Earth-tide and barometric influences on the potentiometric head in a dolomite aquifer near the Vaal River Barrage, South Africa

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Abstract

The natural groundwater level fluctuations recorded in a borehole penetrating a confined dolomite aquifer near the Vaal River Barrage demonstrate a cyclic, semi-diurnal pattern attributed to earth-tide effects. These fluctuations describe a period of 12.3 h, a mean amplitude of 45 mm and a maximum amplitude of 90 mm. Concomitant barometric fluctuations describe a similar pattern with a period of 11.3 h, a mean amplitude of 0.7 mbar and a maximum amplitude of 2 mbar. The short period semi-diurnal potentiometric and barometric fluctuations are superimposed on longer period fluctuations caused by changes in atmospheric pressure. The potentiometric response to these changes demonstrates a barometric efficiency of 63% for the confined aquifer. This assigns a tidal efficiency value of 37% to the aquifer which is in reasonable agreement with the 25% synonymous pore pressure coefficient suggested for limestone. Extending the analysis further yields a range of aquifer storativity values which, for the most likely aquifer specific storage, porosity and saturated thickness values, focuses on a theoretical storativity value in the order of 2.6×10^{-5} at the position of the borehole. The difference between this value and that of some 5.5×10^{-4} obtained from a pumping test performed on the borehole possibly demonstrates the magnitude of variation in the storativity of a comparatively inelastic confined dolomite aquifer in the unstressed (natural) and stressed (unnatural) states respectively.

Introduction

Changes in atmospheric pressure are known to cause natural fluctuations of the groundwater level in boreholes penetrating confined aquifers (Todd, 1959; Freeze and Cherry, 1979). Walton (1970) reports on barometric readings of atmospheric pressure that show diurnal and semi-diurnal fluctuations. Whereas diurnal fluctuations are represented by a single maximum reading coinciding with the coldest hours and a single minimum reading coinciding with the warmest hours in a day, semi-diurnal fluctuations are characterised by two maxima and two minima per day.

Natural cyclic semi-diurnal fluctuations in groundwater level are also known to be caused by earth tides (Todd, 1959; Walton, 1970; Freeze and Cherry, 1979). According to Davis and De Wiest (1966), these fluctuations are small (amplitude less than 30 mm) compared to those resulting from barometric changes. Earth-tide phenomena, which result from the attraction exerted on the earth's crust by the moon and (to a lesser extent) the sun, have been comprehensively described by Robinson (1939) as exhibiting the following characteristics:

- two daily cycles of fluctuations where:
- the average daily retardation of cycles agrees closely with that of the moon's transit;
- the daily troughs of the water level coincide with the transits of the moon at upper and lower culmination; and
- periods of large regular fluctuations coincide with periods of new and full moon, whereas periods of small irregular fluctuations coincide with periods of first and third quarters of the moon.

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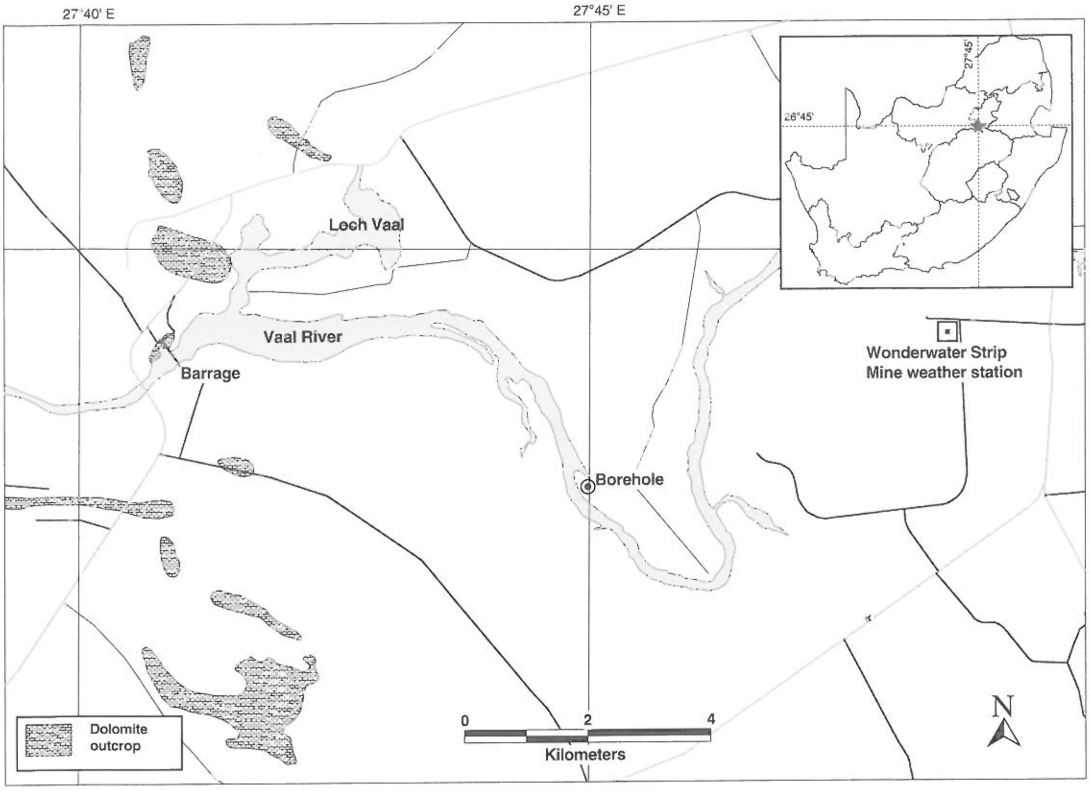
Detailed descriptions of groundwater level fluctuations caused by earth tides and by changes in atmospheric pressure (amongst others) are provided by Van Wyk (1963) for numerous boreholes in northern KwaZulu-Natal. These boreholes penetrate a variety of aquifers (e.g. the contact zone of a dolerite dyke, the transition zone in a basin of decomposition and a fault), demonstrate a wide range of yields (0.1 to 5.1 ℓ/s) and a comparatively broad spectrum of groundwater rest level depths below the surface (8.5 to 19.2 m). The formations penetrated by these boreholes range from Archaean granite, gneiss, migmatite and schist to Cretaceous sandstone, shale and limestone.

