EFFICACY OF DIRECT TIDAL METHODS FOR IDENTIFYING HYDRAULIC PARAMETERS OF COASTAL AQUIFERS

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ABSTRACT: The analysis of tidal effects on groundwater systems plays an important role in coastal aquifer management. In this study, the efficacy of 'tidal efficiency' and 'time lag' models, which are also known as direct tidal methods, for determining hydraulic diffusivities has been assessed by using tide-aquifer interaction data from unconfined and confined coastal aquifers. The effect of spring and neap tidal data on aquifer parameter estimates was also analyzed for the unconfined aquifer. The hourly tide-aquifer interaction data for two unconfined sites of Konan groundwater basin, Japan and three confined sites of Dridrate groundwater basin, Morocco were used in this study. For all the five sites under study, the aquifer hydraulic diffusivities based on the 'time lag' model were found to be much larger (2 to 14 fold for the unconfined sites and 5 to 8 fold for the confined sites) than those based on the 'tidal efficiency' model. It is concluded that the 'tidal efficiency' model is superior to the 'time lag' model for both unconfined and confined aquifers, the numerically computed time lags are more reliable than the time lags obtained by graphical method, and that the spring and neap tidal data have a significant influence on the hydraulic diffusivity estimates.

Keywords: Direct tidal method, Tidal efficiency model, Time lag model, Hydraulic diffusivity, Spring and Neap tides, Coastal aquifer.

1. INTRODUCTION

The cyclic rise and fall of seawater level in the ocean due to tides result in cyclic fluctuations of groundwater levels in adjacent aquifers. Such tide-induced groundwater level fluctuations are a natural and common phenomenon in coastal aquifer systems. These periodic groundwater fluctuations occur when propagating pressure waves, caused by fluctuating hydraulic head at the submarine outcrop of confined or unconfined aquifer systems or by loading and unloading on confined layers extending under the ocean floor, travel inland from the surface-water body (Ferris, 1951; Todd, 1980). In confined aquifer systems, the pressure wave is mostly generated due to changes in fluid pressure, whereas in unconfined aquifer systems it is generated due to changes in storage caused by dewatering and filling of pores. As these periodic fluctuations propagate inland, their amplitude is attenuated and phase-shifts occur. A damping distance for the tidal water table fluctuations in an unconfined aquifer system is several hundred meters, while the tidal influence on a confined aquifer system can extend landward by several thousand meters (Lanyon et al., 1982). In both cases, the tidal fluctuations enhance the exchange between the aquifer and the ocean, and thereby considerably affect flow and transport processes in the aquifer system (Li et al., 1999; Trefry, 1999).

Adequate knowledge of the hydraulic properties of aquifer systems such as transmissivity or hydraulic conductivity, storage coefficient and/or hydraulic diffusivity is essential for all the studies pertaining to groundwater quantity and quality, including the simulation modeling of subsurface flow and transport processes. There are several methods for determining the hydraulic parameters of aquifer systems such as pumping-test or slug-test data analysis, numerical modeling, floodwave-response technique and tidal response technique (e.g., Ferris, 1951; Carr and van Der Kamp, 1969; Erskine, 1991; Pandit et al., 1991; Millham and Howes, 1995; Shih, 1999; Fakir and Razak, 2003; Trefry and Bekele, 2004), among others. Out of these methods, the pumping-test data analysis is very popular and is deemed as the standard method to date. However, the pumping test is very costly, time-consuming and the conventional analysis of pumping-test data is cumbersome and quite subjective. In addition, pumping tests are not always advisable for coastal aquifer systems because they may accelerate seawater intrusion and/or aggravate intrusion problems. Under such circumstances, the relationship describing the aquifer response to tides (i.e., tidal response technique) could be employed for estimating hydraulic parameters of coastal aquifer systems, which is relatively inexpensive also (Millham and Howes, 1995; Trefry and Johnston, 1998; Trefry and Bekele, 2004).

