Poroelastic Response of Shallow Crust Induced Seasonal Changes in Geohydrologic Parameters

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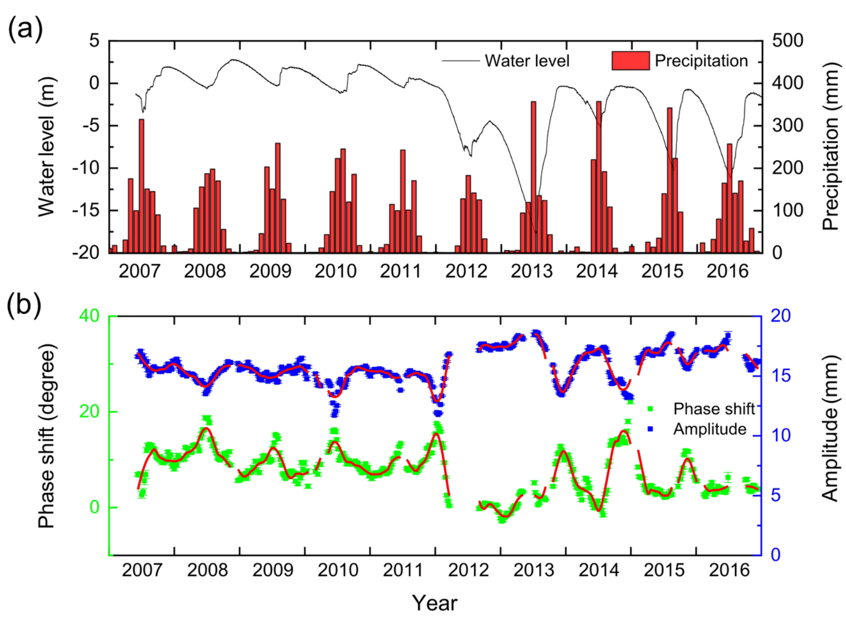
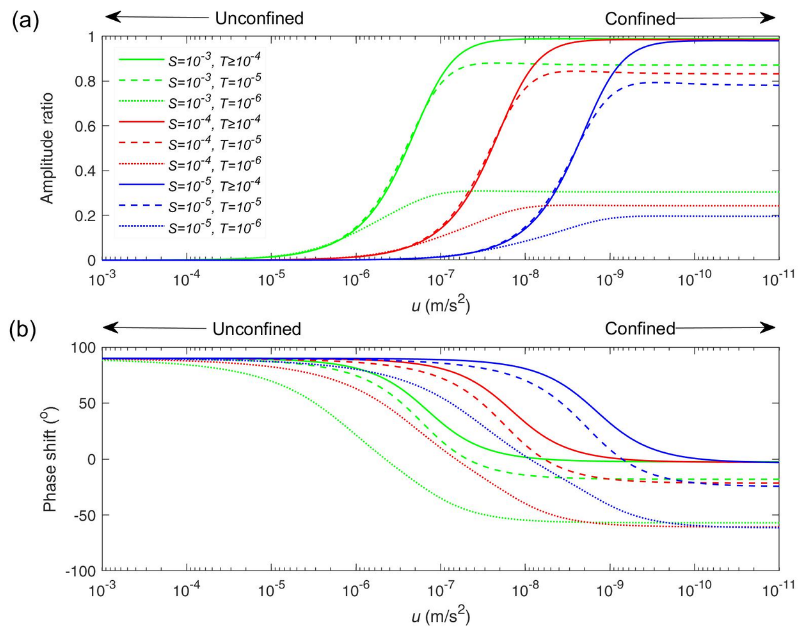
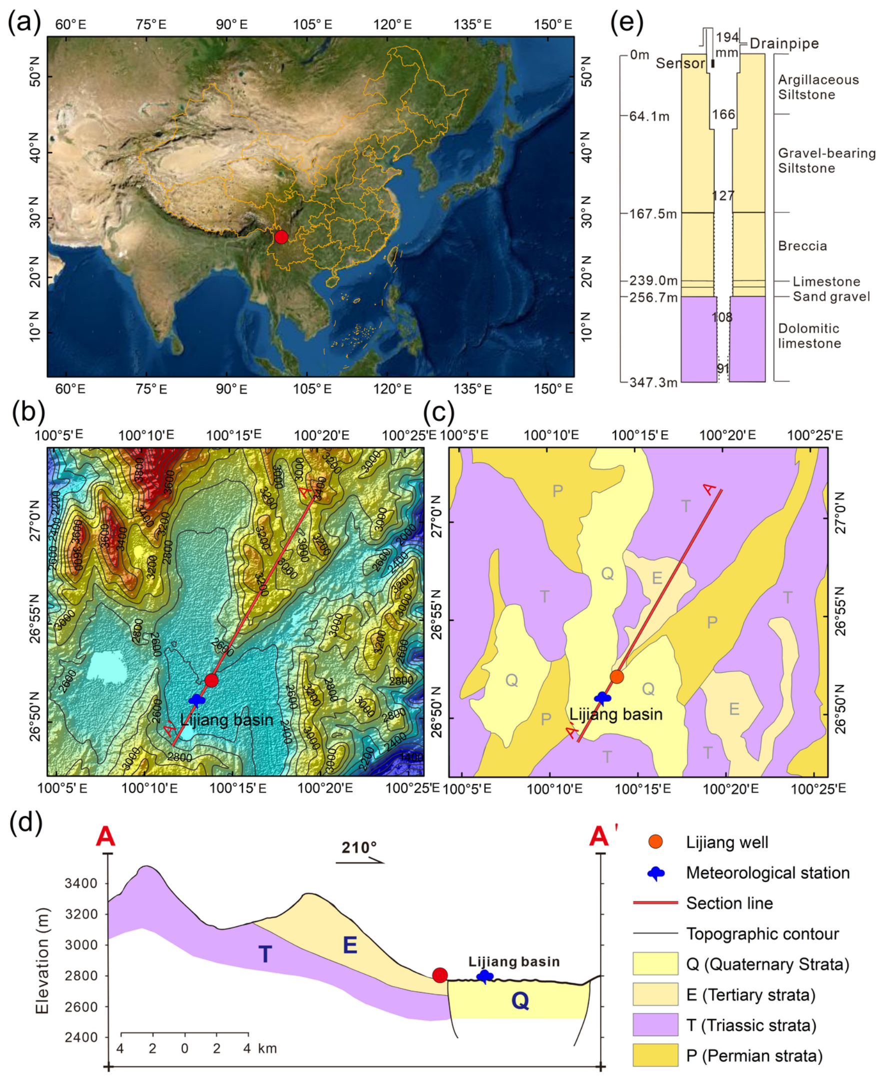
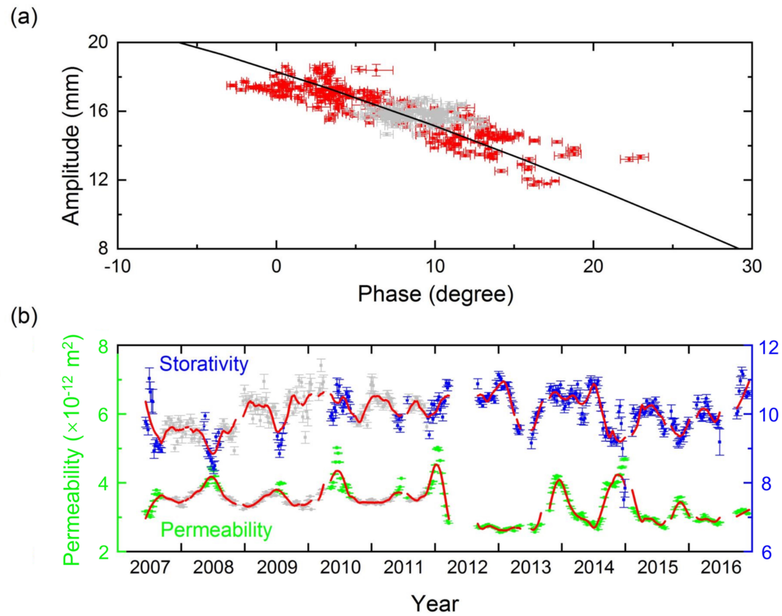
Abstract

