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Groundwater levels and dolomite — nuisance or necessity?

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ABSTRACT: The significance and importance of groundwater level data in a karst environment, whilst acknowledged by geotechnical engineers and engineering geologists, is often not afforded the recognition it deserves. Within the ambit of a geotechnical site stability investigation, the esoteric nature of groundwater affords it a perceived nuisance value, especially when compared to more tangible and concrete site-specific soil and bedrock information typically obtained from trial pits and exploration boreholes. The relevance of groundwater level data in a karst environment is explored on the basis of examples that show how such data can inform a better understanding of this environment. Since knowledge of the magnitude of groundwater level fluctuations in a karst environment enjoys particular geotechnical significance, response patterns evident in hydrographic data are looked at in terms of their reflection of natural and anthropogenic stimuli. The paper concludes with a brief discussion on the legislative framework for groundwater level monitoring, and the collection, evaluation and presentation/reporting of the data.

1 INTRODUCTION

Karst groundwater systems are estimated to provide ~ 25% of the global population with potable water (Bauer et al. 2008, Supper et al. 2008), and karst areas count among the most vulnerable hydrogeologic environments to human impacts in the world. The distribution in South Africa of the major 'hard' sedimentary carbonate deposits (Martini & Wilson 1998) of Vaalian age, namely the Malmani Subgroup and the Campbell Rand Subgroup (located east and west of longitude 25° respectively), are shown in Figure 1. These formations together represent at least 98% of carbonate strata (dolomite, limestone, calcrete, dolocrete, travertine, etc.) in South Africa, and cover ~ 3% of the total area of the country (Van Schalkwyk 1981). The CGS/SAIEEG (2003) guideline provides a concise description of the dolomite and limestone occurrences in South Africa. A more detailed description can be found in Martini & Wilson (1998).

To fully understand the vulnerability of karst hydrosystems requires multi-disciplinary studies that pool expertise from disciplines such as geology, hydrogeology, engineering geology, hydrology, geomorphology, geophysics and geochemistry. This expertise is typically drawn together through the application of geographic information system (GIS) technology. In the face of such complexity, a groundwater level measurement easily represents the most basic and concrete parameter in physical hydrogeology. As such, it constitutes the single most important measurement in the quantitative evaluation of any groundwater system. This paper reflects on the value of groundwater level measurements and, by so doing, hopes to raise the profile of such measurements from nuisance value to that of absolute necessity also in a geotechnical context.

2 CONTEXT

An interrogation of available GIS coverages indicates that the dolomitic strata of the Malmani Subgroup outcrop over 2643km^2 (~ 16%) of Gauteng Province (Fig. 2). Further, that built-up areas (representing residential, commercial, mining and industrial land use) in this province cover 3126km^2, of which 376km^2 (~ 12%) is located on dolomite. These areas occur mainly in the metropolitan municipalities of Johannesburg, Ekurhuleni and Tshwane, which together represent a developing 'polycentric urban region' or megacity with a current population of some 9.5 million, and a projected population by the year 2015 of 14.6 million (SACN 2004). The pressure of urbanisation on available land, including dolomite, is obvious.

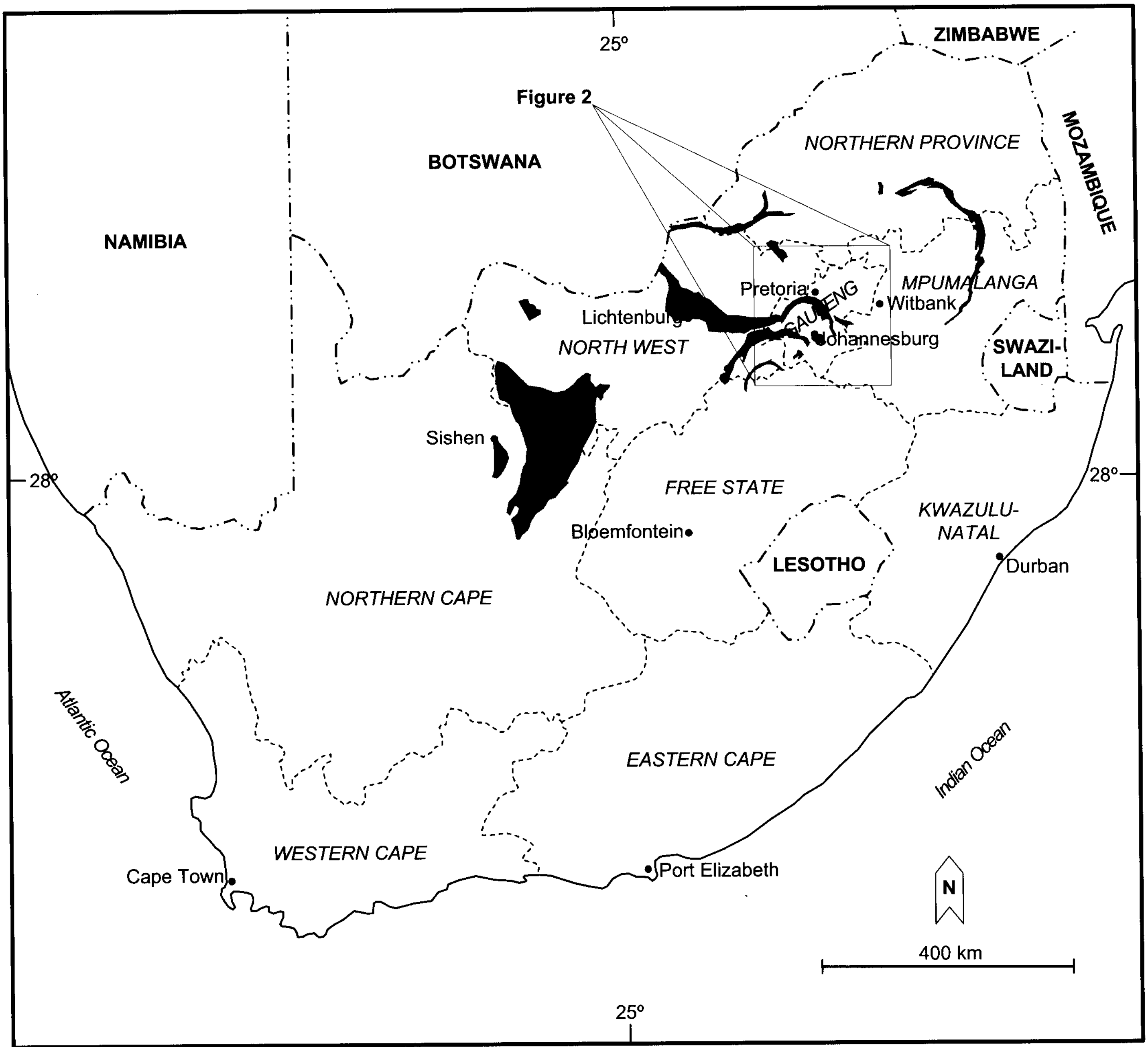

Figure 1. Map showing the distribution of 'hard' sedimentary carbonate deposits (shaded areas) of Vaalian age in South Africa (modified after Martini & Wilson 1998).

