ORIGINAL ARTICLE

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

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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^2 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

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. 1).

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)

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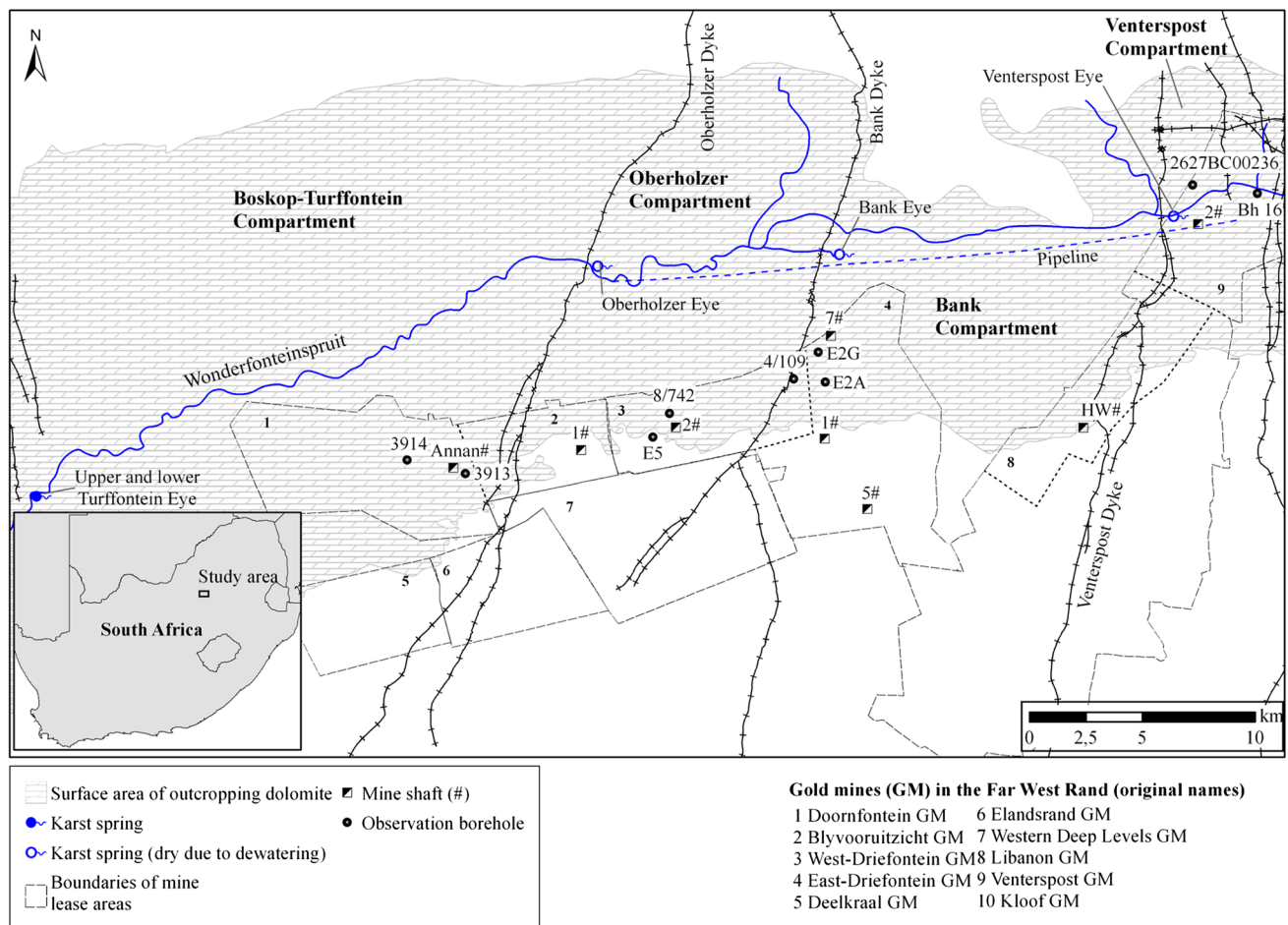e-mail: geotech@netactive.co.za

