ANALYZING THE RESPONSE OF GROUNDWATER LEVEL TO TIDAL WAVE IN COASTAL AQUIFER, TAOYUAN, TAIWAN

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ABSTRACT: Groundwater fluctuation in the coastal region is affected primarily by tidal oscillation. This study aimed to identify the effects of ocean tides on groundwater levels in the coastal aquifer of the Taoyuan-Hukou Table plain, Taiwan. In this study, Fast Fourier Transform (FFT) analysis was conducted to investigate the frequency of groundwater level based on the field monitoring data. The field observation showed that groundwater level fluctuates following the tide and fluctuations similar to a waveform, which suggested tidal wave-induced groundwater level changes periodically. The frequency analysis indicated that groundwater fluctuation was influenced by the multi constituents tide and significant component of the semidiurnal tide (M_2) dominant with a period of 12.3 hours. The results also indicated that the fluctuation amplitudes decreased exponentially, and phase lag increased linearly for dominant tidal signals as they propagated inland. The tidal effects on the groundwater level reached up to 400 m inland from the coast.

1. INTRODUCTION

The coastal region is considered one of the most vulnerable areas since a large portion of the world's population lives there (Bear et al., 1999). In these regions, the coastal aquifer is the primary freshwater supply source for most coastal areas worldwide. However, these aquifers may limit their use as freshwater sources due to seawater intrusion (Werner et al., 2013).

In most coastal regions, tidal forcing is the critical factor that mainly controls groundwater level dynamics and groundwater discharge dynamics (Zhou et al., 2016). Groundwater level fluctuation is caused by infiltration from surface water, the GWL variation due to tidal effect by nearby rivers or coasts, and ocean tides affected by the interaction between astronomical planets (Shih et al., 2000). The groundwater level is controlled by the periodic rise and fall of the tide due to the hydraulic connection between ocean tides with the coastal aquifer. In particular, it is necessary to investigate the relationship between coastal groundwater level dynamics and tidal forcing, which can understand groundwater flow and salt distribution regime and mixes the fresh and saline water. Therefore, these studies could theoretically support coastal environmental and ecological issues, especially contaminated remediation on beaches.

Numerous researches related to the behavior of coastal aquifers have been intensively investigated in recent years. A time-series monitoring model has been developed to solve the beach water table response to tidal fluctuation in many kinds of the aquifer system (Shih et al., 2000; Wang and Tsay, 2001; Kim et al., 2005; Almedeij and Al-Ruwaih, 2006; Hyun et al., 2013; Xun et al., 2006; Fuentes-Arreazola et al., 2018; Chung et al., 2018; Ratner-Narovlansky et al., 2020). Observations of two-dimensional variations in groundwater level on a sandy beach, Lanyon et al. (1982) found that time series curves showed water table change at individual wells along with the profiles. These markedly asymmetrical and oscillation ranges depend on the tidal range and distance landward from the beach face. The implicit finite-difference numerical approaches have been widely used to simulate beach water table response to tidal forcing (Ataie-Ashtiani et al., 2001; Robinson et al., 2007; H. Li et al., 2008; Kuan et al., 2012; Levanon et al., 2017). They found that tide-induced groundwater fluctuation with a periodicity similar to tidal frequency and salt distribution variation. When a tidal wave propagates inland through a coastal aquifer, the amplitude decreases exponentially, while the phase increases with distance, either linearly or as a square root function.

For the coastal groundwater level tidal dynamics, some researchers studied the impact of earth tides on the water level of the monitoring wells. They found that tidal components cause the water level in the monitoring well to change by 1-2 cm. Shih et al. (2000) used spectral analysis to study the effect of ocean tide on groundwater level in the Choshuihsi alluvial plain. The results showed that it is not significant for the seawater and groundwater level nearby influenced by pressure variations. Otherwise, the astronomical tidal components were the main factor that caused ocean water and groundwater levels to fluctuate. Besides, oceanic tidal fluctuations, which subjected coastal aquifer systems, comprise tens of constituents with different fluctuation frequencies and amplitudes (Pawlowicz et al., 2002). It possibly leads to complex and irregular groundwater discharge and salinity distributions. Yu et al. (2021) showed new low-frequency signals in the groundwater recharge and salinity distributions generated by the interaction among tidal constituents.

