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Spectral decomposition of periodic ground water fluctuation in a coastal aquifer

David Ching-Fang Shih,[1,3]* Gwo-Fong Lin,[2] Yee-Ping Jia,[1] Yue-Gau Chen[1] and Yih-Min Wu[1]

[1] *Department of Geosciences, National Taiwan University, Taipei 10617, Taiwan, ROC*
[2] *Department of Civil Engineering, National Taiwan University, Taipei 10617, Taiwan, ROC*
[3] *Institute of Nuclear Energy Research, AEC, Lungtan 32546, Taiwan, ROC*

Abstract:

This research accomplished by the descriptive statistics and spectral analysis of six kinds of time series data gives a complete assessment of periodic fluctuation in significant constituents for the Huakang Shan earthquake monitoring site. Spectral analysis and bandpass filtering techniques are demonstrated to accurately analyse the significant component. Variation in relative ground water heads with a period of 12·6 h is found to be highly related to seawater level fluctuation. Time lag is estimated about 3·78 h. Based on these phenomena, the coastal aquifer formed in an unconsolidated formation can be affected by the nearby seawater body for the semi-diurnal component. Fluctuation in piezometric heads is found to correspond at a rate of 1000 m h^{-1}. Atmospheric pressure presents the significant components at periods of 10·8 h and 7·2 h in a quite different type, compared to relative ground water head and seawater level. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS groundwater; aquifer; spectral analysis; tide

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INTRODUCTION

Many hydrogeological phenomena change periodically with time. Common cases include: changes in ground water level caused by infiltration from surface water, ground water level variation caused by tidal effect from rivers or coasts nearby, and ocean tides affected by the interaction between astronomical planets. For aquifers adjacent to an ocean, a river, or a lake, the ground water table fluctuates with the change in water level in the nearby surface water (Cooper *et al.*, 1965; Bredehoeft, 1967; Maas and De Lange, 1987; Roistaczer, 1988; Erskine, 1991; Shih *et al.*, 1999, 2000; Shih, 1999a,b, 2000, 2002; Shih and Lin, 2002, 2004). As such, data of the disturbed ground water levels, upon application of relevant boundary conditions, can be expressed mathematically by using the spectral relationships through time-frequency domain of tidal effects. With this approach, the spectral characteristics of field data can be used to solve for hydraulic diffusivity as a ratio of transmissivity and storage coefficient (Shih, 1999a,b; Shih and Lin, 2004). Therefore, it is an alternative approach to study aquifer parameters in a large scale by using data from a relevant setting of boundary conditions and water level fluctuation in observation wells.

The water level obtained from five river stages and seven ground water wells in the Taipei basin has been analysed by spectral analysis in time-frequency domain (Shih *et al.*, 1999). The diurnal, semi-diurnal, and quarter-diurnal tidal components of the Tanshui River appeared to be closely related to tides of K_1, M_2, and M_4, respectively. The water level data obtained from 16 ground water wells and two seawater gauge stations, coupled with atmospheric pressure measurements in an alluvial plain in the central-western region of Taiwan, are studied by using spectral analysis in the time-frequency domain. Among which, the semi-diurnal tidal component is observed to be the most noticeable signal, while the diurnal component was the next distinct signal recorded at water level stations. The spectral analysis indicates that the water level adjusted from atmospheric pressure is almost in phase and retained almost the same amplitude in the area. This implies that the effect of atmospheric pressure variations is not significant on seawater and ground water level fluctuation nearby; the astronomical tidal components were the main factor causing fluctuation of seawater and ground water levels in Choshuihsi alluvial plain (Shih *et al.*, 2000). Shih (1999a) also used cyclical frequency to derive theoretical spectral representation and studied the application of spectral density functions of ground water level and hydraulic diffusivity for unsteady state, one-dimensional, horizontal, confined and unconfined aquifer with time-dependent head boundaries on both ends. The hydraulic diffusivity, a ratio of transmissivity to storage coefficient for confined aquifers, or a ratio of transmissivity to specific yield for unconfined aquifers, can be theoretically estimated from the derived non-linear form of spectral representation. Shih (2000) also performed an uncertainty and sensitivity analysis to evaluate the applicability for determining hydraulic diffusivity of one-dimensional flow in an unconfined aquifer

* Correspondence to: David Ching-Fang Shih, Institute of Nuclear Energy Research, AEC, P.O. Box 3-7, Lungtan, 32546, Taiwan, ROC. E-mail: cfshih@iner.gov.tw

with time-dependent fluctuation of lateral head and vertical recharge boundaries, using pre-defined and analytical time series data. The studies of spectral density functions of water level for demonstrating important ground water aspects has been conducted in the northern and the central-west region of Taiwan (Shih *et al.*, 1999, 2000; Shih and Lin, 2002, 2004). The results show that the effect of pressure variations is not significant on seawater and ground water level. It is found that the astronomical tidal components seem to be the main factor causing fluctuation of water levels in the areas. Solid earth tide is almost imperceptible (Godin, 1972, p. 29). Accordingly, the influence of solid earth tide is ignored in this study. The relevant fluctuations in an aquifer system can be well analysed. A special application in central-west region of Taiwan was utilized to inversely determine hydraulic diffusivity in the field using the derived spectral representations (Shih, 1999b). In that case, hydraulic diffusivity has been evaluated as $1{\cdot}8 \times 10^6$ m^2 h^{-1} for a Quaternary alluvial plain.

Taiwan lies at the intersection of the Eurasia Plate and Philippine Sea Plate where the seismic activity is very frequent. With the rapid development of economics, the density of people is rising constantly and the high buildings and large mansions stand in great numbers, which increases the potential danger of an earthquake disaster by a wide margin. Earthquake observations and studies are therefore of importance in this district. Thus the Huakang Shan site has been built for the purpose of monitoring earthquakes in central-eastern Taiwan (Figure 1). Earthquake, ground water level, water and air temperature, rainfall are substantially monitored at the site while nearby oceanic tide level is recorded by the coastal seawater gauge station. It is interesting that the time series data observed, more or less, demonstrate the periodic variation except rainfall. They show that the external disturbance for these parameters is quite complicated. Similar phenomena were demonstrated in other studies (Shih *et al.*, 1999, 2000; Shih, 1999a, 1999b, 2000, 2002; Shih and Lin, 2002; 2004). In this study, relative ground water head supersede the actual ground water level due to losing record of reference level.

