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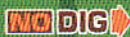
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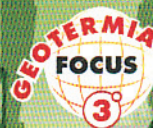


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Correcting water level data for barometric pressure fluctuations

Theoretical approach and a case history for an unconfined karst aquifer (Otavi, Namibia)

Alessio Fileccia*

Abstract

The main concepts for identifying and removing barometric pressure effects in confined and unconfined aquifers are described. Although it is commonly known that barometric pressure changes can effect water level readings, few articles and procedures are provided to correctly manage piezometric data.

Knowing the barometric efficiency reduces errors in calculating piezometric surfaces and drawdowns in the piezometers during pumping tests. Stallman (1967) suggested furthermore, that air movement through the unsaturated zone and the attendant pressure lag, could help to better describe the aquifer properties. Rasmussen and Crawford (1997) described how barometric efficiency varies with time in some aquifers and how to calculate the corresponding barometric response function (BRF). They also showed that this last parameter is related to the degree of aquifer confinement. Finally we present an application of the procedure in an unconfined karst aquifer located in northern Namibia (Otavi mountainland) where a set of four absolute transducers have recorded water level changes and earth tides during a 10 months period at 1 hr interval.

Foreword

Fluctuations of water levels in wells opened to the atmosphere and due to barometric pressure changes were noted first by Blaise Pascal (1663). Since 40's, various Authors tried to better describe this phenomenon and to separate the variations due to water level changes, e.g. the recharge, from those only barometric. Among these reports, those of Jacobs, Weeks, Rasmussen, Crawford, Clark, Bredehoeft etc. are the most important. An interesting result of this approach deals with the validity of the interpretation of piezometric maps. When con-

sidering water level changes and atmospheric pressure, some aquifers show an inverse relationship: increase in barometric pressure creates declines in observed water levels and vice versa. Two important consequences are piezometric map interpretation over large areas and/or with low gradient and pump test analysis. For example, when dealing with pumping tests and piezometers we have to correctly remove barometric pressure influences to calculate transmissivity values. The long duration test should induce drawdowns in the order of 20-30 cm in the piezometer. To achieve this, the pump discharge should be high and/or the borehole closer to the producing well. Moreover, it is widely recognised that the attraction of Moon and the Sun can influence piezometric levels and give useful hints for a correct interpretation of aquifer parameters. We refer to sea and earth tides and the corresponding calculation of the tidal components and harmonic functions. Before describing in more detail this topics, let's revise some important concepts like the barometric efficiency (BE) and the water level transducers.

Air transmission through the unsaturated soil and well casing

To dress up a piezometric map, one normally records the water level in the wells using a water level dipper. The piezometric head is:

$$(1) H = W + B$$

W = elevation of water column above datum

B = barometric head

Lack of atmospheric records can be avoided using an average value over a long period.

Normally in the everyday practice, barometric pressure is not considered and the piezometric head corresponds

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to the height of the water column above datum. Furthermore the well response varies due to casing, well completion and aquifer geometry.

Casing

The borehole responds with a time lag to the external pressure due to:

- Well storage
- Thickness of the mud cake on the walls
- Length and type of screens

The last issues are known as “skin effects”.

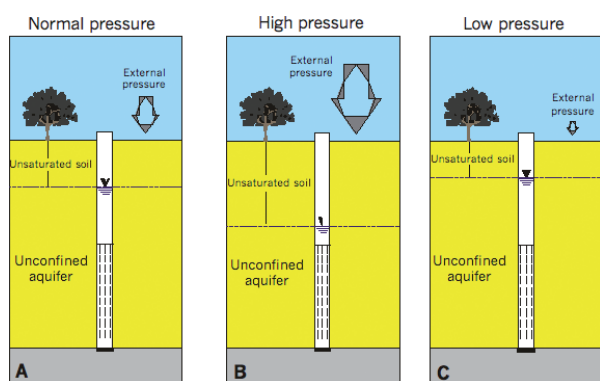
The lag time can be as much as hours or days. Thick mud cakes and short screen lengths slow down the reaching of equilibrium between the water levels on either side of the well. It is something similar to the pumping of a bike inner tube: we force the air through the valve (well screen) using a hand pump (external atmosphere) into the rubber inner tube (the borehole)¹.

Aquifer

We can consider two cases:

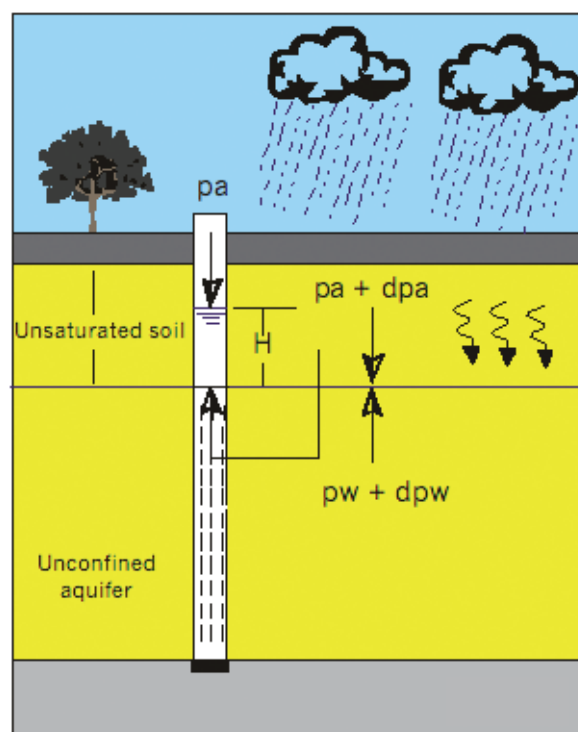
Phreatic aquifer

If the static water level is near to surface and/or the unsaturated layer above the water table is thin, the pressure variation moves fast and the well has a quick response. The water levels do not change.



1. Water level changes in unconfined aquifer due to barometric pressure variations (thin unsaturated soil with high permeability)

A particular case is reported during severe storms. When rainfall is high the decreasing barometric pressure overlaps the water infiltrating vertically through the unsaturated part, trapping and pushing the air towards the water table and the screens into the well. This behaviour can induce quick variations, higher than the barometric². At the equilibrium the atmospheric pressure (p_a) is the same in every point of the aquifer (p_w) and in the well (fig. 2). The water percolating downwards induces a rise in the air pressure trapped above the water table (dp_a) increasing also the pressure on the water by an equivalent amount (dp_w).² The equilibrium at the well is given by:



2. Water level fluctuations due to air entrapment during groundwater recharge in an unconfined aquifer (A. Freeze, J. Cherry 1979, redrawn)

$$(2) p_a + \gamma H = p_w + dp_w$$

since $p_a = p_w$ and $dp_a = dp_w$, we have

$$(3) \gamma H = dp_a$$

1 Special well completion techniques reduce the impact of pressure variation with an isolation of the casing from the atmosphere (isobaric wells)

2 This behaviour has been reported for the blowing wells of the Friuli plain by A. Feruglio, and the sudden rise of piezometric levels in the boreholes during Piave river floods by R. Antonelli.

dpa = atmospheric pressure variation; dpw = water pressure variation (at the aquifer top)

when $dpa > 0$ also $H > 0$ proving that an increase in the entrapped air leads to a rise in the water column inside the well (if opened to the atmosphere).

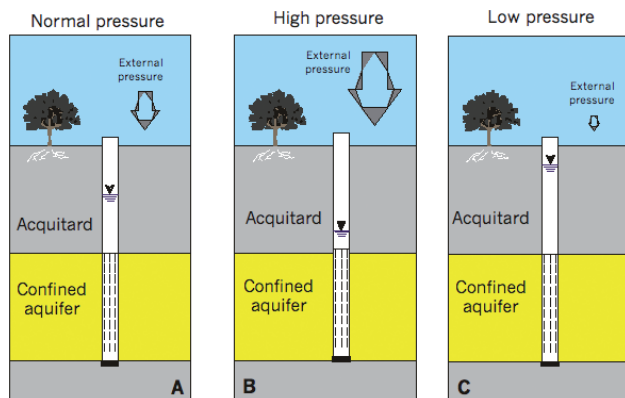
This particular type of piezometric rise bears no relation to groundwater recharge, but can be mistaken for it when associated to rainfall events. In this case the induced pressure change generates well- water level that do not represent actual groundwater potential.

Semiconfine/confined aquifer

For this aquifer the transmission of atmospheric pressure is instantaneous both to well and aquifer, being functions of the degree of confinement, matrix rigidity and specific weight of water.

The pressure at the aquifer top is supported partly from the rock skeleton and partly from the water thus introducing a time lag for the equilibrium to be reached (hours or days).

On the contrary, the level in the well is reached without lag.



3. Water level changes in confined aquifer due to a barometric pressure variation. The relationship is an inverse one: increases in atmospheric pressure creates declines in observed water levels and vice versa

If at the equilibrium we have: (see also equation 1 and fig. 4)

$$(4) \quad p_w = p_a + \gamma h$$

when external pressure increases or decreases (dpa) then:

$$(5) \quad p_w + dpw = p_a + dpa + \gamma h'$$

substituting:

$$(6) \quad dpw = dpa + \gamma (h' - h)$$

and

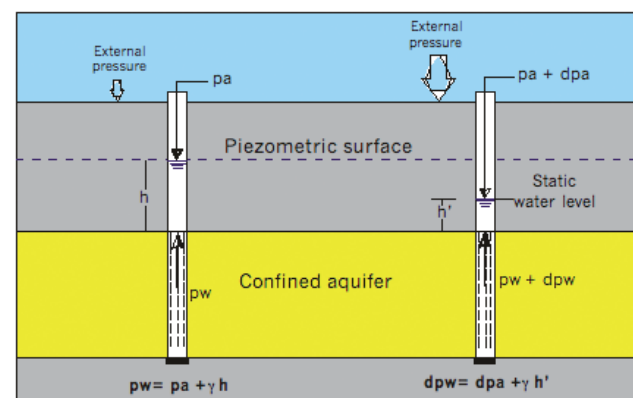
$$(7) \quad dpw - dpa = \gamma (h' - h)$$

being

$$(8) \quad dpa = dpw + ds \quad \text{where } ds \text{ is the effective stress on the grains}$$

then $dpa > dpw$ and $h' < h$

The relationship is an inverse one, increases in barometric pressure create declines of water levels in the wells. It is important to stress that for such aquifers there is a time lag between the drop in the water level in the well and his new equilibrium with the aquifer (time lagged response). This lag is in the order of a few hours or days and higher in case of thick and rigid aquitards or unsaturated layers.



