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Effects of Evapotranspiration and Earth Tides on the Water-Level Fluctuation in a Forest Catchment in Gwangneung

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Abstract

Closing energy and water budgets in terrestrial ecosystems still remains as a challenge, particularly for those with heterogeneous vegetation in complex terrains. This paper presents an attempt to quantitatively estimate parts of water-level fluctuation due to evapotranspiration (ET) and earth tides, and their seasonality at the Gwangneung forest catchment, Korea. The long-term water level was monitored from a piezometer at 5-min intervals from February 2006 to July 2007. For the seasonal variation, summer and winter sub-datasets were analyzed using the power spectral analysis. Cyclic movements with frequencies of 1 cycle / 24.0±0.5 hr were extracted from the water-level monitoring data. Daily fluctuation of water levels ranged from 0.070±0.015 m in the winter to 0.130±0.061 m in the summer of 2006. In winter, the water-level fluctuated on average 13.9 mm, of which 94% was attributed to the effect of earth tide and the remainder to ET. In summer, the fluctuation component associated with ET was on average 25.9 mm (66% of the total fluctuation), which is equivalent to a daily ET of ~2.9 mm. When compared against the ET observed from the eddy covariance flux tower at the same site for the same periods, the ranges of seasonal ET inferred from the water-level fluctuations were virtually the same.

Key words: Water-level fluctuation, evapotranspiration, earth tides, power spectral analysis

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) has evaluated the knowledge of climate change impacts on hydrology and water resources of both regional and global scales, and reported that climate change impacts on freshwater resources may affect and even become a threat to sustainable development in some countries (Arnell *et al*., 2001; Kundzewicz *et al*., 2007). At the affected regions, the sustainable management of fresh water resource has become critical (United Nations, 2002, 2006; World Water Council, 2006). The sustainable water resources management requires the precise interpretation of quantitative and predictive manners of water movement in the Earth environment, while encompassing precipitation, surface runoff, evaporation, transpiration, infiltration, and subsurface flows.

As described by Kim *et al*. (2006), the 'HydroKorea' development project was initiated with the objective of understanding and documenting water cycles in heterogeneous and complex Korean landscapes from plot to regional scales. In order to accomplish this objective, major ecohydrological studies have been carried out at the Gwangneung supersite since the fall of 2004. In order to run interdisciplinary studies, the supersite is equipped with flux towers for meteorological observation and long-term hydrological monitoring systems. As a part of the HydroKorea development project, we started a groundwater monitoring program to understand the part of water movement from land surface to groundwater table with different time scales from events to seasonal and annual variations. For this purpose, groundwater level was observed and its fluctuation was analyzed with corresponding natural processes.

Water levels at the monitoring well represent values from several to hundreds of square meters (Scanlon *et al*., 2002). In many cases, water-level

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fluctuation has been used to estimate the groundwater recharge rates since the 1920s (Meinzer, 1923; Theis, 1937; Rasmussen and Andreasen, 1959; Bear, 1979; Gerhart, 1986; Sophocleous, 1991; Goes, 1999; Ketchum *et al*., 2000; Scanlon *et al*., 2002; Healy and Cook, 2002, Moon *et al*., 2004; Crosbie *et al*., 2005; Lee, 2007; Park and Parker, 2008). Crosbie *et al*. (2005) proposed a method to accommodate water-level changes by natural discharge, which includes lateral flows and evapotranspiration in areas of steep slopes, since other methods generally ignore or assume negligible lateral flows in the water table.

Groundwater level responds not only to natural hydrologic processes such as precipitation, evapotranspiration, atmospheric pressure changes, lateral subsurface flows, and earth tides, but also responds to human induced stresses including pumping and artificial recharge (Freeze and Cherry, 1979). All these factors have different time scales. Evapotranspiration, for example, shows a daily fluctuating pattern, which also fluctuates depending on daily and seasonal climatic conditions. In comparison to the groundwater movement, precipitation events occur irregularly and instantaneously. Lateral groundwater flow through the saturated zone is controlled by hydraulic conductivity of aquifer materials and hydraulic gradients. The aquifer materials contain intrinsic heterogeneities in spatial perspectives due to various geological origins of the materials and their deposition and rock-forming processes. Hydraulic gradient is dependent on groundwater levels in a watershed, and thus, is continuously changing during the rainy season. In addition, earth tides also show cyclic effects on groundwater levels. They can increase or decrease the hydraulic gradient of ground water. Consequently, groundwater level fluctuations are the final results of the complicated effects on ground water from hydrogeologic characteristics of the site with temporal and spatial scales of hydrologic events. Therefore, the objective of this study was to quantitatively estimate the parts of groundwater level fluctuation due to evapotranspiration and earth tides at the Gwangneung supersite. In addition, the water-level fluctuation was examined for the possibility of being an indirect indicator of evapotranspiration. The results of this study can reduce the uncertainty of groundwater recharge estimation for water resource management, and subsequently, the water budget analysis of the studied watershed.