The present study would be expected to understand the groundwater level dynamic in the coastal aquifer of the Taoyuan-Hukou Table plain, which is located on the northwestern coast of Taiwan. In point of literary, there is still limited research on quantify and quality of groundwater behavior in the alluvial coastal plain along the western coast. It is known as Taiwan Strait, a very complex tidal zone containing multiconstituent tides (Jan et al., 2004). This study used frequency analysis to investigate the groundwater behavior under tidal effects by using the Fast Fourier Transform algorithm known as developing the Discrete Fourier transform (DFT), which removes duplicated terms in the mathematical algorithm to reduce the number of mathematical operations performed.

2. MATERIAL AND METHODOLOGY

2.1 Study site

Taoyuan- Hukou tableland is an alluvial system of late Quaternary, consisting of Pleistocene conglomerates and sandstones overlain unconformably by lateritic terrace deposits. The geological structure, combined with the tectonic activity, extends through different original terrace flats and creates a complex topographic feature in this area (Lin et al., 2007). Besides, the hydrological scheme there is influenced by the ocean tides of Taiwan Strait, known as a very complex tidal zone (Jan et al., 2004). The average annual precipitation is 1500 mm to 2000 mm, but the rain is concentrated from May to September.

The area of interest for this study is located at TaiCOAST Station of National Central University, Xinwu district, Taoyuan city. There are several wells drilled at the location of the backshore and foreshore at the field site, as shown in Figure 1.

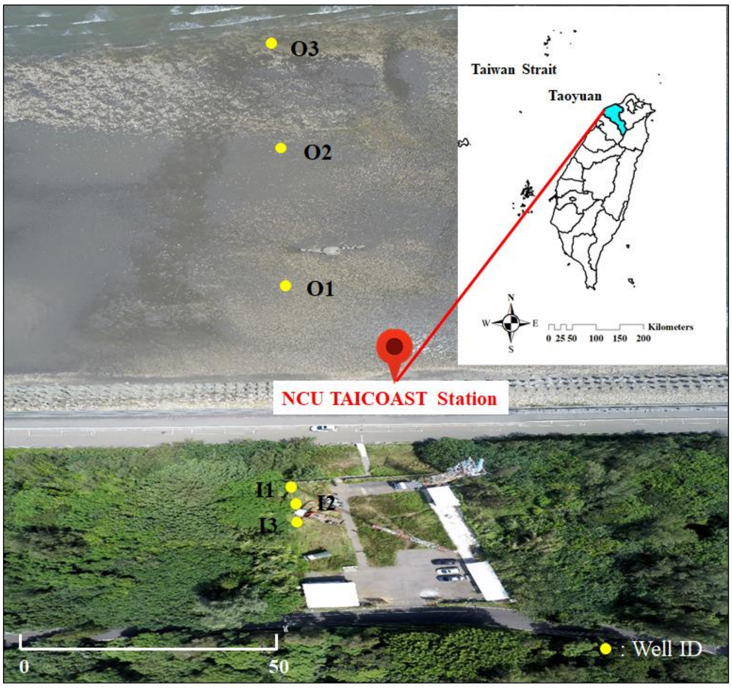

Figure 1. Location of NCU TaiCOAST station and monitoring wells

2.2 Groundwater level monitoring

Measuring groundwater level was conducted on the transect, perpendicular to the ocean. The location and information of the monitoring wells in the transect are shown in Table 1. The reference datum is based on the Taiwan geodetic datum 1997 (TW1997). Water levels were recorded automatically at these wells. AQUATROLL was installed at I1, I2, and I3 wells to measure water levels at specific depths. CTD-Diver was installed at O1, O2, and O3 well, which provides continuous measurements of absolute pressure and temperature. At the same time, barometric pressure was measured using Barometric Diver during the period. The water head was then calculated by absolute pressure and barometric pressure based on the reference depth of each well. Rainfall was negligible during the measured period.

