Filtering techniques for quantifying tidal impacts on groundwater: a comparative analysis

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The analysis of tidal effects on aquifer systems plays an important role in coastal aquifer management. In this study, the impacts of tidal fluctuations on groundwater levels were quantified by three filtering techniques: filtering technique I (tidal efficiency and time lag), filtering technique II (moving average), and filtering technique III (25 h mean). The tide–aquifer interaction data were obtained from the Konan aquifer, Japan (two unconfined sites) and the Dridrate aquifer, Morocco (three confined sites). Groundwater filtering by tidal efficiency and time lag indicated that the peak of the filtered groundwater level had shifted slightly to right and its amplitude decreased. For the unconfined sites, the mean at 13 h by filtering technique III was found to be lower than that obtained by filtering technique II. Similarly, for the confined sites, the mean at 13 h obtained by filtering technique III was relatively low compared to the mean at 36 h by filtering technique II. Although filtering techniques II and III are able to remove solar and lunar harmonics from measured groundwater data, filtering technique I is more useful for practical purposes.

Keywords: Filtering techniques, tidal efficiency, tide–aquifer interaction, time lag.

AQUIFER systems and subsurface processes are complex and hidden in nature. Just as atmospheric pressure changes produce variations of piezometric levels, so do tidal fluctuations by varying the load in confined aquifers extending under the ocean floor. Contrary to the atmospheric pressure effect, tidal fluctuations are direct, that is, as the sea-level increases, the groundwater level also increases. Thus, in coastal aquifers in contact with the ocean, sinusoidal fluctuation of groundwater level occurs in response to tides[1]. Normal tidal movement of the sea level results from the mutual attraction between the moon and the earth, and the rotation of the earth, which generally conforms to a sinusoidal type of curve with two high and two low levels within each lunar day. The lunar day is longer than a calendar day (24 h and 50 min compared to 24 h), resulting in 50 min shift in the time of occurrence of the highest and lowest tides on the following days. If the sea level varies with a simple harmonic motion, a train of sinusoidal waves is propagated inland from the submarine outcrop of the aquifer[1].

For the estimation of hydraulic parameters like storage coefficient, transmissivity, hydraulic conductivity and/or leakage factor of coastal aquifer systems as well as for modelling studies, groundwater-level data must be free from tidal effects[2–4]. Rojstaczer *et al.*[5] investigated the response of water level in a well to earth tides and atmospheric loading under unconfined condition. Several investigators have reported that groundwater of coastal aquifers is influenced by ocean tides, which in turn considerably affect flow and transport processes in the aquifer system[6–9]. The tidal interference can be filtered using tidal efficiency and time lag method[6]. The daily mean groundwater-level data are free from solar and lunar harmonics which occur due to tides[10].

In the present study, three filtering techniques have been employed to explore their efficacy for removing oscillations from groundwater-level data observed at the tide-affected sites of Konan aquifer, Japan (two unconfined sites) and the Dridrate aquifer, Morocco (three confined sites).

Study sites: an overview

Tide–aquifer interaction data used in this study have been obtained from two overseas groundwater basins. Two tide-affected wells, I-2 and H-5, were selected from the Konan groundwater basin located in Kochi Prefecture, Japan[8] and three wells, 1525/34, 1272/34 and 235/26, were selected from the Dridrate aquifer located in Qualidia Sahel, Morocco[11]. In the Konan groundwater basin, the wells H-5 and I-2 are located at 500 m and 350 m from the coast respectively (Figure 1).

The Konan groundwater basin is bounded by the Monobe River (perennial) in the west and the Koso River (intermittent) in the east. Mountains demarcate the northern boundary, and the southern boundary is demarcated by the Pacific Ocean. There are two intermittent rivers, the

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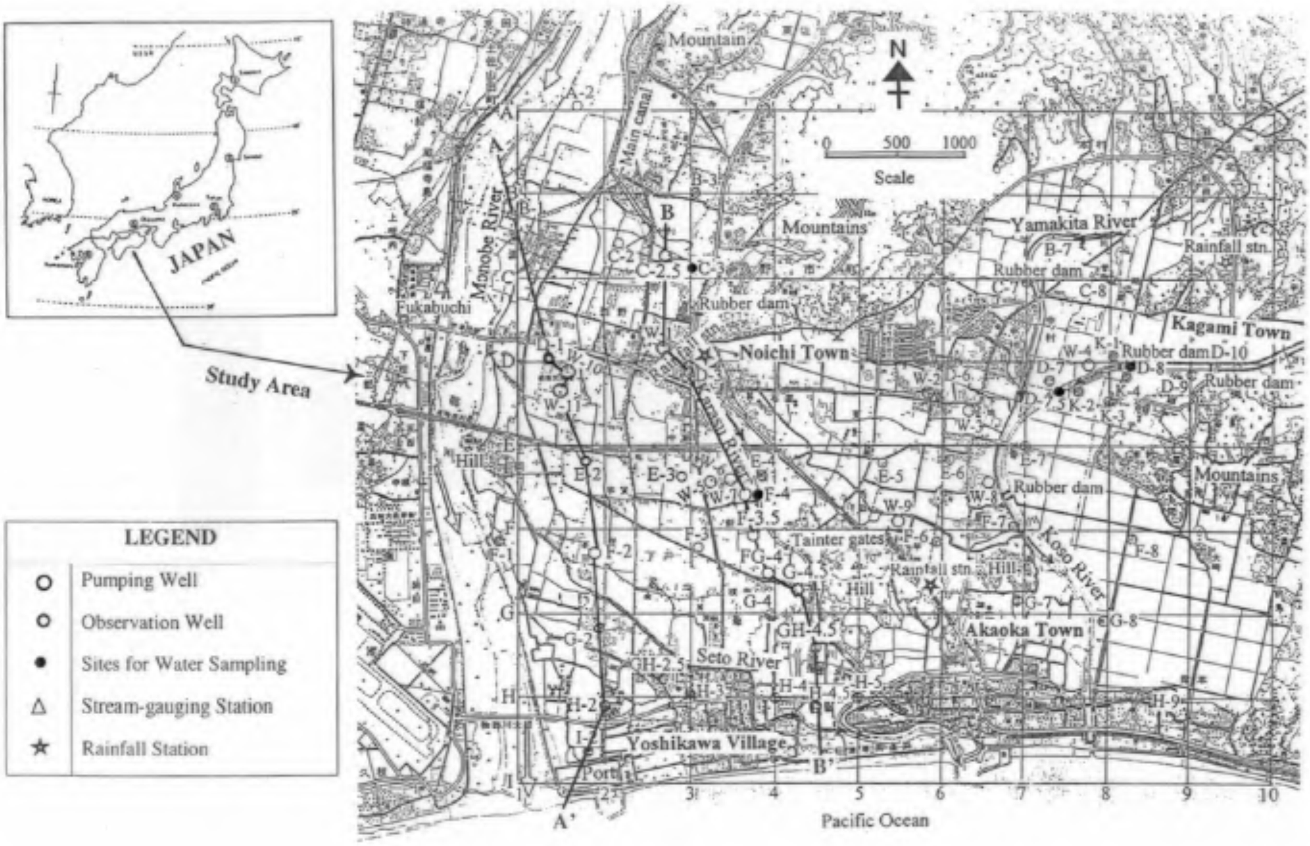