Fig. 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

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
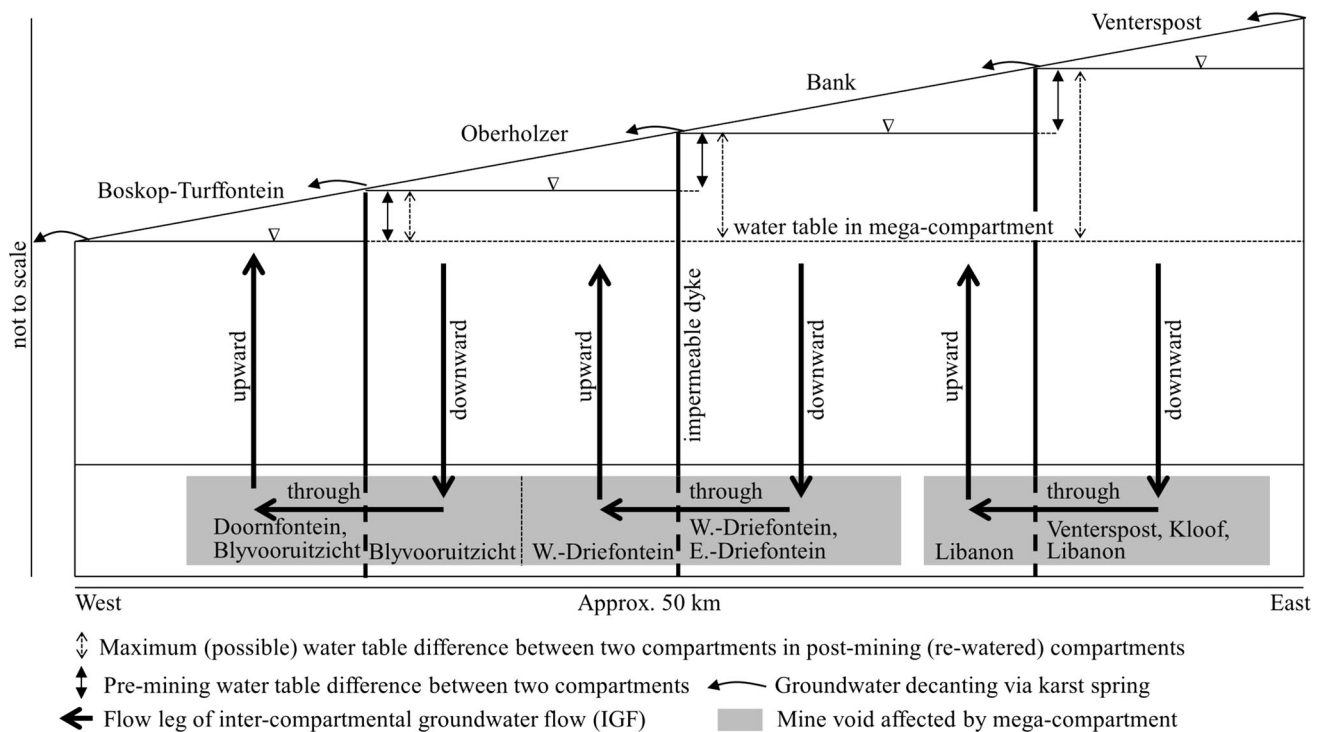
Fig. 2 Conceptual model of the IGF illustrating the various legs for which the flow resistance need to be determined as well as the name of the gold mines that pumped from the various compartments

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.

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. 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 (Δh) and can be calculated by the equation below (Swart et al. 2003a):

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

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

Δh = water level difference between upstream and downstream compartment (m)

r = flow resistance[1] 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:

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

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.[2] Thus, to determine the IGF, the flow resistance for each of the relevant legs needs to be calculated first.

Determining the IGF of all dewatered compartments

The determination of the IGF requires two steps:

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

Calculating flow resistance of down- and upward legs in dewatered compartments

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

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).[3] Table 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

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[1] Simplified expression of the term $\frac{l}{k*A}$ whereas l = *flow path length of through-flow media*, k = *hydraulic conductivity (m/s)*, A = *cross-sectional area of flow path (m^2)*.

