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Tidal effects of groundwater levels in the coastal aquifers near Beihai, China

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Abstract Four times of observation of the ocean tide and groundwater levels in the coastal aquifers near Beihai, China show that fluctuation in the tide-induced groundwater levels follows the tide, with the highest and lowest water levels corresponding to the high water level syzygy tide and the low water level neap tide. The tidal coefficient is less than 0.5, decreasing approximately exponentially with the distance from the coast. The tide can affect the groundwater levels at observation wells as far as about 4,200 and 3,300 m in the southern and northern coasts in Beihai. Observations and spectrum analyses of the time series of the tide and water levels suggest that the tide and water levels have similar changes with complex fluctuations of a long period of 14.37 days and two short periods of 24.7 and 12.5 h. Time lags of water levels to the tide at observation wells last several hours and increases roughly linearly with the distance from the coast. Mathematic models consisting of a periodic term plus a linear term are established to describe the changes in the tide and the groundwater levels. The periodic terms for the tide and water levels are constructed using finite Fourier's series consisting of 7 to 11 terms other than a single term of a sine function in earlier work. Computed water levels with the models can fit the observed water levels with reasonable accuracy and satisfactory prediction of the changes in the water levels is also obtained.

Keywords Coastal aquifers · Tidal effect · Period and lag · Fitting and prediction

Introduction

In coastal areas, the periodic rise and fall of the tide can cause corresponding rise and fall in water levels in hydraulically connected coastal aquifers. Analyzing and describing changes in groundwater levels in coastal aquifers are of important significance for coastal cities relying heavily on fresh groundwater for water supply and for environmental evolution in coastal areas. When dealing with tidal effects in coastal aquifers, the following subjects are of concern and have been studied and discussed by numerous researchers (Jacob 1940; Gregg 1966; Carr et al. 1969; Rhoads and Robinson 1979; Ye 1982; Zhang et al. 1990; Serfes 1991; Erskine 1991; Fetter 1994; Turner et al. 1996; Zhou 1997): (1) the amplitude of water levels compared with the tide, the change in amplitude with distance from coast and the farthest distance affected by the tide, (2) period of the tide and water levels and time lag between the water levels and the tide, (3) mathematic models describing the changes in the tide and water levels and (4) determining aquifer parameters by the tidal method. In this paper, the above three subjects are discussed based on four times of observation of the tide and water levels in the coastal aquifers near Beihai in southern China.

Hydrogeology

The city of Beihai is located in the southern part of Guangxi Zhuang Autonomous Region in southern China and faces the Beibuwan Gulf of the South China Sea (Fig.1). Except the southwestern tip and the northeastern part where low hills exist, the area is a low-lying coastal plain ranging in elevation from 8 to 20 m. Rivers are rare and short. The climate of the study area is subtropical, with a mean annual rainfall of 1,677.7 mm and a mean annual temperature of 22.6°C. The tide is an irregular diurnal one, with the extreme high water level syzygy tide, the lowest water level neap tide and the mean tide level of 3.42, −2.15 and 0.36 m, respectively.

The study area covers the western part of the Nankang Basin. The basement rocks, which outcrop in the southwestern tip and northeastern parts, are impervious mudstone with sandstone and granite. The coastal plain is underlain by Quaternary and Tertiary unconsolidated sediments with a total thickness ranging from 5 to 350 m. The Quaternary and Tertiary sediments consist of sand with gravel and scattered lenses of clay or sandy clay. One unconfined aquifer and three confined aquifers can be grouped in the unconsolidated sediments. The top of the upper confined aquifer occurs at an elevation from 2 to 10 m with a thickness ranging from 8 to 30 m. Good hydraulic connections exist among the aquifers, especially among the confined aquifers, owing to the termination of clay (Zhou et al. 2000a).

Groundwater receives recharge from precipitation and seepage from canals, flows towards northwest and south, finally discharges into the sea. In recent decades, however, artificial withdrawal for water supply has become an important way of discharge. With the increase in abstraction rate duo to the rapid population growth, continual falling in groundwater levels and depression cones in the exploitation centers have existed since 1986. Sea water intrusion once occurred in the northwestern coast during 1989–1993 (Zhou et al. 2000b).

Observation data

Measuring of groundwater levels in the confined aquifers affected by the tide was conducted four times in the northern and southern coasts. Three observation wells in the southern coast were used for the first time from December 15, 1986 to January 20, 1987 (lunar date from November 14, 1986 to December 22, 1986). Groundwater levels were measured a second time at 28 observation wells during September 29–30, 1987 (lunar date