4. The effect of atmospheric pressure in a confined aquifer (high barometric pressure, low water level in the well)

Barometric efficiency

Jacob (1940) was the first who attempted to introduce a parameter describing this particular phenomenon known as barometric efficiency (BE).

Considering a confined bed, the relationship is an inverse one: a raise in barometric pressure induces a lowering in the piezometric head.

Barometric efficiency for the same time interval vari-

es between 0 and 1 and can be expressed as the ratio in hydraulic head change over a change in barometric pressure during the same time interval:

$$(9) \quad BE = \gamma \Delta W / \Delta B \quad \text{with}$$

ΔW = change in hydraulic head

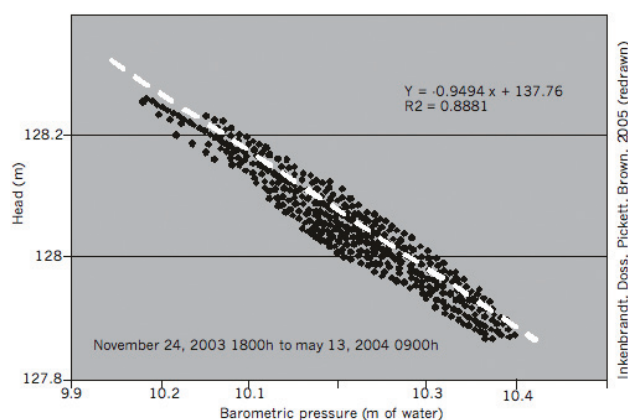
ΔB = change in atmospheric pressure (meters of water)

γ = specific weight of water ($\gamma = \rho g$)

A general approach is to obtain BE from an arithmetically scaled plot of water level changes as a function of concurrent atmospheric pressure changes over a sufficiently long period of time.

The slope of a least squares line fit through the data is the barometric efficiency.

The data time step can be in the order of 15 to 60 minutes for a period of a few days



5. Plot of ground water levels as a function of barometric pressure. The slope of the relationship, is the regression line and represents the Barometric Efficiency (0.95) of the aquifer (Inkenbrandt, Doss, Pickett, Brown, 2005, redrawn)

A method described by Clark (1967) determines the barometric efficiency from the slope of the plot of the incremental changes in water level (ΔW) versus the incremental changes in atmospheric pressure (ΔB). The values are added algebraically and can be both positive or negative when showing the same trend but of unequal sign when e.g. atmospheric pressure increases and water level decreases during the same recording interval. Davis and Rasmussen (1993) describe a slightly modified

method to be used when BE can be influenced by pressure fluctuations other than barometric.

Going back to equation (9) the static water level in the well (H) measured with a common dip meter is comprehensive of the barometric pressure (B) and the water level (W)

Substituting in the equation (1):

$$(10) \quad \Delta W / \Delta B = \Delta (H-B) / \Delta B = (\Delta H / \Delta B) - 1$$

when $\Delta H / \Delta B = 0$ then $BE = 100\%$ and does not affect the total head within the aquifer (e.g. unconfined aquifer with thick and/or rigid unsaturated zone)

when $\Delta H / \Delta B = 1$, the air pressure travels fast through the soil and $BE = 0$ (shallow unconfined aquifer)

If we consider the aquifer water compressibility β (Lohman, 1972):

$$(11) \quad BE = n \gamma b \beta / S \text{ as a percentage}$$

n = porosity ; b = aquifer thickness; S = storage coefficient

Introducing the Specific Storage (S_s), the effective porosity can be calculated from (Jacob 1940):

$$(12) \quad n = (S_s BE) / 1.314 \times 10^{-6}$$

The well response can be easily understood considering the piezometric head in two different points of an unconfined aquifer, as depicted in fig. 6. Point P1 is in the well and point P2 in the aquifer.

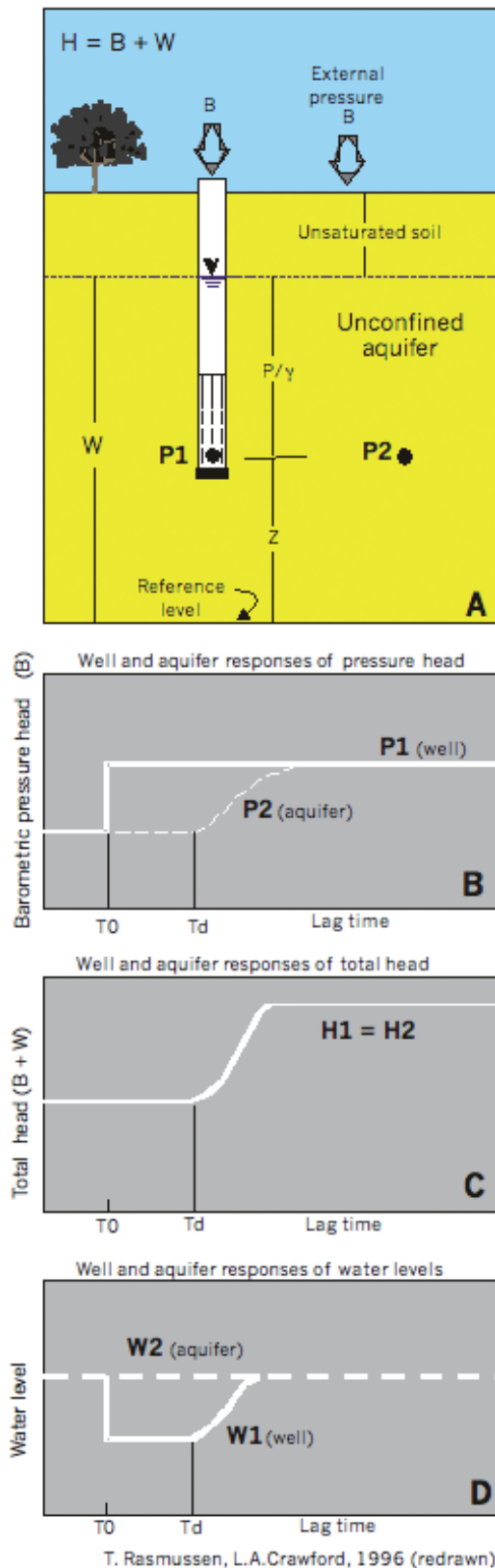
The pressure on the surface of the water inside the well equals the barometric pressure (dpa) minus the pressure change due to the difference in elevation of the water column in the casing (dpw).

As we saw previously this difference is the same or slightly less than the barometric.

High ΔW values lead to high efficiency, the aquifer is confined and the storage S is low.

The well is not at equilibrium with the aquifer and the readings are not representative of a real hydraulic situation.

Well - aquifer responses to barometric pressure changes



When the equilibrium is rapid ($BE = 0$) and $\Delta H/\Delta B = 1$ we are facing an unconfined aquifer with a thin unsaturated zone and/or highly permeable.

One has to consider a piezometric map over a large area with differences in surface elevation or a nearly flat plain with low gradients.

Failure to account for these changes can result in errors in the calculation of the magnitude and direction of the hydraulic gradient. These errors can also be increased if we add earth or sea tides and fluid density variations.

To describe in more detail the subject, one has to consider that the rate of air movement within the vadose zone is a direct function of vertical pneumatic diffusivity, vertical permeability and moisture content (Weeks, 1979).

As a general rule we have that:

- the advantage in the calculation of the barometric efficiency is to better describe the type of aquifer, the permeability of the unsaturated zone and the well efficiency
- BE varies between 0 and 1; linear regression slopes greater than 1 indicate that factors in addition to barometric effects influence the water level fluctuations
- BE close to 0 indicates unconfined porous aquifers overlaid by a thin unsaturated zone and most of the pressure is born from the water
- BE close to 1 indicates confined aquifers or unconfined with thick/rigid unsaturated zone; most of the pressure is born from the rock skeleton; in the extreme case of $BE = 1$ a unit barometric step displaces an equal column of water in the well

From the above we have that the barometric efficiency characterizes the short term response of the aquifer; if we want to study the long term response some Authors

6. Total head and water level response in well ($P1$) and aquifer ($P2$) to a unit change in barometric pressure, are summarized in (A). B) displays the effect of pressure both in the well and in the aquifer. There is a lag in the pressure, in the aquifer due to the time required for the barometric pressure wave to travel down to the open pores in the unsaturated zone, T_d . C) the total head in the aquifer responds once the pressure change reaches the water table. D) the water table in the aquifer ($H-B$) remains constant. However the water level in the well responds instantaneously to the step increase in barometric pressure by first falling and then gradually rising back to the initial water level.

have introduced the Barometric Response Function (BRF) that revealed to be extremely useful for a better aquifer characterization.

