykes are still intact at the level of the water-bearing dolomite, while the inter-compartmental groundwater flow (IGF) will link compartments on mine void level. Thus, compartments will now have two possible discharge points via which groundwater may leave them, namely the karst spring on surface and the pierced dykes at depth. Linked in this way, and filled up with infiltrating groundwater, compartments will resemble a system of communicating vessels. In such a scenario, the final water table in all sub-units of the mega-compartment will be on an equal level only if more water flows out through the pierced dykes at the bottom (IGF) than can be replenished from the top through natural recharge (R), i.e. the mega-compartment scenario, in which a single-elevation water table develops across all four linked compartments, will only materialise if the IGF exceeds R ( $IGF > R$ ). The mechanism on which this is based is the fact that the water pressure difference between two adjacent compartments ( $h$ ) driving the IGF, would gradually be reduced until it disappears completely.

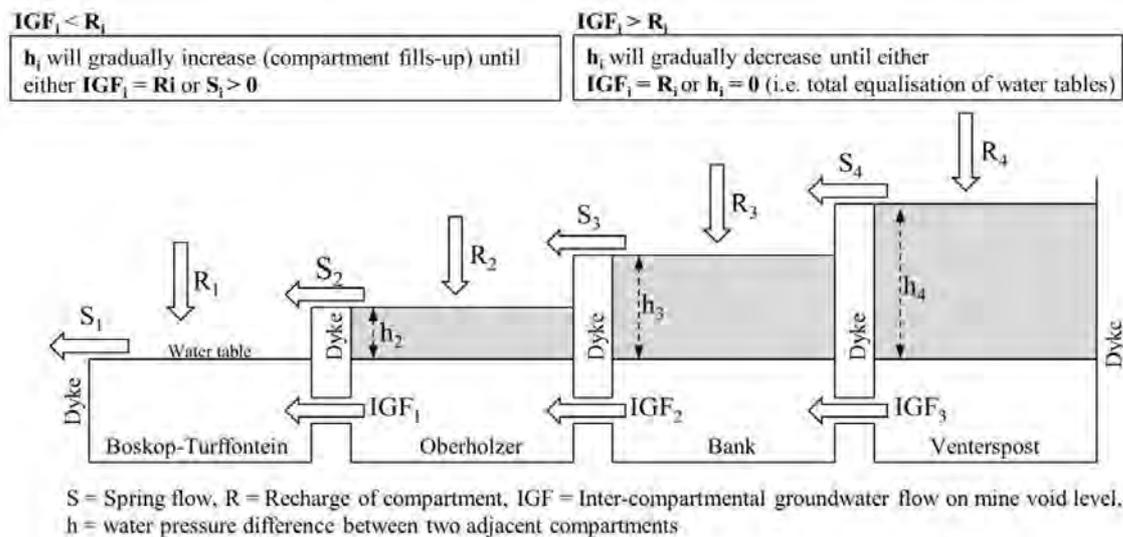


**Fig. 4.4** Illustration showing the conceptual model of the mega-compartment that could form in the WFR as a result of mining through impermeable dykes [based on the model described by Swart et al. (2003), modified]

As Fig. 4.4 depicts, the dykes are still intact at the level of the water-bearing dolomite, while the inter-compartmental groundwater flow (IGF) will link compartments on mine void level. Thus, compartments will now have two possible discharge points via which groundwater may leave them, namely the karst spring on surface and the pierced dykes at depth. Linked in this way, and filled up with infiltrating groundwater, compartments will resemble a system of communicating vessels. In such a scenario, the final water table in all sub-units of the mega-compartment will be on an equal level only if more water flows out through the pierced dykes at the bottom (IGF) than can be replenished from the top through natural recharge (R), i.e. the mega-compartment scenario, in which a single-elevation water table develops across all four linked compartments, will only materialise if the IGF exceeds R ( $IGF > R$ ). The mechanism on which this is based is the fact that the water pressure difference between two adjacent compartments ( $h$ ) driving the IGF, would gradually be reduced until it disappears completely.

If, however, the IGF is reduced in the process to being equal with recharge before the two water levels equalise, the water table elevation in the upstream compartment would stabilise, and thus maintain a certain difference to the water table in the downstream compartment. This difference would be smaller than the original water-level difference and at a lower elevation level. If this occurs before groundwater reaches surface levels, spring flow would not be reactivated either.

This scenario is, thus, inbetween a mega-compartment situation and a full recovery of the groundwater tables to pre-mining elevations (Fig. 4.5).



**Fig. 4.5** Schematic illustration indicating the interaction of the inter-compartmental groundwater flow (IGF), recharge (R), spring flow (S) and the water pressure difference between compartments (h) in a post-mining re-watering situation, resulting in either partly restoring spring flow in each compartment (top left and shaded scenario:  $IGF_1 < R_1$ ) or in a mega compartment with a single elevation water table cutting across all four compartments (top right and non-shaded scenario:  $IGF_1 > R_1$ )

If recharge initially exceeds the IGF ( $IGF < R$ ), the water table would rise until the growing pressure difference (h) between compartments increases the IGF to the level of the recharge (R). In this case, the water table would adjust at an intermediate level somewhere between the present (dewatered) and the original (pre-mining) water level.

By the same token, if the pressure difference between compartments is not large enough to create an IGF that is at least equal to the recharge, then the water table would gradually rise until the spring (S) on surface starts flowing again. In this case, the original flow rate of the spring would be reduced by the volume of the IGF 'lost' to the downstream compartment.

In case the IGF is sufficiently large for a mega-compartment to form, a single nearly horizontal water table would cut across all four compartments only slightly increasing in elevation in up-stream direction at a gradient (1:1,250) that would be even flatter than the topographic surface. For the three upstream compartments this would mean that the groundwater table would remain between 21 and 70 m below its original (pre-mining) elevation leaving no chance of the dried-up karst springs ever being reactivated (Fig. 4.4; Table 4.2). This, in turn, would have a range of severe economic and ecological consequences relating to post-mining land use, use, ground stability, water availability and quality in the area (Kleywegt and Pike 1982; Winde and Stoch 2010).

**Table 4.2** Approximation of water levels in a mega-compartment at dolomitic springs considering a natural gradient of 1:1,250 and a groundwater flow direction from the Venterspost to the Boskop-Turffontein Compartment

	Turffontein eye	Oberholzer eye	Bank eye	Venterspost eye
Pre-mining water level at spring (mamsl)	1,417	1,471	1,502	1,539
Water level at spring in mega-compartment (mamsl) <sup>a</sup>	1,417	1,450	1,458	1,469
Difference between pre- and post-mining water level (m)	0	21	44	70

<sup>a</sup> Assuming a water table in the Boskop-Turffontein Compartment as shown in Fig. 4.4, and a natural east-west gradient of the water table of 1:1,250 in the other Compartments [as proposed by Jordaan et al. (1960)]

In the following, conceptual models for estimating both parameters (IGF and R) are developed to provide a base for their later quantification.

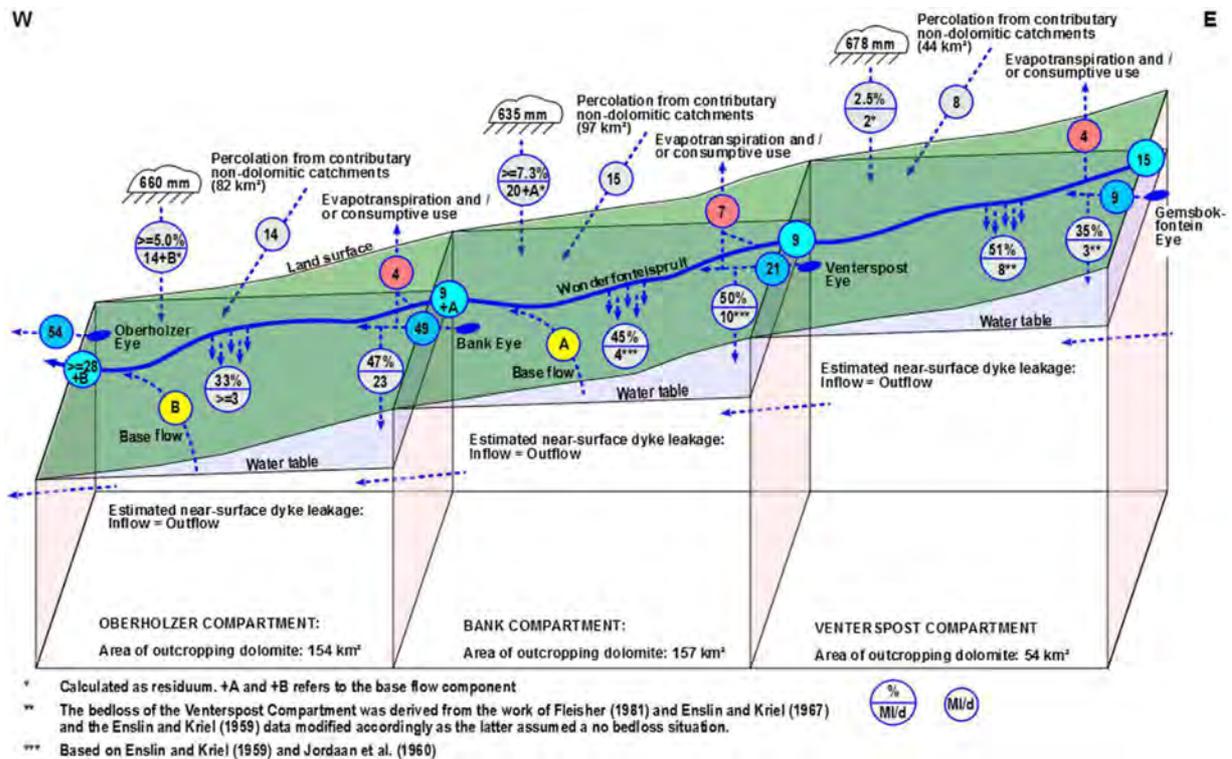
A critical point which is not included in the mega-compartment theory, as discussed in previous studies, is the possibility that the volume of horizontal mining infrastructure (e.g. stoping area, haulages) below a critical mining depth may be reduced over time due to the enormous pressure of the overlying rock. It has been reported that stoping areas have been reduced to mere ‘pencil lines’ within a few years after being abandoned (Brouwer, pers. communication cited in Winde et al. 2006). Winde et al. (2011) estimated a reduction of the mine void of as much as 75 % in the Western and Central basin due to such plastic void closure. This could significantly reduce the IGF, and thus lower the probability for mega-compartment to form. However, measurements of closure rates exist only for short periods (up to several months) and predominantly for areas of active mining (e.g. Walsh et al. 1977; Malan 1999; Malan et al. 2007), while large-scale and long-term investigation are scarce mainly due to the limited accessibility of mined-out areas that are abandoned just after being mined out for safety reasons.

#### 4.4 Post-mining recharge

Estimating recharge faces difficulties because the conditions under which recharge will occur in post-mining times (after compartments have been re-watered) will be different from both the present and pre-mining (natural) situation. The following passage provides an overview on research regarding recharge in the study area and subsequent attempts to predict possible developments for various post-mining scenarios. In order to arrive at a reasonable prediction for post-mining recharge conditions the known natural, pre-mining conditions are analysed first.

**Natural (pre-mining) recharge:** Figure 4.6 depicts a pre-mining water balance synthesised from values extracted from various sources. The model represents an improved version of a concept

originally introduced by Enslin and Kriel (1959). Owing to considerable uncertainties of the underlying data, the water balance should be considered as a first-order approximation only.



**Fig. 4.6** Conceptual model of a pre-mining water balance of dolomitic compartments based on values extracted from various studies and a concept introduced by Enslin and Kriel (1959)

Natural recharge before mining occurred in the form of:

- rainwater directly infiltrating on dolomitic outcrop areas (soil percolation),
- surface run off and interflow intercepted by karst features such as paleo-sinkholes,
- stream water diffusely lost from the riverbed of the Wonderfontein spruit and its tributaries where they cross karstified dolomite ('stream loss'), which includes
- the contribution of karst springs from upstream compartments feeding into the stream. However, most of the spring water was intercepted before it could flow into the stream and diverted into irrigation canals. Leakage losses from those canals were estimated to be in the order of 35–50 % and contributed also to the pre-mining groundwater recharge,
- surface run off from non-dolomitic areas entering dolomitic outcrop areas, and finally,
- groundwater from upstream compartments seeping through weathered dykes near surface (Knight, unpublished data, 1964; Foster 1987, 1988). Vegter (1984) quotes transmissivities between 0.1 and 2 m<sup>2</sup>/day for near-surface dykes. This results in water volumes of 1–14 megalitre per day (Ml/day) that could have passed subterraneously through the weathered

upper parts of dykes in non-dewatered compartments.<sup>2</sup> However, a tracer test conducted in the Oberholzer compartment did not provide sound evidence of significant dyke leakage occurring (National Mechanical Engineering Research Institute, unpublished data, 1957). Further estimates from Knight (unpublished data, 1964) suggested that dyke leakage is rather in the lower range of the above-stated values and therefore of minor importance.

Given the impacts of water use for irrigation, the presented water balance is subject to historical land-use practises. Recharge via direct infiltration of rainfall onto dolomite had been calculated as residuum (in Fig. 4.6) based on the earlier mentioned assumption that (natural) pre-mining spring flow volumes are equal to recharge if the water table is stable. This would be true if springs account for almost all discharge of compartments (Enslin and Kriel 1959, 1968; Jordaan et al. 1960). Pre-mining spring flow volumes are listed in Table 4.3.

**Table 4.3** Recharge estimates for dolomitic compartments from natural spring flow, the Hill method and stable-state pumping rates

Recharge estimated from...	Non-dewatered compartment		Dewatered compartment					
	Spring flow Jordaan et al. (1960)		Hill method Fleisher (1981) <sup>a</sup>			Stable-state pumping rate Swart et al. (2003)		
	ML/d	mm/a/m <sup>2</sup> outcropping dolomite	ML/d	mm/a/m <sup>2</sup> outcropping dolomite	% <sup>b</sup>	ML/d	mm/a/m <sup>2</sup> outcropping dolomite	% <sup>b</sup>
Venterspost	21	142	34	230	164	28	189	134
Bank	49	114	63	146	128	41	95	84
Oberholzer	54	128				25	59	46

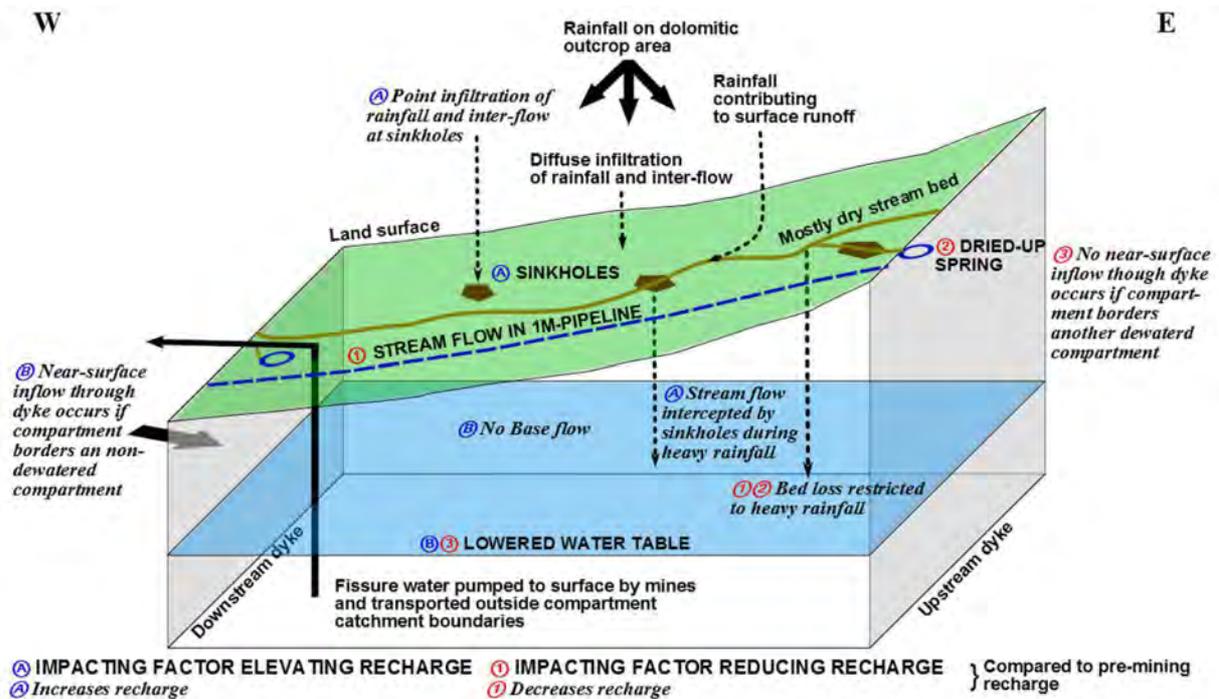
<sup>a</sup> Estimated for 1970–1975 (Bank) and 1965–1975 (Venterspost)

<sup>b</sup> Percentage of pre-dewatering spring flow

Uncertainties in Table 4.3 relate to the fact that the recharge estimated from spring flow does not incorporate groundwater leaving compartments through near-surface weathered dykes (whatever this amount may be) and that it was not considered that the Wonderfonteinspruit is likely to have also received exfiltrating groundwater in the low-lying areas just upstream of the dykes (base flow), where the groundwater table intersects the stream channel which was then transported out of the compartment as pointed out by Enslin and Kriel (1959) and Fleisher (1981).