2. Materials and Methods

a. Study area

The headwater catchment in the Gwangneung National Arboretum covers 0.22 km^2 (22 ha) with elevations ranging from 280 to 470 m above mean sea level (msl) (Fig. 1). The area has mountainous topography, with more than 80% of the site having slopes ranging from 10° to 20°. Geologic materials consist of a thin soil layer underlying a weathered zone of bedrock of the Gyunggi gneiss complex (MOST, 1999). Typical soil depth is from 0.4 to 0.8 m and the soil texture is predominantly sandy loam. For the last three decades from 1982 to 2004, the means of annual temperature and the amount of precipitation in the study area were 11.5 °C and 1332 mm, respectively (Lee *et al*., 2007). The study area has been preserved from public access, and there is no groundwater pumping station which might affect the water-level changes.

b. Monitoring

Two piezometers, G1 and G4, were installed at the top of the headwater area with the depths of 0.65 and 0.55 m, respectively, where the bedrock surface was found at very shallow depths (Choi *et al*., 2007). They have a diameter and a screen length of 60 mm and 200 mm, respectively, and were equipped with data-loggers (CTD Diver-Model DI261, Schlumberger) for hydraulic pressure measurement of the water level. Hydraulic pressures were measured at 5-min intervals, and converted to water levels after calibration for atmospheric pressure changes, which were monitored using an independent data-logger (baro-Diver, Schlumberger). Mechanical error and the sensitivity of pressure transducer (Diver) were ±10 mm and ±1 mm, respectively.

In this study, we analyzed the data from piezometer

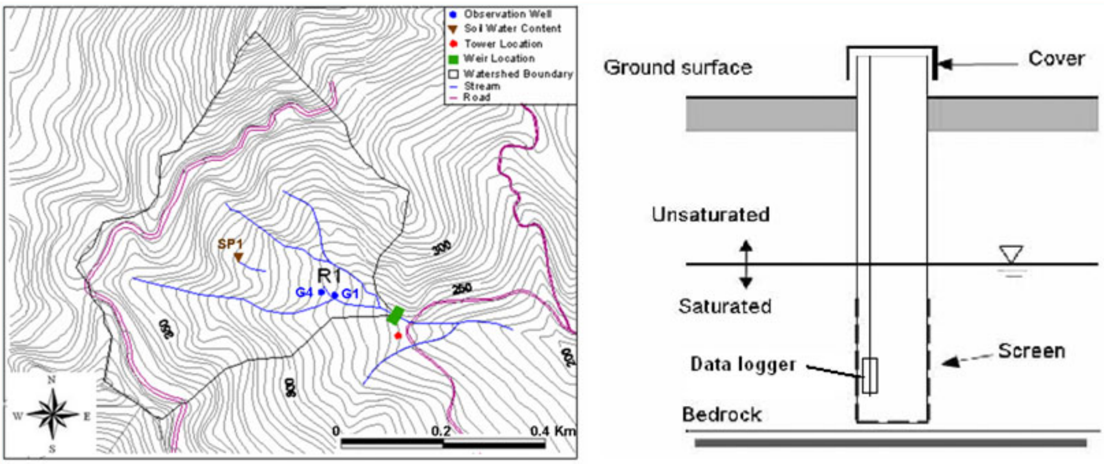

Fig. 1. Study area, location of piezometers and its schematic diagram.