The potentiometric fluctuations recorded in a borehole penetrating a confined dolomite aquifer near the Vaal River Barrage demonstrate a distinctly cyclic, semi-diurnal pattern. The effects of changes in atmospheric pressure are superimposed on this pattern. An analysis of the hydrograph for the period 20 May to 1 June 1997, in conjunction with the barometric record for the same period, has permitted an assessment of the barometric efficiency of the aquifer. Also included in the assessment is the possible influence of loading associated with the Vaal River stage height on the dolomite aquifer. Finally, the analysis is extended to include an estimate of likely aquifer storativity values.

Geology

The rotary percussion borehole occupies a position on the right bank of the Vaal River some 8 km upstream of the Barrage (Fig. 1) and within 10 m of the water's edge. The lithologies intersected by the bore (Fig. 2) include the surficial alluvial deposits representing the late Cenozoic, Quaternary sediments which build the river banks and the early Mesozoic sedimentary strata (mainly sandstone and shale) representing the Vryheid Formation within the Ecca Group of the Karoo Supergroup. Notably absent at this location are the glacial sediments (tillite) representing the Dwyka



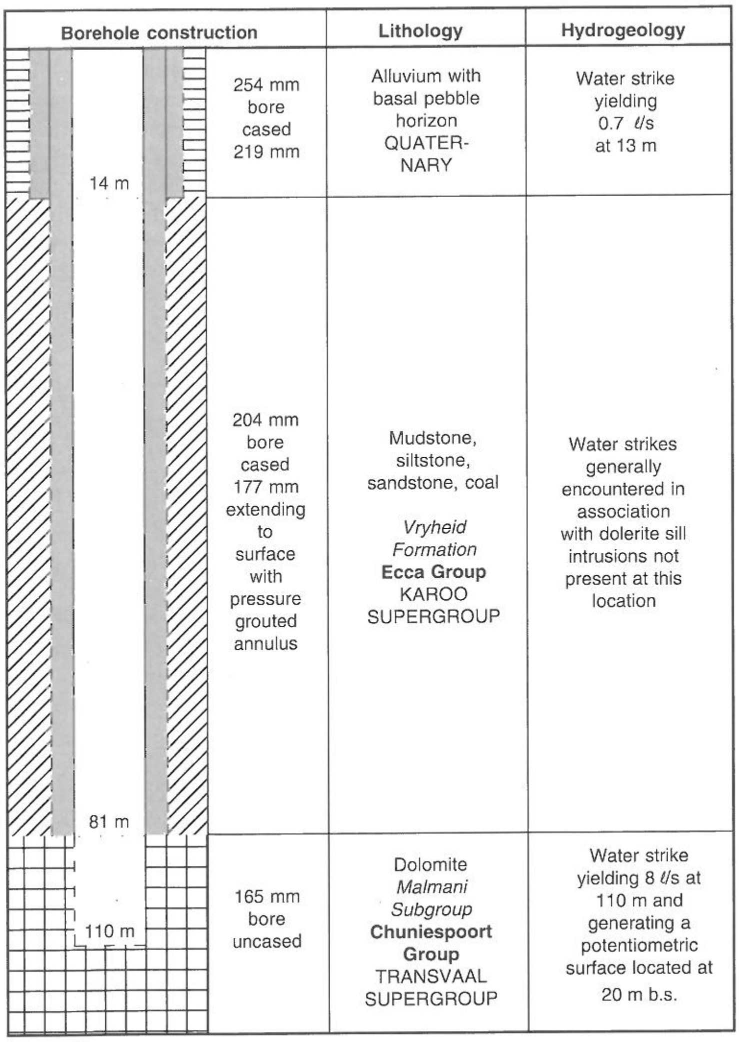


Figure 1 (top)
Locality map

Figure 2 (left)
Simplified borehole construction, lithological and hydrogeological log

Group located at the base of the Karoo Supergroup. This horizon is ubiquitous in its occurrence elsewhere in the region.

The dolomitic "basement" encountered at a depth of 81 m represents Vaalian rocks of the Malmani Subgroup of the Chuniespoort Group within the Transvaal Supergroup. Outcrops of this formation occur to the southwest and west of the borehole and to the north of the Barrage (Fig. 1). Although the dolomite is of the chert-rich variety, it has not been established which of the Monte Christo or Eccles Formations within the Malmani Subgroup it is associated with.