Continuous water level recorders

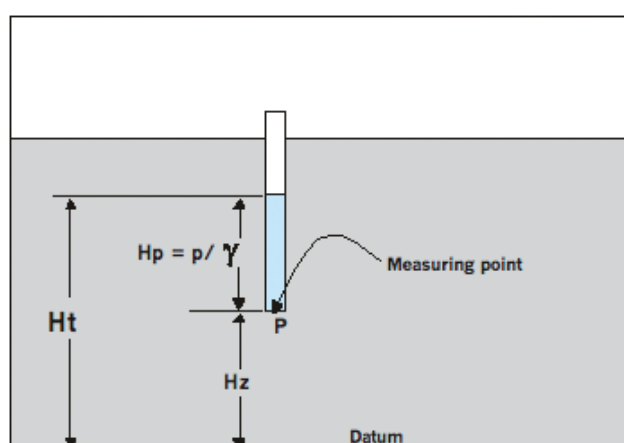
From Bernoulli equation the piezometric head is:

$$(13) H_t = H_z + p / \gamma$$

H_z = elevation head

p / γ = pressure head

$\gamma = \rho_w g$ (ρ_w ground water density; g gravity)



7. The piezometric head is the sum of elevation head (H_z) and pressure head (H_p)

In practice H_t is the elevation of water level above datum and is obtained with a measuring tape (water level dipper) or with an electronic transducer (fig. 7).

Using normal meters to dress up a piezometric map or analyze a well test, does not introduce large errors. The problem arises, on the contrary, with modern transducers, two of which are known on the market: absolute transducers (non vented) and gauge sensors (vented).

The pressure measured from a non vented type is given by the water column height above the sensor and the barometric pressure. To get only the water level fluctuations we need a vented transducer.

Absolute sensors (non vented transducers)

The hardware is fitted into a stainless steel cylinder of 1-3 cm in diameter, lowered into the well by means of a normal cable (nylon, steel...)

The sensor depth depends on its measuring range. The readings are the sum of two figures: water column

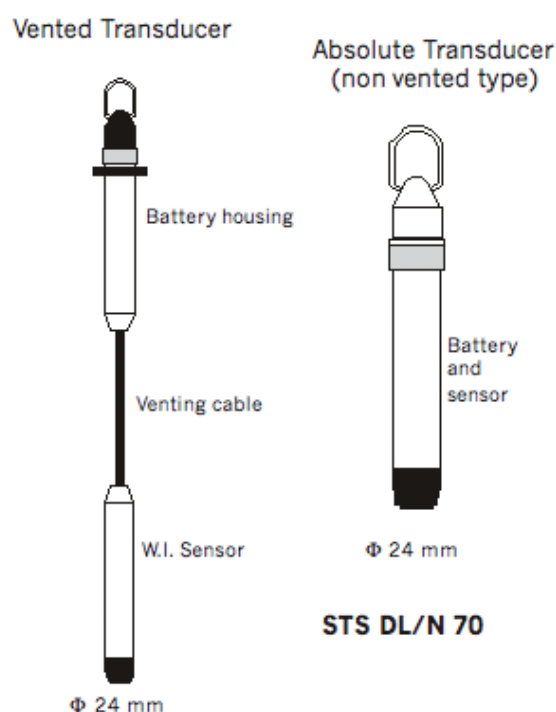
height above sensor and barometric pressure.

Compensation is performed in the office when data are downloaded using readings from another sensor that measured only barometric pressure at the surface.

These instruments are more convenient than the vented type, due to lack of compensation tube.

Gauge sensors (vented transducer)

Two different steel cylinders are connected by a compensation soft tube. The sensor is seated in the lower cylinder and lowered into the borehole below the water table. The upper part is fixed near the top of the casing and houses the batteries. These sensors record only the water column height. Fig. 8 depicts the two sensor types with reference to STS models.



8. Right: Non vented transducer measuring total head (barometric pressure plus water column above sensor); Left: Vented transducer measuring water column height above sensor (Courtesy STS-Italia)

Measuring range

Is a typical feature of this instrumentation corresponding to the maximum water column height that can be recorded.

Overpressure

The maximum pressure a sensor can stand without permanent damage (normally twice the measuring range)

Precision

The error of measurement in relation to other readings of the same phenomena. Normally indicated as the sum of errors as a percentage for a given temperature. If, for example, we foresee water level fluctuations of 1 m during the recording time, we can use a 3 m range sensor with accuracy of 0,1%. The error will be 0,3 cm over the entire pressure range and the sensor may be lowered 1 m below the initial water level.

Records obtained by the sensors

The piezometric head is obtained by the sensor at screen level and elevation z above datum.

Referring to equation (13) the readings (P_{meas}) from a vented transducer are:

$$(14) P_{meas} = (\gamma_w H_p + P_{bar}) - P_{ref}$$

Where:

$\gamma_w H_p$ = water column pressure above sensor

P_{bar} = barometric pressure

P_{ref} = reference pressure, constant (usually 10,19 m)

If we consider that P_{bar} at the well head on surface is the same as that at the static water level, we can get the real water column height (H_p) above the sensor:

$$H_p = p / \gamma_w$$

We have seen by far that the total piezometric head (H_t) into the well does not correspond, in general, to that of the surrounding aquifer. The magnitude of water level change and formation pressure change is a function of the degree of confinement, the skeletal matrix and the well efficiency (skin effect).

Being the last ones unknown, simply removing barometric fluctuations does not accurately solve the problem.

As a general rule, when the well is not sealed, the total head is measured by an absolute transducer.

Main advantages are that they are not featured with a vent tube and one does not need to record barometric pressure. The final value (total head) can vary more than the barometric pressure and be used to calculate both horizontal and vertical groundwater gradients. One disadvantage is the poorer accuracy due to a higher range of measurement. It is also known that piezometric

readings by a simple water level dipper are equivalent to those made by an absolute transducer (non vented) and undergo barometric pressure variations.

In case of unconfined surficial aquifers the barometric pressure does not change in the well and in the aquifer, while with thick and rigid aquifers this imbalance has a time lagged response through the unsaturated zone.

The measured water column height in the well (H_p) is different from that of the aquifer and will reach equilibrium after hours or days.

Barometric removal techniques

These techniques have been examined by several investigators and are focused on some mathematical methods that are beyond the object of this paper and have been treated in detail by Chien, Rojstaczer, Furbish etc.

A relative simple equation for residual (corrected) head, removes barometric influences on measured ground water levels (Rasmussen, Crawford, 1997) :

$$(15) R = W + BE (B - C)$$

R = corrected head

W = water level in the well

B = barometric pressure

C = constant (barometric pressure at sea level)

The R value should not be used for plotting a piezometric map. Alternatively one can use the readings from a water level dipper, an absolute transducer or a vented sensor adding a mean value of the barometric pressure over a long time ³

Spane (1999) suggests the following steps for preparing a piezometric map or determining the groundwater flow directions:

- Use only water level dippers or absolute transducers
- Monitor well screens on the same equipotential surface
- Monitor similar depth intervals within the same hydrogeologic unit
- Measure all water points close in time (4-12 hours approximately)
- Monitor wells that are 80-100% efficient (skin effect negligible)

³ This approach can be misleading in some cases

Same cautions should be observed during pumping tests, particularly when analyzing piezometers, removing external stresses that can change the dynamic water level other than the pump discharge. In the same case barometric effects can exceed artificial stresses and, being applied over large areas, small differences of 2-3 cm produce water level changes of as much as 20-30 cm. Confined aquifers have a sudden response to barometric variations that are easily removed. The same does not apply for unconfined aquifers showing a time delayed response.

A suggested simplified method to reduce the error is:

- Record the trend in barometric pressure and water levels prior to pumping (4-5 days)
- Plot the data, barometric pressure versus water levels to evaluate barometric efficiency; alternatively during the test, one can use a well outside the influence of the pump to monitor the atmospheric pressure

When all variables are measured in the same pressure units (meters of water) with a non vented transducer, the correction is:

$$15) ds = WL - BE dpa$$

ds = pumping induced drawdown

WL = observed water level in the well

BE = barometric efficiency

dpa = barometric pressure variation

With WL = measured pressure - barometric pressure

The Barometric Response Function

Jacob's approach to calculate barometric efficiency dealt originally with confined aquifers, where the air pressure wave travels fast. The BE value obtained this way, refers to the short term period (1-2 hours) and does not vary too much in time. When other effects are present (e.g. marine tides, earth quakes, natural recharge etc.) BE values are incorrect. Some investigators noted that for a given pressure load BE varies with time and this fluctuation can be used to glean valuable insights into the well aquifer system.

These Authors introduced therefore the barometric Re-

sponse Function (BRF) as a more effective mean for characterizing the longer term response (Rasmussen, Crawford 1997; Spane 2002)

The BRF is used to remove the influence of the barometric pressure from the water level records and the diagnostic plots obtained can reveal:

- Aquifer and aquitard type
- Degree of aquifer confinement
- Skin effect

Estimating the time - lag response between barometric pressure changes and water level responses in a well, can be accomplished using regression deconvolution method (Furbish, 1991). A simpler way makes use of the software BETCO (Sandia National Laboratories) allowing to calculate the corrected, adjusted, values and to trace the BE as a function of time since the imposed load. This procedure helps understanding why in some situations the initial BE is different from the final one. In an aquifer rehabilitation project, e.g. the BRF obtained for various boreholes can be useful to demonstrate aquitard properties or aquifer confinement. Things that are not always clear from lithologic logs alone.