The Tshwane metropole (population ~ 2.2 million) alone draws ~ 10% (22.7Mm^3) of its annual water supply from the karst aquifer (Hobbs 2004), establishing this groundwater resource as one of the most productive currently contributing to an urban water supply in South Africa, if not southern Africa. The dolomitic strata also host the Cradle of Humankind World Heritage Site with its internationally renowned fossiliferous cave systems. GIS analysis shows that irrigated agriculture (excluding so-called 'improved grassland') in Gauteng Province covers 275km^2, of which 95km^2 (~ 35%) is located on dolomite. This testifies to the fact that the karst landscape lends itself admirably to large scale irrigated agriculture, with the attendant threat of over-abstraction of groundwater. Finally, the consequences associated with mining and related dewatering / rewatering phenomena constitutes a clear and present danger in the form of acid mine drainage (AMD) and ancillary geo-environmental impacts.

At the Stockholm Water Symposium 2006, the South African Minister of Water Affairs and Forestry informed the world of concerns regarding the impact of climate change on the water security of the country. Issues of particular hydrogeological concern include groundwater level fluctuations and the increased risk of subsidence and sinkhole formation (already a characteristic in residential areas located on dolomite), the presence of informal settlements located on dolomite, the impact of poor quality surface water infiltrating a karst aquifer, and acid mine drainage from the growing number of defunct and rewatering gold mines. Against this background, groundwater levels represent a key parameter in evaluating and managing the impacts of human activity on any hydrosystem, let alone karst aquifers.

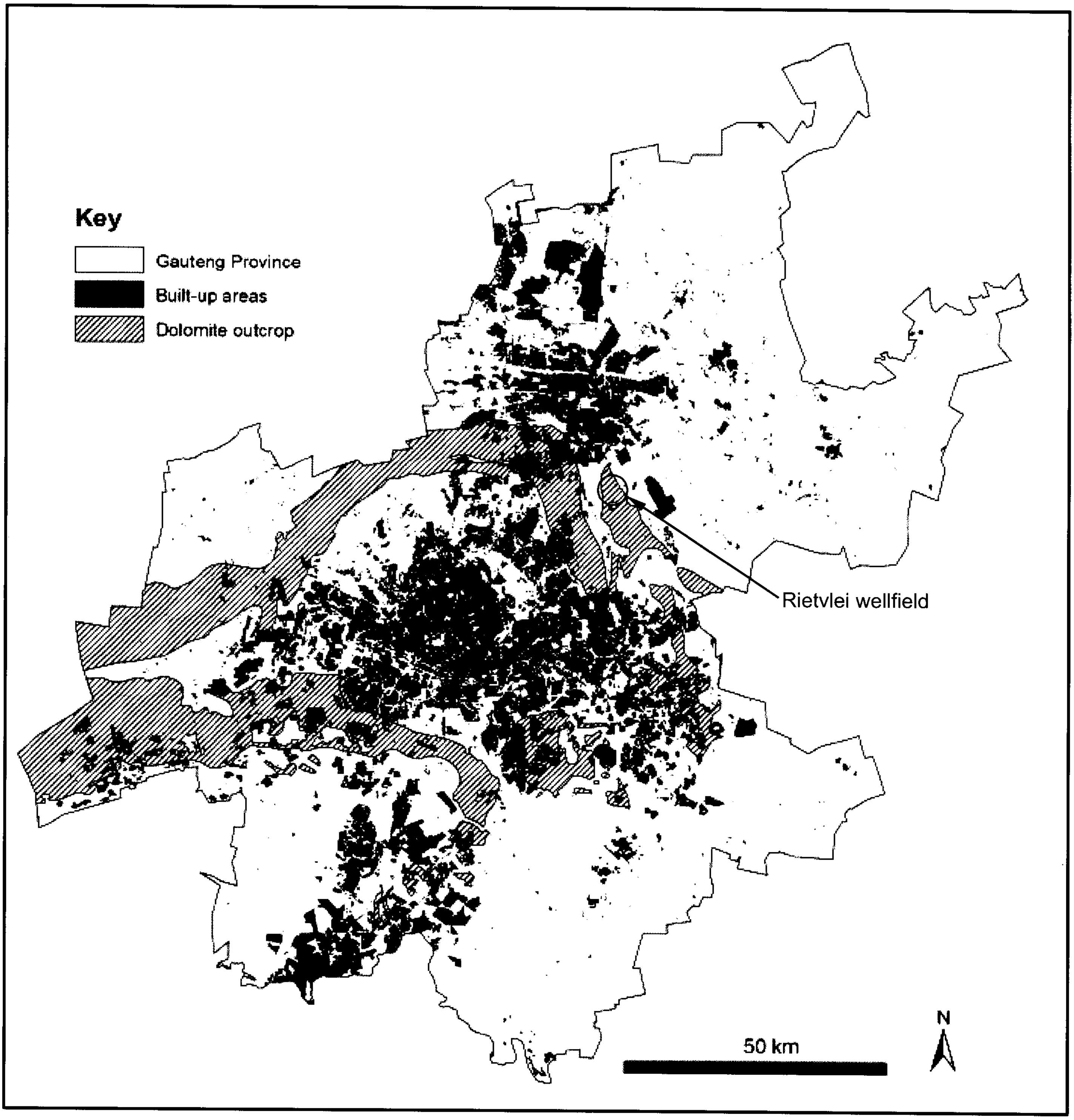

Figure 2. Map showing the distribution of built-up areas and dolomite outcrop in Gauteng Province.