This study conducts a mathematical application in the Huakang Shan monitoring site to analyse significant constituents of the periodic ground water head variation of a coastal aquifer in an unconsolidated formation. Rainfall and atmospheric pressure are factors substantially from climate system. Most fluctuation for the ocean tidal level is dominated by astronomical components. For the target aquifer, periodic fluctuations of ground water head are somehow caused by the external disturbances. A conceptual model for hydrogeology is established for understanding water level disturbances between target aquifer and its disturbed boundaries. Ground water head signals in the study area and its cross relationship of other parameters are also demonstrated using spectral analysis in the frequency domain. Descriptive statistics is used for detecting the normality of the time series before conducting the short period signal for the stationary spectral analysis.

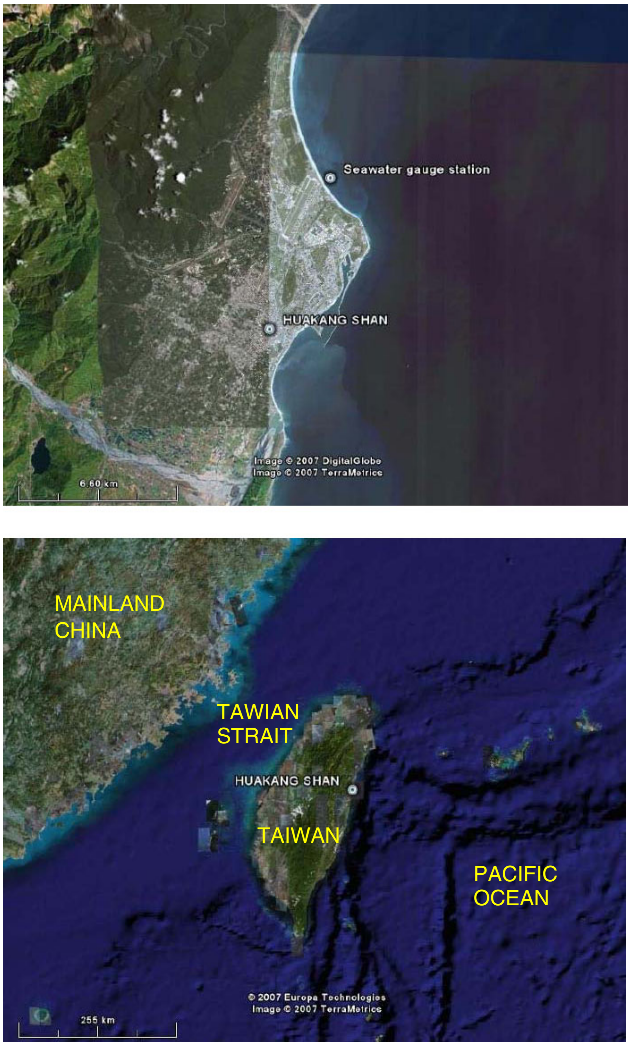

Figure 1. Well location for Huakang Shan site (original source: Google, 2007)

CONCEPTUAL MODEL OF HYDROGEOLOGY

The study site is located at Hualien City in eastern-central Taiwan and is situated at a distance of nearly 375 m to the shoreline (Figure 1). Well log data indicate that ground water well tapped in a confined aquifer of the unconsolidated formation consisting of with the gravel, sand and its mixes (Figures 2 and 3). The aquifer is present in a horizontal alluvium formation, and reaches seawater boundary at a distance of about 3·7 km from the well at a depth of about 140 m to 170 m below ground surface (Figure 3). Gravel, sand and its mixture constitute the materials of Holocene alluvia of Quaternary. Target aquifer presents likely a confined aquifer as its mixed material with coarse sand and layered muddy silt. As universally known, total energy in confined aquifer is conducted by the pressure, velocity, and datum elevation. Pressure term can be converted to hydraulic head by

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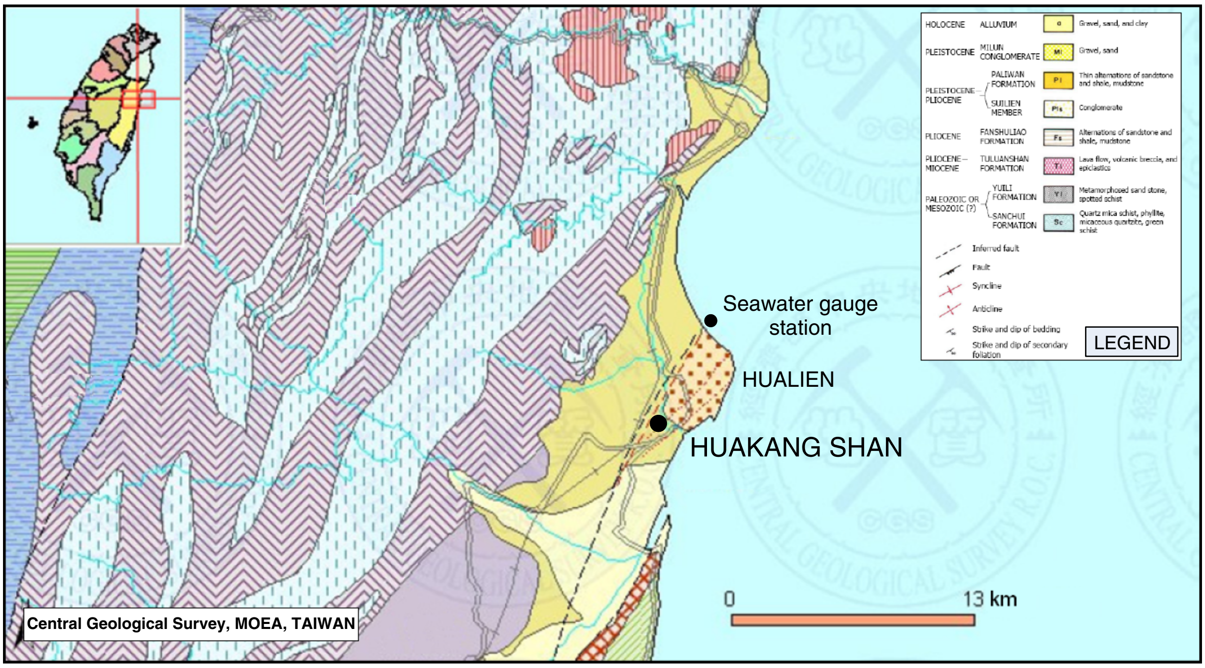

