Establishment of earth tide effect on water-level fluctuations in an unconfined hard rock aquifer using spectral analysis

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Short-interval water-level measurements using automatic water-level recorder in a deep well in an unconfined crystalline rock aquifer at the campus of the National Geophysical Research Institute, near Hyderabad show a cyclic fluctuation in the water levels. The observed values clearly show the principal trend due to rainfall recharge. Spectral analysis was carried out to evaluate correlation of the cyclic fluctuation to the synthetic earth tides as well as groundwater withdrawal time series in the surrounding. It was found that these fluctuations have considerably high correlation with earth tides, whereas groundwater pumping does not show any significant correlation with water-table fluctuations. It is concluded that earth tides cause fluctuations in the water table. These fluctuations were hitherto unobserved during manual observations made over larger time intervals. It indicates that the unconfined aquifer is characterized by a low porosity.

WATER levels in an aquifer are an important parameter in groundwater hydrology and a careful and detailed analysis of its spatio-temporal variation reveals useful information on the aquifer system. Among various causes affecting the groundwater levels are groundwater withdrawals, rainfall recharge, evapo-transpiration, interaction with surface water bodies, etc. Ocean tides are also known to affect the groundwater fluctuation in the coastal aquifers.

The water levels measured in a well located in an unconfined hard rock aquifer, located far away from the sea are characterized by cyclic fluctuations. Knowing that fluctuations due to evapo-transpiration cycles appear only in very shallow aquifers and are consequently not relevant in the studied case, these fluctuations can be due to two different factors. The first one is anthropogenic. It is well known that the groundwater withdrawal from an aquifer or from a field of wells induces water-level decline, creating a cone of depression depending, among other parameters, on the aquifer hydrodynamic parameters and geometry. But, after the pumping is stopped, the level starts coming up due to recuperation to attain equilibrium. This gives a sort of cyclic fluctuation if the pumping follows a regular interval and the levels are recorded continuously.

The second cause able to induce daily water-level fluctuations is the earth tides. Actually, the effect of earth tides has been observed in the groundwater-level fluctuation of an aquifer, when monitored continuously or at a shorter interval[1–3]. The dilatation of the earth due mainly to the position of the moon and the sun induces measurable water-level fluctuations in the well. The effects of earth tides can be observed in 'most wells completed in a well-confined aquifer', according to Bredehoeft[1], and in aquifers that have 'low porosity' and are 'relatively stiff', according to Rojstaczer and Agnew[4].

A time series of water levels, gravity field fluctuations due to earth tides and water pumping cycles have been studied using spectral analysis, to identify the principal cause affecting the water levels in the studied well.

The observations of water-level fluctuations have been taken from a well located in the National Geophysical Research Institute (NGRI) campus in Hyderabad (Figure 1), in a hard-rock region, using a data-logger from 1 to 12 June 2000 with a time interval of 42′04″.

The well (location: 78°33′03.2″; 17°25′02.1″) was drilled in granite up to 173 m, cutting across a number of minor/major fractures after a weathered cover of about 20 m. The groundwater depth is about 15 m before the monsoon and 9 m after.

The water level (water above the pressure probe) has an increasing trend corresponding to the effect of recharge from the rainfall (Figure 2). The moving average (on 50 values, averaging window of 35 h duration) is slowly increasing between 1 and 5 June, and the same has greater slope after 5 June. After a relatively dry month of May with only two days of rain, high rainfall of