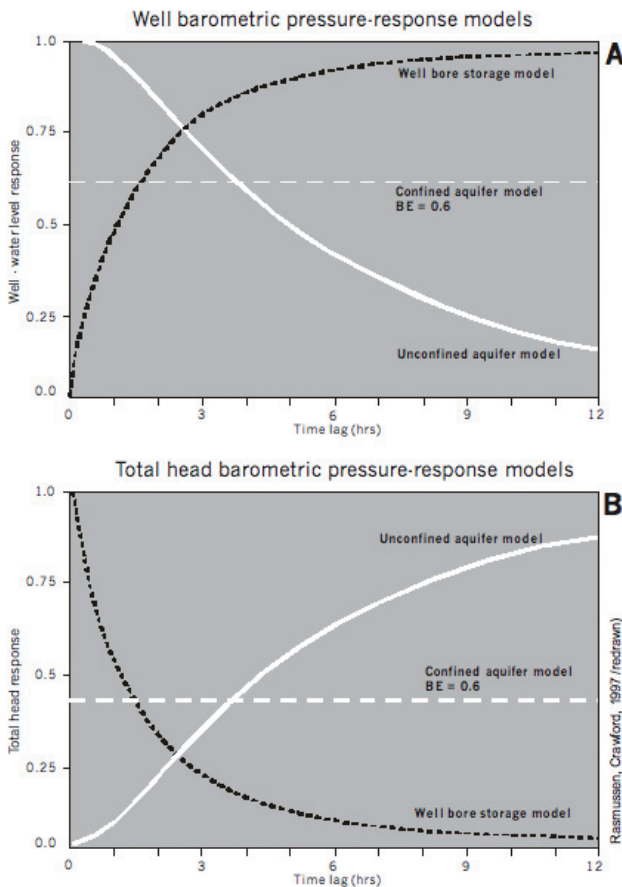
BRF properties

Keeping in mind what we discussed previously, Rasmussen and Crawford (1997) provided diagnostic plots for the barometric response function (fig. 9).

Curves may be different regarding the type of instrumentation used. With a vented transducer BRF is a function of BE (well-water level) while is a function of 1-BE with a non vented type. In any case we get an instantaneous response for confined aquifers and a time lagged response in case of unconfined aquifer or skin effect presence. The interpretation is similar in both circumstances.

The three diagnostic plots for the well-water level response are the following:

- Confined aquifer model independent of lag time
- Unconfined aquifer with lag, due to the delay required for the barometric pressure change to travel through the unsaturated zone
- Delayed response due to well bore storage and skin effect



9. Diagnostic plots for three well response models. The plots show the time lag dependance of each barometric response model associated with a unite step change in atmospheric pressure (Rasmussen, Crawford 1997, redrawn)

Confined aquifers

The air pressure transmission is rapid both for the aquifer and the well, but rigidity of the first prevents the reaching of the equilibrium. The pressure load within the well is born entirely by the water. The pressure imbalance is revealed by an instantaneous water level change in the well.

Refferring to fig. 9A, the dotted horizontal line shows a $BE = 0.6$ constant with time, meaning that the barometric pressure acts in the well without further fluctuations during the recording interval.

Unconfined aquifers (thick unsaturated zone/low permeable)

The piezometric level varies in a different way than that described for the confined aquifers.

The air pressure wave is slowed down due to the vadose zone but is very rapid for the well that will reach equilibrium with the surrounding aquifer after a certain time.

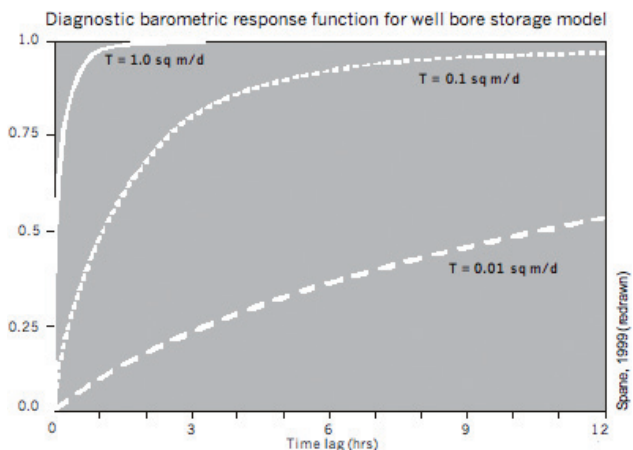
The sloping curve (fig. 9A) shows that the pressure rise is rapid for the well but delayed in time for the aquifer; BE diminishes slowly until reaching a new equilibrium. Keeping in mind the barometric efficiency definition, $BE = \gamma \Delta W / \Delta B$, ΔW is high then decreases while ΔB is going up.

Skin effect

The above mentioned description assumes a 100% well efficiency. Actually the barometric fluctuation is reduced at the well face due to the presence of the mud cake, type and length of screens and well storage. The effect is to increase the time for the well to reach the equilibrium with the aquifer, consequently also BE is varying with time.

In fig. 9A a steep ascending limb shows good well efficiency and therefore the hydrogeological parameters obtained from a pumping test are more reliable.

Spaine suggests that aquifers do not show important time lag when $T > 10 \text{ m}^2 / \text{day}$ ($10 \text{ m}^{-4} \text{ m}^2 / \text{s}$) and the well storage is negligible after 5 minutes approximately. Increasing the well diameter and decreasing the aquifer storage leads to a rise in the time lag (see gentle slope in fig. 10).



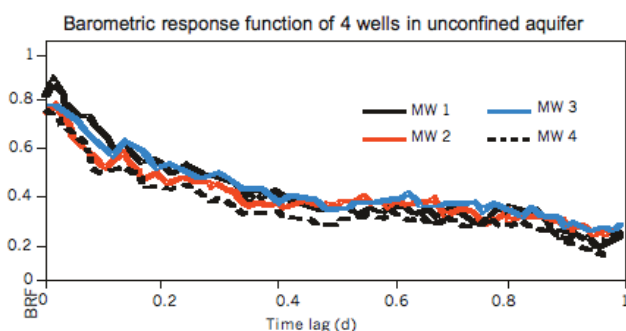
10. Diagnostic plot for the barometric response model and well bore storage (Spaine, 1999, redrawn)

The shape of the BRF allows to judge the type of the aquifer on the basis of the fluctuation of the barometric efficiency:

- Unconfined aquifers: initial $BE >$ final BE
- Confined aquifers: initial $BE \leq$ final BE
- Skin effect important: initial $BE <$ final BE

In practice there could be also the situation for which the aquifer model behavior overlaps the skin effect model, leading to a composite pattern. An advantage of using this technique arises when comparing various BRF from different wells or for the same well, screened at different interval depths. Such approach can reveal the reliability of the water points for a piezometric map.

Fig. 11 shows the similar trend for four different boreholes. The agreement clearly indicates that the aquifer system is not changing too much despite the wells are separated by 1-1.5 km distance. The short term response with high BE values decreasing with time compared to the lithology, indicates an unconfined aquifer with thick unsaturated zone.



11. Comparison of various BRF to detect hydraulic connection / homogeneity of aquifer

A similar trend of the plots indicates that the wells monitor the same horizons, there is a good hydraulic connection and the degree of confinement is negligible. In case of a marked divergent trend, like e.g. between a piezometer inside a containment system and one in the external unconfined aquifer we could guess the good performance of a cutoff wall isolating the ground water from the waste site.

Another interesting application is the feasibility study for CO₂ sequestration and in general to highlight horizontal porosity variations.

Earth Tides

The water level transducers can measure small fluctuations, in the order of a few mm, creating a near continuous record over time. Despite these developments, piezometric variations due to earth tides are not routinely

analyzed in the hydrogeological practice. Recent studies have proved the existence of tight bounds between hydrogeological parameters and earth tides. As a consequence they can be applied for a better scheduling and interpretation of field tests.

Solar and lunar gravitational attraction exerts earth and ocean deformations. When the Sun and the Moon pass over a point on the earth surface they generate a strain in the rock, changing the volume of the fractures, thus increasing the general porosity and decreasing its piezometric head. After the passage of the celestial bodies the gravitational attraction diminishes, and so does the overall aquifer porosity but the piezometric head increases. A lower aquifer rigidity corresponds to a higher deformation and hydraulic head (Hsieh, 1987). These phenomena are known as earth tides and are characterized by being periodic. Due to their complex motions the tides also are complex and have many components of different frequencies and amplitudes.

Each tidal component is likely to have a different influence due to the vector force applied, i.e. the moon on the horizon exerts force in a different direction than when it is overhead.

Referring to rock fractures, a tangential force will have a smaller effect on apertures than a normal force. Thus a Moon overhead may affect horizontal fractures while vertical ones when on the horizon.

These components are expressed as “harmonics”, sinusoidal functions of given amplitude and frequency and are known, based on decades of astronomical observations. While frequencies are common to all ocean and earth tide data, amplitude and phase relations for each component are bound to a particular position. (Melchior, 1983; Godin, 1972). A practical consequence is that of all the harmonic components only five are recognised as responsible for 95% of the tidal potential (Table 1, Galloway, Rojstaczer 1988).

Tidal component	Type	Period (hrs)	Frequency (cycles per solar day)
O1	Lunar	25.81934169	0.929535706
K1	Lunar-solar	23.93446961	1.002737909
N2	Lunar	12.65834823	1.895981969
M2	Lunar	12.42060121	1.932273614
S2	Solar	12.00000000	2.000000000

Table 1: Periods and frequencies of the principal Earth tides (Galloway, Rojstaczer 1988)

S2 and K1 are mostly due to periodic fluctuations of atmospheric pressure, derived from solar radiation and consequently they are not used for hydrogeologi-

cal evaluations. N2 also is often neglected because the large signal to noise ratio is a potential source of error. From Table 1 it is easily seen that the components have periods of 12 to 25.8 hours and frequencies of 0.9 to 2 cycles per day, while daily deformations reach some tenths of centimeters.

Recent investigations have tried to extend data to hydrogeological studies. The reason is that these forces are uniform in magnitude over large areas and so are the effects on the confined aquifers, without inducing additional lateral flow. This particular approach for studying bounds between earth tides and aquifer properties can be summarized in four different steps (Merritt, 2004):

- Calculation of diffusivity (T/S)
- Calculation of specific storage for confined aquifers (Ss)
- Calculation of transmissivity (T) and storage (S) for confined aquifers
- Calculation of vertical hydraulic conductivity (Kv)

Bredehoeft (1967) showed that the fluctuation of the hydraulic head in a well, due to earth tide, is a function of the specific storage (Ss) and this last parameter can be calculated knowing the Poisson's ratio of the aquifer. Others (Gelkdon, Earle, Umari, 1997; Merritt, 2004) suggest that there is a direct relationship between the tidal component and aquifer transmissivity.