Figure 2. Geological map for Huakang Shan site (original source: CGS/TAIWAN, 2007)

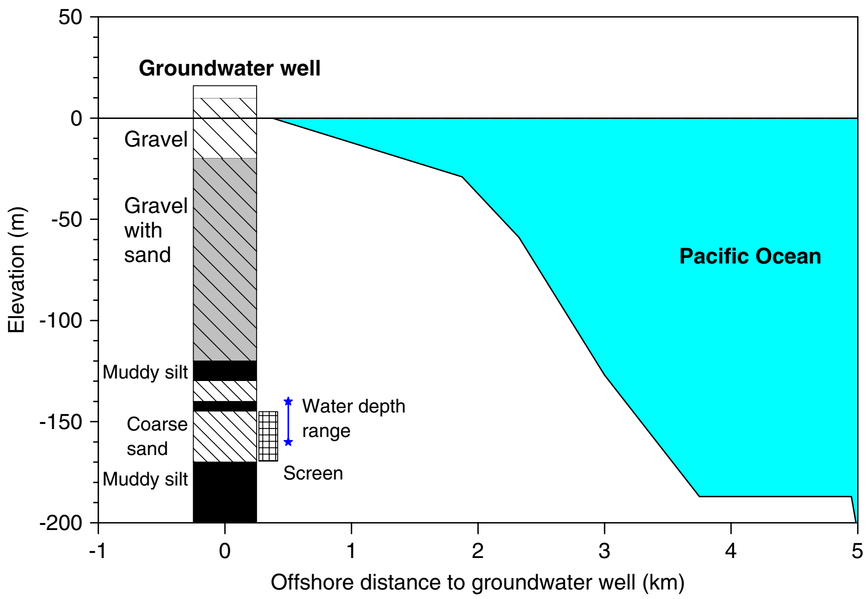

Figure 3. Hydrogeological profile for Huakang Shan site. The aquifer approximately penetrates to a horizontal alluvium formation, and reaches the seawater boundary at a distance of about 3·7 km from the well and a depth of about −140 m to −170 m

a factor, i.e. specific weight of water in this case. In porous media flow, velocities are relatively low. Then, ground water flow in confined aquifer will be balanced with driving force from differences in hydraulic heads between spatial points, if energy loss is insignificant. Tidal fluctuation of seawater level can be regarded as dominant water head in the coastal boundary of the aquifer. However, aquifer parameter as hydraulic conductivity or storage co-efficient, can be determined by analysing drawdown data from a local pumping test. Using background information, ground water head, atmospheric pressure, tidal level in the coastal boundary, temperature of air, temperature of ground water and rainfall are substantially physical factors, which can be observed. Rainfall is an external input which likely affects fluctuation of ground water flow. Temperature of air and ground water can be expected as minor factors in the environment in this study. It suggests that relative ground water head fluctuations may be induced from some factors. In such a system, barometric effect and external tidal fluctuation are main possible factors on ground water head. Temperature of air and ground water may be the indirectly index for the fluctuated ground water head. By nature, this research uses spectral analysis to analyse observed time series data to evaluate the coherence for the considered parameters. It is possible to find the relationship between input and output of aquifer system from the observed water level in coastal boundary and monitoring wells with some unknown information in the aquifer, but clearly message of input and output can be observed. The analysed message of the observed time series data also represents the average condition for the larger scale of targeted aquifer.

SPECTRAL ANALYSIS

Spectral analysis is a useful method to evaluate characteristics of the periodic fluctuation in time-frequency domain. Original presentation of the spectral techniques can be found in the studies of Bendat and Piersol (1991). Applications of spectral analysis to identify fluctuation