**Current recharge rates (de-watering situation):** After dewatering commenced, recharge conditions changed in affected compartments. Figure 4.7 schematically illustrates factors impacting on recharge in the present situation, as well as their increasing or decreasing effects on recharge compared to pre-mining conditions explored above.

<sup>2</sup> Calculation of values based on Darcy's law and the following assumptions: North to south length of dykes along outcropping dolomite = 12,000 m, thickness of dykes = 50 m, water table difference of adjacent compartments = 30 m.



**Fig. 4.7** Schematic illustration of factors relevant for groundwater recharge in dewatered compartments (present situation). Also indicated are the negative and positive effects these factors have on recharge compared to the pre-mining water balance (Fig. 4.6). Recharge is elevated by (A) the appearance of sinkholes, (B) the lowering of the water table and occasionally increased hydraulic gradients between compartments

The major changes affecting recharge in the dewatered compartments are the following:

- the massive formation of sinkholes, often directly in the stream bed of the Wonderfontein-spruit, increasing recharge through enhanced interception of surface run off
- the diversion of stream flow out of the natural stream bed into a watertight pipe reducing recharge through the prevention of stream loss (notwithstanding accidental leakages and spillages)
- the drying up of upstream karst springs not feeding into the stream, reducing the recharge the general lowering of the groundwater table indirectly increasing recharge rates through minimising seepage losses through the weathered (upper) part of dykes.

In order to estimate the net effect of the various factors, each is analysed in more detail:

- a. More than a 1,000 sinkholes formed throughout the FWR as a consequence of dewatering. Concentrated along the stream bed of the Wonderfontein-spruit and in the vicinity of geological structures (predominantly associated with the chert-rich Monte Christo and Eccles Formations), sinkholes intercept sizable amounts of surface water providing direct pathways to the dolomitic aquifer (Swart et al. 2003b, Winde and Stoch 2010). The magnitude of this process was described by Swart (unpublished data, 2000), who reports a period of abnormal

high precipitation (December 1999 to February 2000) during which the Donaldson Dam at the eastern boarder of the Venterspost Compartment discharged at a rate of 143 Ml/day into the Wonderfonteinspruit. After flowing in the streambed for a short distance, the entire water volume was intercepted by sinkholes. The same happened to the stream water of several minor streams of the area. Major points of stream water interception are indicated in Fig. 4.1 (after Swart, unpublished data, 2000).

- b. Lowering of the water table cuts off possible stream–groundwater interactions by preventing any exfiltrating groundwater (base flow) diffusively feeding into the stream as it may have occurred prior to dewatering in the Bank and Oberholzer Compartment (Enslin and Kriel 1959; Fleisher 1981), thus effectively increasing the net-recharge.

As indicated in Fig. 4.7, dewatering could reverse the hydraulic gradient between a dewatered and non-dewatered compartment which could theoretically result in additional groundwater inflow through leaking dykes.

Factors that reduce recharge at present are: (1) the canalisation of the Wonderfonteinspruit in a pipeline, (2) the drying up of upstream springs as a consequence of dewatering and (3) the lowering of the water table, which prevents near-surface flow through dykes.

- (1) Between 40 and 90 Ml/day (average 67 Ml/day) are transported in the pipeline across the dewatered compartments (flow gauging station C2H277, Department of Water Affairs 2013) restricting the flow in the now dry stream bed of the Wonderfonteinspruit to periods of abnormal rainfall, where runoff cannot be accommodated by the pipeline. Given that 33–51 % of stream flow was lost to the underlying aquifer, the reduction of recharge associated with the installation of the pipeline is significant (Fig. 4.6).
- (2) The same applies to the drying up of springs as they also contributed significantly to recharge, especially in case of the Bank eye which crossed the dyke before merging with the Wonderfonteinspruit. Given that about 50 % of the upstream spring flow was estimated to contribute to the recharge of the downstream compartment, this change also significantly reduced the recharge compared to natural, pre-mining conditions.

Several estimates exist for the actual amount of recharge taking place in dewatered compartments (Table 4.3).

From the point in time when water tables of dewatered compartments have stabilised (Fig. 4.3), pumping rates were considered to be equal to recharge as indicated earlier. However, estimating recharge from pumping rates includes some major uncertainties that originate from a lack of

information with regard to the water balance of the mines as well as the method that is used to derive the data of the pumping volume. This is discussed in detail in the second part of this series.

Another estimate for recharge of the dewatered Bank and Venterspost Compartment was provided by Fleisher (1981) applying the Hill method (see Conkling 1946; Todd 1959), which uses pumping figures and water-level drawdown to estimate recharge. It can be seen in Table 4.2 that values given by the author, derived before the canalisation of the Wonderfonteinsspruit in 1977, are much higher than that given by Swart et al. (2003a), which could indicate the significant effect of the pipeline on groundwater recharge.

The recharge in dewatered compartments, indicated by Swart et al. (2003a), appears to be slightly lower than natural recharge before dewatering started (Table 4.3). It is apparent that adding 50 % of the pre-mining spring flow (which approximates the pre-mining groundwater recharge from the upstream spring, Fig. 4.6) to present stable-state pumping rates, results almost exactly in the values of pre-mining spring flow volumes (applies to the Bank and Oberholzer Compartment). This leads to the conclusion that the currently lower recharge volumes could be caused by the drying up of springs. Then the other effects (i.e. mainly of the pipeline and sinkholes) would offset one another. However, current recharge estimates from pumping rates are subject to uncertainties; therefore, this interpretation should be treated with caution.

***Post-mining recharge (re-watering situation):*** In post-mining times, the amount of water lost from any compartment as IGF instead of spring flow, will effectively increase the recharge of the receiving compartment as 100 % of the IGF will contribute to the recharge of the receiving compartment. In contrast, if water is lost from the compartment as spring flow, this water feeds into the Wonderfonteinsspruit and only a part of this water will infiltrate into the dolomite as bed loss and recharge the receiving compartment, while some water will be transported across the compartment and outside the catchment boundaries. Therefore, recharge of the downstream compartment will be the higher the more water from the upstream compartment is discharged as IGF (instead of spring flow).

The future amount of spring flow that will recharge the downstream compartment as bed loss is not known, and will also depend on the usage of the water. It could be higher as compared to pre-mining times if spring flow is not used and much spring flow be intercepted by sinkholes. If canalised and used for irrigation farming, less spring flow might contribute to recharge since canal leakage could be less than in pre-mining times (if canals are better sealed). Furthermore,

post-mining recharge will depend on whether the pipeline is retained or not. At the present state it is highly likely that the pipeline will be dismantled, which would significantly increase recharge. This leads to the fact that to a high degree, post-mining recharge is a matter of choice.

**Semi-quantitative estimate of post-mining recharge:** Table 4.4 summarises the factors identified above that impacts on the individual recharge components (e.g. percolating rainwater, infiltration from stream bed, etc.) in the present and the post-mining (re-watering) situation in comparison to the pre-mining (natural) situation. Table 4.5 presents an attempt to assess the modification of recharge in post-mining times based on the careful examination of the factors listed above (for different scenarios as many factors such as the volume of the IGF or the usage of spring flow are unknown).

**Table 4.4** Cross table showing factors elevating or reducing recharge in dewatered (present) and re-watered (post-mining) compartments as compared to the pre-mining (natural) situation

Compartment situation	Infiltrating rainwater	Infiltration stream flow/ bed loss	Contribution from upstream spring flow to groundwater recharge <sup>g</sup>	Near-surface flow through dykes
Dewatered (present)				
Elevating factors	Sinkholes <sup>a</sup>	Sinkholes <sup>c</sup>		Increased hydraulic gradients between compartments <sup>f</sup>
	Lowering of water table <sup>b</sup>	Lowering of water table <sup>b</sup>		
Reducing factors		Pipeline <sup>d</sup>	Drying up of upstream spring <sup>e</sup>	Lowering of the water table <sup>b</sup>
Re-watered (post-mining)				
Elevating factors	Sinkholes	Sinkholes	Sinkholes	Inter-compartmental flow (IGF)
		Pipeline (if dismantled)	No utilisation of water <sup>g</sup>	
Reducing factors		Pipeline (if retained)	Inter-compartmental flow (IGF) Removal of water from system <sup>g</sup>	

<sup>a</sup> Winde et al. (2006), <sup>b</sup> Fleisher (1981), <sup>c</sup> Swart, unpublished data (2000), Winde et al. (2006), Winde and Stoch (2010), <sup>d</sup> Swart et al. (2003b),

<sup>e</sup> Jordaan et al. (1960), <sup>f</sup> Knight, unpublished data (1964), Fleisher (1981), Foster (1987, 1988)

<sup>g</sup> In pre-mining times, water from spring flow was canalised and used for irrigation farming. Because of seepage loss from the canals and irrigation losses to groundwater, some of this water recharged the downstream aquifer. Whether this amount will be higher or lower in post-mining times depends on the way of usage.

For most scenarios, it is assumed that recharge will be equal or higher than in pre-dewatering times. Recharge will be greater if the pipeline is dismantled regardless of the volume and usage of spring flow and the volume of IGF, because then much stream flow of the Wonderfontein-spruit will be intercepted by the many sinkholes that are formed in or near the stream channel as a result of dewatering.

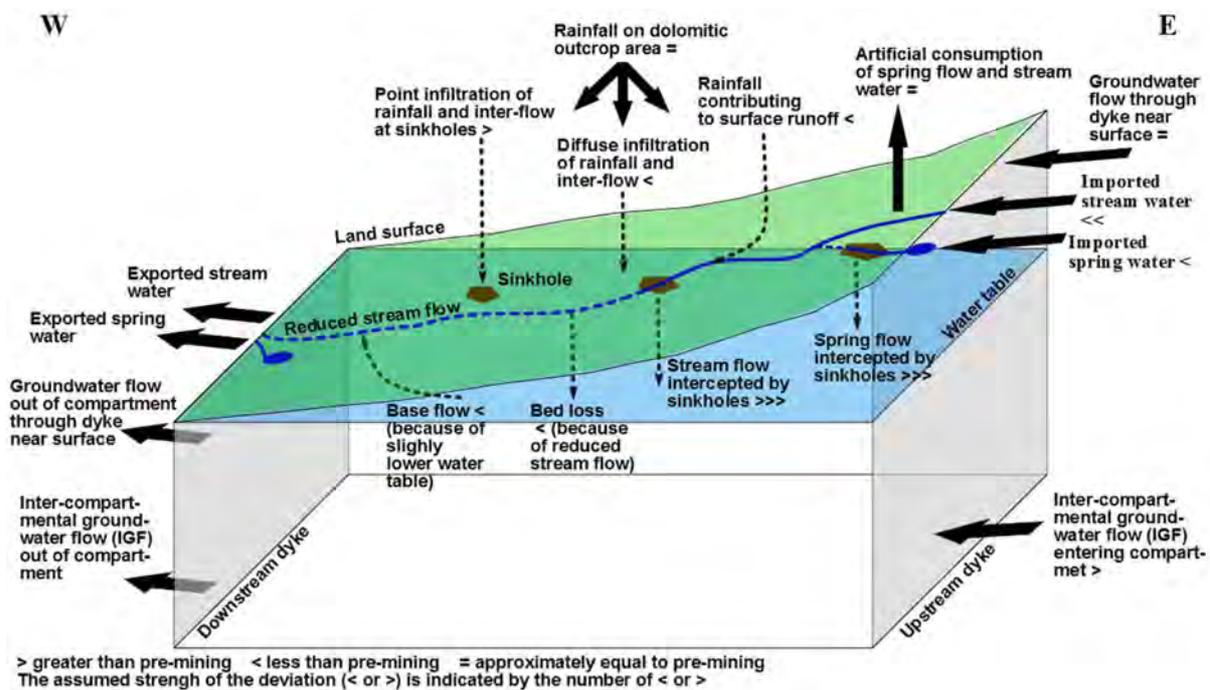
Lower recharge is only to be expected for a situation where the pipeline remains in use, and a low IGF when at the same time much spring flow is abstracted from the system and

used/consumed in a way so that it does not contribute to recharge. As an example, Fig. 4.8 depicts a schematic illustration of scenario E, which is considered a likely scenario.

**Table 4.5** Table showing different future scenarios of recharge (A-E) in which different factors have a varying influence on recharge (\* indicates the condition of the factors)

	Recharge scenario					
	A	B	C	D	E	F
Pipeline						
Retained	*	*	*			
Dismantled				*	*	*
IGF						
High	*			*		
Low		*	*		*	*
Spring flow						
High		*	*		*	*
Low	*			*		
Artificial consumption of spring flow						
High		*			*	
Low			*			*
Post-mining : pre-mining recharge	=	<	=	>>>	>	>>

For each scenario, the ratio of post-mining to pre-mining recharge is given (> post-mining recharge greater than pre-mining recharge; < post-mining recharge smaller than pre-mining recharge. Number of < or > indicate the strength of the deviation



**Fig. 4.8** Schematic illustration of a changed groundwater recharge in re-watered compartments (post-mining situation) based on scenario E listed in Table 4.5

## 4.5 Inter-compartmental groundwater flow (IGF)

**Conceptual model of IGF:** The IGF is the second important factor that will determine if a mega-compartment will form. Swart et al. (2003a) were the first to provide a detailed conceptual model of the IGF, also making a quantitative assessment. Their model is based on the premise that all mining infrastructure such as shafts, tunnels and drives were sealed from ingress by cementation techniques except for the stoping area, where the actual extraction of the ore took place.

According to their model, the IGF includes three flow legs (indicated by arrows in Fig. 4.4). Post-Transvaal (anticlinal) fault zones and associated joints and fissures constitute the downward leg in the upstream compartment conducting water from the dolomitic aquifer down to the mine void. The through-flow leg through dykes separating the compartments is formed by horizontal infrastructure such as tunnels and haulages in the mine void. The upward leg is again formed by fault zones and associated joints and fissures connecting the mine void with the dolomitic aquifer in the downstream compartment. The driving force of the flow is the hydraulic gradient defined by the pre-mining (natural) water table elevation difference between two adjoining compartments (Swart et al. 2003a).

The mine void, comprising of tunnels with diameters of several metres, will be capable of accommodating sizable flow volumes. For that reason, the IGF will not be restricted by the mine void (i.e. the through-flow leg) but by the flow resistance of the upward and/or downward legs.