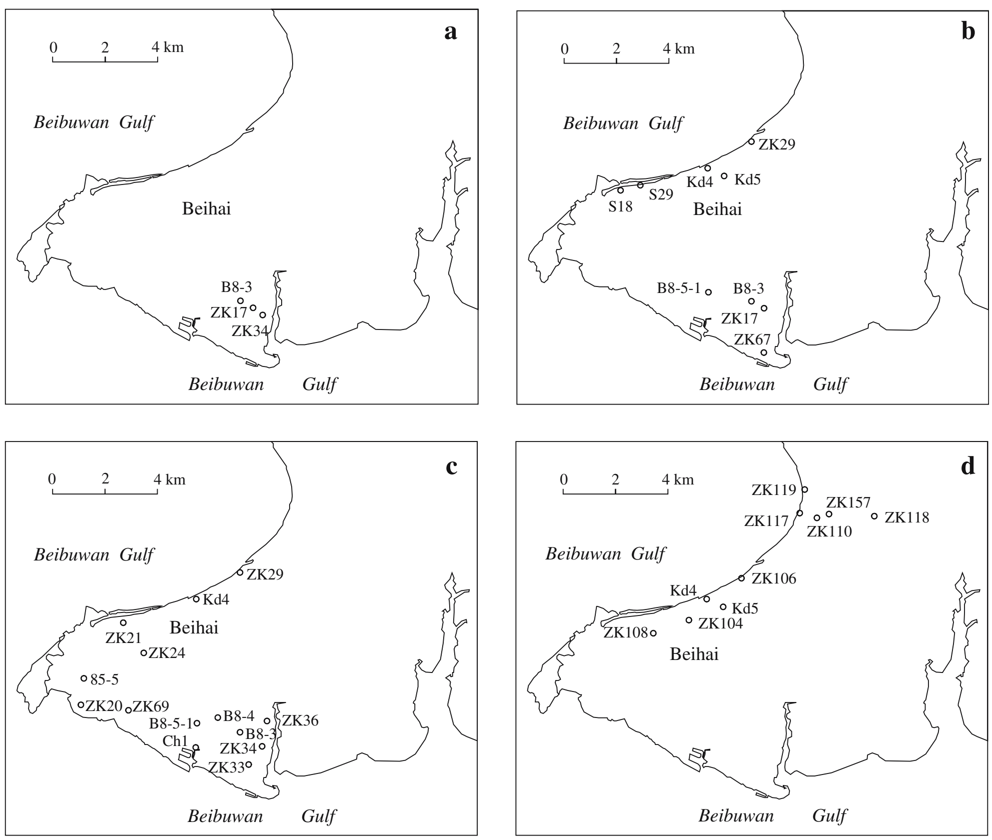

Fig. 1 Location of the observation wells for measurements of groundwater levels **a** from December 15, 1986 to January 20, 1987, **b** during September 29–30, 1987, **c** from November 6, 1987 to November 11, 1987 and **d** during September 18–22, 1992

during August 8–9, 1987). Groundwater levels were measured for the third time at 14 observation wells from November 6, 1987 to November 11, 1987 (lunar date from September 15, 1987 to September 20, 1987). Groundwater levels were measured for the fourth time at 11 observation wells in the northern coast during September 18–22, 1992 (lunar date during August 22–26, 1992). The first time of observation had only three observation wells but lasted a longer time (about 37 days). The latter three times of measurement had more observation wells but lasted only several days. The tide was observed at the corresponding periods of measurement of the groundwater levels. The time interval for all the measurements was 1 h. The measurements of groundwater level were carried out in dry seasons or non-rainy days to avoid the effect of infiltration from precipitation. The first time measurements of groundwater levels were believed not to be affected by artificial abstraction of groundwater during the periods of measurements, and fluctuations in water levels at the three observation wells were only caused by the tide. Water levels at some of the observation wells for the latter three times of measurements, however, were affected by artificial pumpage to a greater or lesser degree. Relatively reasonable fluctuations in water levels are found at 9, 14 and 10 observation wells for the second, third and fourth times of measurement, respectively. In addition, barometric pressure was considered to have negligible influence on the measurement of water levels. Location of the selected observation wells is shown in Fig. 1, and the water levels vs time, in Figs. 2, 3, 4 and 5.

Tidal range, amplitude of water levels and tidal coefficient

Fluctuations in the groundwater levels in the coastal confined aquifers near Beihai were caused by oscillations in the tide, with each rise or fall in the water levels corresponding to the same flood tide or ebb tide (Figs. 2, 3, 4, 5). The amplitude of the water levels at all the observation wells, however, is less than the corresponding tide, indicating that a damping effect of water levels at the observation wells is significant. The spring tide occurs 2 to 3 days later than lunar dates 1 (during a new moon) and 15 (during a full moon) in each month, and the neap tide occurs 2 to 3 days later than lunar dates 7 (during the first quarter of the moon) and 23 (during the last quarter of the moon) in each month. The water levels in the coastal aquifers follow exactly the tide, with a time lag decreasing with the distance from the shoreline. The range of the spring tide near Beihai is 4 to 5 m (The maximum value is 5.4 m in Fig. 2), whereas the amplitude of the water levels affected by the spring tide at all the observation wells are usually less than 2 m (The maximum value is 1.92 m at well Kd4 in Fig. 4), decreasing with the distance from the coast. The range of the neap tide is usually 0.5 to 1 m, whereas the amplitude of the water levels affected by the neap tide at the observation wells are less than 0.3 m. Tidal effect can be described using the tidal coefficient, which is defined as the ratio of the change in water level in a well to the change in tide stage (Jacob 1940; Gregg 1966). The tidal coefficient at the observation wells in the coastal area near Beihai is commonly less than 0.5, depending on the distance from the seashore. The relationships between the tidal coefficient and the distance from the seashore for the second, third and fourth times of observation are shown in Fig. 6. Rough exponential decreases in the tidal coefficient with the distance from the coast can be observed, as indicated in the theoretical model (Jacob 1950) and noted by Erskine (1991), Fetter (1994) and Turner et al. (1996). Some scatter on the graphs exists. This may be attributed to the various assumptions of the theoretical model (for example, vertical seashore boundary and uniform nature of the aquifer). Inferred from these relationships, it is found that groundwater levels at wells about 3,300 and 4,200 m far from the northern and southern coasts, respectively, will not be affected by the tide in the Beihai area.