Hydrogeology

The 81 m thick sediments which overlie the dolomite at the position of the borehole represent the confining horizon. The dolomite aquifer demonstrated a blow-out yield of 11 ℓ/s following a water strike at a depth of 82 m. The recognition of fresh (unleached) dolomite from a depth of 92 m below surface to the final depth of 110 m suggests an aquifer thickness of only 10 m at the position of the borehole. For the groundwater rest level of 18 m below surface at the time of borehole establishment in April 1997, the hydrostatic head (calculated as the height of the groundwater rest level above the strike depth) amounted to 64 m. This represents a hydraulic

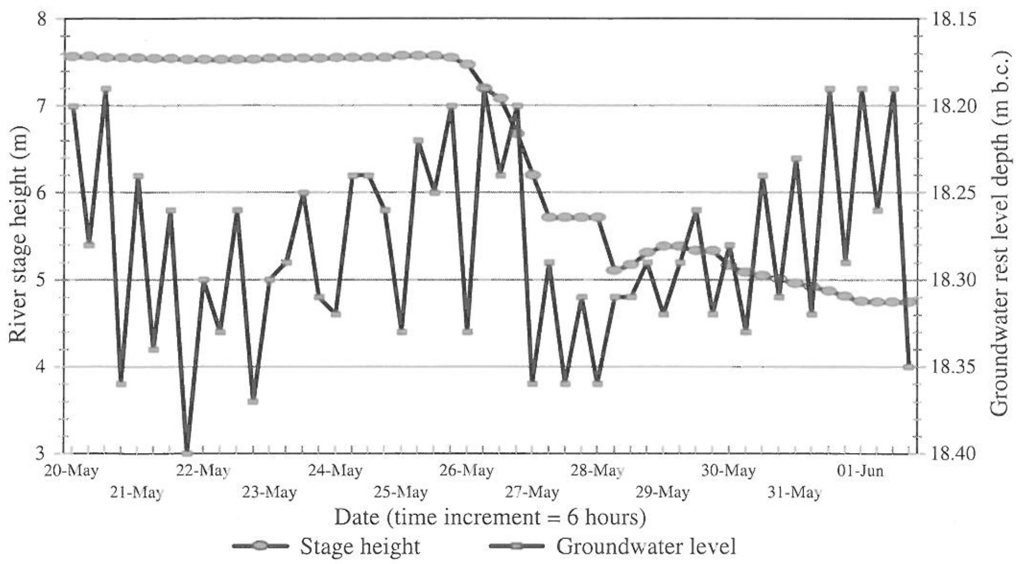


Figure 4
Stage height and potentiometric graphs for the period 20 May to 1 June 1997

barometric record. This is due to the possibilities that:

- the mass of water itself is susceptible to tidal effects, and
- significant fluctuations in the stage height alone might influence the loading on the dolomite aquifer in much the same manner as passing trains are known to do (e.g. Todd, 1959; Van Wyk, 1963).

The operational level of the Barrage is maintained at a stage height of approximately 7.5 m. This is equivalent to an absolute elevation of very nearly 1 421 m a.m.s.l. for the Vaal River upstream of the Barrage. The volume of water impounded by the Barrage for a distance of approximately 50 km upstream thereof amounts to some 61.8 x 10^6 m^3 (Small, 2000). The surface area encompassed by the first 8 km upstream of the Barrage (i.e. as far as the borehole), and which includes the Loch Vaal basin (Fig. 1), has been calculated at some 539 ha. Assuming an average depth of water of only 3 m (compared to the maximum depth of some 7.5 m at the Barrage) returns a volume of water in the order of 16.2 x 10^6 m^3. Since this represents a quite feasible 26% of the total volume impounded by the Barrage, then the operational loading on this portion of the river bed totals 16.2 x 10^6 t. By comparison, train loadings reported by Van Wyk (1963) as causing groundwater level fluctuations ranging from less than 30 mm to 180 mm, albeit under different hydrogeological conditions, varied from some 200 to 1 800 t respectively.

In order to assess the possibility that fluctuations in the stage height might influence the load carried by the dolomite aquifer, stage recordings captured by Rand Water at the Barrage were obtained from this organisation. These readings, captured on an hourly basis, were reduced to the 6 h values reported in **Appendix 1**. Graphs of the stage height at the Barrage and the groundwater level in the borehole for the period of record are presented in Fig. 4. The rapid decline in stage height manifested in the second half of the record follows the opening of the Barrage on 26 May 1997 to accommodate overflow from the Vaal Dam. This was precipitated by the substantial rainfall experienced in the region in April and May 1997, resulting in the Vaal Dam reaching a capacity of 117.6% on 29 and 30 May 1997 and realising a maximum discharge of 1 345 cumec recorded on 30 May 1997 (Holemans, 2000) at the Annie's Rust gauging station immediately downstream of the dam. The maximum discharge at the Barrage amounted to some 1 750 cumec in this period (Small, 2000).

Flood management measures under the above circumstances dictated the "draining" of the Barrage. The stage height at the Barrage reached a minimum of around 3.7 m on 2 and 3 June 1997, after which the Barrage was gradually closed and the stage height recovered to its operational level of 7.5 m by 10 June 1997.

Observations

An inspection of the graphs presented in Fig. 3 reveals the inverse relationship that exists between atmospheric pressure and hydrostatic head. This is most evident in circular area A of Fig. 3. The relationship manifests a damping effect on the amplitude of potentiometric fluctuations in the presence of a relatively rapid rise in atmospheric pressure (circular area B), which circumstances are reversed when the barometric pressure starts to fall equally rapidly (ellipsoidal area C).

The coincidence of a hydrostatic low with the time of upper culmination of the full moon at 11:13 on 22 May 1997 (vertical line I) and of its last quarter at 09:51 on 29 May 1997 (vertical line II) is also evident in Fig. 3. The interval of 6.96 d between these culminations closely approaches a quarter (6.83 d) of the moon's rotation period of 27.32 d (Moore, 1970) around the earth. The presence of a second hydrostatic minimum each day demonstrates the influence of the second culmination of the moon experienced by the earth. To an observer on earth, the non-circumpolar orbit of the moon renders this a non-visible lower culmination. Since the gravitational attraction of the moon is greatest at its culminations, the sympathetic reduction in the overburden load on a confined aquifer allows it to expand slightly, causing a concomitant hydrostatic minimum.

