Indian Journal of Geo Marine Sciences
Vol. 47 (11), November 2018, pp. 2278-2286

Tidal effects on groundwater level in coastal region under human disturbance

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Received 11 April 2017; revised 11 June 2017

Seawater intrusion has become a worldwide environmental alarming problem with global warming and sea level changes. A series of achievements have been made during last several decades, but the role of tidal effect in seawater intrusion has not yet been revealed, especially under the human disturbance. In this paper, cross-spectral and autocorrelation analysis were performed to identify the periodic relationship between the groundwater level and tidal level in a typical coastal area. After eliminating the long-term trend, Fourier transform and inverse Fourier transform were performed on the groundwater level data to extracted 0.040-0.085 frequency. Weconcluded that in the coastal region which is strongly affected by human interference, this is a effective approach to identify the tidal effects on groundwater level from other factors, especially human disturbance.

[**Keywords:** Seawater intrusion; Tidal fluctuation; Cross-spectral; Autocorrelation]

Introduction

Many countries and regions have found the problem of seawater intrusion, such as China, the United States, Australia, Lebanon, Israel, Japan, and Egypt[1]. In the early stage, the researchers assumed a static balance between the underground freshwater and saltwater, and used a model of abrupt interface between them, called the Ghyben-Herzberg formula[2]. The abrupt interface is an ideal assumption, then the results using the mixing zone model developed by Henry(1964) match the practical environment much better[3]. Thereafter, Pinder (1976) improved the numerical mixing zone model[4], subsequently many other mathematical analysis and numerical simulation methods were developed to extend the application of the mixing zone model[5,6,7,8,9,10].

Tidal fluctuation is a basic element of coastal hydrogeology, as well as a significant driving force of groundwater flow in coast aquifer[11,12]. Acworth et al.(2007) and Morrow et al.(2010) concluded that the impact of tidal fluctuation on interface of saltwater-freshwater is relatively small, but the impact on the structure and thickness of mixing zone is much more[13,14]. Further, the landform and stratigraphic characteristics of beach are considered to be key factors when evaluating the effect of tidal fluctuation on coastal groundwater[15,16,17,18].

Time series analysis can efficiently analyze the time variation patterns of hydrologicalprocesses and the impulse response characteristic of aquifer systems[19], many researchers started to use time series analysis with field measurements to solve the problem of tidal fluctuation on coastal groundwater. Lanyon et al. (1982) researched the variable process of water table with the changing of sea level near a beach in Australia[20].Kim et al.(2005) studied the changes in groundwater level and conductivity with respect to the changing sea level[21]. Their results show that the coastal groundwater quality is mainly controlled by the tide. Using water level and conductivity data, Park *et al.* (2012) discussed the hydro chemical characteristics of seawater intrusion under tidal fluctuation in fractured bedrock aquifer at the west coastal zone of North Korea[22]. Using time series, Kim *et al.* (2006) analyzed the groundwater level data collected at the eastern side of Jeju Island in Korea[23]. Although a series of achievements have been made, tidal effect on groundwater level has not yet been revealed in coastal area, especially under the human disturbance.

Materials and Methods

Laizhou Bay is located along the northwest coast of Shandong Province, China (Figure 1). The waves,