Figure 1. Location map of the Konan groundwater basin.

Karasu and Yamakita, and an ephemeral stream, the Seto River. Cold and dry winters, and warm and humid summers characterize the regional climate. January and February are the coldest months and July–August the hottest months. The minimum ambient temperature is –4°C in February and maximum is 37°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. Though the rainfall is usually distributed throughout the year, October through February (winter season) is characterized as a dry period. The mountainous landforms and many paved roads provide a rapid and considerable run-off during rainstorms. Phreatic aquifers comprising alluvial sand and gravel, and/or diluvial silty sand and gravel are predominant over the Konan basin. The hydrogeologic profiles of the Konan basin along two north-south sections *A–A′* (containing site I-2) and *B–B′* (containing site H-5) are illustrated in Figure 2 *a* and *b*.

The Dridrate aquifer is located alongside the Atlantic Ocean and directly overlain by Plioquaternary formations downstream between Qualidia and El Akarta. The wells 1525/34, 235/26 and 1272/34 are located at 2650, 400 and 2800 m respectively from the seashore. The Dridrate aquifer is composed of sandy and dolomitic limestone, which is separated from Plioquaternary terrains by the overlying reddish sandy and argillaceous deposits. Therefore, the Dridrate aquifer is generally considered as confined underneath the red sandy clays[11]. These red clays constitute the basement of the Plioquaternary sediments composed of calcareous sandstones. The hydrogeological profile of the Dridrate aquifer is illustrated in Figure 3.

Quantification of tidal impacts

The regular groundwater readings recorded in a coastal groundwater basin were adjusted to compensate for tidal effects. Tidal fluctuation generally complicates any pumping test analysis using drawdown data from observation wells[4]. Various filtering techniques have been reported in the literature[6,10,11]. In this study, three widely used filtering techniques have been employed to explore their efficacy for removing unwanted erratic oscillations from groundwater level data observed in tide-affected observation wells.

Tidal efficiency and time lag method: filtering technique I

The tidal efficiency and time lag method was used to filter tidal effects from observed groundwater data. The tidal