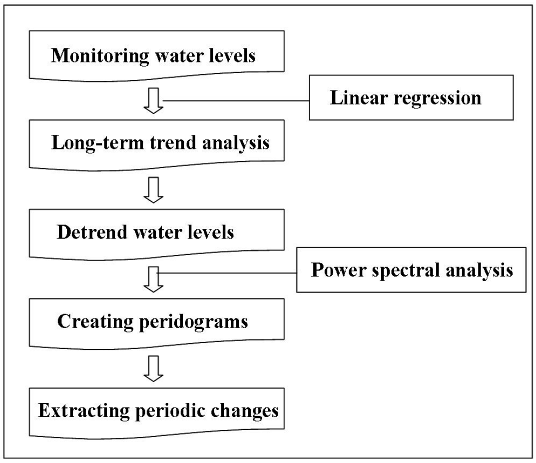

Fig. 2. Procedure of the water-level data analysis in this study.

G1, which was collected from 21 Feb. 2006 to 14 July 2007, covering about 17 months of time series. Data from the other piezometer G4 showed too little fluctuations to be analyzed for changes, and therefore, we focused more on the data from G1 in this analysis.

c. Data Analysis

Data analysis followed the procedure presented in Fig. 2. After calibration for atmospheric pressure changes, observed water levels from Feb. 2006 to July 2007 were plotted in time series (Fig. 3). During the monitoring period, the highest and the lowest levels were 265.131 m and 264.481 m above msl, respectively, with the maximum variation of 0.65 m. From this time series, two subsets of seasonal data were extracted for the rainy summer season from 1 June to 30 August in 2006, and for the dry winter season from 1 Dec. 2006 to 1 March 2007, respectively.

A linear regression technique was applied to calculate the long-term trend for each season. Next, in order to extract the periodic portion of water-level change, the long-term trend was removed from the monitored data. Using the Fourier transforms with the MATLAB 7.0.4 program (MathWorks, 2005), we performed the power spectral analysis on the de-trended water-level data. This method is applicable because the response of aquifers or water level to periodic function can be represented by a sinusoidal function in time domain. The resulting peridogram shows a series of peaks corresponding to periodicity. A large peak-value implies the strong effects of the periodicity in the time series.

Finally, periodic changes with frequencies of 1 cycle / 24.0±0.5 hr were extracted to see the changes in water levels caused by the cyclic phenomena. This frequency was selected to cover major diurnal components of tides (Table 1) and possible daily fluctuations of evapotranspiration. The power spectral analysis

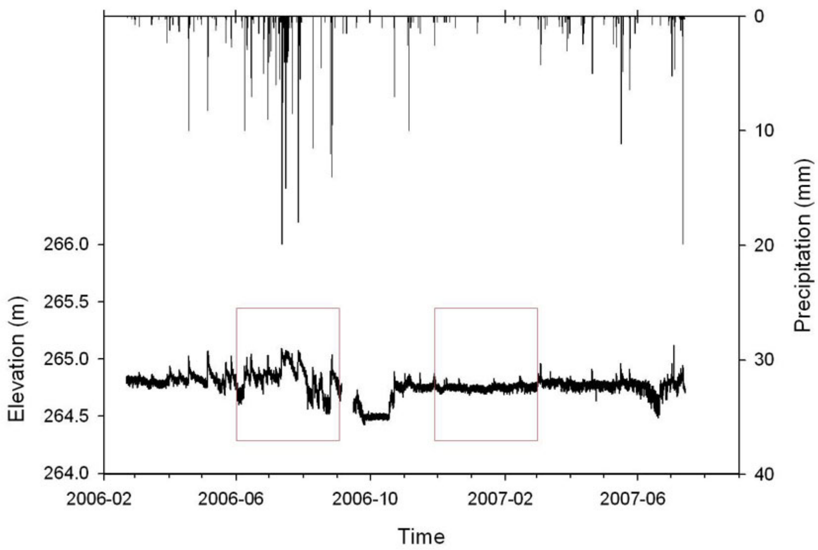

Fig. 3. Water levels at the piezometer G1 from February 2006 to July 2007 with precipitation records. Rectangles in the plot indicate summer and winter subsets for detailed analysis.

Table 1. Principal diurnal harmonic components of tide. (after Knauss, 1997).