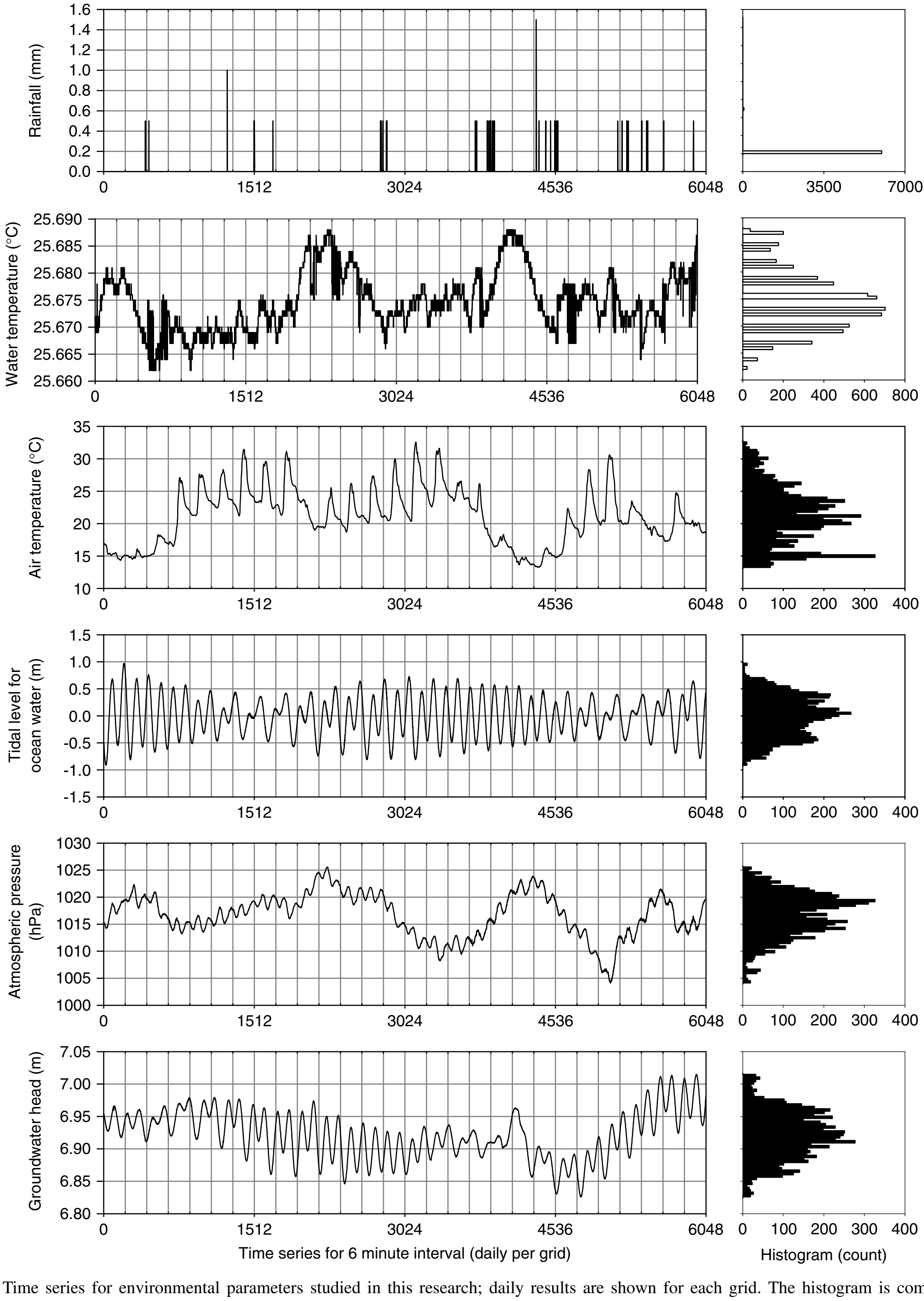

Figure 4. Time series for environmental parameters studied in this research; daily results are shown for each grid. The histogram is comprised by count. It is interesting that the observed time series demonstrates the periodic variation except for rainfall

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frequency and phase propagation in tidal water level of aquifers and rivers has been demonstrated (Shih *et al.*, 1999, 2000; Shih, 2002; Shih and Lin, 2002). Autospectral density is used to detect the stronger signal in time series, while cross-spectral density and coherence are measured to identify the intensity of specific components between two time series. The 95% confidence interval of autospectral density and non-zero coherence level for cross-spectral density are also evaluated to pick up significant components in frequency domain. Basic development of spectral analysis and its expansion to the applications in tidal hydrological aspects are available in relevant references (Bendat and Piersol, 1991; Shih *et al.*, 1999, 2000; Shih, 2002; Shih and Lin, 2002, 2004). The following briefly describes the general procedure derived by Bendat and Piersol (1991).

Considering a random variable in the time domain $x = x(t)$, the complex Fourier components in the frequency domain can be expressed as

$$X(f) = \int_{-\infty}^{\infty} x(t)e^{-2\pi f t i}dt \quad (1)$$

where x is a random variable in the time domain, t is the elapsed time, f is circular frequency, X is the complex Fourier components in the frequency domain, and i is $\sqrt{-1}$ (Bendat and Piersol, 1991).

In a practical application, let the finite time factor be incorporated in Equation (1), which can be rewritten as:

$$X(f, T) = \int_{0}^{T} x(t)e^{-2\pi f t i}dt \quad (2)$$

where T is a finite time sequence.

It is obvious that the transformed component X is not only a function of frequency but also a function of the finite time length. For a small time period, Equation (2) cannot be satisfied due to lack of statistical significance and the effect of related physical property of water level fluctuations is ignored.

Consider a stationary time series $x(t)$ of total length T, and let the time record be divided into n_d contiguous segments, such as length T_s, it follows that two-sided autospectral density function (Bendat and Piersol, 1991) for each segment can be estimated by

$$S_{xx} = \frac{1}{T_s}|X(f, T_s)|^2 \quad (3)$$

The total time length T is divided into n_d independent discrete segments T_s. To average each of the resulting components we can obtain a final 'smooth' component. It should be satisfied with required statistical significance level (Bendat and Piersol, 1991).

Given Δt as the sampling rate in time domain, the discrete frequency is defined as

$$f_k = \frac{k}{T_s} = \frac{k}{N\Delta t} \quad k = 0, 1, 2, \ldots, N-1 \quad (4)$$

where N is the length of segments.

The smoothed, one-sided autospectral density is expressed as

$$\tilde{G}_{xx} = \frac{2}{n_d N\Delta t}\sum_{i=1}^{n_d}|X_i(f_k)|^2 \quad k = 0, 1, 2, \ldots, \frac{N}{2} \quad (5)$$

In order to obtain the cross-spectral density in frequency domain for two different time series, for example $x(t)$ and $y(t)$, the raw estimate of cross-spectral density for each sub-record is computed through Fourier components $X(f_k)$ and $Y(f_k)$ using

$$\tilde{G}_{xy} = \frac{2}{n_d N\Delta t}\sum_{i=1}^{n_d}[X_i^*(f_k)Y_i(f_k)] \quad (6)$$

where $X^*(f_k)$ is the complex conjugate of $X(f_k)$, and $k = 0, 1, 2, \ldots, \frac{N}{2}$.

As previously mentioned, the smooth estimate of cross-spectral density functions for n_d blocks of time series can be expressed as

$$\tilde{G}_{xy}(f_k) = \tilde{C}_{xy}(f_k) - i\tilde{Q}_{xy}(f_k) = |\tilde{G}_{xy}(f_k)|e^{-i\tilde{\theta}_{xy}(f_k)} \quad (7)$$

$$\tilde{\theta}_{xy}(f_k) = \tan^{-1}[\tilde{Q}_{xy}(f_k)/\tilde{C}_{xy}(f_k)] \quad (8)$$

$$\tilde{\gamma}_{xy}^2(f_k) = \frac{|\tilde{G}_{xy}(f_k)|^2}{\tilde{G}_{xx}(f_k)\tilde{G}_{yy}(f_k)} \quad (9)$$

where $\tilde{C}_{xy}(f_k), \tilde{Q}_{xy}(f_k), \tilde{\theta}_{xy}(f_k), \tilde{\gamma}_{xy}^2(f_k)$ are co-spectrum, quadrature-spectrum, phase angle and squared coherence respectively for $k = 0, 1, 2, \ldots, \frac{N}{2}$.

The autospectral density using 95% confidence interval is then given as

$$\frac{n\tilde{G}_{xx}(f_k)}{\chi^2_{n;0\cdot 05/2}} \le \tilde{G}_{xx}(f_k) \le \frac{n\tilde{G}_{xx}(f_k)}{\chi^2_{n;1-0\cdot 05/2}} \quad (10)$$

where $\chi^2_{n;\alpha}$ is the Chi-square distribution such that probability $[\chi^2_n > \chi^2_{n;\alpha}] = \alpha$ for a percentage α with n degrees of freedom, $n = 2n_d$ (Bendat and Piersol, 1991).