Table 1. Description monitoring wells

Well ID	Latitude	Longitude	DS	LSE	WD
O3	250744.833	2762120.862	83.0	0.081	7.73
O2	250768.747	2762098.530	50.0	0.346	7.74
O1	250811.800	2762069.382	2.10	1.461	7.82
I1	250843.186	2762023.753	-57.0	6.477	100
I2	250847.522	2762020.696	-63.0	6.497	50
I3	250851.014	2508510.014	-68.3	6.516	50

(Note: DS is the distance from the shoreline assigned of 0 [m]; LSE is the land surface elevation [m]; WD is the well depth [m])

2.3 Fast Fourier Transform algrorithm

Frequency analysis is a technique that allows us to discover the complex periodic behavior of some hydrological data (e.g., rainfall, ocean tides). The frequency domain is beneficial for data manipulation, as it permits extracting a signal with a particular frequency that can be unclear in the time domain data (Acworth et al., 2015). Fast Fourier transform is a mathematical method for transforming the time-series data to the frequency domain. FFT computes the DFT and produces precisely the same result as evaluating the DFT.
Data collected in the field site were computed the discrete Fourier transform (DFT). For x and y, length n are Fourier transform and inverse Fourier transform, respectively. The computation of the discrete-time data is calculated using a fast Fourier transform (FFT) algorithm in MATLAB. These transforms are defined as follows (Frigo and Johnson, 1998):

$$Y(k) = \sum_{j=1}^{n} X(j) W_n^{(j-1)(k-1)} \quad (1)$$

$$X(j) = \frac{1}{n} \sum_{j=1}^{n} Y(k) W_n^{-(j-1)(k-1)} \quad (2)$$

Where $W_n = e^{(-2\pi i)/n}$ is one of the n roots of unity (3)

3. RESULTS AND DISCUSSION

3.1 Groundwater level fluctuation

During the field investigation, monitoring data analysis showed that the water level fluctuations were recorded in five complete tidal cycles (Figure 2). Hydraulic heads gradually decreased in a seaward direction. The average groundwater level on the most seaward well (O3) is the lowest, and its range is from 2.40 to 2.81 m (above reference datum height), while the average GWL on the most landward well (I1) is highest with a range from 0.64 to 0.75 m. However, the lowest range is from 0.41 to 0.55 m at I2, located 63 m from the shoreline. The average groundwater level variation by distance is given in Table 2.

Table 2 Monitored groundwater level from the shoreline

	I3	I2	I1		O1	O2	O3
Distance (m)	-68.3	-63	- 57	0	2.1	50	83
Average GWL (m)	4.51	4.36	4.46		1.85	1.06	0.90
Range (m)	0.64-0.75	0.41- 0.55	0.6-0.78		1.0-1.02	1.81-2.1	2.45-2.55

(Note: distance is 0m indicating the location of the shoreline)