Name of Tides	Symbol	Period in solar hours	Coefficient ratio (M_2=100)
Lunisolar diurnal	K_1	23.93	58.4
Principal lunar diurnal	O_1	25.82	41.5
Principal solar diurnal	P_1	24.07	19.4
Larger lunar elliptic	Q_1	26.87	7.9
Smaller lunar elliptic	M_1	24.84	3.3

of the observed evapotranspiration data (KoFlux, 2008) showed periodic features with a 24-hr cycle and 12-hr cycle in both summer and winter seasons.

3. Results & Discussion

In the data subset for rainy summer seasons, water levels vary from the highest of 265.094 m above msl to the lowest of 264.519 m above msl with the difference of 0.575 m (Fig. 4a). In dry winter seasons, however, they were 264.865 m and 264.695 m above msl, respectively, with the difference of 0.170 m (Fig. 5a). Daily fluctuation of water levels ranged from 0.130± 0.061 m and 0.070 ± 0.015 m in the summer and winter seasons, respectively. Water-level variations in summer is about twice as much as that of in the winter, implying that some factors of water-level fluctuation in the summer season might not affect the water level during the winter season.

For the rainy summer season of 2006, the long-term (seasonal) trend of water-level fluctuation was calculated. It had a slope of -0.8 mm day^{-1}, implying that groundwater table was slightly declining during this period. After removing the seasonal trend (Fig. 4b), the cyclic movement of water levels with the frequency of 24.0±0.5 hr was extracted from the de- trended level data (Fig. 4c,d). Tidal components of ocean tide origin are O_2 and M_2, the lunar harmonics, with cycles of 25.82 hr and 12.42 hr, respectively. Their effects were also examined and found negligible for this study, confirming the results of Lee *et al*. (2004). Finally, the mean amplitude of water-level fluctuation was 38.9 mm with the maximum and minimum fluctuations of 46.7 and 32.2 mm, respectively (Table 2).

For the dry winter season of 2006 and 2007, the seasonal trend of water level fluctuation shows a

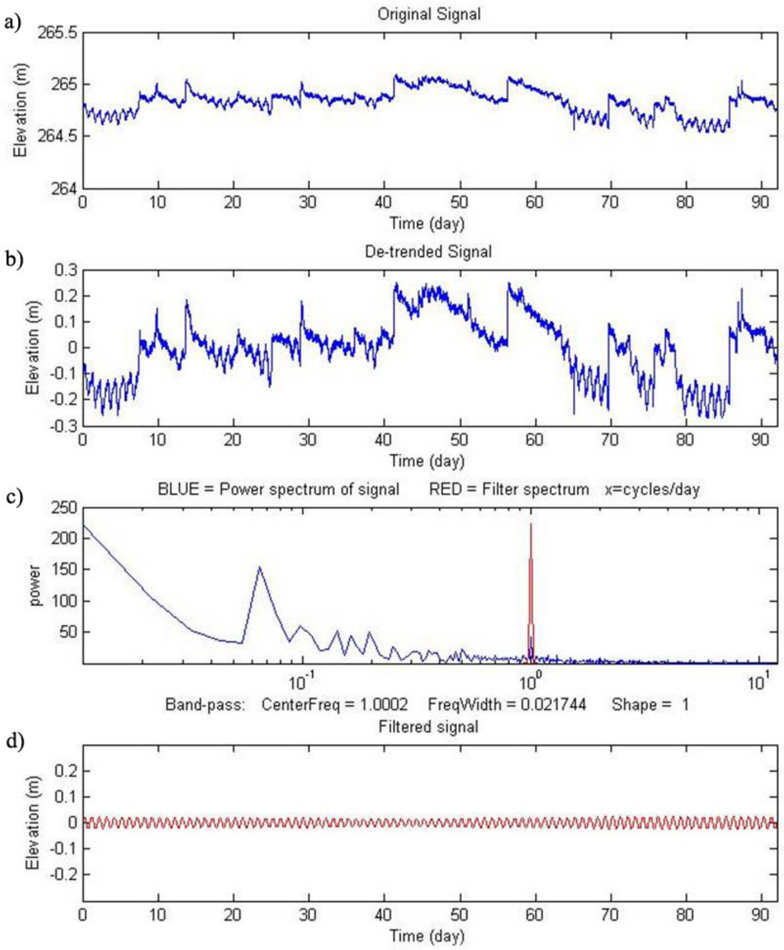

Fig. 4. Sequential analysis of water-level monitoring data in summer from 1 June to 30 August 2006: (a) water-level data, (b) de-trended water-level data, (c) the power spectrum signal, and (d) the filter spectrum for the cyclic fluctuation.