For small random error, the coherence with 95% confidence interval approximately given by Bendat and

Table I. Basic data for Huakang Shan site. Six-minute interval data were collected for nearly 25 days

Site title	Huakang Shan	
Location	Hualien City/Taiwan	
Ground water well		
Position	E	N
	Longitudinal	Latitude
	121°36′18″	23°58′37.2″
Elevation	16.088 m	
Water depth	140–160 m	
Position of seawater gauge station	121°37′52″	24°02′07″
Data collected for spectral analysis	6 min interval data for a total of 6048 samples observed from 2005/2/1 00:00.	

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Table II. Abbreviation and unit of observed environmental time series

Parameter	Abbreviated	Unit
Ground water head	GWH	m
Atmospheric pressure	BAR	hPa
Tidal level in ocean	TID	m
Temperature of air	TMA	°C
Temperature of ground water	TMW	°C
Rainfall	RAN	mm

Piersol (1991) is then

$$1 - \frac{2\sqrt{2}(1-\tilde{\gamma}(f_k)^2)}{|\tilde{\gamma}(f_k)|\sqrt{n_d}} \le \tilde{\gamma} \le 1 + \frac{2\sqrt{2}(1-\tilde{\gamma}(f_k)^2)}{|\tilde{\gamma}(f_k)|\sqrt{n_d}} \tag{11}$$

Therefore, 95% non-zero coherence significance level (NZC; Shih *et al.*, 1999) is derived as

$$\tilde{\gamma}(f_k) = |\tilde{\gamma}(f_k)| = \frac{\sqrt{n_d + 32} - \sqrt{n_d}}{4\sqrt{2}} \tag{12}$$

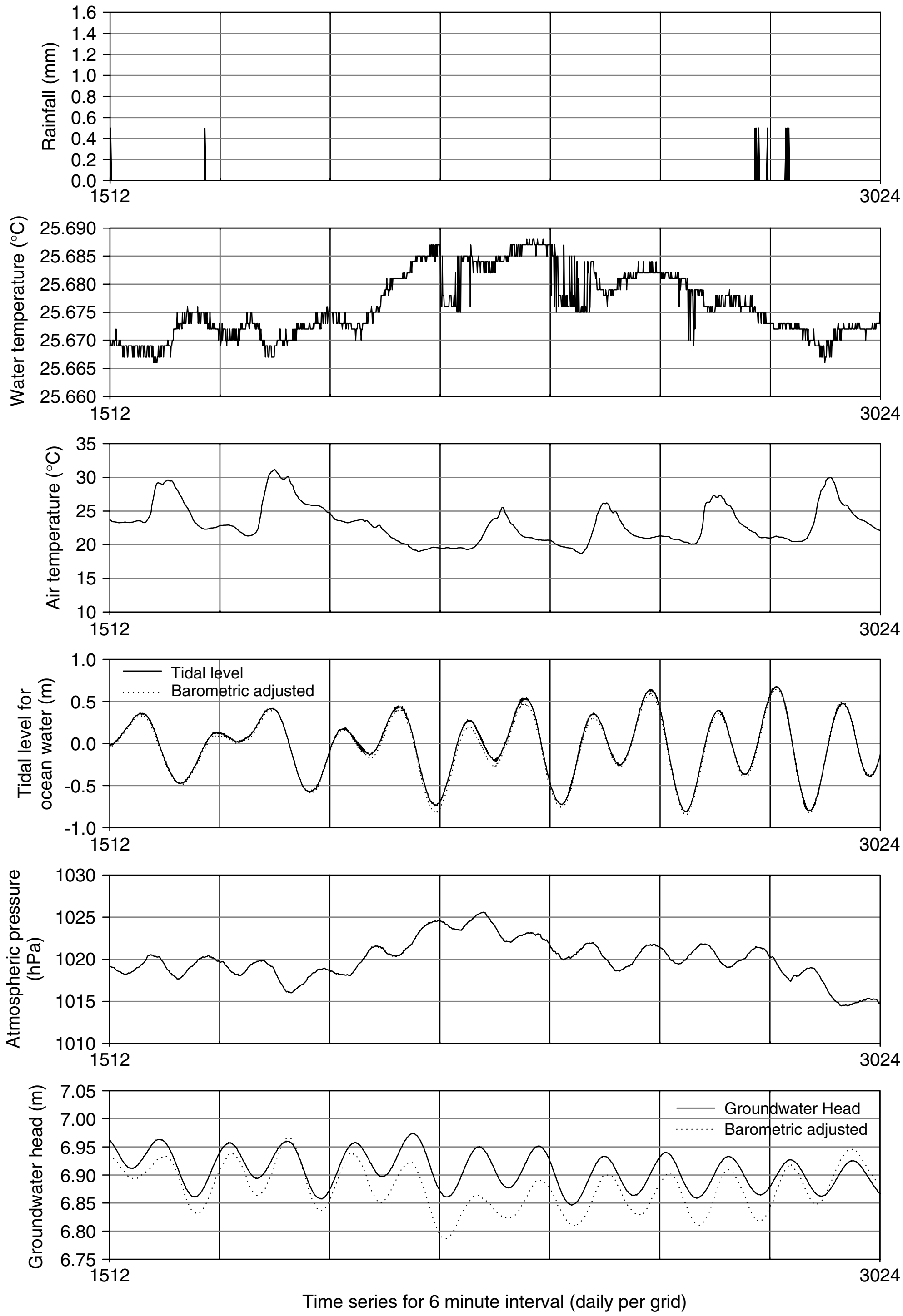

Figure 5. Time series enlarged in time axis; daily results are shown for each grid. Periodic fluctuation is clearer

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Table III. Descriptive statistics of observed environmental time series

Parameter	Size	Missing	Mean	Std Dev.	Std Error	CI of mean
GWH	6048	0	6·922	0·0370	0·0004760	0·000933
BAR	6048	0	1016·704	4·0370	0·0519000	0·102000
TID	6048	0	−0·0111	0·3720	0·0047900	0·009380
TMA	6048	0	21·186	4·3030	0·0553000	0·108000
TMW	6048	0	25·675	0·0054	0·0000695	0·000136
RAN	6048	0	0·00455	0·0508	0·0006540	0·001280

Parameter	Range	Max.	Min.	Median	25%	75%
GWH	0·189	7·015	6·826	6·922	6·895	6·949
BAR	21·460	1025·589	1004·129	1017·047	1014·026	1019·648
TID	1·885	0·971	−0·914	0·014	−0·314	0·283
TMA	19·341	32·599	13·258	21·126	18·011	23·909
TMW	0·026	25·688	25·662	25·675	25·670	25·678
RAN	1·500	1·500	0·000	0·000	0·000	0·000

Parameter	Skewness	Kurtosis	K-S Dist.	K-S Prob.	Sum	Sum of squares
GWH	−0·0169	−0·400	0·0275	<0·001	41861·797	289758·612
BAR	−0·4190	−0·142	0·0664	<0·001	6149026·914	6251839952·081
TID	−0·0991	−0·782	0·0444	<0·001	−67·300	838·788
TMA	0·2040	−0·549	0·0511	<0·001	128133·530	2826615·009
TMW	0·4440	−0·233	0·1130	<0·001	155280·175	3986761·544
RAN	13·1130	220·043	0·5270	<0·001	27·500	15·750

Note: Std Dev, standard deviation; Std Error, standard error; CI, confidence interval; Max., maximum value; Min., minimum value; K-S Dist.,:K-S distance; K-S Prob., K-S probability.