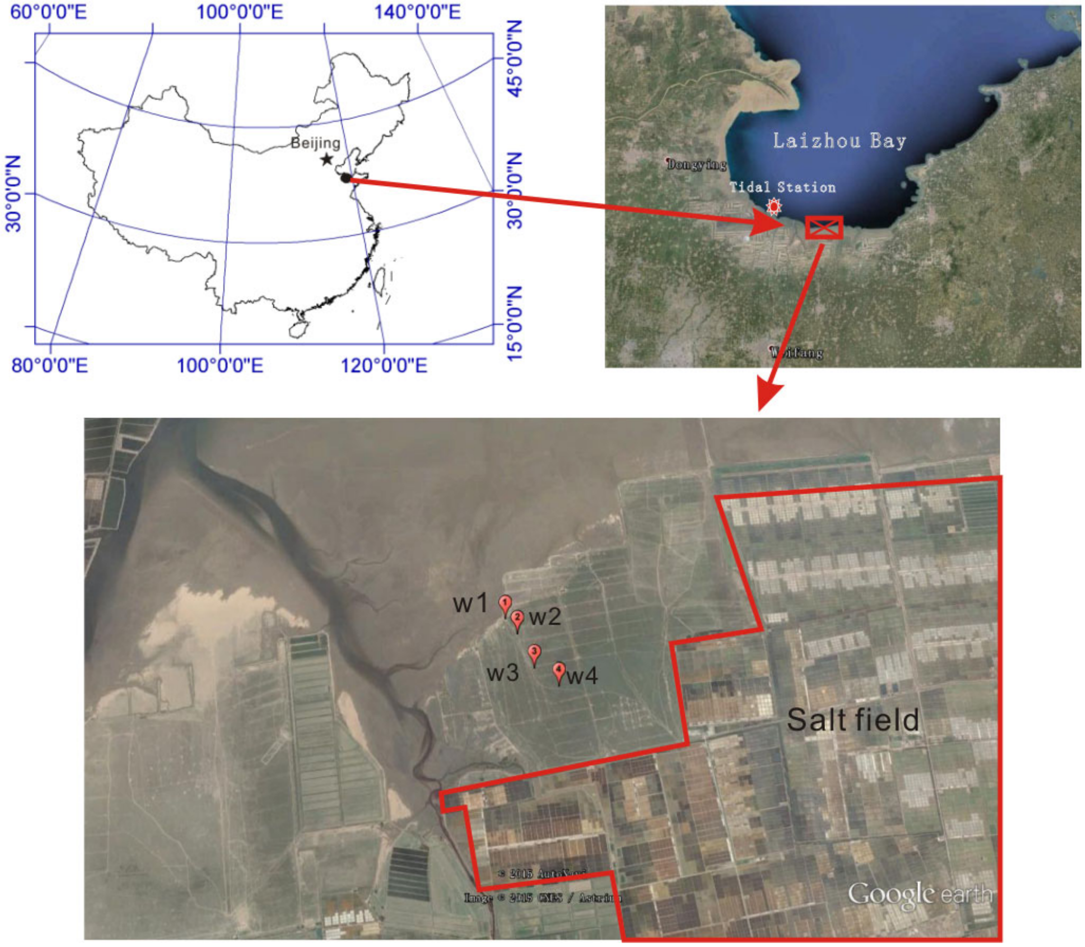

Fig. 1 — The study area and the distribution of observation wells

controlled by monsoon, is mainly stormy wave whose frequency of occurrence is up to 80%. Moreover, Laizhou Bay has a irregular mixed semi-diurnal tide. The flood tide flows in the south-west direction and the ebb tide flows in the north-east direction.

There is abundant subsurface brine resource in the southern coastal region of Laizhou Bay. It is the largest production base of salt and chemical industry in China. Its crude salt production capacity can reach 15 million tons per year. Although there are disputes on the formation of the brine, most researchers agreed that seawater is the main source of the mineral deposit[24]. Since the Late Pleistocene, this region has been on a long-term process of subsidence. Marine stratum and the continental stratum of Late Pleistocene and Holocene was researched systematically by Zhang et al. (2005)[25].They found that three large-scale seawater intrusions occurred in this region and these intrusions can be confirmed. Moreover, multilayer subsurface brines could have been formed during these three times of transgressions and regressions. In the research area, the subsurface brine is mainly within the unconsolidated sediment of Quaternary marine stratum, and the aquifer consists of mainly silt, fine sand and muddy silt. Its general degree of mineralization is 50-150 g/l, and the highest value is up to 217 g/L. The brine layers can be divided into three groups from top to bottom: the phreatic group, the upper pressure group, and the lower pressure group. Their depths below the ground surface are 0-20 m, 30-45 m, and 40-60 m respectively[24]. Thin pressure brine layer exists in part of the district, and its depth is more than 60 m. Among the groups, the phreatic brine layer is within the sandy silt layer of Holocene marine bed, and it is connected with the seawater[26].

In this study, Cera-Diver probe was used to measure the groundwater levels at four observation wells. These wells are located in the southern coast of

Laizhou Bay, as shown in Figure 1. The well of w1 is situated near the average high-tide line. Direct distances of w2-w4 to w1 are 335m, 1015m and 1550m respectively. A large number of salt pans are placed in southeast of the research area. The well of w4 is the nearest well to these salt pans, and distance is about 1.5-1.8 km. From 17:00 on December 14, 2013 to 23:00 on January 31, 2014, the groundwater levels of w1-w4 were continuously observed for 1159 hours on an hourly basis. For the corresponding tidal levels, they were recorded at the Weifang tide station, Weifang marine environmental monitoring center. The tide station was located 20 km northwest of the observation wells (Figure 1). Measurement time of tidal levels was the same as that of the groundwater levels. There was no effective rainfall during the observation period.