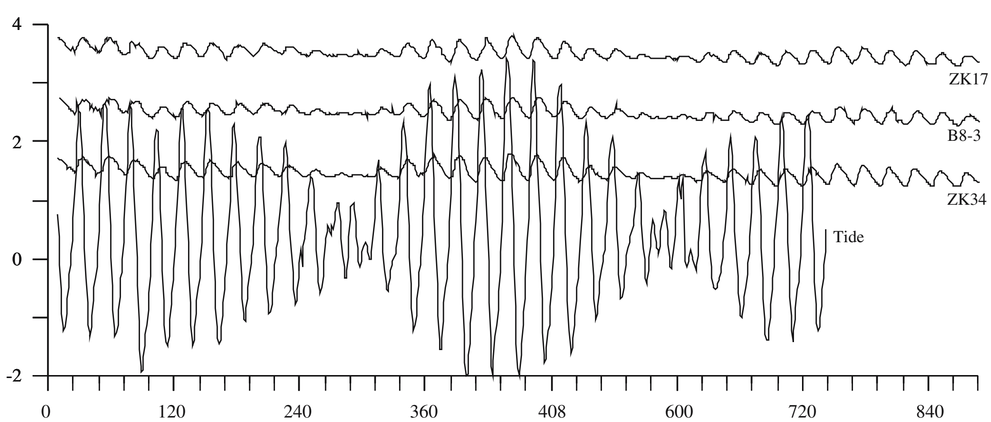

Fig. 2 Changes in the tide and water levels measured from December 15, 1986 to January 20, 1987 (Vertical coordinate is the elevation of water levels (m), horizontal coordinate is the time (h); Water levels at well ZK17 are added by 1 m for reasons of clarity)

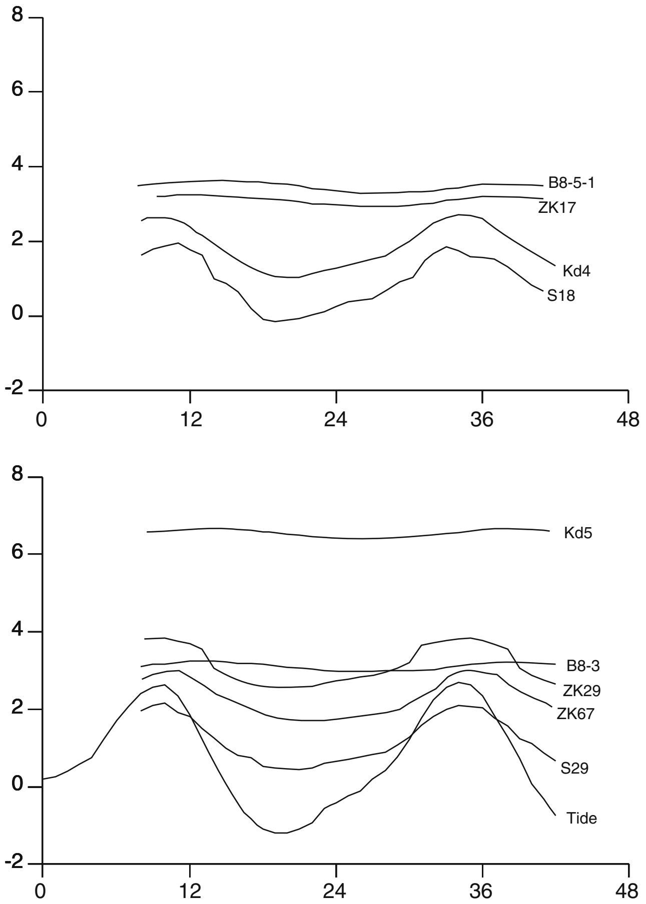

Fig. 3 Changes in the tide and water levels measured during September 29–30, 1987 [Vertical coordinate is the elevation of water levels (m), horizontal coordinate is the time (h)]