Table IV. Basic input and output parameters of spectral analysis

Item	Value	Unit
Time series length[a]	6048	6 min interval
FFT time series block length[a]	1512	6 min interval
Time interval[a]	0·1000	h
FFT time series overlaping rate[a]	0·0000	
FFT time series block used[a]	4	
Frequency resolution	$0{\cdot}66138 \times 10^{-2}$	cph
Nyquist frequency	5·00000	cph
Confidence level	0·95000	
Confidence lower level for autospectral density	0·45624	
Confidence upper level for autospectral density	3·67020	
Non-zero coherence significant level, NZC	0·70711	

[a] For input; others are computed.

Table V. Significant components evaluated by autospectral analysis

	Frequency (cph)	Period (h)	Spectra	
Ground water head	0·0794	12·6	0·0357	m^2 cph^{-1}
	0·0397	25·2	0·0102	
Atmospheric pressure	0·0926	10·8	64·4330	hPa^2 cph^{-1}
	0·1389	7·2	2·4426	
Tidal level	0·0794	12·6	9·4371	m^2 cph^{-1}
	0·0397	25·2	2·1967	
Air temperature	0·0926	10·8	44·9960	$°C^2$ cph^{-1}
	0·0463	21·6	209·3300	
Water temperature	—	—	—	
Rainfall	—	—	—	

DATA ANALYSIS AND DISCUSSION

Six-minute interval data were collected for nearly 25 days, and a total of 6048 samples are acquired (Figures 4 and 5, Table I). Monitored parameters are also summarized and abbreviated as shown in Table II. The descriptive statistics is calculated to demonstrate the basic level of data before conducting the spectral analysis. In this study, the Kolmogorov-Smirnov distance (K-S distance) is the maximum cumulative distance between the histogram of the data and a Gaussian distribution curve of the data, while kurtosis is a measure of how peaked or flat distribution of observed values is compared to a normal distribution. Normality assessment can be derived from the Kurtosis and K-S distance and finally evaluated using the K-S test. A normal distribution has Kurtosis equal to zero. Normality test fails for all parameters, although atmospheric pressure and ground water head demonstrate the lowest value of Kurtosis and K-S distance, respectively (Table III). In order to reduce random error of spectral density function, the data are divided into four sub-records to obtain a smooth estimate. To suppress the seasonal variation in the time series, removal of linear trend is adopted on each sub-record using the

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least-square method, while the Hanning window is used to suppress leakage problem (Bloomfield, 1976). The resolution of discrete frequency is $0{\cdot}66138 \times 10^{-2}$ cph (Table IV). The autospectral density with 95% confidence interval has the lower and the upper extremes of 0·45624 and 3·67020, respectively. Non-zero coherence significant level is calculated to be 0·70711. Although the confidence interval of the cross-spectral density function is dependent on coherence at each discrete frequency interval, it is reasonable that the significant peak