3 BASIC CONCEPTS

The relative permanency of boreholes drilled for groundwater investigation purposes contrasts sharply with the typically impermanent nature of exploration boreholes drilled for geotechnical site investigation purposes. Whereas the former are generally transformed into long-term water supply facilities, the latter are backfilled and destroyed typically within days of their establishment. These circumstances probably account somewhat for the perception that water level measurements made in the context of engineering geological or geotechnical engineering studies differ from those made in the context of hydrogeological studies. Hodgson (1988) refers to "*The mystique associated with ground-water monitoring……….*" against the background of timeously providing information for management purposes in order to gain acceptance. Hatheway (2007) expresses the view that "*Groundwater is one of the most unruly elements that must be dealt with in the practice of Engineering Geology*".

For the engineering geologist / geotechnical engineer, a borehole is a temporary hole in the ground that, for all the other valuable information on the subsurface it provides, might or (hopefully) might not be 'wet' and yield a water level measurement. The latter is often left to the drilling contractor to obtain, often in the course of a punishing schedule that encompasses many other ostensibly more important activities and deadlines. Nevertheless, a single (unique) water level measurement is no less permanent than a 100-year time series of such measurements. Importantly, it registers the 'state' of the groundwater regime at the time of its measurement, if taken correctly to ensure its representativeness as a static water level.

Typically expressed in relative terms as a depth in metres below surface (mbs), or in absolute terms as an elevation in metres above mean sea level (mamsl), it defines the potentiometric head (or simply 'head') in an aquifer at the position and time of measurement. The Department of Water Affairs and Forestry (DWAF) recognises the term static water level (SWL) as the standard descriptor for a groundwater rest level measurement (DWAF 2003).

In theory, a minimum of three spatially separate SWL measurements for the same aquifer uniquely defines the potentiometric surface between the measuring points in space and time. The potentiometric surface is not to be confused with the commonly used but more restrictive term 'water table'. Since the latter defines the potentiometric surface in an unconfined (also termed phreatic) aquifer only, its use in regard to non-phreatic (i.e. semi-confined and confined) aquifers is inappropriate. Use of the term potentiometric surface is unequivocal under all hydrogeologic circumstances.

The greater the degree of confinement, the larger the difference between the depth at which groundwater is first encountered in a borehole during drilling, and the SWL. Within the context of the preceding discussion, the significance of this in terms of risk assessment is obvious. The first (and any subsequent) water strike is generally observable during drilling in the amount of water returning to surface from the bore. These circumstances, however, add complexity to the concept of a SWL under circumstances where subsequent water strikes are associated with aquifer horizons that might be hydraulically disconnected to that in which groundwater is first encountered. Further, cavities in a karst environment may 'swallow' the returning compressed air and its entrained water and rock chips, so masking any indication of a water strike. This necessarily applies to the air rotary percussion technique, the most common and cheapest drilling method used in geotechnical investigations.

Springs or 'eyes', a common feature in karst environments, mark the intersection of the potentiometric and land surfaces. Elsewhere, the SWL is readily determined in boreholes and other structures (e.g. dug wells, mine shafts) that penetrate a groundwater resource. The value of SWL measurements far outweighs the miniscule cost of their collection, especially when evaluated in concert with other similarly 'cheap' groundwater information. These circumstances change somewhat when a series of measurements is required in order to establish a temporal trend in this parameter that provides "........*information about the hydrologic stresses acting on aquifers, and how these stresses affect groundwater recharge, storage and discharge.*" (Taylor & Alley 2001). A groundwater level record spanning one or more decades generally reveals the potential range of head fluctuation in an aquifer at the position of the monitoring borehole (Taylor & Alley 2001). Groundwater level fluctuations not only reflect directly the conditions (e.g. geology, hydrology and climate) that affect an aquifer (Olin 1995). Without such data, a confident prediction of groundwater level behaviour into the future, whether interpolated, extrapolated or modelled, is impossible.

A synoptic set of SWL data (Taylor & Alley 2001) collected in a short space of time (typically within 1 to 2 months) facilitates the compilation of a groundwater level contour (or potentiometric) map. In its simplest form, such a map presents a snapshot in time of the direction of groundwater movement. An assessment of contour spacing may also provide an indication of spatial variations in aquifer transmissivity (T). All other factors, e.g. aquifer saturated thickness, hydraulic conductivity and aquifer width being constant, more closely spaced contours indicate lower T-values, and wider spacing zones of greater transmissivity. The SWL data can also be compiled to give a spatial representation of the depth to groundwater rest level. This parameter, together with groundwater level fluctuations, is recognised as a key risk assessment factor in the engineering-geological characterisation of dolomitic environments (CGS/SAIEEG 2003).

4 GROUNDWATER LEVEL FLUCTUATIONS

Temperley (1978) discusses at length the "*fluctuation of the water-table*" in the dolomitic groundwater environment south of Pretoria. Van Wyk (1963) identifies and describes water level fluctuations in northern Natal and Zululand associated with recharge from rain, induced by pumping, and caused by earth-tides, changes in atmospheric pressure and loading effects from passing trains. The Ohio Department of Natural Resources (ODNR 2008) additionally reports responses due to earthquakes and loading from heavy traffic. These factors can be categorised as either natural or anthropogenic (human-induced) influences which, of course, can and often do occur together. In regard to karst formations, Wagener (1985) distinguishes between dolomite "*with a static water table*" and dolomite "*be-*

"*being dewatered*". These represent the 'non-dewatering' and 'dewatering' scenarios addressed in the CGS/SAIEEG (2003) guideline. They may also be interpreted as representing natural and stressed karst environments, respectively.