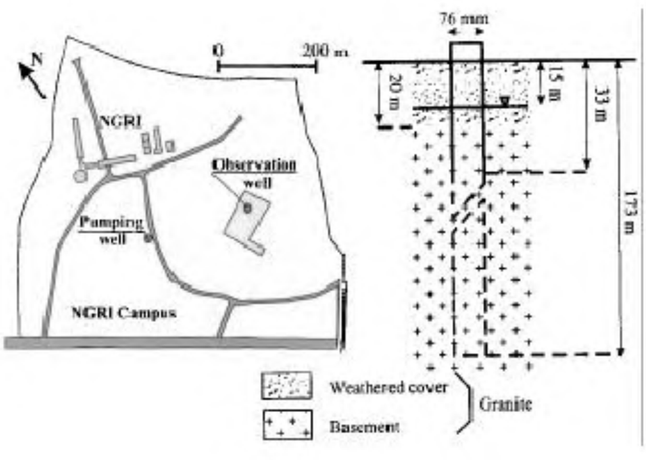

Figure 1. Location map and schematic geological cross-section of the observation well.

*For correspondence. (e-mail: ifcgr@satyam.net.in) about 72 mm occurred on 4 June at the meteorological station, NGRI, a few hundred of metres from the well. After that, a couple of more rainfall events occurred during the measurement period.

A typical annual variation of water level with rise during the monsoon and decline in the remaining period, with an inlet of the study period is shown in Figure 3. It appears just at the beginning of the water level increase due to the monsoon recharge.

Earth tides are the result of a visco-elastic deformation of the earth under the action of gravitational pull of the moon and the sun. Among the 386 existing tide waves, only high-amplitude waves have an effect on the aquifers. Melchior[3] indicates that five large main waves are responsible for almost 95% of water-level fluctuations observed in the wells. These waves can be divided into two groups: tesseral waves of daily period and sectorial waves of semi-daily period (Table 1).

These tides induce a cubic dilatation of the earth which is responsible for water-level fluctuations in the wells. Gravity-field fluctuations due to synthetic earth tides have been computed at the well site in Local Standard Time (Time Zone: 5 East) with a special code taking into account the main tidal components.

The only water pumping present in the neighbourhood of the observation well is located at 215 m to the southwest (Figure 1). Groundwater pumping is of variable duration everyday in the well.

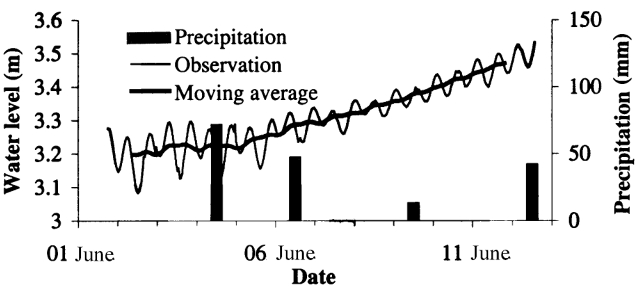

Figure 2. Water level and precipitation during the observation period.

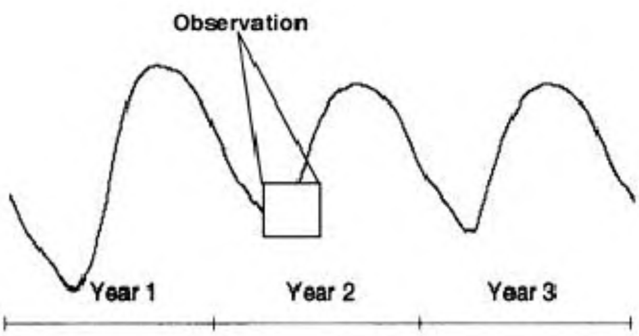

Figure 3. Schematic showing time-evolution of groundwater level in a monsoon region.

Figure 4 illustrates the comparison between observed water-level fluctuations, computed earth tide effect on gravity field (μGals) and water pumping periods in local time (GMT + 5:30). The cycles of earth tides seem to have the same frequency as the water level fluctuations. A local maximum of gravity corresponds to a local maximum of water level. On the other hand, pumping does not seem to be correlated with water level: some pumping periods are characterized by an increasing water level, while some off-periods are characterized by a declining level.