Quantitative evaluations of hydrological processes that induce changes in the geohydrologic parameters of groundwater systems are of great significance in subsurface hydrology. In this study, the tidal response of the water level in Lijiang well was considered as an indicator of the hydrological parameters, and the seasonal changes of the tidal response were investigated. The results suggested that the seasonal change of tidal response should be attributed to the seasonal changes in the geohydrologic parameters, which are caused by the opening/closing of pre-existing fractures or fracture aperture changes in the groundwater system, owing to regional precipitation recharge that produces a poroelastic response in the groundwater system. This suggests that the groundwater system in the shallow crust can be viewed as a natural positive feedback poroelastic-hydraulic coupled system during the hydrological processes. These findings may have far-reaching implications for the safety of the subsurface environment, ecosystem, and groundwater resources.

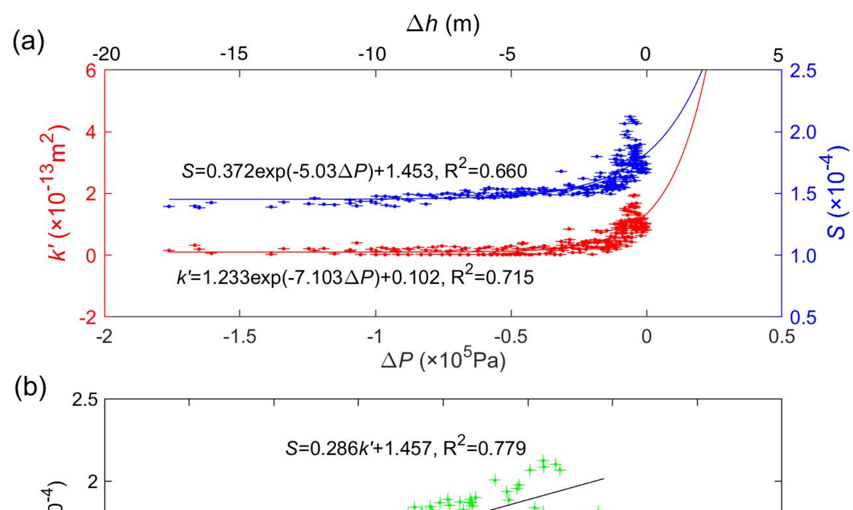



(a)
Unconfined
Confined
S=10^-3, T≥10^-4
S=10^-3, T=10^-5
S=10^-3, T=10^-6
S=10^-4, T≥10^-4
S=10^-4, T=10^-5
S=10^-4, T=10^-6
S=10^-5, T≥10^-4
S=10^-5, T=10^-5
S=10^-5, T=10^-6
Amplitude ratio
u (m/s^2)
(b)
Unconfined
Confined
Phase shift (°)
u (m/s^2)


(a)
60° E
75° E
90° E
105° E
120° E
135° E
150° E
50° N
40° N
30° N
20° N
10° N
(b)
100°5'E
100°10'E
100°15'E
100°20'E
100°25'E
27°0'N
26°55'N
26°50'N
Lijiang basin
(c)
P
T
Q
E
A
A'
Lijiang basin
(d)
A
A'
210°
Elevation (m)
3400
3200
3000
2800
2600
2400
T
E
Q
Lijiang basin
4 2 0 2 4 km
(e)
194 mm
Drainpipe
0m
Sensor
Argillaceous Siltstone
64.1m
166
Gravel-bearing Siltstone
127
167.5m
Breccia
239.0m
Limestone
256.7m
Sand gravel
108
Dolomitic limestone
91
347.3m
Lijiang well
Meteorological station
Section line
Topographic contour
Q (Quaternary Strata)
E (Tertiary strata)
T (Triassic strata)
P (Permian strata)



(a)
Amplitude (mm)
Phase (degree)
(b)
Storativity
Permeability
Permeability (×10^-12 m^2)
Storativity (×10^-4)
Year



(a)
Δh (m)
S=0.372exp(-5.03ΔP)+1.453, R^2=0.660
k'=1.233exp(-7.103ΔP)+0.102, R^2=0.715
k' (×10^-13 m^2)
S (×10^-4)
ΔP (×10^5 Pa)
(b)
S=0.286k'+1.457, R^2=0.779
S (×10^-4)
k' (×10^-13 m^2)

Poroelastic Response of Shallow Crust Induced Seasonal Changes in Geohydrologic Parameters

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Key Points:

- The seasonal variation in geohydrologic parameters may be caused by changes in fracture apertures.
- Precipitation induced poroelastic response may change the geohydrologic parameters seasonally.
- Groundwater system is a poroelastic–hydraulic coupled system with positive feedback in the shallow crust.