Tide usually fluctuates at a regular period. Laizhou Bay has a irregular mixed semi-diurnal tide, and two main frequency components are within the frequency spectrum. When the groundwater is affected by the tide fluctuation, the effect is reflected in the two frequencies. Spectral analysis is an analytical method which can divide a time series into a series of frequencies of fixed periods. As for the cross-spectral analysis, it analyzes the degree of frequency correlation between two time series. In this study, the software Arand for Windows was used to calculate the cross-spectral function between the measured tidal level and groundwater levels. Hence, it analyzed the frequency correlation between the measured tidal levels and groundwater levels.

Under the natural state, due to the effect of tidal fluctuation, the groundwater level within the coastal region also fluctuates at a regular period. Using time series, Kim et al.(2005) have verified this phenomenon[21]. However, in particular area like Laizhou Bay, this periodic law may not be apparent under the strong human interference. Thus, it is necessary to identify the factors that affect groundwater level due to tidal fluctuation. In this study, using Fourier transform, the time series of the groundwater levels were transformed into a frequency spectrum. Then, the frequency information affected by the tide was extracted. Finally, using inverse Fourier transform, the frequency information was transformed back to time series.

Autocorrelation analysis can partly describe the character of a random process, and it can show the relativity between adjacent data in a time series. If a time series is uncorrelated, the autocorrelation function decreases rapidly, and its value becomes zero within a short time. If a time series has strong correlation and long-term memory effect, the autocorrelation function is a curve with a slow decreasing slope, and its value is nonzero even after a long time[15]. Kimet al.(2005)and Tularam et al.(2006)derived the mathematical formula of the autocorrelation function[23,27].

Results and Discussion

In this study, due to the shortage of accurate altitude data, the absolute altitude of the groundwater levels was not considered. Instead, only the relative groundwater levels were used to analyze the fluctuation changes. Hence, the average values of the measured groundwater levels and tidal level were calculated first. Then, the time series were formed using the measured data subtracting their respective average value. Figure 2 shows the groundwater levels and the tidal level (subtracting the average values). The results display that the tide is irregular semi-diurnal, which means the tide period is 12 hours, and the amplitudes of adjacent tides are not equal.

During the observation period, the tidal fluctuation is relatively regular and the amplitude do not change significantly. For the changes of groundwater levels in w1-w4, it is apparent that the trends of all four wells are the same, and the groundwater levels have an upward fluctuation tendency. The decreasing exploitation of subsurface brine is related to this upward tendency. Because the tidal level was basically stable, the decrease in brine exploitation made the seawater intrude into the land, the groundwater levels therefore raise gradually.

Among the four wells, the largest fluctuation range of water level is w1, which is more than 120 cm. For w2 and w3, the ranges are basically the same, about 85 cm. The range of w4 is the smallest, which is less than 40 cm. Further, the groundwater levels are lower from w1 to w4 in the sea to land direction. Figure 2 shows the groundwater levels in w1-w4 increase steadily from measurement beginning to 300 hours. After 300 hours, the groundwater levels fall slightly, and the lowest level is at about 400 hours. Soon after, the trend is back to a stable uptrend. Because there were no effective rainfall and no abrupt change in sea level, this phenomenon can be attributed to the abrupt change in groundwater exploitation. Not only the overall rising groundwater level trends of w1-w4 are the same, but also the corresponding times of peak in

