The future of the dolomitic springs after mine closure on the Far West Rand, Gauteng, RSA

C. J. U. Swart · A. R. James · R. J. Kleywegt · E. J. Stoch

Abstract Approximately 1.2 km of dolomitic limestone overlies the Far West Rand gold reefs southwest of Johannesburg, South Africa. This karst aquifer is partitioned into several groundwater compartments by predominantly north–south trending syenite dykes. Prior to mining, the primary water flow was westwards, decanting over dyke boundaries as a succession of springs along the Lower Wonderfontein Spruit. Dewatering of the overlying dolomitic aquifer for safety and economic reasons by deep gold mining operations, caused the water levels of four compartments to drop and their respective springs to dry up. By perforating dykes, formerly separated aquifers were hydraulically interconnected by mining. Using historical and recent data of water flow—surface and groundwater—and pumping rates, a geohydrological model is presented. The results suggest that the water tables will rise to their pre-mining levels within 30 years after mining ceases and that the dry springs will flow again, despite the compartments being connected by the extensive mining operations.

Keywords Dewatering · Dolomite · Mining · Rewatering · Republic of South Africa

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C. J. U. Swart (✉)
GFL Mining Services Limited Ground Stability Group,
P.O. Box 6171, Oberholzer 2501, South Africa
E-mail: gsg@worldonline.co.za
Tel.: +27-18-7874435
Fax: +27-18-7875972

A. R. James
Metago Environmental Engineers (Pty) Ltd.,
P.O. Box 1596, Cramerview 2060, South Africa

R. J. Kleywegt
Council for Geoscience, Private Bag X112,
Pretoria 0001, South Africa

E. J. Stoch
P.O. Box 9, Welverdiend 2495, South Africa

Introduction

Background

The northern catchment boundary of the Lower Wonderfontein Spruit, the target area of this review, is the Atlantic Ocean/Indian Ocean watershed (Fig. 1). The bed of the Wonderfontein Spruit passes in a southwesterly direction from its source, south of Krugersdorp, to the Mooi River for approximately 80 km (Figs. 1 and 2). The dolomite of the Far West Rand, which is drained by the Lower Wonderfontein Spruit, is approximately 50 km southwest of Johannesburg in the Gauteng Province of the Republic of South Africa (Fig. 1). The Donaldson Dam is the upstream boundary of the Lower Wonderfontein Spruit and the downstream boundary is its confluence with the Mooi River (Fig. 2).

Until the turn of the 19th century, the Far West Rand was a rural area producing a wide range of agricultural products. Farming was initially associated with the abundant supply of dolomitic water that issued from the numerous springs. Mining followed, almost 100 years later, attracted by the quality of the gold ores. In the early years of gold production, which started in the 1930s, these two major activities co-existed. As mining intensified, large capacity pumps had to be deployed to drain the mines, a practice that allowed mining to continue safely and economically. The associated drop of the water tables caused the related springs to dry up. Surface subsidence in the form of sinkholes and 100-m-plus diameter depressions started to pockmark the countryside.

The interest excited by the discovery of gold waned when, in 1912, the first attempt to access the rich gold-bearing reefs beneath the dolomite was frustrated by an inrush of dolomitic groundwater, pouring from intercepted caverns in the karstic aquifer.

The study area is partitioned by several syenite dykes into large contiguous compartments (Fig. 2). As the 12- to 16-m-wide dykes were for all practical purposes impermeable, springs formed in the valley at their upstream edges.

This paper focuses on the four compartments that were dewatered as a consequence of mining. They were named after settlements in their areas and are known, from east to west, as the Western Gemsbokfontein, Venterspost, Bank and Oberholzer Compartments. These, on average 10-km-wide compartments, which cover approximately 500 km^2, are traversed by an east–west running streambed, known as the Lower Wonderfontein Spruit. This Spruit was

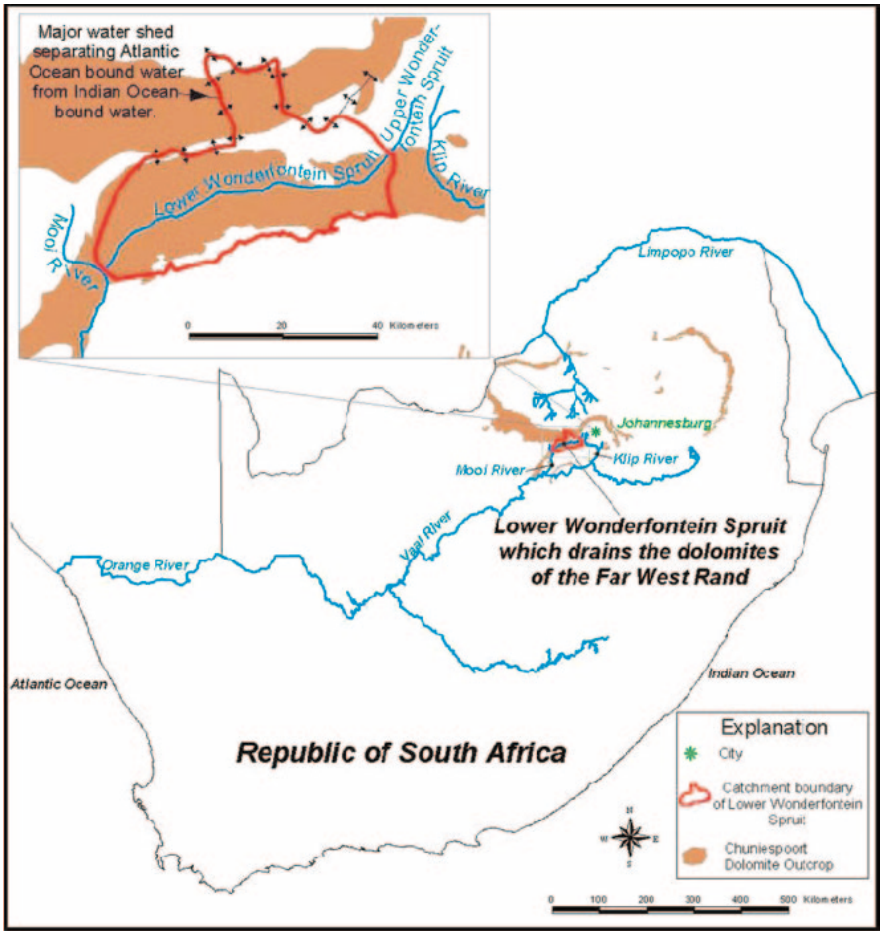


Fig. 1
Locality plan

initially drained by irrigation canals built by the settlers (Fig. 2). This streambed intersects each dyke not more than 1.5 km from its associated spring. The Klip River Spring, shown near the right-hand edge of Fig. 2, falls outside the focus area. This spring ran dry in the early 1900s and finally stopped flowing in the 1930s due to sustained extraction from the Eastern Suurbekom Compartment of water for domestic and industrial purposes.

In the early 1960s the State accepted a proposal by some gold mines operating in the region stating that the dolomitic compartments impacted by mining should be dewatered. The water tables in the four dewatered compartments were eventually lowered by about 100 m on average.

Initially, water pumped from the mines and discharged into the Lower Wonderfontein Spruit during the dewatering phase, substituted for the natural flow of the springs. At present, with the exception of the Western Gemsbokfontein Compartment—which as yet is not fully dewatered (Van Biljon, unpublished data 2001) as it is the most recent compartment to be affected—a dynamic equilibrium has been attained in the Venterspost, Bank and Oberholzer Compartments. Water that flows into the mines is removed by pumps and discharged well beyond the catchments of the four compartments being drained (Fig. 3). A 1-m-diameter pipeline was laid parallel to the Lower Wonderfontein Spruit from the Donaldson Dam in the east to the Boskop-Turffontein Compartment in the west to prevent Upper Wonderfontein catchment water from recharging the dewatered compartments (Fig. 3).

Mining pierced several dykes (aquicludes) below, and often well below, the dolomite (Fig. 2). The potential consequence was commented on by the Director of Water Affairs, who chaired an Interdepartmental Committee from 1956 to 1960 (Director of Water Affairs 1960), through De Freitas (1974) and Wolmarans (1986) to Hodgson and others (2001). These authors predict that interlinked mining operations will cause the water tables of connected compartments to equilibrate at an elevation that would result in the formation of a single, mega-compartment issuing from the lowest unaffected spring, namely the Turffontein Springs (Fig. 2). This, in their opinion, will occur after all mining, and consequently pumping, has ceased. Hodgson and others (2001) suggest that in the "mega-compartment" scenario, the elevation of the post-mining water table would be flat and that the depth of the water table would increase progressively from 0 m in the Turffontein portion of the Boskop-Turffontein Compartment, to approximately 150 m in the Western Gemsbokfontein Compartment to the east (Fig. 2).

This paper suggests an alternative. A thesis that the water tables will return to the pre-mining elevations and, as a result, the four springs will flow again, is promoted.