Tide-aquifer interaction technique (also called ‘tidal response technique’ or simply ‘tidal method’) is a method of analyzing groundwater-level fluctuations in a well or piezometer in response to changes in the sea level caused by tides. Thus, this technique requires time series of tide levels and the corresponding time series of groundwater levels at the sites affected by tidal fluctuations. This technique can be used to determine the hydraulic characteristics of coastal aquifer systems by inverse modeling or by direct calculation using ‘time lag’ and ‘tidal efficiency’ models, which may avoid the need of pumping tests. However, the use of this technique is very limited possibly due to the lack of adequate field data and/or awareness about tide-aquifer interaction technique. In this study, the tide-aquifer interaction data from both unconfined and confined coastal aquifer systems have been used to evaluate the efficacy of direct tidal methods (‘tidal efficiency’ and ‘time lag’ methods) for identifying aquifer parameters.

2. OVERVIEW OF STUDY SITES

In the present study, two tide-affected sites I-2 (well depth = 25 m and screen length = 1 to 25 m) and H-5 (well depth = 15 m and screen length = 1.12 to 15 m) were selected from the Konan groundwater basin located in Kochi Prefecture, Japan (Jha et al., 1999) and three sites 1272/34, 1525/34, and 235/26 were selected from the Dridrate groundwater basin located in Qualidia Sahel, Morocco (Fakir and Razack, 2003). Sites I-2 and H-5 are located at 350 and 500 m from the Pacific Ocean coast, respectively (Fig. 1) and the sites 1272/34, 1525/34, and 235/26 are located respectively at 2800, 2650 and 400 m from the Atlantic Ocean coast (Fig. 2).