A further assumption used by Swart et al. (2003a) was the linear relation between ingress volume and the size of the mined area, particularly referring to the stoping area. Even though this relationship does not exist in all phases of mining, they used the assumption to arrive at a possible overestimation of ingress to make any finding against the formation of a mega-compartment more robust. The applicability of Darcy's law, yet to be confirmed in the karstified dolomite at hand, was also presupposed by the authors. Based on this conceptual model, Swart et al. (2003a) calculated that the IGF through the Bank Dyke could be around 39 Ml/day.

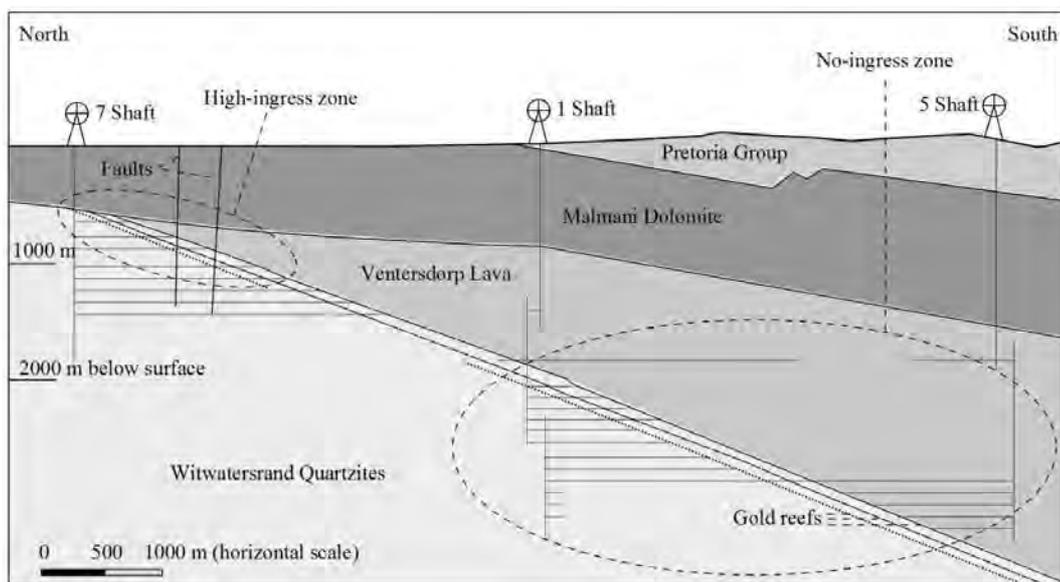
### ***Vertical groundwater flow between the dolomitic aquifer and the mine void (downward leg):***

The ingress to the mine void depends on the number of faults reaching down from the dolomitic aquifer on top that were intercepted by the stoping area. The probability of intersecting faults will become higher as the stoping area extends. For that reason, some mines experienced a proportional growth of ingress and stoping area during the early years of mining (Interdepartmental Committee on Dolomitic Water pumped by Mines, unpublished data, 1958; Irving, unpublished data, 1964; Wolmarans 1982). However, the number of faults reaching to deeper mining levels is

comparatively small, as can be judged from the Western Deep Levels mine (mining vertically much deeper than Driefontein under a much thicker layer of Ventersdorp Lavas), which is so dry that it has to import water. For that reason, the relationship of ingress and stoping area is not maintained in deeper level of mining where no direct interface between dolomite and quartzite is present. Ingress is largely confined to the stoping area where mined reefs sub-outcrop at the dolomite as shown in Fig. 4.9.

This part of the mine void is just a fraction of the total mine void. In some cases, single large fissures delivering exceptional high amounts of water disturb any correlation between stoping area size and ingress volumes. An example is West Driefontein in the Bank Compartment that receives about 90 % of its water from a single large feeder, i.e. the Big Boy fault (Swart et al. 2003a).

**Quantification of the high-ingress stoping area:** The water volume ingressing into the mine void is approximately given by the volume pumped by mines from the mine void to the surface. On one side, the ingress volume depends on the hydraulic head above the mine void. However, as long as the ore exploitation takes place in the zone of the high-ingress stoping area (Fig. 4.9), the ingress volume increases also as a function of the increasing stoping area. The effect of the growing stoping area on the ingress volume ends as soon as mining moves to deeper levels where no ingress takes place (Fig. 4.9). Any stoping at these deeper levels has no effect on ingress volumes.



**Fig. 4.9** North - south section through West-Driefontein mine in the Bank Compartment showing the geologic setting and indicates parts of the mine void that potentially receive high or no (low) ingress volumes (Gold Fields 2009, modified)

If historical pumping volumes (representing ingress) were used for example to quantify the IGF, it is very important to determine from when stoping had no longer an effect on the pumping volume. Taken out of the equation, this would allow one to calculate the ratio between hydraulic heads and ingress, and assess whether or not Darcy's law—according to which this relationship should be linear if it were to be applicable—indeed applies to the karst setting.

One way of determining this point in time is to use the size of the high-ingress stoping area. Based on this, it can be calculated when this critical size was reached using the average annual expansion rate of the stoping area. The size of the stoping area can in turn be calculated from historic pumping figures and water-level data. For example, the size of the high-ingress area of the West Driefontein mine in the Oberholzer Compartment is calculated. This is done by comparing the stoping area, the pumping volume (representing ingress) and the hydraulic head above the mine void of 1955 and 1988 as well as a hypothetical situation in 1988—for which the same hydraulic head as in 1955 is assumed, but related to the much bigger stoping area that was then reached (Table 4.6). Based on Table 4.6 the Figs 4.10a and b were constructed.

**Table 4.6** Stoping area and parameters relevant to ingress into West-Driefontein mine in 1955 and 1988

	Stoping area (no-ingress + high-ingress) (km <sup>2</sup> )	Ingress (Ml/day)	High-ingress stoping area (% of stoping area)	Ingress per high-ingress stoping area (Ml/d/km <sup>2</sup> )	Hydraulic head above mine void (m)
1955	0.41	28	100	68	972 <sup>b</sup>
1988	12 <sup>a</sup>	39	To be calculated	To be calculated	131
1988 (hypothetic)	12 <sup>a</sup>	289	To be calculated	68 (assumption)	972

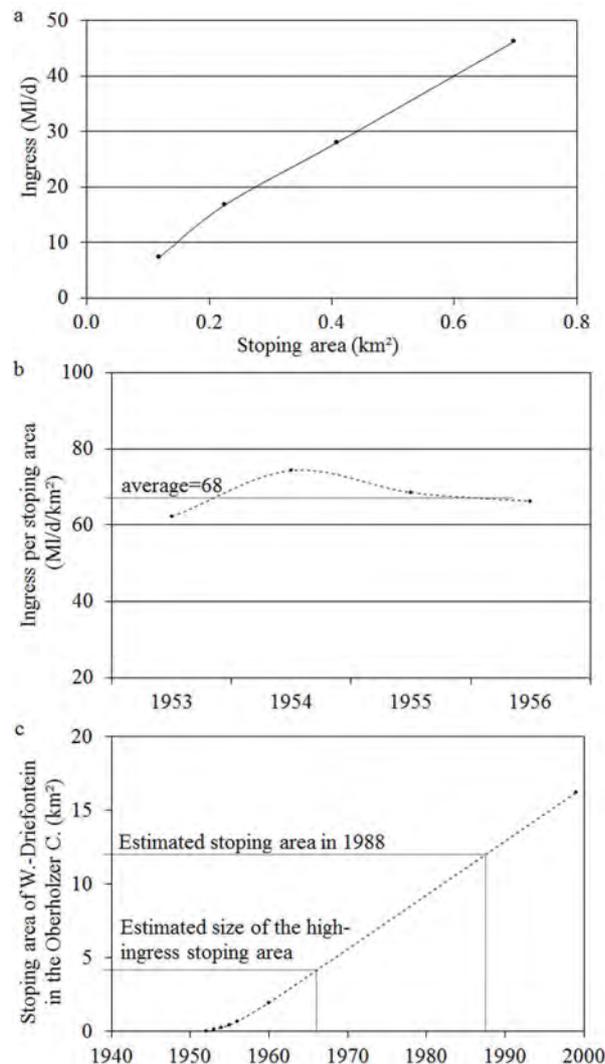
<sup>a</sup> Interpolated from Winde et al. (2006) based on Whymer (unpublished data, 1999).

<sup>b</sup> Assuming the shallowest mining depth where West Driefontein No. 1 Shaft intersects the base of the dolomite at 499 meters above mean sea level (mamsl) (de Kock 1964).

Figure 4.10a shows that from 1953 to 1955 the increase of the ingress volume and the stoping area were in linear relation to each other. This implies that 100 % of the stoping area effectively received ingress, and therefore can be considered as a high-ingress stoping area. Fig. 4.10b shows that—extrapolated to a full square kilometre—the stoping area received an ingress volume of approx. 68 Ml/day/km<sup>2</sup> under the given head of 972 m. Based on this, the ingress can be calculated that would have occurred in 1988 when the actual stoping area was much larger, assuming that the entire area would indeed receive ingress. In order to have the same driving force for ingress to take place at the same intensity, the hydraulic head as being present in 1955, i.e. 972 m, is assumed. Based on a size of the stoping area in 1988 of 12 km<sup>2</sup> this would have resulted in an associated ingress volume (assuming a linear relationship) of 816 Ml/day.<sup>3</sup> In the

<sup>3</sup>  $12\text{km}^2 \cdot \frac{68\text{Ml}}{\text{day}}/\text{km}^2$

next step, the ingress volume that would have occurred in 1988 under a hypothetical head of 972 m is calculated from the ingress volume and the groundwater level actually measured in 1988 based on Darcy's law. The calculated volume amounts to only 289 MI/day.<sup>4</sup>



**Fig. 4.10 a)** Diagram showing the development of the ingress volume against the increase of the stopping area of West-Driefontein mine from 1953 to 1956. **b)** Diagram showing the ingress volume per stopping area against time during 1953-1956 **c)** Development of the stopping area of West-Driefontein during 1952-1999 (interpolated; based on data from Winde et al. (2006) and Whymer (unpublished data, 1999) cited in Winde et al. (2006)

Based on a linear relationship between ingress and stopping area, this suggests that of the 12 km<sup>2</sup> total stopping area that was reached in 1988 only 4.25 km<sup>2</sup> or 35 % received ingress.<sup>5</sup> From that it

<sup>4</sup> This amount is calculated from the ingress volume and the hydraulic head observed in 1988 (approach based on Swart et al. 2003a):  $E1: \frac{h_1}{Q_1} = \frac{1}{T} = \frac{131\text{m}}{39\text{MI/day}} = 290\text{s/m}^2$   $E2: Q_2 = \frac{h_2}{\frac{1}{T}} = \frac{972\text{ m}}{290\text{ s/m}^2} = 289\text{ MI/d}$  Whereas:  $h_1$  = hydraulic head observed in 1988,  $h_2$  = hypothetical hydraulic head in 1988,  $T$  = Transmissivity between dolomite aquifer and mine void,  $Q_1$  = ingress in 1988,  $Q_2$  = hypothetical ingress at a hypothetical head of 972 m.

<sup>5</sup>  $\frac{\text{calculated ingress under a hydraulic head of 972}}{\text{ingress per high-ingress stopping area}} = \frac{289\text{MI/day}}{68\frac{\text{MI}}{\text{day}/\text{km}^2}} = 4.25\text{km}^2$

is possible to determine the point in time, when the stoping area reached the area of 4.25 km<sup>2</sup>. It can be seen from Fig. 4.10c that this area was reached approximately in 1966. It is concluded from the above calculation that ingress in the West Driefontein mine operating in the Oberholzer Compartment was only tied to the size of the stoping area up until about 1966. Thereafter, further expansion of the stoping area had no increasing effect on ingress, leaving the hydraulic head as the only factor controlling ingress into the mine. Thus if pumping figures from before 1966 are analysed (for example to calculate the IGF), the dependence on the size of the stoping area needs to be considered.

#### **4.6 Summary and conclusion**

This article, being the first of a twofold series of articles, explores the concept of a mega-compartment that was suggested to form in the FWR dolomitic aquifers as a result of deep-level mines piercing through previously impermeable dykes. Through the created linkage, previously separated groundwater compartments may be merged into a single large compartment once mining ceases and the voids flood. Whether or not a mega-compartment will form depends on the ratio between (1) the groundwater recharge of individual compartments, and (2) the inter-compartmental groundwater flow on mine void level (IGF) between adjacent compartments. A mega-compartment will only form if the respective IGF is larger than the recharge of each corresponding compartment. A major objective of this study, therefore, was to develop a conceptual model that allows for identifying factors that control both parameters for a post-mining re-watering scenario.

- (1) It was found that post-mining recharge will strongly depend on the utilisation of spring flow and surface water including the retention or dismantling of a pipeline that was established to reduce groundwater recharge. Thus, much will depend on choices taken in post-mining land and water management. However, due to the effects of some irreversible changes (such as the formation of sinkholes and piercing of dykes) most scenarios predict the post-mining recharge to be higher than the natural recharge was before dewatering commenced. This, in turn, favours the reactivation of springs over the formation of a mega-compartment.
- (2) The conceptual model of the IGF provided by Swart et al. (2003a) was used and improved upon with regard to a more realistic assumption of the actual dependency of ingress from the size of the underground stoping area. By establishing the point in time up until which ingress volumes were affected by the stoping area expansion, the findings allow for a more accurate evaluation and usage of historical pumping figures when calculating the IGF as done in the second article of this series. Altogether, the results of the conceptual and semi-quantitative

considerations presented in this study point to a low probability that a mega-compartment will form.