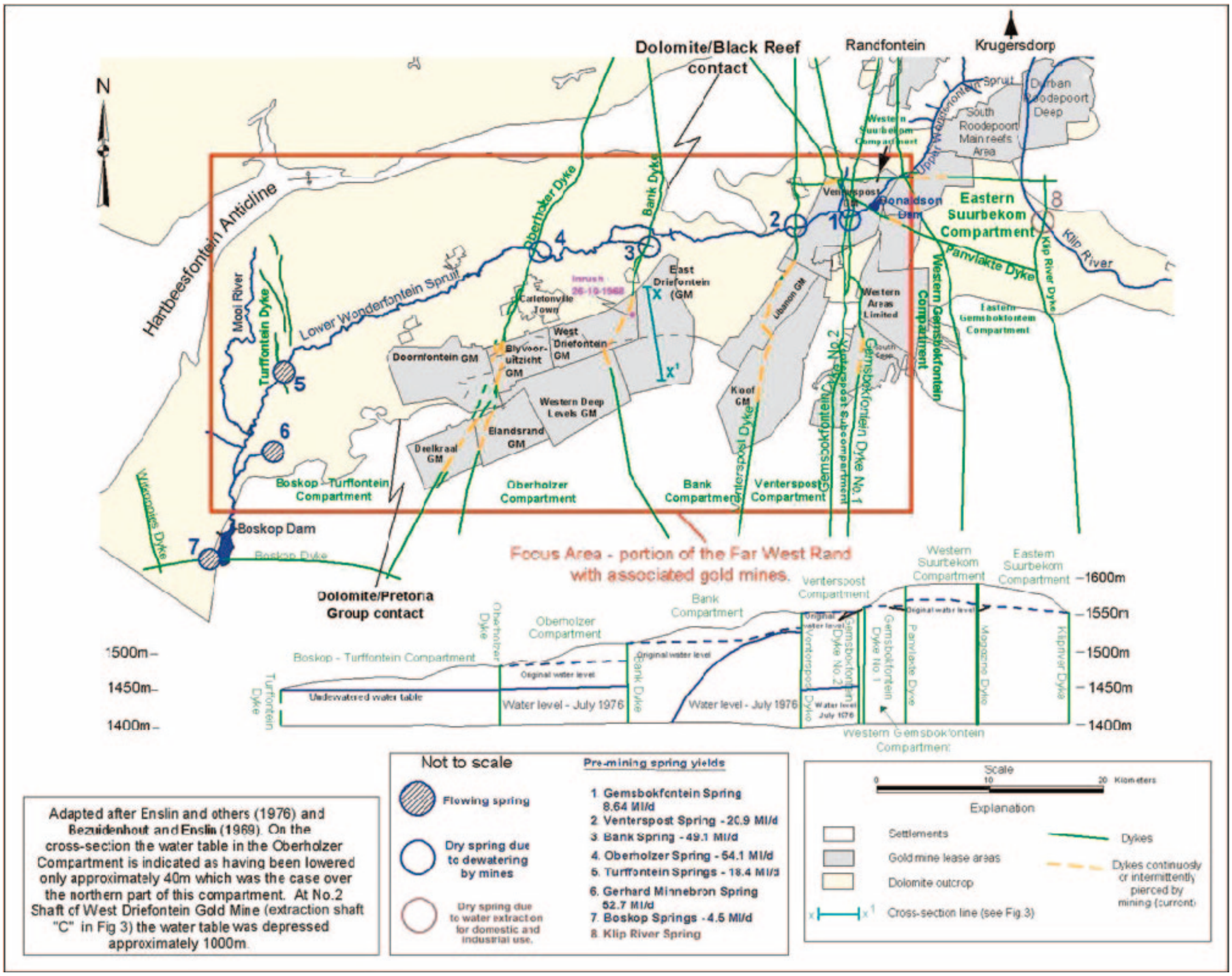


Fig. 2
The dolomitic groundwater compartments on the Far West Rand

According to Stirling (personal communication 2003), all the mine shafts have concrete lined barrels. Thus, water in the dolomite aquifer should not be able to flow down the shafts into the mine void below. It is also standard practice to seal exploration boreholes at the base of the dolomite after drilling. The view advanced in this paper thus assumes that no dolomitic water could access the mine void via boreholes or shafts. If not, these potential conduits need to be sealed at the base of the dolomite during mine closure.

From the evidence at hand, it appears that after pumping has ceased, water from the highly weathered and cavernous portions in the upper dolomite aquifer—hereafter referred to as the "cavernous aquifer"—will continue to drain along fissures to the mine voids several hundred to a few thousand meters below. Once the mine and fissures have filled, the transmissivity of the fissures between the cavernous aquifer and the mine would be sufficiently low to redirect some, in certain cases most, infiltrating rain water to flow laterally and thereby gradually fill the cavernous aquifer which, upon replenishment, will cause the springs to flow again. In contradistinction to the assumption that all the rain water would percolate vertically through the water-filled fissures into the flooded mine below and, purportedly decant at the Turffontein Springs as a mega-compartment, it is postulated that the resistance to vertical flow will be sufficient to restore the pre-mining water levels and that the original springs will flow again, albeit intermittently and at changed volumes. Jennings (unpublished data 1965), referring to near-surface voids in "dolomitic residuum"[1], expressed the view that a "recharge (rewatering) of the compartments might weaken the skin of some voids, which may then collapse (to form a sinkhole)." This prediction was confirmed by Beukes (1987) who observed that where the water table returns to pre-mining levels, sinkholes that occurred

[1]Wagener (1984) defined dolomitic residuum as that portion of the dolomite which remains behind when part of the rock has been removed by chemical weathering processes and leaching. It comprises chert gravel, wad and small quantities of clay. The residuum is usually mixed with transported material which filters from above.

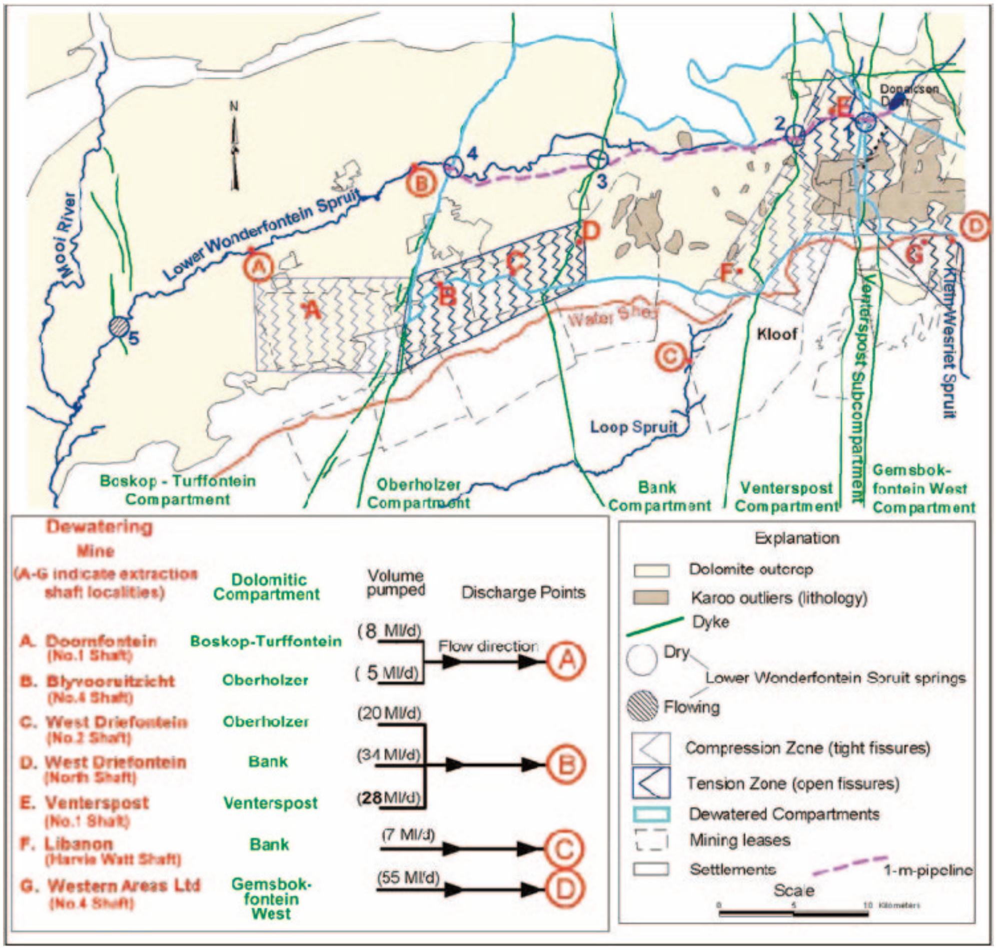


Fig. 3
The Far West Rand showing *1* Compression and tension zones in mines; *2* dolomitic water (groundwater) extraction points; *3* transfer of pumped water

during the dewatering phase could reactivate and that new sinkholes formed. It is, therefore, projected that rewatering will have major implications on the dewatered compartments for the rail and road infrastructure as well as the reticulation of municipal services. The latter is a source of concern given the experience that water pipes affected by relatively minor subsidence, which may occur during rewatering, can rupture. The resultant leaks may, even if located in previously sinkhole-free dolomitic areas, initiate sinkholes.

This investigation was motivated by the strong likelihood of ground movement and the associated socio-economic implications should the water tables be restored to their original elevations in the four dewatered compartments. For a first-order estimate of the post-mine closure, hydrological sequence and consequences was obtained from a model developed to simulate the impact of mining on the dolomite aquifer. Water quality aspects of the rewatering process, however, falls outside the scope of this paper.

Some post-mining issues that need to be resolved include:

- Estimating the time it will take to flood the mines;
- Determining the time it will take for post-mining groundwater levels to be established;
- Predicting the maximum levels to which the groundwater will rise and whether this will reach the pre-mining levels, in which event the affected springs will flow again.

Some of these issues were comprehensively investigated by an Interdepartmental Committee from 1956 to 1960 (Director of Water Affairs, (1960). With the information at their disposal it was estimated that all the mines would be closed by 1980 and it was projected that, if the springs should flow again, this would occur some 60 years later, in 2040. The fact that active mining may still be taking place in the year 2040 is an example of how difficult venturing predictions is in an anthropomorphic environment.

Geology and geohydrology of the study area

General sequence of strata

The gold reefs mined in the Far West Rand area occur within the Witwatersrand Supergroup and the contact between the Witwatersrand Supergroup and the overlying Ventersdorp Supergroup (where present). Part of the Black Reef Formation is directly underlain by the Ventersdorp Supergroup, the remainder by the Witwatersrand Supergroup (Fig. 4). The Black Reef Formation in turn is overlain by the

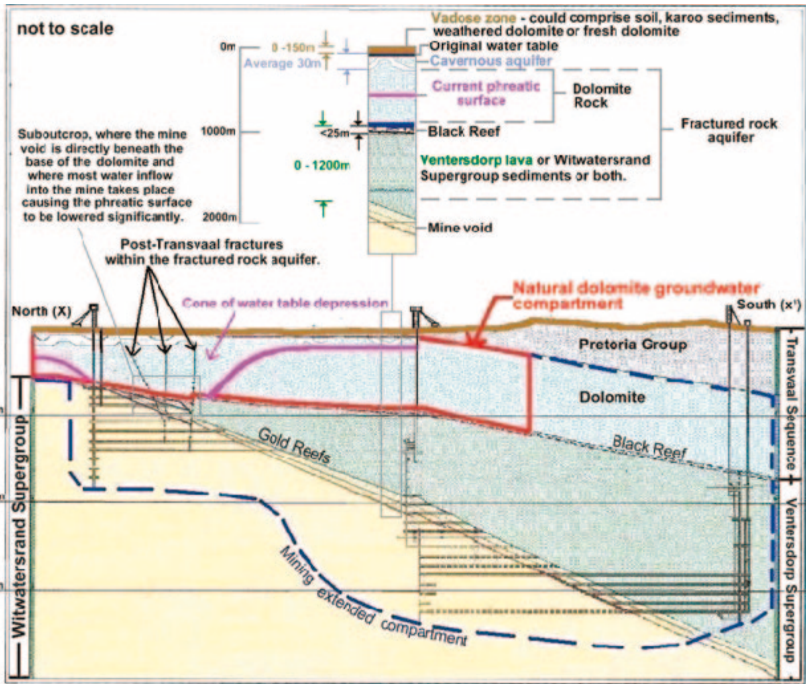


Fig. 4
Simplified cross section through X–X′ in Fig. 2

Chuniespoort Group (Proterozoic) dolomite, which on the Far West Rand is approximately 1,200 m thick and consists of alternating layers of dolomite and chert.

