A Conceptual Numerical Model to Simulate Aquifer Parameters

Pallavi Banerjee Chattopadhyay · Nimisha Vedanti · V. S. Singh

Abstract While in constant head aquifer, groundwater level before pumping and after recovery attain a constant value, it is quite challenging to estimate the actual discharge value in an atoll aquifer where the head fluctuates with tides. Lens shaped atoll aquifers are fragile in nature and pumping causes the water table to fall which could further aggravate sea water intrusion. Thus the objective of the study is to propose an alternative method and demonstrate the importance of tide-induced head fluctuations in analysing the aquifer parameter in atoll environment. The solution to a one-dimensional unsteady groundwater flow model in an atoll aquifer with sinusoidal fluctuations of the tide shows that the tidal response method (TRM) is reliable and safe in comparison to conventional methods of aquifer characterization. The aquifer parameter is described by the ratio of transmissivity to storage coefficient, known as hydraulic diffusivity. The observations of the tide and groundwater levels using loggers at 16 wells over the Kalpeni Atoll, Lakshadweep, India show that with distance from the coast, tidal efficiency decreases roughly exponentially and time lag increases linearly. The calculated hydraulic diffusivity (T/S) values using TRM range from 764 to 1,090,000 m^2/day. In parallel, pumping tests are conducted in six shallow dug wells to validate the TRM data. Draw down and recovery data during pumping test are influenced by the tide-induced head fluctuations. The effect complicates the interpretation of the drawdown data. After subtracting the net tidal effects from the draw down data, the calculated parameter values are observed to be closer to the estimated parameter values from TRM.

Keywords Atoll · Tidal response method (TRM) · Aquifer characterization · Pumping test · Time lag method (TLM) · Tidal efficiency method (TEM)

1 Introduction

Large population of world (about 80 %) lives along the coast and utilize local aquifers for their water supply (Bobba 1999; Chang et al. 2011). Seawater and groundwater interaction in coastal areas is one of the most important study topics for hydrology (Sherif and Singh 1990;

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Lia and Jiao 2003). Seawater-freshwater interaction studies are important because gradient flow and fluctuations cause an increase in local diffusivity and dispersivity that enhances seawater-freshwater mixing (Cirpka and Attinger 2003; Dentz and Carrera 2005). Atoll aquifers are small, fragile, lens shaped aquifers, floating over ocean where groundwater being the only source of fresh water resource because of highly permeable geological formation. Connectivity of aquifer to the sea is an important environmental challenge near coast that needs to be taken into account (Ferreira da Silva and Haie 2007). The understanding of the hydrodynamic behavior of the aquifer is necessary to delineate the impact of groundwater-seawater mixing for sustainable management of groundwater, especially in the wake of increasing population (Rejani et al. 2009). It demands a reliable characterization of hydrogeological parameters in order to develop a proper management scheme (Sreekanth and Datta 2011; Sedki and Ouazar 2011; Werner et al. 2011). Water levels of the aquifer fluctuate with the rise and fall of the tide and this property is used for hydraulic parameter estimation (Carotenuto et al. 1980; Banerjee et al. 2008).

Groundwater is only freshwater resource in the atolls and surface water is absent due to high permeability of the formation. The aquifers are exploited by the islanders for their domestic, agricultural and industrial needs. The excess use of the fragile resource due to increasing population may cause sea water intrusion. Banerjee et al. (2011) has explained the impact of pumping test based on electrical conductivity (EC) data collected during varying pumping rates over the atoll. The results show that the excess abstraction may trigger the imbalance in hydrostatic pressures of freshwater and seawater balance. As a result, instead of a sharp freshwater – seawater interface, a transitional saline zone exists which is expanding inland, towards the aquifer zone. Thus excessive pumping is not permissible in the atoll environment.

Hydraulic diffusivity is an indicator of hydrogeological parameter, particularly in fragile environments. Aquifer parameter estimation using aquifer test data have been studied by many researchers (Jacob 1940; Hantush 1956; Walton 1970; Wikramaratna 1985; Aziz and Wong 1992; Zhan et al. 2001; Chen and Chang 2002, 2003; Balkhair 2002). Pumping test is the well-known method for quantification of aquifer hydrogeological properties such as storage coefficient and transmissivity, based on draw down and recovery data analysis. But the aquifer parameters obtained by the type-curve graphical method are not very reliable for tidally influenced small island aquifer systems (Aziz and Wong 1992; Balkhair 2002). Because there is no theoretical method to analyze a tidally influenced pumping test data to extract the corresponding values of T and S from the drawdown curves (Chapuis et al. 2006). Also pumping test may cause the saltwater intrusion in sensitive atoll aquifers.