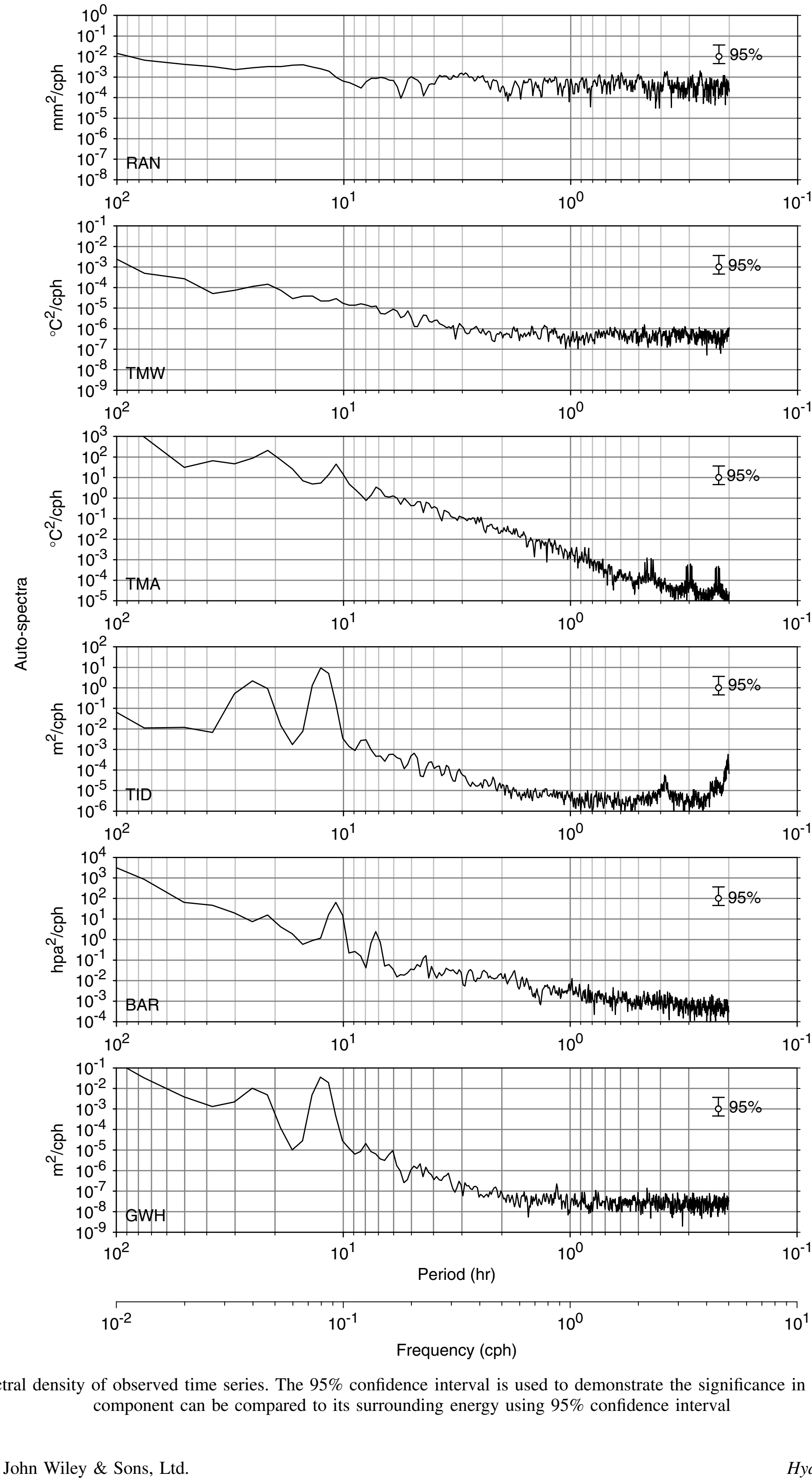

Figure 6. Autospectral density of observed time series. The 95% confidence interval is used to demonstrate the significance in statistics. Significant component can be compared to its surrounding energy using 95% confidence interval

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in cross-spectral density function can be evaluated by the non-zero coherence instead of the confidence interval (Shih *et al*., 1999). Semi-diurnal component is significant in the ground water head, seawater level and atmospheric pressure (Figure 6). Atmospheric pressure somewhat presents the period of 10·8 h, it is different to 12·6 h of ground water head and seawater level (Table V). For the semi-diurnal band of ground water head and seawater level, time lag is evaluated about 3·78 h, it is related to a change rate 1000 m h^{-1}. Secondary peaks are also shown for ground water head, seawater level, atmospheric pressure, and air temperature at some frequency

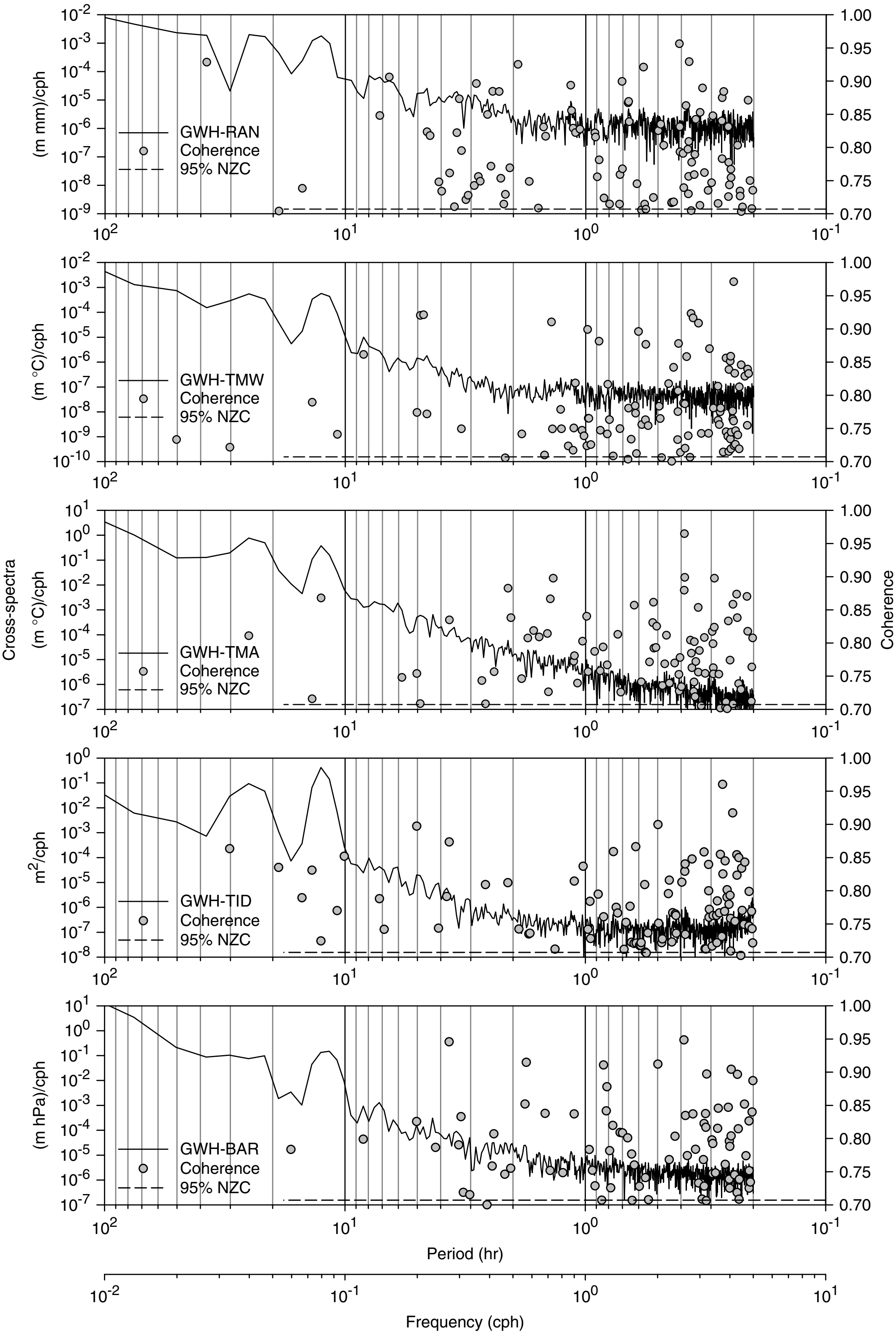

Figure 7. Cross-spectral density for parameter pairs. NZC, non-zero coherence is used to identify the significant coherence