Plain Language Summary

In this study, we investigated the unexpected seasonal changes in the tidal response of the water level observed in a well in Southwest China. We concluded that the seasonal geohydrologic parameters changes, including the changes in vertical permeability and storativity, can be explained by the fracture aperture changes in the groundwater system caused by regional precipitation recharge that induces pore pressure or effective stress changes. This suggests that the geohydrologic parameters are mutable properties during a hydrologic year, and that the groundwater system can be viewed as a positive feedback poroelastic–hydraulic coupled system during hydrological processes. Feedback from the seasonal geohydrologic parameters changes in the shallow crust may impact the subsurface system, including altering potential groundwater contamination risks, compromising the safety of nuclear waste storage, and influencing the diffusion and transport of subsurface contaminants.

Abstract

Quantitative evaluations of hydrological processes that induce changes in the geohydrologic parameters of groundwater systems are of great significance in subsurface hydrology. In this study, the tidal response of the water level in Lijiang well was considered as an indicator of the hydrological parameters, and the seasonal changes of the tidal response were investigated. The results suggested that the seasonal change of tidal response should be attributed to the seasonal changes in the geohydrologic parameters, which are caused by the opening/closing of pre-existing fractures or fracture aperture changes in the groundwater system, owing to regional precipitation recharge that produces a poroelastic response in the groundwater system. This

suggests that the groundwater system in the shallow crust can be viewed as a natural positive feedback poroelastic–hydraulic coupled system during the hydrological processes. These findings may have far-reaching implications for the safety of the subsurface environment, ecosystem, and groundwater resources.

Keywords: geohydrologic parameters; seasonal changes; groundwater system; poroelastic response; precipitation

1 Introduction

Hydrogeological parameters are important parameters reflecting the hydrogeological characteristics of the groundwater system, which control the quality and quantity of groundwater resources in the crust. More and more studies have found that the geohydrologic parameters can be modified by earthquakes (e.g., Elkhoury et al., 2006; Liao et al., 2021; Shi et al., 2019; Zhang et al., 2019), and anthropogenic processes such as wastewater injection (Barbour et al., 2019; Fan et al., 2019; Wang et al., 2018). Even seasonal hydrological processes could change permeability, which is an important geohydrologic parameter, of groundwater system (Liang et al., 2022; Liao & Wang, 2018; Liao et al., 2022; Wang et al., 2019). However, the mechanism responsible for seasonal geohydrologic parameter variations during hydrological years remains an enigma.

The tidal response method can be used effectively to study the geohydrologic parameters changes by utilizing continuous water level data from a groundwater well (Hsieh et al., 1987; Roeloffs, 1996; Wang et al., 2018). The advantages of the tidal response approach over other traditional methods, such as the pumping test, are the lower cost, the ability to monitor the geohydrologic parameters in real time, and the absence of disturbance to the aquifer (Xue et al., 2016). Consequently, this technique is widely employed to explore the effects of earthquakes, anthropogenic and hydrological processes on the geohydrologic parameters (e.g., Elkhoury et al., 2006; Liao & Wang, 2018; Liao et al., 2021, 2022; Wang et al., 2018; Shi et al., 2019).

To gain insights into the potential mechanism for seasonal geohydrologic parameter changes during hydrological years, we investigated the unexpected seasonal changes in the tidal response of the water level in the Lijiang well in Southwest China by employing an entirely new theoretical response model. The results show that the geohydrologic parameters may be connected with a seasonal change in the pore pressure of the aquifer. Based on this discovery, we proposed a new mechanism that may account for the seasonal variations in the geohydrologic parameters. Since the changes in geohydrologic parameters may control the storage and migration of groundwater and solutes, the present finding may have broad implications for understanding the safety of groundwater resources and the security of subsurface waste repositories during natural hydrological processes.

2 Observations

The Lijiang well (26°52'N, 100°14'E) was located in the northeastern part of the Lijiang Basin in Yunnan Province, Southwest China (**Figure 1a & 1b**). The subsurface geohydrology of the region consists of mid-Triassic carbonate rocks, which function as an aquifer and are partially covered by younger Tertiary sedimentary rocks (siltstone), which act as an aquitard (for detailed information see **Figures 1c, 1d & 1e**). The edge of the Lijiang Basin, in which the well is located, is the groundwater discharge area, which is regionally recharged by the precipitation from the mountains to the north of the basin (**Figure 1d**). The well is 347.3 m deep and revealed a carbonate aquifer at depths from 167.5 to 310 m, which is covered by a 167.5-meter thick siltstone aquitard (**Figure 1e**).