The influences of the sea tide on the mean water level have been studied by many researchers (Philip 1973; Smiles and Stokes 1976; Knight 1981; Parlange et al. 1984; Nielsen 1990). Tide induced groundwater fluctuations are common phenomena in island/coastal environment that can be viewed as large-scale aquifer tests. The groundwater head fluctuations with respect to mean sea level can be schematized as a sinusoidal function of the hydraulic head vs. time. This relation provides large-scale information on aquifer diffusivity (Alcolea et al. 2007). Variety of mathematical expressions for the response of aquifers to particular periodic boundary conditions is available (Trefry and Johnston 1998; Townley 1995; Ferris 1951; Carr and Kamp 1969). An analytical solution is obtained in the study from a one-dimensional unsteady groundwater flow model for an atoll aquifer with sinusoidal fluctuation of the tide. The analytical solution shows that the tidal efficiency decreases exponentially and the time lag increases linearly with distance from the coast line and that is supported by

observations (Banerjee et al. 2008). The aquifer property is determined based on the damping constant of the tidal efficiency and the slope of the time lag with distance on the basis of tidal measurements. The one-dimensional solution permits the determination of two simple expressions of tidal efficiency and time lag involving the aquifer diffusivity T/S. These results are used to determine the aquifer parameters using tidal measurements (Erskine 1991; Jeng and Barry 2002; Banerjee et al. 2011). The approach gives valuable information of aquifer parameter to manage the aquifer system in a cost-effective way (Schultz and Ruppel 2002). TRM is possibly the best way to determine the hydraulic diffusivity (D = T/S, where T is transmissivity, S is storage coefficient) of highly hydraulically conductive aquifer system connected with ocean. The point values of effective hydraulic diffusivity are easily obtained from the interpretation of tidal response at a borehole (Mannadiar 1977; Tripathi 1999; Jhan et al. 2003; Fkir and Razack 2003; Shih and Lin 2004; Trefry and Bekele 2004; Alcolea et al. 2007; Banerjee et al. 2008).

2 Site Descriptions

Kalpeni is one of the atolls of Lakshadweep archipelago located in west coast off India. There are 36 islands, 12 atolls, 3 reefs and 5 submerged coral banks spread over an area of 32 km^2 in the Arabian Sea (Fig. 1a). Ten of these islands are habited. The study area is one of these habited atolls with very high population density and situated in the latitude of 10°05′ N and longitude of 73°38′E, covered the area of 2.79 km^2. The island do not show any major topographical features and mostly low and flat topped with a height of less than 6 m above sea level (Fig. 2a). They are small, fragile, lens shaped aquifers and floating over the sea. All the geological and geographical conditions of the atoll lead to very limited water storage.

The archipelago is continuation of the volcanic mountain chain, where the top layer of the islands is built of coral reefs and they are believed to have been formed as the result of coral growth (Wagle and Kunte 1993; Nazeeb 1995). Geology, geomorphology and hydrogeology of the island have been described in detail by many researchers (Pandit et al. 1991; Tripathi 1999; Singh and Gupta 1999; Mallik 2001; Revichandran et al. 2001; Banerjee et al. 2011, 2012; Chattopadhyay Pallavi and Singh 2013). Coral formations (coral sand and coral lime stone) are generally porous and, surface water is completely absent. Drinking water supply depends on dug wells. The recent development has brought many of these wells equipped with solar pumps, which in turn has increased the abstraction of groundwater.

3 Methodology and Discussions

In the study, aquifer parameter is determined by conventional pumping test method as well as by TRM. Atoll aquifers are strongly hydraulically connected to the sea. Therefore, the accuracy of parameter determination depends on the acquisition of long term piezometric level data collection from observation wells. The groundwater level of the aquifer fluctuates with tidal variations. Under these conditions, observed hydraulic head during pumping is tidally influenced. It is assumed that the mean hydraulic head within the aquifer is equal everywhere with respect to sea level. The observations of the sea tide and groundwater level at 16 dug wells (with the interval of 10 min) have been made. Finally, aquifer parameters are

calculated by pumping test method with tidal correction and the corresponding results are compared with the parameters estimated by TRM.