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## 4.7 References

- Bezuidenhout CA, Enslin JF (1970) Surface subsidence and sinkholes in the dolomitic areas of the Far West Rand, Transvaal, Republic of South Africa. *Land Subsidence*, vol 88. IAHS Publ, pp 482–495
- Brink, ABA (1979) *Engineering Geology of South Africa*, vol. 1. Building Publications, Pretoria
- Conkling H (1946) Utilization of ground-water storage in stream system development. *Trans. Am Soc Civ Eng.* 111:275–354
- de Kock WP (1964) The geology and economic significance of the West Wits Line. *The Geology of some ore deposits in Southern Africa*. Geological Society of South Africa, Johannesburg, pp 323–386
- Department of Water Affairs (2013) Flow monitoring data. Department of Water Affairs, Pretoria. <http://www.dwaf.gov.za/iwqs/wms/data/riv.kmz> (Cited 9 Oct 2013)
- Dill S, James AR (2003) The assessment of the impacts on groundwater quality associated with the backfilling of dolomitic cavities with gold mine tailings. Report to the Water Research Commission. Report No. 3. Metago Environmental Engineers (Pty) Ltd, Sandton
- Els BG (1987) The auriferous Middelvllei Reef depositional system, West Wits Line, Witwatersrand Supergroup. PhD, Rand Afrikaans University, Johannesburg
- Els BG (2000) Unconformities of the auriferous, Neoarchæan Central Rand Group of South Africa: application to stratigraphy. *J. Afr Earth Sci.* 30:47–62
- Engelbrecht CJ (1986) The West Wits Line. In: Antrobus ESA (ed) *Witwatersrand Gold - 100 Years*. Geological Society of South Africa, Johannesburg, pp 199–223
- Enslin JF, Kriel JP (1959) Some results obtained from a hydrological study of a dolomitic catchment area in the Transvaal, Union of South Africa. DWA Technical Report No. GH 1841. Department of Water Affairs, Pretoria
- Enslin JF, Kriel JP (1968) The assessment and possible future use of the dolomitic ground water resources of the Far West Rand, Transvaal, Republic of South Africa. *Papers of the International Conference on Water for Peace*, 1967 May 23-31, Washington DC, vol 2. US Government Printing Office, Washington, pp 908–918
- Enslin JF, Kleywegt RJ, Buekes JHT, Gordon-Welsh JF (1977) Artificial recharge of dolomitic ground-water compartments in the Far West Rand Gold Fields of South Africa. In: *Proceedings of the second international symposium on land subsidence*, Anaheim, California, vol 121. IAHS Publ, 495–506
- Fleisher JNE (1981) The geohydrology of the dolomitic aquifers of the Malmani subgroup in the South-Western Transvaal Republic of South Africa. DWA Technical Report No. GH 3169. Department of Water Affairs and Forestry, Pretoria
- Foster MBJ (1987) First revision of the geohydrology of the Zuurbekom and Gembokfontein Compartments. DWA Technical Report No. GH 3542. Department of Water Affairs and Forestry, Pretoria
- Foster MBJ (1988) Second interim report on the geohydrology of the Zuurbekom and Gembokfontein Compartments. Estimation of ground water leakage across the Magazine Dyke due to mine dewatering. DWA Technical Report No. GH 3563. Department of Water Affairs and Forestry, Pretoria

- Gold Fields (2009) Driefontein Gold Mine technical short form report. Gold Fields Ltd. [http://www.goldfields.co.za/reports/rr\\_2009/tech\\_drie.php](http://www.goldfields.co.za/reports/rr_2009/tech_drie.php) (Cited 15 Oct 2013)
- Jordaan JM, Enslin JF, Kriel J, Havemann A, Kent LE, Cable WH (1960) Final report of the Interdepartmental Committee on Dolomitic Mine Water: Far West Rand. Department of Water Affairs and Forestry, Pretoria
- Kleywegt RJ, Pike DR (1982) Surface subsidence and sinkholes caused by lowering of the dolomitic water-table on the Far West Rand Gold Field of South Africa. *Ann Geol Surv S Afr* 16:77–105
- Malan DF (1999) Time-dependent behaviour of deep level tabular excavations in hard rock. *Rock Mech Rock Eng* 32:123–155
- Malan DF, Napier JAL, Janse van Rensburg AL (2007) Stope deformation measurements as a diagnostic measure of rock behaviour: a decade of research. *S Afr Inst Min Metall* 107:743–765
- Morgan DJT, Brink ABA (1984) The Far West Rand dolomites. Technol., 1984, Johannesburg, South Africa, vol 2. National Water Well Association, pp 554–573
- Schwartz HI, Midgley DC (1975) Evaluation of geo-hydrologic constants for the Far West Rand dolomitic formations. *Civ Eng S Afr* 17:31–36
- Swart CJU, James AR, Kleywegt RJ, Stoch EJ (2003) The future of the dolomitic springs after mine closure on the Far West Rand, Gauteng, RSA. *Environ Geol* 44:751–770
- Swart CJU, Stoch EJ, van Jaarsveld CF, Brink ABA (2003a) The lower Wonderfontein Spruit: an exposé. *Environ Geol* 43:635–653
- Todd DK (1959) Ground water hydrology. Wiley, New York
- Usher BH, Scott R (2001) Post mining impacts of gold mining on the West Rand and West Wits Line, Chap. 5. In: Hodgson FDI, Usher BH, Scott R, Zeelie S, Cruywagen LM, de Necker E (eds) Prediction techniques and preventative measures relating to the post-operational impact of underground mines on the quality and quantity of groundwater resources. WRC Report No. 699/1/01. Water Research Commission, Pretoria, pp 5.1–5.117
- van Niekerk HJ, van der Walt IJ (2006) Dewatering of the West Rand dolomitic area by gold mining activities and subsequent ground instability. *Land Degrad Dev* 17:441–452
- Vegter JR (1984) Dolomitic water supplies with special reference to southern and western Transvaal. DWA Technical Report No. GH 3353. Department of Water Affairs and Forestry, Pretoria
- Walsh JB, Leyde EE, White AJA, Carragher BL (1977) Stope closure studies at West Driefontein Gold Mine. *Int J Rock Mech Min Sci Geomech Abstr* 14:277–281
- Winde F, Stoch EJ (2010) Threats and opportunities for post-closure development in dolomitic gold mining areas of the West Rand and Far West Rand (South Africa) - a hydraulic view. Part 1: mining legacy and future threats. *Water SA* 36:69–74
- Winde F, Stoch EJ, Erasmus E (2006) Identification and Quantification of Water Ingress into Mine Voids of the West Rand and Far West Rand Goldfields (Witwatersrand basin) with a View to Long-Term Sustainable Reduction thereof. Final report, Project No. 5512, Council for Geoscience, Pretoria
- Winde F, Stoch EJ, Erasmus E (2011) Desktop assessment of the risk for basement structures of buildings of Standard Bank and ABSA in Central Johannesburg to be affected by rising mine water levels in the Central Basin. Final Report (Volume I of III). Mine Water Re-search Group, North-West University, Potchefstroom
- Wolmarans JF (1982) The least unsafe route, vol. 1. Webb and Partners, Carletonville

## **5 Using impacts of deep-level mining to research karst hydrology—a Darcy-based approach to predict the future of dried-up dolomitic springs in the Far West Rand goldfield (South Africa). Part 2: predicting inter-compartmental flow and final groundwater tables**

Aljoscha Schrader<sup>1</sup>, Frank Winde<sup>2</sup>, Ewald Erasmus<sup>2</sup>

<sup>1</sup> Faculty of Natural Sciences, North-West University, Potchefstroom, South Africa, <sup>2</sup> Mine Water Re-Search Group, North-West University, Vanderbijlpark, South Africa

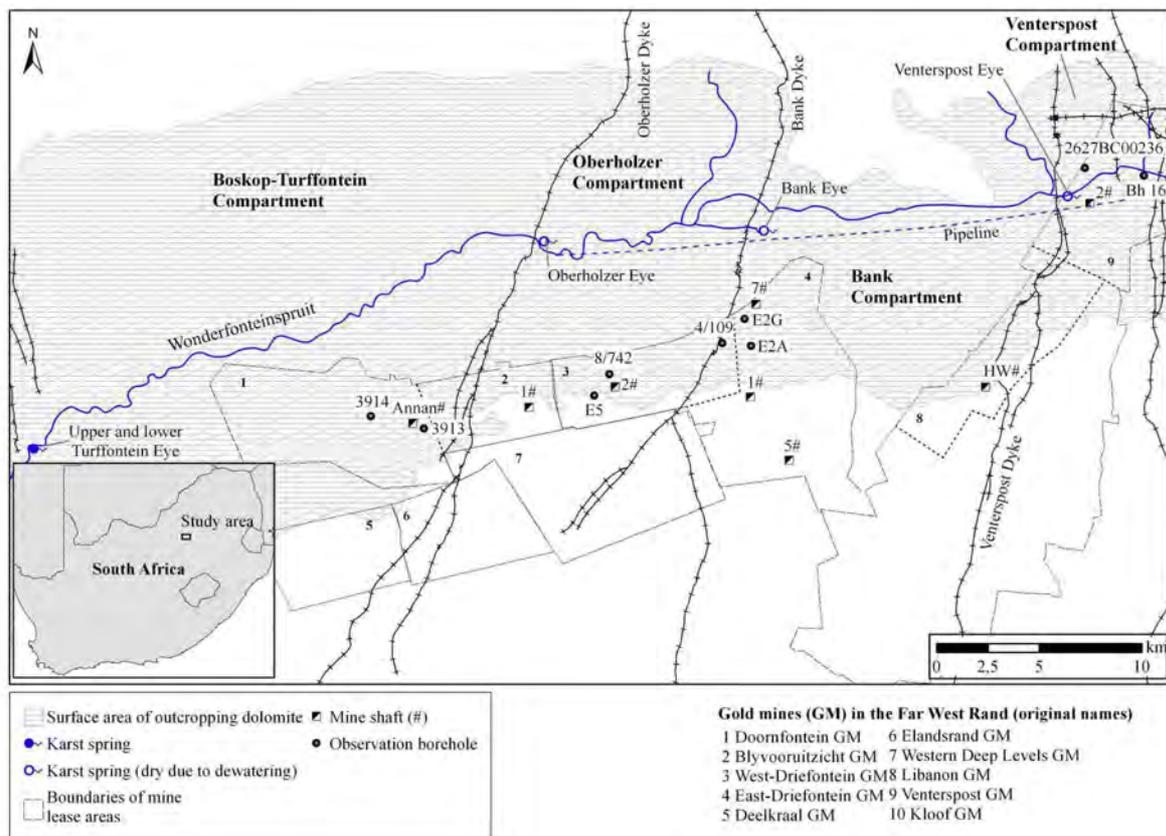
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**Abstract** Some of the world's deepest goldmines operate below dolomitic karst aquifers in the Far West Rand (FWR) goldfield, South Africa. Associated impacts include the continuous dewatering of karst aquifers for over six decades and irreversible changes of the hydrogeological setting. Affecting an area of approximately 400 km<sup>2</sup> by drawing down the water table up to 700 m, these impacts, and the large amounts of data generated in the process, are used as unique research opportunities to better understand the complex karst hydrology. The focus of this study is on predicting final water table elevations in rewatered aquifers after mining ceases taking the fact that mines hydraulically linked previously disconnected aquifers into account. While part 1 of this series develops the conceptual model, this second part utilises large sets of pertinent data to calculate actual flow rates for predicting the fate of dried up springs after mine closure. Following a Darcy-based approach first applied by Swart et al. (*Environ Geol* 44:751–770, 2003a) it is not only predicted that the springs will flow again but also shown that linear relationships exist between flow rates through a combined system of karst-fractured aquifers overlying the mine void and the associated hydraulic head driving them. This suggests that—at this scale—porous media-based equations can be meaningfully used to predict flow in non-porous media.

**Keywords** *Deep-level mining, Dewatered dolomitic compartments, Darcy's law, Dried-up karst springs, Post-mine closure rewatering*

## 5.1 Introduction

The dolomite aquifers of the Far West Rand (FWR), South Africa, are subjected to large-scale dewatering by deep-level gold mines as well as irreversible changes of geologic conditions controlling groundwater flow between the various compartments. The impacts of dewatering as well as of the massive perforation of solid watertight dykes that used to hydraulically separate adjacent compartments from each other are in detail described in part 1 of this series (Schrader et al. 2014). The most profound impacts were the drying up of strong karst springs due to the lowering of the regional groundwater table and the associated formation of sinkholes that significantly increased the groundwater recharge rate as well as the perforation of dykes that used to hydraulically separate adjacent compartments from each other (Fig. 5.1).



**Fig. 5.1** Locality plan and map of the study area showing the surface area of outcropping dolomite, surface projections of dykes, the boundaries of lease areas of mines as well as the positions of relevant boreholes and mine shafts on surface

Even though the dykes were pierced well below the actual karst aquifers it was feared that, once mining ceases and mine voids and aquifers are rewatered, the created underground connections will ultimately link the aquifers into a single large ‘Mega-compartment’ (Jordaan et al. 1960; Usher and Scott 2001). Acting like a system of communicating vessels this would result in an equal water table elevation across all linked compartments. As this removes the historical water

level differences between adjacent compartments that were created by the (un-mined) dykes forcing dammed groundwater to surface in the form of karst springs it would result in all dried-up springs to remain dry indefinitely despite rewatering of the karst aquifers. This, in turn, would pose a serious challenge for local gold mines in obtaining closure certificates as the reactivation of spring flow was made a condition when the State granted permission to dewater the compartments in the 1960s (Constitution of the Far West Rand Dolomitic Water Association 1964).

Based on a large number of hydrogeological studies and data, in part 1 of this series, a conceptual model was developed that identified the factors and their interdependencies which control the final water table elevation once rewatering is complete. The model suggests that the ratio between the rate at which deep groundwater flows across pierced dykes from one compartment onto the other ('Inter-compartmental groundwater flow', IGF) and the rate at which shallow groundwater is recharged from the surface is the single most important parameter determining whether or not the karst springs will ever flow after the mines closed.

Based on the conceptual model developed in part 1, this part concludes the series by quantifying the IGF using extensive data sets. While normally required data for such calculations such as hydraulic transmissivity (or flow resistance) are derived from pumping tests using boreholes drilled from surface, this study employs unique data only available due to the presence of deep-level mining. While pumping tests commonly operate with limited drawdowns (10–100 m) and relatively short observation periods (days to weeks), this study uses data covering a drawdown exceeding 700 m and observation periods spanning from 3 to 38 years with a total of more than 600 pairs of WL-measurements and pumping rates being evaluated.

Apart from providing a robust answer to this important question and the profound impacts this will have on mine closure and post-closure development the paper also explores to what extent the law of Darcy, originally developed for porous media with laminar water flow, can perhaps be meaningfully applied to karstified aquifers too. Factors impacting on the applicability of Darcy's law are discussed using concrete examples from the dewatered compartments which represent a combination of a highly weathered karst aquifer on top with a non-karstified fractured aquifer below.

## **5.2 Methodological approach**

Since the future of the dolomitic springs will depend on the elevation of the final water table in each compartment, this elevation needs to be determined. This determination is based on the conceptual model described in part 1 where the elevation of the water table in the rewatered

compartments will depend on the ratio between water influx from surface (termed ‘groundwater recharge’) and the rate at which water is lost to the downstream compartment via mined-through dykes at the bottom (termed ‘Inter-compartmental groundwater flow’ or IGF).

While the IGF can be relatively reliably predicted for the post-closure period using available data the same is not true for the recharge rate. As explored in part 1, mining profoundly changed the natural runoff recharge ratio and much of the future, post-mining recharge rate will depend on the way the surface and groundwater resources are managed. To account for this uncertainty, a range of plausible recharge scenarios introduced in part 1 are used to predict whether or not, and under what circumstance, the dried-up karst springs will flow again. To calculate the IGF, the groundwater flux through each dyke is subdivided into three flow legs [Schrader et al. (2014) (part 1), Swart et al. 2003a, Fig. 5.2]:

1. the downward leg where groundwater flows down vertical fault zones, which connect the karstified dolomite on top with the mine void below,
2. the horizontal leg where groundwater after entering the mine void flows horizontally along the stoping area as well as other mining infrastructure (such as drives, haulages, etc.) and crosses the dykes via holings generated by mining
3. the upward leg where horizontally flowing groundwater from the mine void is forced to flow upwards back to surface again along fault zones, fissures and fractures in the solid overlying rock that connect the mine void with the karstified dolomite on top of the receiving (downstream) compartment.

It is assumed that the vertical flow of the up- and downward leg occurs exclusively along natural geologic structures (such as fault zones, fissures, fractures etc.) but not along vertical mining infrastructure (e.g. shafts), which is considered to be sealed (Stirling, personal communication quoted in Swart et al. 2003a).

Thus, the only connection between the downward leg and the horizontal flow leg is the (unsealed) stoping area at which the fissures and fractures of the overlying rock are intersected. To a lesser extent, ingress may also occur at horizontal tunnels, drives, haulages, cross cuts, etc. that connect the stoping area (where the ore is excavated) to the shafts (at which the mined ore is lifted to surface).

Based on Darcy’s law, the IGF is driven by the water level difference between two adjacent compartments ( $\Delta h$ ) and can be calculated by the equation below (Swart et al. 2003a):

$$IGF = \frac{\Delta h}{r_{down} + r_{through} + r_{up}} \quad (1)$$

*IGF* = Inter-compartmental groundwater flow on mine void level through the dyke ( $m^3/s$ )

$\Delta h$  = water level difference between upstream and downstream compartment (m)

*r* = flow resistance<sup>1</sup> encountered by groundwater flow in particular flow leg ( $s/m^2$ )

$r_{down}$  – flow resistance for downward leg,  $r_{through}$  – flow resistance for horizontal flow leg,  $r_{up}$  – flow resistance for upward leg

It follows from Eq. 1 that the highest flow resistance in one of the three legs will determine the rate of the total IGF. The mine void leg ( $r_{through}$ ), comprising large open tunnels of several metres in radius, will obviously not restrict any flow coming through small fissures and therefore can be ignored in the calculation.