[2] 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

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Footnote 2 continued

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.

[3] 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 1 Data used for the calculation of flow resistance for up-and downward legs in each of the relevant compartments including results

Compartment *Dyke*	Flow leg	Underlying period for estimation of flow resistance	Range of observed water table (mamsl) (Difference)	Approx. depth at which ingress occurred[a] mamsl	Location[b]	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 (Ml/d)	Number of data pairs (WL – puming rate)	Calculated flow resistance (s/m²)
Venterpost Compartment *Venterspost Dyke*	down	1979-1987 (8 years)	1419-1476 (47 m)	935	Intersection Venterspost No. 2 Shaft and Ventersdorp Contact Reef[e]	484-551 (9)	2 (*Venterspost No. 2 Shaft, Bh 16*)	Venterspost, Libanon Kloof[e]	64-78	101	614
Bank Compartment	up	1979-2006 (27 years)	831-1036 (205 m)	400	Intersection of Harvie Watt Shaft and base of dolomite[c]	431-636 (32)	1 (*Libanon Harvie Watt Shaft*)	Libanon	10-38	193	2470
Bank Compartment *Bank Dyke*	down	1968-1996 (28 years)	771-1504 (732 m)	693	Inrush depth at Big boy fault[d]	78-810 (90)	3 (*E2A, E2G, 4/109*)	West-Driefontein	30-386	164	177
Oberholzer Compartment	up	1975-1988 (13 years)	622-690 (68 m)	499	Intersection of West-Driefontein No. 2 Shaft and base of dolomite[c]	123-191 (36)	2 (*8/742, West-Driefontein No. 2 Shaft*)	West-Driefontein	34-59	98	320
Oberholzer Compartment *Oberholzer Dyke*	down	1957-1995 (38 years)	975-1465 (490 m)	380	Intersection of Blyvooruitzicht No. 1 Shaft and base of dolomite[c]	595-1085 (45)	1 (*Blyvoor-uitzicht No. 1 Shaft*)	Blyvooruit-zicht	5-75	80	1470
Boskop-Tfnt. Compartment	up	1986-1989 (3 years)	1423 (0 m)	450	Intersection of Annan Shaft and base of dolomite[c]	973 (0)	2 (*3913, 3914*)	Doornfontein, Blyvooruit-zicht	17	2	4919

[a] Used to transfer water level measurements (in mamsl) into values of hydraulic head above the mine void (m)

[b] 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

[c] de Kock (1964), [d] derived from Cousens and Garrett (1969)

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

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/m², as the flow resistance is the reciprocal of the transmissivity, which is usually given in m²/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 Research Group, email-conversation, 12 Mrz 2011). Figure 3a
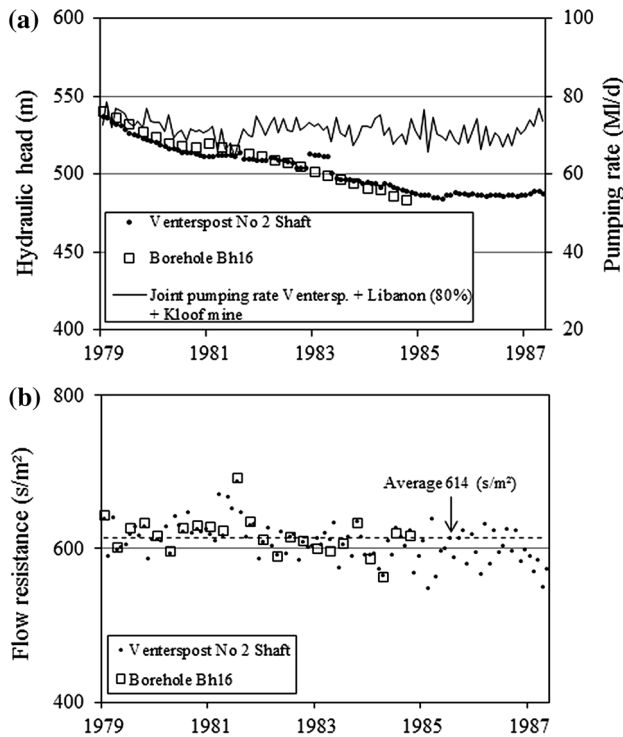
Fig. 3 a Estimated joint pumping rate of Venterspost, Libanon and Kloof mine from the Venterspost Compartment and change in hydraulic head derived from water level measurements in Venterspost No. 2 Shaft and borehole Bh16 during 1979–1987 b Development of flow resistance for the downward leg in the Venterspost Compartment during 1979–1987