3.1 Sea Level Fluctuation

Ocean tides are a natural high-frequency force which makes the groundwater head fluctuates periodically in coastal aquifers. The shape and amplitude of real tidal curves vary day to day, with irregularities that are not easy to handle. The tide levels for the Arabian Sea were measured by specially designed data logger fitted in the sea that avoids the interference due to sea waves. Generally, the tide of the Arabian Sea is of semi-diurnal type, varying according to the moon phases, with a period close to 12 h. 25 min. The tidal data has been collected for
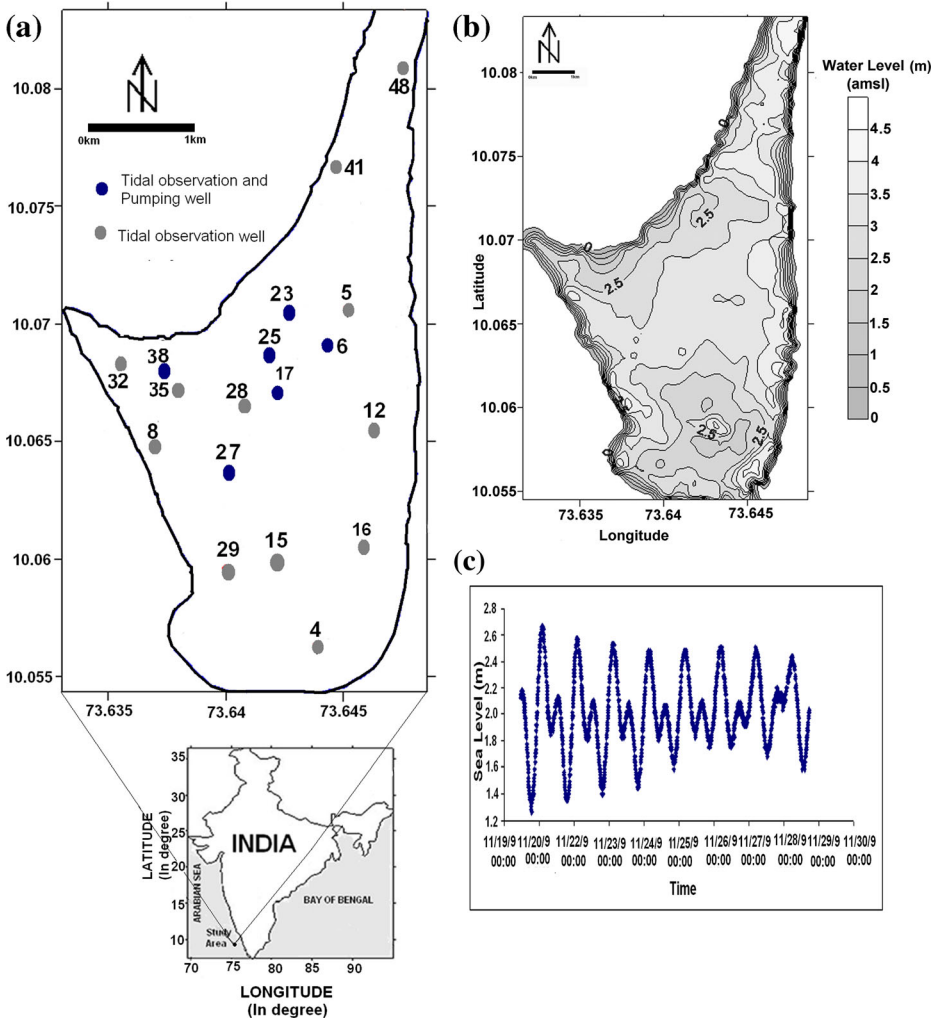

Fig 1 a Location of study area and Location of dug wells over atoll. b Yearly averaged water level data. c Time series tidal fluctuation data
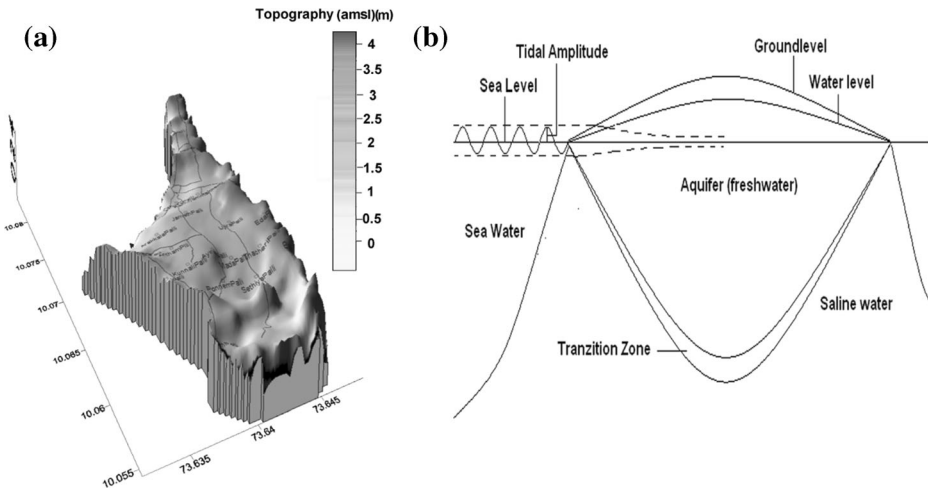
Fig 2 **a** Topographical map. **b** Hydraulic connectivity of aquifer to the sea

9 days (20 to 29November 2009). The maximum tide was on the date of 20 November 2009 (Fig. 1c).