Also evident in Fig. 3 is an apparent "weekly" fluctuation in hydrostatic head defined by the rising trend Lines 1 and 2 (fitted visually) which demonstrate a pattern that is divorced from that of atmospheric pressure. For example, the rising trend defined by Line 2 initially coincides with a rise in atmospheric pressure, although closer inspection reveals that the actual potentiometric response is camouflaged by the magnitude of the earth-tide effects. This fluctuation demonstrates a period of between 5.75 and 6.25 d, which is slightly shorter than that of the interval (6.96 d) between full moon and last quarter culminations. It is also significantly shorter than the 7.38 d period which represents a quarter of the 29.53 d interval (lunation) between one new moon and the next (Moore, 1970). The "band-width" (shaded areas) encompassing these trend lines is remarkably similar. Also evident at the start of the record (on 20 May 1997) is the end of a previous cycle and, at

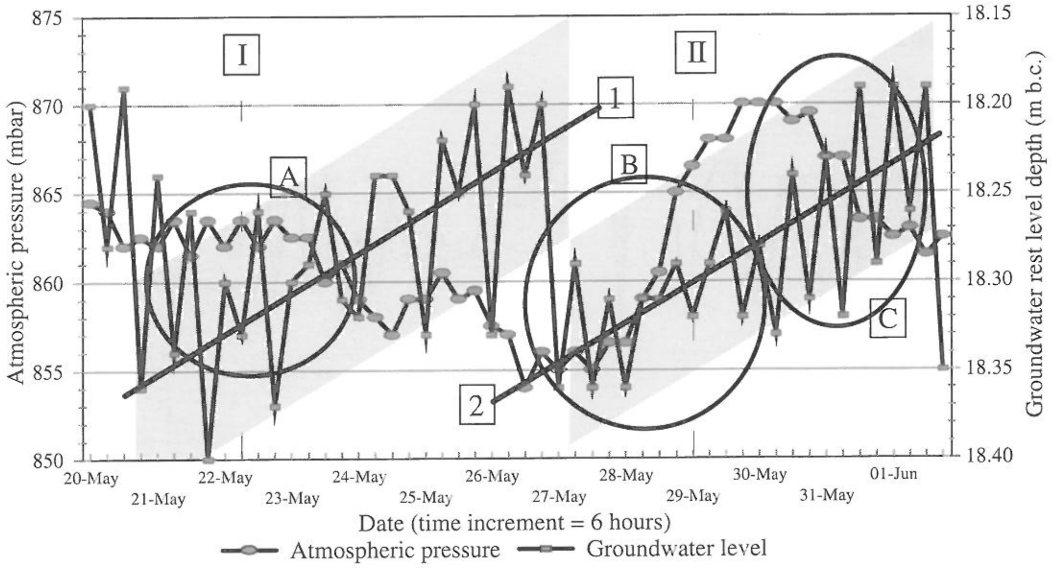


Figure 3
Barometric and potentiometric graphs for the period 20 May to 1 June 1997

pressure of approximately 630 kPa (6.3 bar) at the level of the water strike.

The yield potential of the dolomite aquifer was later confirmed by a short (4 h duration) constant discharge test performed at a yield of 17.4 ℓ/s and which realised a final drawdown of 32.27 m. Recovery was 99% within 2 min of pump shut-off. Analysis of the pumping test data by the FC-method (Van Tonder and Xu, 1999) returned a transmissivity value of 2 700 m^2/d and a late time approximate storativity value of 5.5×10^{-4} for an aquifer thickness of 10 m. The short duration of the test negated the need to correct the drawdown data for barometric effects. This, together with the manifestation of a substantial drawdown, also nullified to a large extent the influence of earth-tide effects on the drawdown data. Other rotary percussion boreholes penetrating this aquifer elsewhere in the area have demonstrated yield capacities of greater than 25 ℓ/s accompanied by comparatively small (less than 15 m) drawdowns during longer duration constant-discharge testing.

Barometry

The barometric data derive from a chart-recording barometer which forms part of the climatic monitoring station located some 6 km to the northeast at Sasol Coal's Wonderwater Strip Mine (Fig. 1). A close inspection of the barometric data indicates a mean barometric value of 862.2 mbar in the record period. The data also describe a semi-diurnal pattern with a period of 11.3 h, a mean amplitude (half range) of 0.7 mbar and a maximum amplitude of 2 mbar. These circumstances are considered to reflect the relatively stable climatic conditions experienced during the typically dry and cold winters at an elevation of some 1 400 m a.m.s.l. on the South African Highveld.

Walton (1970) reports occurrences of semi-diurnal barometric maxima at about 10:00 and 22:00, and minima at about 04:00 and 16:00. The barometric record used in this study shows maxima occurring in the periods 11:00 to 13:00 and 22:00 to 24:00, and minima in the periods 05:00 to 07:00 and 17:00 to 18:00. The barometric data were reduced to the 6 h readings presented in **Appendix 1**. The pattern described by the reduced data (Fig. 3) is characterised by a mean amplitude of 0.6 mbar and a maximum amplitude of 2.3 mbar. The similarity to the non-reduced data is self-evident in these values.

Potentiometry

Groundwater level data for the period 20 May to 1 June 1997 were captured autographically by means of a chart recorder mounted on the borehole. The installation was visited three times in this period. On each of these occasions, the groundwater rest level was determined manually using a dipmeter and both the measurement and its time of determination were recorded. This information was later used to confirm the veracity of the autographic record. Although located within 10 m of the Vaal River and intersecting 14 m of alluvial sediments overlying 67 m of Karoo sediments, the method of construction of the borehole (Fig. 2), which included grouting of the annulus, ensured that the groundwater level represented the potentiometric head in the dolomite aquifer.