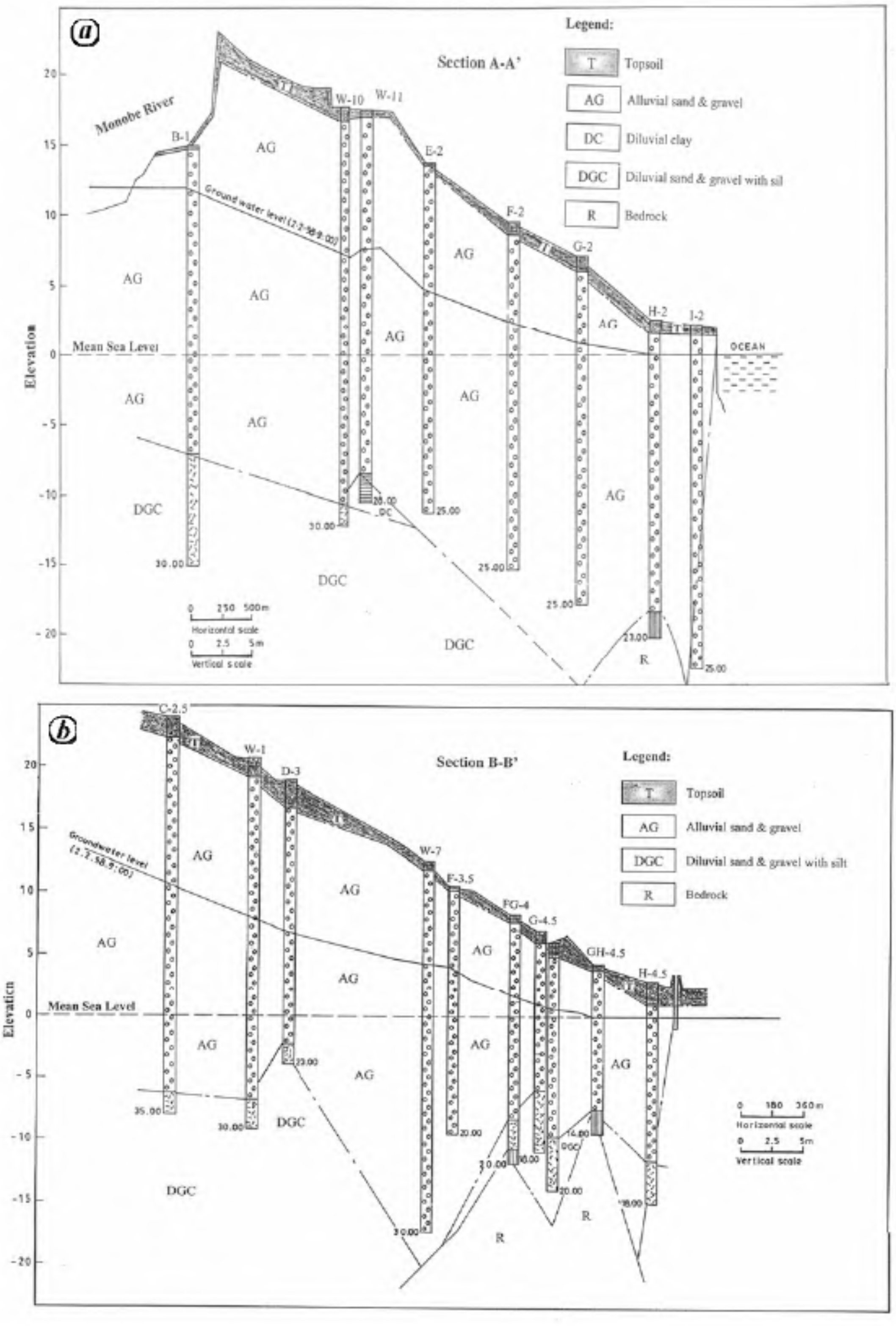

Figure 2. Hydrogeologic profile of the Konan aquifer along section A–A' near site I-2 (***a***) and along section B–B' near site H-5 (***b***)[8].

efficiency was determined by the ratio of the standard deviation of groundwater readings to that of the tide readings. Using all the data has advantages over the peak data for computing tidal efficiency[6,8]. The time lag was com-

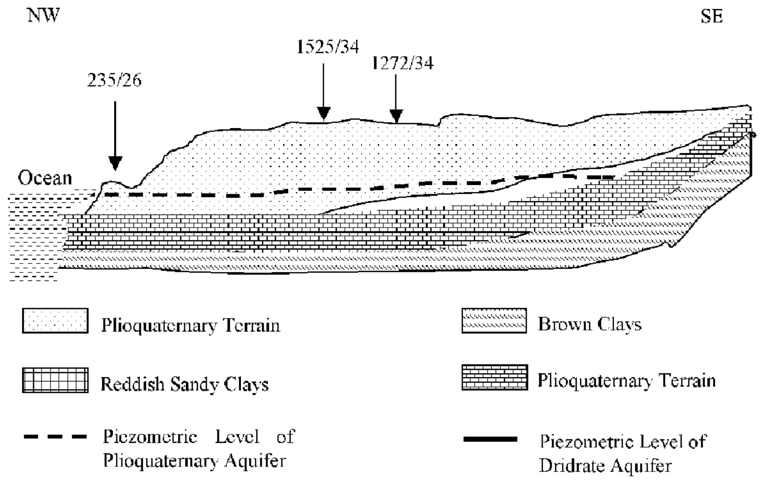

Figure 3. Hydrogeologic cross-section of the Dridrate aquifer (modified from Fakir and Razack[11]).