To summarize

- Water level fluctuations in wells are not only due to recharge and a consistent percentage is related to barometric variations
- The amount of water level fluctuation in a well due to barometric pressure must be known to correctly analyze aquifer tests
- Barometric pressure is transmitted rapidly in the well but with a certain delay in the aquifer
- Total head (H) accounts for the water level elevation (W) and barometric pressure (B)
- In low gradient area, barometric pressure fluctuations should be calculated to depict underground flow directions correctly
- In confined aquifers there is an inverse relationship (e.g. water level declines with an increase of the atmospheric pressure)
- In porous unconfined aquifers and or thin vadose zone the water level change is negligible

- In deep unconfined aquifers with rigid vadose zone, the pressure fluctuation is transmitted rapidly to the well but displays a time-lagged response at the water table, because air must move into or out of the overlying vadose zone to transmit the change in pressure
- During an aquifer test, drawdowns in the piezometer should be more than 0.2 m to be reliable and not influenced by barometric fluctuation
- The magnitude of water level change is a function of aquifer confinement, matrix rigidity and specific weight of the water
- Generally speaking the elastic aquifer behavior decreases with the increase of the overburden and barometric efficiency
- A simplified method to calculate BE for confined aquifers is to prepare a plot of barometric pressure values versus water levels for a certain time ($BE = \Delta W / \Delta B$)
- BE varies between 0 and 1
- The barometric response function (BRF) is a function of time since the imposed load
- Harmonic components derived from earth tides proved to be related to some hydrogeological parameters

Piezometric suveys of Otavi karst aquifer_ (data analysis through barometric efficiency calculation)

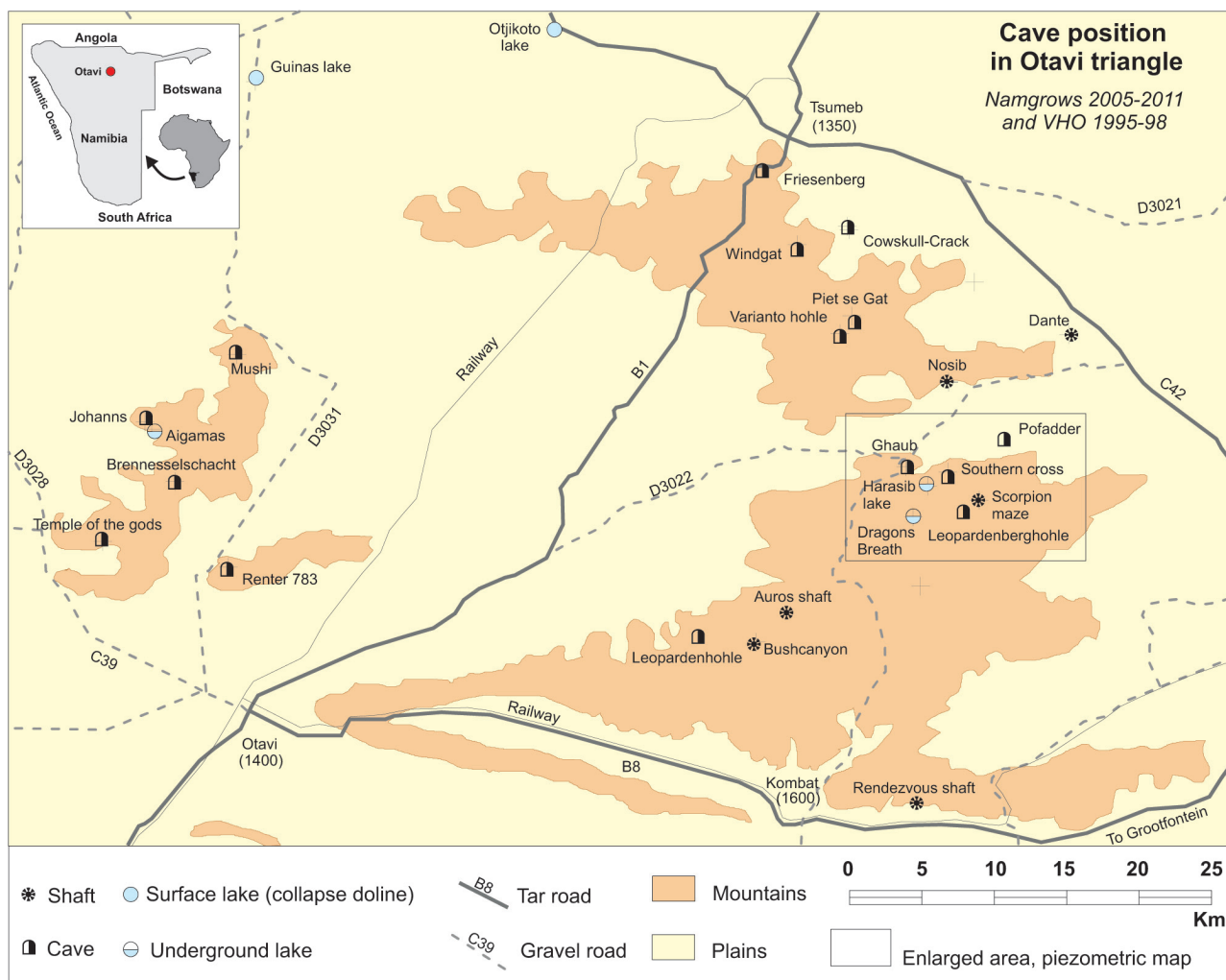
As an application of the theory above, we present some data collected and analysed for the karst aquifer of Otavi mountainland in northern Namibia.

General framework

The area under investigation is in the SE part of a 6000 sq km plateau with average elevation of 1300-1500 m asl and hills reaching 2000 m (fig. 12).

Rock formations are made of thick dolomitic limestone beds with stromatolites (500 b.p.).

The strata have been folded into a number of synclines and anticlines generally striking east-west. The southern part of the study area is bordered by a long fault with various mineral occurrences (copper, vanadium, lead, zinc). Due to the high fracturing, low vegetation cover and lack of soil, surficial runoff is almost nil. Two natural water basins, collapsed dolines, of 100-200 m in large, are located further north and outside the project area. The mean annual rainfall is 540 mm (1926 - 1992) with peaks during summer, between december and march. Since mid '70s and until the year 2000 the area suffered



12. Position of main caves and underground lakes in the study area. The surface elevation is between 1300-2000 m (asl)

a fall in precipitation that, together with mining activity (Kombat, Tsumeb, Abenab) was responsible for the lowering of the water table of as far as 20-30 m in some places.

From 2005 on, this trend has reversed due to the reduced activity of the mines and a new meteorological regime.

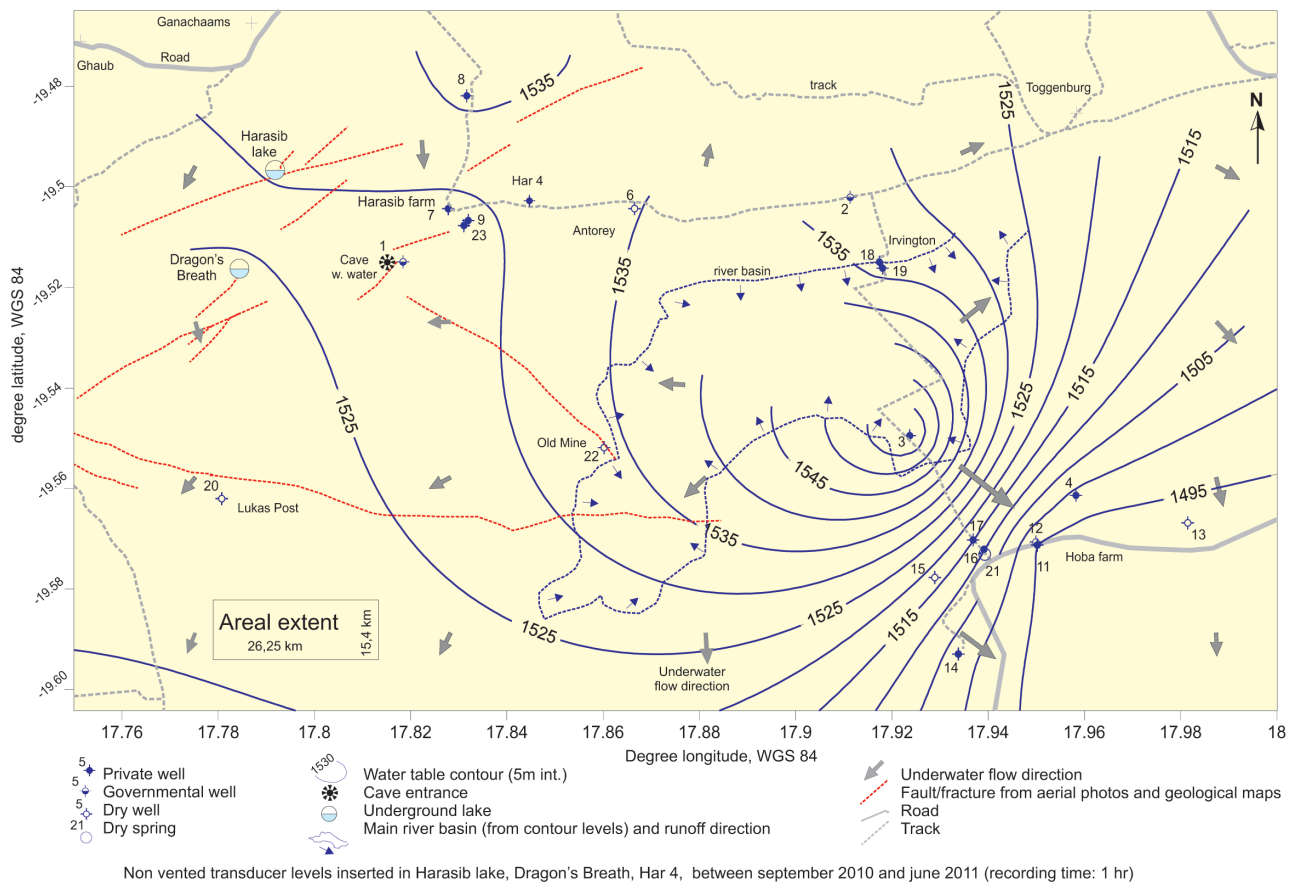
Hydrogeological framework

This region is well known for its karst features, and hosts some wide underground lakes located between 70 and 120 m below ground surface.