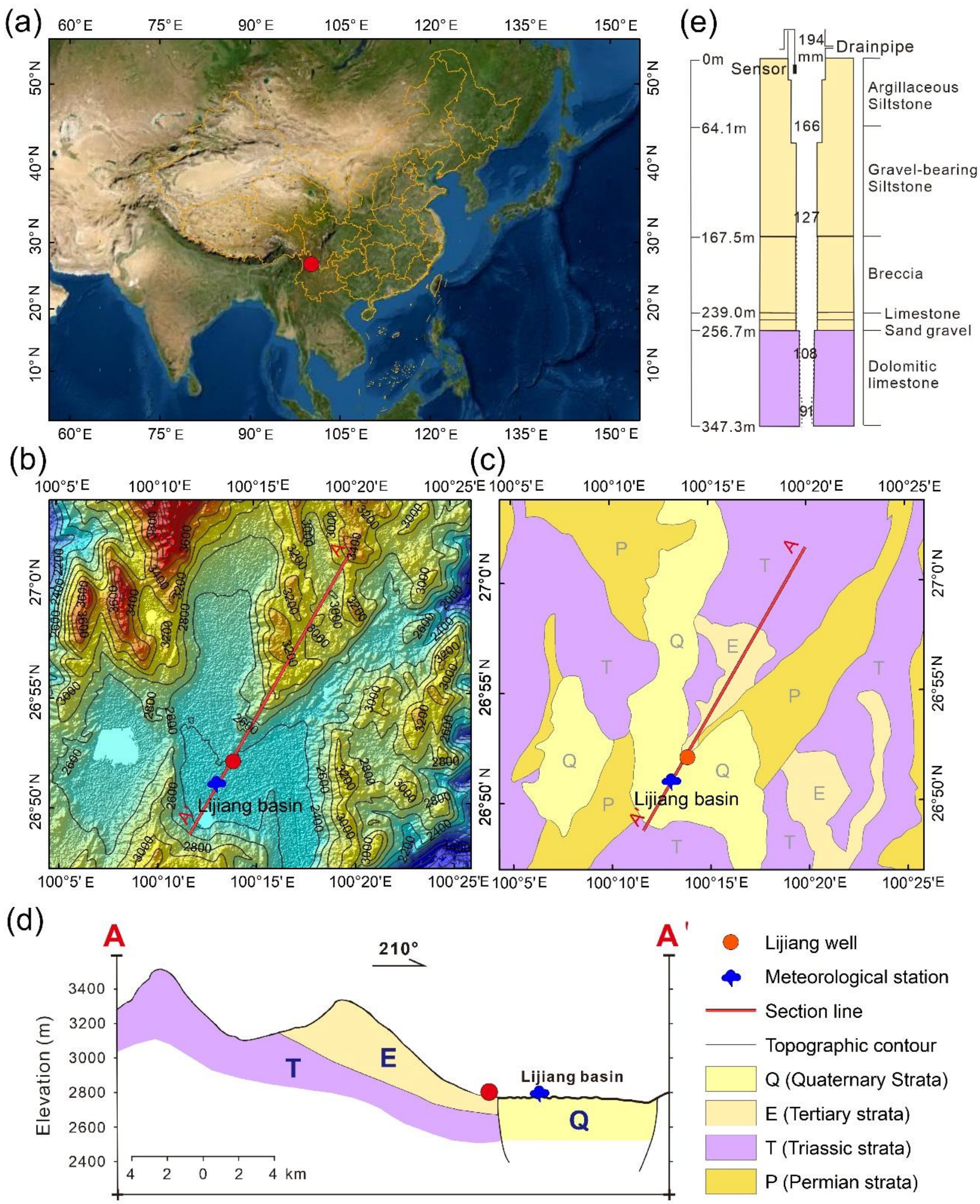

Figure 1. Overview of the observation well and its surrounding area. (a) The location map of the Lijiang well and Lijiang meteorological station. The Lijiang meteorological station is to the Southwest of the Lijiang well (about 2.5 km away). (b) Topography around the Lijiang well. (c)

Simplified hydrogeology around the Lijiang well. (d) Simplified cross-section of topography and hydrogeology around the Lijiang well. (e) Simplified diagram of the Lijiang well showing the lithology and the inner diameter of the well in mm. The dashed lines indicate the open section of the well.

Figure 2a shows water level data recorded in the Lijiang well from 2007 to 2016 and the local precipitation. This region experiences seasonal precipitation from June through September. The well water level annually rises from July to October and falls from November to June. Interestingly, the water levels do not respond to the local precipitation, implying that the aquifer is not hydraulically connected to the surface but is recharged at a distance from the well. **Figure 2b** shows the changes in the amplitude and phase of the tidal response of the water level to the Earth tide. We employed the widely used Baytap-G routine (Tamura et al., 1991) for the tidal analysis, selected a 30-day window, and used the response to the semi-diurnal M2 lunar tide (Doan et al., 2006). Note that the amplitude and phase are negatively correlated and are related to the well water level (**Figure 2b**).