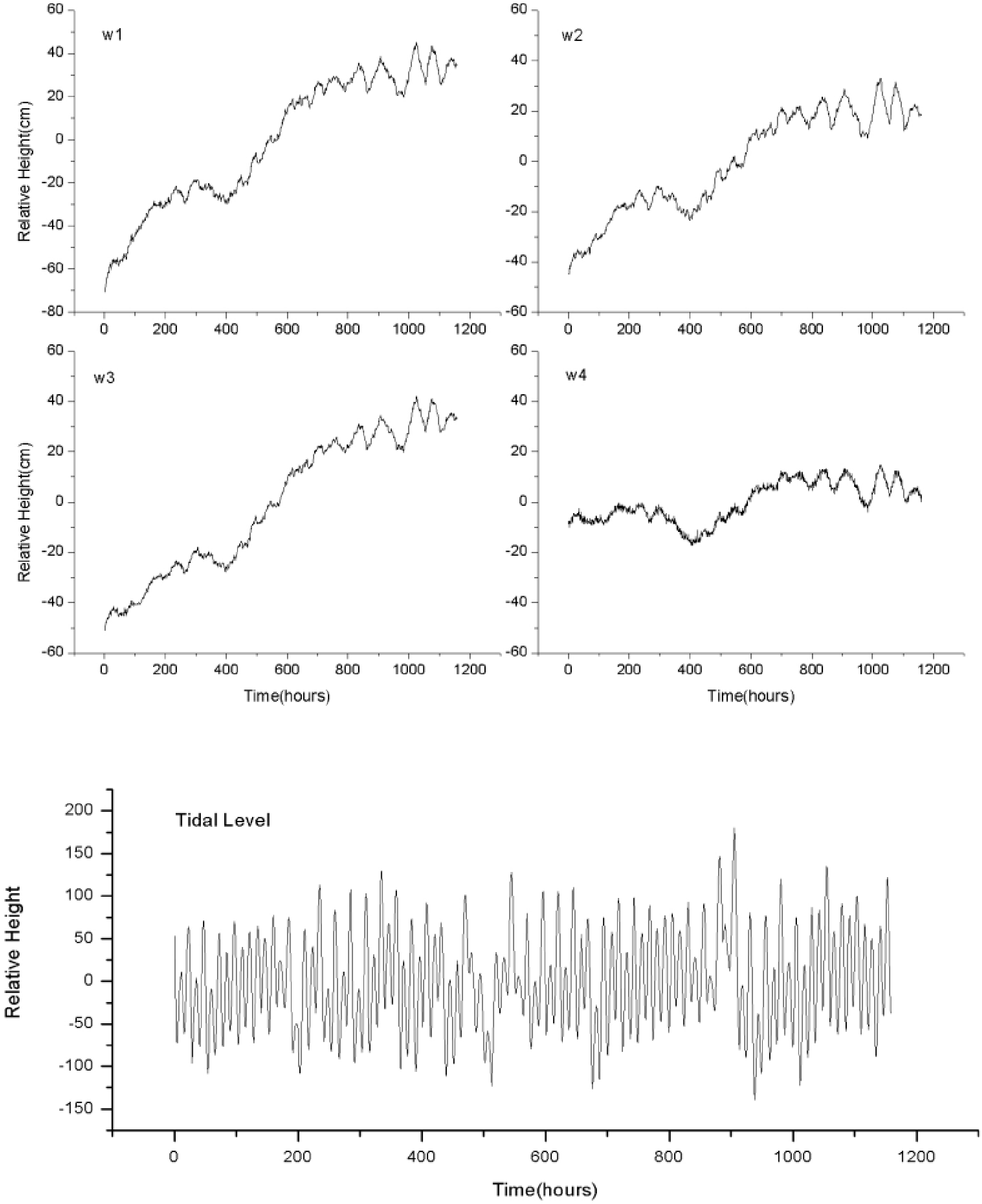

Fig. 2 — Variation of groundwater levels of observation wells and tidal level with time

the fluctuation are basically the same, which shows that the main controller of groundwater levels in w1-w4 is the same.

The cross-spectral analysis results of the groundwater levels of w1-w4 and the tidal level are shown in Figure 3, and there are two main wave crests in the tidal level. Their frequencies are about 0.083 and 0.042, and the corresponding periods are 12 hours and 24 hours, which are the same as those in Figure 2. Moreover, the spectral density analysis results of w1-w4 show that there are also wave crests around the frequencies 0.083 and 0.042, which are the same as those in the spectral density of the tidal level.