3.2 Pumping Test in Tidally Forced Aquifer

Conventional hydrological investigations often rely upon pumping tests, which place an artificial stress on the aquifer for a finite duration of time (Chen and Jiao 1999). This method is now in wide spread use for studying aquifers that are bounded by various boundary conditions. One of the challenges in the study is that the pumping test data of the atoll aquifers are strongly influenced by the tidal effect and interpretations are not very accurate to derive hydraulic parameters (Barlow et al. 1996; Trefry and Johnston 1998). Therefore, correction of draw down data for tidal influence is important. Numbers of researchers have used different correction techniques for tidal fluctuation to analyze the water table data in coastal environment (Carr 1969; Singh and Gupta 1991). In the study, pumping time is selected very small to ignore the negative impact of abstraction and also to avoid the tidal influence.

3.2.1 Tidal Correction

The least square technique is used to determine the best fit recovery data after the pumping. Perturbation caused by sea tides propagates from the coastline to the aquifer, where the piezometric level is an oscillating function. The magnitude of water-level fluctuation of the observation wells is largely dependent upon the distance to a large tidal body. The mean variation of the sea level was assumed sinusoidal with an amplitude h_0 and a constant period t_0. The rapid fluctuations of mean sea level, due to tides, decreases to propagate within the aquifer due to damping effects. The problem is solved by analogy with heat conduction in a semi-infinite solid submitted to cyclic variations of temperature (Ferris 1951). The peak in the tide and the corresponding peak in the hydraulic head is denoted by time lag (τ) and is linearly increased with the distance of wells from the sea. Time lag (τ) is calculated from the

water level time series data of sea and in each wells. Least square techniques are used to calculate the best fit time lags and attenuation factors for the tidal fluctuations in each monitoring well.

$$f(a, \tau) = \sum_{n=0}^{n} (FC \, of \, sea(t_n) - FC \, of \, well(t_n - \tau)/a)^2 \tag{1}$$

where in Eq. (1), α is attenuation factor. FC is the fluctuation component that is calculated from the time series data of sea and water level from the observation wells, respectively. Summation is performed over all the measured water levels. The calculated values of attenuation factor and time lag are shown in Table 1. These best-fit tidal parameters are used to generate tidal correction functions for the monitoring wells. The estimated tidal fluctuation component

$$f_i(t) = a_i \times FC \, of \, sea(t - \tau_i) \tag{2}$$

where in Eq. (2), the well number is denoted by 'i'. The correction factor ($f_i(t)$) is subtracted from the water level data recorded during recovery to correct the observed data of pumping test for tidally influence wells (Fig. 3). The results demonstrate a step function as the sensitivity of the logger used was in the scale of 0.01 m and so we have used a trend line fitting the average values.

3.2.2 Pumping Test

Six short term constant rate pumping tests are carried out using existing fully penetrating dug wells (well no.6, 17, 23, 25, 27 and 38) over the different locations of the atoll in order to provide information on the short term water table response of the aquifer (Fig. 1a). Water levels in the observation wells are logged by combination of automatic means. Automatic water level probes enabled water levels to be logged at minimum 30 s to maximum 2 min intervals. Average water level distribution over the area is shown in the Fig. 1b. The discharge rate from these pumping wells varies from 18 to 20 m^3/hr. The duration of the tests were kept 3 to 10 min depending on the drawdown observed in the observation wells. The linear equation for 1D groundwater movement is used:

$$\frac{\partial^2 s}{\partial r^2} + \frac{1}{r} \frac{\partial s}{\partial r} = \frac{S}{T} \frac{\partial s}{\partial t} \tag{3}$$

where in Eq. (3), r is the radial distance to the pumping well that fully penetrates the aquifer. Initial drawdown in the well is zero, $s(0)=0$. Initial drawdown in the aquifer is zero, $s(r,0)=0$.