The area is also classified as one of the most impor-

tant aquifer of the country (Dept. of Water Affairs, MAWRD, area E-F). To glean more valuable insights into this particular environment and locate alternative positions for water boreholes we prepared two piezometric maps (2007-2010) and installed 4 water level transducers in some water points at 2-4 km distance in Harasib farm (fig. 13).

The 2007 piezometric surface shows a recharge area, coincident with the topographic highs and fed by rain infiltration. From this point, underground flow directions are to SW and SE. During this stage we focused our researches to define:



13. Piezometric map (february 2007) and position of three water level loggers (STS DLN/70)

- Type of aquifer
- Aquifer connections between Harasib and Dragon's lakes
- Recharge

Chemical analysis of surface and deep waters were conducted in 2007, while continuous barometric pressure and water level readings were made during a ten months period, between september 2010 and june 2011.

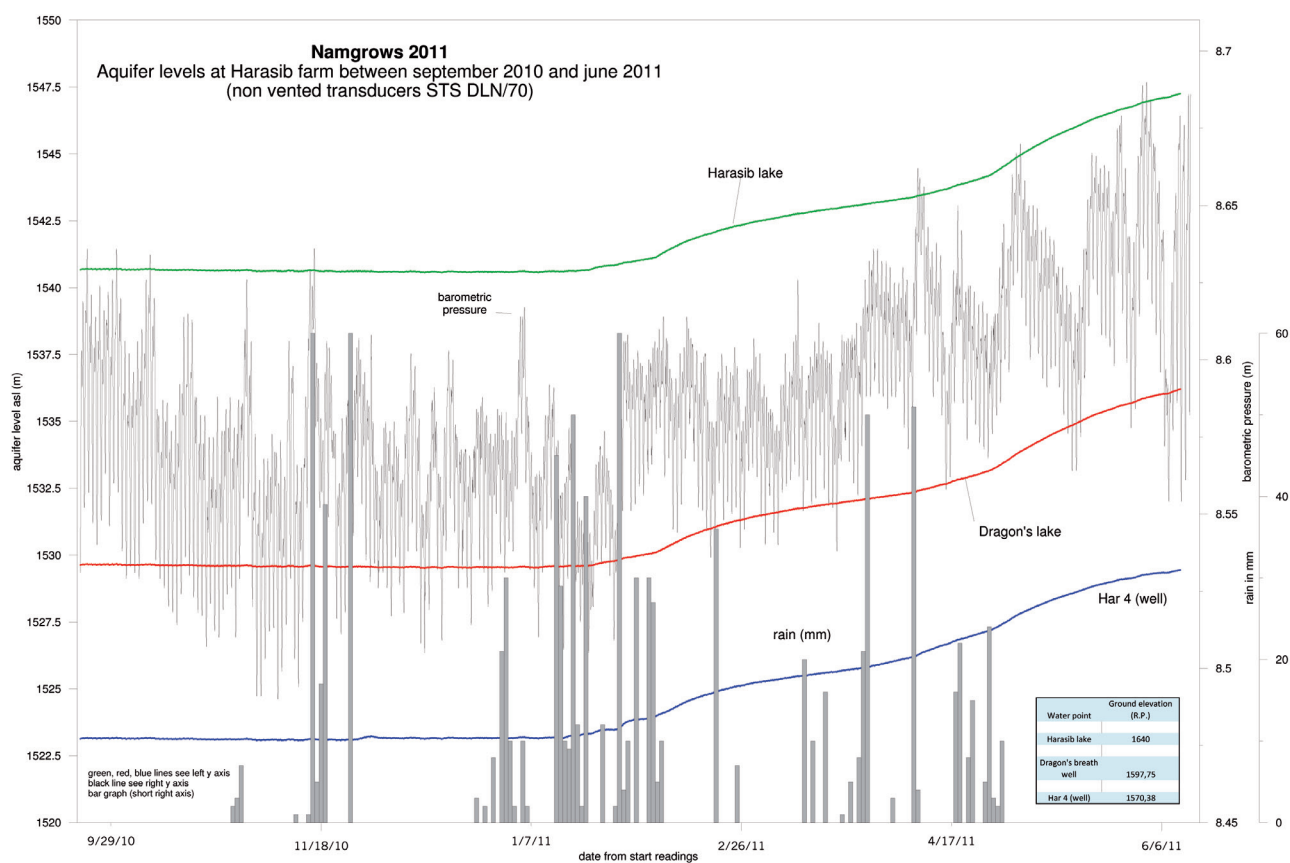
Fig. 14 shows all data gathered during the monitoring interval at hourly readings. The graphs are quite similar with a rising in water level of 5-7 m.

During this interval rain was particularly abundant for the season, with more than 1000 mm. The rain gauge was installed at the Harasib farm, 1-2 km far from the loggers. The aquifer recharge starts when cumulative rain

exceeds 400-500 mm. The thickness of the unsaturated part ranges from 40 to 100 m. Taking into account that this value is close to the average annual rainfall, and the aquifer is karstic and highly fractured, one should note that one or two years of scarce precipitation is enough to decrease dramatically the exploitable yield.

Barometric efficiency (BE) and barometric response function (BRF)

The water level readings have been analysed with the software BETCO (Sandia National Laboratories), to remove the effects of the barometric pressure changes. The measured and corrected values are depicted in fig. 16 and refer to the dry period (september-january) while fig. 17 shows the plots of barometric pressure versus water level changes, used for the calculation of the barometric efficiency.

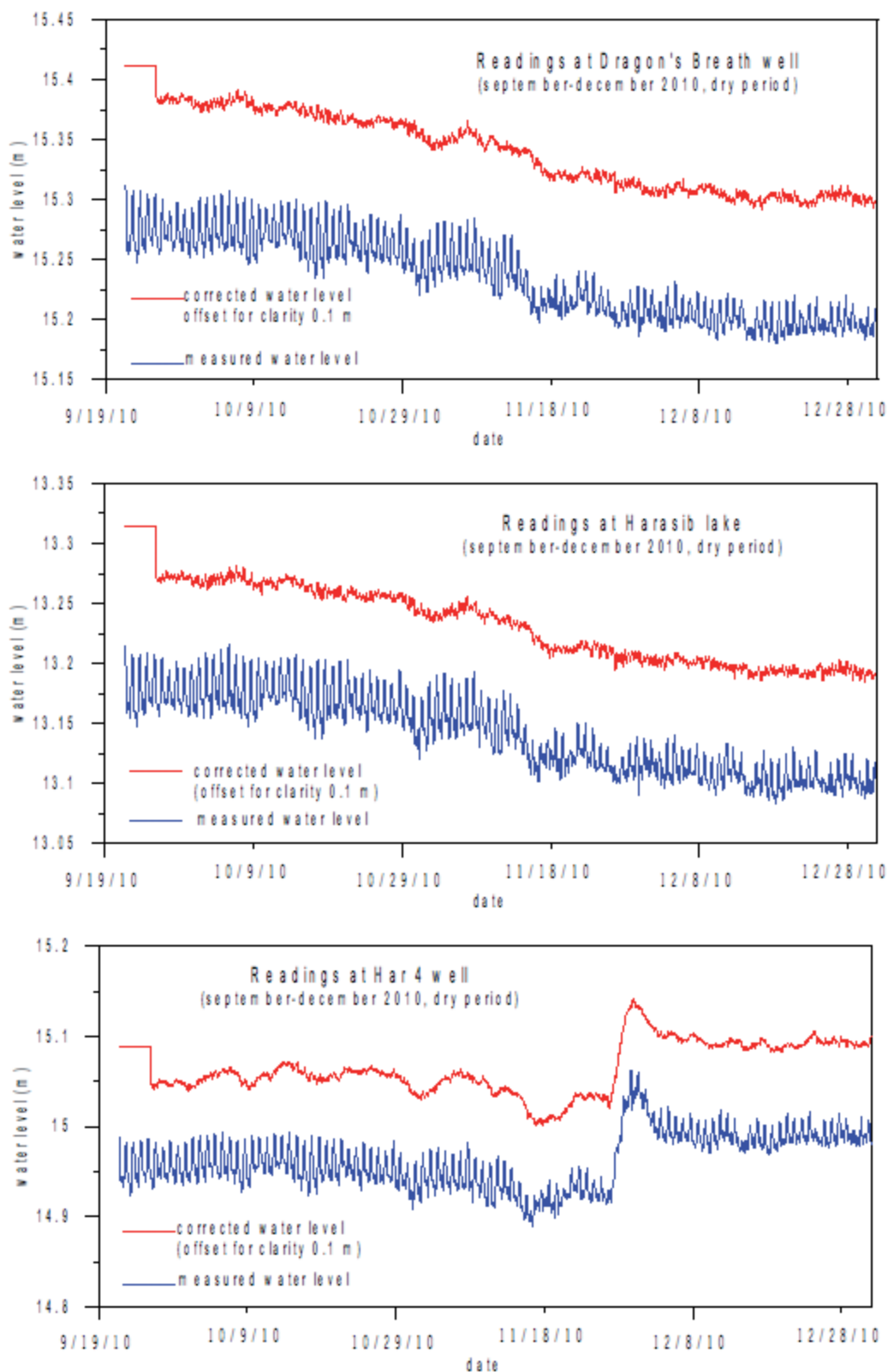


14. Data from four water level loggers, three of them below the water table and one barometric (model type STS DLN/70)



Ph. A. Favaro, Namgrows 2011

15. The Dragon's Breath lake, located 70 m below ground is one of the three monitored water points. The lake extension was 180 m in June 2011 and its depth more than 105 m.