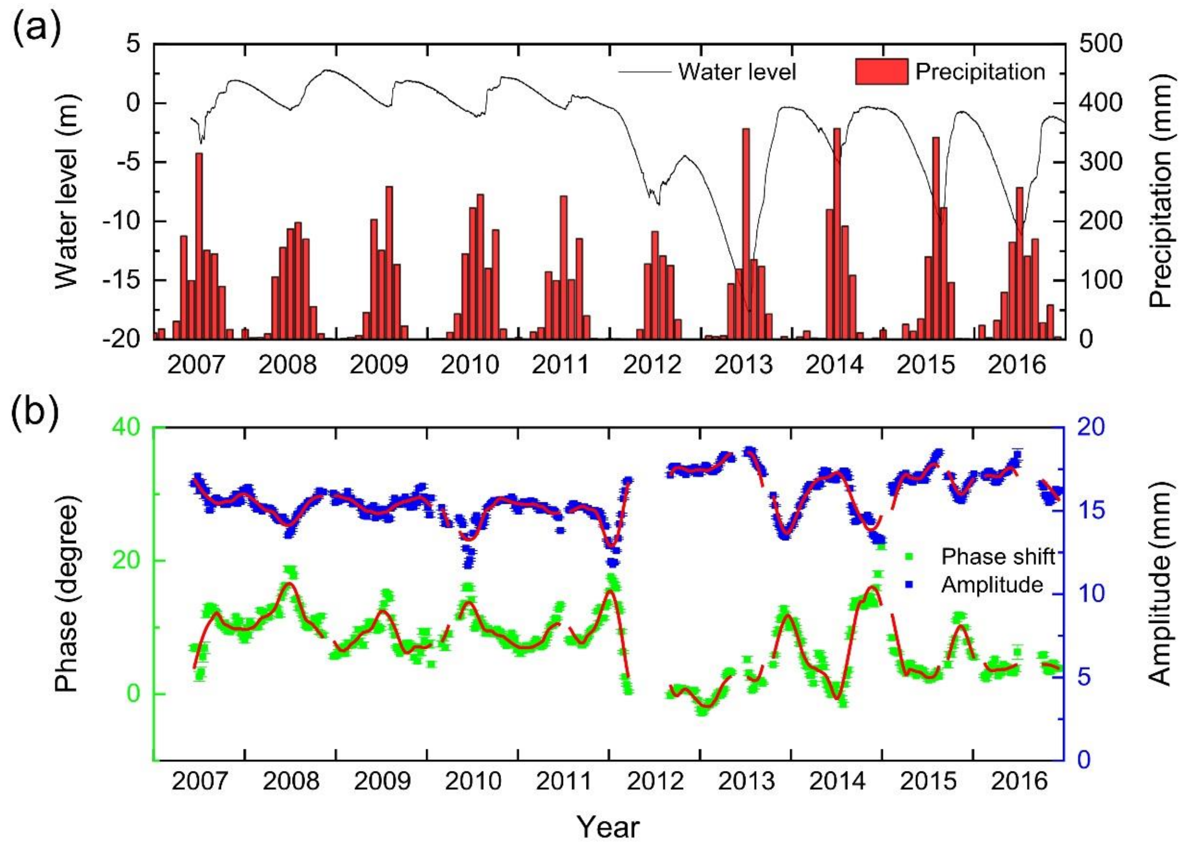

Figure 2. (**a**) The Lijiang well's water level and precipitation near the well over a ten-year period. Excess water above the ground surface was drained through a drainpipe (**Figure 1e**). (**b**) Amplitude and phase of the tidal response of the water level in the Lijiang well to the M2 (theoretical) tide plotted together with error bars as a function of time. The solid red line represents the result of the amplitude and phase after smoothing.

3 Theoretical Model

Here, we briefly show the solution for the tidal response of a horizontally extensive leaky confined aquifer to the Earth's tide (Wang et al., 2018). The aquifer is open to a well with a radius of r_w, and the radius of the cased well is r_c. The phase shift (η) and amplitude ratio (A) of tidal response of the water level in the well referenced to the tidal-strain equivalent head $\left(\frac{BK_u\varepsilon_0}{\rho g}\right)$ are given by, respectively,

$$A = \left|\frac{i\omega S}{(i\omega S+u)\xi}\right|, \quad (1)$$

$$\eta = \arg\left[\frac{i\omega S}{(i\omega S+u)\xi}\right]. \quad (2)$$

where,

$$\xi = 1 + \left(\frac{r_c}{r_w}\right)^2 \frac{i\omega r_w}{2T\beta}\frac{\mathrm{K}_0(\beta r_w)}{\mathrm{K}_1(\beta r_w)}, \quad (3)$$

$$\beta = \left(\frac{u+i\omega S}{T}\right)^{\frac{1}{2}}, \quad (4)$$

B, K_u, ε_0, and ρ are the Skempton's coefficient, undrained bulk modulus, bulk strain, and density, respectively, of the aquifer, g is the acceleration due to gravity, $T = K * b$, $u = K'/b'$, and S are the transmissivity, leakage, and storativity, respectively, of the aquifer, K and b are horizontal hydraulic conductivity and thickness, respectively, of the aquifer, K' and b' are the vertical hydraulic conductivity and thickness, respectively, of the aquitard, ω is angular frequency of the water level tidal response to the Earth tide (for M2 tide, $\omega = 1.9324\ \mathrm{d}^{-1}$), and K_0 and K_1 are the modified Bessel function of the second kind of the 0th and the 1st order, respectively.

For a given well, the amplitude ratio (A) and phase shift (η) of a specific tidal wave for water level tidal response are related to the geohydrological parameters, including the storativity (S), transmissivity (T), and leakage (u) of the leaky confined aquifers. The analytical model for the tidal response of the leaky confined aquifer described above, referred to here as the Wang et al. (2018)'s model, also can be applied to estimate the hydrodynamic parameters of semi-confined aquifers, as well as other different aquifer types, including unconfined aquifers and confined ones. As shown in **Figure 3**, when the leakage is low enough, the semi-confined aquifer acts as a confined aquifer, of which the tidal response is insensitive to the leakage changes (also see Hsieh et al., 1987); while when the transmissivity is small enough, the semi-confined aquifer acts as an unconfined aquifer, of which the tidal response is insensitive to the changes in transmissivity (also see Roeloffs, 1996).