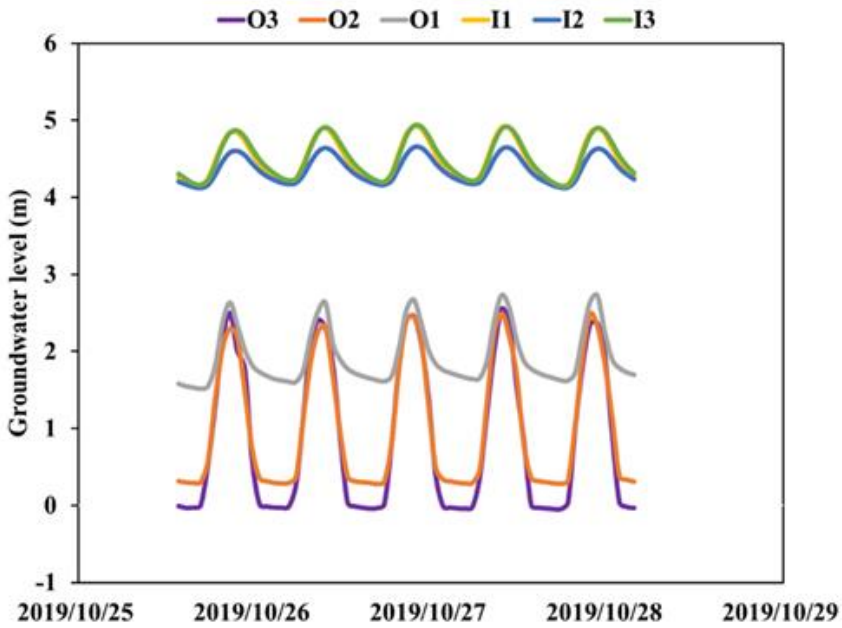

Figure 2. Groundwater level monitoring at the observation wells

3.2 The tidal variation on groundwater level

Data collected during two field investigations were subjected to Fourier transform analysis using the FFT function in MATLAB. The results illustrate the identification of different peaks representing periodical phenomena at the site. Groundwater variation was influenced by three dominant constituents, in which the amplitude and the phase lag are given in Table 3 and Figure 3. Each component had its period, phase, and amplitude, representing the dynamic of groundwater-related tidal variation. These behaviors of groundwater fluctuation were found to repeat to each other and change with flowing periodicity. The results showed that a frequency of 2.258E-05 1/s corresponding with a period of 12.3 hours was strongly detected at all monitoring wells. These results indicated that the effect of semidiurnal appears to be closely related to astronomical tides as M2 on groundwater significantly. According to Huang and Yu. (2003), they pointed out that the M2 tidal movement plays a role in the western coast of Taiwan. Besides, two other tidal constituents were detected, which illustrated a local wave that leads to groundwater variation with 6.15 and 4.1 hours.

We found only two constituents (2.26E-05 1/s and 4.52E-05 1/s) in the inland area, similar to wells in the ocean area. The frequency of 6.775E-05 1/s was absent from the inland zone, indicating the reduction of the ocean tide as penetrating to the inland. The effect of ocean tides was decreased when propagating to the inland due to complex beach topography.

Table 3 Fast Fourier Transform analysis for the monitoring wells.

ID	Tidal constituent	1	2	3	ID	Tidal constituent	1	2
O3	Frequency (1/s)	2,26E-05	4.52E-05	6,78E-02	I1	Frequency (1/s)	2.26E-05	4.52E-05
	Periodicity (h)	12.3	6.15	4.10		Periodicity (h)	12.3	6.15
	Amplitude (m)	1.33	0.37	0.09		Amplitude (m)	0.27	0.04
	Phase (rad)	0.80	0.62	0.36		Phase (rad)	0.71	-0.50
O2	Frequency (1/s)	2,26E-05	4.52E-05	6,78E-02	I2	Frequency (1/s)	2.26E-05	4.52E-05
	Periodicity (h)	12.3	6.15	4.1		Periodicity (h)	12.3	6.15
	Amplitude (m)	1.10	0.37	0.04		Amplitude (m)	0.17	0.04
	Phase (rad)	0.80	0.62	0.33		Phase (rad)	0.74	-0.31
O1	Frequency (1/s)	2.26E-05	4.52E-05	6.78E-05	I3	Frequency (1/s)	2.26E-05	4.52E-05
	Periodicity (h)	12.3	6.15	4.1		Periodicity (h)	12.3	6.15
	Amplitude (m)	0.45	0.22	0.08		Amplitude (m)	0.52	0.06
	Phase (rad)	0.76	0.61	-0.52		Phase (rad)	0.58	-0.54