16. The three curves show the total head (TH) and adjusted, with barometric pressure removed (BP). There is less fluctuation in the adjusted values, but there is still a slight effect, most probably due to earth tides and other (non barometric) effects.

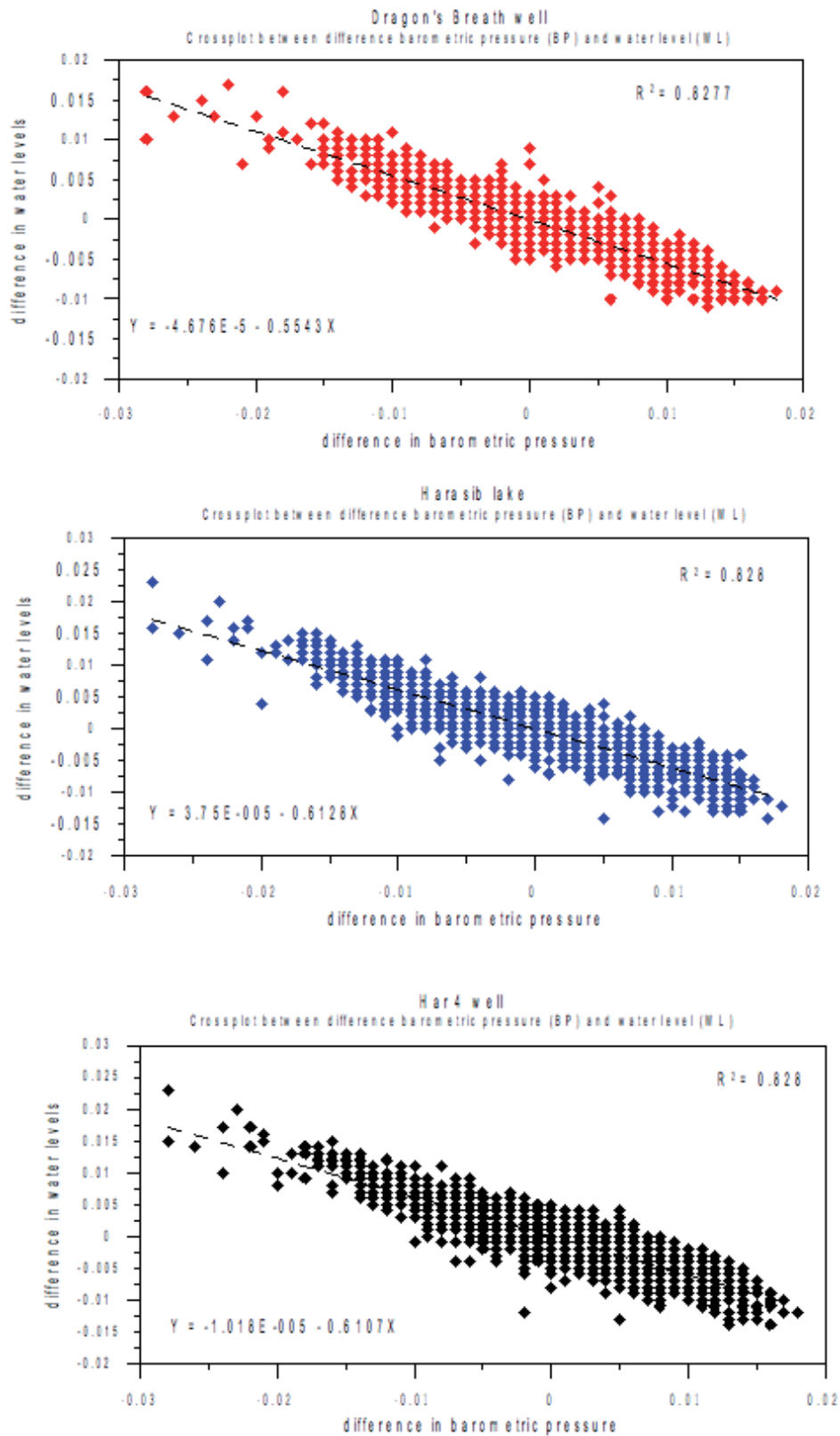


Fig 17: Difference in barometric pressure and water levels during the dry period (sept.-dec. 2010)

In all examples we notice that:

- There is a good correlation between measured and corrected values, even if with lower amplitude
- There still is a variation diminishing in the corrected values; being excluded skin effects phenomena this behaviour could be ascribed to other non barometric effects (earth tides, double porosity)
- The initial barometric efficiency values are quite similar (0.55-0.61)

In fig. 18 is depicted the barometric response function (BRF) that characterises the water level response over time to a step change in barometric pressure; essentially BRF is a function of time since the imposed load.

A good agreement is observed for all three water points. In Dragon's Breath lake e.g, there is a quick rise to 0.5 and a longer term decay to a lower value (0.2 - 0.3 after 20 hrs), due to the slow passage of air through fractures. The balance between external pressure and the aquifer is reached at 0.1 value.

The shape of the three curves indicate an unconfined aquifer with good hydraulic connections especially between Dragon's Breath and Harasib lake, this last one at 2 km distance.

The correlation has also been proved by isotopic and chemical analysis made in 2007 (prof. Franco Cucchi, Dept. of Geology, Trieste University).

Generally speaking the collected data confirm the unconfined behaviour of the aquifer, overlaid by a thick and rigid unsaturated layer, well fractured and hydraulically connected. The initial barometric efficiency is higher than the final.

Earth tides and sensor readings

Regarding this last topic, data collected are still scarce but we think is nevertheless interesting to illustrate some thoughts. When inspected in detail the curves show a distinctive zig-zag pattern with peaks every 10-12 hrs (fig. 19).

This behaviour supports the effect of earth tides, producing slight changes in the volume of the fractures and pores and hence in the groundwater potential. The Fourier analysis (Shumway, 1988) shows the harmonic structure for the three water points in fig. 20 and the tide components in fig. 21.

The area close to Harasib lake has the higher values for

the M2 component and this can be considered as an indication of a higher transmissivity zone (Merritt, 2004). This fact is partly confirmed by the presence of a local fracture elongated ENE-WSW very close to Harasib lake.

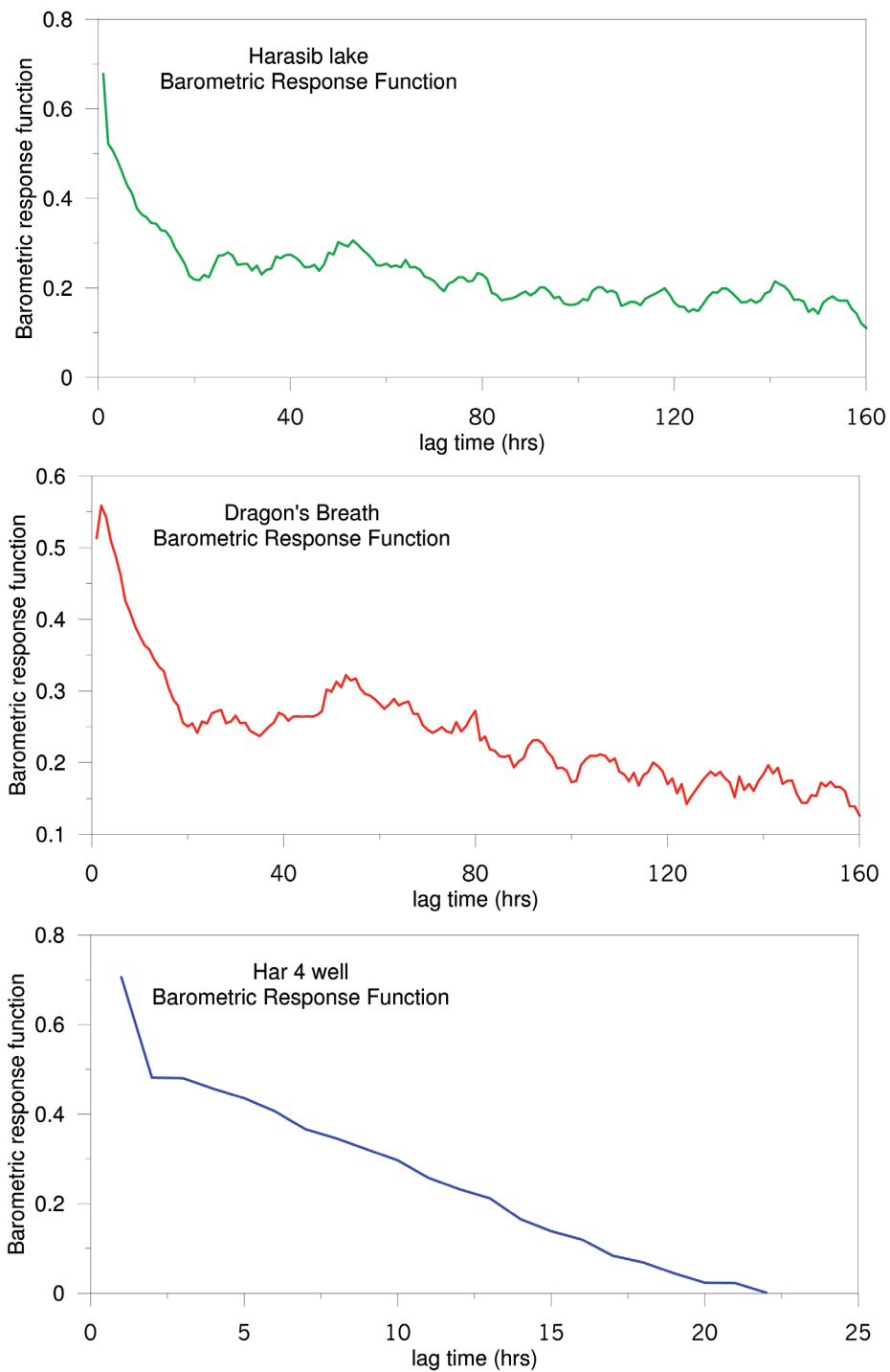
Concluding remarks

Water levels fluctuations in aquifers are not only due to recharge variations. Barometric pressure and tides are among the main concerns. Knowing barometric pressure variation for a particular site, helps to validate a piezometric map or a pumping test. Modern pressure transducers vented to the atmosphere are recognised to be extremely useful when installed into boreholes. Recordings are different following the type of aquifer and the graphs can be diagnostic of the degree of confinement for the monitored levels.