Inspection of the hydrographic data indicates a mean groundwater rest level of 18.28 m below collar in the record period. The data further describe a semi-diurnal, sinusoidal pattern with a period of 12.3 h, a minimum amplitude of 15 mm, a mean amplitude of 45 mm and a maximum amplitude of 90 mm. The latter value substantially exceeds the maximum amplitude of some 30 mm ascribed to this phenomenon by Davis and De Wiest (1966).

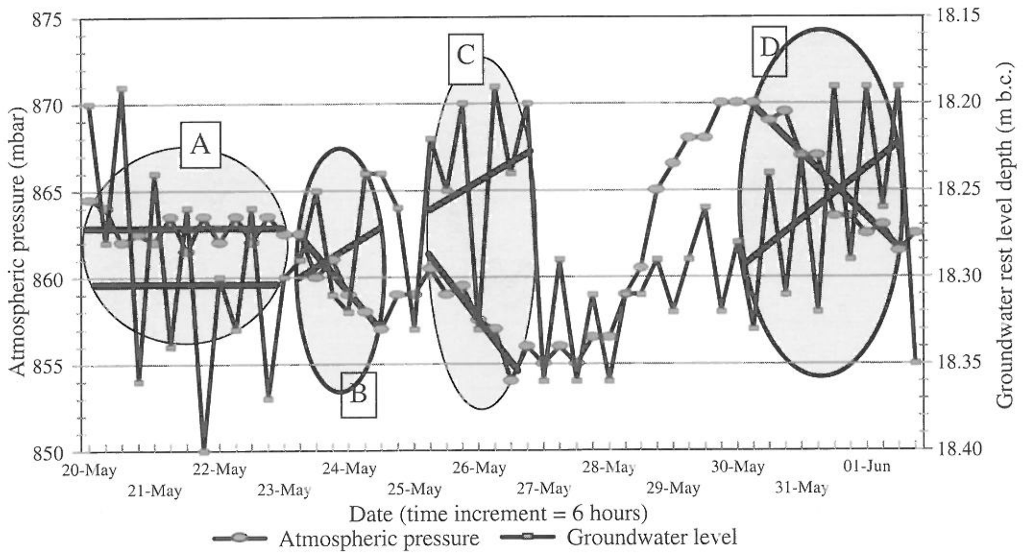
The record also shows that potentiometric minima (greatest depths) and maxima (shallowest depths) lag from to 2 to 4 h behind those of the associated barometric maxima and minima. This can be ascribed in part to the geographic separation of some 6 km between the climatic station and the borehole (Fig. 1). Even in instances where there is no separation, however, there exists a tendency for lowest water levels to either precede the moon's transit (Van Wyk, 1963) or lag behind it (Robinson, 1939). Van Wyk (1963) reports a time difference of up to 2 h, but also notes that the difference "*.......did not even remain constant for a particular borehole during two successive months.*"

The data were reduced to the 6 h readings presented in **Appendix 1** and used to compile the graph in Fig. 3. The reduced data describe a pattern characterised by a mean amplitude of 35 mm and a maximum amplitude of 85 mm. The similarity to the non-reduced data is again self-evident.

Hydrology

The proximity of the borehole to the Vaal River and the Barrage (Fig. 1) indicates that consideration must also be given to the stage height of the Vaal River in the period of potentiometric and

Figure 5
Barometric and potentiometric graphs used for barometric efficiency calculations



the end of the record (on 1 June 1997), the commencement of a following "weekly" cycle. The short length of the hydrographic and barometric records used in this paper is inadequate to properly define the longer-term pattern of this cycle, a factor which militates against a rigorous analysis of this phenomenon. The authors postulate, however, that it might relate to the additional "tidal" influence exerted by the sun's position relative to that of the moon in the precession of the tides.

Finally, the graphs of stage height vs. groundwater level in Fig. 4 demonstrate the independent behaviour of these phenomena. The constancy of stage height around a value of 7.5 m is clearly evident in the first half of the record. The rapid decline associated with the "draining" of the Barrage represents a decrease in the load on the dolomite aquifer of some 16.2 x 10^6 t (from previous calculations). The concomitant response of the potentiometric head in the dolomite aquifer is, at first glance, exaggerated in its drop of 160 mm. Closer inspection of the start and end of the potentiometric record, however, indicates groundwater level responses of similar magnitude despite relatively stable stage heights of 7.5 m and 4.8 m respectively. Since the potentiometric head in the dolomite aquifer appears to be relatively insensitive to variations in river stage (at least at the position of the borehole), it is hypothesised that the confining horizon is sufficiently competent to resist the associated unloading/loading effects. It is acknowledged, however, that a longer period of record is required to establish conclusively the apparent insensitivity of potentiometric head to variations in stage height.

Barometric and tidal efficiency

Todd (1959) views barometric efficiency (BE) as a measure of the competence of overlying confining strata to resist pressure changes, equating thicker strata with a higher BE-value. Conversely, tidal efficiency (TE) is viewed as a measure of the incompetence of overlying confining strata to resist pressure changes, equating thicker strata with a smaller TE-value. As stated previously, the ostensible insensitivity of the potentiometric head in the dolomite aquifer to variations in river stage points to the competency of the overlying confining strata. It is therefore also likely that the confined dolomite aquifer supports a high BE-value.