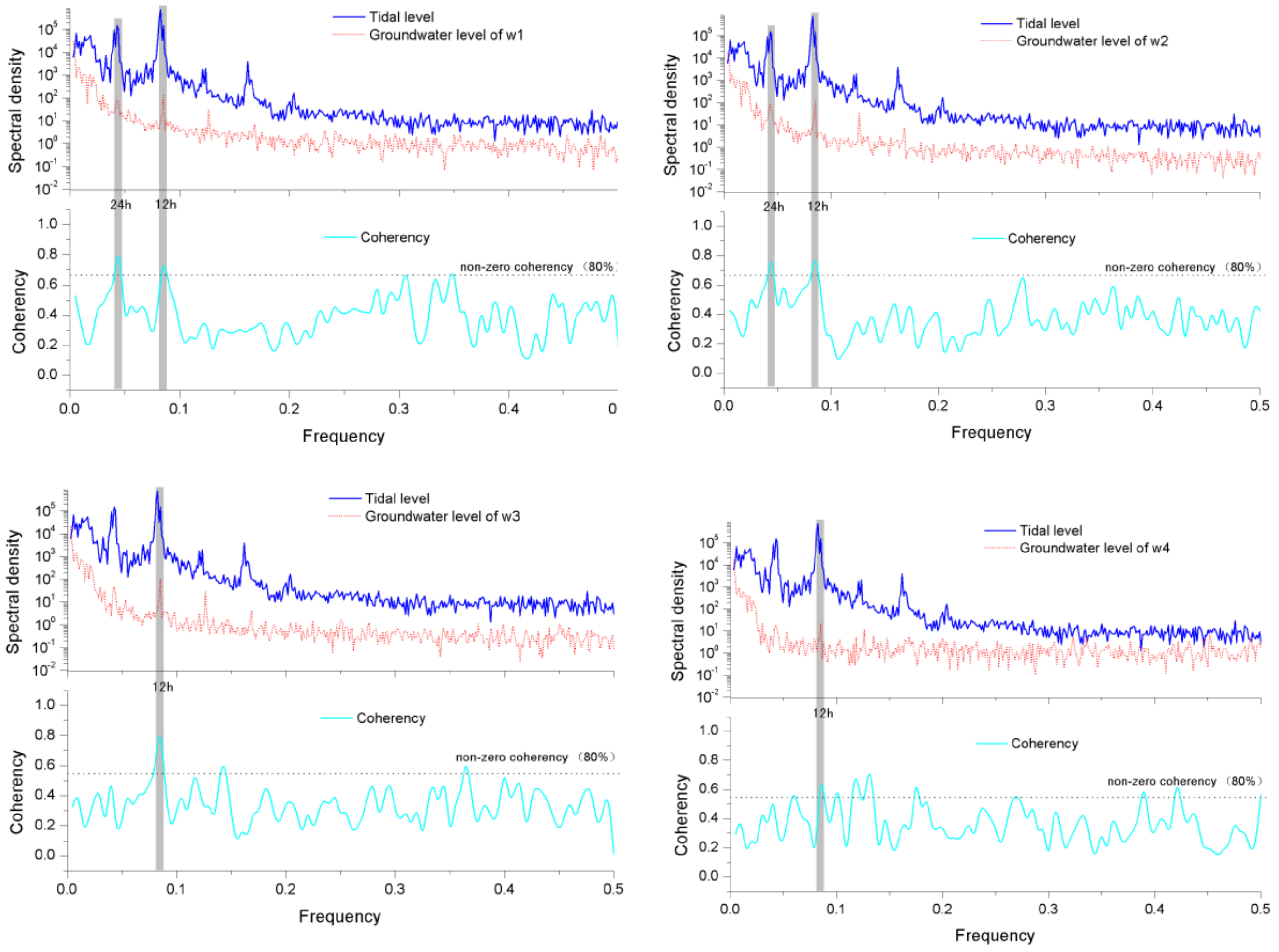

Fig. 3 — The cross-spectral analysis results of the groundwater levels and tidal level

The spectral density is higher when the groundwater level frequency is lower than 0.042, which is related to the long-term trend caused by human interference. Further, according to the cross-spectral analysis, when the frequency is around 0.083 and the corresponding period is about 12 hours, all the cross-spectral analysis of groundwater level of w1-w4 pass the 80% consistency test. This demonstrates that the groundwater levels of w1-w4 are significantly affected by the 12 hours period tidal fluctuation. In addition, the groundwater levels in w1 and w2 also pass the 80% consistency test when the frequency is 0.042, while the consistencies of the groundwater levels in w3 and w4 are not obvious, but the values are high. This is an indication that the groundwater levels are affected by the tide. For 24 hours period, it is not easy to identify the effect, which shows that the effect of the tide on the groundwater decreases when the distance from the shoreline into the land increases.