The flow resistance (which equals the reciprocal of transmissivity) for the upward and downward flow legs, respectively, can be calculated using ingress volumes represented by historical pumping figures of mines ( $Q$ ) and the hydraulic head above the mine void ( $h$ ) under which ingress occurred:

$$\frac{h}{Q} = r \quad (2)$$

$Q$  = Ingress to the mine void ( $m^3/s$ )

$h$  = water pressure (hydraulic head) above the mine void (m)

The IGF through each dyke can be calculated by inserting the respective values of the flow resistance into Eq. 1.<sup>2</sup> Thus, to determine the IGF, the flow resistance for each of the relevant legs needs to be calculated first.

### 5.3 Determining the IGF of all dewatered compartments

The determination of the IGF requires two steps:

1<sup>st</sup>: Calculation of the flow resistance for the down- and upward leg in each dewatered compartments using ingress (=pumping data) and the corresponding hydraulic heads data (derived from monitored water levels in associated boreholes), and

<sup>1</sup> simplified expression of the term  $\frac{1}{k \cdot A}$  whereas  $l$  = flow path length of through-flow media,  $k$  = hydraulic conductivity (m/s),  $A$  = cross sectional area of flow path ( $m^2$ )

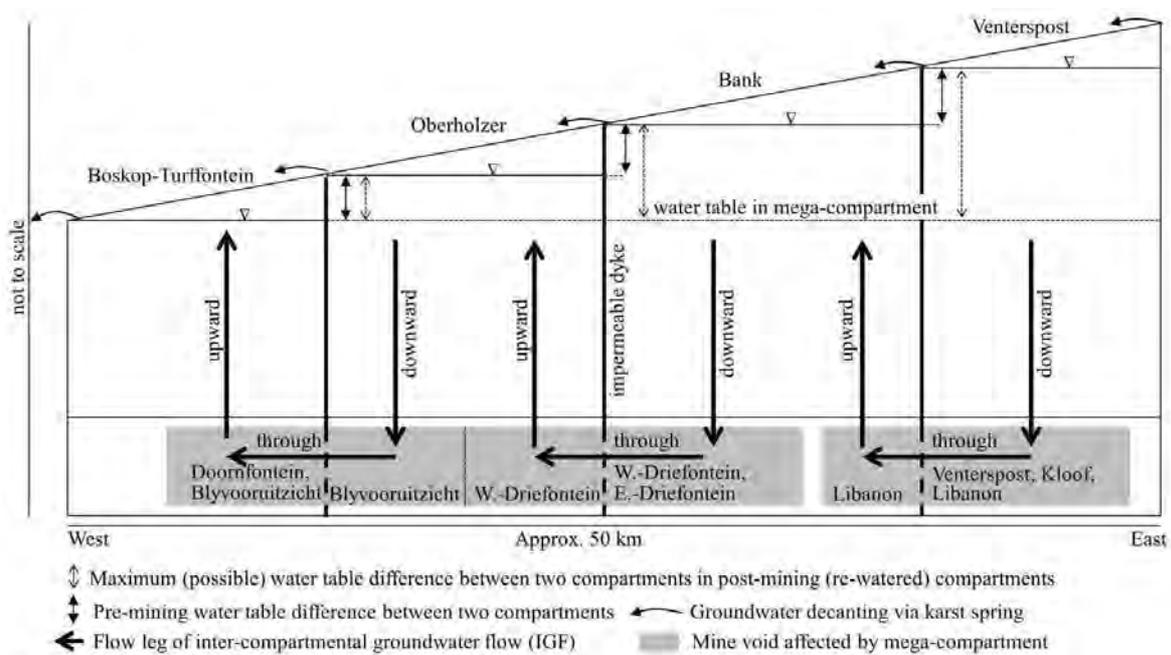
<sup>2</sup> The approach used to derive values for the flow resistance (Eq. 2) hypothetically assumes a plane drawdown of the water table over the whole horizontal extent of the compartment, which is caused by exclusively vertical groundwater flow between the dolomitic aquifer and the mine void. Therefore, the approach is virtually equal to a laboratory falling head setting, which is a general method used to determine the hydraulic conductivity/transmissivity of soil in the laboratory [e.g. described in Todd (1959)]. Actually during drawdown in the study area (steep) depression cones formed above the mine void and horizontal groundwater flow transported water towards the centre of the depression cone. This would be in contradiction to the theoretical basis of the approach. However, it is assumed that near the centre of depression cone vertical flow dominated and that water level measurements from those areas can be used in the above (falling head) approach.

2<sup>nd</sup>: Using the obtained values to calculate the IGF by applying Darcy's law (Eq. 1).

### 5.3.1 Calculating flow resistance of down- and upwards legs in dewatered compartments

To arrive at values for the entire system the flow resistance for the following legs is to be determined (Fig. 5.2):

- Venterspost Dyke, downward leg
- Venterspost Dyke, upward leg
- Bank Dyke, downward leg
- Bank Dyke, upward leg
- Oberholzer Dyke, downward leg
- Oberholzer Dyke, upward leg



**Fig. 5.2** Conceptual model of the IGF illustrating the various legs for which the flow resistance need to be determined as well as the name of the gold mines that pumped from the various compartments

**Data basis:** To derive reasonable values of the flow resistance of each flow leg the study uses time series of historical pumping volumes (representing ingress to the mine void) and water level drawdown data that had been measured during the dewatering of compartments (to calculate the

corresponding hydraulic head).<sup>3</sup> Table 5.1 provides an overview of the type of data used to derive the flow resistance of each flow leg.

In the following section, the assessment of the flow resistance of each flow leg is explained. Pumping volumes are consistently given in megaliters per day (Ml/d) because this unit was frequently used in previous publications concerned with mining-related groundwater problems in the study area. Values of flow resistance are expressed in  $s/m^2$ , as the flow resistance is the reciprocal of the transmissivity, which is usually given in  $m^2/s$ .

**Venterspost Dyke, downward leg:** Data from initial dewatering of the Venterspost Compartment (around 1950) cannot be used to assess the flow resistance since during this period the ingress volume changed not only as a function of the hydraulic head above the mine void but also increased as a function of the growing stoping area (Wolmarans 1982).

Therefore, and in respect of the data availability, data from 1979 to 1987 were sampled to assess the flow resistance. Three mines abstracted water from the Venterspost Compartment, namely Venterspost, Kloof and Libanon mine, the latter also drew an estimated 20 % of water from the adjacent Bank Compartment (Stoch, Mine Water Re-search Group, email-conversation, 12 Mrz 2011). Figure 5.3a displays the development of pumping rates and the hydraulic head (derived from 2 boreholes/shafts) from 1979 to 1987. The positions of shafts and boreholes are shown in Fig. 5.1.

No pumping figures were available for Kloof mine for the assessed period. The pumping rate of the mine was considered with 20 Ml/d that were added to the pumping rates of Libanon and Venterspost mines. This is a conservative estimate in the sense that it favours a megacompartment scenario rather than the re-establishing of pre-mining condition as the actual pumping volume of Kloof mine during the period 1993–1997 was only 13 Ml/d.

Figure 5.3b displays the resulting development of the flow resistance as calculated from the above time series of the joint pumping rates and the hydraulic head.

The average flow resistance amounts to  $614 s/m^2$ . Given the low fluctuation in Fig. 5.3b, a constant flow resistance around this value appears to be plausible and therefore is used to calculate the IGF.

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<sup>3</sup> The used data is a selection of a much larger compilation of data that were compiled electronically after converting them from a variety of original formats including hand-drawn diagrams, data sheets, maps and unpublished reports that were scattered over a multitude of sources including private collections, archives, mining companies, governmental departments and academic institutions. The data were collected and compiled over decades by Professor E.J. Stoch (Mine Water Re-search Group, North-West University, South Africa), who prevented many of them from being irretrievably lost.

**Table 5.1** Data used for the calculation of flow resistance for up- and downward legs in each of the relevant compartments including results

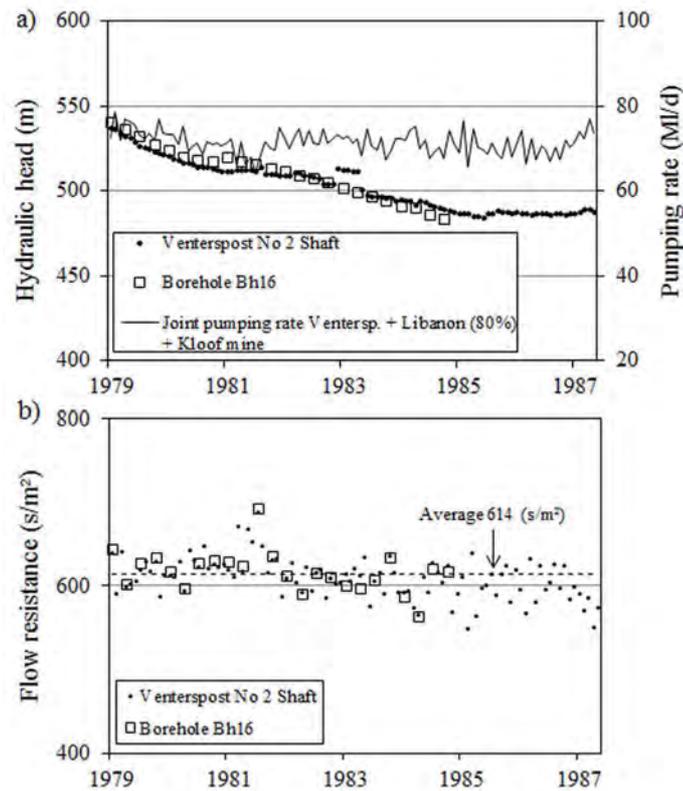
Compartment <i>Dyke</i>	Flow leg	Underlying period for estimation of flow resistance	Range of observed water table (mamsl) (Difference)	mamsl	Approx. depth at which ingress occurred <sup>a</sup>  Location <sup>b</sup>	Range of hydraulic head (m) (min-max in % of max)	No. of observation boreholes/shafts (names, codes)	Name of dewatering mines	Range of average pumping rate (MI/d)	Number of data pairs (WL – pumping rate)	Calculated flow resistance (s/m <sup>2</sup> )
<b>Venterspost</b> Compartment  <i>Venterspost Dyke</i>	down	1979-1987 (8 years)	1419-1476 (47 m)	935	Intersection Venterspost No. 2 Shaft and Ventersdorp Contact Reef <sup>c</sup>	484-551 (9)	2 ( <i>Venterspost No. 2 Shaft, Bh 16</i> )	Venterspost, Libanon Kloof <sup>e</sup>	64-78	101	614
<b>Bank</b> Compartment	up	1979-2006 (27 years)	831-1036 (205 m)	400	Intersection of Harvie Watt Shaft and base of dolomite <sup>c</sup>	431-636 (32)	1 ( <i>Libanon Harvie Watt Shaft</i> )	Libanon	10-38	193	2470
<b>Bank</b> Compartment  <i>Bank Dyke</i>	down	1968-1996 (28 years)	771-1504 (732 m)	693	Inrush depth at Big boy fault <sup>d</sup>	78-810 (90)	3 ( <i>E2A, E2G, 4/109</i> )	West-Driefontein	30-386	164	177
<b>Oberholzer</b> Compartment	up	1975-1988 (13 years)	622-690 (68 m)	499	Intersection of West-Driefontein No. 2 Shaft and base of dolomite <sup>c</sup>	123-191 (36)	2 ( <i>8/742, West-Driefontein No. 2 Shaft</i> )	West-Driefontein	34-59	98	320
<b>Oberholzer</b> Compartment  <i>Oberholzer Dyke</i>	down	1957-1995 (38 years)	975-1465 (490 m)	380	Intersection of Blyvooruitzicht No. 1 Shaft and base of dolomite <sup>c</sup>	595-1085 (45)	1 ( <i>Blyvooruitzicht No. 1 Shaft</i> )	Blyvooruitzicht	5-75	80	1470
<b>Boskop-Tfnt.</b> Compartment	up	1986-1989 (3 years)	1423 (0 m)	450	Intersection of Annan Shaft and base of dolomite <sup>c</sup>	973 (0)	2 ( <i>3913, 3914</i> )	Doomfontein, Blyvooruitzicht	17	2	4919

<sup>a</sup> Used to transfer water level measurements (in mamsl) into values of hydraulic head above the mine void (m)

<sup>b</sup> The elevation at which ingress occurred had to be determined by using geological features serving as proxies. For example, in case of Venterspost downward leg Venterspost No. 2 Shaft was used as proxy assuming no mining could take place above this point.

<sup>c</sup> de Kock (1964), <sup>d</sup> derived from Cousens and Garrett (1969)

<sup>e</sup> Pumping volumes of Kloof mine were not available for the assessed period. The pumping volume of the mine was estimated at 20 MI/d to rather overestimate the probability of a mega-compartment to form. Actual average pumping volume during the period 1993–97 was only 13 MI/d.

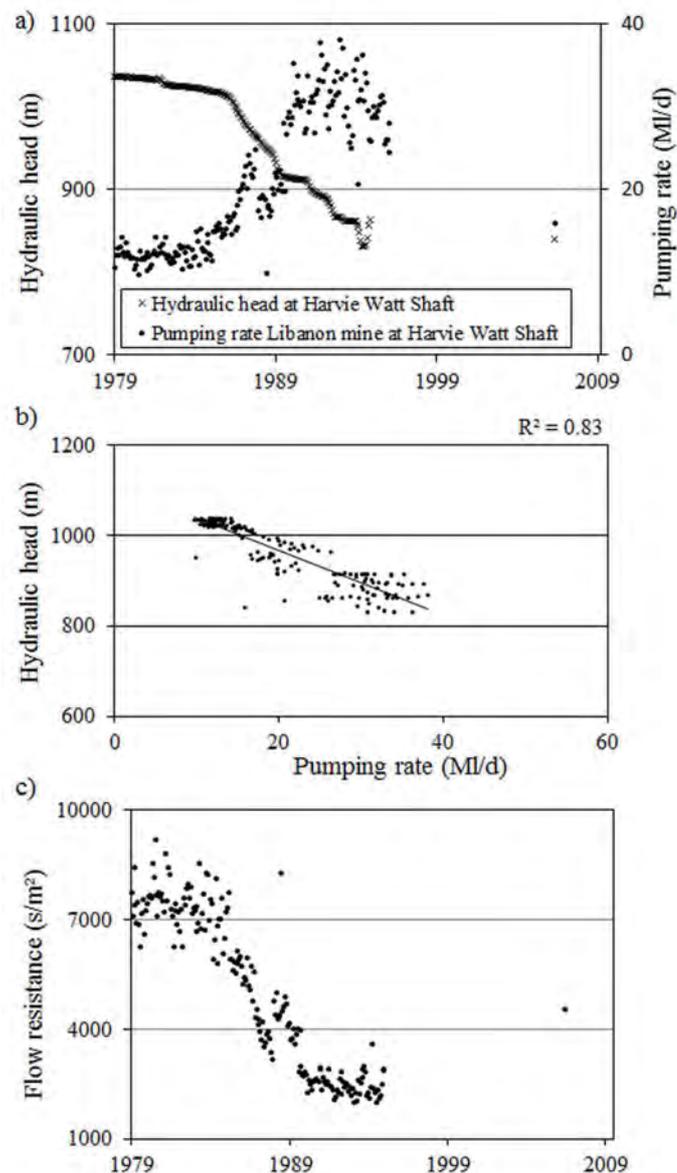


**Fig. 5.3 a** Estimated joint pumping rate of Venterspost, Libanon and Kloof mine from the Venterspost Compartment and change in hydraulic head derived from water level measurements in Venterspost No. 2 Shaft and borehole Bh16 during 1979–1987 **b** Development of flow resistance for the downward leg in the Venterspost Compartment during 1979–1987

**Venterspost Dyke, upward leg:** The flow resistance of the upward flow leg in the Bank Compartment (Fig. 5.2) volume of Libanon mine at Harvie Watt Shaft. As indicated above, Libanon drew only an estimated 20 % of its water from the Bank Compartment. However, this value may have changed over the years. To stick to a conservative estimation, all water pumped by the mine is allocated to the Bank Compartment. Figure 5.4a shows the pumping rate and the corresponding hydraulic head at Harvie Watt Shaft.