During the observation period, detailed analysis shows that maximum earth tide fluctuations between 2 and 3 June corresponds to maximum water-level fluctuations with an amplitude of 10 cm, and minimum of earth-tide fluctuations during 8 June corresponds to a minimum of water-level fluctuation with an amplitude of less than 3 cm. The amplitude of water-level fluctuations was used by Marsaud *et al.*[5], applying the theory of Bredehoeft[1] to determine the storage coefficient of the aquifer.

A preliminary observation of the studied signals tends to show that the water-level fluctuations are better correlated with earth tides than with water pumping. This statement is verified by spectral analysis.

A filter must be applied on the water-level data to enhance useful components and remove the ones that hide the cycles of interest. In the studied case, the trend corresponding to the monsoon recharge needs to be removed as seen in Figures 2 and 3. As proposed by Marsaud *et al.*[5] according to Box and Jenkins[6], the trend can be removed using a first-order differencing calcu-

Table 1. Origin, period and frequency of the principal tidal fluctuations

Code	Frequency (degrees/h)	Period (d)	Origin
M_1	1°098′033	13.66	Lunar, variation of declination
O_1	13°934′036	1.07	Lunar, main term – tesseral
K_1	15°041′069	0.99	Lunisolar, main term – tesseral
N_2	28°439′730	0.53	Lunar, main term (orbital ellipsoid) – sectorial
M_2	28°984′104	0.52	Lunar, main term – sectorial
S_2	30°000′000	0.42	Solar, main term

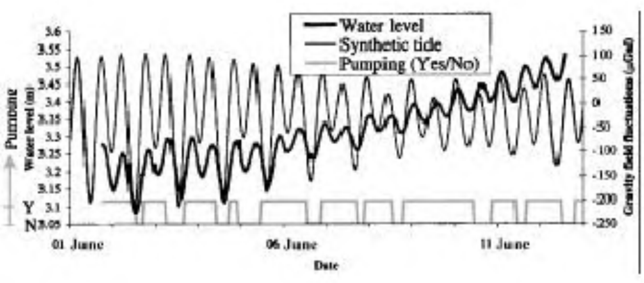

Figure 4. Gravity-field fluctuations due to synthetic tides, water-level fluctuations and water pumping.

lating the punctual increase of the time data series. Given $X(t)$ a time data series, the differentiated $Y(t)$ is computed as following:

$$Y(t) = X(t-1) - X(t).$$

This method conserves the structure and the amplitude of the phenomenon, while removing the trend[5]. The data used below have been filtered using this method.

The computation of the power spectrum allows identification of the frequencies of a periodic signal. For a given signal, the power spectral density is high for the frequencies that characterize this signal, and is low for other frequencies. Thus, as an example, the power spectral density of a periodic signal with three cycles at frequencies, say f_1, f_2 and f_3, will be characterized by three peaks at the frequencies f_1, f_2 and f_3. The relative power spectral density was computed for the synthetic earth tides, filtered water-level observations and water-pumping data (Figure 5). While the power spectral density of water pumping is different, those of water levels and earth tides are similar, with two peaks appearing at frequencies f_1 and f_2 (see Table 2). The periods of these cycles correspond exactly to the daily tesseral waves O_1 and K_1, and to the semi-daily sectorial waves N_2 and M_2.

The amplitude function expresses, for each frequency, the magnitude of the input–output relation. Usually, only relations between input and output for frequencies where amplitude of covariance is high can be interpreted. For other frequencies, a low covariance indicates that there is no input–output relation. In this case (Figure 6), the high value of amplitude at frequencies f_1 and f_2 confirms that there is a relation between earth-tide (as input) and water-level (as output) fluctuations. This is not the case for water pumping and water-level fluctuations.

Coherency describes the degree of relation between two signals of same period. The square of coherency lies between 0 and 1. When $|Csr|^2 = 1$, for a given frequency $f = f_0$, then, there is a linear relation between both signals (at the frequency $f = f_0$). Figure 7 shows that for earth tides and water levels, $|Csr|^2 = 1$ at frequencies f_1 and f_2. This indicates that earth tide and water level signals not only have the same frequencies, but are linearly related at these frequencies. The coherency between water pumping and water level is low at all the frequencies. There is no direct linear relation between these signals.