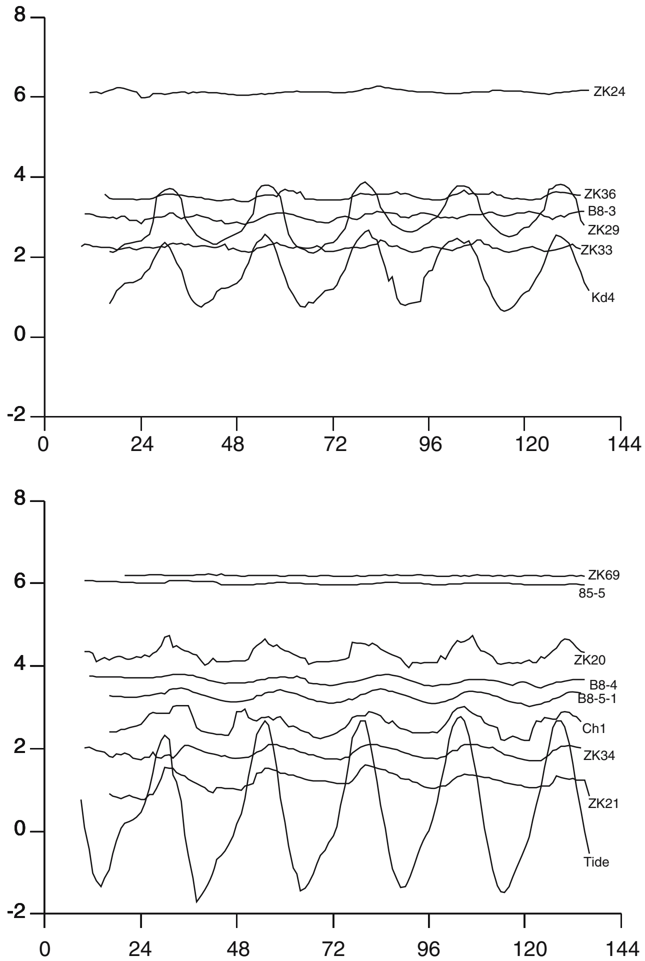

Fig. 4 Changes in the tide and water levels measured from November 6, 1987 to November 11, 1987 (Vertical coordinate is the elevation of water levels (m), horizontal coordinate is the time (h))

Tidal period and time lag

It can be seen in Fig.2 that the tide and the water levels at observation wells ZK34, ZK17 and B8-3 have a short period of about 1 day and a long period of approximately 15 days. In Figs.3, 4 and 5, time lags of several hours are found in water levels at the observation wells, increasing with the distance of the wells from the coast. The method of spectrum analysis can be used to periodic time series to determine the period of a time series and the lag of a time series to another time series. Calculation of power spectrum is needed to determine the period of a time series and calculation of correlation coefficient is needed to determine the lag of a time series to the associated time series. To calculate the power spectrum and correlation coefficient, Fourier's transfer is performed to the time series. By plotting the power spectrum in a frequency field and in a time lag field, the period and lag of the time series can be examined. Mathematic description of the spectrum analysis is presented in textbooks and articles (Chen et al. 1988; Zhou 1990; Li 1994), only the results are given as follows.

Times series of the first time of observation, which lasted a longer time, is used to undertake spectrum analyses. Power spectrum of the tide and water levels at observation wells ZK34, ZK17 and B8-3 are shown in Fig. 7. Correlation coefficients of water levels at observation wells ZK34, ZK17 and B8-3 to the tide are presented in Fig. 8. Results are also listed in Table 1. The power spectrum of the observation wells ZK34, ZK17 and B8-3 have extremes at frequencies 0.0029, 0.0405 and 0.08, indicating that three kinds of fluctuations with corresponding periods of 14.37days, 24.7 h and 12.5 h exist in the water levels in the coastal aquifers. The tide in Fig. 7 shows two kinds of oscillations with corresponding periods of 24.7 and 12.5 h, but does not exhibit the fluctuation with a period of 14.37 days. The possible

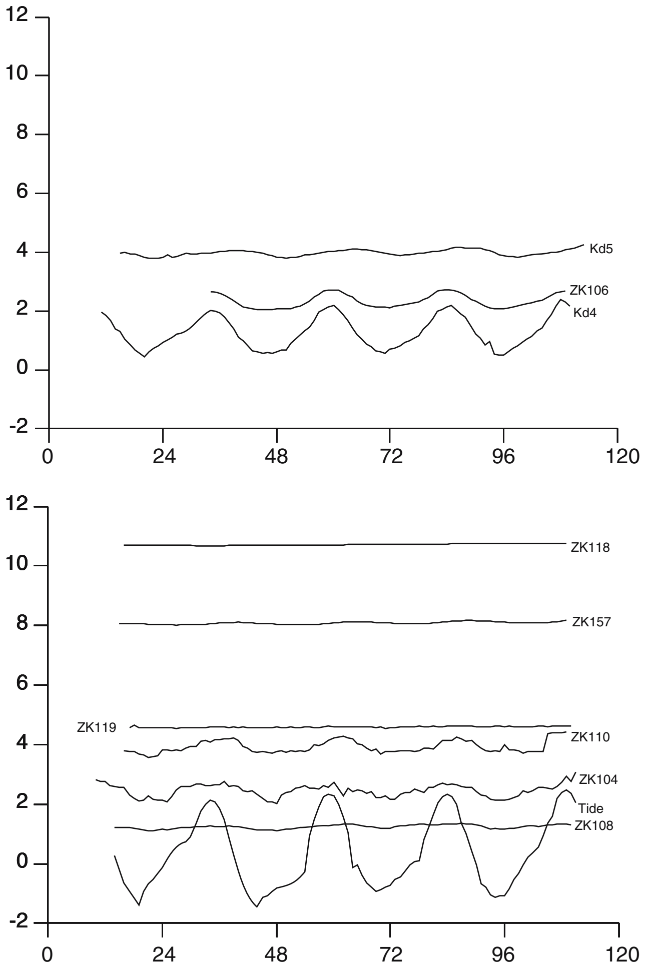

Fig. 5 Changes in the tide and water levels measured during September 18–22, 1992 [Vertical coordinate is the elevation of water levels (m), horizontal coordinate is the time (h)]