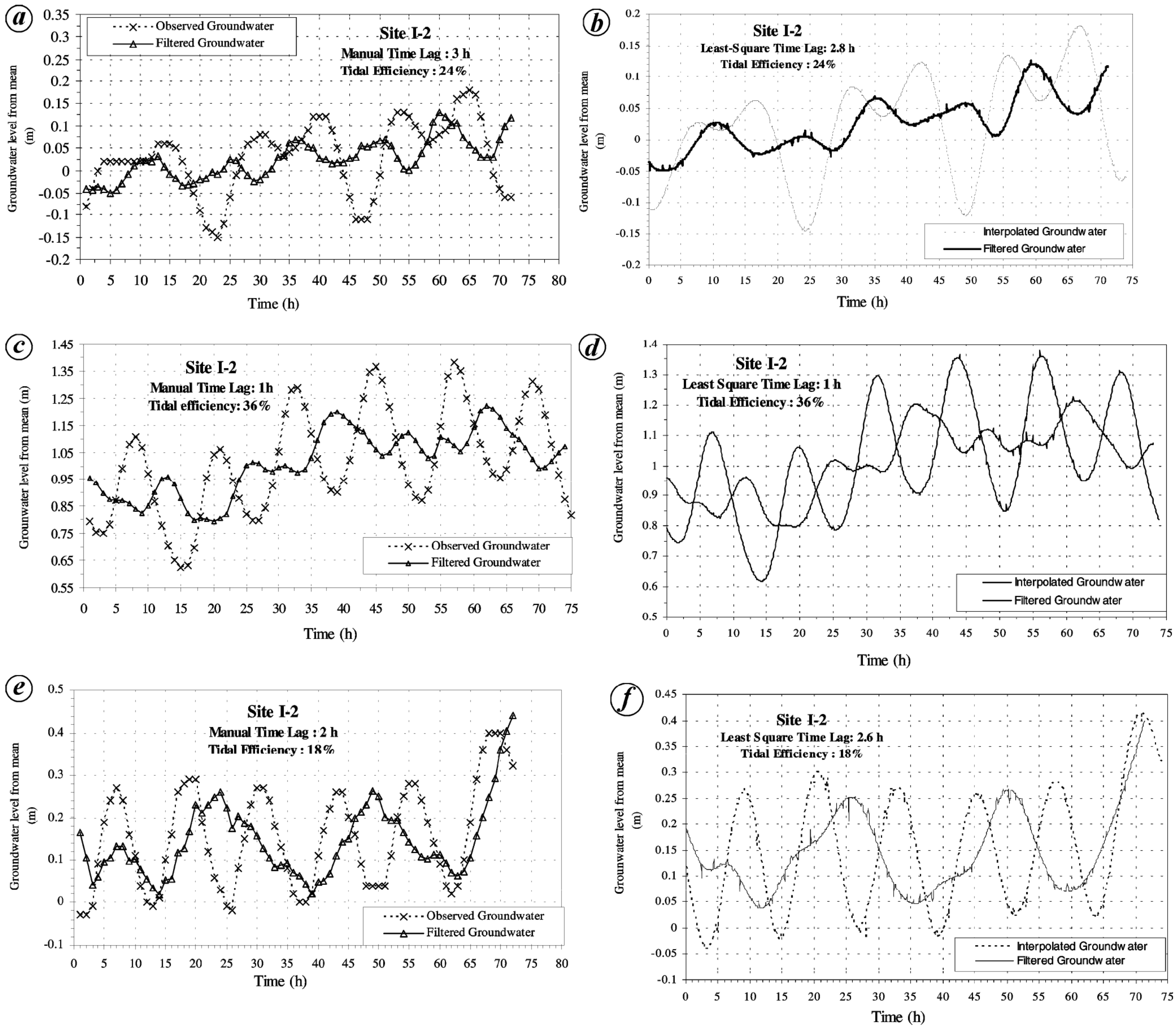

Figure 4. Observed and filtered groundwater levels at site I-2. ***a***, ***b***, Data used: 1–3 March 2000. ***c***, ***d***, Data used: 14–16 September 2000 – spring tide. ***e***, ***f***, Data used: 21–23 January 2000 – neap tide.

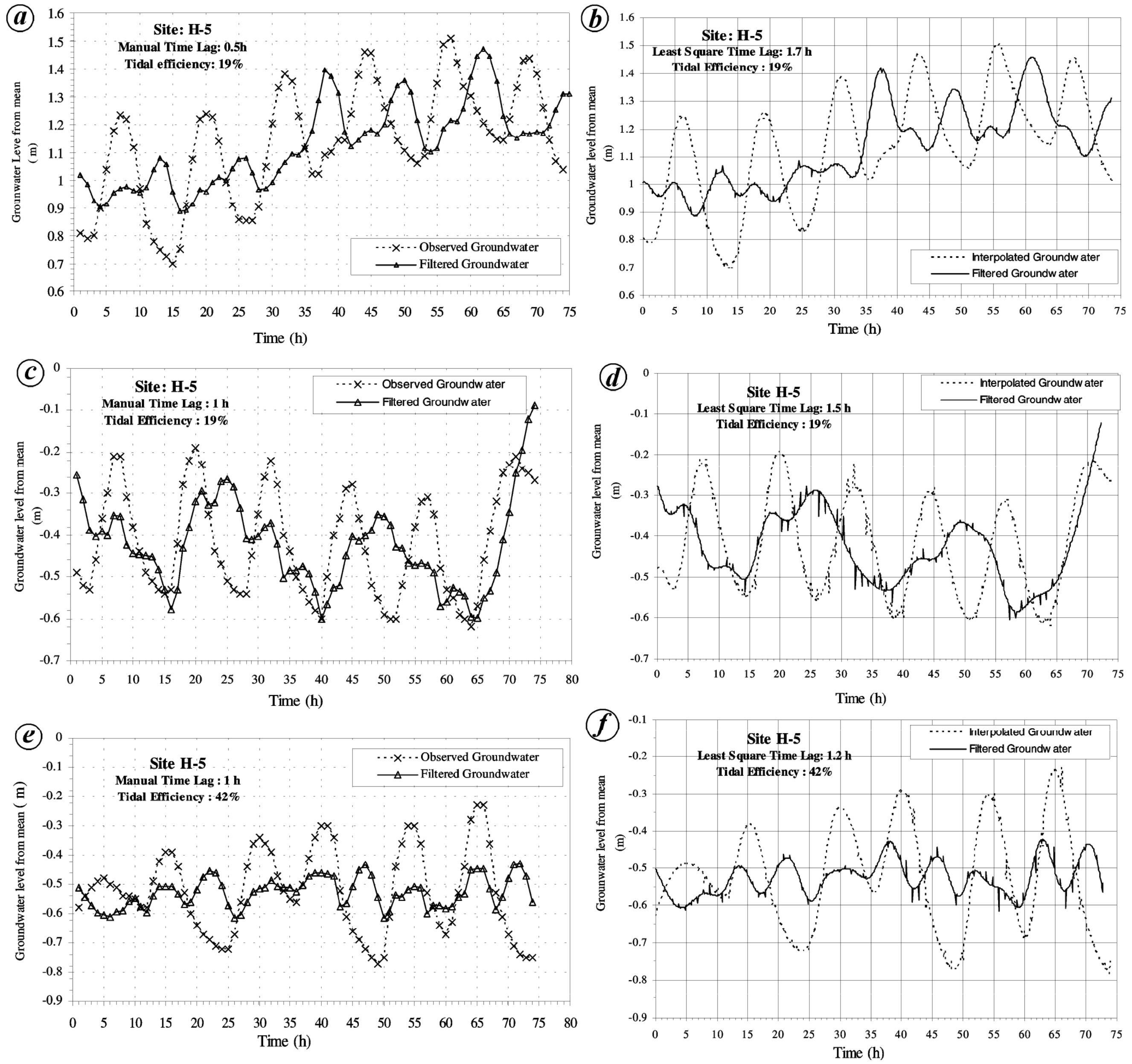

Figure 5. Observed and filtered groundwater levels at site H-5. ***a***, ***b***, Data used: 14–16 September 2000 – spring tide. ***c***, ***d***, Data used: 21–23 January 2000 – neap tide. ***e***, ***f***, Data used: 1–3 March 2000.