It has previously been observed that both barometric and earth-tide effects produce an antithetic response in groundwater rest levels, i.e. potentiometric minima coincide with barometric maxima and with the moon's transit respectively (Fig. 3). Ocean-tide effects, on the other hand, produce a sympathetic response, i.e. a rising tide produces rising (and often lagging) groundwater levels. Since the moon's transit itself precedes high tides by up to 3 h, the potentiometric maximum associated with high tide could lag as much as 6 h behind the moon's transit. These circumstances suggest that earth-tide and ocean-tide effects possess a dissimilar nature. This is borne out by the established statement of effective stress acting on a confined aquifer which, according to Domenico and Schwartz (1998), is given as:

$$\mathrm{TE} + \mathrm{BE} = \frac{\partial P}{\partial \sigma} + \frac{\partial \bar{\sigma}}{\partial \sigma} = \frac{\beta_p}{\beta_p + \eta\beta_w} + \frac{\eta\beta_w}{\beta_p + \eta\beta_w} = 1 \qquad (1)$$

where:

$\partial P/\partial\sigma$ = the pore pressure coefficient representing the percentage of the load (stress) that is carried by the fluid under undrained conditions and therefore representing the tidal efficiency of the aquifer

$\partial\bar{\sigma}/\partial\sigma$ = the percentage of the stress that is carried by the rigid matrix which, also under undrained conditions, represents the barometric efficiency of the aquifer

β_p = the vertical compressibility of the rigid matrix (3.3 x 10^{-10} to 6.9 x 10^{-10} m^2/N for fissured rock)

β_w = the isothermal vertical compressibility of the fluid (4.8 x 10^{-10} m^2/N for groundwater at 25°C)

η = porosity of the groundwater system.

It is apparent, therefore, that earth-tide effects demonstrate a greater affinity to barometric effects in that they relate to the stress carried by the rigid matrix rather than to that carried by the fluid. If so, then the relative prominence of the earth-tide effects experienced by the dolomite aquifer suggests that this groundwater system possesses a high barometric efficiency value (conversely a low tidal efficiency value). Since from Eq. (1):

$$\mathrm{BE} = 1 - \mathrm{TE} = \frac{\eta\beta_w}{\beta_p + \eta\beta_w} \qquad (2)$$

it can be seen that BE approaches one (and TE approaches zero) as β_p approaches zero, i.e. the aquifer matrix (skeleton) becomes less and less compressible (or more and more rigid). Perfect rigidity (inelasticity/incompressibility) would be reached when $\beta_p = 0$, so that a BE-value of one implies that the percentage of storage attributable to compression of the aquifer matrix must equal zero and, therefore, the percentage of storage attributable to expansion of the water equal to 100%. Conversely, the smaller the barometric

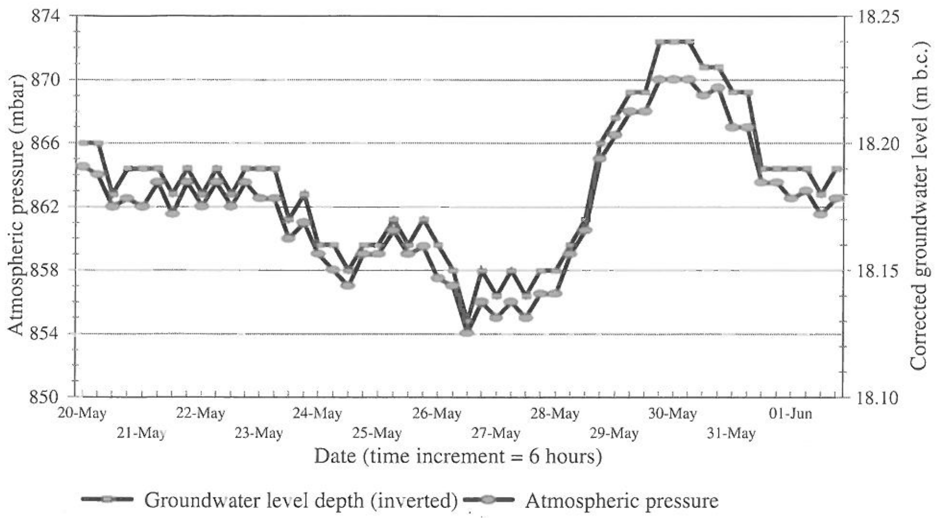


Figure 6
Graphic correlation between barometric and corrected groundwater rest level data

efficiency of the aquifer, the more compressible its solid matrix.

The barometric efficiency of a groundwater system is calculated from the equation:

$$\text{BE} = \frac{dh}{dP_a} \qquad (3)$$

where:

dh = the change in hydrostatic head, and
dP_a = the change in atmospheric pressure for a corresponding period.

The hydrograph presented in Fig. 5 shows various sets of dh vs. dP_a data which might be used for the calculation of a BE-value. The first set is represented by the antithetic semi-diurnal fluctuations in shaded area A (Fig. 5). Individually, these provide a wide range of dh/dP_a ratios returning improbable percentage values of 100 to 3 400%. The lines drawn through the barometric and potentiometric graphs in shaded area A, however, represent the respective response patterns in the absence of semi-diurnal fluctuations. The horizontal and parallel form of these responses indicates the extent to which earth-tide effects camouflage responses associated with barometric effects.

The second set of dh vs. dP_a data which might be used for BE calculations is represented by the longer period fluctuations identified in shaded areas B, C and D (Fig. 5). The first period (shaded area B) demonstrates a fall in barometric pressure (dP_a) of 5.5 mbar (55.7 mm H_2O) which is matched by a rise in hydrostatic head (dh) of 30 mm. Application of these values in Eq. (3) returns a BE-value of 0.54 (54%). A similar analysis of the second period (shaded area C) also returns a BE-value of 54%. The third period (shaded area D) returns a BE-value of 81% (from dh and dP_a values of 70 mm and 8.5 mbar respectively). The results together assign a mean barometric efficiency of 63% to the dolomite aquifer at the position of the borehole. The wide range of BE-values reflects the sensitivity of the calculation to small variations in either or both of dh and dP_a values. The veracity of the BE-value is shown in Figs. 6 and 7 where the barometric values are plotted against potentiometric values which have been corrected for barometric effects using a factor 0.63. The corrected groundwater level depth data in Fig. 6 are purposefully inverted to emphasise the correlation.