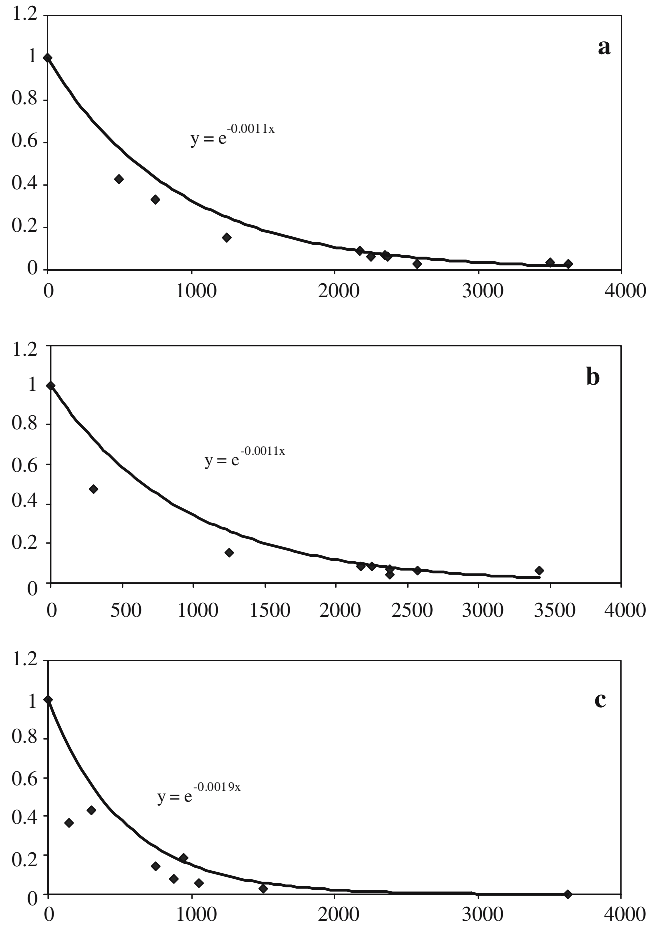

Fig. 6 Relationships between the tidal coefficient and the distance from the coast for measurements at some of the observation wells: **a** during September 29–30, 1987, **b** from November 6, 1987 to November 11, 1987 and **c** during September 18–22, 1992 [Vertical coordinate is tidal coefficient (dimensionless), horizontal coordinate is distance (m)]

reason for this is that the length of the time series of the tide in Fig. 2 is not long enough. In fact, a syzygy tide and a neap tide alternatively occur with a period of 14.37 days, meanwhile, water levels fluctuate with a period of 24.7 h (Fig. 2). The tide and water levels also change with a period of 12.5 h, which cannot easily be observed in Fig. 2. The time lag of water levels at observation wells ZK34, ZK17 and B8-3 to the tide are 5.5, 6.25 and 7.0 h, respectively (Fig. 8). Shown in Fig. 9 are relationships between time lag and distance from the coast for the second, third and fourth times of observation. It can be seen in Fig. 9 that the time lag of water levels at observation wells increases roughly linearly with the distance from the coast, as indicated in the theoretical model (Jacob 1950) and noted by Erskine (1991), Fetter (1994) and Turner et al. (1996). There is also some scatter on the graphs for the same reasons as for the tidal coefficient. In addition, the straight line in Fig. 9c has a greater slope, indicating a larger time lag at wells for a given distance from the coast. This may reflect a relatively low transmissivity in the northern coastal area near Beihai.

Models describing the tide and water levels

Mathematic models describing changes in groundwater levels include hydraulic models (Jacob 1950; Fetter 1994; Sun 1997; Li and Jiao 2003) and time series models (Houston 1983; Yang and Han 1998). Mathematic models describing the tide and tide-induced groundwater levels obtained through analyses of time series are usually a sine or cosine function in pervious work, due mainly to a short time (several days) observations of the tide and water levels. As can be seen in Fig. 2 and discussed above, when the observations are long enough (longer than one month with time interval of one hour),

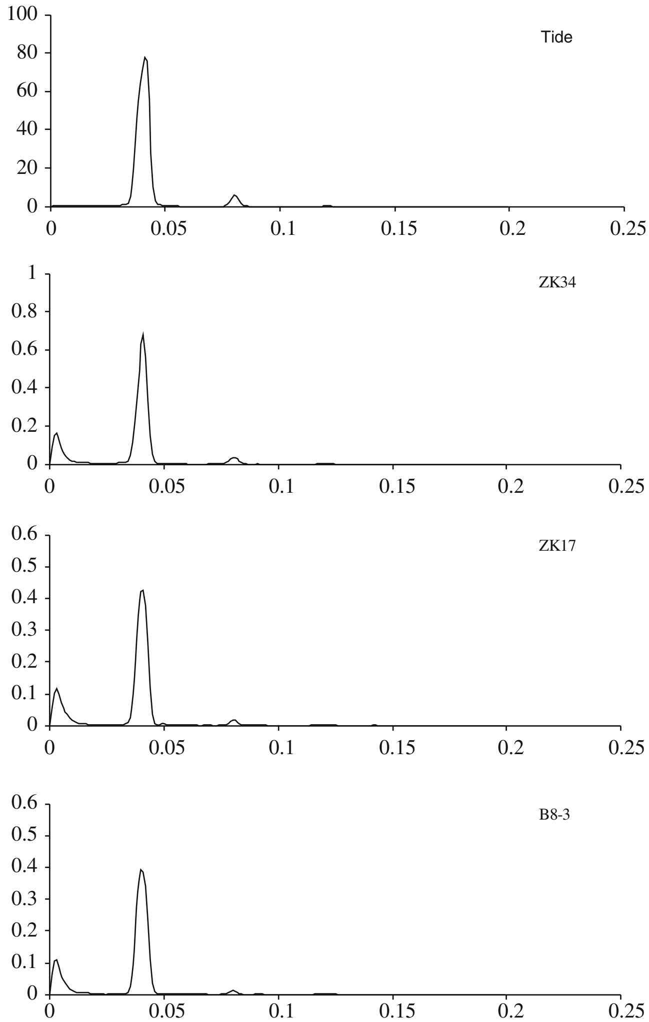

Fig. 7 Power spectrum of the tide and water levels measured from December 15, 1986 to January 20, 1987 (Vertical coordinate is the power (m^2), horizontal coordinate is the frequency (1/h))