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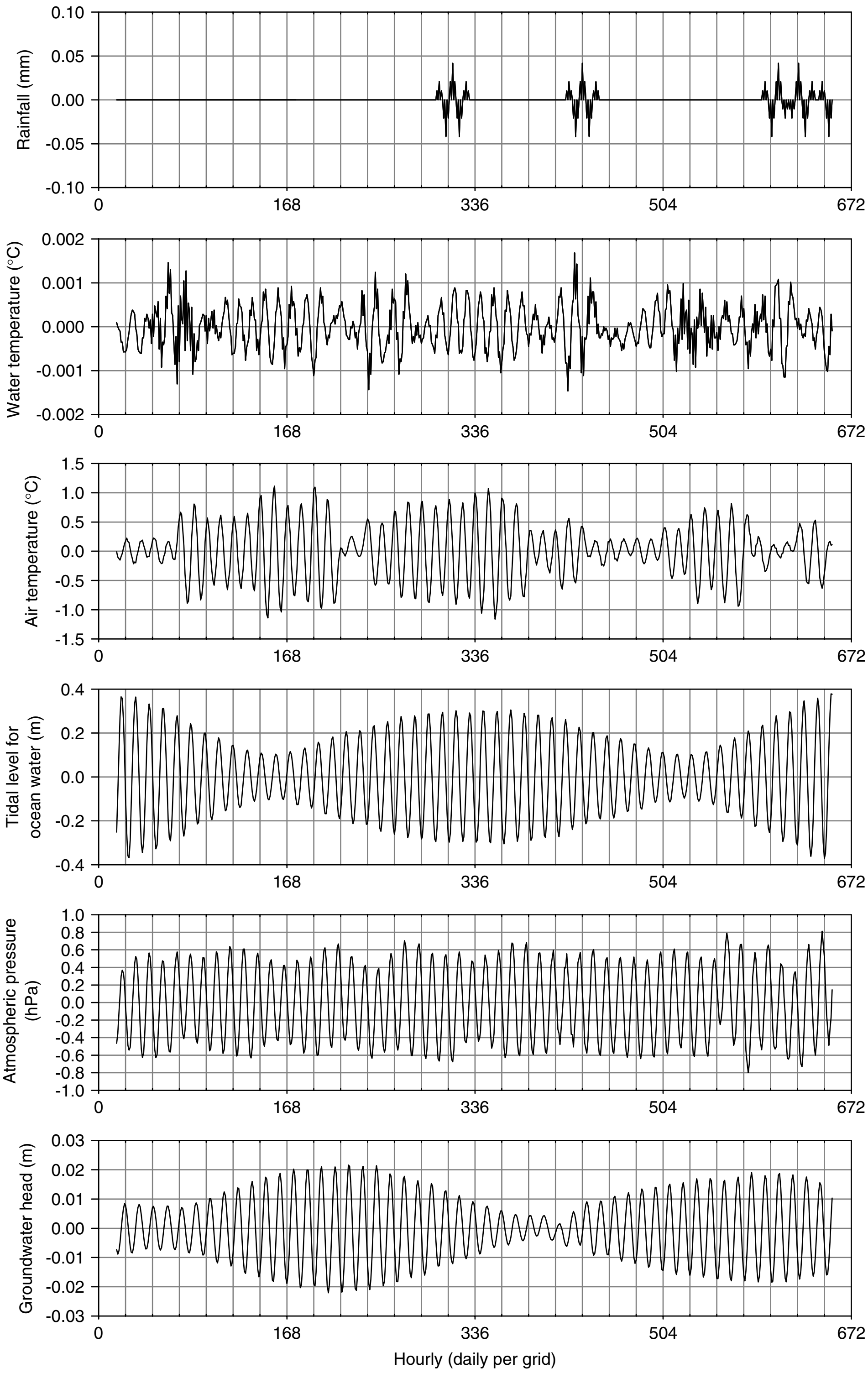

Figure 8. Semi-diurnal component of time series using Doodson's bandpass filter

bands (Table V). A more significant demonstration of the diurnal component can be found for a time series enlarged in the time domain (Figure 5). However, barometric adjusted and unadjusted cases for ground water head represent the same fluctuation type. By profiling cross-spectral and coherence analysis, specific component with a period of 12·6 h for ground water head and seawater level also has the most significant power (Figure 7 and Table VI). For a semi-diurnal component, a Doodson bandpassed filter (Godin, 1972; Shih and Lin, 2004) is suitable for passing semi-diurnal signal. It is apparent that semi-diurnal constituent of ground water head is highly related to the seawater level (Figure 8). Even their envelopes are harmonized and represent 15 days cycle exactly.

The subject selects five kinds of environmental factor to demonstrate disturbed constituents in ground water head fluctuation of Huakang Shan site. Autospectral and

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Table VI. Cross-spectral density for ground water head and seawater tidal level (GWH-TID pair)

Frequency (cph)	Period (h)	Spectral density (m^2 cph^{-1})			Cross-spectral density (m^2 cph^{-1})	
		Co-	Quadrature-	Cross-	Lower bound	Upper bound
0.03968	25·20000	0·07581	−0·05559	0·09401	−0·59412	2·59410
0.07937	12·60000	−0·12936	−0·39986	0·42027	−0·38077	2·38080

Frequency	Period	Coherence	Phase (deg)	Standard deviation for phase (deg)	Time-lag (h)
0.03968	25·20000	0·62731	−36·24900	25.14800	−2·53750
0.07937	12·60000	0·72423	−107·93000	19.28700	−3·77740

cross-spectral analysis are demonstrated to accurately analyse the significant component with a period of 12·6 h of ground water head, which is highly related to seawater level fluctuation. For the series in the time domain, Doodson's bandpass filter strikes the same type of periodic phenomena and envelope. From these evidences, it can be ascertained that the water level fluctuation of an aquifer formed in an unconsolidated formation can be affected by the nearby seawater body. The resultant phenomena are similar to other studies (Shih *et al*., 1999, 2000; Shih and Lin, 2002, 2004). Atmospheric pressure presents the significant components at periods of 10·8 h and 7·2 h in a quite different type of fluctuation.

In the future, it can be expected, from the spectral analysis in the time-frequency domain, the relationship of water level fluctuation can be measured in observation wells and nearby boundaries to determine hydrogeological parameters such as hydraulic diffusivity. The results obtained by this kind of method should represent the average property of the entire aquifer of interest and could be different, to a limited extent, from pumping test results accounting for local aquifer property.

CONCLUSIONS

For an earthquake monitoring site, autospectral and cross-spectral analysis are accurately used to analyse periodic constituents for six kinds of selected parameters. It shows that a significant component with a period of 12·6 h of ground water head, is highly related to seawater level fluctuation. It is found that water level fluctuation in the aquifer formed in an unconsolidated formation can be affected by the nearby seawater body. Water level fluctuation nearly corresponds to at a rate of 1000 m h^{-1}. Atmospheric pressure presents the significant components at periods of 10·8 h and 7·2 h in a different type of fluctuation.

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