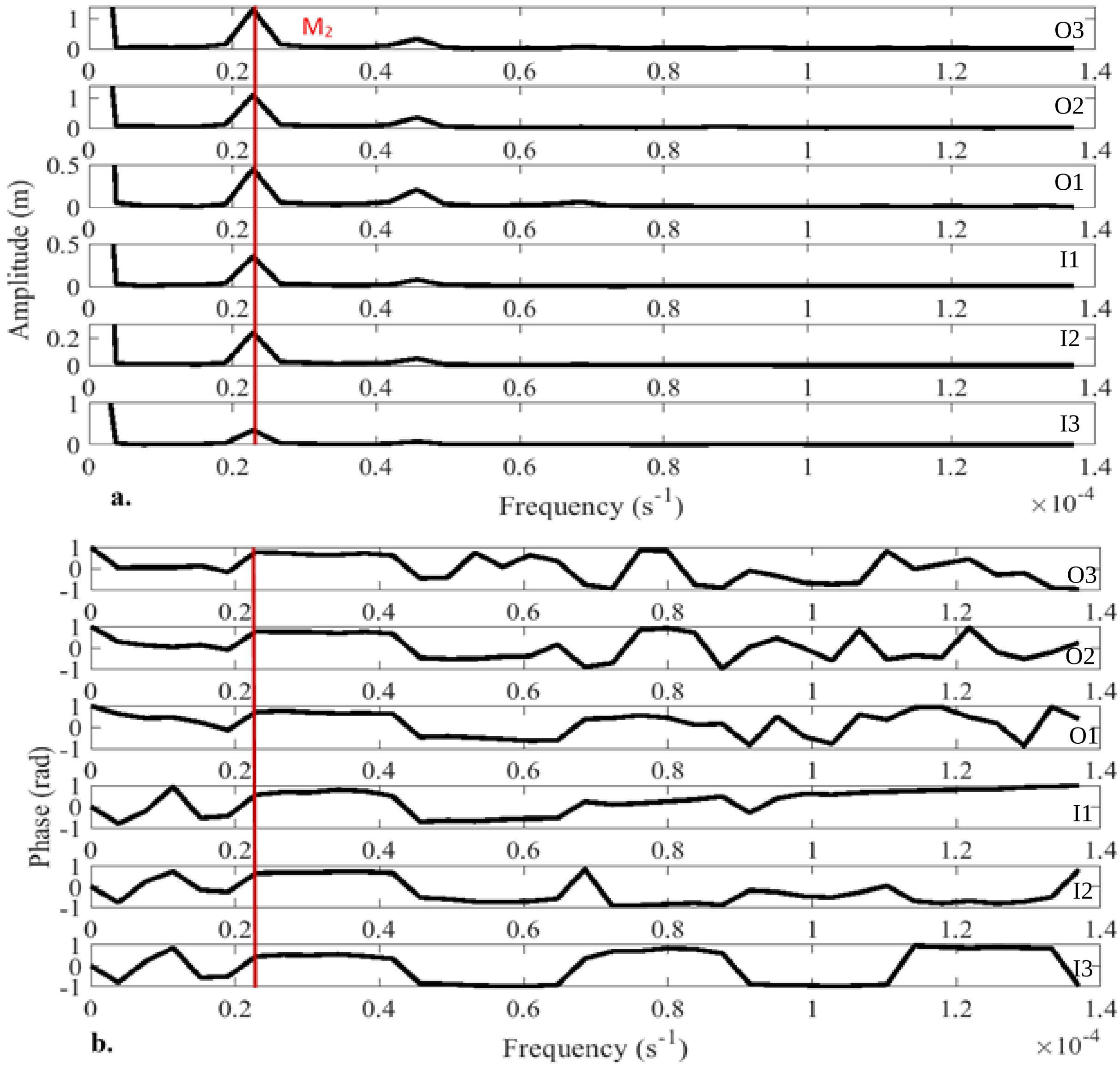

Figure 3. Fast Fourier Transform analysis of groundwater level. a. The amplitudes, and b. The phase of different frequencies. The solid line is represented for the dominant M_2 constituent.