slope of +0.2 mm per day, indicating that groundwater table is slightly rising. Since a few precipitation events occurred with relatively small amounts in this winter (Fig. 3), the slight seasonal rising of water level could be attributed to the recharge of snowmelt from the surface. After the seasonal trend was removed, the cyclic component of water levels was extracted (Fig. 5c-d), showing the mean amplitude of water-level fluctuation of 13.9 mm with the maximum and minimum fluctuations of 16.8 and 10.7 mm, respectively (Table 2).

The study area was a remote place beyond public access, and therefore the ET by vegetation and earth tides were considered to be the possible natural factors affecting water-level changes with daily and diurnal cycles. During the winter period of this study, the average daily variation of ET was 0.1 mm (Table 2). Variation of ET can be converted to that of the water-level considering the specific yield (S_y) or the effective porosity of the geologic materials where the water level moves. The specific yield of the study site was measured to be 0.113 by particle size analysis (Choi, 2006). Therefore, 0.1 mm of water equivalent changes by ET corresponds to 0.9 mm of water-level changes in the geologic layer.

During the winter period, the observed water-level

Table 2. Evapotranspiration in summer and winter periods observed from the flux tower and estimated from the water-level fluctuations.

Items	Season	Daily Variation (mm)		
		Mean	Maximum	Minimum
Observed evapotranspiration (ET)	Summer	2.0	3.9	0.4
	Winter	0.1	0.5	0.0
Water-level change equivalent to observed ET (S_y = 0.113)	Summer	17.7	34.5	3.5
	Winter	0.9	4.4	-
Observed water-level fluctuation (S_y = 0.113)	Summer	38.9	46.7	32.2
	Winter	13.9	16.8	10.7
Tidal component of water-level fluctuation (S_y = 0.113): 13.0				
ET component of water-level fluctuation (S_y = 0.113)	Summer	25.9	33.7	19.2
	Winter	0.9	3.8	-
Estimated ET equivalent to water column	Summer	2.9	3.8	2.2
	Winter	0.1	0.4	-
Ratio of estimated ET vs. observed ET	Summer	1.45	0.97	5.5
	Winter	1.0	0.8	-