4.1 *Natural environments*

Brink (1996) quotes the observation, made in the public enquiry report by the Chief Inspector of Mines (Bennie 1963) into the West Driefontein Mine sinkhole disaster of 12 December 1962, that "........*the water table in dolomitic areas fluctuates several inches twice daily due to lunar and solar attraction,* ....", and the fact that "........*it was full moon the day prior to the accident and that the moon and sun were diametrically opposed,* ....". This is put forward as a possible contributing causative factor, together with dewatering, structural loading, heavy machinery induced vibration and mining-related earth tremors, in triggering the sinkhole. Hobbs & Fourie (2000) show that the SWL in a dolomite aquifer confined beneath > 80m of Karoo sediments exhibits a natural diurnal fluctuation of up to 0.15m due to earth-tide and barometric effects. Clearly then, the concept of a 'static' water level is somewhat of a misnomer even in such prolific aquifers as are represented by karst hydrosystems.

Temperley (1978) remarks that "........*as the water-table fluctuation in dolomite is generally small, 3m or less, the date on which a depth measurement was made is of little consequence.*" This statement was examined on the basis of an assessment of hydrostatic fluctuations comparing the various circa 1972 groundwater contour maps presented by Temperley (1978) with those produced by Kok (1985), Leskiewicz (1986), Hobbs (1988a) and Kuhn (1989). The results for 22 localities are summarised in the following observations:

- Nineteen localities (86%) showed either no change (13) or a change of 5m or less (6),
- All six localities that exhibited a change of = 5m are associated with declines (negative change),
- Only one locality exhibited a substantial decline (17m), and
- Only two localities showed a rise of > 5m.

The above observations suggest that the 3m regarded by Temperley (1978) as representing the general maximum magnitude of natural "*water-table*" (or hydrostatic) fluctuation in this specific karst environment might be adjusted to 5m. This finds support in an analysis of hydrostatic behaviour over a period of ~ 20 years recorded in 51 boreholes distributed between 10 dolomite compartments south of Pretoria (Hobbs 2004). The analysis suggests that the natural groundwater rest level fluctuation seldom exceeds 8m, and more typically averages in the order of 5m. Further, that:

- The greater amplitude of groundwater level fluctuation is manifested in the upper portions (headwaters) of dolomite compartments, whereas closer to the discharge area (lower reaches) more muted hydrostatic variations are manifested,
- The greatest average monthly rate of sustained groundwater level decline is observed in the upper reaches of compartments, and
- The period over which natural fluctuation maxima occur is not seasonal, but rather a few (3 to 5) years.

The first two observations suggest that the upper reaches of dolomite compartments are more susceptible to sinkhole and doline development than the lower reaches. The recent sinkhole development around Bapsfontein in the upper dolomitic reaches of the Rietvlei Dam catchment might reflect this situation. In this regard, the value of potentiometric maps in defining compartment geometry (boundaries, upper and lower reaches, etc.) is self-evident.

Finally, a maximum fluctuation of ~ 16m in the late 1970's, but more typically < 6m, is recorded in the > 70-year hydrographic record (starting in 1922) for the Wondergat (Bredenkamp et al. 1995), a cenote near Lichtenburg in the North West Province (Fig. 1). Also, an analysis of Carletonville gold field (Far West Rand) data suggests 5 to 6m as representing the maximum drawdown permissible before ground movement due to dewatering is initiated (De Beer 1988).

4.2 *Stressed environments*

Groundwater level fluctuations caused by anthropogenic influence are 'stand-out' phenomena that are generally easily recognisable in hydrographs. The dewatering of some of the Far West Rand dolomitic compartments to mitigate potentially catastrophic flooding of underground mine workings (Brink 1996) undoubtedly represents the most extreme example hereof in southern Africa. Drawdown in the Oberholzer Compartment exceeded 300m in the mid-1960's (Foose 1967) in the endeavour of West Driefontein Mine to 'make safe' its mine workings. Prior to this, the Venterspost Compartment had been 'dewatered' by the early-1960's when pumping rates peaked at ~ 57ML/d (Brink 1996), and for which Swart et al. (2003) report a drawdown of 118m in early-1974. Similar impacts were manifested in the Bank Compartment in the early-1970's following dewatering at rates of up to 340ML/d (Brink 1996).

The impact of over-abstraction from municipal water supply boreholes by the City of Tshwane Metropolitan Municipality in the Rietvlei wellfield southeast of Pretoria (Fig. 2) is illustrated in Figure 3. The recovery of water levels in this wellfield following the implementation of a ~ 40% reduction in pumping rate (from 135 to 77L/s) in 1996, is also reflected. The decline in the last part of the record again reflects the response to a gradual increase in pumping rate. Dewatering of the Campbell Rand Subroup karst aquifer at Sishen Iron Ore Mine on the Ghaap Plateau (Fig. 1) has resulted in water level drawdowns of > 100m, raising concerns for the impact on small scale users and the environment (Van Dyk et al. 2007).

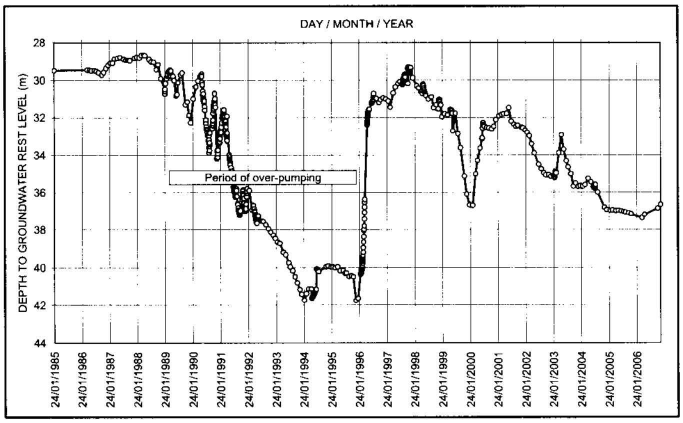

Figure 3. Hydrograph of an observation borehole in the Rietvlei wellfield southeast of Pretoria, showing the effects of both over-pumping and water level recovery following reduced abstraction (after Hobbs 2004).

5 GENERAL OBSERVATIONS AND APPLICATIONS

The above-mentioned analysis by Hobbs (2004) also included a correlation of groundwater rest level depth with surface elevation for 262 boreholes in the 10 compartments. The result is shown in Figure 4, which indicates a very poor ($R^2 = 0.01$) negative correlation. Nevertheless, the data reveal a clearly defined lower limit represented by the broken line (Fig. 4).