Table 1 Time lag and attenuation factor calculated by least square method

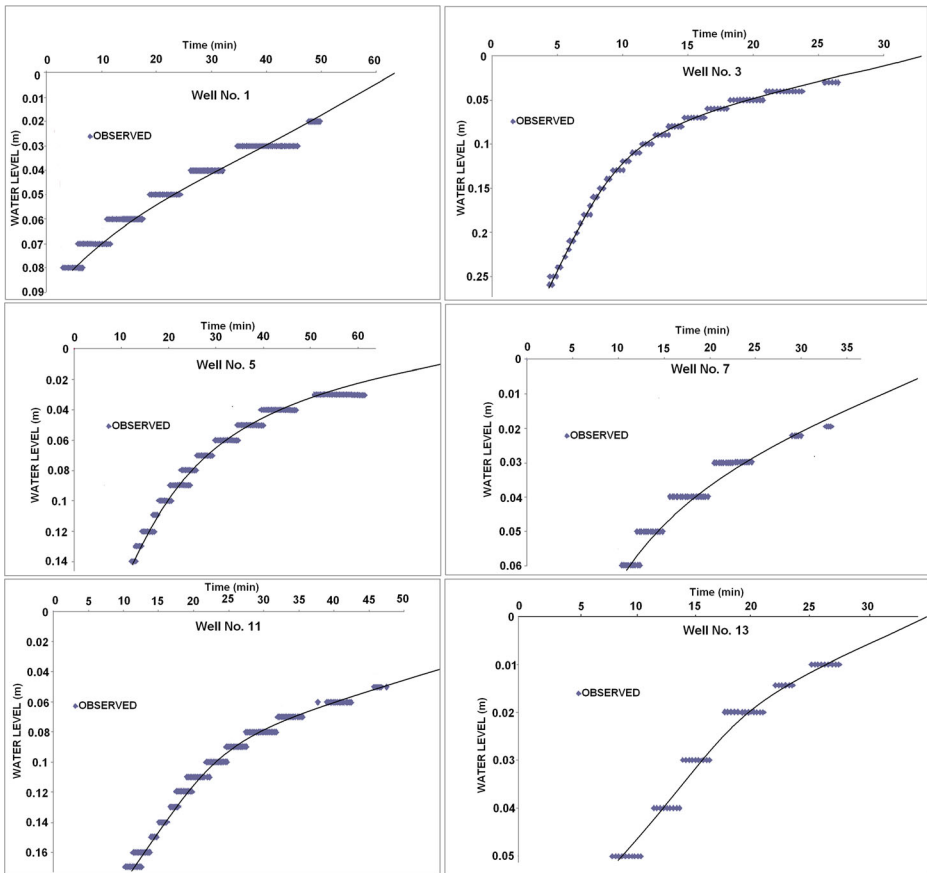| S.N.	Well No.	Shortest distance from coast line (m)	α	τ
1	6	347.3	0.55	1.48
2	17	517.5	0.67	2.12
3	23	218.7	0.27	1.43
4	25	402.1	0.09	2.98
5	27	466.1	9.47E-05	3.08
6	38	117.4	0.51	2.13

Fig 3 Correction of pumping test data influenced by tidal effect

The equation depends upon the boundary conditions. At any time the drawdown in the aquifer at the face of the well is equal to that in the well, $s(r_w,0)=s_w(t)$ and at large distance drawdown is zero at a time t $s(\infty,t)=0$.

3.2.3 Type Curves Analysis

Pumping test involves the measurement of the fall (draw down) and rise (recovery) of water level with respect to time. The change in water level with time is then interpreted to determine the aquifer parameter. Water level of the wells is influenced with the tidal force and recovery data could not establish the steady state condition. Therefore tidally corrected data are used for the curve matching step.

In the present study, the simpler Theis method for isotropic confined aquifer is used (Kruseman and Ridder 1994). The approach considers both the data phase and solves groundwater flow equation using finite difference method. The computed data is compared with the observed data. The aquifer parameters are progressively modified in an iterative manner until satisfactory match is achieved between the observed and calculated time drawdown/recovery. The best fit-time drawdown/ recovery curve gives the representative aquifer parameters.

Table 2 Aquifer characterization by pumping test method

S.N.	Well No.	Pumping Time (min)	Recovery Time (min)	Draw down (m)	Q (mc/day)	T (m²/day)	S	DC (m²/day)
1	6	7.25	16	0.05	22.94	185	0.0001	1.85E+06
2	17	3.5	44	0.08	62.74	45	0.001	4.50E+04
3	23	4.5	22.5	0.26	122.7	154	0.0009	1.71E+05
4	25	10.5	23.5	0.06	16.24	125	0.008	1.56E+05
5	27	12	49	0.14	21.74	50	0.006	8.33E+03
6	38	11	35	0.17	29.25	58	0.0003	1.93E+05

Q Discharge, *T* Transmissivity, *S* Storage Coefficient, *DC* Diffusion Coefficient (T/S)