The cross-correlation function represents the interrelationship between the input and output series. The time lag at which the maximum cross-correlation occurs determines the stress transfer velocity of the system. The cross-correlation diagram between tidal fluctuations and water levels shows that the correlation at the origin is positive (Figure 8): a local maximum of gravity corresponds to a local maximum of water level: high earth gravity (due to lower moon or sun attraction) induces a contraction of the earth and a water level increase due to decrease of porosity. A maximum positive correlation is found after about 1 h. This is the delay in the reaction of the aquifer to the earth tide depending on hydraulic conductivity and storage coefficient of the aquifer[7]. Various scientific approaches exploit this dependence to determine the hydraulic parameters of an aquifer using the response of water level to earth tides[5,7–9].

The detailed study of water-level fluctuations measured in a well located in a hard-rock aquifer shows that earth tides (not water pumping) are responsible for observed daily and semi-daily period fluctuations. Frequencies of synthetic earth tides and water-level observations signals are similar. Tesseral waves of daily period (O_1, K_1) and

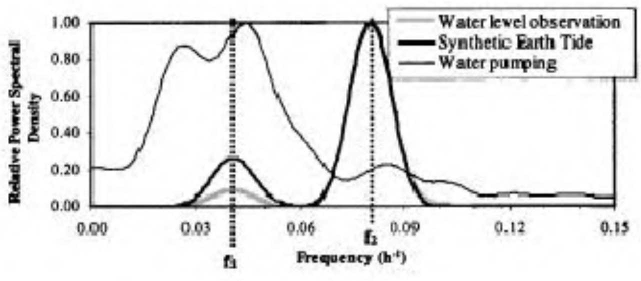

Figure 5. Relative power spectral density of synthetic earth tides, pumping cycles and filtered water levels.

Table 2. Characteristic of observed frequencies on signals

Frequency (h^{-1})	Period	Earth tide
$f_1 = 0.04109$	P_1 = 24.34 h (1.01 day)	O_1, K_1
$f_2 = 0.08009$	P_2 = 12.48 h (0.52 day)	N_2, M_2

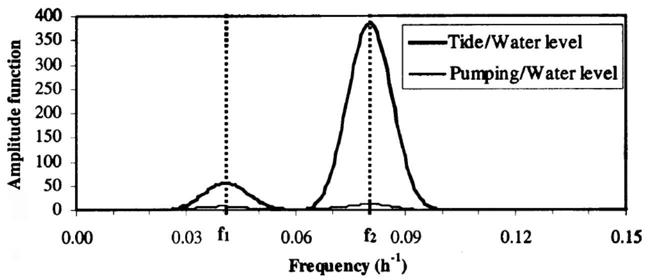

Figure 6. Amplitude function between tidal fluctuations and filtered water levels, and between pumping cycles and filtered water levels.

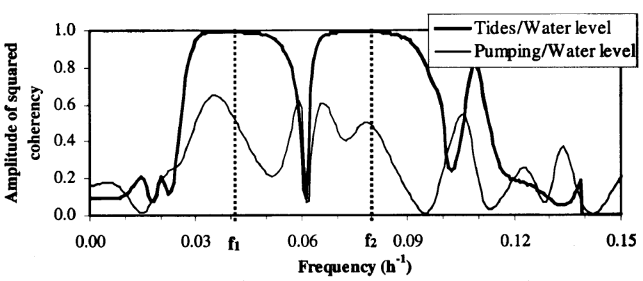

Figure 7. Coherency between tidal fluctuations and filtered water levels, and between pumping cycles and water levels.