Pretoria Group sediments overlie the dolomite south of the southern dolomite outcrop boundary as shown in Figs. 2 and 4. The Pilanesberg syenite dykes which intruded the succession, including the Pretoria Supergroup, effectively subdivide the dolomite into compartments (Fig. 2). Karoo (Palaeozoic) sediments are infrequently found as outliers filling deeply weathered areas in the dolomite. The Lower Wonderfontein Spruit incised the Karoo deposits (where present along its course) into dolomite (Fig. 2).

The succession occurs on the southern limb of the Hartbeesfontein Anticline (Fig. 2). The Witwatersrand and Ventersdorp Supergroups dip approximately 25° south while the Black Reef Formation, through to the Pretoria Group, dips between 5° to 10° in the same direction (Fig. 4; Table 1).

Dolomite weathering and aquifer development

The thickness of the dolomite residuum is variable over short distances, ranging from 0 m where the dolomitic bedrock outcrops to about 200 m below ground surface. In spite of the variable thickness of the residuum and the presence of highly irregular subsurface bedrock topography, the dolomitic terrain is characterized by a relatively flat topography and sparse outcrops.

Where the surface of the dolomite is not covered by Pretoria Group sediments—termed “Pretoria unshielded dolomite”— and exposed to the elements, it has, in places, developed a highly weathered horizon close to the pre-mining phreatic surface. These highly weathered horizons are prevalent near deeply weathered vertical fractures which provided relatively easy passage for carbonic acid-charged rainwater to infiltrate and dissolve the dolomite on its way to, at, and especially immediately below, the phreatic surface. This was described by Brink (1979) as follows: “Most solution, however, takes place below the water table, in the phreatic zone. Phreatic solution manifests itself in two ways:

- Immediately below the level of the water table, where the water is more acidic than deeper down, large horizontal caverns are corroded into the rock, and
- At depth within the phreatic zone, where widening of fissures by corrosion continues to take place”.

The loosely compacted residuum, and cavities so generated, constitute the cavernous aquifer as it provides a large storage capacity for groundwater.

The horizontal discontinuity of the cavernous aquifer is explained by Kleywegt and Pike (1982) as— dolomitic residuum in the phreatic zone, forming a substantial part of the aquifer in the easternmost dolomitic compartments where the cavernous aquifer is thus horizontal and fairly continuous. Westwards, however, due to lower decant levels over the successive dykes, the contribution of the residuum, along solution widened fissures, to the aquifer decreases until its average depth lies well above the phreatic surface. As a result of post-Transvaal pre-Karoo tectonic fracturing (some of which manifested as widely spaced deep reaching faults) vertical planes (zones) of more intense leaching have developed. The dolomitic residuum in these zones extends as much as 40–50 m (and occasionally much more) below the water table due to the intensity of leaching in certain areas. This results in these zones, together with the dissolution of horizontal caverns leading from the deep reaching faults into dolomitic rock immediately below the pre-mining water table, contributing to the aquifer almost exclusively in the western compartments.

Table 1
Lithostratigraphic column of the Far West Rand (Brink 1979 and Wolmarans 1984)

			Formation	Thickness (m)	Description
Karoo Supergroup (~200 Ma)		Dwyka/Ecca	Vryheid	0–200	Carbon-rich, interlayered gritstone, sandstone, arkoses and carbon-rich mudstone
		Pilanesberg			Syenitic and diabase intrusions
Transvaal Supergroup	Pretoria Group		Rooihoogte	10–150	Chert breccia, conglomerate, gritstone, quartzite and shale
	Chunniespoort Group	Malmani Sub-group	Eccles	~380	Chert-rich, dark-coloured dolomite with stromatolites and oolitic bands. Chert content increases to top
			Lyttelton	~150	Chert-free, dark-coloured dolomite with large stromatolitic mounds
			Upper Monte Cristo	~258	Chert-rich dolomite
			Middle Monte Christo	~162	Chert-poor dolomite
			Lower Monte Christo	~275	Chert-rich dolomite
			Oaktree	~200	Chert-poor dolomite with interlayered carbon rich shale towards the base
			Black Reef	~30	Basal conglomerate and quartzite with interlayered carbon-rich shale
Ventersdorp Supergroup	Klipriviersberg Group			0 – 2,400	Basic to acidic lavas with associated agglomerates and tuffs. Occasional sedimentary deposits
Witwatersrand Supergroup	Central Rand Group			Not known	Mainly sedimentary rocks (all grain sizes) with gold in conglomerates
	West Rand Group			Not known	Slates and lavas
Basement Granite-gneiss				Not known	

Table 2
The time related importance of the recharge mechanisms (quantity only)

Recharge Mechanism	Pre-mining	Mining	Post Mining
Natural recharge from rainfall infiltration	Very Important	Very Important	Very Important
Recharge from the Wonderfontein Spruit and dolomite springs under normal rainfall events	Very important	Except for storm events, relatively unimportant	Depends on future of pipeline[a]
Recharge from the Wonderfontein Spruit and other drainage channels under extreme rainfall events	Unimportant	Very significant but rare	Important
Leakage through dykes from adjacent compartments	Unimportant	Unimportant	Important
Recharge from mine dewatering operations	Nil	Boskop-Turffontein and Eastern Gemsbokfontein	Nil

[a]The pipeline mentioned in column 3 refers to a 1-m-diameter pipeline which connects Donaldson Dam and the Boskop-Turffontein Compartment to convey the water in the Wonderfontein Spruit across the dewatered dolomite compartments, thereby reducing recharge to the mines and related pumping costs

In addition to the cavernous aquifer, dominant fractures associated with the post-Transvaal tensional tectonics extend through the entire dolomite succession and the Ventersdorp lavas (where present) into the underlying Witwatersrand Supergroup. Although the dolomitic bedrock along these fractures has undergone considerably less leaching than higher up—such as in the vicinity of the water table and shallower— the voids created along them, especially in the brittle chert-rich zones, are also part of the system and should therefore be considered when studying the total geohydrological picture. This portion of the geohydrological system is referred to as the "fractured rock aquifer" (Fig. 4). Although displaying a significantly lower storativity and hydraulic transmissivity than the cavernous part of the dolomitic aquifer, it effectively connects the latter with the mine some several hundred to a few thousand meters below. Under the subsection headed "The effect of crustal stresses and thick Pretoria Group strata covering the dolomite on the hydrology" it will be explained that the transmissivity of the fractured rock aquifer is more effective in some instances, less in others.

Compartmental boundaries

Prior to mining, the compartments were discrete aquifers, recharged by surface runoff, spring flow decant over its eastern boundary-dyke, and stream flow. The compartments had differential water tables stepped across the dykes (Enslin and Kriel 1959). The groundwater compartments under broader consideration are from east to west: the Western Gemsbokfontein, Venterspost Sub-, Venterspost, Bank, Oberholzer and Boskop-Turffontein Compartments. These dolomite compartments are bounded as follows (Fig. 2):

North: The Venterspost Sub-, Venterspost , Bank, Oberholzer and the Boskop-Turffontein, Compartments are effectively confined by the outcrop of the southward dipping, underlying Black Reef Formation. The Western Gemsbokfontein Compartment's northern boundary is the Panvlakte Dyke.

South: All the compartments are limited by the southward dipping Pretoria Group quartzites and shales, which restrict the development of a cavernous horizon within the dolomite further south. In the case of the Western Gemsbokfontein Compartment a reverse fault "duplicated" some Pretoria Group sediments and the southern boundary is considered by Parsons (unpublished data 1987) to be Pretoria Group sediments south of two large dolomitic inliers.

East and west: North–south trending syenite dykes create effective hydraulic barriers between the compartments.

A gravimetric survey conducted from 1963 to 1974 by Kleywegt (unpublished data 1975), identified a north–south oriented broad dolomite bedrock crest which practically divides the southern Bank Compartment into a western and an eastern groundwater subunit. The two subunits are, however, connected in the northern part of this compartment (Swart 1986). When dewatering by West Driefontein Gold Mine in the southwestern corner of the Bank Compartment started in 1969, the water table in the western subunit dropped far more dramatically than in the eastern subunit (see cross-section at the bottom of Fig. 2).

The nature of the pre-mining water tables

The pre-mining water level of each compartment was controlled by the elevation of the unweathered dyke where the springs emerged at each compartment's western boundary. Slight downward nett westward gradients, less than 1:250 according to Enslin and Kriel (1967), were maintained towards the spring by the converging flows within a compartment. The average slope of the ground surface of the southern flank of the Lower Wonderfontein Valley is 1:50 and that of the northern flank, 1:100 (De Kock 1967). Below the streambed with a surface gradient of 1:300 (De Kock 1967), the gradient of the water table could be as flat as 1:1,250 (Council for Geoscience unpublished borehole data 1970).

Prior to human settlement, the Lower Wonderfontein Spruit was a westerly draining perennial stream (Director of Water Affairs 1960) augmented by the springs. The natural phreatic surface changed dramatically from a gradual slope towards the springs to inverted cones with a sink (or lowest point) forming above each dewatering mine as the large-scale pumping of groundwater seeping into the underground mine workings progressed. As most of the water enters the mine workings close to the sub-outcrop of the gold reefs against the Black Reef Formation at the base of the dolomite (Fig. 4), the sink is generally established between the dewatering shaft and the closest mined-out suboutcrop.

Intercompartmental flow

It was stated earlier that prior to mining, intercompartmental groundwater flow through the dykes was accepted as insignificant. Historically, most of the groundwater flowed over the dykes from one compartment to the next occurring via the Lower Wonderfontein Spruit and the succession of springs.

Recharge

Where mining impacts, recharge of the dolomitic aquifers occurs both naturally and by artificial means. The relative contribution of the different recharge mechanisms changed from the pre-mining to the mining period and it is expected to change once more during the post-mining period as indicated in Table 2. While some recharge processes remain significant throughout, others are only significant during one or two of the periods. The average yields of the springs feeding into the Lower Wonderfontein Spruit prior to mining, as calculated by the Interdepartmental Committee (Director of Water Affairs 1960), are listed in Fig. 2.