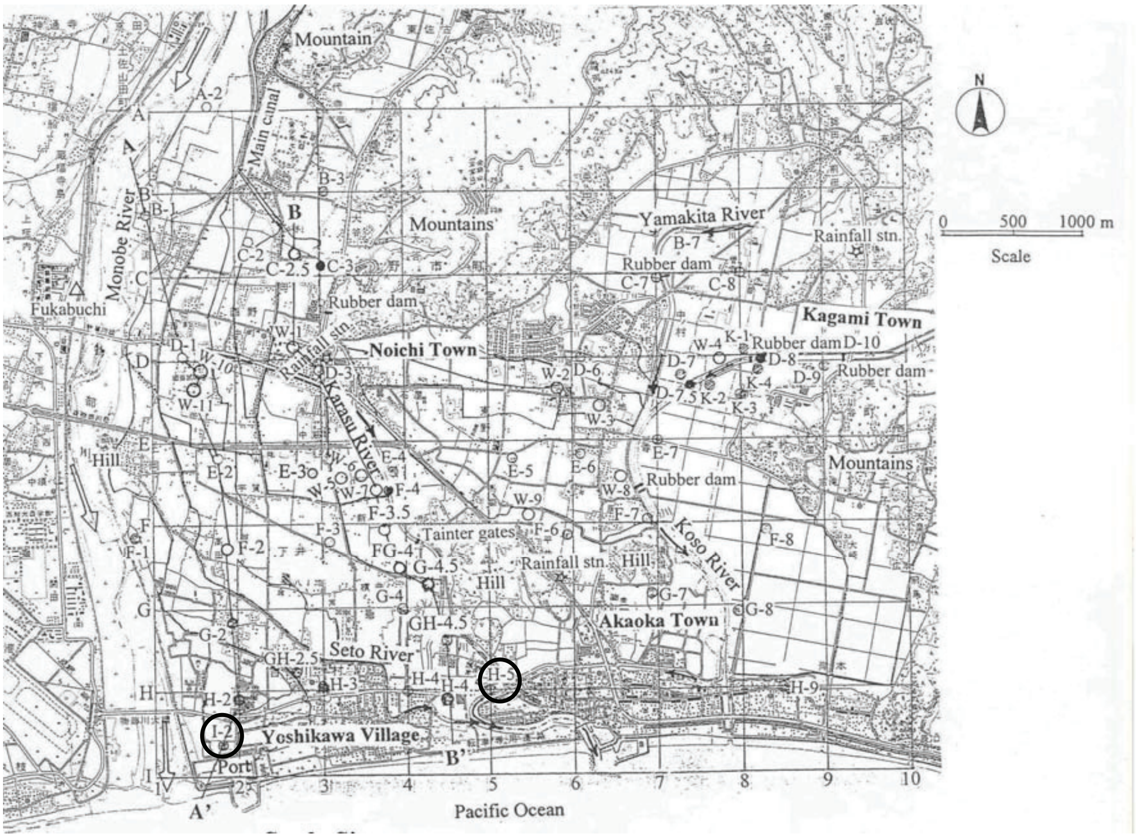

Fig. 1. Map of the Konan groundwater basin.

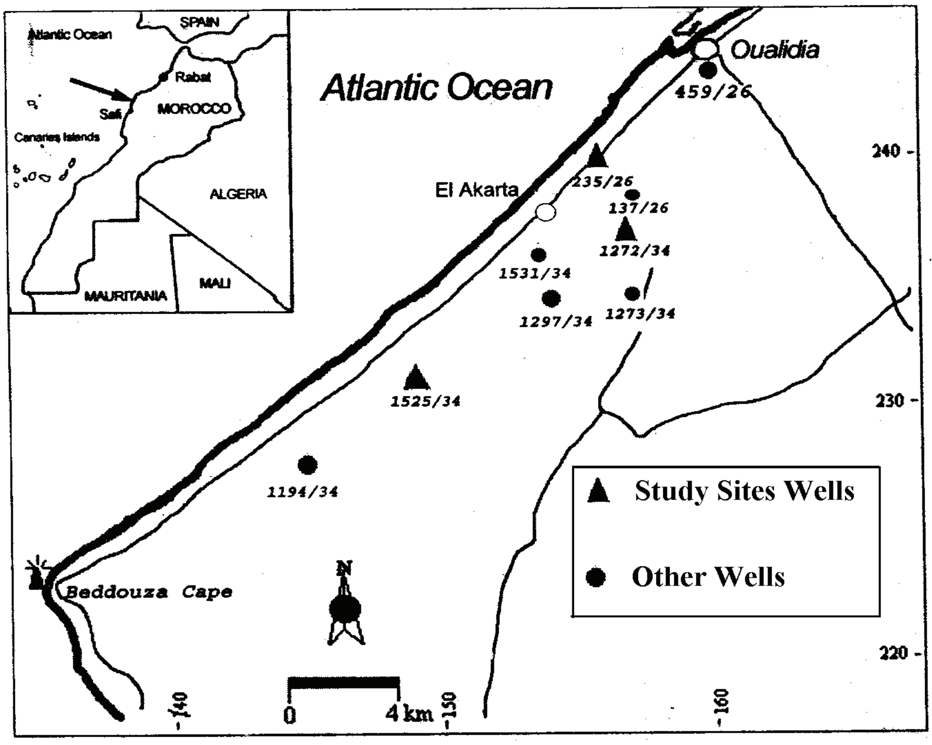

Fig. 2. Map of the Dridrate groundwater basin (after Fakir and Razack, 2003).

The Konan groundwater basin is bounded by the Monobe River (perennial) in the west and the Koso River (intermittent) in the east as shown in Fig. 1. Mountains demarcate the northern boundary and the southern boundary is demarcated by the Pacific Ocean. Cold and dry winters, and warm and humid summers characterize the regional climate. The minimum ambient temperature is -4 ^{o}C in February and maximum is 37 ^{o}C in August. The mean annual rainfall and evapotranspiration in the region are about 2600 mm and 800 mm, respectively. More than 50% of the total rainfall occurs during June through September. Unconfined aquifers comprising alluvial sand and gravel and/or diluvial silty sand and gravel are predominant over the Konan basin. Further details of the hydrogeology of Konan groundwater basin can be found in Jha et al. (1999).