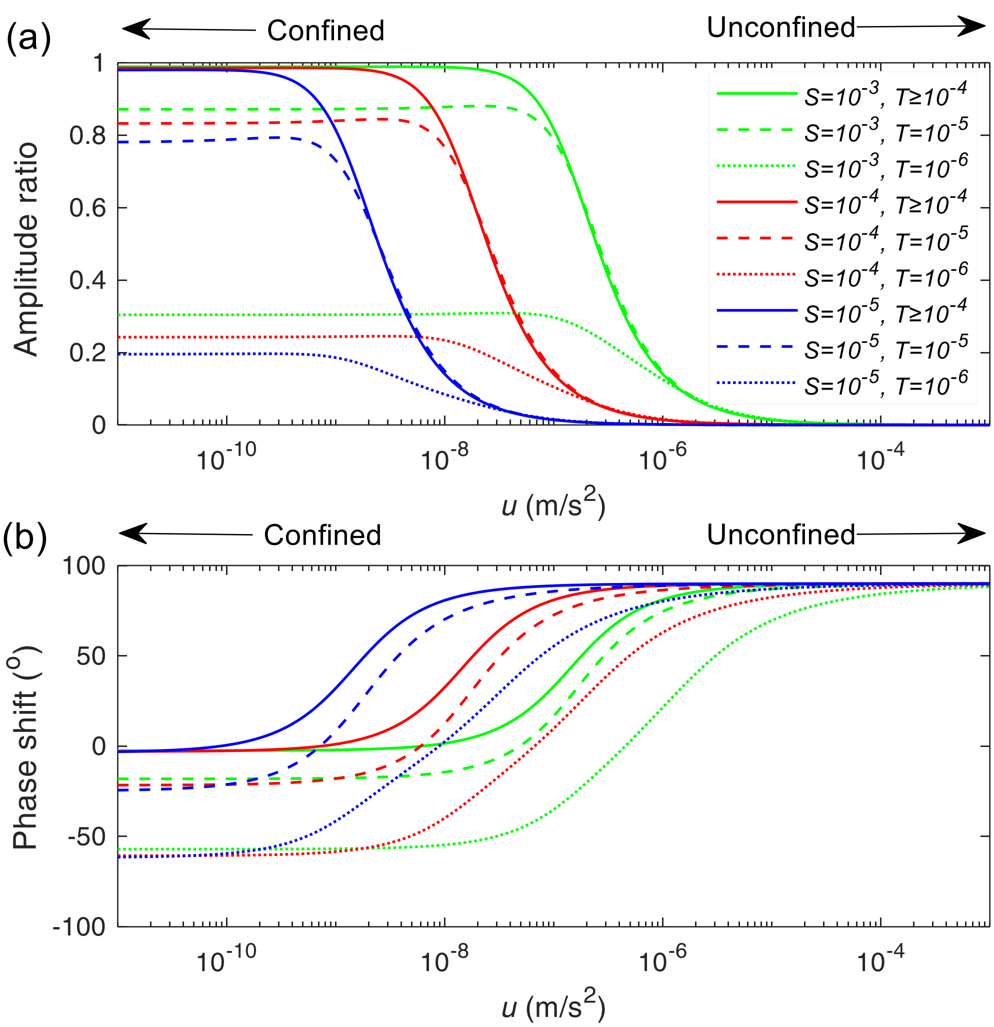

Figure 3. (**a**) Amplitude ratio and (**b**) phase shift of water level tidal response to the M2 (semidiurnal lunar) tide, plotted against the leakage (u) for different transmissivities (T) and storativities (S), with $r_w = r_c = 10$cm. Negative values of phase shift indicate phase lag.

4 Interpretation

Wang et al. (2019) and Liang et al. (2022) analyzed, respectively, the possible effect of the capillary zone on the tidal response of the water level in the Lijiang well using numerical simulations and analytical model, and attributed the variations in the tidal response of the water level to the impact of the capillary zone. However, their simulation assumes that the observed aquifer is unconfined (despite of the fact that it is a semi-confined or a leaky aquifer, see **Figure 1d & 1e**), indicating that the capillary effect on the water level tidal response may be considerably overestimated. Zhu (2022) then discussed the capillary effect of semi-confined aquifer on the tidal response of water level in Lijiang well through numerical simulation. Although her complex numerical models could fit the correlation between amplitude (ratio) and phase (shift), the reliability of fitting results was insufficient to explain the seasonal changes in the tidal response of water level because there are no actual geohydrological parameter values used during the fitting. Moreover, the actual process of tidal response of well water level without capillary hysteresis (see **Figure 4a & 5**) is inconsistent with the tidal response caused by capillary effect which shows that there are differences between the tidal response during the rising of water level and that during the falling of water level (see **Figure 4b** in Liao et al., 2022), which indicates that the seasonal changes in tidal response is not caused by the seasonal changes in capillary action.

Liao and Wang (2018) used Roeloffs (1996)'s tidal response model for an unconfined aquifer to explain the changes in the tidal response of the well water level. They attributed the changes in the tidal response to the changes in the vertical permeability of the unconfined aquifer. Nevertheless, based on the geohydrological setting (**Figure 1c & 1d**) and the fact that the amplitude and phase are inversely proportional **(Figure 4a**), we concluded that the aquifer observed by the Lijiang well is a semi-confined or leaky confined aquifer. Therefore, we employed Wang et al. (2018)'s theoretical model to explain the tidal response of water level in the Lijiang well. As shown in **Figure 4a**, the amplitude and phase can be fitted with Wang et al. (2018)'s model, indicating that the tidal response of the water level in the Lijiang well can be explained by the tidal response model of a leaky confined aquifer.

Based on the tidal response model of a leaky confined aquifer (see **Theoretical Model**; Wang et al., 2018), we were able to estimate the vertical permeability (k') of the aquitard and the storativity (S) of the aquifer during the study period using the amplitude (or amplitude ratio) and phase (or phase shift) of the tidal response of the well water level (see **Figure 4b**). As shown in **Figure 4b**, the vertical permeability and storativity are positively correlated and change seasonally. The vertical permeability and storativity decreased synchronously between July and October (during the rainy season) and increased synchronously between November and June (during the dry season). In our study, the horizontal permeability or transmissivity of the aquifer cannot be estimated because the amplitude ratio and phase shift are insensitive to changes in the transmissivity at high transmissivity ($T_h \sim 10^{-1} \mathrm{m}^2/s$; refer to Liao and Wang (2018) who estimated the transmissivity by using the seasonal response of water level to the precipitation) (see **Figure 3**).