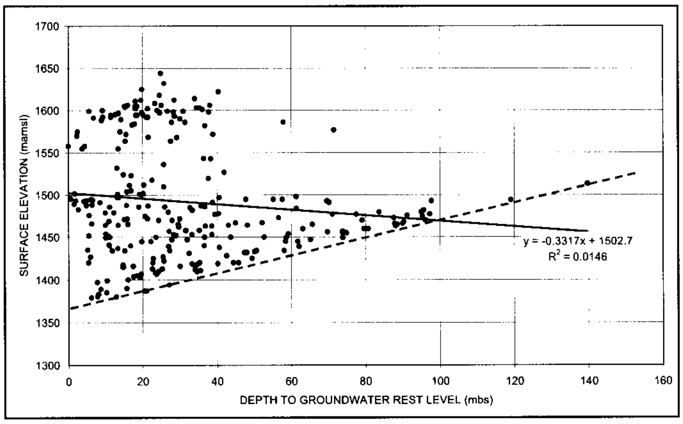

Figure 4. Correlation of depth to groundwater rest level with surface elevation for 262 boreholes in 10 dolomitic compartments south of Pretoria (after Hobbs 2004).

This aspect was explored by splitting the data set into compartment-related subsets. The results are illustrated in Figure 5, which shows the individual 'lower limit' graphs for each compartment. The insert graphs (Fig. 2) reveal the clear definition of these limits unique to each compartment.

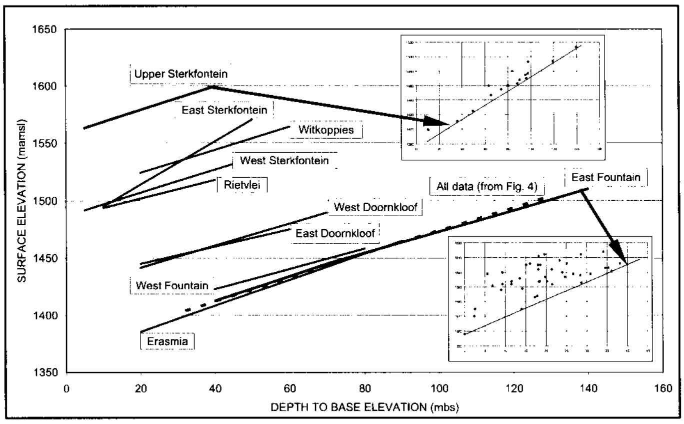

Figure 5. Composite graph of aquifer base level regression lines for 10 dolomitic compartments south of Pretoria (after Hobbs 2004). Insert graphs provide examples of detailed analyses for the Upper Sterkfontein and East Fountain compartments, showing the congruence of the base level regression lines. Note the singular variance represented by the East Sterkfontein base level.

Olin (1995) derived aquifer base levels from an analysis of groundwater level recession rates for a small (8.5km^2) granitic catchment supporting shallow primary aquifers of limited areal extent. Since the veracity of the analysis depends on the data values representing "*......the maximum recession rate at a certain level, and that the recharge thus can be assumed to be zero.*", the derived base level represents "*.......a drainage level for the aquifer that represents the lowest groundwater level that will occur from groundwater flow only.*" (Olin 1995).

The derivation of aquifer base levels for much larger karst hydrosystems as illustrated above is therefore considered significant. It is shown in Table 1 that the individual zero depth to base levels indicated for each compartment, coincide reasonably well with the surface elevations of the main discharge or decant point of that compartment. These circumstances suggested an application in the setting of resource quality objectives for groundwater quantity of the karst hydrosystems (Hobbs 2004) as required in groundwater resource directed measures (GRDM) studies (Parsons & Wentzel 2007).

The derivation of aquifer storativity values from hydrostatic response patterns associated with earth-tide and barometric influences (Hobbs & Fourie 2000) illustrates a further application of groundwater level data.

Table 1. Synthesis of aquifer base level data and associated information for ten dolomitic compartments south of Pretoria (after Hobbs 2004).

Compartment	Base elevation equation	Lowest base elevation (mamsl)	Decant position	Decant elevation (mamsl)
East Fountain	$y = 0.96x + 1375.8$	1375.8	East (Upper) Fountain	~ 1374
West Fountain	$y = 0.88x + 1388.2$	1388.2	West (Lower) Fountain @ ~1370 mamsl	~ 1370
East Doornkloof	$y = 0.75x + 1430.0$	1430.0	Pretoria Dyke / Sesmylspruit intersection	~ 1425
West Doornkloof	$y = 0.96x + 1422.7$	1422.7	Irene Dyke / Sesmylspruit intersection	~ 1410
East Sterkfontein	$y = 1.86x + 1476.4$	1476.4	Sterkfontein Spring	~ 1480
West Sterkfontein	$y = x + 1487.0$	1487.0	Sterkfontein Dyke/Kaalspruit intersection	~ 1480
Upper Sterkfontein	$y = 1.06x + 1557.6$	1557.6	Tweefontein Dyke/Swartspruit intersection	~ 1554
Rietvlei	$y = 0.80x + 1486.0$	1486.0	Rietvlei springs (average of 3 springs)	~ 1486
Witkoppies	$y = x + 1504.0$	1504.0	Grootfontein Spring	~ 1500
Erasmia	$y = 1.13x + 1363.5$	1363.5	Erasmia pumping station	~ 1368
All data	$y = 1.02x + 1371.7$	1371.7	See Figure 4	~ 1372

6 GROUNDWATER LEVEL MONITORING

6.1 *Legislative framework*

Chapter 14 of the National Water Act (RSA 1998) recognises that "*Monitoring, recording, assessing and disseminating information on water resources is critically important for achieving the objects of the Act.*" In this regard, the Act places a duty on the Minister to establish national monitoring systems. This is given effect by the national and regional groundwater monitoring programmes operated and managed by the DWAF.The DWAFs monitoring programmes are, however, directed at informing national groundwater management imperatives, and not at the specific needs of those water users and landowners for which such information is important. The latter are accommodated in Section 141, which reads "*The Minister may require in writing that any person must, within a reasonable given time or on a regular basis, provide the department with any data, information, documents, samples or materials reasonably required for-*

> *(a) the purposes of any national monitoring network or national information system; or*
>
> *(b) the management and protection of water resources.*"

Section 141 therefore clearly provides a mechanism for the DWAF, in concert with other relevant authorities such as the National Home Builders Registration Council (NHBRC), the Council for Geoscience (CGS) and District/Local Municipalities, to impose groundwater monitoring obligations on landowners. In the case of residential estates or industries developed on dolomitic land, such obligations might be imposed on the Body Corporate (BC), Home Owners' Association (HOA) or Management.