The Dridrate groundwater basin (Fig. 2) of Morocco is located along the Atlantic Ocean coast and is composed of sandy and dolomitic limestones, which is separated from Plioquaternary terrains by overlying reddish sandy and argillaceous deposits. Therefore, the Dridrate aquifer is generally considered as confined underneath the red sandy clays (Fakir and Razack, 2003). These red clays constitute the basement of the Plioquaternary sediments composed of calcareous sandstones. The details about the Dridrate aquifer can be found in Fakir and Razack (2003).

3. METHODOLOGY

3.1 Tide-Aquifer Interaction Datasets

Hydraulic diffusivities at the five selected sites (two unconfined and three confined) were determined by using the ‘tidal efficiency’ and ‘time lag’ models. The datasets used for this analysis were: (a) three sets of hourly tide-aquifer interaction data at the unconfined Sites I-2 and H-5 of the Konan aquifer corresponding to the normal tidal event (1-3 March 2000), spring tidal event (21-23 January 2000), and neap tidal event (14-16 September 2000); and (b) one dataset comprising half-hourly time series of tide and groundwater levels for three lunar days (i.e., 74 hours and 30 min) at the confined Sites 1272/34, 1525/34 and 235/26 of the Dridrate aquifer; these data correspond to a normal tidal event.

3.2 Tidal Efficiency Model

Tidal efficiency (TE) is defined as the ratio of the amplitude of groundwater fluctuations in the coastal aquifer to the amplitude of tidal fluctuations at the aquifer-sea boundary. The tidal efficiency model describes the spatial dependence of tidal efficiency on the distance to the shoreline, and is mathematically expressed as (Ferris, 1951; Todd, 1980):

$$TE = \exp(-x/x_o) \tag{1}$$

Where,

$$x_o = [T\ t_o/(\pi S)]^{1/2} \tag{2}$$

and is called 'reference distance' [L], x = distance of observation well from the seashore [L], t_o = tidal period [T], T = aquifer transmissivity [L^2/T), and S = aquifer storage coefficient. It is worth to mention that Eqn. (1) is also known as 'tidal efficiency factor'.

It is obvious from Eqn. (1) that the tidal efficiency decreases exponentially with increasing distance from the seashore. From Eqn. (2), the expression for hydraulic diffusivity (D) can be written as:

$$D = \pi\, x_o^2 / t_o \tag{3}$$

Firstly, the tidal efficiency at each site was determined by the ratio of the standard deviation of groundwater levels at the site to that of tide levels, because using all the data has advantages over the peak data for computing tidal efficiency (Erskine, 1991; Jha et al., 2003). Then, the reference distance (x_o) based on tidal efficiency was computed for each site using Eqn. (1). Finally, given the reference distance and the tidal period, hydraulic diffusivities based on the tidal efficiency model were calculated at all the five sites using Eqn. (3).

3.3 Time Lag Model

The time lag (t_{lag}) is defined as an inverse measure of the velocity of tidal wave propagation as it moves through the aquifer. In other words, it is the time difference between a peak or trough of the tidal hydrograph and a peak or trough of the corresponding groundwater hydrograph. The time lag model is expressed as (Ferris, 1951; Todd, 1980):

$$t_{lag} = x\, t_o/(2\pi x_o) \tag{4}$$

Where t_{lag} = time lag [T], and the remaining symbols have the same meaning as defined earlier. Clearly, the time lag increases linearly with increasing distance from the seashore. In this study, the time lag was computed both graphically and numerically as described below.