Equating a BE-value of 63% to the fluid pressure coefficient implies that the pore pressure coefficient is represented by a TE-value of 37%. The latter value is in reasonable agreement with that of 25% for limestones suggested by the work of Palciauskas and Domenico (1989). It also supports the earlier observation in regard to the low TE-value concluded from the prominence of the earth-tide effects, and points to the relative incompressibility of the aquifer matrix.

Aquifer storativity

Domenico and Schwartz (1998) report the following relationship between barometric efficiency and specific storage (S_s):

$$\text{BE} = \frac{\rho_w g \eta \beta_w}{S_s} \qquad (4)$$

where:

ρ_w = the density of water (1 000 kg/m^3), and
g = the gravitational constant (9.81 m/s^2)

Determining the specific storage of the aquifer from Eq. (4) requires only the assumption of a porosity (η) value, since the values for the other parameters are known. Based on the range of 0 to 40% for the porosity of karst limestone/dolomite (Domenico and Schwartz, 1998), specific storage values calculated for η-values of 10, 20, 30 and 40% are given as follows:

S_s = 7.5×10^{-7} m^{-1} for η = 0.1
S_s = 1.5×10^{-6} m^{-1} for η = 0.2
S_s = 2.2×10^{-6} m^{-1} for η = 0.3
S_s = 3.0×10^{-6} m^{-1} for η = 0.4

Since the storativity (S) of a confined aquifer is defined as the product of its specific storage (S_s) and its saturated thickness (b), a value for S can be determined for any assumed (or known) value of b and known (or assumed) S_s-value. This is shown in Table 1 for each of the previously calculated S_s-values.

The most likely aquifer storativity value, as indicated by the shaded cells in Table 1, is in the order of 2.6×10^{-5}. It is noted that this value is an order of magnitude smaller than the approximate late time S-value of 5.5×10^{-4} previously reported for the pumping test analysis applying the FC-method of Van Tonder and Xu (1999). This result also indicates that substantial increases in either or both of the porosity (η) and thickness (b) values are required for the theoretically derived storativity value to approach that obtained from the pumping test analysis. For example, an impossible η-value of 736% will return an S-value of 5.5×10^{-4} for an aquifer thickness of 10 m. Likewise, the aquifer thickness would need to approach 183 m to return a similar S-value for a porosity of 40%. It is hypothesised that both S-values, viz. 2.6×10^{-5} and 5.5×10^{-4},

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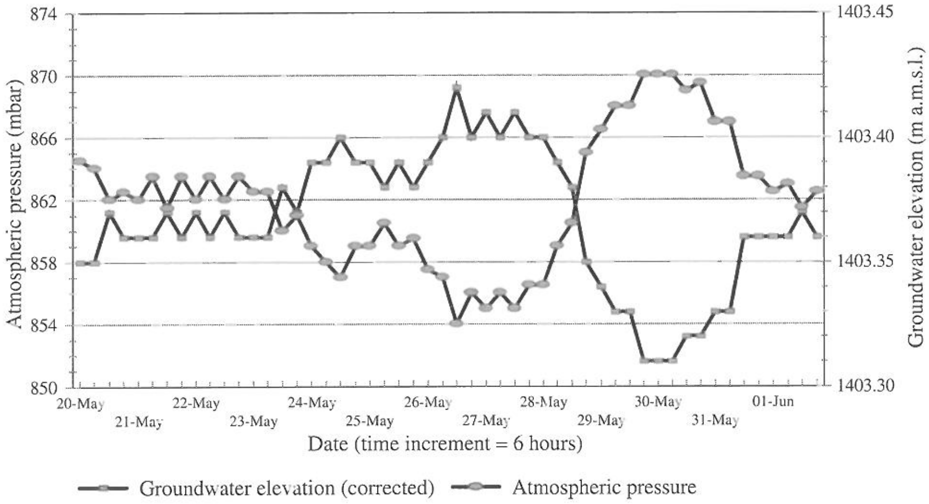

Figure 7
Graphic correlation between barometric and corrected groundwater elevation data

TABLE 1
Theoretically Derived Values of Dolomite Aquifer Storativity

Specific storage (m^{-1})	Porosity (%)	Storativity			
		for b = 5 m	for b = 10 m	for b = 15 m	for b = 20 m
7.5 x 10^{-7}	10	3.8 x 10^{-6}	7.5 x 10^{-6}	1.1 x 10^{-5}	1.5 x 10^{-5}
1.5 x 10^{-6}	20	7.5 x 10^{-6}	1.5 x 10^{-5}	2.3 x 10^{-5}	3.0 x 10^{-5}
2.2 x 10^{-6}	30	1.1 x 10^{-5}	**2.2 x 10^{-5}**	3.3 x 10^{-5}	4.4 x 10^{-5}
3.0 x 10^{-6}	40	1.5 x 10^{-5}	**3.0 x 10^{-5}**	4.5 x 10^{-5}	6.0 x 10^{-5}

are correct under their specific local circumstances. These circumstances describe the same aquifer in an unstressed (natural) state and a stressed (unnatural) state, respectively.