3.3 Tidal Response Model

An approximate analytical solution is developed based on a perturbation method to investigate the mean water table in the island region near the coastline (Jacob 1950; Todd 1980; Nielsen 1990). Complete analytical solutions describing tidal groundwater wave propagation in coastal
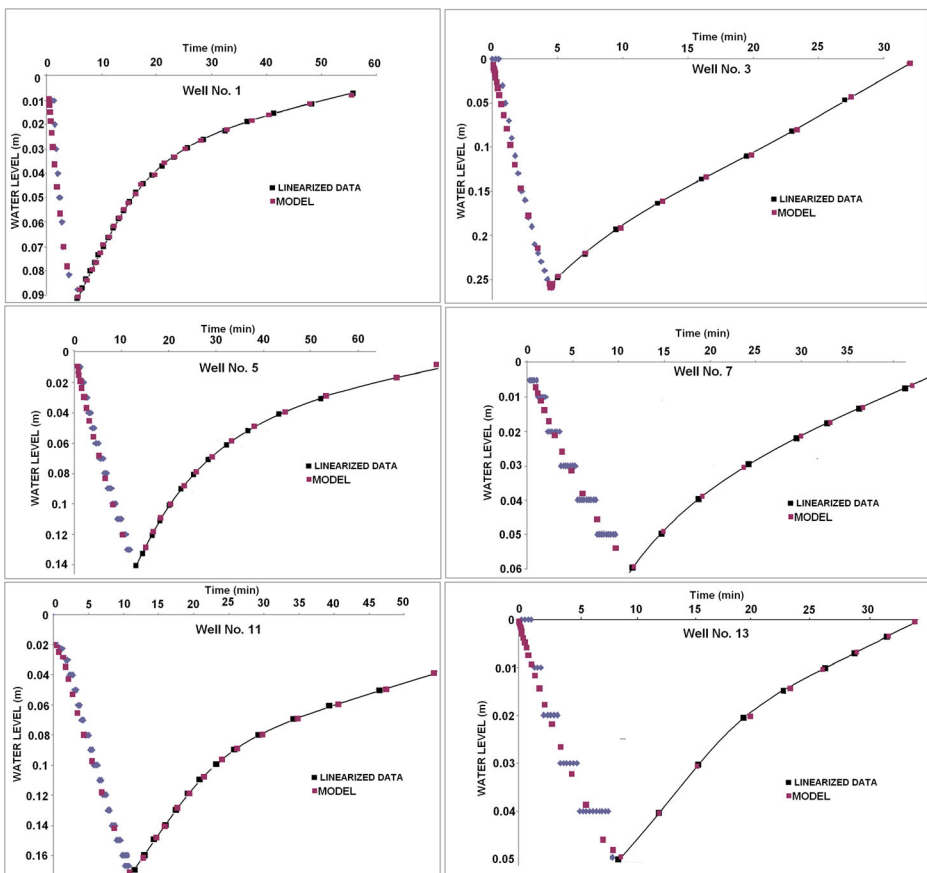

Fig 4 Corrected draw down and recovery data used for curve matching
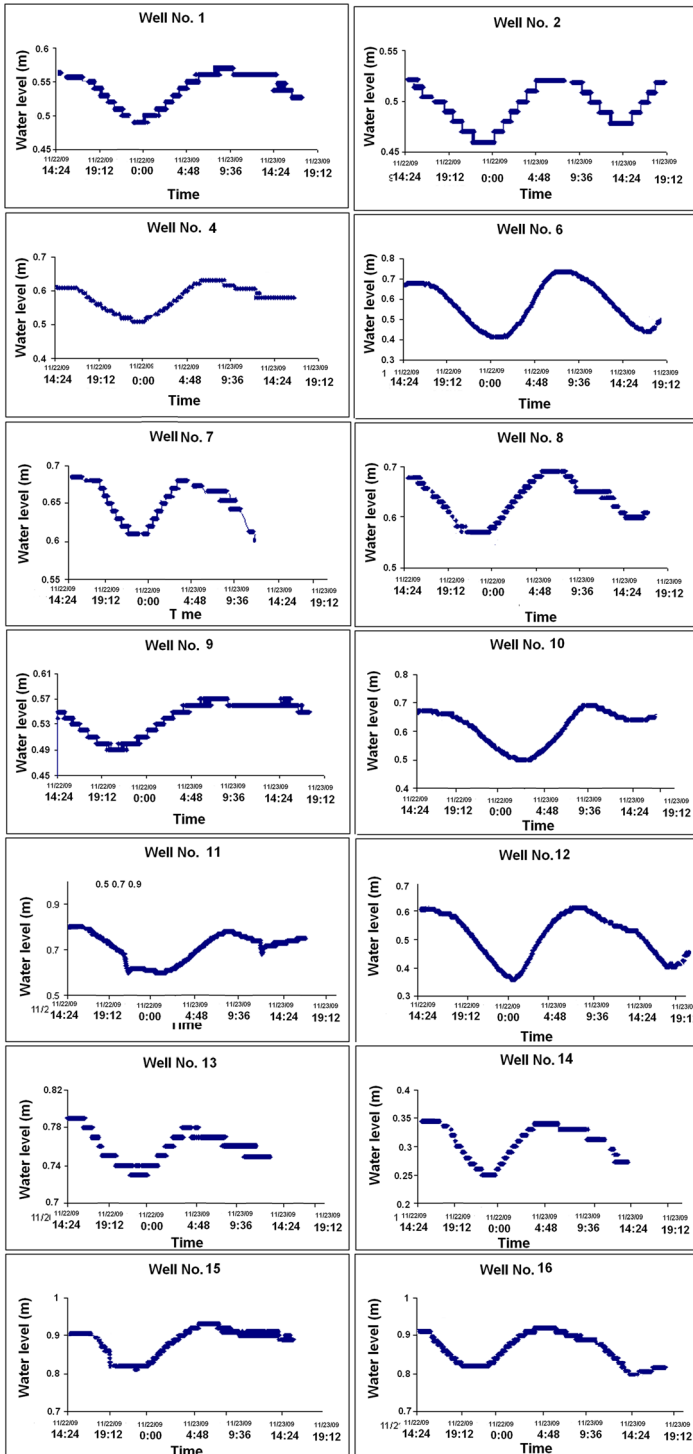
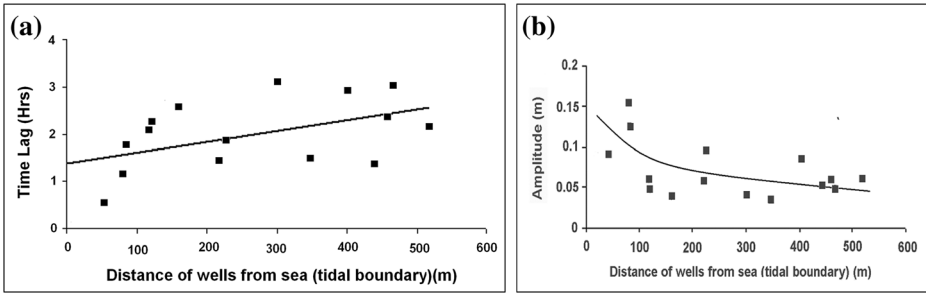Fig 5 Water level fluctuation data from the dug wells