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. 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 mega-compartment 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 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/m². Given the low fluctuation in Fig. 3b, a constant flow resistance around this value appears to be plausible and therefore is used to calculate the IGF.

Venterspost Dyke, upward leg

The flow resistance of the upward flow leg in the Bank Compartment (Fig. 2) was determined from the pumping
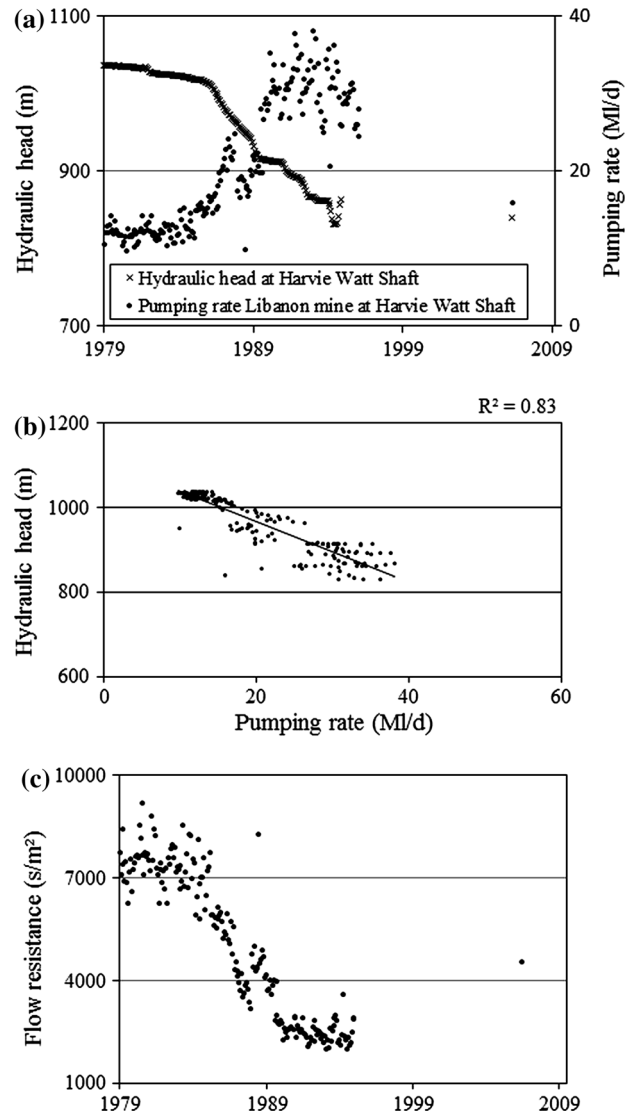

Fig. 4 Diagrams showing **a** time series and **b** *scatter plot* of the pumping rate at Libanon Harvie Watt shaft and the hydraulic head derived from water level measurements in the same shaft during 1979–2006 in the Bank Compartment **c** Development of flow resistance for the upward leg in the Bank Compartment during 1979–2006

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 4a shows the pumping rate and the corresponding hydraulic head at Harvie Watt Shaft.