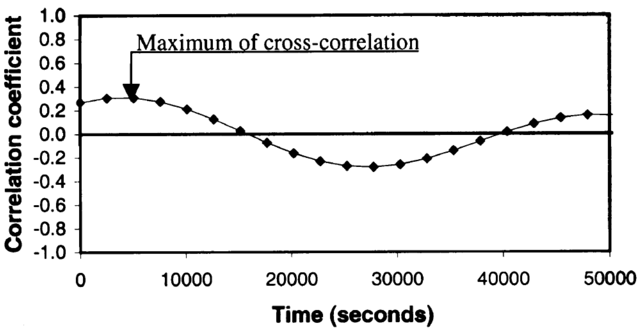

Figure 8. Cross-correlation function between gravity fluctuations due to synthetic earth tides and water levels.

sectorial waves of semi-daily period (N_2, M_2) are identified as the origin of the water-level fluctuations. Spectral analysis has shown that there is a direct linear relation between earth tides and water-level fluctuations in the studied well. The observation of such fluctuations in this hard-rock aquifer, apparently unconfined, implies that the aquifer is characterized by a low porosity.

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Continental mayfly burrows within relict-ground in inter-tidal beach profile of Bay of Bengal coast: A new ichnological evidence of Holocene marine transgression

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The present study documents the first record of preserved mayfly burrows and an important record of continental ichnofauna in India. Ecologically, mayfly burrows suggest continental ephemeral stream bank (saturated edges just under water level) settings. Their presence in the Holocene relicts of the Kalna surface exposed in the modern inter-tidal beach profile (Nabadwip surface) at Bakkhali (West Bengal coast) provides a new ichnological evidence of the Holocene rise in sea level and consequent marine transgression of the Bay of Bengal Sea, a fact otherwise well supported globally as well as regionally by many geological features. The specific orientation of mayfly burrows with respect to river bank may be useful in interpreting palaeochannel courses (or aquifers) in rock records. The present application of mayfly burrows for interpretation of environment, sea level and aquifers remains unmatched in published literature.

MARINE ichnology is now an advanced scientific discipline within palaeontology. Continental ichnology, on the contrary, is a relatively new field and has begun to be incorporated into the theoretical framework of ichnology. The main credit goes to some very significant recent studies that have revealed 166 examples of continental ichnocoenoses (trace fossil assemblages)[1], 58 ichnocoenoses of palaeosol insect origin with 29 as recurring examples of *Coprinisphaera* ichnofacies[2] and a large number of ichnocoenoses of lacustrine[3–6] and freshwater inner estuarine[7–10] palaeoecosystems. These studies have also revealed that a large community of non-marine organisms is capable of making environment-sensitive and distinct traces, the most delicate of which can also be preserved in the rock records. Insects, in particular, are prolific trace-makers. Among them, stoneflies (Plecoptera), mayflies (Ephemeroptera), dragonflies (Odonata), Alder and Dobson flies (Megaloptera), bugs (Hemiptera), caddisflies (Trichoptera), beetles (Coleoptera), flies (Dioptera), ants (Hymenoptera) and crickets (Orthoptera) are very well represented in continental ichnocoenoses[11] reported from Argentina, Australia, Ecuador, Egypt, France, Ethiopia, Kenya, Namibia, South Africa, UAE, Uruguay and USA[2]. From India there is only one record of continental ichnofaunas (*Termitichnus* and meniscus burrows) from Plio-Pleistocene Upper Siwalik sub-Group (previously Boulder Formation) of Punjab Himalayas[12].

The present study focuses on the Holocene relict-grounds of Bakkhali inter-tidal beach (the Bay of Bengal) from where documentation of mayfly burrows is made, and discusses their significance relative to Holocene sea-level changes and depositional environment.

The coastal plains of the Bay of Bengal incorporate a part of the Ganges Delta Complex that exposes from north to south successively younger deltaic surfaces (Figure 1 *a*). The complex has a very dynamic Quarternary