3.3 Amplitude and phase variation of M2 along the cross-section

The amplitude damping and phase shift for the dominant constituent (M_2) were based on FFT analysis, given in Figure 4. The result indicated that when fluctuations propagate to the inland, the amplitude of signal M_2 decreased exponentially, and phase lag increased linearly, following previous results (Mao et al., 2006; Xun et al., 2006). Based on the tidal efficiency equation (Figure 4a), it is suggested that the tidal wave impacting on groundwater reached up to a distance of 400m from the shoreline. However, the trend of amplitude damping and the phase shift is not entirely apparent due to the hydrogeological heterogeneity in this area, possibly leading to different tidal impacts. According to Li et al. (2000) and Mao et al. (2006), along-shore flow interacting with the cross-shore transmission of the tidal signal lead to this trend. Besides, a large scale of seepage face formation is also considered impacting groundwater response.

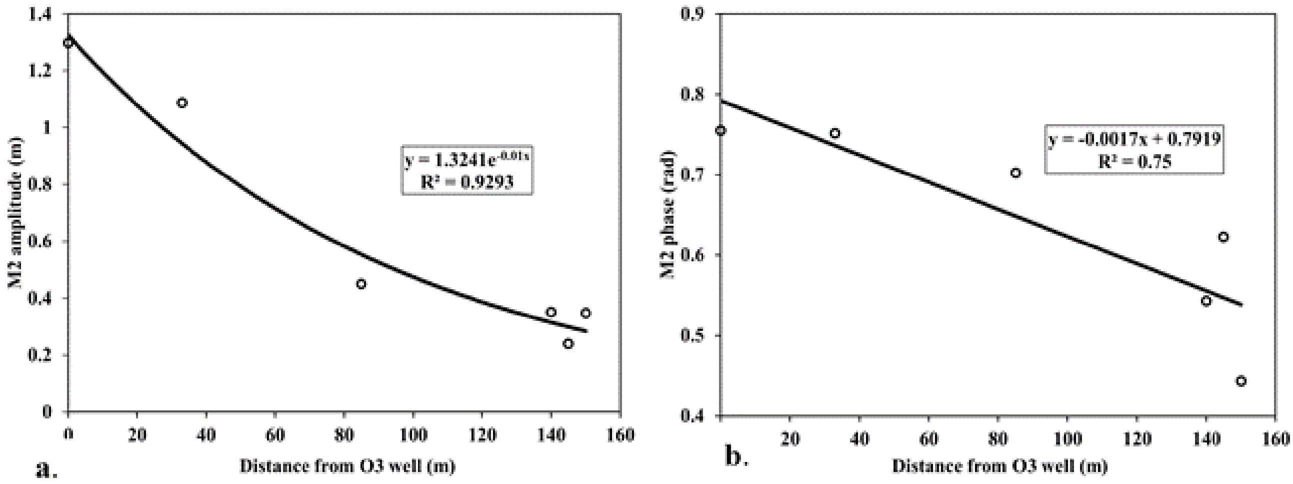

Figure 4. a. Amplitude, and b. Phase variation of M2 signal along the cross-section.

4. CONCLUSION

The present study was conducted to study the relationship between ocean tide and groundwater fluctuation in the coastal aquifer in Taoyuan City, Taiwan. Based on findings, we infer that tidal variation strongly influenced groundwater variation corresponding to tidal periodicity from the above results. These suggest that the groundwater level is subjected to change following seasonal events such as spring or neap tide. Additionally, although six principal tidal components appeared at the Taiwan Strait (Li et al., 2000), several constituents are detected in the GWL at the site. These demands were continuous observed data for more than a month with one-hour intervals to accurately provide results (Levanon et al., 2013).

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