3.4 Computation of Time Lag by Graphical Method

In this case, the time lag was estimated by simply finding out the difference between the time to peak tide-level and time to peak groundwater-level. It was accomplished using the combined plots of 'tide level versus time' and 'groundwater level versus time' on the arithmetic scale. This method of time lag computation is straightforward, and hence is most likely to be used by researchers or practicing hydrologists/hydrogeologists.

3.5 Computation of Time Lag by Numerical Method

The observed time series (hourly for the Konan aquifer and half-hourly for the Dridrate aquifer) of groundwater and tidal readings were interpolated using the radial basis function of artificial neural network (Haykin, 2002) with the help of MATLAB software. First of all, observed groundwater levels or tide levels were used to train the artificial neural network.

The desired simulated outputs were obtained at the number of hidden neurons ranging from 9 to 11 for the datasets under study. Then, at a particular neuron number, the input was set for the desired number of interpolation and the corresponding simulated output (i.e., interpolated time series of groundwater level or tide level) was obtained. Thereafter, the interpolated groundwater levels were shifted in elevation to have the same mean value as that of the interpolated tide levels using the following expression (Erskine, 1991):

$$h'(t) = H_{mean} + [h(t) - h_{mean}]/TE \tag{5}$$

Where $h'(t)$ = shifted groundwater level at time t [L], H_{mean}= mean tide level [L], $h(t)$ = observed groundwater level at time t [L], h_{mean}= mean groundwater level [L], and TE = tidal efficiency (fraction).

Using the time series of shifted and amplified groundwater levels ($h'(t)$) and the time series of tide levels, the time lag (t_{lag}) was computed by least-square technique with the following objective function:

$$\mathrm{Min} \sum [h'(t) - H(t - t_{lag})]^2 \tag{6}$$

A computer program in ‘C’ language was developed to calculate time lag numerically.

Using the time lags obtained by the above-mentioned two methods and the distance of observation well from the seashore (x), the reference distance (x_o) based on time lag was computed from Eqn. (4). Then, aquifer hydraulic diffusivities based on the time lag model were computed for all the five sites using Eqn. (3).

Thus, three estimates of aquifer hydraulic diffusivity based on the tidal efficiency and time lag models were obtained at each site without any knowledge about the aquifer transmissivity (T) or aquifer storage coefficient (S).

4. RESULTS AND DISCUSSION

4.1 Hydraulic Diffusivity of the Unconfined Aquifer

The tidal efficiency and time lag at the two unconfined sites for three datasets corresponding to different tidal events are presented in Table 1. It is obvious from this table that the tidal efficiency is higher and time lag is lower for Site H-5 which is farther from the seashore compared to Site I-2 (nearer to the seashore). Although this finding is contrary to the theory [Eqns. (1) and (4)], it is reasonable for this site because of the fact that the tidal influence at Site H-5 is aggravated due to tidal wave propagation through the lower reach of Koso River (Jha et al., 2003). Also, whenever the time lag is different from 1 hour (time interval for the tide and groundwater readings) or its some multiple, the numerical computation yields more accurate time lag values (henceforth called “numerical time lag”) than those by graphical computation (henceforth called “graphical time lag”).

Table 1. Summary of tidal efficiency and time lag at the two unconfined sites

Description	Tidal Efficiency and Time Lag at Sites I-2 and H-5 for Different Tidal Events						Mean ± S.D.	
	Normal Tide		Spring Tide		Neap Tide			
	I-2 (350 m)	H-5 (500 m)	I-2 (350 m)	H-5 (500 m)	I-2 (350 m)	H-5 (500 m)	I-2 (350 m)	H-5 (500 m)
Tidal Efficiency (%)	23.9	41.3	36.3	38.6	18.4	19.3	26.2±9.2	33.1±11.9
Graphically Computed Time Lag (h)	3.0	1.0	1.0	1.0	2.0	1.0	2 .0±1.0	1.0±0
Numerically Computed Time Lag (h)	2.8	1.2	1.0	0.5	2.6	1.7	2.1±0.9	1.1±0.6

Note: Bracketed figures below the site-name show the distance of the site from the seashore; S.D. = Standard deviation.