The pumping rate increased while the hydraulic head decreased (Fig. 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
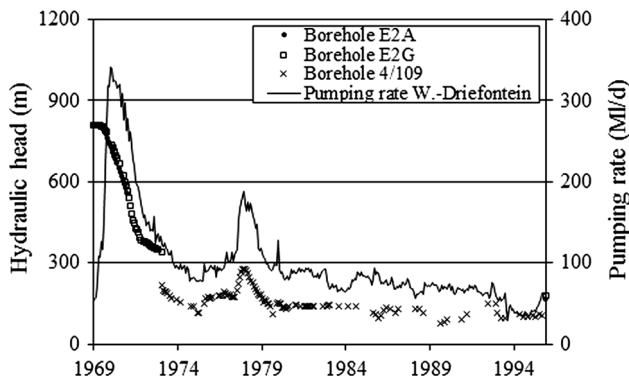
Fig. 5 Time series of the pumping rate of West-Driefontein and the corresponding change in hydraulic head recorded in three boreholes during 1969–1996
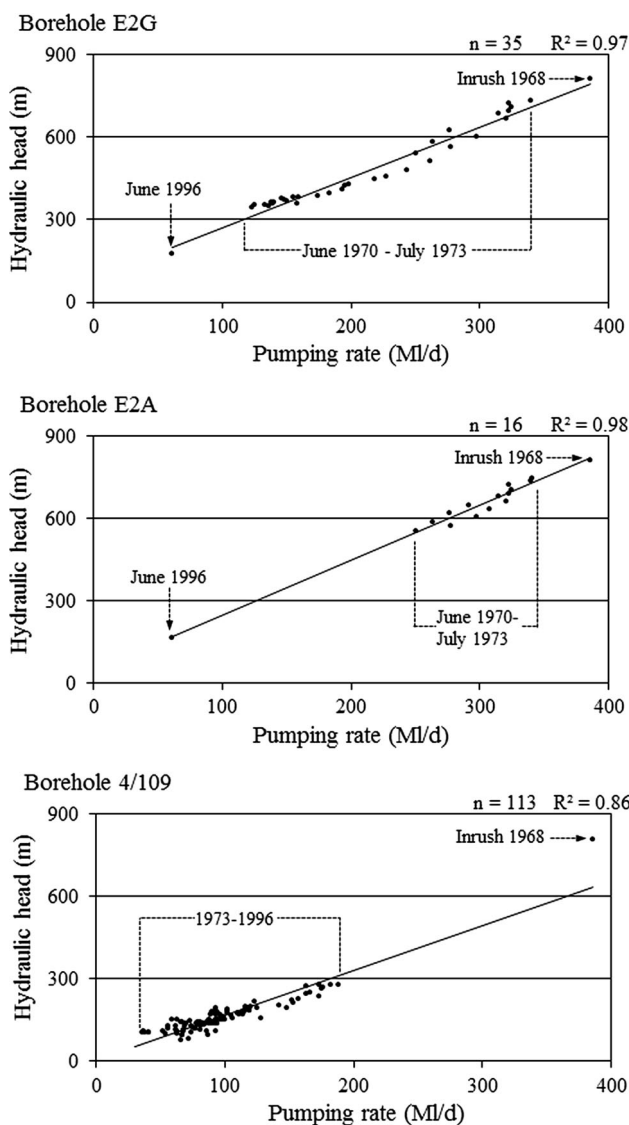

Fig. 6 *Scatterplots* of hydraulic head in boreholes E2G, E2A and 4/109 against pumping rate of West-Driefontein in the Bank Compartment

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'.

Figure 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^2. 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 shows the pumping rate during dewatering and the corresponding drawdown observed in three boreholes.

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 6 shows scatterplots of the hydraulic head against the pumping volume[4] 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 7 shows the flow resistance as calculated

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[4] 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.
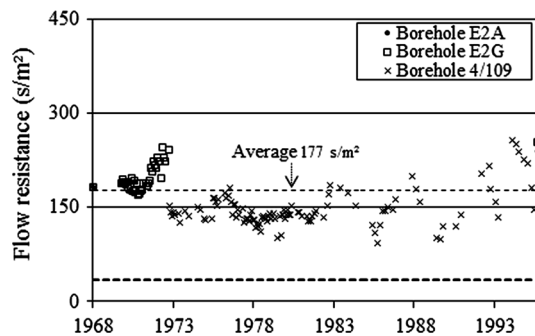
Fig. 7 Development of the flow resistance of the downward flow leg in the Bank Compartment during 1968–1996

Table 2 Statistical variation of flow resistance between 1968 and 1996

	E2G	E2A	1/109
Number of data points (n)	35	16	113
Average flow resistance (s/m^2)	199	186	147
Min flow resistance (s/m^2)	170	171	93
Max flow resistance (s/m^2)	252	238	256
Relative standard deviation (%)	11	8	20

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), 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.