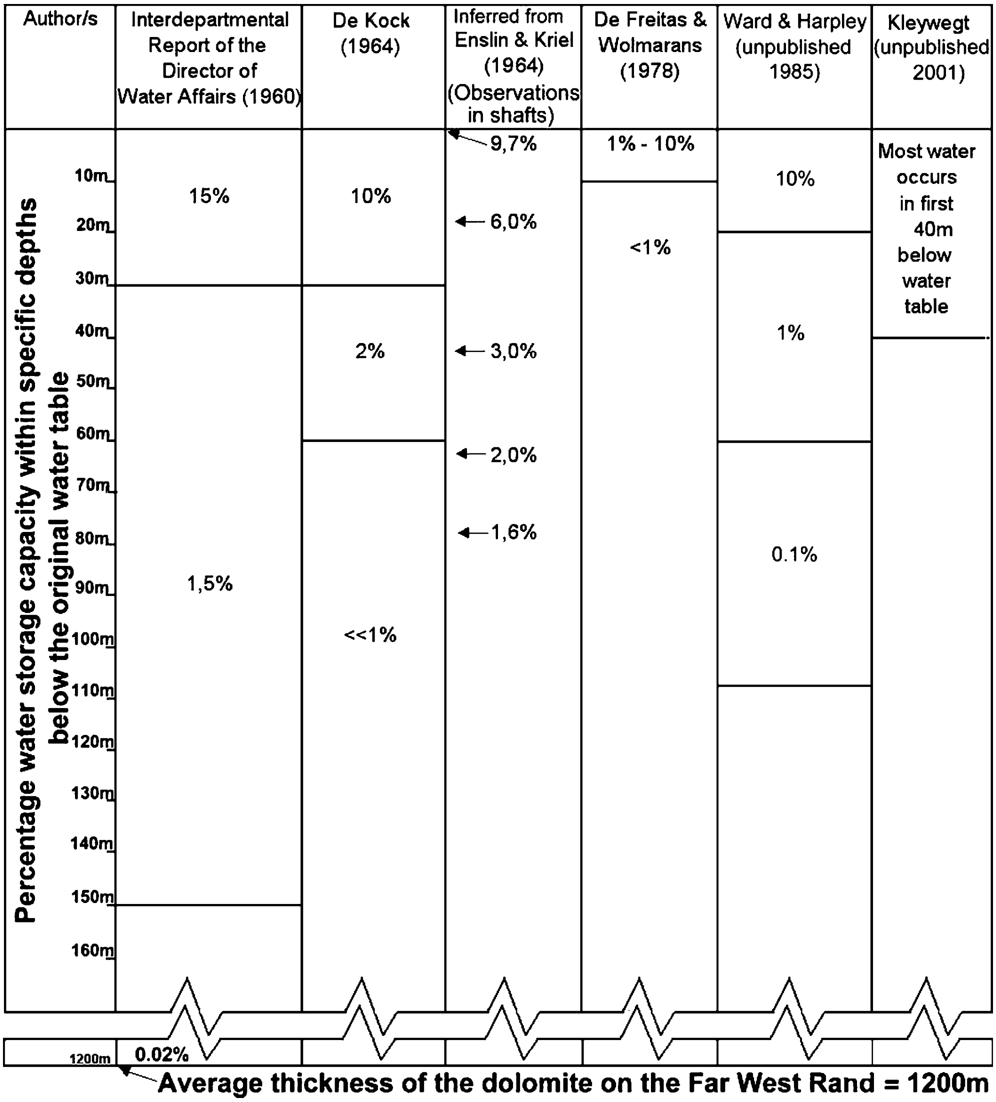
Storativity

The Director of Water Affairs, using geological sections through mine shafts and water balance studies, concluded that on the Far West Rand the storativity of dolomite decreases from approximately 15% within the first 30 m of the pre-mining water level to an estimated 1.5% below the cavernous aquifer and much less in deeper areas (Director of Water Affairs 1960). This estimate is compared to those of later researchers in Table 3.

Enslin and Kriel (1967) estimated the combined storage capacity of the Venterspost (0.45 million Ml) and Oberholzer (0.675 million Ml) Compartments to be about 1.125 million Ml (1.125 km^3). Schwartz and Midgley (1975), using a different method, calculated the storage capacity of the Bank Compartment to be 2 million Ml. The total amounts to 3.125 million Ml, which approximates the aggregate of 3.5 million Ml reported by Vegter (1987) for the three compartments.

In the section headed "Geology and geohydrology" it was stated that the degree of development of dolomitic residuum and thus the cavernous aquifer, in deeply leached zones is more prominent in the eastern compartments than further west. Swart and others (2003) evaluated the bedrock depths encountered in 3,579 boreholes scattered

Table 3
Comparison of water storage capacities of the dolomite according to various authors between 1960 and 2001



over the dolomite outcrop area of the Venterspost, Bank and Oberholzer Compartments. It was found that, on average, the bedrock in the Venterspost Compartment is 14 m below the original water table, that of the Bank Compartment 0.5 m below the original water table, whereas in the Oberholzer Compartment the average bedrock is 30 m above the original water table. In the latter compartment, the dolomite bedrock on the southern edge of the compartment rises to approximately 175 m above the original water table as compared to 140 m in the case of the adjacent Bank Compartment. The dolomite surface area of the Venterspost Compartment (54.38 km^2) is approximately a third of that of the Bank and Oberholzer Compartments (approximately 155 km^2 each). The following explains the storage capacity differential of the compartments listed above. The Venterspost Compartment, though its surface area is only a third of that of the Oberholzer Compartment, is weathered deeper relative to the pre-mining water table and therefore its storage capacity is two-thirds that of the Oberholzer Compartment. Brink (1975) expressed reservations whether the Bank Compartment's storage capacity could be as high as 2 million Ml, as calculated by Schwartz and Midgley (1975).

The effect of crustal stresses and thick Pretoria Group strata covering the dolomite on the geohydrology

Inflow into the mines from the overlying dolomitic aquifer is a function of the hydrostatic head and the transmissivity of the post-Transvaal faults within the fractured rock aquifer (Director of Water Affairs 1960; Fig. 4).
Transmissivity on the Far West Rand in turn, is influenced by differential tectonic crustal stresses that manifest as approximately 8-km-wide alternating compression (several post-Transvaal faults tightly cemented with mylonite) and tension zones (mostly post-Transvaal faults filled with clay and loose brecciated material; Wolmarans and Guise-Brown 1978). These geological features govern the rate of flow into the mine and determine whether a mine remained relatively "dry" or became "wet." There is thus a resistance to flow through the fractured rock aquifer which is eased when in a tension zone. In that case, a steady copious flow of water percolates through the fractured rock aquifer, which necessitates dewatering to allow safe and economic mining.

Table 4
The range of recharge values for some compartments drawn from the literature and pumping figures supplied by some of the mines

Compartment	Pre-mining spring flow ascribed to the recharge of the compartment Enslin and Kriel 1959	Calculated recharge if contribution of upstream spring is removed Director of Water Affairs (unpublished 1960)	Recharge based on the mean annual precipitation Enslin and Kriel 1967	Current mine pumping[1] (with 1 m pipeline installed to reduce recharge) Mahlangu and Ransuchit (unpublished data 2001)
Venterspost	20.9 Ml/day		15 Ml/day	28 Ml/day
Bank	49.1 Ml/day	39 Ml/day		41 Ml/day
Oberholzer	54.1 Ml/day	31 Ml/day		25 Ml/day

[1]excludes consumptive use and evaporation losses

The location of alternating tension and compression zones, which were observed only within specific mine boundaries, is illustrated in Fig. 3. From east to west they occur as follows:

- In the Western Gemsbokfontein Compartment, the Western Areas Limited Gold Mine being in a tension zone is a wet mine and had to implement dewatering.
- In the Venterspost Compartment, Venterspost Gold Mine is in a tension zone which necessitated dewatering of that compartment. The northeastern half of Libanon Gold Mine is in a compression zone.
- In the Bank Compartment, the southwestern half of the Libanon Gold Mine is in a compression zone and the eastern extremity of the West Driefontein Gold Mine is in a tension zone. The Bank Compartment had to be dewatered after a major inrush of water in 1968. The Harvie Watt Shaft of Libanon Gold Mine (Fig. 3) is pumping 7 Ml/day rendering the area surrounding the shaft moderately dewatered. Wolmarans and Guise-Brown (1978) did not classify East Driefontein Gold Mine to be located within a tension/compression zone as it was still a relatively new mine at the time.
- In the Oberholzer Compartment, West Driefontein and the Blyvooruitzicht Gold Mines fall within a tension zone and, as a result, are wet mines which required the dewatering of the Oberholzer Compartment. However, comparing the numerical values of the pumping per unit-area-mined of these two mines in 1960, indicates that the transmissivity of the rock strata above the West Driefontein Gold Mine is about six times higher than that of the geological succession above Blyvooruitzicht's mine. At that stage virtually all mining in West Driefontein Gold Mine took place within the central parts of a tension zone traversing the Oberholzer Compartment. Blyvooruitzicht Gold Mine is off the center of the tension zone. It was concluded that permeability appears to attain a maximum over the central portion of a tension zone.
- Within the Boskop-Turffontein Compartment, the Doornfontein Gold Mine is in a compression zone, and is consequently a dry mine. The Boskop-Turffontein Compartment is thus not dewatered.

Where a thick (>150-m) succession of Pretoria Group sediments covers the dolomites above the point where the Witwatersrand gold reefs suboutcrop against the Black Reef at the base of the dolomite, the resultant deep dolomite is protected from weathering and is therefore logically not a Pretoria unshielded dolomite. The reduced water storage capacity of such an under-developed dolomite aquifer renders the underlying mine relatively dry even if the mine is in a tension zone.

The effect of wedges of Ventersdorp Supergroup lava on the geohydrology

The lava wedges tend to restrict the inflow of water into the mines as a consequence of fractures that are tighter than those within the dolomite, or in the Witwatersrand Supergroup. In Fig. 4, the wedge of Ventersdorp Supergroup lava separating the dolomite from the Witwatersrand Supergroup is shown in green. The wedge which within the gold mines attains the greatest thickness in the Bank Compartment, increases vertically from 0 m at the suboutcrop of the Ventersdorp Contact (gold) Reef to approximately 2,000 m at the southeastern corner of East Driefontein and Kloof Gold Mines (Figs. 2 and 4; Engelbrecht and others 1986). On the mines where the lava wedge underlies Pretoria unshielded dolomite, the maximum thickness is only 1,200 m.

In the gold mines of the three eastern compartments under discussion, i.e. Western Gemsbokfontein, Venterspost and Bank, Pretoria unshielded dolomite is in most parts underlain by Ventersdorp Supergroup lava. This implies that Pretoria unshielded dolomite, within which the cavernous aquifer could be well-developed, is separated from the deeper lying mine by Ventersdorp Supergroup lava in gold mines such as Western Areas Limited, Venterspost, Libanon, the northern parts of East Driefontein and the southeastern extremity of that part of West Driefontein in the Bank Compartment (Fig. 2).

In the Oberholzer and Boskop-Turffontein Compartments, the lava wedge is almost absent within gold mines such as West Driefontein (that part of the mine which is in the Oberholzer Compartment), Blyvooruitzicht and Doornfontein Gold Mines (Fig. 2). In these mines the Witwatersrand Supergroup directly underlies the base of the Pretoria unshielded dolomite.