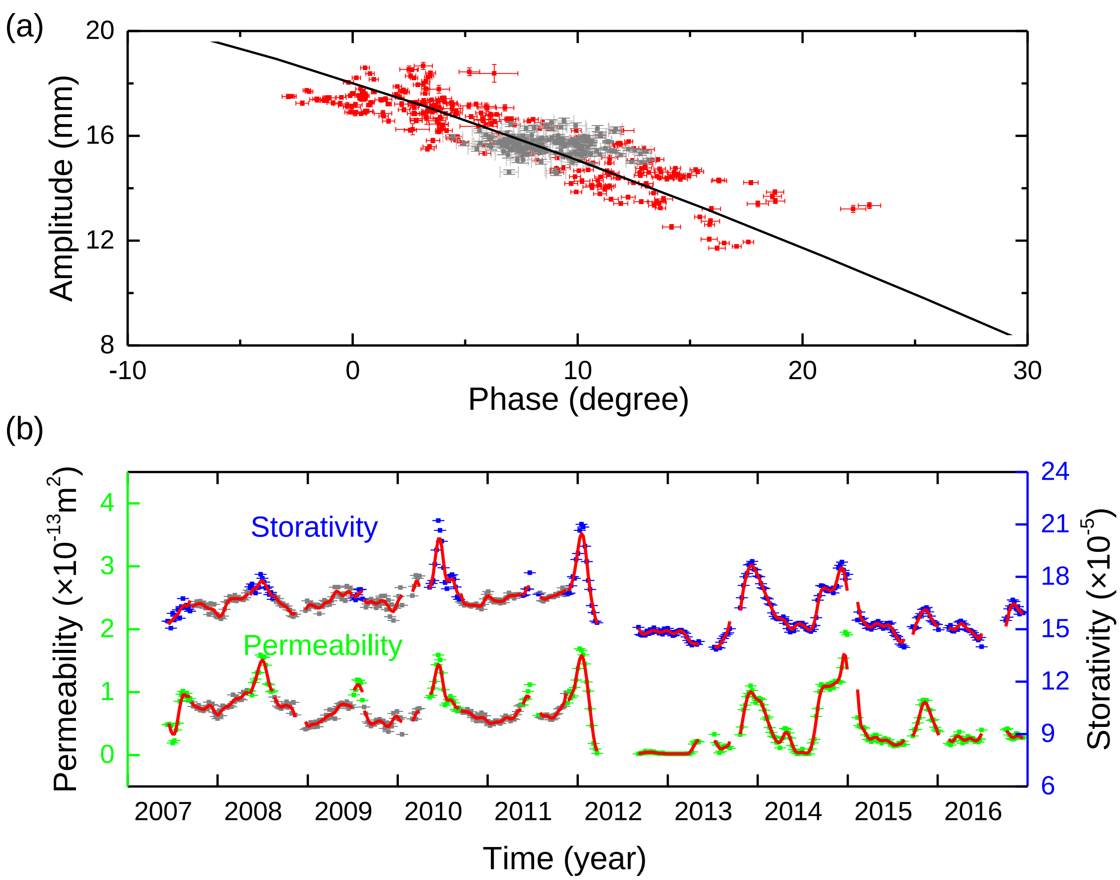

Figure 4. (**a**) Actual and theoretic correlation between the amplitude and phase of the M2 tide of the water level. The scatter plot was generated using water level data recorded in the Lijiang well; and the theoretical curves were obtained using Wang et al. (2018)'s theoretical model by setting $T = 10^{-1} \mathrm{m}^2/\mathrm{s}$ (refer to Liao and Wang, 2018). The gray dots represent the amplitude and phase under drainage conditions that were not analyzed further, as the well water drainage

has effect on the tidal response of the well water level. (**b**) Vertical permeability (k') of the aquitard and storativity (S) of the aquifer over time with error bars by using Wang et al. (2018)'s theoretical model. The solid red line represents the vertical permeability and storativity after smoothing. Note that the estimated values of the vertical permeability and storativity differed significantly (by an order of magnitude) from those reported by Liao and Wang (2018), who used an unconfined aquifer model.

5 Discussion

Given that the vertical permeability is positively correlated with the well water level or pore pressure in the groundwater system, Liao and Wang (2018) argued that the clogging and unclogging of fractures induced by changes in the pore pressure is responsible for the seasonal changes in vertical permeability. The changes in vertical permeability caused by the aforementioned mechanism tend to lag behind the changes in well water level or pore pressure because the process of fracture clogging and unclogging takes time. However, the field data does not support this mechanism, as no lag loop was observed between the vertical permeability & storativity and the well water level or pore pressure, which suggests that the seasonal response of the geohydrologic parameters to the hydrologic process is immediate and nonhysteretic (see **Figure 4**). Therefore, a plausible new mechanism is required to explain the observed fluctuations in both the amplitude (ratio) and phase (shift) of the tidal response of the well water level.

Figure 5 shows the correlation between the hydrogeological parameters, including the vertical permeability (k'), the storativity (S), and the change in pore pressure (ΔP) or well water level (Δh).The fitting relationship between hydrogeological parameters and pore pressure demonstrated by on-site observation data is the same as the empirical one proposed by Raghavan and Chin (2004) to determine the permeability of pore pressure or stress sensitive fractured aquifers during the poroelastic response process. The exponential relationships between vertical permeability and storativity and pore pressure indicate that the seasonal response of the groundwater system is significantly dependent on pore pressure or effective stress of the groundwater system, implying that the geohydrologic parameters of the groundwater system are extremely sensitive to pore pressure changes. In addition, the vertical permeability and storativity are linearly correlated with each other, which implies that the same mechanism should be responsible for the changes in both quantities during the response process.