The pumping rate increased while the hydraulic head decreased (Fig. 5.4b). Owing to the decreasing hydraulic head the pumping rate should have decreased, too. Thus it is not possible that the increasing pumping rate was caused by the change of the hydraulic head, but the pumping rate must have increased for other reasons. One explanation could be that Libanon mine drew ingress water (also termed ‘fissure water’) from two compartments. The amount drawn from the Bank Compartment was assumed at a fixed value (i.e. 20 %). If the amount drawn from the Bank Compartment was not fixed, but increased over time, this could explain why the pumping rate increased in defiance of the decreasing hydraulic head. This is assumed to be the most likely explanation. In addition, the pumping figures may reflect other water sources of the mines’ water

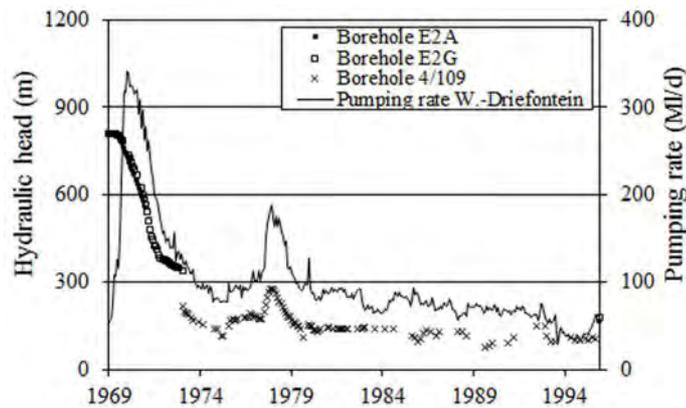
balance as well as certain errors in the data as explained below in the section ‘Applicability of Darcy’s law’.



**Fig. 5.4** Diagrams showing **a** time series and **b** scatter plot of the pumping rate at Libanon Harvie Watt shaft and the hydraulic head derived from water level measurements in the same shaft during 1979–2006 in the Bank Compartment **c** Development of flow resistance for the upward leg in the Bank Compartment during 1979–2006

Figure 5.4c shows the flow resistance calculated from the time series above. The lowest flow resistance is calculated for the time period during 1990–1994 averaging 2,470 s/ m<sup>2</sup>. This minimum value is used for the calculation of the IGF, as a low flow resistance results in high ingress (and thus IGF) and therefore favours the formation of a mega-compartment rather than the re-establishing of original water tables.

**Bank Dyke, downward leg:** The flow resistance of the downward leg in the Bank Compartment is derived from the pumping volume of West-Driefontein mine. Figure 5.5 shows the pumping rate during dewatering and the corresponding drawdown observed in three boreholes.



**Fig. 5.5** Time series of the pumping rate of West-Driefontein and the corresponding change in hydraulic head recorded in three boreholes during 1969–1996

Only the pumping rate after the peak (in June 1970) is evaluated, because it is assumed that from then on the pumping volume represented the water volume ingressing according to the hydraulic head above the mine void. Before that time the pumping rate may have been influenced by management decisions and may therefore not reflect the actual water volume that ingressed into the mine. Figure 5.6 shows scatterplots of the hydraulic head against the pumping volume<sup>4</sup> indicating a very good statistical connection between both parameters ( $R^2$  between 0.86 and 0.98).

The linear relation between hydraulic head and pumping rate follows exactly what is predicted by Darcy's law. This shows that the Bank aquifer behaves as predicted by Darcy. Confidence in the correlation is high given the large thickness covered by the data (732 m), the long period of time (28 years) from which the data are derived as well as the large number of utilised data points (164 single data points). Figure 5.7 shows the flow resistance as calculated from the time series of the pumping rate and the hydraulic head.

It can be seen that the flow resistance is more or less constant without showing any (upward or downward) trend. Indeed the curve shows a sinusoidal progression, which is predominantly caused by periodic fluctuations of the pumping rate (for example peaks in 1983 and 1988, compare Fig. 5.5), which are not caused by changes of the hydraulic head. Therefore, it is assumed that the periodic fluctuations are attributable to the internal water balance of the mines.

<sup>4</sup> Scatterplots include the inrush volume of some 386 ML/d observed during an accidental inrush event in October/November 1968 (described in Cartwright (1969) that appeared under the hydraulic head of a completely filled-up compartment.

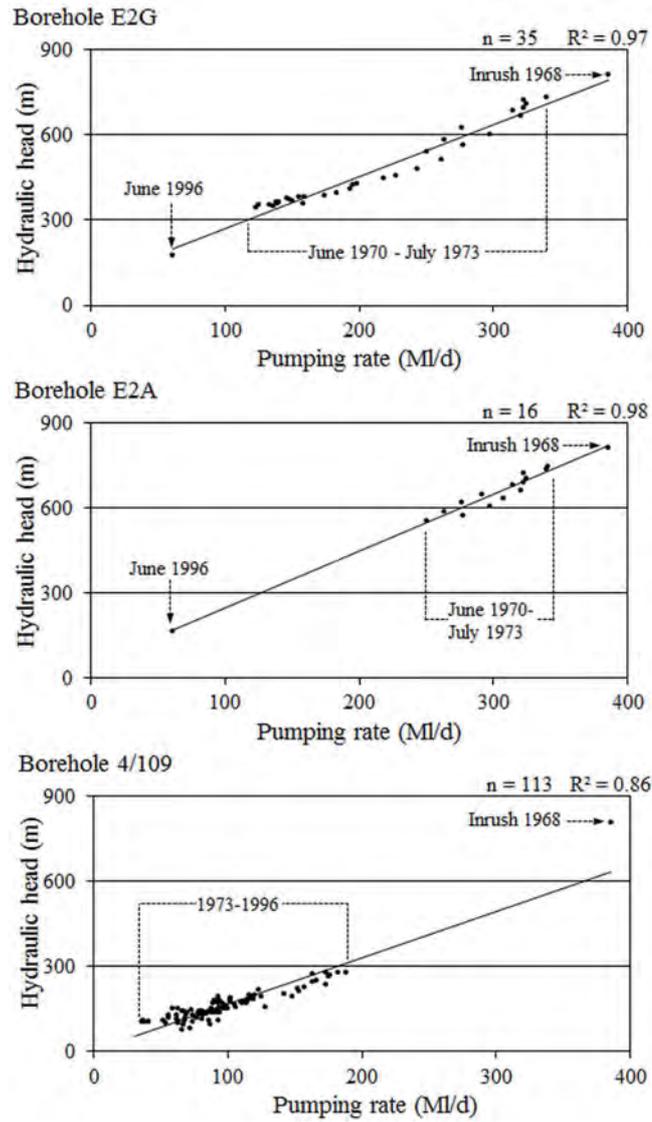


Fig. 5.6 Scatterplots of hydraulic head in boreholes E2G, E2A and 4/109 against pumping rate of West-Driefontein in the Bank Compartment

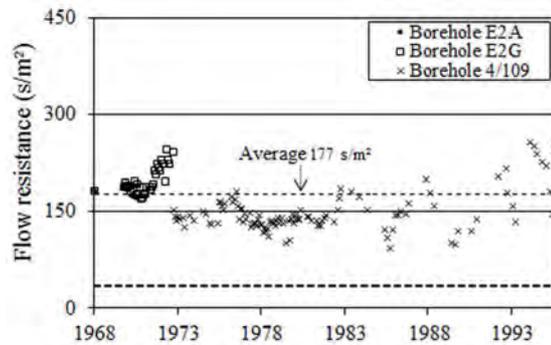


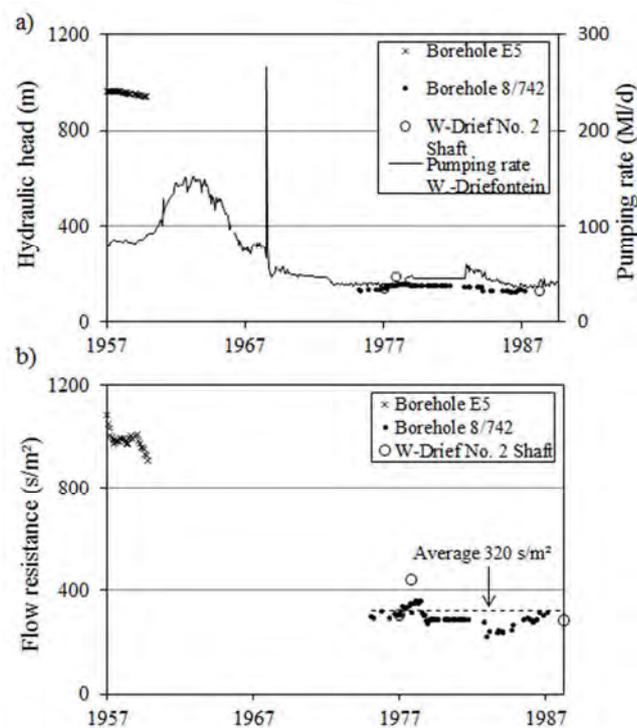
Fig. 5.7 Development of the flow resistance of the downward flow leg in the Bank Compartment during 1968–1996

The flow resistance averages  $177 \text{ s/m}^2$ , which is much higher than the  $35 \text{ s/m}^2$  previously calculated by Swart et al. (2003a). Table 5.2 lists statistic parameters that confirm minor fluctuations (relative standard deviation 8–20 %) that, however, are considered negligible in respect of the span of the underlying time series, the dimension of drawdown and uncertainties associated with the measuring of pumping volumes (as mentioned in the first article of this series).

**Table 5.2** Statistical variation of flow resistance between 1968 and 1996

	E2G	E2A	4/109
Number of data points (n)	35	16	113
Average flow resistance ( $\text{s/m}^2$ )	199	186	147
Min flow resistance ( $\text{s/m}^2$ )	170	171	93
Max flow resistance ( $\text{s/m}^2$ )	252	238	256
Relative standard deviation (%)	11	8	20

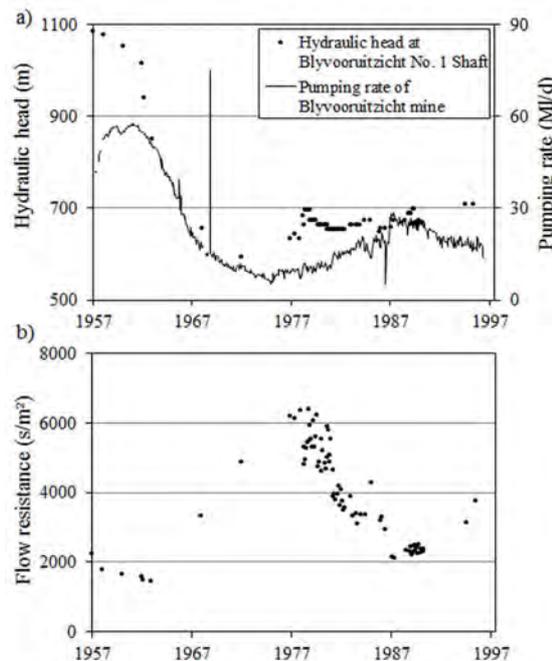
**Bank Dyke, upward leg:** The flow resistance of the upward flow leg in the Oberholzer Compartment was derived from water level measurements in three boreholes/shafts as well as the pumping rate of West-Driefontein mine in the Oberholzer Compartment. Figure 5.8a shows the respective time series. Figure 5.8b displays the calculated flow resistance.



**Fig. 5.8 a** Pumping rate of West-Driefontein in the Oberholzer Compartment and change of hydraulic head measured at three different locations. **b** Development of the flow resistance of the upward flow leg in the Oberholzer Compartment during 1957–1988

The flow resistance resulting from the hydraulic head at No. 2 Shaft and borehole 8/742 averages  $320 \text{ s/m}^2$ . The significantly higher flow resistance in the early years of mining (calculated from water levels measured at borehole E5) is ignored since ingress during that period increased due to the extension of the stoping area [Interdepartmental Committee on Dolomitic Water pumped by Mines, unpublished data, 1958; Wolmarans 1982; Schrader et al. 2014 (part 1)].

**Oberholzer Dyke, downward leg:** The flow resistance of the downward flow leg in the Oberholzer Compartment is estimated from water level measurements at Blyvooruitzicht No. 1 Shaft and the pumping rate of Blyvooruitzicht mine during 1957–1995 (Fig. 5.9a). All water pumped by the mine is allocated to the Oberholzer Compartment, although the mine drew a certain amount of water from the Boskop-Turffontein Compartment (Fig. 5.1). Figure 5.9b shows the development of the flow resistance over time as calculated from the time series above. The flow resistance shows a high variability indicating that the pumping rate and the hydraulic head were not in linear proportion. Figure 5.9a shows an increase of the pumping rate during 1976 and 1988. During the same period of time the hydraulic head shows a rapid increase after which it remains on a more or less constant level. The different progression of the curves causes the peak of the flow resistance in 1978 (Fig. 5.9b). The increase of both the hydraulic head and the pumping rate were most likely caused by an exceptionally high rainfall period in the early-mid 1970s (reported in Swart et al. 2003b).



**Fig. 5.9 a** Pumping rate of Blyvooruitzicht mine and change of hydraulic head measured at Blyvooruitzicht No. 1 Shaft in the Oberholzer Compartment during 1957–1995. **b** Development of the flow resistance of the upward flow leg in the Oberholzer Compartment during 1957–1995

The pumping rate continuously increased even after the hydraulic head peaked, which indicates that the mine pumped additional water that did not ingress into the mine void via the downward leg. Probable sources for the additional water pumped from Oberholzer may include ingress water from the Bank compartment that was diverted to the pumping station in the Oberholzer compartment and surface runoff after heavy rain events entering the mine void via shafts and other vertical conduits that are normally dry. The latter is based on observations underground where turbid waters appeared in the mine void within a few hours to days after heavy rains occurred carrying high loads of reddish soil typically found on surface. However, despite of this fluctuation, the calculated flow resistance, in over 40 years, never fell below  $1,470 \text{ s/m}^2$ . Therefore, this value can be used with confidence for calculating the IGF.

***Oberholzer Dyke, upward leg:*** The Boskop-Turffontein Compartment had never been dewatered, since concerned mines in the area, i.e. Western Deep Levels, Doornfontein and Blyvooruitzicht mine faced little or almost no ingress. To calculate the flow resistance for the upward flow leg in the Boskop-Turffontein compartment the amount pumped by Doornfontein plus half of the volume pumped by Blyvooruitzicht is used. Available pumping figures cover a period from 1986 to 1989 showing a more or less constant pumping rate averaging 17 ML/d (Fig. 5.10). The respective hydraulic head above the mine void, constant over time, approximates 973 m. From that follows a flow resistance of  $4,919 \text{ s/m}^2$  (deviation due to rounded values presented above).