South Deep, Kloof, the southern part of East Driefontein, Western Deep Levels, Elandsrand and Deelkraal Gold Mines (Fig. 2), due to Pretoria shielding are dry mines as they are overlain by much less weathered dolomite. Amis (unpublished data 2003) estimates that Western Deep Levels Gold Mine will in future discard only approximately 0.5 Ml/day. Although a lava wedge is present in these mines, the dryness is mainly due to the thick Pretoria Group sediment cover, which restricted the development of the cavernous aquifer.

The following examples illustrate that the impact of the lava wedge is subordinate to the influence of the crustal stresses discussed in the section headed "Crustal stresses and the effect of thick Pretoria Group strata covering the dolomite":

- In 1943, the Venterspost Gold Mine, which is in a tension zone and where the lava wedge is present, experienced an inflow of approximately 7 Ml/day, whereas in 1956, when the West Driefontein Gold Mine (which was also mining in a tension zone but where the lava wedge is absent) had mined a similar area, the inflow was nearly seven times more, i.e., 45 Ml/day. According to Wolmarans (1984, personal communication 2001), this confirms that lava wedges retard the inflow of water. The geologic differences despite both mines being in tension zones, had to dewater.
- Doornfontein Gold Mine is in a compression zone (Fig. 3), and notwithstanding the lava wedge being absent it was never necessary to dewater the compartment (Boskop-Turffontein Compartment) of this mine.

Data gathered and observations made during mining which are considered relevant with respect to the rewatering scenario

The geohydrology of the cavernous aquifer

- Natural recharge: Accepting that intercompartmental flow through the dykes was negligible prior to mining, the long-term average spring flow is a reasonable estimate of the recharge rate of the compartments (Fig. 2). This view was expressed by the Inter-colonial Commission (1905). Subsequent efforts to estimate the nett recharge are documented[2]. Table 4 lists the current pumping rates in column 4. The difference in estimates between column 1 and columns 2, 3 and 4 in the table may be accounted for by the fact that the latter do not account for water entering the respective compartments via upstream sources (the upstream spring is dry and stream flow is diverted into the 1-m-diameter pipeline). Column 2 presents the pre-mining recharge, excluding water originating upstream of the Oberholzer and Bank Compartments.

The current volumes pumped from the individual mines as shown in Table 4, should also reflect the rate of recharge. When comparing columns 1 and 4 of Table 4, the pumping volume of the Venterspost Compartment (28 Ml/day) is approximately 33% higher than its pre-mining spring yield (21 Ml/day), while for the Oberholzer Compartment pumping (25 Ml/day) is about 116% lower than the compartment's original spring flow (54 Ml/day).

A larger disparity (744% higher) exists in the Western Gemsbokfontein Compartment, where the original spring yield of 9 Ml/day, is much lower than the current pumping volume, 67 Ml/day. According to Van Biljon (unpublished data 2001) the compartment appears to be in an intermediate stage of dewatering and he projects that the pumping will decline to 48 Ml/day at which time dynamic equilibrium will set in when the aquifer is considered dewatered. In an attempt to explain why the pumping rate of this compartment is so much higher than the yield of the pre-mining spring, Van Biljon sited, among others, the following two factors:

- Steep phreatic gradients, caused by dewatering allowing groundwater from surrounding non-dewatered compartments such as the Western Suurbekom and Eastern Gemsbokfontein Compartments, to leak into this compartment through the compartment's boundary dykes; and
- Re-circulation from surface streams into which pumped water was discharged. He further expects that after rewatering of the Western Gemsbokfontein Compartment has taken place, the yield at the Gemsbokfontein Spring will be a maximum of 17 Ml/day.

What contributes to the imbalance in all the dewatered compartments, by not being accounted for, is the loss of water via the mine ventilation system, as well as evaporation and seepage via the extensive tailings dams. Not all the water enters the mine from the dolomite aquifer nor does all the water leave via dewatering pumps[3]. Currently, the volume of water bought from the water authorities (Rand Water) by East Driefontein and West Driefontein Gold Mines, amounts to 9 Ml/day. This artificial water gain by the two mines is coincidentally nearly offset by 8 Ml/day of water loss through ventilation shafts plus 3 Ml/day evaporation from tailings dams (Ransuchit, personal communication 2003).

Although further investigation is required to solve the problems raised in this subsection, Table 4 demonstrates that the aggregate of column 1 (124 Ml/day) compares favourably with the sum of the average flow entering the

[2]Inter-colonial Commission (1905), Enslin (1967) and Hodgson and others (2001) assumed the pre-mining yield of the spring of a compartment to be equivalent to the recharge of that compartment. This convention was also adopted in this paper.

[3] Some pumped water re-enters the underground as mine service water, water also leaves the mine through evaporation via the ventilation shafts and tailings dams. Neither volume has been measured on a continuous and regional basis, consequently aquifer draw-down was, estimated from volume pumped minus natural recharge, assumed to be equivalent to the pre-mining spring flow.

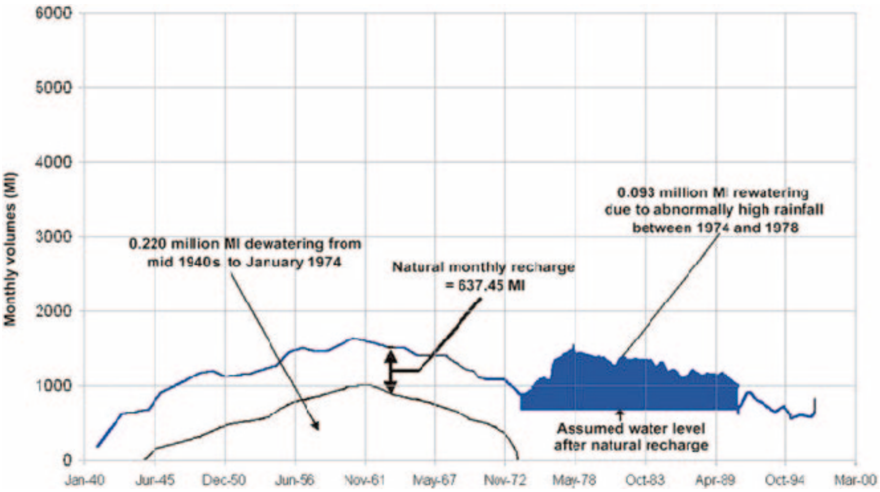


Fig. 5
Venterspost Compartment—Water balance (pumping vs. natural recharge)

1-m-pipeline (Fig. 3) from Donaldson Dam (approximately 30 Ml/day) and the aggregate of column 4 (94 Ml/day). This would suggest that the pumping volumes and the spring yields uphold one another on a regional scale. This allows the use, with a greater measure of confidence, of the pre-mining spring flows as the recharge volumes of the respective compartments.

- The estimated nett dewatered volumes (differences between the pre-mining aquifer storage volume and the current volume stored) of the compartments: This, in the example of the Venterspost Compartment, was calculated by subtracting the historic recharge, being the average long-term pre-mining spring flow, from the volume pumped, for the period of the mid-1940s to January 1974 (Fig. 5). Table 5 lists the dolomite dewatering volumes of the Western Gemsbokfontein, Venterspost, Bank and Oberholzer Compartments. The locations of the dewatering mine shafts (Table 5, column 5) are indicated in Fig. 3.
- Compartments are only partially dewatered: The seventh column of Table 5 shows the combined aquifer draw-down of the Venterspost, Bank and Oberholzer Compartments to be approximately 0.90 million Ml. The 0.90 million Ml represents approximately a quarter of the 3.5 million Ml as referred to in the section headed "Storativity." The practical implication is, therefore, that only partial dewatering of a portion of the dolomitic aquifers in question has taken place.
- An example of temporary, partial rewatering: Earlier in this section it was pointed out that for the Venterspost, Bank and Oberholzer Compartments, the present fairly consistent pumping rates appear to tend to a volume equivalent to their combined pre-mining spring yield which in turn is assumed to reflect the recharge rate, as "what flows in must be pumped out, or the mine would progressively flood." This thesis is supported by the lowered water tables. This trend is reversed during high rainfall periods where the water table rises in concert with increased pumping by the mine. Between 1974 and 1978 abnormally high rainfall in the Venterspost Compartment resulted in a significant rise of the water table (Fig. 5), which rose rapidly by more than 62 m, from 118 m below pre-mining elevation in February 1974, to 55.7 m below pre-mining elevation in July 1977. According to Beukes (1987), the water level below the Lower Wonderfontein Spruit in the Venterspost Compartment peaked at 10 m below the pre-mining water table in early 1978. Beukes (1987) estimated the recharge (rewatering) of the Venterspost Compartment during the exceptionally wet seasons in the 1970s at 0.05 million Ml, which is approximately 50% of the 0.093 million Ml reported in Table 5. From this observation it should be noted that any prediction as to how long it would take to rewater after mining ceased may be considerably "shortened" by extreme and unexpected flood events.
- The anticipated post-mining recharge rate of the compartments: Due to the multitude of sinkholes capable of accepting surface storm flow, particularly in the streambed of the Lower Wonderfontein Spruit (Swart and others 2003), the post-mining rate of recharge is expected to exceed that of the pre-mining period (Table 6).

Groundwater flow down the fractured rock aquifer

- Where mining takes place in tension zones and underlying Pretoria unshielded dolomite water inflow generally increases as mining progresses: In the early stages of mining, the inflow of water into the mine via the fractured rock aquifer generally increased in relation to the stope area developed, as progressively more water- bearing fractures were intersected. A direct relationship between "area mined" and "water inflow" was noted and documented by several observers namely:

  - Louw (unpublished data 1960) on the West Driefontein Gold Mine in the eastern Oberholzer Compartment
  - Irving (unpublished data 1960) on the Blyvooruitzicht Gold Mine in the western Oberholzer Compartment

Table 5
Data used for establishing crude dewatering and re-watering volumes in the Western Gemsbokfontein, Venterspost, Bank and Oberholzer Dolomitic Compartments

Dolomitic Compartment	Surface area (km^2)	Total dolomite aquifer capacity (10^6 MI)[a]	Estimated volume of mine void	Yield of original spring[b]	Date dewatering commenced	Shafts from which dewatering is effected	Dolomite dewatered volume (10^6 MI)	Percentage dewatered	Expected recharge time after mine void had been flooded assuming recharge = figures in column 4	Volume recharged by the 1970s higher than normal rainfall (10^6 MI)
Gemsbok-fontein	115.37	–	0.7×10^6 MI	8.64	Mid-1986	No. 4 ShaftWAL	0.087[c] 0.240[d]	–	6.5 years[c]	Not known
Venterspost	54.38[b]	0.46		20,90	1947	No. 1 Shaft Venterspost	0.220	48%	16 years if normal rain 10 >years if higher than normal rain	0.093
Bank	156.69[b]	2.0		49,10	Mid-1969	North Shaft West Driefontein	0.227	16%	18 years	0.092
					1985	Harvie Watt Shaft Libanon	0.046 BankTotal = 0.323			
Oberholzer	153.85[b]	1.05		54,1	1957	No. 2 Shaft West Driefontein	0.303	34%	18 years	Not known
					1964	No. 1 Shaft Blyvooruitzicht	0.053 Oberholzer Total = 0.356			

[a]Vegter (1987)
[b]Enslin and Kriel (1967)
[c]Van Biljon (unpublished data 2001)
[d]Swart (unpublished data 2001)

Table 6
Inflow to mine in the different compartments

Mine	Compartment	Influx from Dolomite Aquifer (Ml/day)
Venterspost	Venterspost	28
Libanon and	Bank	7
West Driefontein		34
West Driefontein	Oberholzer	20
and Blyvooruitzicht		5
Doornfontein	Boskop-Turffontein	8

  - Enslin and others (1976) on the Western Areas Limited Gold Mine in the Western Gemsbokfontein Compartment
  - Wolmarans (1984) on the Venterspost Gold Mine in the Venterspost Compartment and that part of the West Driefontein Gold Mine in the Oberholzer Compartment.