The hydraulic diffusivities obtained by the tidal efficiency and time lag models at the unconfined sites for three different tidal events are summarized in Table 2, while Table 3 presents the mean and standard deviation (S.D.) of the datasets used in this study. The hydraulic diffusivities based on the tidal efficiency model were found to vary from 3 to 8.4 m^2/s for Site I-2 and from 6.5 to 22.5 m^2/s for Site H-5 with a relatively low standard deviation (S.D.), and these figures based on the time lag model were found to range from 3.7 to 33.6 m^2/s for Site I-2 and from 23.7 to 274.4 m^2/s for Site H-5 with a large S.D. (barring Site H-5 for graphical time lag). It should be noted that the hydraulic diffusivities based on the time lag model are consistently greater than those based on the tidal efficiency model at both the sites for all the datasets, except at Site I-2 for the normal tidal event. This finding is in agreement with that obtained by earlier researchers such as Ferris (1951), Erskine (1991), Serfes (1991), Trefry and Johnston (1998), Schultz and Ruppel (2002), Fakir and Razack (2003), Jha et al. (2003), and Trefry and Bekele (2004). This difference in hydraulic diffusivity estimates based on the 'time lag' and 'tidal efficiency' models were often attributed to the presence of a phreatic surface in unconfined aquifer systems, depth-dependent storage coefficient, or spatial heterogeneity. It is also obvious from Table 2 that the hydraulic diffusivities based on the numerical time lag are generally lower than those based on the graphical time lag for both the sites, but they are also high compared to those based on the tidal efficiency model. Since the numerically computed time lag is more accurate than the graphically computed time lag for the hourly tide-aquifer interaction data, the use of former is recommended for obtaining better estimates of hydraulic diffusivity. However, as far as the estimation of aquifer parameters is concerned, the use of 'time lag' model should be restricted to preliminary studies only.

Moreover, in order to explore the impact of spring and neap tidal data on the parameter estimate, the spring tidal dataset (21-23 January 2000) and the neap tidal dataset (14-16 September 2000) were also used for calculating hydraulic diffusivities at the unconfined Sites

Table 2. Hydraulic diffusivities by direct methods at the two unconfined sites

Method	Hydraulic Diffusivities (m^2/s) at Sites I-2 and H-5 for Different Tidal Events						Mean Diffusivity ± S.D. (m^2/s)	
	Normal Tide		Spring Tide		Neap Tide			
	I-2 (350 m)	H-5 (500 m)	I-2 (350 m)	H-5 (500 m)	I-2 (350 m)	H-5 (500 m)	I-2 (350 m)	H-5 (500 m)
Tidal Efficiency	4.2	22.5	8.4	19.4	3.0	6.5	5.2±2.3	16.1±6.9
Graphical Time Lag (h)	3.7	68.6	33.6	68.6	8.4	68.6	15.2±13.1	68.6±0
Numerical Time Lag (h)	4.3	47.6	33.6	274.4	5.0	23.7	14.3±13.7	115.2±112.9

Note: Bracketed figures below the site-name show the distance of the site from the seashore; S.D. = Standard deviation.

Table 3. The mean and variance of the tidal data and the groundwater level data used