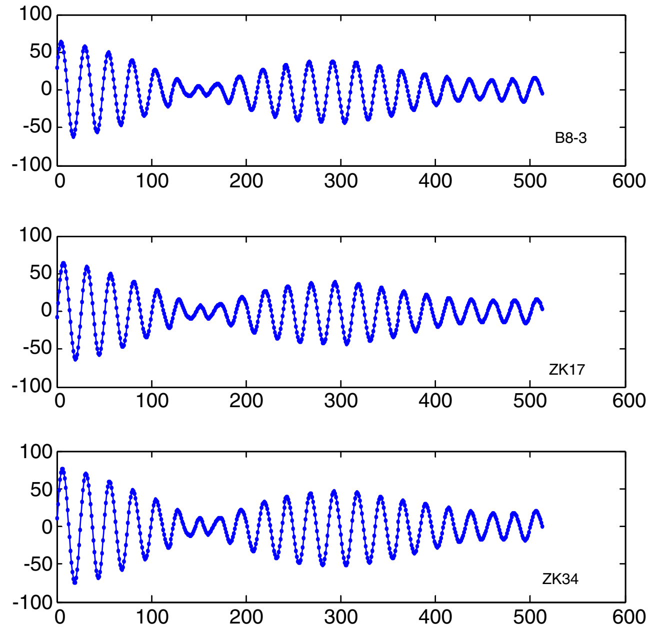

Fig. 8 Interrelation coefficient of the tide and water levels measured from December 15, 1986 to January 20, 1987 [Vertical coordinate is the correlation coefficient (dimensionless), horizontal coordinate is the time (h)]

the tide and the water levels exhibit changes of a long period of about 15 days and two short periods of about one day and half of a day, they can be described using a Fourier's series other than a sine or cosine function. In Fig. 2, the groundwater levels also display a decreasing trend owing to measurements in a dry season. For this reason, the groundwater levels induced by the tide in the coastal aquifers near Beihai can roughly be described with a Fourier's series plus a linear function:

$$P(t) = Q(t) + Z(t) \tag{1}$$

where t is the time, $P(t)$ is the water level, $Q(t)$ refers to a linear trending term (which is easily determined with the observation data by regression analysis) and $Z(t)$ stands for a periodic term described with a Fourier's series. For the tide, only the periodic term $Z(t)$ exists.

If a time series $Z(t)$ consists of p harmonic waves, $Z(t)$ can be described with a finite Fourier's series as follows:

$$Z(t) = a_0 + \sum_{p=1}^{m} a_p \cos 2\pi f_p t + \sum_{p=1}^{m} b_p \sin 2\pi f_p t \tag{2}$$

Table 1 Data and results of the spectrum analysis method for the first time of measurements

Time series	Distance from coast (m)	Number of data	Time interval (h)	Frequency 1 (1/d)	Period 1 (d)	Frequency 2 (1/d)	Period 2 (h)	Frequency 3 (1/d)	Period 3 (h)	Time lag (h)
Tide	0	735	1			0.0405	24.7	0.08	12.5	0
ZK34	2175	882	1	0.0029	14.37	0.0405	24.7	0.08	12.5	5.5
ZK17	2350	882	1	0.0029	14.37	0.0405	24.7	0.08	12.5	6.25
B8-3	2375	879	1	0.0029	14.37	0.0405	24.7	0.08	12.5	7.0

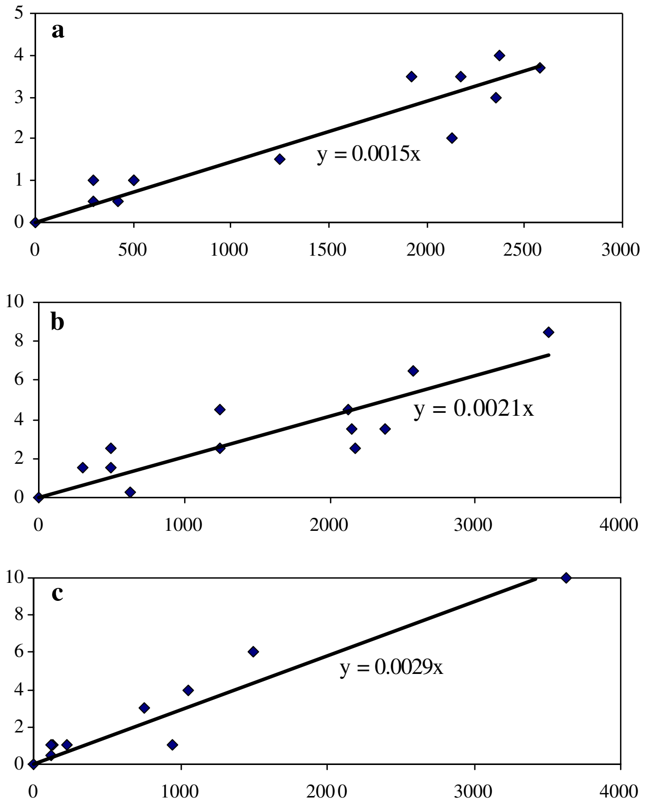

Fig. 9 Relationships between the time lag and the distance from the coast for measurements at some of the observation wells: **a** during September 29–30, 1987, **b** from November 6, 1987 to November 11, 1987 and **c** during September 18–22, 1992 [Vertical coordinate is time lag (h), horizontal coordinate is distance (m)]

where f_p is the frequency, which can be determined with the method of spectrum analysis (Xu et al. 2001), a_0, a_p and b_p are the Fourier's coefficients, which can be determined with the least square method (Chen et al. 1996), m is the number of the term of the Fourier's series.