The results of the autocorrelation analysis are demonstrated in Figure 4. The results further strength the understanding of the 12 hours and 24 hours tidal periods, as positive and negative peaks of the auto correction tidal data transform every 6 hours. Time interval of two adjacent positive peaks and negative peaks is about 12 hours, but the adjacent peaks are not equal. However, they are consistent with the next peak, and the negative and positive peaks have similar characteristics. With increasing time, the autocorrelation coefficient shows there is less volatility in the overall trend. This finding is consistent with that of Kim and Tularam[23,27].

The auto correction curve of water level w1 has no obvious trend, and the periodicity is also not clear. This is because there is a long-term trend in the original data, and this long-term trend has concealed the periodicity characteristics. So, it is necessary to eliminate the long-term trend in groundwater level.

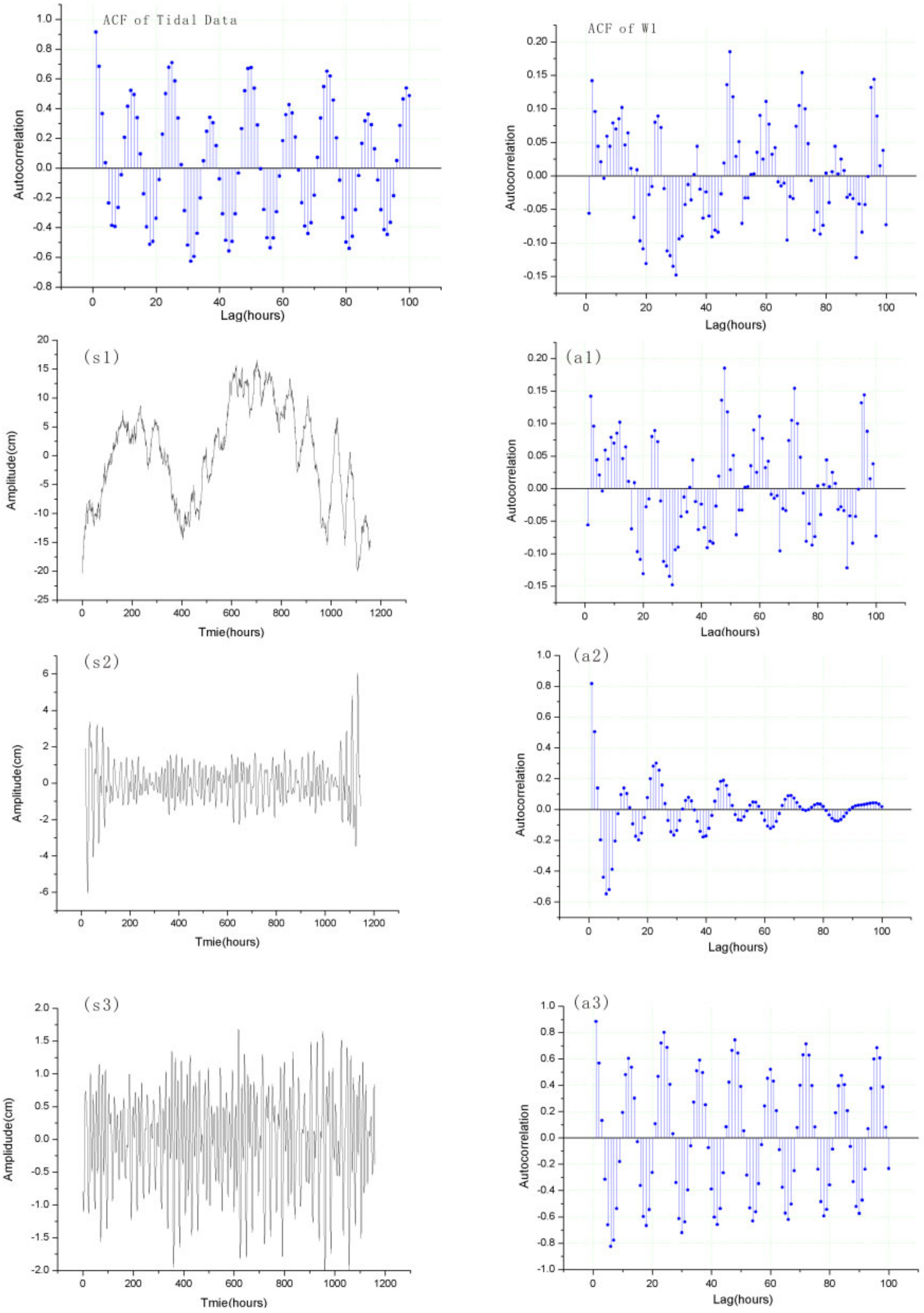

Fig. 4 — Groundwater level of w1 under different conditions and the autocorrelation curve (Note: s1-s3 are the groundwater level data of w1 with the treatment of the long-term trends, 0.040-0.085 frequency filtering, as well as the filtered curve after eliminating the long-term trend, a1-a3 are the corresponding autocorrelation curve of the s1-s3 curves)