- A major inrush of water into the mine in a non-dewatered compartment: West Driefontein Gold Mine tunneled through the Bank Dyke from the Oberholzer Compartment into the virgin rock of the Bank Compartment during the early 1960s. Stoping (excavating reef) within the southwestern part of the Bank Compartment commenced during 1964. An unprecedented inrush of 360 Ml/day into the mine occurred on 26 October 1968, when water broke through the thin wedge of Ventersdorp Supergroup lava along what is termed a "décollement zone" connecting the Bank Compartment dolomite with the mine (Wolmarans 1986; Fig. 2). The inrush occurred near West Driefontein No. 4 Shaft and continued for the 24 days that it took to construct two watertight concrete plugs to isolate No. 4 Shaft from the inrush area (Taute and Tress 1971; Fig. 2). The Bank Spring gurgled to a stop within a few days after the inrush. As a result of the dramatic inrush, it was decided to dewater the Bank Compartment as well.
- The permeability (transmissivity) of the fractured rock aquifer: This factor will initially determine the rate at which water will report at the mine, which will, in turn, ultimately influence the degree of intercompartmental flux through the mined-through dyke. In this paper, estimates of permeability are derived for a part of the central portion of the Oberholzer Compartment, as this is an area for which appropriate data exist. Regional geological considerations, coupled with patterns of water inflow into the mines, indicate that, with the exception of the uncharacteristic groundwater inrush that took place in the Bank Compartment in 1968, the estimated permeability of this central portion of the Oberholzer Compartment is higher than the average of the other dewatered compartments. It thus follows that if the higher rate of inflow derived from this estimate is applied to the full extent of the dewatered Oberholzer Compartment, the estimate will fall within the upper bound (conservative) limit (Kleywegt and Swart, unpublished data 2002).
  When determining the permeability of the Bank Compartment, the higher permeability (transmissivity) derived for the Oberholzer Compartment was added to the yield of the fracture through which the inrush into the Bank Compartment in 1968 occurred. This approach is considered conservative as it over-compensates for possible future unexpected higher permeabilities.
  Whereas the infiltration into the Oberholzer Compartment is diffused throughout the mined-out area, the inrush experienced in the Bank Compartment in 1968 was down a single large fracture, which still produces approximately 30 Ml/day. No similar fractures that produced as great an inrush have been encountered.
- A conservative estimate of what the pumping rate of the Oberholzer Compartment would have been today if no dewatering had taken place and recharge was sufficient, is derived as follows: By April 1960, when the West Driefontein Gold Mine mined[4] only 194 ha and the water table had dropped relatively little, the pumping rate had reached 92 Ml/day. The respective figures for the Blyvooruitzicht Gold Mine were 715 ha mined, with approximately 60 Ml/day re-circulated. The water table at the re-circulating Blyvooruitzicht shaft remained close to its pre-mining elevation, as the hydraulic head at the suboutcrop had only dropped by 4%. The Blyvooruitzicht and West Driefontein Gold Mines have now almost mined out their entire lease areas: approximately 3,500 ha in the Oberholzer Compartment, which is 18 times larger than the area mined out by West Driefontein by 1960. To arrive at a conservative estimate of what the pumping rate of a non-dewatered Oberholzer Compartment would have been today, the rate of inflow (92 Ml/day) into West Driefontein Gold Mine in 1960 is multiplied by 18 which gives approximately 1,650 Ml/day.

The size of the total mine void and the intercompartmental dykes punctured by it

The mine void will become an artificial aquifer with a significant water storage capacity below the dolomite aquifer: The volume of the mined out areas can be estimated from the mass of rock hoisted by them. This additional artificial volume, which currently stands at 0.6 million Ml (600 million m^3 for the Far West Rand), needs to be taken into consideration when calculating the time that it will take to restore the water tables of the affected compartments (Hodgson and others 2001). Mining has therefore amplified the capacity of the compartments by excavating extensive, deeper-lying connections—haulages and stopes—in the rock beneath the dolomite. Some dykes (aquicludes between compartments) were transected by haulage tunnels, and to a lesser extent by stoping operations, thereby connecting previously unconnected compartments. Figure 2 illustrates the current position with respect to the dykes having been

[4] In 1960, Blyvooruitzicht Mine, also in the Oberholzer Compartment, was merely re-circulating pumped water.

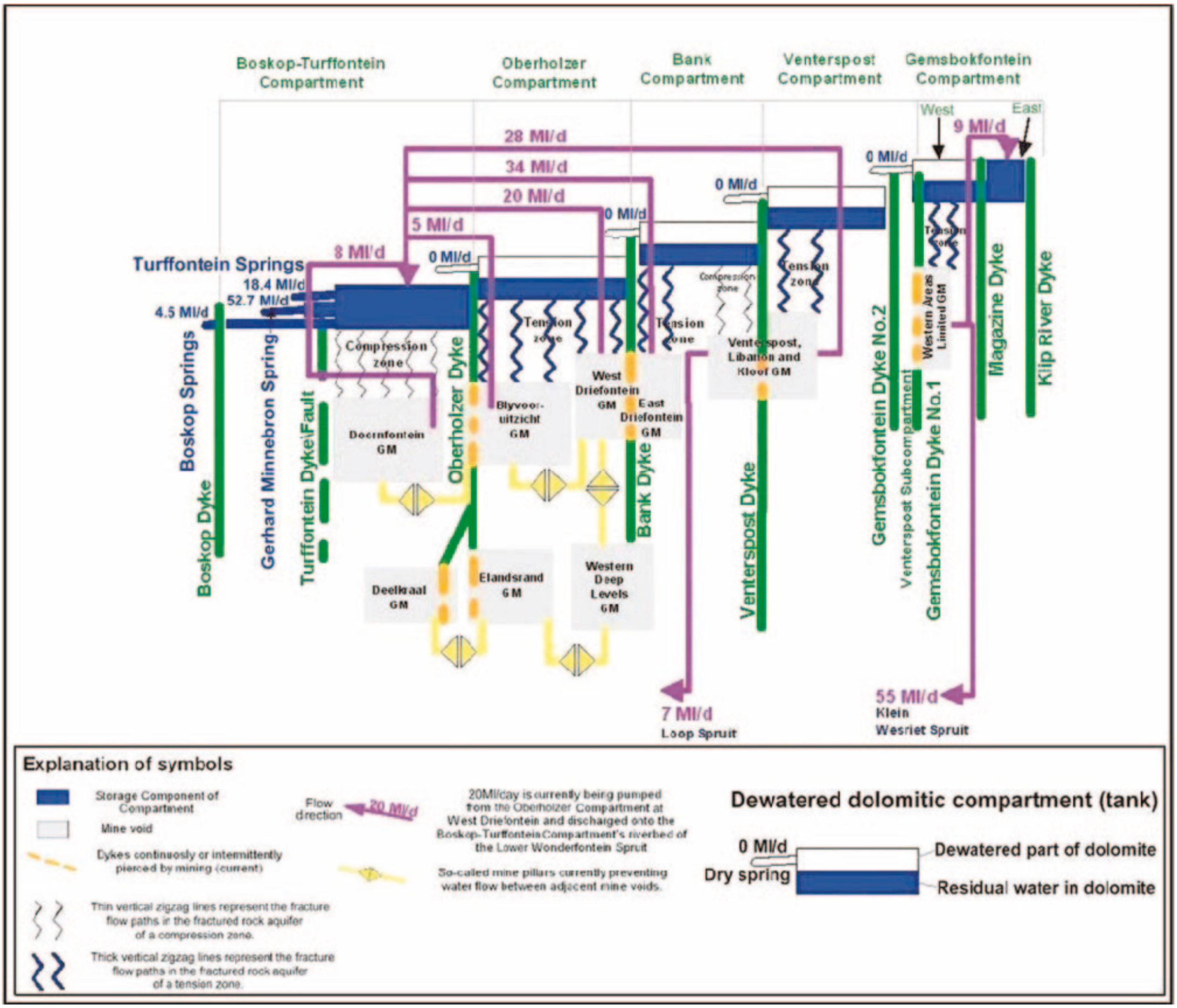


Fig. 6
Cross section of mines and dolomitic compartments showing current water volumes (during mining) being pumped and spring yields

pierced by intermittent thoroughfares (unpublished data, shareholders documents, or mining progress reports, of the various mines 1997).

A schematic representation of the current geohydrology

Based on the information presented in the previous sections, a model was constructed to predict the inter-compartmental flow of the post-mining era. Figure 6, as a diagram of the current Far West Rand dolomitic and mine water flow, provides the basis for the model. Figure 7 amplifies Fig. 6. The storage capacity of the dolomite compartments is represented by a series of tanks. The blue/white tanks represent compartments that have been dewatered, with full blue, indicating the compartments not being dewatered. As the fractured rock aquifer below a compartment presents resistance to flow, it is represented by vertical zigzag blue lines connecting the tank to the mine(s) indicated by gray squares at the base of Fig. 6. Fracture flow resistance varies according to the nature of the conduits with the result that the collective resistance to flow within the fractured rock aquifer will be restricted within a compressive zone. Fractures in compression zones (high resistance) are therefore indicated by thin zigzag blue lines, whereas those in tensional zones (lower resistance) are indicated by thicker zigzag lines (Fig. 6).

Relatively large volumes of water have and are still being removed from the four dewatered compartments, with rainfall being the primary recharge source. Recharge from streamflow in the Lower Wonderfontein Spruit is reduced by a 1-m-pipe which acts as a stream diversion (Fig. 3). On rewatering, water will initially fill the mines, decanting into adjacent compartments where the mine workings transect the dykes (Fig. 6, broken brown lines). Presently not all the dykes have been punctured by mining (Fig. 2). However, this situation is subject to change.