<table>
<tr><th rowspan="3">Dataset</th><th colspan="4">Unconfined Sites</th></tr>
<tr><th rowspan="2">Mean (S.D.) of the Tidal Data (m MSL)</th><th colspan="3">Mean (S.D.) of the Groundwater Level Data (m MSL)</th></tr>
<tr><th>Site I-2</th><th colspan="2">Site H-5</th></tr>
<tr><td>1-3 March 2000</td><td>-0.26 (0.34)</td><td>0.024(0.08)</td><td colspan="2">-0.53(0.14)</td></tr>
<tr><td>22-24 February 2000</td><td>-0.24(0.49)</td><td>0.05(0.09)</td><td colspan="2">-0.52(0.09)</td></tr>
<tr><td>22-23 February 1999</td><td>-0.31(0.34)</td><td>0.01(0.07)</td><td colspan="2">-0.36(0.09)</td></tr>
<tr><td>Spring Tide</td><td>0.07(0.53)</td><td>1.01(0.19)</td><td colspan="2">1.13(0.21)</td></tr>
<tr><td>Neap Tide</td><td>-0.39(0.65)</td><td>0.15(0.12)</td><td colspan="2">-0.42(0.13)</td></tr>
<tr><td colspan="5">Confined Sites</td></tr>
<tr><td rowspan="2">One Dataset</td><td rowspan="2">0.00(0.58)</td><td>Site 1272/34</td><td>Site 1525/34</td><td>Site 235/26</td></tr>
<tr><td>-0.64(0.09)</td><td>0.21(0.27)</td><td>-0.08(0.16)</td></tr>
</table>

I-2 and H-5. The hydraulic diffusivities obtained using the spring tidal data are higher (ranging between 8.4 and 33.6 m^2/s for Site I-2, and between 19.4 and 274.4 m^2/s for Site H-5) than those obtained using the neap tidal data (ranging between 3 and 8.4 m^2/s for Site I-2, and between 6.5 and 68.6 m^2/s for Site H-5). The neap tidal data tend to yield hydraulic diffusivity lower than that yielded by the normal tidal data. Thus, the spring and neap tidal data significantly affect the hydraulic diffusivity estimates based on the 'tidal efficiency' and 'time lag' models. Hence, a proper selection of the tide-aquifer interaction dataset is essential for a reliable estimation of aquifer parameters by the tidal response technique.

Based on the results of this study, the use of spring and neap tidal datasets is not encouraged while using the simple one-dimensional tide-aquifer interaction model. In fact, spring and neap tides significantly affect the dynamics of coastal aquifer systems. For instance, the moving shoreline boundary induces interactions between the two primary tidal oscillations as they propagate in the aquifer system. Such interactions lead to the generation of long-period and slowly damped spring-neap tidal water table fluctuations (Li et al., 2000). The dynamics of spring and neap tides could be handled effectively by numerical modeling technique, provided necessary field data are available.

4.2 Hydraulic Diffusivity of the Confined Aquifer

In the case of the Dridrate aquifer, the tidal efficiency is lower and time lag higher for the site farthest from the seashore (Table 4), which is consistent with the theory. However, the tidal efficiency and time lag values for a farther site (Site 1525/34) are the same as the site nearest to the seashore (Site 235/26), which is attributed to the heterogeneity of the aquifer system (Fakir and Razack, 2003). The hydraulic diffusivities based on the tidal efficiency and time lag models at the three confined sites are presented in Table 5. In this case also, the hydraulic diffusivities based on the tidal efficiency model are much lower than that based on the time lag model for all the three sites under study. The hydraulic diffusivity based on the graphical time lag was found to be higher than that based on the numerical time lag. For the confined sites also, the numerical computation of time lag is better because of the half-hourly tide-aquifer interaction data. Thus, the hydraulic diffusivity results by the direct methods for the confined sites have the same trend as that for the unconfined sites. Therefore, the free surface does not appear to be responsible for the exceptionally high hydraulic diffusivity yielded by the ‘time lag’ model. As the Ferris/Jacob tide-aquifer interaction models are highly simplified representation of actual complex tide-groundwater dynamics, other possible reasons for the amplitude-lag inconsistencies could be vertical flows, anisotropy, beach slopes, variable aquifer thickness and nonlinearities associated with capillarity and density-driven flow (Trefry and Bekele, 2004).