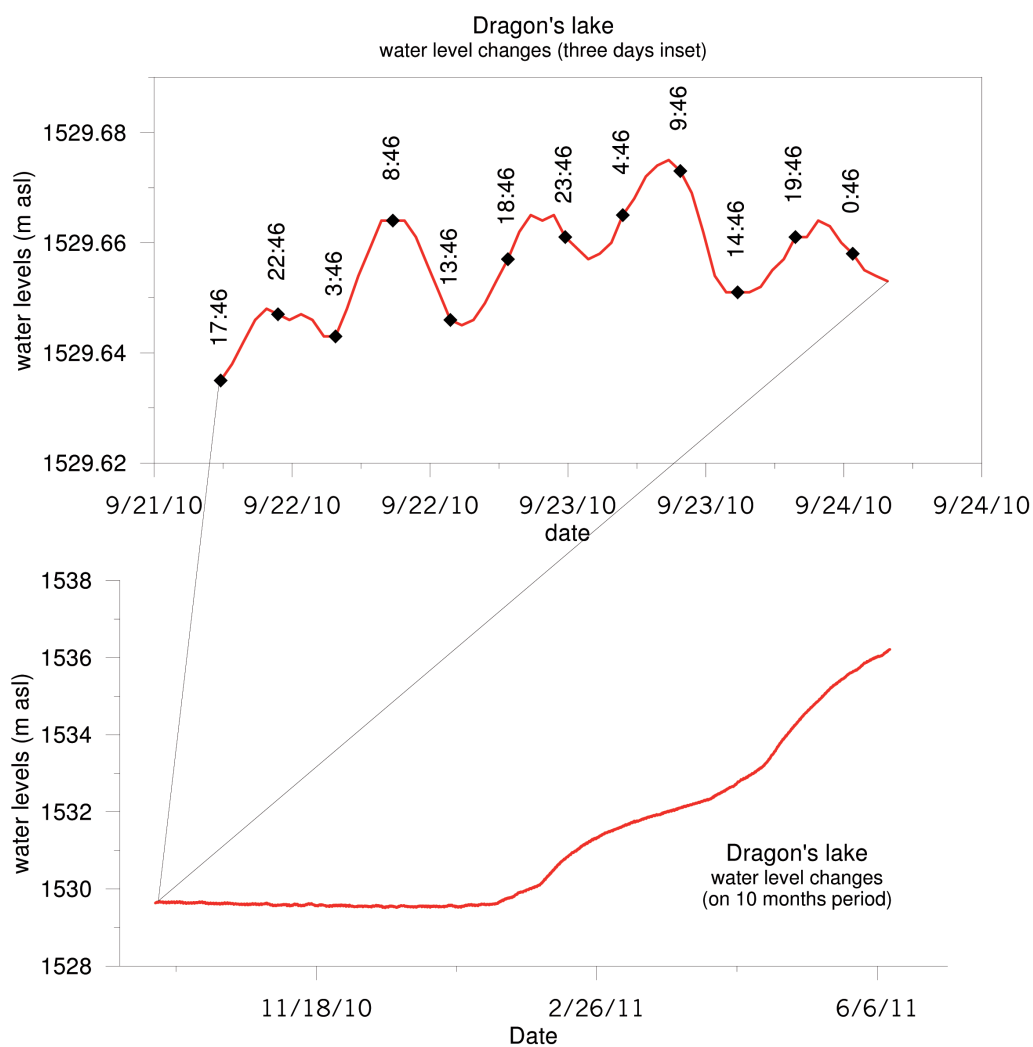
Useful parameters that characterize this behaviour are the barometric efficiency (BE) and the barometric response function (BRF). The latter characterizes a deep unconfined aquifer when values are initially high and approximate 0 on the long term response, conversely the aquifer is confined/semiconfined when values stay constant or approximate 1 on the long term response. Removing barometric effects is sometimes necessary to correctly interpret a pumping test or dress up a piezometric map. Finally a particular analysis of the water level data allows to calculate the harmonic components due to tides and hence some hydrogeological features.

This theoretical approach has been applied to the data gathered for a project study of an unconfined karst aquifer in northern Namibia. Water levels have been monitored during a 10 months period, with hourly readings and by means of four transducers. The data confirmed the general assumptions obtained during preceding investigations and have underlined the importance of the use of such instruments for aquifer assessment, showing particularly:

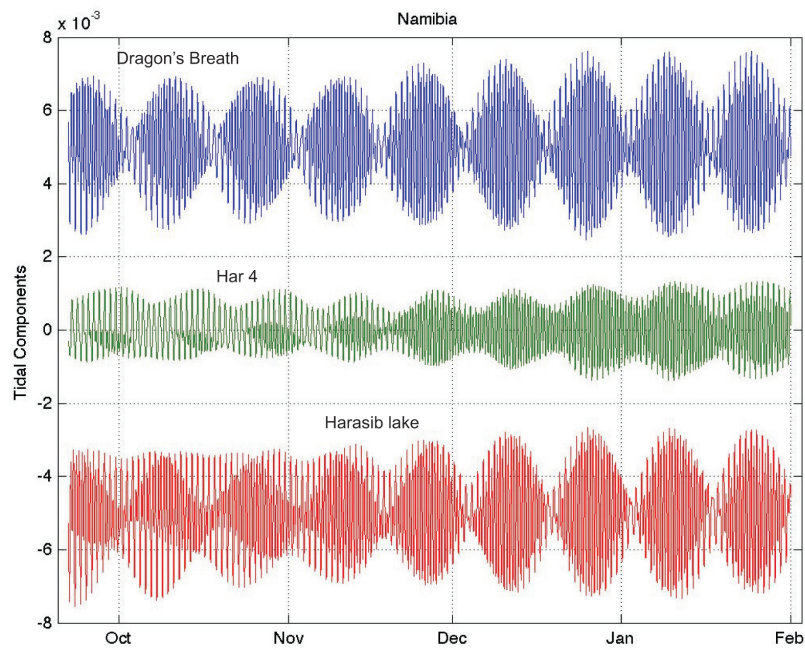
1. The role of the recharge due to rainfall and high transmissivity around Harasib lake area
2. The good hydraulic connection and conductivity for the aquifer
3. The lack of confining layers (it's a deep and rigid unconfined aquifer)
4. The storage effect of the unsaturated part, above the water table, that starts draining when rain exceeds 400/500 mm
5. The other pressure effects, such earth tides, can be highlighted using water level transducers



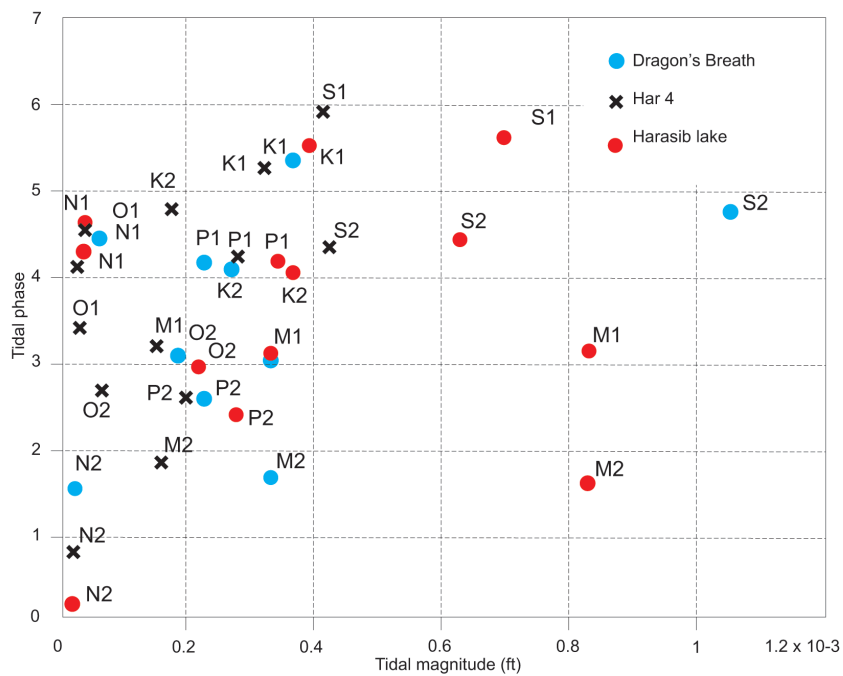
18. Barometric Response Functions for the three water points. The curves are similar (especially Dragon's Breath and Harasib lake) suggesting an unconfined aquifer with perhaps a double porosity component.



19. Water levels asl in the underground lake. The enlargement above shows small cyclic differences due to earth tides



20. Harmonic components for the three water points



21. Tidal magnitude for the main harmonic components (values in ft)

Acknowledgements

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