Mathematic models containing a linear trending term and a periodic term can be obtained with the long series of the tide and water levels at the observation wells (Fig. 2). Models for the tide ($Z(t)$) and wells ZK34 ($P_1(t)$), B8-3 ($P_2(t)$) and ZK17 ($P_3(t)$) are as follows:

$$Z(t) = a_0 + \sum_{p=1}^{7} a_p \cos 2\pi f_p t + \sum_{p=1}^{7} b_p \sin 2\pi f_p t \qquad (3)$$

$$P_1(t) = -0.0002t + 1.5748 + a_0 + \sum_{p=1}^{11} a_p \cos 2\pi f_p t + \sum_{p=1}^{11} b_p \sin 2\pi f_p t \qquad (4)$$

$$P_2(t) = -0.0002t + 2.6069 + a_0 + \sum_{p=1}^{11} a_p \cos 2\pi f_p t + \sum_{p=1}^{11} b_p \sin 2\pi f_p t \qquad (5)$$

$$P_3(t) = -0.0002t + 3.6142 + a_0 + \sum_{p=1}^{11} a_p \cos 2\pi f_p t + \sum_{p=1}^{11} b_p \sin 2\pi f_p t \qquad (6)$$

where f_p is given in Table 2, and the Fourier's coefficients are listed in Table 3. In Eq.3, there are seven terms of the Fourier's series, whereas in Eqs. 4, 5 and 6 exist 11 terms of the Fourier's series.

Models 3, 4 5 and 6 can be employed to compute and predict changes in the tide and water levels. Figure 10 shows the observed and computed series of the tide and water levels for the first time observations in 1986 and predictions of 25 days for wells ZK34, B8-3, and ZK17 and 30 days for the tide. The computed water levels fit the observations perfectly and exhibit changes similar to the observations. They show fluctuations with the syzygy tide and the neap tide, and a decreasing trend in water levels is also displayed at the observation wells. Only in the first several days of prediction of the tide are the predicted tidal ranges smaller than expected.

Summary

Tide-induced groundwater levels in coastal aquifers in Beihai have fluctuations similar to those of the diurnal ocean tide, but the amplitude of the water levels is significantly smaller than the tidal range. The tidal coefficient varies from around 0.1 to 0.5, depending on the distance from the coast. The amplitude of water levels or the tidal coefficient decreases roughly exponentially with the distance from the coast. Water levels at observation wells about 3,300 and 4,200 m from the northern and southern coasts, respectively, are thought not to be affected by the tide in the Beihai area.

Table 2 Frequency of the time series of the tide and water levels for the first time of measurements

Time series	f_1	f_2	f_3	f_4	f_5	f_6	f_7	f_8	f_9	F_{10}	f_{11}
Tide	0.0371	0.0381	0.0391	0.041	0.042	0.0439	0.0801				
ZK34	0.002	0.0029	0.0068	0.038	0.0391	0.04	0.041	0.042	0.043	0.0439	0.0811
B8-3	0.001	0.002	0.0029	0.004	0.0068	0.0381	0.0391	0.04	0.041	0.042	0.0801
ZK17	0.002	0.0029	0.0039	0.0068	0.0098	0.0381	0.0391	0.04	0.041	0.042	0.0801

Table 3 Fourier's coefficients of the time series of the tide and water levels for the first time of measurements

p	Tide		ZK34		B8-3		ZK17	
	a_p	b_p	a_p	b_p	a_p	b_p	a_p	b_p
0	0.4096		−0.0114		−0.0176		−0.0138	
1	0.0889	−0.6122	0.0244	0.0106	0.0009	0.0273	0.0264	0.0062
2	0.1116	−0.1212	−0.0062	−0.0344	0.0057	0.0048	0.007	−0.003
3	1.0396	−0.0045	0.0619	0.0241	0	−0.0306	−0.0066	−0.0169
4	−0.269	−0.2181	0.0236	−0.0264	0.0634	0.0246	0.053	0.0296
5	0.1775	−0.6167	−0.0074	0.0072	0.0131	0.0014	0.0352	−0.0292
6	−0.353	0.2288	0.0047	−0.0247	−0.0108	0.0129	0.0002	−0.0196
7	0.0462	−0.1995	0.0266	0.0224	−0.0217	0.0162	0.0188	−0.0246
8			−0.0243	0.0298	−0.0233	0.0204	0.0215	0.0139
9			0.0022	−0.0336	−0.0151	0.0052	−0.0269	0.0387
10			0.0738	0.0106	−0.0116	−0.0395	0.0022	−0.0275
11			0.0056	0.0095	0.0530	−0.0093	0.0474	−0.0169