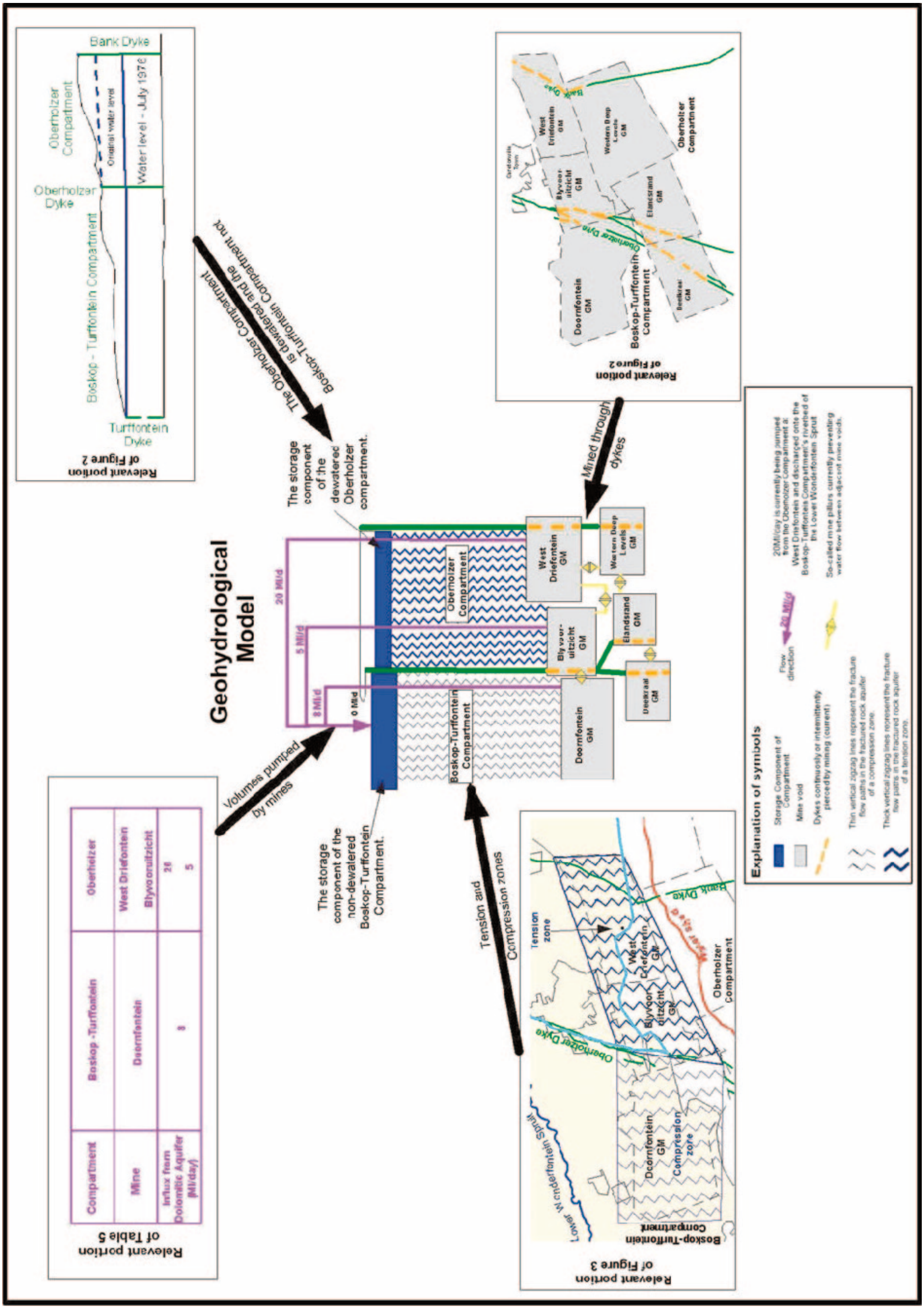


Fig. 7
An illustration using the Boskop-Turffontein and Oberholzer Compartment area as an example to show how information in Table 5, Figs. 2 and 3 was converted into symbols used in the Fig. 6 diagram

A first approximation geohydrological model to estimate post-mining intercompartmental flux, e.g. predicted flux through the mined-through Bank Dyke

To arrive at an estimate of the intercompartmental flow that will prevail in the post-mining period, loosely referred to as the model, some parameters derived from information presented in Fig. 6 as well as from the accumulated historical data were integrated. For reasons of simplicity, the model projects a situation that could prevail should all pumping cease simultaneously. It is anticipated that the following sequence of events will apply (some of the support thereto will be provided in the next section).
Initially, the mines will flood, followed by a rapid rise of the water table through the fractured rock aquifer before the dewatered cavernous aquifer is recharged. The rise of water through the dewatered cavernous aquifer will be much slower than through the fractured rock aquifer. Some adjacent mines are separated by "mine pillars" (yellow lines with arrowheads in Fig. 6). These pillars could in the long-term collapse due to the superincumbent surcharge and periodic seismic events. The increase in hydrostatic head, as rewatering progresses, may also result in them becoming permeable. The view that is advanced in this paper suggests that a dynamic equilibrium will ultimately be reached in each compartment at water levels consistent with the historic levels. The head across adjoining compartments should, despite the dykes pierced at mine level, be maintained at the historic elevation differentials of about 35 m. The restoration of the historic heads would result in the rejuvenation of the natural springs of the Lower Wonderfontein Spruit.
Figure 6 is the forerunner of the model which will be employed to estimate the volume of intercompartmental flux in the post-mining area. If the post-mining intercompartmental flux is less than the recharge of that compartment, the relevant spring will flow again. The model is based on calculations which assume that Darcy's law for saturated flow through a porous medium will apply to a fractured rock aquifer, shown as vertical zigzag lines (conduits) in Fig. 6. The smaller the calculated flux, the greater the possibility that the springs will flow again.
Assuming that the water level of an upper (eastern) compartment will be higher than the adjacent lower (western) compartment, the hydraulic head will drive water down the upper compartment (downward leg) through the "horizontal" mine void and pierced dyke and then up the lower compartment (upward leg). The upward leg is thus the downslope (lower) compartment where water will flow from the mine upwards to recharge the cavernous aquifer of that compartment. According to James (unpublished, 2003), it is appropriate to assume an effective permeability k for the fractured rock aquifer as a single layer. This postulation allows the flux through a mined-through dyke to be approximated by Eq. (1).

$$Q = \frac{\Delta h}{\sum_{i=1}^{n} \frac{l_i}{k_i A_i}} = \frac{\Delta h}{\frac{l_1}{k_1 . A_1} + \frac{l_2}{k_2 . A_2} + \frac{l_3}{k_3 . A_3}} \quad (1)$$

where:

Q = Total flux passing through the mined-through dyke (Ml/day or m^3/s)
l_i = Flow path length across the ith porous media (m)
A_i = Area of cross-section of flow path (m^2)
k_i = Effective permeability of the fractured media (m/s)
k_1 = Downward leg
k_2 = Flow through mine connecting compartments
k_3 = Upward leg
Δh = The elevation difference between the water tables of the adjacent compartments (m).

The second term in the denominator can be ignored as the permeability of the mine excavations (k_2) will be high relative to the fractured rock aquifers (k_1 and k_3).
Before Eq. (1) can be used to calculate the intercompartmental flux through the mined-through Bank Dyke in the post-mining era, it is necessary to determine values for the terms $\frac{l_1}{k_1 . A_1}$ (the downward leg in the Bank Compartment) and $\frac{l_3}{k_3 . A_3}$(the upward leg in the Oberholzer Compartment). These terms give a reasonable indication of the hydraulic resistance of the fractured rock aquifer represented by zigzag lines in Fig. 6.
The hydraulic resistance of the Oberholzer Compartment (upward leg in this example) was determined first. Use was made of some of the data/conclusions discussed in the section headed "Data gathered and observations made during mining which are considered relevant in respect of the rewatering scenario", where it was, for instance, explained that:

- Data from the central portion of a tension zone over the Oberholzer Compartment were extrapolated to areas where the relatively lower values of a compression zone may apply, in support of predictions which are conservative. A "flow" of 1,650 Ml/day was calculated.
- The vertical distance between the pre-mining water table and the sink of the dewatering cone at West Driefontein Gold Mine's No. 2 Shaft (a dewatering shaft) (Fig. 3; Table 5 column 6) is approximately 1,000 m, where Q' is the volume of water per unit time that would flow into the "fully mined-out" void of the Oberholzer Compartment when the water table is back at its pre-mining elevation and $\Delta h'$is the vertical distance between the pre-mining water table and the suboutcrop (or lowest point (sink) of the dewatering cone) in the Oberholzer Compartment, in the following equation:

$$\frac{\Delta h'}{Q'} = \frac{l_3}{k_3 . A_3} \quad (2)$$

The same hydraulic resistance was applied to the downward leg (in the Bank Compartment) as the mined-out area of the Bank Compartment is comparable to that of the Oberholzer Compartment (3,300 vs. 3,500 ha). Owing to a thick Pretoria Group cover, future mining in the Bank Compartment would not cause additional inflow. The conservative approach is to allow for the largest possible flow across the mined-through Bank Dyke; the 360 Ml/day inrush that occurred in the Bank Compartment in 1968, is added to the *Q'*-value obtained for the Oberholzer Compartment, when calculating the potential flux through the mined-through Bank Dyke.
This will represent a first order estimate of the maximum post-mining flux. Additional reasons why the potential flow through the upward and downward legs used represent conservative values (probable over estimates) are:

- Initial mining took place near the suboutcrop in these compartments. Due to the proximity of the mining operations to the base of the dolomite, inflow into a mine was generally higher than further down-dip along the reef horizon.
  In calculating the *k*-value of the Oberholzer Compartment in West Driefontein Gold Mine, the permeability further down-dip, although generally lower, was assumed to be the same as at the suboutcrop.
- In the area of the suboutcrop of important gold reefs in the Blyvooruitzicht Gold Mine and the West Driefontein Gold Mine in the Oberholzer Compartment, the Ventersdorp Supergroup lavas, which vertically separate the base of the dolomitic succession from the gold-bearing reefs below, are absent. This is not the case in the Bank Compartment where fractures within the lava are relatively tight and tend to hamper the penetration of water into the mine workings. Nevertheless, the *k*-value of the "lava wedge devoid" geological succession at West Driefontein Gold Mine in the Oberholzer Compartment, was applied to the Bank Compartment as well.
- In the Oberholzer Compartment the higher transmissivity of West Driefontein Gold Mine in 1960, when operations of this mine were confined to the central portion of a tension zone, was also applied over the Blyvooruitzicht Gold Mine despite it being situated off the center of the tension zone.