The CGS/SAIEEG (2003) guideline provides for the design of a risk management plan that includes "*groundwater monitoring*", described as entailing measuring and recording of the groundwater level. Appendix 3, "Minimum Reporting Requirements", of the guideline describes the geohydrological aspects that need to be addressed in all dolomite stability reports.

6.2 *Distribution*

An extended period of drought during the early- to mid-1980's prompted a concerted period of karst groundwater exploration by the DWAF. This programme sought to establish the viability of using dolomitic groundwater resources to augment critically low 'traditional' surface water resources such as the Vaal Dam (Roberts 1988). In the period late-1983 to mid-1987, some 400 large diameter (= 165mm) boreholes were sunk in the dolomitic strata of the Pretoria/Witwatersrand/Vereeniging (PWV) area (Hobbs 1988b, Mulder 1988). The distribution of karst groundwater level monitoring stations in Gauteng Province is largely a legacy of this focused karst aquifer exploration programme.

A total of 502 boreholes are employed by DWAF for karst aquifer water level monitoring purposes nationally (Bertram 2008). The geographic distribution of these stations is indicated in Table 2.

Table 2. Geographic distribution of karst aquifer water level monitoring stations operated nationally by the DWAF (after Bertram 2008).

Province	Geographic area	No. of stations	Karst hydrosystem
Gauteng	Centurion	13	Malmani Subgroup
	East Rand	84	
	Kempton Park	13	
	Natal Spruit	67	
	Pretoria	5	
	Rietvlei	20	
	Tarlton	37	
	West Rand	58	
North West	Bo-Molopo	122	
	Dinokana	16	
	Lichtenburg	5	
	Polfontein	11	
	Ventersdorp	37	
Northern Cape	Danielskuil	14	Campbell Rand Subgroup
Total		502	

It is evident that the Gauteng and North West provinces, with 297 (59%) and 191 (38%) stations respectively, together host 97% (488) of the stations. The > 20-year hydrographic record of many of these stations provides an invaluable window into the regional hydrostatic behaviour of the karst hydrosystems monitored.

Given the focus of this paper, the location (and number) of groundwater level monitoring stations in a site-specific context such as a residential estate, factory or even water-intensive farming operation bears consideration. Specifications in this regard are scarce, if they exist at all, and this paper can therefore only provide guidance on this matter in specific regard to karst hydrosystems.

Development on dolomitic land is subject to rigorous geotechnical risk assessment procedures (CGS/SAIEEG 2003) which include the drilling of exploration boreholes. The number of such boreholes varies according to the extent of higher risk areas that are identified within the area of proposed development. This is typically based on gravimetric survey information. The need to 'prove' the extent of these 'poor' areas therefore dictates the distribution of such boreholes. These circumstances also mean, however, that boreholes in such areas represent better monitoring candidates, since they are more likely to intersect karst features associated with groundwater occurrence. One borehole in a 'poor' area is sufficient for hydrogeologic monitoring, provided that it does in fact support an unequivocal groundwater level. It is the author's experience, however, that very few such boreholes are completed and secured for this purpose.

A measure of unequivocalness in groundwater level data is reflected in the shallowness of the hydraulic gradient across the area of concern. Karst hydrosystems are typically characterised by very weak hydraulic gradients (flat potentiometric surfaces) over large expanses. For example, the dolomitic compartments south of Pretoria, which vary in size from ~ 25 to ~ 125km^2, display hydraulic gradients of between 0.0015 (1 in ~ 650) and 0.0061 (1 in ~ 150). The potentiometric surfaces are disrupted by 'steps' at positions where a hydraulic barrier (typically dyke structures) marks the boundary between compartments. Significant variations in groundwater level, i.e. more than a few metres over a few hundred metres, might therefore reasonably signify caution in the acceptance of the data as being unequivocally representative of a common potentiometric surface in comparatively small areas (typically < 5km^2, or 500ha) such as are generally considered for development.

6.3 *Frequency*

The choice of groundwater level measurement frequency should be sufficient to define short-term and seasonal fluctuations, and to differentiate between the effects of short- and long-term stresses (Taylor & Alley 2001). This may be undertaken continuously or periodically.

Continuous monitoring by means of an automated water level sensing and recording instrument installed in a monitoring borehole offers the greatest measurement resolution. These instruments can be programmed to record water level values at any specified frequency, from every second to intervals of hours, days, weeks or even months. Their use finds greatest application in aquifers that exhibit a frequent, substantial and rapid hydrostatic response to stresses. Other hydrogeological factors that inform the frequency of groundwater level measurements are given in Figure 6.

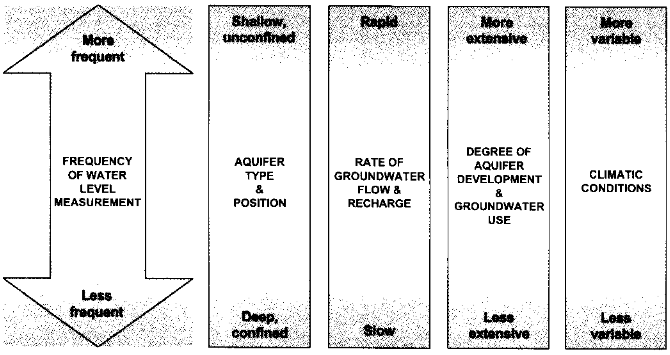

Figure 6. Frequency of groundwater level measurements as informed by various influencing factors (modified after Taylor & Alley 2001).

In a geotechnical context, however, a frequency of no more than weekly is considered adequate, and for which purpose periodic measurements are sufficient. Such measurements are easily made by hand using a dipmeter (electronic-sensor tape, chalked metal tape, acoustic sounding device, etc.). The potential disadvantages of periodic monitoring, namely missing hydrostatic responses due to short-term stresses manifested between measurements, uncertainty in determining extreme fluctuations, and introducing a potential bias in apparent trends due to the choice of monitoring frequency (Taylor & Alley 2001), are not considered critical factors in environments where excessive stresses due to anthropogenic impacts, e.g. groundwater abstraction, do not exist. A change in circumstances will necessarily precipitate a review of the monitoring frequency.