The flow resistance averages 177 s/m^2, which is much higher than the 35 s/m^2 previously calculated by Swart et al. (2003a). Table 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).

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 8a shows the respective time series. Figure 8b displays the calculated flow resistance.
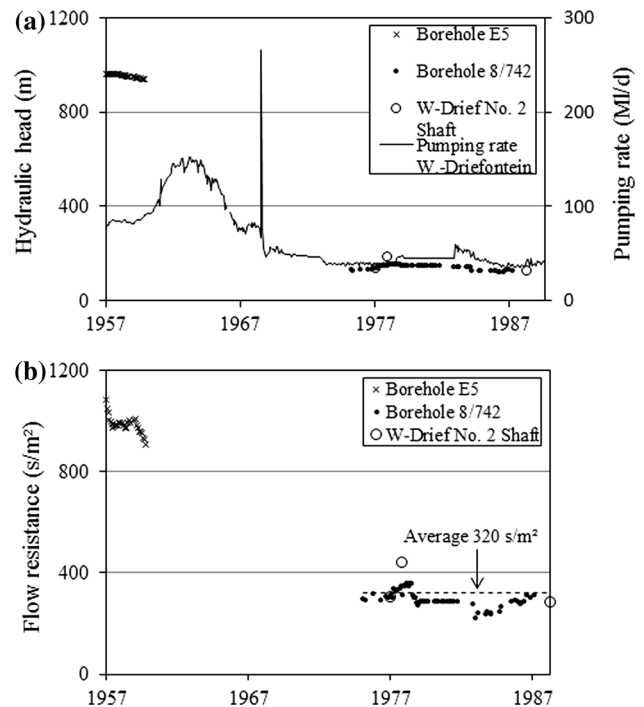

Fig. 8 a Pumping rate of West-Driefontein in the Oberholzer Compartment and change of hydraulic head measured at three different locations. b Development of the flow resistance of the upward flow leg in the Oberholzer Compartment during 1957–1988

The flow resistance resulting from the hydraulic head at No. 2 Shaft and borehole 8/742 averages 320 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. 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. 1). Figure 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 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
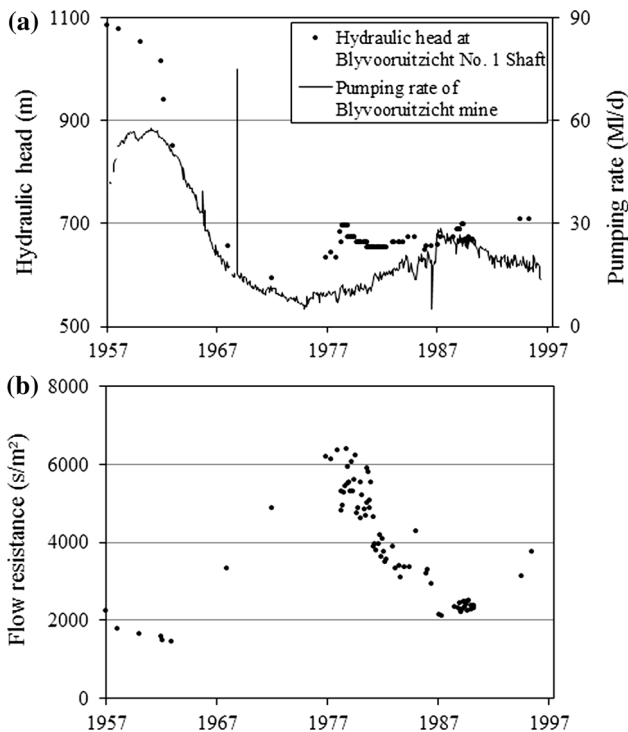
Fig. 9 **a** Pumping rate of Blyvooruitzicht mine and change of hydraulic head measured at Blyvooruitzicht No. 1 Shaft in the Oberholzer Compartment during 1957–1995. **b** Development of the flow resistance of the upward flow leg in the Oberholzer Compartment during 1957–1995

Fig. 10 Joint pumping rate of Doornfontein mine and Blyvooruitzicht mine (50 % of pumping volume) during 1986–1989

Table 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-compartments (maximum IGF)
Venterspost–Bank	37	122
Bank–Oberholzer	31	84
Oberholzer–Boskop-Turffontein	54	54

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. 10).