The head ($\Delta h'$) is the height of the pre-mining water table above the suboutcrop which is approximately 1,000 m.[5]
As $\Delta h''$and Q' are effectively known, $\frac{l_3}{k_3.A_3}$for the upward leg (Oberholzer Compartment) can be solved.

$$\frac{l_3}{k_3.A_3} = \frac{\Delta h'}{Q'} = \frac{1000m}{1650Ml/d} = \frac{1000m}{19m^3/s} = 52s/m^2\left(\text{which is}\frac{1}{transmissivity}\right)$$

Having calibrated the model, it is now possible to apply the model to provide first order estimates of the flux arriving in the cavernous aquifer at the top end of the upward leg in the Oberholzer Compartment.
It follows that: $\frac{l_1}{k_1.A_1}$ for the downward leg (Bank Compartment), where the pre-mining water table is 800 m above the sink, is

$$\frac{\Delta h'(Bank)}{Q'(Oberholzer)+360(volume\ of\ the\ inrush\ in\ 1968)} = \frac{800m}{1650+360} = \frac{800m}{2010Ml/d} = \frac{800m}{23m^{3/s}} = 35s/m^3$$

The calculated values for $\frac{l_1}{k_1.A_1}$ and $\frac{l_3}{k_3.A_3}$ can now be used in Eq. (1) to calculate the potential flux through the Bank Dyke:

$$\text{Flux} = Q = \frac{\Delta h}{\frac{l_1}{k_1.A_1}+\frac{l_2}{k_2.A_2}+\frac{l_3}{k_3.A_3}} = \frac{35\ \text{m}}{52\text{s/m}^2+0+35\text{s/m}^2} = \frac{35\ \text{m}}{87\text{s/m}^2} = 0.4\text{m}^2/\text{s} = 35\text{M1/day}$$

where: Q is the potential intercompartmental flux through the mined-through Bank Dyke and Δh is the difference in elevation of the pre-mining water tables either side of the Bank Dyke.
The value of 35 Ml/day calculated above should be compared with the pre-mining discharge (Table 4, column 1) from the spring of that compartment (Bank Compartment in this case). The potential intercompartmental flux (35 Ml/day) being less than the average recharge rate of the Bank Compartment (49 Ml/day) suggests that after the mine in the Bank and Oberholzer Compartments had been flooded, the water table in the Bank Compartment will rise until eventually the Bank Spring will flow again; although owing to the very conservative calculations by Kleywegt and Swart (unpublished data 2002), its average discharge will be only 30% of the pre-mining volume.
However, recharge from the Wonderfontein Spruit will probably be higher if the flow in the 1-m-pipe conveying water over the compartments is removed and this water is allowed to enter the compartments as potential recharge—mainly through sinkholes, subsidence-related ground cracks, etc. Accelerated recharge, compared to the pre-mining period, will take place if storm water is allowed to enter the sinkholes. It may therefore be concluded, based on this first approximation, that the pre-mining water levels will once again be re-established. Table 4, columns 2 and 4, also provides lower bound values when no water flows in from higher up the Lower Wonderfontein Spruit for recharge of the Bank Compartment, i.e. 39 and 41 Ml/day. The latter values are very close to the flux (Q) calculated above (35 Ml/day). This scenario suggests that the Bank Spring could be near-stagnant during long dry spells.
The following explains how the post-mining period compares to the pre-mining period. Recharge of the dolomite from the Lower Wonderfontein Spruit will initially be

[5]The vertical distance between the pre-mining water table and the sink of the dewatering cone at West Driefontein Gold Mine's No. 2 Shaft (a dewatering shaft) (Fig. 3, Table 5 column 6) is approximately 1,000 m.

higher than during the pre-mining period, due to sinkholes and ground surface cracks which allow a significant increase in the rate of recharge. New sinkholes forming during rewatering will aid this process temporarily. The recharge may later decrease as the sinkholes become choked with silt and other erodible detritus. Increased urbanization will significantly increase runoff, causing over-saturation of waterlogged areas. This higher infiltration will increase recharge.
In pre-mining times, water flowed down the Lower Wonderfontein Spruit and did not trigger any problematic sinkholes. It is thus suspected that, well after the rewatering phase, stability to the riverbed would ultimately return. However this needs to be investigated in follow-up studies. Factors hitherto not fully evaluated and that may increase the transmissivity of the fractured rock aquifer thereby causing the intercompartmental flux to be higher than that estimated above, include the following:

- The hydraulic conductivity in the zone immediately above the mine may increase with time as a result of subsidence and an increase in the number of fractures.
- In areas where the top of the dolomitic bedrock is lower than the pre-mining water table, exploration boreholes, which were not sealed at their intersection with the Black Reef Formation, may serve as conduits between the newly replenished cavernous aquifer and the mine void. Areas where the cement lining of that part of the shaft barrel that runs through the dolomite are deficient or damaged, may also increase flow towards the mine void.

Time to reach final elevation

Assuming a recharge rate to be that of the pre-mining spring flow, a conservative (longer) estimate, subsequent to the flooding of the mine, is that the cavernous aquifer will fill in less than 20 years (Table 5, column 9). Thus given a normal rainfall distribution, the pre-mining water levels will re-establish within 30 years from cessation of pumping (Table 5).
The time required to completely rewater will, however, depend to a large extent on periods of high rainfall and the associated flood events. This qualification is supported by mine pumping data that show dramatic increased pumping rates corresponding with wet cycles (Fig. 5).
The major rewatering impact will, initially, be in the Venterspost Compartment, which is the highest of the succession of dewatered compartments that has large, unfilled sinkholes along the riverbed. The catchment area of the Venterspost Compartment is effectively four times larger than the surface area of the compartment as it covers the entire Upper Wonderfontein Spruit's catchment. Many sinkholes occur in the riverbed of the Venterspost Compartment, which is not the case with the Western Gemsbokfontein Compartment which is immediately upstream of the former. The corresponding ratios (catchment area: compartment area) for the Bank and Oberholzer Compartments are approximately 1:1. Thus, initially, the Upper Wonderfontein Spruit flow will be attenuated by losses into the Venterspost Compartment. Recharge of the Bank Compartment, will accelerate after the Venterspost Compartment has filled. After the Bank Compartment has filled, the recharge rate of the Oberholzer Compartment from the surface fed by spring water will improve.

Expected post-mining intercompartmental flux from east to west in the study area starting at the Gemsbokfontein Dyke

Through the Gemsbokfontein No. 2 Dyke

Owing to the fact that the Gemsbokfontein No. 2 Dyke is not mined through and provided it remains intact in the future, no intercompartmental flux from the Western Gemsbokfontein Compartment via the Venterspost Subcompartment (the Gemsbokfontein No. 1 Dyke is mined through) towards the Venterspost Compartment would be possible (Fig. 2).

Through the Venterspost Dyke

The Libanon and Kloof Gold Mines mined through the Venterspost Dyke (Fig. 2); however, further north the dyke is intact in the Venterspost Gold Mine. Intercompartmental flux between the Venterspost and Bank Compartments through the Venterspost Dyke where it is pierced by the Libanon and Kloof Gold Mines, will be small due to the upward leg represented by the eastern Bank Compartment being relatively impermeable for the following reasons:

- A compression zone is situated over that part of the Libanon Gold Mine in the Bank Compartment (Wolmarans and Guise-Brown 1978; Figs. 2 and 6)
- The dolomite above the point where Kloof Gold Mine pierced the Venterspost Dyke is being protected from weathering by the overlying Pretoria Group sediments.

Here, and in a later subsection headed "Through the Oberholzer Dyke" a more realistic approach with respect to determining the degree of potential intercompartmental flux was adopted. This is in contrast to the conservative approach where flux through the Bank Dyke was calculated earlier in this paper. The reason is that a critical portion of the mined-through Bank Dyke is flanked on either side by tension zones which renders the potential intercompartmental flux through the Bank Dyke more probable than through any other mined-through dyke in the study area. Should, therefore, the very conservative calculations involving the future of the Bank Spring indicate that this spring will resume flow, i.e., intercompartmental flux will not exceed natural recharge, then the other three dried springs will, as a corollary, also flow again.
It is therefore expected that water rising in the upward leg above those parts of Libanon and Kloof Gold Mines on the

eastern end of the Bank Compartment will, due to the partial hydrological barrier discussed in the section headed "Compartment boundaries," have practically no (or little) access to the tension zone over the western Bank Compartment.

Through the Bank Dyke

This was discussed in detail in the section headed "Calibration of the model based on historic dewatering data, e.g. predicted flux through the mined-through Bank Dyke", where it was suggested that the Bank Spring will flow again although much intercompartmental flux will also take place.

Through the Oberholzer Dyke

The same explanations offered when discussing flux through the Venterspost Dyke above, apply to the potential flux expected between the Oberholzer and Boskop-Turffontein Compartments (through the mined-through Oberholzer Dyke). Doornfontein Gold Mine is in a compression zone and the dolomite of Deelkraal and Elandsrand Gold Mines are covered by thick Pretoria Group sediments. The upward leg is thus very impermeable, indicating a small potential intercompartmental flux. Due to the anticipated flux through the Bank Dyke the post-mining yield of the Oberholzer Spring is expected to be higher than in pre-mining times.
The above subsections strongly suggest that in the post-mining era, the Gemsbokfontein, Venterspost and Oberholzer Springs will certainly resume flow due to the expected low intercompartmental flux predictions. The Bank Spring may not flow during dry spells. It is suggested that should pumping cease today, discounting the contribution of flood events, it may take less than 10 years to fill the mine void and an additional approximately 20 years to recharge the dewatered dolomitic compartments of the Far West Rand, which should be regarded as an upper (long) limit estimate.

To sum up

The data provided by some of the mines in the study area was extrapolated to the other situations on the Far West Rand. The combined pre-mining natural recharge of the four dewatered compartments on the Far West Rand is about 133 Ml/day. It was calculated that the present mine void has a capacity of 0.6 million Ml and that the dolomite aquifer is approximately 1.14 million Ml below its pre-mining water storage capacity. Under the present conditions, "wet period recharge" will increase disproportionately due to the presence of sinkholes, especially along the Lower Wonderfontein Spruit. In the event of flooding, these sinkholes will provide major conduits for rapid recharge of the dolomite aquifer as was experienced in the Venterspost Compartment in the 1974–1978 wet period.
In the absence of a major flood and assuming simultaneous decommissioning of all the mines, it will take approximately 10 years, for the mines to flood. Once the mines have been flooded, the water level will rise rapidly through the fractured rock aquifer. Thereafter, the rate of rise will decrease significantly through the cavernous dolomite aquifer particularly when it enters the final 50 m before reaching the pre-mining water level. This is due to the fact that, 40 to 50 m below the pre-mining water table, the dolomite is cavernous and responsible for up to 15% storage capacity of the aquifer.
Except for the occurrence of unusual flood events, it is estimated that the water level will reach its pre-mining elevation approximately 30 years after the cessation of pumping by the mines.

Conclusion

The hydraulic resistance of the fractured rock aquifer in the lower dolomites is sufficiently high to sustain a head differential of approximately 35 m between compartments which will enable the water tables of the four compartments to return to pre-mining levels. In consequence the now dry springs will flow again.

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