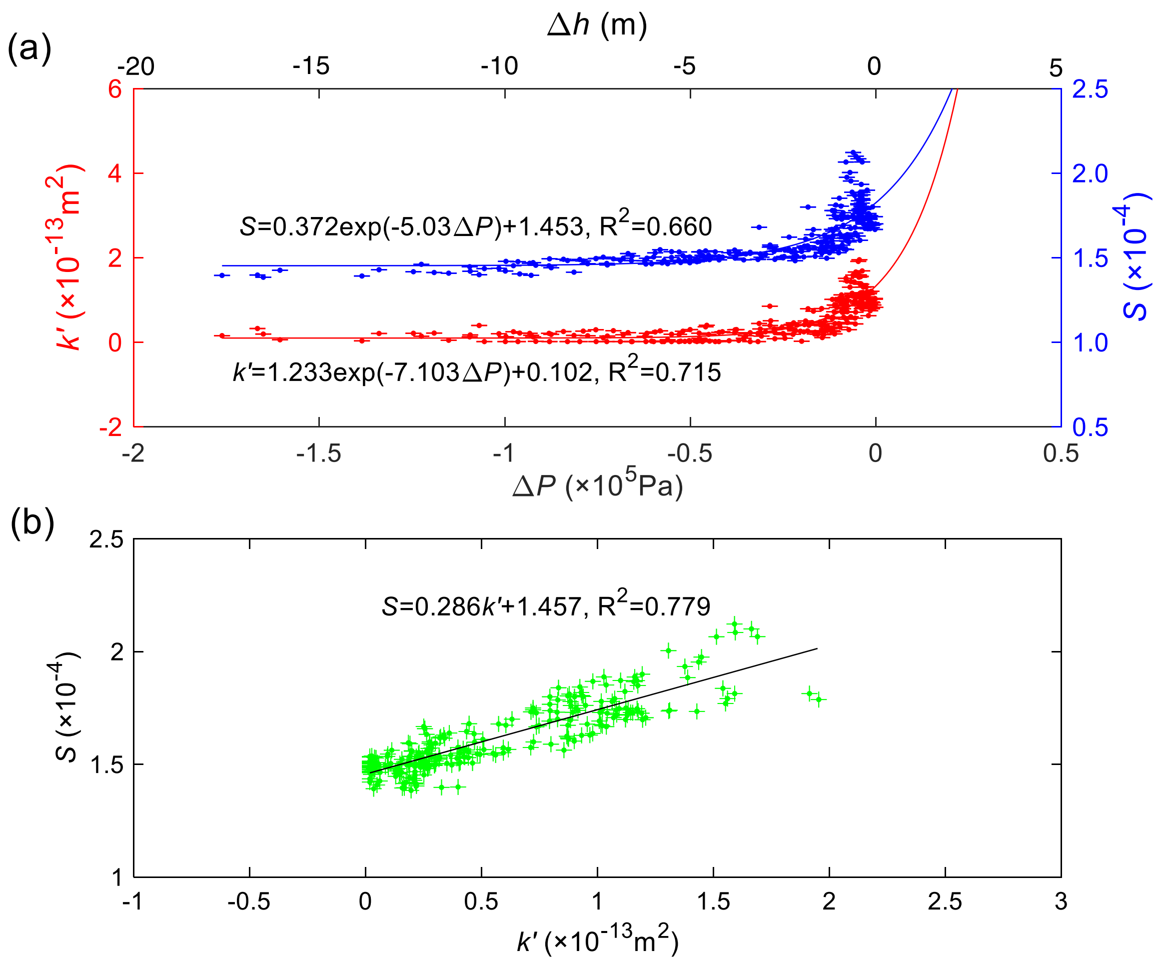

Figure 5. **(a)** Correlation between the storativity (S) or the vertical permeability (k') and the change in pore pressure (ΔP) or well water level (Δh). **(b)** Correlation between the storativity (S) and the vertical permeability (k'). The water level was averaged over a 30-day period. The pore pressure (P) was calculated using $P = \rho g h$, where $\rho = 10^3 \mathrm{kg/m^3}$ is the density of the groundwater, $g = 9.8 \mathrm{m/s^2}$ is the acceleration due to gravity, and h is the well water level. The best fit of the correlation between the vertical permeability (k') and the changes in pore pressure

(ΔP) is $k' = k'_0 e^{-d\Delta P} + k'_1$, where $d = 7.103 \times 10^{-5}\mathrm{Pa}^{-1}$ is the characteristic parameter of the rock mass, $k'_0 = 1.233 \times 10^{-13}\mathrm{m}^2$ is the "initial" permeability when the pore pressure is sufficiently high, $k'_1 = 0.102 \times 10^{-13}\mathrm{m}^2$ is the "residual" permeability when the pore pressure is low enough. The best fit of the correlation between the storativity (S) and the changes in pore pressure (ΔP) is $S = S_0 e^{-d'\Delta P} + S_1$, where $d' = 5.030 \times 10^{-4}\mathrm{Pa}^{-1}$ is the characteristic parameter of the rock mass, $S_0 = 0.372 \times 10^{-4}$ is the "initial" storativity when the pore pressure is sufficiently high, and $S_1 = 1.453 \times 10^{-4}$ is the "residual" storativity when the pore pressure is low enough.

Based on the nonhysteretic exponential correlation with the pore pressure, the seasonal changes in vertical permeability and storativity can be attributed to the poroelastic response in the fracture aperture caused by the seasonal changes in the pore pressure or effective stress of the groundwater system, rather than the fracture unclogging/clogging proposed by Liao & Wang (2018). Increases in pore pressure result in an increase in the fracture aperture, which in turn leads to an increase in the vertical permeability and storativity. On the other hand, as the pore pressure decreases, the fracture aperture decreases, lowering the vertical permeability and storativity. A change in the fracture aperture caused by a change in pore pressure is a poroelastic response and usually doesn't take time; therefore, the vertical permeability, storativity, and pore pressure changes occur almost simultaneously, which is consistent with observations from the Lijiang Well (see Figure 4 & 5).

We proposed a novel potential mechanism to explain the seasonal vertical permeability and storativity changes. These seasonal changes can be attributed to seasonal fracture aperture changes or seasonal fractures opening/closing in the groundwater system, which are caused by regional rainfall recharge inducing changes in pore pressure or effective stress during a hydrologic year. The cyclic seasonal changes in the vertical permeability and storativity also suggest a reversible poroelastic process throughout a hydrological year. Because of this regional precipitation recharge, the pore pressure of the groundwater system will increase, leading to increases in the fracture apertures, vertical permeability, and storativity. In contrast, as the pore pressure decreases, the vertical permeability and storativity will recover to their pre-recharge level.

It has been suggested that seasonal hydrologic processes can reshape groundwater systems through seasonal variations in geohydrologic parameters, thereby affecting the seasonal hydrologic response in subsurface systems. Recharging groundwater makes the groundwater system more permeable and storable during the rainy season. Therefore, the groundwater is a linked poroelastic–hydraulic system with positive feedback. The feedback may have a seasonal effect on the subsurface ecosystems and environments, such as groundwater security, the safety of nuclear waste storage, and diffusion and transport of pollutants, increasing the risks associated with a number of ecological and environmental issues in the subsurface system.

6 Conclusions

In this study, motivated by the fact that changes in the vertical permeability and storativity of the groundwater system occurred almost simultaneously with the changes in the pore pressure, as seen by the Lijiang well, we proposed a new mechanism to explain the seasonal pore pressure dependent geohydrologic parameter fluctuations inferred from the tidal response of the water level in the Lijiang well. We attributed the seasonal geohydrologic parameter fluctuations to the fracture aperture changes or the opening/closing of pre-existing fractures in the groundwater system that resulted from the pore pressure perturbation-induced poroelastic response of the groundwater system. Such seasonal geohydrologic parameter changes are expected to alter groundwater storage, flow patterns, and transport processes in the groundwater system during a rainy season. Considering that these processes may impact the migration of contaminants and the security of subsurface waste repositories, the findings of this study may have far-reaching implications for the safety of the subsurface environment, ecosystem, and groundwater resources.

Acknowledgments

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Data Availability Statement

Well-water level data may be downloaded through an application of China Earthquake Networks Center, National Earthquake Data Center (URL: https://data.earthquake.cn/datashare/login.jsp). Precipitation data may be downloaded through an application of China Meteorological Data Service Centre, China Meteorological Administration (URL: http://data.cma.cn/data/cdcindex/cid/0b9164954813c573.html).

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