Fig 6 **a** Relation of time lag with distance from sea. **b** Relation of tidal efficiency factor with distance from sea

aquifer systems to investigate the tide induced groundwater level fluctuations (Li and Jiao 2001 and 2002).

Tidal response model is supposed to be a one dimensional flow from sea to aquifer (Fig. 2b). The origin of the x axis is at the intersection of the mean sea surface and beach face. The x axis is positive towards the land. It is considered that the aquifer material is homogeneous and isotopic. The mean variation of the sea level is assumed sinusoidal with an amplitude h_0 and a constant period t_0. The flow velocity in the confined aquifer is essentially horizontal. Thus the one-dimensional Darcy flow equation is applied to explain the flow in the aquifer bounded by free water body that fluctuates periodically and the flow equation is expressed as:

$$\frac{\partial^2 h(x,t)}{\partial x^2} - \frac{S}{T}\frac{\partial h(x,t)}{\partial t} = 0 \qquad (4)$$

where in Eq. (4), h=groundwater level from its mean at time t [L]; x=distance inland from the coast [L]; S=aquifer storativity (dimensionless); T=aquifer transmissivity [L^2/T]; and t=Time [T].

Table 3 Diffusivity value calculated by TRM

S.N.	Well No.	Distance from coast line (m)	Time Lag (minutes)	DC (m²/day): TEM	DC (m²/day): TLM
1	4	119.963	2.27	7.64E+02	1.15E+03
2	5	225.785	1.85	8.39E+03	1.76E+04
3	6	347.32	1.48	1.09E+06	3.80E+06
4	8	52.098	1.05	8.54E+03	1.07E+04
5	15	441.097	1.25	8.28E+02	1.41E+03
6	17	517.519	2.12	5.30E+04	7.89E+04
7	23	218.701	1.43	8.68E+04	2.25E+05
8	25	402.067	2.98	9.11E+04	1.81E+05
9	27	466.108	3.08	8.05E+03	1.66E+04
10	28	457.973	2.32	9.51E+03	1.94E+04
11	29	160.102	2.6	8.02E+02	1.64E+03
12	32	124.504	124.504	1.72E+04	2.42E+04
13	35	301.229	301.229	7.74E+03	1.25E+04
14	38	117.439	2.13	9.95E+04	3.73E+05
15	41	84.006	1.82	6.07E+02	1.24E+03
16	48	79.884	1.13	8.99E+02	2.58E+03

DC Diffusion Coefficient, *TEM* Tidal Efficiency Method, *TLM* Time Lag Method

Finally, the contact between the sea and the aquifer is a vertical plane. Thus, the initial and boundary conditions are expressed as

$$h(0,t) = h_0 \sin \omega t \; at \, x = 0 \quad and \quad h = 0 \; at \; x = \infty$$

The hydraulic head (h) at a distance x is measured from the contact sea-aquifer intersection (x=0). Angular frequency is denoted by $\omega \left(\frac{2\pi}{t_0}\right) \left(rad \; second^{-1}\right)$ and t_0 is tidal period [T]. Amplitude of the tidal component is h_0 [L] (at x=0). The tide has no effect far inland as x approaches infinity ($h(\infty,t)$=0).