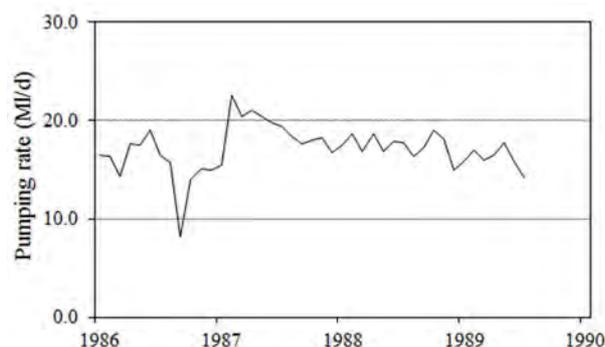


Fig. 5.10 Joint pumping rate of Doornfontein Mine and Blyvooruitzicht mine (50 % of pumping volume) during 1986–1989

### 5.3.2 Calculating the inter-compartmental groundwater flow (IGF)

To calculate the IGF for each of the three dykes, the respective values of the flow resistance (e.g. Venterspost downward leg and Bank upward leg for the flow through the Venterspost dyke) were plugged into Eq. 1. Subsequently the IGF is calculated for two post-mining rewatering

scenarios. In the first scenario, the water table elevation difference between two compartments ( $\Delta h$  in Eq. 1) was estimated from pre-dewatering (natural) water table elevations represented by the elevation of the respective karst springs. A second scenario uses the water table elevation difference between the pre-mining water level of a particular compartment and the Turffontein Eye that would represent the lowest possible water table elevation in a mega-compartment (Fig. 5.2) Table 5.3 lists values of the water table elevation difference for both scenarios. Table 5.4 list results for the IGF<sup>5</sup> for both scenarios.

**Table 5.3** Values for the water table elevation difference between compartments for two scenarios considered in the calculation of the IGF

Compartments	Cross-compartmental differences driving IGF	
	Scenario 1: natural condition (minimum IGF)	Scenario 2: mega-compartment (maximum IGF)
Venterspost-Bank	37	122
Bank-Oberholzer	31	84
Oberholzer–Boskop-Turffontein	54	54

**Table 5.4** Results for the IGF calculated for two post-mining rewatering scenarios assuming pre-mining water table differences (likely) and maximum possible water table differences (unlikely)

IGF across Dyke	Inter-compartmental groundwater flow (IGF) (Ml/d)		Original (pre-mining) spring flow (Ml/d)	IGF (% of original spring flow)	
	Scenario 1: minimum IGF	Scenario 2: maximum IGF		Scenario 1: minimum IGF	Scenario 2: maximum IGF
Venterspost	1.0	3.4	21	4.8%	16.2%
Bank	5.4	14.7	49	11%	30%
Oberholzer	0.7	0.7	54	1.3%	1.3%
Total	7.1	18.8	124	5.7%	15.2

## 5.4 Discussion

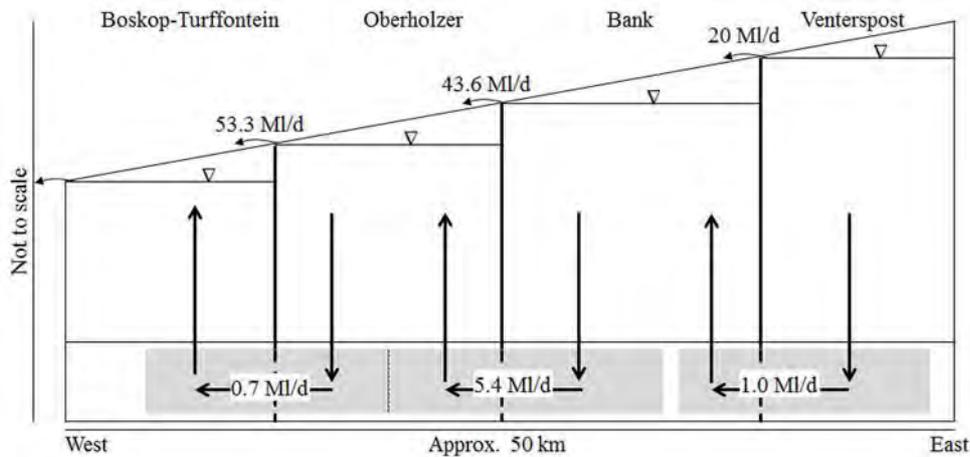
### 5.4.1 The future of the dried-up karst springs

Values of the IGF for both post-mining scenarios, ranging from 0.7 to 14.7 Ml/d, are well below pre-mining spring flow volumes, accounting for 4.8 % (Venterspost Eye), 11 % (Bank Eye) and 1.3 % (Oberholzer Eye) of the corresponding spring flow (21–54 Ml/d). Therefore, it is unlikely that a mega-compartment will form in the FWR (Table 5.4).

<sup>5</sup> Example for the calculation of the IGF through the Venterspost Dyke:

$$\text{IGF} = \frac{37 \text{ m}}{614 \text{ s/m}^2 + 2470 \text{ s/m}^2} = 0.01 \frac{\text{m}^3}{\text{s}} = 1.04 \text{ Ml/d}$$

As a consequence, the continuous influx of surface water replenishing the aquifers in each compartment (recharge) will always exceed the amount of water lost through the pierced dykes resulting in a gradual increase of the groundwater level until the latter intersect the surface where the dried-up springs are located. Discharging the surplus water into the nearby stream the dried-up springs are reactivated even though the discharge volumes will be reduced by the amount lost to downstream compartments. The resulting spring flow volumes are shown in Fig. 5.11. This also means that the pre-mining differences between groundwater levels of adjacent compartments will be re-established.



**Fig. 5.11** Predicted volumes of spring flow and the IGF (ignoring the effects of IGF increasing the recharge rate of receiving downstream compartments)

While the IGF lost from the upstream compartment reduces the flow of the associated spring it simultaneously increases the spring flow in the receiving (downstream) compartment by effectively increasing the groundwater recharge. This interdependence was not considered in Fig. 5.11 to avoid masking the principle aimed to be illustrated. However, owing to the generally small volumes of the IGF compared to spring flow (accounting for 1.3–11 %) those changes are regarded as marginal compared to effects of environmental changes such as the increase of recharge through the presence of sinkholes intercepting surface runoff or the diversion of the Wonderfonteinspruit into a pipeline preventing stream loss recharging the underlying aquifer [Schrader et al. 2014 (part 1)].

However, especially for the Bank eye where losses through the mined-through dykes reach over 10 % of the average spring flow, an unfortunate coincidence of seasonal low flow periods with extended dry spells or even droughts may compromise the perennial nature of spring flow. This is in particular if the Wonderfonteinspruit would remain in the pipeline.

### **5.4.2 Applicability of Darcy's law**

Since Darcy's law was originally derived from observations of porous media its application to karst aquifers and fractured aquifers as are present in this study can, of course, be contested and is not straight forward. Its application for calculating the flow resistance will only deliver reasonable results, if the hydraulic head above the mine void ( $h$ , Eq. 2) is directly proportional to the ingress volume ( $Q$ ). This means that the flow resistance must be (more or less) constant when calculated from a time series of ingress and corresponding hydraulic head (as observed during dewatering). This, in turn, requires that the ingress into the mine void is exclusively controlled by the hydraulic head above the mine void. It also requires that the data used as a proxy for the ingress (in this case the recorded pumping rates of dewatering mines which pump all water that enters the mine void back to surface) as well as the corresponding water level records from borehole monitoring are correct. Lastly, the used data must also be spatially and temporally representative, i.e. the water level drawdown achieved by dewatering must be deep enough to cover the described aquifers and the observation period must be long enough to avoid short-term fluctuation masking the prevailing long-term conditions. Unfortunately, only data pertaining to the downward leg in the Bank Compartment are close to fulfil all of these requirements. Consequently only these data could be used to assess the applicability of Darcy-based flow calculation for that specific aquifer.

Analysing the relationship between ingress rate and overlying hydraulic head for other legs (mines) resulted in a range of deviations from the perfect linear relationship underlying Darcy's law. This may be explained by one or several of the following reasons:

The ingress water pumped to surface by a certain mine originates from more than one compartment (often from two adjacent compartments straddled by the mine void) without records being available to determine what amount originates from each compartment. Furthermore, the ratio of ingress received by each compartment may have changed over time. Usually it is not possible to deduce such shifting ratios from a single set of pumping figures. Thus, pumping figures overestimate the ingress volume from a certain compartment disturbing the relationship with the observed water levels (hydraulic head) in that compartment.

The pumping figures do not only reflect the ingress volume, but may also include additional water from other sources (neighbouring mines, Rand Water) deliberately added by the mines as service water, cooling water, etc. It may also include seepage water from tailings dams placed on top of the drained dolomitic aquifer. Due to the cavernous nature of the dolomite and the many sinkholes present, contributions from tailings seepage to ingress may be considerable in some

cases, especially where tailings were placed deliberately on sinkholes or where sinkholes developed later (as was the case at no. 2 slimes dam of Blyvooruitzicht where 52 sinkholes developed over a period of 11 years, L. Stoch, pers, communication). This too would result in an overestimation of attributable ingress and thus disturb a linear relationship with the observed hydraulic head.

Pumping rates may not truly reflect the ingress volume as pumping volumes were not directly gauged but derived indirectly from metered electricity consumption of pumps and calculated based on pump capacity and efficiency coefficients. The latter are generally regarded as constant even though they are not and usually decrease in the life-time of pumps resulting in a slight underestimation of true pumping (= ingress) rates (Winde et al. 2006).

The ingress volume at some mines is not only determined by the hydraulic head but also depends on other factors, such as the size of the mined out stoping area at which the water-bearing fissures were intersected (Wolmarans 1982). This aspect, comprehensively described in the first part of these articles, mainly appears when the stoping area extends close to the dolomite (high-ingress zone) as was the case at the East-Driefontein gold mine. Once mining proceeds to greater depths the shielding effect of a wedge of impermeable Ventersdorp Lava increasingly prevents groundwater ingress at lower mining levels (no-ingress zone).

Some water, especially during periods of heavy rainfall, may also be conducted via other pathways than the fractures and fissures in the aquifer. Ingress was observed to enter the void directly via vertical structure such as shafts. As the rate of this ingress is not dependent on the hydraulic head in the (by-passed) aquifer it also disturbs a linear relationship between the two parameters.

## **5.5 Conclusions and recommendations**

As the second part of a two-part series this paper investigated the probability of the suggested formation of a mega-compartment in the FWR goldfield as a result of piercing impermeable dykes by deep-level gold mining by calculating the actual flow rate of groundwater across the dykes. These calculations were based on the assumption that the flow rate through a combined system of relatively large conduits of karstified dolomite on top and much smaller fissures in unweathered solid dolomite below are directly proportional to each other (i.e. increasing hydraulic heads cause increasing ingress). While this is the case in porous aquifers with laminar water flow as stated in Darcy's Law, it was by no means certain that the same principle is applicable to a combined system of a karst aquifer and a fractured aquifer where different types of water flow are likely to occur. Nevertheless, the approach was applied following an earlier study by Swart et

al. (2003a) that found a mega-compartment being unlikely to form based on a case study of a single dyke. This finding is now confirmed by the present study proving for all dykes and compartments that the IGF will not be high enough to exceed the influx of surface water as prerequisite for a mega-compartment to form. Compared to Swart et al. (2003a) this study not only considered all dykes instead of only one but is also based on significantly larger data sets increasing the robustness of the finding considerably. It also allowed replacing some speculative assumptions in Swart et al. (2003a) by more realistic ones.

The increased confidence in the finding is all the more important as the future of the springs is a crucial aspect in granting mine closure certificates as well as for developing post-closure water management strategies. Apart from water availability and corresponding land use this information will also be crucial for predicting the volumes and outflow points of acidic mine water which currently poses a serious threat in other (mined out) goldfields of the Witwatersrand basin especially in and around the metropolitan areas of Johannesburg.

A second major aspect of the study was to assess the applicability of an approach based on Darcy's law originally developed for laminar flow in homogenous porous media. While Swart et al. (2003a) applied such approach they did not provide any indication that this is indeed justified. This was achieved in this study by analysing a large number of data not evaluated before. Despite the fact that the investigated compartments represent combined karst-fractured aquifers, whose turbulent flow in conduits is not covered by Darcy's law, it was found that the observed groundwater flow in several instances behaves according to Darcy's law, i.e. flow volumes are directly proportional to the associated hydraulic head. This, we believe, provides a sound base for the application of the Darcy-based approach in this study instilling confidence in the obtained results.

The study also identified plastic closure of deeper parts of the horizontal mine void infrastructure (especially the poorly supported stoping areas) as a point not considered so far. As a result of the enormous pressure of the overlying rocks the phenomenon of plastic closure of void parts is likely to further restrict the groundwater flow between compartments making the formation of a mega-compartment even more improbable.

It is thus concluded with a reasonable degree of confidence that, despite remaining uncertainties, all dried-up karst springs will be reactivated once deep mining operations cease and the dewatered compartments are allowed to fill up with water again. The time required for rewatering to be completed will depend on a range of factors such as recharge rates and size of the final

mine void that should be determined as soon as possible as this is important for the pro-active preparation of the inevitable closure of mines.

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## 5.6 References

- Cartwright AT (1969) West Driefontein - ordeal by water. J.G. Ince & Son Pty Ltd, Gold Fields of South Africa
- Cousens RRM, Garrett WS (1969) The flooding at the West Driefontein mine. *South Afr Inst Min Metall* 69:421–463
- de Kock WP (1964) The geology and economic significance of the West Wits Line. *The Geology of some ore deposits in Southern Africa*. Geol Soc S Afr, Johannesburg, pp 323–386
- Jordaan JM, Enslin JF, Kriel J, Havemann A, Kent LE, Cable WH (1960) Final report of the Interdepartmental Committee on Dolomitic Mine Water: Far West Rand. Department of Water Affairs and Forestry, Pretoria
- Schrader A, Winde F, Erasmus E (2014) Using impacts of deep level mining to research karst hydrology—a Darcy-based approach to predict the future of dried-up dolomitic springs in the Far West Rand goldfield (South Africa). Part 1: a conceptual model of recharge and inter-compartmental flow. *Environ Earth Sci*. doi:10.1007/s12665-014-3263-0
- Swart CJU, James AR, Kleywegt RJ, Stoch EJ (2003a) The future of the dolomitic springs after mine closure on the Far West Rand, Gauteng, RSA. *Environ Geol* 44:751–770
- Swart CJU, Stoch EJ, van Jaarsveld CF, Brink ABA (2003b) The lower Wonderfontein Spruit: an exposé. *Environ Geol* 43:635–653
- Todd DK (1959) *Ground water hydrology*. Wiley, New York
- Usher BH, Scott R (2001) Post mining impacts of gold mining on the West Rand and West Wits Line, Chapter 5. In: Hodgson FDI, Usher BH, Scott R, Zeelie S, Cruywagen LM, de Necker E (ed) *Prediction techniques and preventative measures relating to the post-operational impact of underground mines on the quality and quantity of groundwater resources*. WRC Report No. 699/1/01. Water Research Commission, Pretoria, pp 5.1–5.117
- Winde F, Stoch EJ, Erasmus E (2006) Identification and quantification of water ingress into mine voids of the West Rand and Far West Rand Goldfields (Witwatersrand basin) with a view to long-term sustainable reduction thereof. Final report, Project No. 5512, Council for Geoscience, Pretoria
- Wolmarans JF (1982) *The least unsafe route*, vol 1. Webb and Partners, Carletonville



## **6 Synoptic conclusion**

### **6.1 Summary**

Karst aquifers that developed in soluble rocks such as limestone or dolomite occur in many parts of the world. Often yielding large quantities of good-quality groundwater they represent an important natural water resource especially in semi-arid countries such as South Africa. For the sustainable utilisation of this resource proper management and understanding of karst hydrology are essential (Chapter 1). This, however, is often problematic as karst aquifers are characterised by turbulent groundwater flow in networks of large solution conduits and are highly heterogeneous and anisotropic systems fundamentally differing from porous or fractured aquifers. Therefore, understanding the hydrologic behaviour of complex karst systems in many cases necessitates special methodological approaches described in detail in Chapter 2.

Against this background the thesis investigated and discussed the impacts of deep-level mining on a fractured-karst aquifer developed in up to 1200 m-thick dolomites located in the Far West Rand (FWR) near Johannesburg, South Africa. Despite storing significant volumes of groundwater, the aquifer was neither utilised nor adequately managed since the early 20<sup>th</sup> century after industrial deep-level mining arrived in the region. This was because the aquifer had been dewatered to a large degree, in order to enable economic and safe extraction of gold deposits situated below a water column of several hundred meters in the overlying dolomitic aquifer.