Trefry and Bekele (2004) investigated the tidal efficiency and time lag inconsistencies and found that the horizontal layering in aquifer properties was the most probable cause of

Table 4. Tidal efficiency and time lag at the three confined sites

Description	Site 1272/34 (2800 m)	Site 1525/34 (2650 m)	Site 235/26 (400 m)	Mean ± S.D.
Tidal Efficiency (%)	14.9	20.1	20.2	18.4±3.0
Graphically Computed Time Lag (h)	1.5	1.0	1.0	1.2±0.3
Numerically Computed Time Lag (h)	1.7	1.2	1.2	1.4±0.3

Table 5. Hydraulic diffusivities by direct methods at the three confined sites

Method	Hydraulic Diffusivity (m^2/s)			Mean Diffusivity ± S.D. (m^2/s)
	Site 1272/34 (2800 m)	Site 1525/34 (2650 m)	Site 235/26 (400 m)	
Tidal Efficiency	151.8	192.2	4.4	116.1±98.8
Graphical Time Lag	956.2	1927.2	43.9	975.7±941.8
Numerical Time Lag	744.5	1457.2	33.2	744.9±712.0

these inconsistencies, not one-dimensional effects, and that the tidal efficiency-based diffusivity estimates are more reliable than the time lag-based estimates even in layered aquifer systems. In addition, it is reported that one-dimensional tide-aquifer interaction model can be useful for the inverse characterization of aquifers with macroscale hydrogeologic structures, and that the analysis of measured propagation bias (i.e., above-mentioned inconsistency) has the potential to provide extra information on aquifer properties in the vertical direction.

5. SUMMARY AND CONCLUSIONS

Adequate knowledge of the hydraulic properties of aquifer systems such as transmissivity or hydraulic conductivity, storage coefficient and/or hydraulic diffusivity is essential for all the studies pertaining to groundwater quantity and quality, including modeling. In this study, the tide-aquifer interaction data from both unconfined and confined coastal aquifer systems have been used to evaluate the efficacy of direct tidal methods (‘tidal efficiency’ and ‘time lag’ methods) for identifying aquifer parameters. Aquifer hydraulic diffusivities at the two unconfined sites (I-2 and H-5) of the Konan groundwater basin, Japan and at the three confined sites (1272/34, 1525/34 and 235/26) of the Dridrate groundwater basin, Morocco were computed directly by using ‘tidal efficiency’ and ‘time lag’ models. The effect of spring and neap tidal data on parameter estimates was also analyzed for the unconfined aquifer.

The analysis of the results revealed that the ‘time lag’ model consistently yielded very large hydraulic diffusivity values for both the unconfined and confined sites compared to the ‘tidal efficiency’ model. For the ‘time lag’ model, the numerical computation of time lag proved to be more accurate than the graphical computation of time lag because the tide-aquifer interaction datasets were available only at a resolution of one hour or of half an hour; such a resolution of field data is most likely in practice. Hence, the numerical computation of time lag should be preferred for hourly and half-hourly datasets in order to obtain better estimates of hydraulic diffusivity despite the fact that the graphical computation of time lag is much easier and faster. In general, however, the use of time lag model for determining hydraulic diffusivity should be avoided. If at all this model is to be used, it can be employed for a rough estimation of aquifer parameters.

Moreover, the tide-aquifer interaction datasets corresponding to spring and neap tidal events yielded completely different hydraulic diffusivity values for both the unconfined sites compared to the tide-aquifer interaction dataset corresponding to the normal tidal event. Therefore, the tide-aquifer interaction data should be selected carefully for the determination of aquifer parameters by the tidal response technique. Based on the present findings, spring and neap tidal datasets should be avoided for estimating aquifer parameters by the tidal response technique.

Overall, it is concluded that: (i) the ‘tidal efficiency’ method is superior to the ‘time lag’ method for both unconfined and confined coastal aquifer systems, (ii) the numerically computed time lags are more reliable than the time lags obtained by graphical method, and (iii) spring and neap tidal data have a significant influence on the hydraulic diffusivity estimates.

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