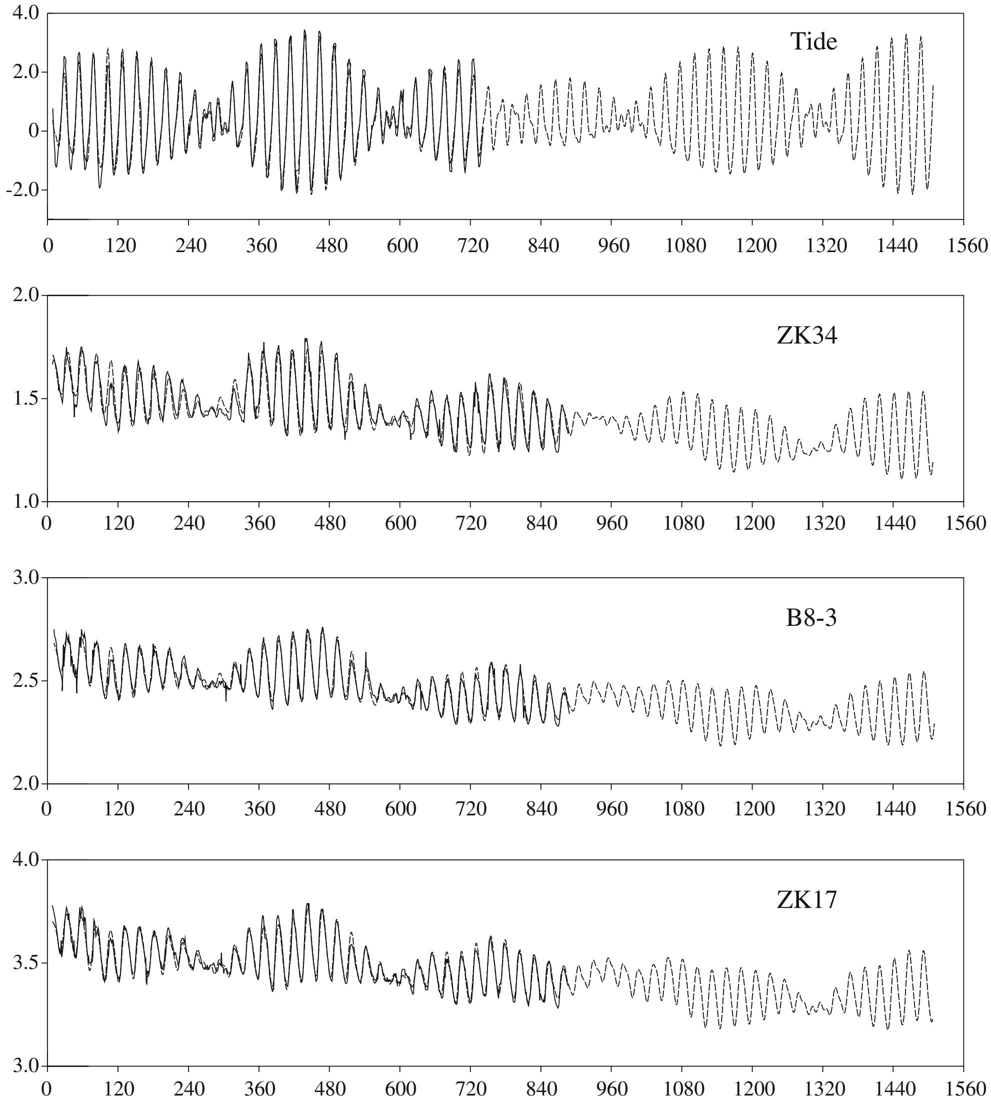

Fig. 10 Fitting and prediction of the tide and groundwater levels near the coast (*solid line*, observed data from December 15, 1986 to January 20, 1987; *broken line*, computed data. Vertical coordinate is the elevation of water levels (m), horizontal coordinate is the time (h); water levels at ZK17 are added by 1 m)

Long time series of observations of the tide and water levels and results of spectrum analyses show that the tide and the groundwater levels in coastal aquifers near Beihai have fluctuations of a long period of 14.37 d and two short periods of 24.7 and 12.5 h. Time lags of water levels to the tide at three observation wells 2,175, 2,350 and 2,375 m from the coast are 5.5, 6.25 and 7 h, respectively. The time lag increases roughly linearly with the distance from the coast. To obtain reasonable results, observations of the tide and groundwater levels are as long as possible (longer than 1 month) and the time interval of the observations is as short as possible (not longer than 1 h).

Groundwater levels at observation wells in the coastal aquifers near Beihai exhibit not only periodic fluctuations but also a slowly decreasing trend in dry seasons. Mathematic models describing the changes in the tide or the water levels can be obtained through time series analyses, with a Fourier's series describing the periodic fluctuations in the tide or water levels and a linear function describing the decreasing trend in the water levels. Computed tide and water levels with the models can perfectly fit the observed tide or water levels and predict the changes in the tide or water levels corresponding to the syzygy tide and the neap tide. The terms of the Fourier's series in the models are not too many (only 7 terms for the tide and 11 terms for the water levels), and differ from the textbook models consisting simply of a sine or cosine function. In addition, the time for predictive computations of the tide and groundwater levels are generally not too long since the models are established only based on time series of observations. Hydraulic models describing the tide-induced groundwater levels in the coastal aquifers will further be discussed in another article.

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