The respective hydraulic head above the mine void, constant over time, approximates 973 m. From that follows a flow resistance of 4,919 s/m^2 (deviation due to rounded values presented above).

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 (*Δh* in

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. 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). 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 s/m^2. Therefore, this value can be used with confidence for calculating the IGF.
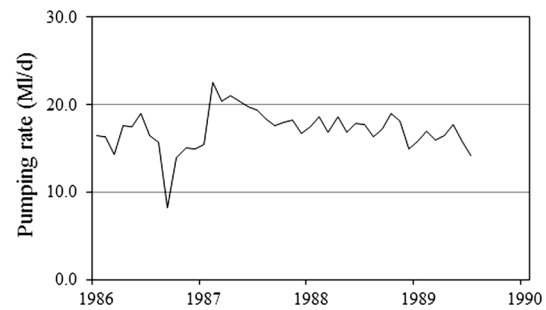
Table 4 Results for the IGF calculated for two post-mining rewatering scenarios assuming pre-mining water table differences (likely) and maximum possible water table differences (unlikely)

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

Fig. 11 Predicted volumes of spring flow and the IGF (ignoring the effects of IGF increasing the recharge rate of receiving downstream compartments)
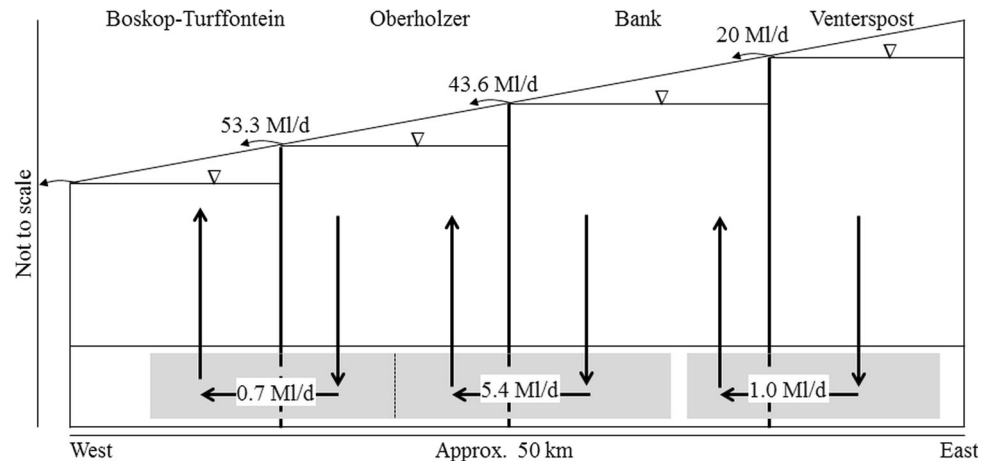
Eq. 1) was estimated from pre-dewatering (natural) water table elevations represented by the elevation of the respective karst springs. A second scenario uses the water table elevation difference between the pre-mining water level of a particular compartment and the Turffontein Eye that would represent the lowest possible water table elevation in a mega-compartment (Fig. 2) Table 3 lists values of the water table elevation difference for both scenarios.

Table 4 list results for the IGF[5] for both scenarios.

Discussion

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 4).

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[5] Example for the calculation of the IGF through the Venterspost Dyke: $IGF = \frac{37m}{614 s/m^2 + 2470 s/m} = 0.01 \frac{m^3}{s} = 1.04 Ml/d$.

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. 11.

This also means that the pre-mining differences between groundwater levels of adjacent compartments will be re-established.

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. 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.

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 lifetime 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. Ingres was observed to enter the void directly via vertical structure such as shafts. As the rate of this ingress is not depended on the hydraulic head in the (by-passed) aquifer it also disturbs a linear relationship between the two parameters.

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.

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