6.4 *Collection and reporting*

The collection of groundwater level data comprises the measurement itself, as well as its recording and capture in a suitable repository. The former entails measurement by any of the means described in the previous section. The latter might take the form of simple hand-written entries in a logbook or, in advanced applications, capture in off-the-shelf database software. For comparatively low-key applications, spreadsheets offer a viable alternative also for their charting functionality. It is important to record both the date and time of each measurement.

The collection of groundwater level data is pointless if the information is not evaluated and the results gainfully employed, e.g. to identify the potential advent of higher risk circumstances and adjust/improve groundwater resource management accordingly. An example of a groundwater level record presenting the results of a statistical analysis of hydrographic data is shown in Figure 7.

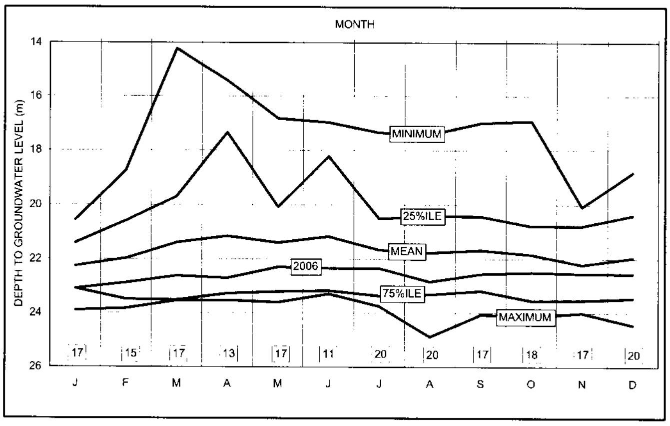

Figure 7. Graphical presentation of monthly groundwater level information for a DWAF monitoring borehole over a 20-year period of record; boxed values indicate number of measurements in record for that month.

The reporting of groundwater monitoring information should be accurate, unequivocal, practical and timeous. The CGS/SAIEEG (2003) guideline recommends the submission of this data to the DWAF. Custodianship within this organisation lies with the Chief Directorate: Information Management (Bertram 2008).

6.5 *Other considerations*

This manuscript would be incomplete if it did not also draw attention to other considerations of significance in the framework of groundwater monitoring. The most important of these is undoubtedly rainfall, the principal natural 'driver' of hydrostatic response patterns due to recharge.

Another parameter that in the author's experience receives very little (if any) attention, especially during stability assessment investigations, is that of groundwater chemistry. The chemical analysis of a water sample from a 'wet' exploration borehole can assist in 'unraveling' otherwise conflicting information, e.g. multiple water strikes in an exploration borehole or disparate groundwater levels across a site. A basic inorganic analysis for the major ions (calcium, magnesium, sodium, sulphate, chloride and total alkalinity) together with pH and electrical conductivity, is typically sufficient for this purpose.

In the long-term, changes in groundwater quality might inform an evaluation of risks also in a geotechnical context. A bi-annual (6-monthly) sampling frequency is considered sufficient for this purpose. Application of and adherence to a consistent sampling procedure (e.g. Weaver et al. 2007) will add rigour to and cultivate confidence in the analytical results, especially if the analyses are undertaken by a SANAS-accredited laboratory.

7 CONCLUSIONS

The geotechnical and engineering geological aspects that inform investigations on dolomitic land have been 'sharpened' to the extent where they are succinctly described in the CGS/SAIEEG (2003) document and enforced by the relevant authorities, primarily the Council for Geoscience and the National Home Builders Registration Council. Whilst this also extends, though in smaller measure, to the hydrogeological components of such investigations, it is the author's opinion that the post-investigation and, for that matter, the post-development groundwater monitoring imperatives unfortunately still enjoy a low priority.

The value of karst hydrosystems as a source of potable water is given recognition in the form of the DWAF (2006) guideline devoted to the assessment, planning and management of groundwater resources in dolomitic areas. The mutual threat that underlies the continued co-existence of the natural and anthropogenic domains defines at the same time a symbiosis and an antibiosis that we ignore at our peril. The perception that groundwater level monitoring is a 'nuisance-value' requirement persists, and the danger that its relevance as a precautionary measure will fade with time, especially in the absence of a 'failure event', is cause for concern. If nothing else, neglect in this regard demonstrates a simple disregard for due diligence on the part of all parties concerned.

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REFERENCES

Bauer, C., Kellerer-Pirklbauer, A. & Lieb, G.K. 2008. Human impact on karst environments; A case study from central Styria, Austria. *Geophysical Research Abstracts* 10. EGU2008-A-01339.

Bertram, E. 2008. Assistant Director: Data Management. Directorate: Hydrological Services. Department of Water Affairs and Forestry. Email communication. 18 March 2008. Pretoria.

Bennie, J.K. 1963. Report on the circumstances attending the subsidence at the sorting and crushing station, No. 2 Shaft, West Driefontein Gold Mining Company, on 12 December 1962. GME Report 3. Department of Mines.

Bredenkamp, D.B., Botha, L.J., Van Tonder, G.J. & Van Rensburg, H.J. 1995. Manual on quantitative estimation of groundwater recharge and aquifer storativity. Rep. TT 73/95. Water Research Commission. 363 pp. Pretoria.

Brink, A.B.A. 1996. Case History 18: Malmani Subgroup – Sequence of events relating to mining and the accelerated development of sinkholes and dolines in the Far West Rand. *Engineering Geology of South Africa.* Vol. 1. 240-248.

CGS/SAIEEG 2003. *Guideline for engineering-geological characterisation and development of dolomitic land.* Council for Geoscience/South African Institute of Engineering and Environmental Geologists. 66 pp. Pretoria.

De Beer, J.H. 1988. Surface stability considerations related to abstraction of ground water from dolomite. In Proceedings of the Workshop on Dolomitic Ground Water of the PWV area. Ground Water Division. 80-85. Pretoria.

DWAF 2003. Standard descriptors for boreholes. Version 1.0. Norad / Department of Water Affairs and Forestry. 93 pp. Pretoria.