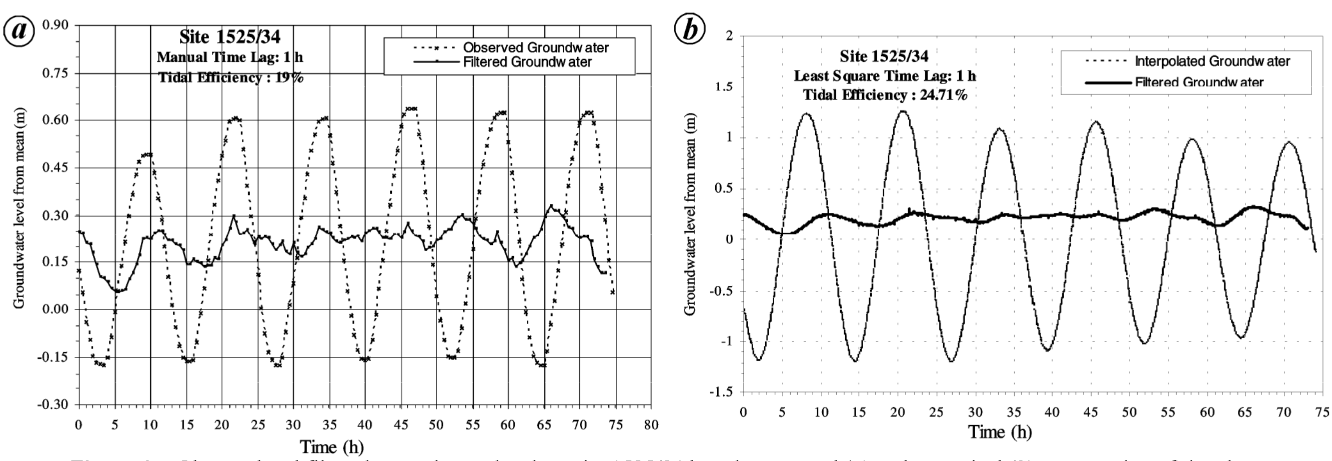

Figure 6. Observed and filtered groundwater levels at site 1525/34 based on manual (***a***) and numerical (***b***) computation of time lag.

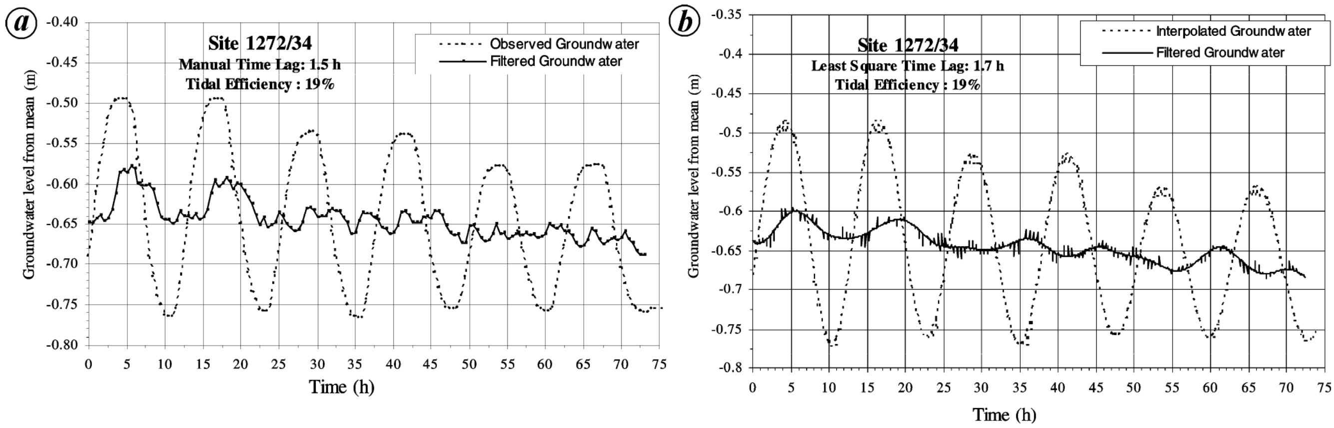

Figure 7. Observed and filtered groundwater levels at site 1272/34 based on manual (***a***) and numerical (***b***) computation of time lag.

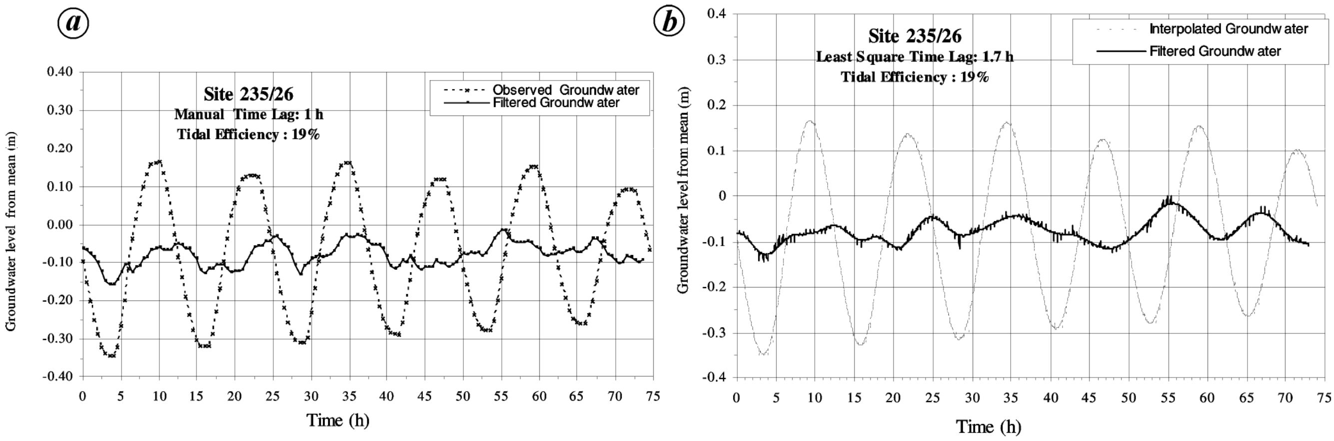

Figure 8. Observed and filtered groundwater levels at site 235/26 based on the manual (***a***) and numerical (***b***) computation of time lag.