Conclusions

Based on the observation that larger amplitude cyclic semi-diurnal fluctuations reflect a more rigid aquifer matrix, it is possible to interpret smaller amplitude, earth-tide-induced fluctuations registered in boreholes elsewhere in the region as indicating the dolomite aquifer to be more compressible (elastic) at these localities than at the study site. Based on the premise that a more elastic aquifer matrix will produce more water when placed under stress (for example by pumping) than a less elastic aquifer, these circumstances will almost certainly also be reflected in a greater productivity of the dolomite aquifer as mirrored in the yield capacity of boreholes.

The available evidence also suggests that stage-dependant variations in the loading associated with a substantial overlying surface water body do not have a noticeable effect on the natural potentiometric head fluctuations in the dolomite aquifer under the circumstances described in this paper. It is acknowledged, however, that a longer period of record is required to establish conclusively the mutual exclusivity of these responses.

The authors must also concur with the conclusion reached by Van Wyk (1963) that earth-tide effects occur more generally than is commonly believed. Under these circumstances, the substantial natural fluctuation manifested in the potentiometric data indicates that caution should be exercised when routine, manually captured groundwater levels associated with a confined aquifer are evaluated. For example, an observed groundwater level decline of 0.15 m between successive measurements, particularly if measured within hours or days of each other, might too readily be attributed to the influence of nearby groundwater abstraction.

Finally, the study suggests that the comparatively inelastic confined dolomite aquifer demonstrates a variable storativity depending on its state. For example, its storativity in an unstressed state appears to be one order of magnitude smaller than its storativity in a stressed state.

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APPENDIX 1

Reduced Barometric, Potentiometric and Hydrological Data

Period		Barometric data		Potentiometric data			Hydrological data
Date	Time	Reading (mbar)	Δp (mbar)	Depth (m b.c.)	Δh (mm)	Corrected depth (m b.c.)	Stage height (m)
20 May 1997	06:00	864.5	Start	18.20	Start	Start	7.56
	12:00	864.0	-0.5	18.28	-80	18.20	7.56
	18:00	862.0	-2.0	18.19	90	18.18	7.55
	24:00	862.5	0.5	18.36	-170	18.19	7.55
21 May 1997	06:00	862.5	0.0	18.24	120	18.19	7.55
	12:00	863.5	1.0	18.34	-100	18.19	7.54
	18:00	861.5	-2.0	18.26	80	18.18	7.54
	24:00	863.5	2.0	18.40	-140	18.19	7.53
22 May 1997	06:00	862.0	-1.5	18.30	100	18.18	7.53
	12:00	863.5	1.5	18.33	-30	18.19	7.53
	18:00	862.0	-1.5	18.26	70	18.18	7.53
	24:00	863.5	1.5	18.37	-110	18.19	7.53
23 May 1997	06:00	862.5	-1.0	18.30	70	18.19	7.54
	12:00	862.5	0.0	18.29	10	18.19	7.54
	18:00	860.0	-2.5	18.25	40	18.17	7.54
	24:00	861.0	1.0	18.31	-60	18.18	7.54
24 May 1997	06:00	859.0	-2.0	18.32	-10	18.16	7.55
	12:00	858.0	-1.0	18.24	80	18.16	7.55
	18:00	857.0	-1.0	18.24	0	18.15	7.55
	24:00	859.0	2.0	18.26	-20	18.16	7.55
25 May 1997	06:00	859.0	0.0	18.33	-70	18.16	7.57
	12:00	860.5	1.5	18.22	110	18.17	7.57
	18:00	859.0	-1.5	18.25	-30	18.16	7.57
	24:00	859.5	0.5	18.20	50	18.17	7.55
26 May 1997	06:00	857.5	-2.0	18.33	-130	18.16	7.47
	12:00	857.0	-0.5	18.19	140	18.15	7.20
	18:00	854.0	-3.0	18.24	-50	18.13	7.08
	24:00	856.0	2.0	18.20	40	18.15	6.68
27 May 1997	06:00	855.0	-1.0	18.36	-160	18.14	6.20
	12:00	856.0	1.0	18.29	70	18.15	5.71
	18:00	855.0	-1.0	18.36	-70	18.14	5.71
	24:00	856.5	1.5	18.31	50	18.15	5.71
28 May 1997	06:00	856.5	0.0	18.36	-50	18.15	5.71
	12:00	859.0	2.5	18.31	50	18.16	5.10
	18:00	860.5	1.5	18.31	0	18.17	5.17
	24:00	865.0	4.5	18.29	20	18.20	5.31
29 May 1997	06:00	866.5	1.5	18.32	-30	18.21	5.38
	12:00	868.0	1.5	18.29	30	18.22	5.38
	18:00	868.0	0.0	18.26	30	18.22	5.33
	24:00	870.0	2.0	18.32	-60	18.24	5.33
30 May 1997	06:00	870.0	0.0	18.28	40	18.24	5.16
	12:00	870.0	0.0	18.33	-50	18.24	5.08
	18:00	869.0	-1.0	18.24	90	18.23	5.04
	24:00	869.5	0.5	18.31	-70	18.23	5.01
31 May 1997	06:00	867.0	-2.5	18.23	80	18.22	4.96
	12:00	867.0	0.0	18.32	-90	18.22	4.92
	18:00	863.5	-3.5	18.19	130	18.19	4.87
	24:00	863.5	0.0	18.29	-100	18.19	4.81
1 June 1997	06:00	862.5	-1.0	18.19	100	18.19	4.75
	12:00	863.0	0.5	18.26	-70	18.19	4.74
	18:00	861.5	-1.5	18.19	70	18.18	4.74
	24:00	862.5	1.0	18.35	-160	18.19	4.74