DWAF 2006. A guideline for the assessment, planning and management of groundwater resources within dolomitic areas in South Africa. IHP Project no. 14/14/5/1. 3 volumes. Department of Water Affairs and Forestry. Pretoria.

Foose, R.M. 1967. Sinkhole formation by groundwater withdrawal: Far West Rand, South Africa. *Science* 157(3792). 1045-1048.

Hatheway, A.W. 2007. Book review: Groundwater in the Environment: An Introduction. Paul L Younger, 2007, Blackwell Publishing, Oxford, UK & Malden, Massachusetts, 318 pp. ISBN 1-4051-2143-2. *Quarterly Journal of Engineering Geology & Hydrogeology.* 40(2). 194-195.

Hobbs, P.J. 1988a. Hydrogeology of the Verwoerdburg dolomite aquifer. Rep. GH3502. Directorate Geohydrology. Department of Water Affairs and Forestry. Pretoria.

Hobbs, P.J. 1988b. Recent test pumping of the Malmani Subgroup dolomite in perspective. In Proceedings of the Workshop on Dolomitic Ground Water of the PWV Area. Ground Water Division. 35-42. Pretoria.

Hobbs, P.J. 2004. Intermediate groundwater Reserve determination for quaternary catchments A21A and A1B. Project 2002-316. Department of Water Affairs and Forestry. 179 pp. Pretoria.

Hobbs, P.J. & Fourie, J.H. 2000. Earth-tide and barometric influences on the potentiometric head in a dolomite aquifer near the Vaal River Barrage, South Africa. *Water SA* 26(3). 353-360.

Hodgson, F.D.I. 1988. Ground-water monitoring in dolomitic areas. In Proceedings of the Workshop on Dolomitic Ground Water of the PWV area. Ground Water Division. 128-131. Pretoria.

Kok, T.S. 1985. ’n Beraming van die grondwaterpotensiaal van die dolomiet te Rietvallei 377, Distrik Pretoria. Rep. GH3383. Directorate Geohydrology. Department of Water Affairs and Forestry. Pretoria.

Kuhn, C. 1989. Hydrogeology of the Midrand–Kempton Park dolomite. Rep. GH3501. Directorate Geohydrology. Department of Water Affairs and Forestry. Pretoria.

Leskiewicz, A.F. 1986. Exploitable potential of ground water resources in storage in the dolomite of the Bapsfontein, Delmas and Springs area for emergency supplies. Rep. GH3463. Directorate Geohydrology. Department of Water Affairs and Forestry. Pretoria.

Martini, J.E.J. & Wilson, M.G.C. 1998. Limestone and dolomite. In M.G.C. Wilson & C.R. Anhaeusser (eds.), *The Mineral Resources of South Africa.* Handbook 16. Council for Geoscience. 433-440. Pretoria.

Mulder, M.P. 1988. Dolomitic resource quantification. In Proceedings of the Workshop on Dolomitic Ground Water of the PWV area. Ground Water Division. 54-60. Pretoria.

ODNR 2008. Ground water level monitoring in Ohio. Fact Sheet 93-20. Ohio Department of Natural Resources. Available (online) at http://www.dnr.state.oh.us/Water/pubs/default/tabid/4079/Default.aspx#anchor12200387. Accessed on 07 March 2008.

Olin, M. 1995. Estimation of base level for an aquifer from recession rates of groundwater levels. *Hydrogeology Journal* 3(2). 40-51.

Parsons, R. & Wentzel, J. 2007. Groundwater resource directed measures manual. Rep TT 299/07. Water Research Commission. 109 pp. Pretoria.

Roberts, C.P.R. 1988. An overview of the proposed emergency ground water supply project in the Pretoria-Witwatersrand-Vereeniging (PWV) area. In Proceedings of the Workshop on Dolomitic Ground Water of the PWV area. Ground Water Division. 1-6. Pretoria.

RSA 1998. Act No. 36 of 1998: National Water Act, 1998. Republic of South Africa Government Gazette. 398(19182). 201 pp. Cape Town.

SACN 2004. State of the Cities Report 2004. South African Cities Network. ISBN 620-31150-9.

Supper, R., Motschka, K., Bauer-Gottwein, P., Ahl, A., Römer, A., Neumann-Gondwe, B., Merediz Alonso, G. & Kinzelbach, W. 2008. Spatial mapping of karstic cave structures by means of airborne electromagnetics: An emerging technology to support protection of endangered karst systems. *Geophysical Research Abstracts* 10. EGU2008-A-01126.

Swart, C.J.U., James, A.R., Kleywegt, R.J. & Stoch, E.J. 2003. The future of the dolomitic springs after mine closure on the Far West Rand, Gauteng, RSA. *Environmental Geology* 4. 751-770.

Taylor, C.J. & Alley, W.M. 2001. Ground-water-level monitoring and the importance of long-term water-level data. Circular 1217. US Geological Survey. 68 pp. Denver. Colorado.

Temperley, B.N. 1978. Groundwater in Pretoria and surrounding areas. Vol. 2. Directorate of Water Affairs. Department of Environment Affairs. Pretoria.

Van Dyk, G., Esterhuyse, C.J. & Goussard, F. 2007. Groundwater observations and impact management in the mining, urban and industrial environment of the Sishen Kathu aquifer. In Proceedings of the Groundwater 2007 Conference. Ground Water Division. Geological Society of South Africa. 5-7 October 2007. Bloemfontein.

Van Schalkwyk, A. 1981. Ontwikkelingspatroon en risiko-evaluasie in dolomietgebiede. In Proceedings of the Seminar on the Engineering Geology of Dolomite Areas. Department of Geology. University of Pretoria. 26- 27 November 1981. 9-24. Pretoria.

Van Wyk, W.L. 1963. Ground-water studies in northern Natal, Zululand and surrounding areas. Memoir 52. Department of Mines. 135 pp. Pretoria.

Wagener, F. von M. 1985. Problem soils in South Africa – state of the art: Dolomites. *The Civil Engineer in South Africa* 27. 395-407.

Weaver, J.M.C., Cavé, L. & Talma, A.S. 2007. Groundwater sampling (Second edition). TT 303/07. Water Research Commission. 168 pp. Pretoria.