Table 1. Mean level at hour 36 for unconfined sites of the Konan aquifer

Site	Mean level at hour 36 by filtering technique II (m)
Data used: 1–3 March 2000	
I-2	0.0207
H-5	–0.516
Data used: 21–23 January 2000	
I-2	0.1347
H-5	–0.4326

Table 2. Mean level at hour 36 for confined sites of the Dridrate aquifer

Site	Mean level at hour 36 by filtering technique II (m)
1525/34	–0.0753
1272/34	–0.645
235/26	0.563

puted manually and numerically as described in succeeding sections. Thereafter, the filtering process was done using the following equation[6]:

$$h_f(t) = h(t) - E[H(t - t_{\text{lag}}) - H_{\text{mean}}], \quad (1)$$

where $h_f(t)$ is the filtered groundwater level at time t, $[L]$; $h(t)$ the groundwater level at time t, $[L]$; E the tidal efficiency (fraction); t_{lag} the time lag, $[T]$; $H(t)$ the tide level, $[L]$, and H_{mean} the mean tide level, $[L]$.

Manual computation of time lag

In this method, the time lag was estimated by simply finding the difference between the time to peak of tide level and that of groundwater level. It was computed by comparing the plots of tide level versus time, and groundwater level versus time.

Numerical computation of time lag

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 (ANN)[12] with the

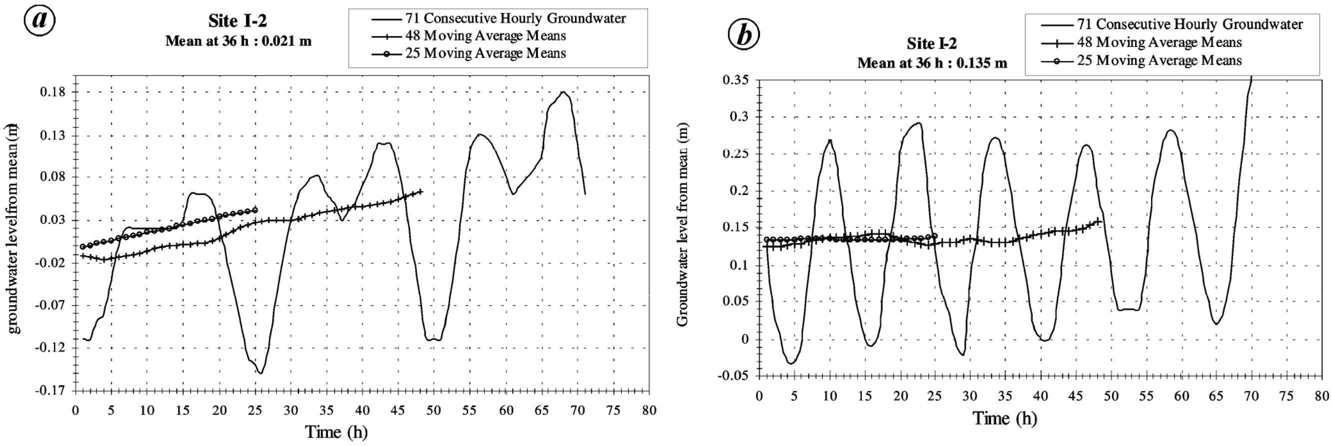

Figure 9. Moving average means at site I-2 for dataset 1–3 March 2000 (***a***) and dataset 21–23 January 2000 (***b***).

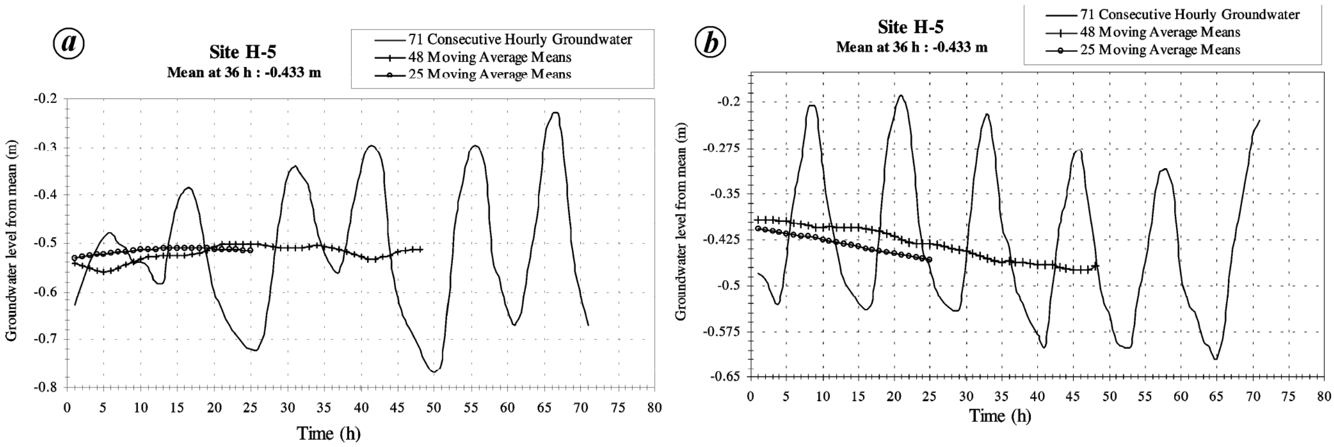

Figure 10. Moving average means at site H-5 for dataset 1–3 March 2000 (***a***) and dataset 21–23 January 2000 (***b***).