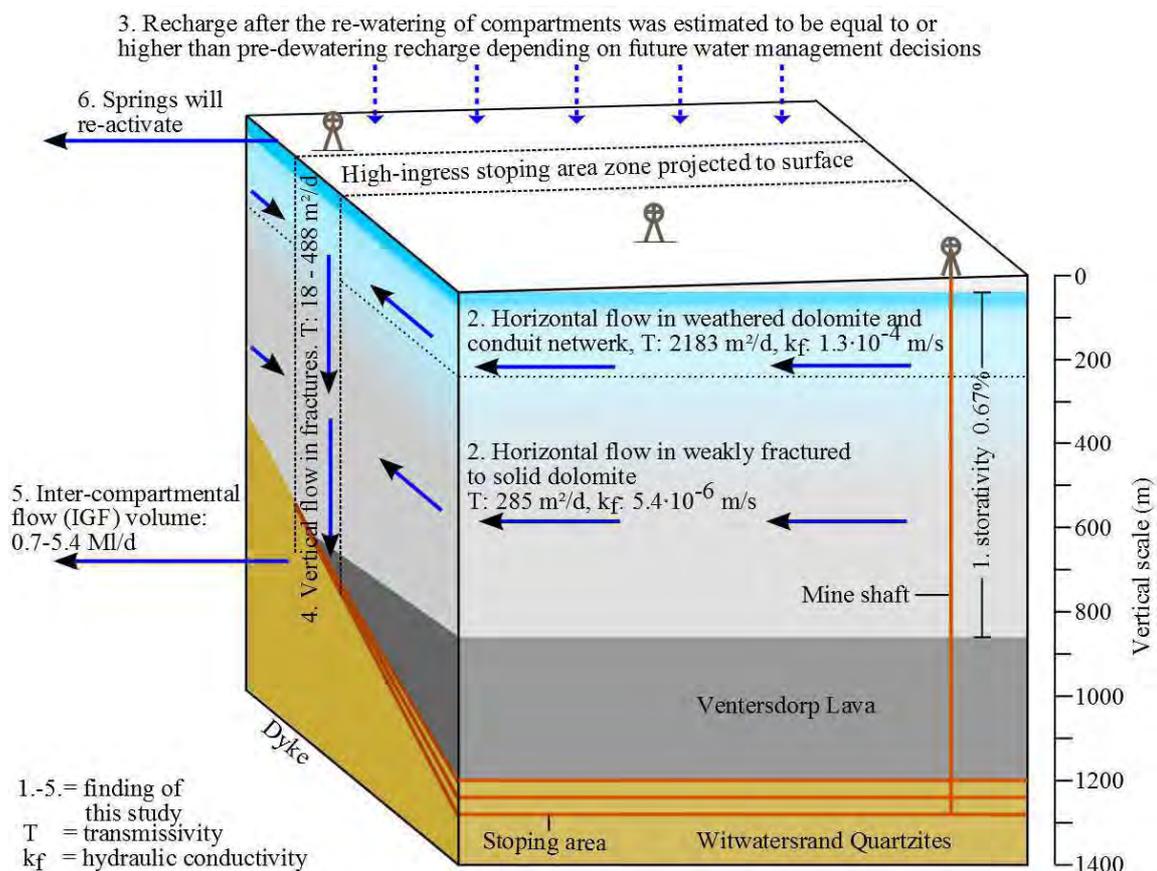
As all mines will successively close down over the next few decades or so, a sustainable management of the aquifer based on a thorough understanding of its hydrology will be necessary to prepare pro-actively for future water management. This even more so in the face of current examples in the West, Central and East Rand goldfields where highly contaminated acidic mine water floods abandoned mine voids causing damage to the receiving environment and enormous amounts of associated costs for eternal pump-and-treat based coping strategies. To avoid a similar scenario playing out in the most water rich of all remaining active goldfields future water management in the Far West Rand needs to consider a situation when the artificial draining of the aquifer has stopped, and the mine voids as well as the overlying dolomitic aquifer are flooded with infiltrating groundwater. Achieving an adequate aquifer management in the future requires shifting the emphasis away from gold exploitation towards defining a pro-active mine closure strategy while mines are still in operation. Yet, formulating the necessary steps faces difficulties owing to some critical gaps in understanding the long-term impacts more than six decades of

deep-level mining had on the intertwined ground- and surface water hydrology of the region. This thesis aims to fill some of these gaps. The thesis' main objective is to predict the effects of mining on the water level after re-watering of the dolomites, considering the fact that mines, by penetrating naturally impermeable dykes, created hydraulic linkages between formerly separated groundwater compartments. These linkages, situated on mine void level well below the dolomites, could merge the currently dewatered dolomitic compartments into one large 'mega-compartment'. In such a scenario pre-mining water table differences between compartments would not re-establish, but a corresponding single water table across all affected compartments would form that would remain well below its pre-mining level. This would not only affect water quality and ground-stability issues, but would also be critical for water availability on surface as it would prevent three high-yielding karst springs, currently dry due to the dewatering of compartments, from ever flowing again. This has also important ramifications for prospective land-use and water management strategies, not least because the re-activation of springs, which will not happen in a 'mega-compartment' scenario, was made a pre-condition for governmental permission to close the mines.

To respond to the issue whether natural water tables will re-establish after the re-watering of compartments or not, this thesis comprehensively characterised the dolomitic aquifer including the underlying mine void and the relevant surface hydrology. For that purpose it relied largely on historical data predominantly originating from the large-scale dewatering of the compartments. Having been collected during non-repeatable events (such as the dewatering or a major accidental mine flooding event), the analysed data are in many regards unique. Therefore in Chapter 2 it was pointed out the urgent need for creating a modern electronic database in order to prepare and consolidate existing relevant data as well as the extensive amount of (mostly unpublished) studies generated by more than six decades of hydrological research in the FWR. This would not only be desirable from a scientific point of view, but greatly assist with designing appropriate long-term water and land use management strategies for the preparation of mine closure and post-closure development concepts after the mines. This even more so as it was the lack of proactive planning and the hap-hazard approach to mine closure that resulted in the current situation experienced in all three major mining basins in and around Johannesburg, where the pumping and treating of highly polluted acidic mine water is bound to burden the taxpayer for eternity.

For the analysis of the data, the study employed mainly methods based on Darcy's law. While the latter was designed for saturated flow in homogenous porous media, various examples in the scientific literature demonstrated that it can be successfully used in karst aquifers provided the

spatial scale of the investigation is sufficiently large. As this prerequisite was met in this study, considering a monitored drawdown of several hundreds of meters over several tens of square kilometres of surface area, historical data never utilised before have been used to add another example of successfully applying Darcy's law to non-Darcy conditions meeting the second major objective of the study. The evaluation of the data comprises a pumping test analysis (Chapter 3), a conceptual and semi-quantitative analysis of groundwater recharge (Chapter 4), the conceptualisation and quantitative prediction of the groundwater flow that will establish between the re-watered dolomitic compartments, i.e. the inter-compartmental groundwater flow (IGF), and finally the prediction of post-mine flooding water tables (Chapters 4+5). The following section briefly summarises the essential findings of the individual chapters. Additionally the most important results are graphically captured and condensed in the 3D-geological section below (Fig. 6.1). For details pertaining to the outlined results the respective chapters may be consulted.



**Fig. 6.1** Conceptual model of a geological section of the dolomitic compartments of the FWR karst aquifer illustrating selected findings on groundwater flow conditions after mining stopped and the dewatered compartments filled up with water again

Chapter 3 approached the hydrology of an individual compartment, i.e. the Bank Compartment. It dealt with the question whether drawdown data from the draining of the aquifer as well as

from an accidental mine flooding event (in 1968) can be analysed as an analogy to an ultra-large (long-term) pumping test in order to derive hydraulic parameters of the dolomite aquifer, namely the horizontal transmissivity and the storage coefficient. The employed methods were well-established analytical methods based on Darcy's law as well as the software tool MLU (Multi-layer Unsteady state, Hemker and Post 2012).

From the analysis an average storativity of 0.67% ( $S$  in Fig. 6.1) was obtained that was used to estimate a total water volume of 923 Mm<sup>3</sup> stored in the dolomites of the Bank compartment. Results for the horizontal transmissivity ( $T$ ) (average 2468 m<sup>2</sup>/d) varied approximately one order of magnitude between the three analysed data sets. This was explained by the different zones of the drawdown covered by the respective data sets. In one data set the highly permeable zone in the uppermost dolomite was drained at the onset of the observed period. Therefore the results predominantly reflected the zone of weakly fractured to solid dolomite starting approximately 200 m below the original water table (Fig. 6.1).

Although some deviations of the data curves from the applied models indicated that the analytical methods do not accurately reflect the groundwater flow, the obtained hydraulic parameters were in general within a realistic range for the investigated fractured-karst aquifer and confirmed results of previous studies.

Chapter 4 provides a conceptual model of the hydrology of the compartments in respect of the possible formation of a 'mega-compartment'. In particular, it focused on the groundwater recharge and the IGF that will occur between individual groundwater compartments after the filling-up of the mine void and the overlying dolomites. The major outcomes from Chapter 4 can be compiled as follows:

- The **ratio of recharge and the IGF** will determine the final water table after re-watering. Theoretically several **water table scenarios** are possible. This includes full recovery of pre-mining water tables, equalisation of fully corresponding water tables (mega-compartment) and intermediate water table elevations somewhere in-between those extremes.
- From the evaluation of several hydrological studies, a historical **pre-dewatering water balance** was compiled, showing the situation around the middle of the 20<sup>th</sup> century. As part of the water balance individual re- and discharge components (e.g. base flow, recharge from upstream spring flow, recharge from rainfall) had been quantified.
- A conceptual water balance for both the present and post-mining period was created and subsequently used to evaluate several **post re-watering groundwater recharge scenarios**.

Findings suggest that recharge will depend to a large extent on management decisions such as the consumption of spring flow or the retaining or dismantling of a 30 km-long pipeline established in 1977. By inference, **recharge was estimated to be higher (3)** than pre-mining recharge due to some irreversible changes of the hydrogeology such as the abundant development of sinkholes and the piercing of dykes on mine void level.

- An existing model of the IGF (Swart et al. 2003) was modified by introducing a more realistic concept for the **dependency of fissure water (ingressing into the mine void) from the size of the stoping area**. A mathematical approach was used to show that ingress is restricted only to certain parts of the mine void, termed in this study ‘high-ingress stoping area’ (Fig. 6.1). The point in time was estimated when ingress volumes were affected by expanding the stoping area. This allows for a more accurate evaluation of historical pumping and drawdown figures.

In Chapter 5 the IGF was quantified on the basis of historical pumping figures and water level drawdown data in order to assess the probability of a ‘mega-compartment’ to form. The applied methodological approach was based on Darcy’s law and followed the conceptual model of Swart et al. (2003) assuming that the IGF will be restricted by the flow resistance (i.e. reciprocal of transmissivity) of the fracture zone through which water is transported towards the mine void (Fig. 6.1). In contrast to Swart et al. (2003) who applied Darcy’s law without providing a scientific justification in this chapter data were analysed before being used whether or not they indeed comply with the fundamental relationship between hydraulic head and flow rate stipulated by Darcy. The flow resistance was determined for all affected compartments (4). Subsequently it was used to calculate the IGF. Results for the IGF (5) range from 0.7-5.4 Ml/d, whereas the minimum and maximum value was calculated for flow through the Oberholzer dyke and the Bank dyke, respectively. The results show that the IGF will be distinctly lower than the expected groundwater recharge volumes. From that it follows that a ‘mega-compartment’ will not form in the FWR goldfield, but after mines stop abstracting water from the compartments, the latter will gradually re-water until natural pre-mining water tables are re-established and the karst springs on surface start flowing again (6).

## 6.2 Discussion and recommendations

The approach used to characterise the groundwater flow in the investigated groundwater compartments can be summarised in a basic conceptual model, where exclusively vertical groundwater flow prevails in the centre of the depression cone that formed as a result of draining the aquifer. The centre of the depression cone forms above the part of the mine void referred to as

‘high-ingress stoping area’ (Fig. 6.1). In a zone dominated by horizontal flow conditions, groundwater is transported towards the vertical flow zone. Both zones are connected by a zone of mixed flow conditions<sup>1</sup>. The groundwater flow in each zone was approached separately, whereas it was considered as a homogeneous equivalent porous medium characterised by laminar groundwater flow.

However, separating the heterogeneous karst aquifer into homogeneous zones with exclusively horizontal and/or vertical flow is an oversimplification. Furthermore evaluating groundwater flow in karst aquifers by applying an equivalent porous medium approach based on Darcy’s law is often considered as problematic (Chapter 2). Therefore the validation of the used methods still needs to be further explored. The results for the vertical groundwater flow between the dolomitic aquifer and the mine void (Chapter 5) were encouraging. In this case the match of the data curves with the predictions from Darcy’s law indicates that the conceptual model of the used method describes the situation with a sufficient accuracy. Nevertheless, it should be tested in a follow-up study, if the observed match with Darcy’s law can be extrapolated using more recent data.

Some uncertainties remain as to the pumping test analysis and the resulting hydraulic parameters that describe the horizontal groundwater flow in the aquifer (Chapter 3). Although realistic results were obtained, some discrepancies occurred between the type curves of the used analytical methods and the real data curves. In order to evaluate the quality of the results and thus the applicability of Darcy-based methods, it is recommended that the data be analysed with analytic or even numeric methods specifically designed for karst or fractured aquifers and subsequently compare the results.

The study also included a water balance study of the concerned compartments, aiming towards the conceptual and semi-quantitative assessment of post-mining groundwater recharge. The investigation showed that anthropogenic interferences to the surface and subsurface hydrological system caused ongoing changes over the past decades, which also includes irreversible changes of the natural groundwater recharge conditions. This makes the prediction of groundwater recharge difficult, which is insofar relevant as groundwater recharge is –in addition to the IGF – the second most important factor determining post-mining water tables and thus spring flow and finally the water availability on surface. Even though it follows from the low volumes of the IGF that springs will re-activate, the exact determination of groundwater recharge would be desirable

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<sup>1</sup> In the case of the Bank Compartment the vertical flow zone has a radius of 1147 m, i.e. the distance from the centre of the depression cone to the furthestmost considered observation borehole (Chapter 5). The horizontal flow zone stretches between 2000 and 6000 m around the centre of the depression cone (Chapter 3).

in order to predict more accurately volumes of spring flow. The first requirement to achieve this would be a comprehensive water management program with the associated monitoring of artificial water consumption, import and export. As a second step, the previous recharge assessments, largely based on proxy-variables (spring flow, pumping volumes), should be supplemented with the measurement or at least the assessment of individual recharge components, in particular those that were permanently altered due to the dewatering of the compartments, such as additional groundwater recharge at sinkholes. Quantifying those components would be a major component towards the reassessment of groundwater recharge and spring flow.

Finally it is emphasised that the re-establishing of pre-mining groundwater tables and the re-activation of springs is expected to have far reaching environmental consequences for the FWR region. This may include for example implications for (a) the inter-action of re-watered compartments with contaminated surface water / mine tailings, (b) the formation and draining of acidic mine water and (c) the development of sinkholes and related aspects of ground-stability. Being ecologically and economically significant, these issues need to be addressed in follow-up research that ideally would lead to a comprehensive mine closure strategy. The magnitude of this challenge once more highlights the need for the implementation and/or strengthening of independent, long-dated and problem orientated basic research in the FWR.

### **6.3 References**

- Hemker K, Post V (2012) MLU for Windows. Well flow modeling in multilayer aquifer systems. Amsterdam. 30 pp. <http://www.microfem.com/download/mlu-user.pdf> (Cited 7 Nov. 2013)
- Swart CJU, James AR, Kleywegt RJ, Stoch EJ (2003) The future of the dolomitic springs after mine closure on the Far West Rand, Gauteng, RSA. *Environ Geol* 44(7):751–770