Considering all the geometric conditions and the boundary conditions, the solution for groundwater flow is

$$h(x,t) = h_0 e^{-x\sqrt{\frac{\pi S}{t_0 T}}} \sin\left(\frac{2\pi t}{t_0} - x\sqrt{\frac{\pi S}{T t_0}}\right) \tag{5}$$

The Eq. (5) shows that the amplitude of piezometric fluctuations at a distance x from the shore line decreases with x, and depends on the ratio S/T, whereas the time lag depends on both x and S/T.

The above solution shows that sinusoidal fluctuations will propagate along the aquifer with a linearly increasing time lag (τ) and exponentially decreasing efficiency factor (η).

$$\tau = x\sqrt{\frac{t_0 S}{4\pi T}} \tag{6}$$

$$\eta = \frac{h}{h_0} = \exp\left(-x\sqrt{\pi S / t_0 T}\right) \tag{7}$$

Aquifer parameter values (T/S) are calculated using the above two relations (time lag and tidal efficiency factor).

4 Result and Conclusion

TRM, TLM and conventional pumping test method with tidal correction are used to estimate the hydraulic parameter of the atoll aquifer. Pumping tests are conducted in limited numbers of wells to restrict the saline intrusion. Hydrogeological parameters obtained by pumping test method from six existing dug wells are presented in Table 2. After subtracting the net tidal effect from the draw down and recovery data, the pumping test method becomes amenable for the standard analysis (Fig. 4).

Sinusoidal fluctuations are displayed by data loggers fitted in 14 dug wells over the atoll and measured at 15 min intervals (Fig. 5). Tidal fluctuation causes significant fluctuations in the piezometric level of aquifer. The time lags and tidal efficiency factors are plotted against the distance of the wells from the ocean shown in Fig. 6a and b respectively. The plots show that the calculated time lag values are linearly increasing and the calculated efficiency factors are exponentially decreasing with distance of wells from the sea. While efficiency factors and time lag values are calculated for spatially isotropic and one dimensional function, tidal influence from any other direction has the potential to influence these estimation. These observations have drawn the clear picture of tidal effect over groundwater head. This result of time lag and tidal efficiency factor show that the geological formation of the atoll aquifer is

nearly homogeneous and tide induced pressure in the direction of shortest distance between well and coastline significantly dominates the head fluctuation patterns through porous medium (coral sand).

The hydraulic diffusivity values calculated by time lag method andtidal efficiency method are reported in Table 3. The differences among the calculated results obtained from the three methods (TRM, TLM, and PTM) are due to the uncertainty in hydraulic head measurements, spatial variations in hydraulic parameters, delayed physical effects (not considered in the linear differential equations), geometric effects, and also due to the fact that the shape and amplitude of real tidal curves varies day to day, with irregularities.

The coral atolls aquifers are the only fresh water resource and play a major social and economic role in the tiny islands. The characterization of the aquifer system is vital to manage fresh water resources in the area. Growing demands for freshwater resources necessitates an advanced sustainable groundwater management scheme. It demands a reliable and safe aquifer characterization method. Atolls are the best example to apply the TRM to characterize the small aquifer system with limited freshwater resource and homogeneous hydro-geologic conditions where pumping test method (PTM) is not advisable. Tidal variations may influence water levels in observation wells during the pumping test thereby adding noise to observed water level before pumping and after recovery which in turn results in incorrect hydrogeological parameter values.

It is relatively complex to estimate accurately the linearly increasing time lag (τ) values of head fluctuations than efficiency factor (η). Here, it is considered that the induced flow is horizontal from the coastline to the selected well in the shortest direction and aquifer structure will not influence the mathematical model. The shortest distance along x-axis is positive landward and perpendicular to coastline, but time lag value could be influenced by other complex parameters particularly in central part of the aquifer where the tidal influence could be considerable from other directions along with the shortest one. TEM mainly depends on amplitude of fluctuating head and sea tide. It is comparatively simple and accurate to calculate the amplitude of water head and tide. Therefore, as an alternative of PTM, it is suggested that the hydrogeological parameters analysis by tidal response method (TEM) offers a cost-effective and an environment friendly approach to assess aquifer characterization. The tidal method is characterized by relatively easy data acquisition and processing operations. The process to extract the aquifer parameters from the analysis of head fluctuations (under tidal influence exclusively) are more economical than those obtained using a pumping test.

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