Figures 5-s1 and 5-a1 demonstrate the groundwater level and autocorrelation curve after the elimination. The rising trend of the groundwater level has disappeared, but the autocorrelation curve is also not obvious. According tothe cross-spectral analysis that w1 groundwater level has the same 12 hours and 24 hours period as that of tidal level data at the frequency of about 0.042 and 0.083(Figure 3), so the frequency of 0.040-0.085 could cover the component of the groundwater level affected by the tidal fluctuation.

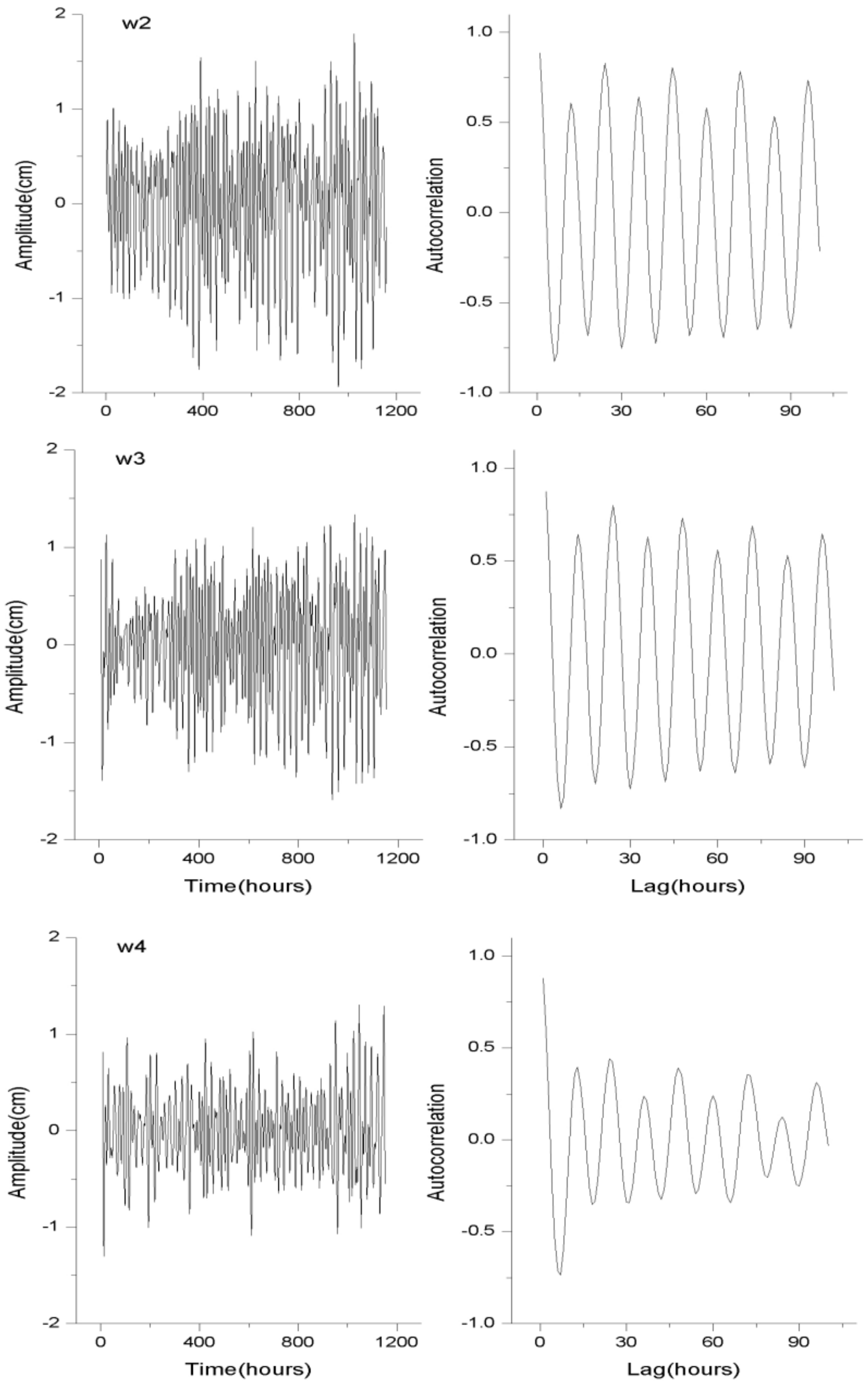

Fig. 5 — Groundwater levels and autocorrelation curves of w2-w4 after elimination of long-term trends

Hence, the method of Fourier transform and inverse Fourier transform are used to extract the groundwater level within the 0.040-0.085 frequency. Figures 5-s2 and 5-a2 show the groundwater level and the autocorrelation curves after the transformation. The groundwater level curve has periodicity, but the groundwater level at the beginning and the end of the measurement period are abnormal. This means that the groundwater level is affected by the long-term trend significantly. Although the autocorrelation coefficient also shows periodicity, it decreases rapidly with time, and there is no regular peak. Further, by eliminating the long-term trends, and extracting the data for the 0.040-0.085 frequency, the groundwater level data of w1 are processed, and the results are shown in Figures 5-s3 and 5-a3. Groundwater level data are similar to the tidal data, and auto correlation curves are basically the same, indicating that by eliminating the human interference, it is an effective method to identify the factors that affect the groundwater level in w1. Figure 5-a3 displays the weakening trend of the autocorrelation curve with time, which is an indication that the effect of tidal action on the groundwater level in w1 weakens over time [27]. In addition, the autocorrelation coefficient of the groundwater level does not fluctuate uniformly along the horizontal axis, and of the adjacent two peaks, the positive value is generally larger than the absolute negative value. This expresses that the effect of tidal fluctuation on the groundwater level is greater during the high tide as compared to the low tide.