help of MATLAB. First, observed groundwater levels or tide levels were used to train the ANN. The desired simulated outputs were obtained at the number of hidden neurons ranging from 9 to 11 for the datasets under study. Thereafter, at a particular neuron number, the input was set for the desired number of interpolations and the corresponding simulated output (i.e. interpolated time series of groundwater level or tide level) was obtained. The interpolated groundwater readings were then shifted in elevation to have the same mean value as that of the interpolated tidal readings. Mathematically, this shift and amplification of groundwater level can be expressed as[6,11]:

$$h'(t) = H_{\text{mean}} + [h(t) - h_{\text{mean}}]/E, \qquad (2)$$

where $h'(t)$ is the shifted groundwater level at time t, [L]; $h(t)$ the groundwater level at time t, [L]; h_{mean} the mean groundwater level, [L]; H_{mean} the mean tidal level, [L], and E the tidal efficiency (fraction). Finally, the shifted and amplified groundwater level ($h'(t)$) was directly compared with the tidal data to compute the time lag (t_{lag}) by least square technique with the following objective function:

$$\text{Min}\sum[h'(t) - H(t - t_{\text{lag}})]^2. \qquad (3)$$

To accomplish this entire task, a computer code in 'C' language was developed.

Moving average method: filtering technique II

The gravitational forces exerted by the moon and the sun produce tidal waves, which are composed of lunar and solar frequencies, and hence are much more complex than a single sinusoidal wave. The lunar tidal effects are about 50% more effective than the solar influence[10]. The moving average technique removes all the diurnal and semi-diurnal lunar and solar frequencies using moving averages on 72 consecutive hourly groundwater-level data.

First, a sequence of means was computed using eq. (4) for 24 observations, yielding a total of 48 means. Secondly, a similar series of means was calculated using eq. (5), yielding a total of 25 means. Lastly, a mean was computed from the 25 means using eq. (6), yielding a mean groundwater level at hour 36. Mathematically, moving average filtering technique can be expressed as follows[10]:

$$X_i = \sum_{k=0}^{23} \frac{O(k+i)}{24}, \quad i = 1, 2, 3, \ldots, 48, \tag{4}$$

$$Y_j = \sum_{i=0}^{23} \frac{X(i+j)}{24}, \quad j = 1, 2, 3, \ldots, 25, \tag{5}$$

$$\text{Mean} = \sum_{j=1}^{25} \frac{Y_j}{25}, \tag{6}$$

where X_i is the 48 sequence of means, Y_j the 25 sequence of means, and Mean the mean groundwater level at hour 36.

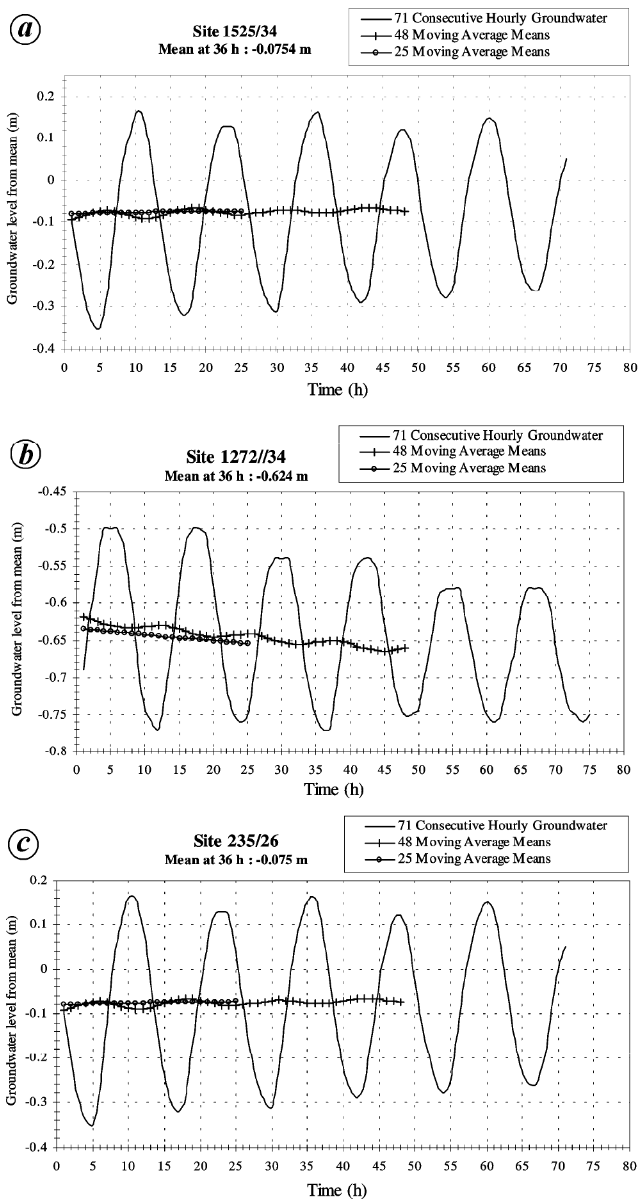

Figure 11. Moving average means at site 1525/34 (***a***), site 1272/34 (***b***) and site 235/26 (***c***).

Twenty five-hour mean method: filtering technique III

The 25 h mean technique requires lesser data than the moving average filtering technique and can be used to approximate the mean water level also. It is the mean of 25 consecutive hourly groundwater levels only, which filters out most of the lunar frequencies but permits some of the solar frequencies, hence resulting in a slight error to mean[10]. The mean yielded by this method represents the mean groundwater level at hour 13. Although this technique is less accurate than the moving average filtering technique, it is less time-consuming, easier to calculate, and in many cases is accurate enough to draw preliminary conclusions regarding groundwater flow.