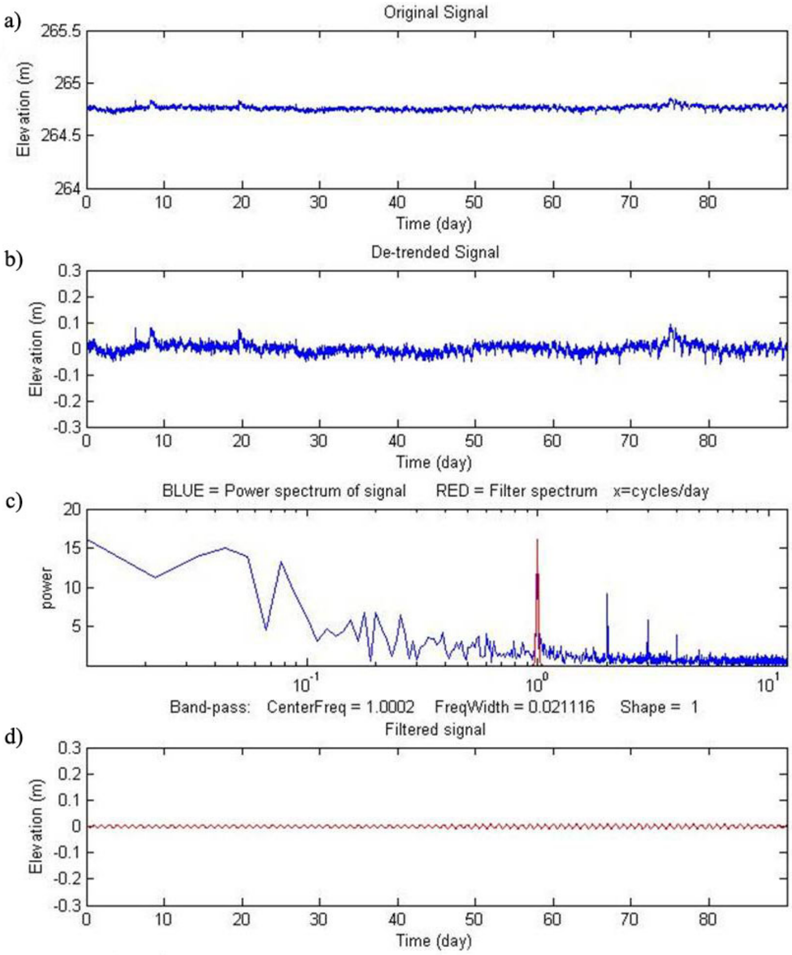

Fig. 5. Sequential analysis of water-level monitoring data in winter from 1 December 2006 to 1 March 2007: (a) water-level data, (b) de-trended water-level data, (c) the power spectrum signal, and (d) the filter spectrum for the cyclic fluctuation.

fluctuation of 13.9 mm (Table 2) contains the components of both earth tide and ET. Since the mean water-level change due to ET is 0.9 mm, the effect of earth tide should be 13.0 mm. Then, if the effect of earth tide is consistent in summer, the effect of ET could be calculated from the difference between the total mean fluctuations and its tidal component as follows: 38.9 mm − 13.0 mm = 25.9 mm. Again, this ET component of water-level fluctuation in a geologic layer can be converted into the equivalent water column as follows: 25.9 mm × 0.113 (S_y) = 2.9 mm. As a result, this estimated ET (2.9 mm) based on the water-level fluctuation is 45% larger than the observed value (2.0 mm) from the flux tower (Table 2).

In this estimation, errors could occur from the accuracy of the specific yield value measured from the laboratory analysis. In general, the specific yield of unconsolidated materials could range from 0.01 to 0.3 (Freeze and Cherry, 1979), and therefore, should be measured in field conditions with the appropriate field technology utilizing methods such as pumping tests. However, the study site has very thin unconsolidated materials with bedrocks at shallow depths. Therefore, pumping tests were impossible to perform in this study, leaving room for error in the accuracy of the specific yield. On the other hand, this result implies that, if we have specific yield values through field tests, then based on the long-term water-level monitoring data with seasonal variations, the amount of ET could be estimated reasonably and used as an additional constraint for water budget closure.

In addition, for the removal of long-term trend of water-level change, we calculated the trend for three months period for both the summer and winter seasons. In winter, without many precipitation events causing direct infiltration and corresponding water-level changes, three months would be long enough to identify the seasonal trend. However, in the summer, with many precipitation events with corresponding water-level rises, the three month data may cause error in drawing the seasonal trend. Therefore, the seasonal trend analysis should be adopted with careful reviews of the observed water-level data. In our analysis, we used 3-month windows to draw data subsets of the summer and winter seasons, at least to maintain the consistency in the temporal scale of the data period.

4. Conclusion

Fluctuations in groundwater level are the consequences of the complicated effects of (1) hydro geologic characteristics of the site and (2) temporal and spatial scales of hydrologic events. We have monitored such fluctuations at the Gwangneung KoFlux supersite in order to estimate the relative contributions of earth tides and ET, and to ascertain their seasonality. The following conclusions could be drawn from this study:

- Daily fluctuation of water levels ranged from 0.130±0.061 m and 0.070±0.015 m in the summer and winter seasons of 2006, respectively.
- In winter, the cyclic component of water level fluctuates 13.9 mm on average. The observed ET from the flux tower explains 0.9 mm of fluctuation, and then the rest of the 13.0 mm (94%) of the total fluctuation can be attributed to the effect of earth tide.
- In summer, the mean groundwater-level fluctuation was 38.9 mm, and its fluctuation component due to ET was estimated to be 25.9 mm (66% of the total fluctuation), which corresponds to the equivalent water column of 2.9 mm.
- Despite the possible errors in the specific yield values and in selecting windows for regression analysis, the estimation of ET using water-level fluctuation data can be used as an additional constraint for closing the water balance in a forest catchment in a complex terrain.

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