The results of the groundwater level spectral analysis of w2 and w1 are the same as their cross-spectral analysis results (Figure 3). Groundwater levels of w3 and w4 have passed the consistency test with tidal level data at 0.042 frequency. Although the consistency test result is not significant at 0.083 frequency, the value is relatively high which makes it easy to be compared. The processing is conducted with long-term trends eliminated and the groundwater level within the frequency of 0.040-0.085 extracted, and the results of w2-w4 are displayed in Figure 5. After treatment, the water levels in w1-w4 fluctuate with time. Further, the 12 hours and 24 hours periods are also clear, which are consistent with the data of the tidal peaks. In addition, from w1 to w4, the amplitude of the groundwater level decreases gradually in the sea to land direction, indicating that the effect of tidal action on the groundwater level is decreased gradually. Autocorrelation curves show that the regulars of w1-w4 are nearly the same, but with increasing time, the decaying autocorrelation coefficient of w1-w4 gradually increase, which is a confirmation that the effect of tidal fluctuation on the groundwater level is lessen in the sea to land direction.

Conclusion

A time series approach to identify the influencing mechanism that contribute to the effect tidal fluctuation on groundwater levels has been introduced. Based on certain practical cases, the change in groundwater levels may not only be caused by tidal fluctuation , but also be caused by some other factors, such as human exploitation of groundwater, and rainfall. These factors generally affect the result of time series analysis. In this study, the periodicity relationship between the groundwater levels and tidal level has been analyzed using the cross-spectral analysis and autocorrelation analysis. After eliminating the long-term trend in the groundwater levels, Fourier transform and inverse Fourier transform were performed on the groundwater level data to extracted 0.040-0.085 frequency. Further, autocorrelation analysis method was also used to test the extracted groundwater levels and tidal level data. We found that the periods for both groundwater levels and tidal level are 12 hours and 24 hours. Furthermore, the periodicity of the tidal fluctuation on the groundwater levels is lessen with increasing distance from the shoreline to the land. A stronger correlation was found for the 12 hours period than the 24 hours period. We concluded that in the coastal region which is strongly affected by human interference, it is a good approach to eliminate long-term trend from the data and then extract the data for a certain frequency range, and the factors that caused tidal fluctuation on the groundwater levels can be identified.

Acknowledgements

This research was supported by ChinaNational Key Research Project (2016YFC0402801), and National Natural Science Foundation(41406072).

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