All the above-mentioned filtering techniques were used to filter groundwater level datasets of different sizes, viz. groundwater level data of sites I-2 and H-5 (unconfined sites) constitute normal tidal event (1–3 March 2000), spring tidal event (21–23 January 2000) and neap tidal event (14–16 September 2000). In addition, groundwater level data of confined sites 1525/34, 1272/34 and 235/26 of the Dridrate aquifer were used for filtering.

Results and discussion

Groundwater filtering by tidal efficiency and time lag method

Before filtering, the observed groundwater data showed oscillations due to tidal effects. Filtering technique I was applied to remove these oscillations from the observed groundwater levels (three datasets each for sites I-2 and H-5 and one dataset each for sites 1525/34, 1272/34 and 235/26). The hydrographs of filtered and observed groundwater levels are shown in Figures 4 and 5 for sites I-2 and H-5 respectively, as well as in Figures 6–8 for sites 1525/34, 1272/34 and 235/26 respectively.

It is obvious from the figures that the effects of tides are considerably high for both the confined and unconfined datasets. It is also apparent that the peaks of the filtered groundwater levels at all the unconfined and confined sites are shifted to right and there is an appreciable decrease in the amplitude of all the peaks. The remaining variations in the filtered groundwater levels could be attributed to groundwater recharge and pumping at nearby sites. It can be inferred that the tidal efficiency and time lag method is effective in removing noise due to tidal phenomena for different types of datasets used in this study. Also, it is emphasized that the numerical computation of time lag is more accurate than the graphical computation of time lag because the tide–aquifer interaction datasets are usually available at a resolution of 1 h or of half an hour. Hence, the numerical computation of time lag should be preferred for hourly and half-hourly datasets in order to obtain better filtering results, though the graphical computation of time lag is much easier and faster.

Filtering by moving average

Consecutive 71 h groundwater level data were used to filter diurnal and semi-diurnal lunar and solar harmonics by the moving average method. For the Konan aquifer, the mean at 36 h obtained by filtering technique II for the two datasets ranges from 0.0207 to 0.1347 m for site I-2 and from –0.516 to –0.4326 m for site H-5 (Table 1). On the other hand, for the Dridrate aquifer the means at 36 h obtained by filtering technique II were found to be –0.0753, –0.645 and 0.563 m for sites 1525/34, 1275/34 and 235/26 respectively (Table 2). The hydrographs of consecutive 71 h groundwater-level, the 48 moving average means based on 24 observations, the 25 moving average means based on 24 observations, and finally a mean of the 25 means at 36 h for the individual sites are shown in Figures 9–11. Clearly, the moving average method is effective in filtering the lunar and solar harmonics from the groundwater-level data of both unconfined and confined sites.

Furthermore, the patterns of well hydrographs obtained by filtering technique II at sites I-2 and H-5 of the Konan aquifer as well as at sites 1525/34, 1271/34 and 235/26 of the Dridrate aquifer are in agreement with those obtained by Serfes[10].

Groundwater filtering by 25 h mean

The 25 h filtering technique was used by simply calculating the average of consecutive 25 h groundwater-level data. The mean calculated by this method was the mean level at hour 13, which was computed at sites I-2 and H-5 of the Konan aquifer for two datasets (Table 3) and at sites 1525/34, 1272/34 and 235/26 of the Dridrate aquifer for one dataset (Table 4).

It is evident from Tables 1–4 that for the Konan aquifer, the mean at 13 h was found to be low (–0.0164 to 0.1248 m for site I-2 and –0.5488 to –0.3956 m for site H-5) compared to that obtained by filtering technique II (0.0207 to 0.1347 m for site I-2 and –0.516 to –0.4326 m for site H-5). Similarly, for the Dridrate aquifer, the mean at 13 h obtained by filtering technique III was relatively low (–0.088 m for site 1525/34, –0.624 m for site 1272/34 and 0.0542 m for site 235/26) compared to the mean at 36 h by filtering technique II (–0.0753 m for site 1525/34, –0.645 m for site 1272/34 and 0.563 m for site 235/26).

It is worth mentioning that filtering techniques II and III could not filter all the observed groundwater-level data. Rather, filtering technique II yielded a mean at 36 h and filtering technique III yielded a mean at 13 h, thereby filtering only diurnal and semi-diurnal lunar and solar harmonics. Therefore, for practical purposes, filtering technique I should be preferred to the other techniques because it enables real filtering of tidal effects. Furthermore, filtering techniques II and III are dependent on a relatively large number of data and time interval, which may be a limiting factor, especially in developing nations.

Table 3. Mean level at hour 13 for unconfined sites of the Konan aquifer

Site	Mean level at hour 13 by filtering technique III (m)
Data used: 1–3 March 2000	
I-2	–0.0164
H-5	–0.5488
Data used: 21–23 January 2000	
I-2	0.1248
H-5	–0.3956

Table 4. Mean level at hour 13 for confined sites of the Dridrate aquifer

Site	Mean level at hour 13 by filtering technique III (m)
1525/34	–0.088
1272/34	–0.624
235/26	0.0542

Conclusion

The analysis of tidal impacts on aquifer systems is of great significance for coastal aquifer management. In this article, the quantification of tidal impacts on groundwater level was performed using three filtering techniques. The results of the groundwater filtering by tidal efficiency and time lag indicated that the peak of the filtered groundwater level had shifted slightly to right and its amplitude had decreased for all the confined and unconfined sites under study. For the two unconfined sites, the mean at 13 h by filtering technique III was found to be low, compared to that obtained by filtering technique II. Similarly, for the three confined sites, the mean at 13 h obtained by filtering technique III was found to be relatively low compared to the mean at 36 h by filtering technique II.

Overall, it can be concluded that though groundwater filtering by filtering techniques II and III removes solar and lunar harmonics, filtering technique I (using tidal efficiency and time lag) is more useful for practical purposes because it effectively removes the influence of tides on groundwater levels. The impact of tidal waves on coastal aquifers is of major concern for researchers and field hydrogeologists.

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Received 21 July 2008; accepted 7 January 2009