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Posted Date: 22 February 2024

doi: 10.20944/preprints202402.1243.v1

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## Article

# Based on the Periodic Dynamic of Water Level in Well BB to Es-Timate the Time Series Changes of Aquifer Parameters

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**Abstract:** Due to the long duration and high cost of traditional pumping tests, the response of well water level to seismic wave, earth tide, and barometric pressure provides a feasible method for determining continuous changes in aquifer hydraulic parameters. Aiming at the problem that the response phase shift of well BB water level to tidal tide  $M_2$  is greater than that of tide  $O_1$ , this paper preferentially calculated the time series changes of  $S$ ,  $B_e$ ,  $n$  and  $BK_u$  based on the response mechanism of well water level to barometric pressure and earth tide and with the help of smooth moving method. Then by using the mixed flow model, the variation of transmissivity and leakage coefficient over time were simultaneously obtained, and the evolution process and characteristics of aquifer parameters near well BB caused by the Wenchuan earthquake were ultimately discussed. The calculation results are basically consistent with the previous pumping test, and have been verified and compared by using other scholars' methods. This solving process avoids the problems such as excessive dependence on initial values, multiple solutions, and unstable tide  $O_1$ , which has a promoting effect on the study of the impact of seismic activity on aquifer systems.

**Keywords:** tidal response; hydraulic characteristics; transmissivity; leakage coefficient

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## 1. Introduction

The transmissivity ( $T$ ) and leakage coefficient ( $\sigma$ ) are main hydrodynamic parameters of aquifers, which directly determine the hydrodynamic characteristics of aquifers and the law of groundwater transport [1]. The accurate calculation of aquifer hydraulic parameters and their continuous changes play an important role in guiding the rational development and utilization of groundwater resources, and also provide a theoretical basis for the stability analysis of underground space, the safe burial of nuclear waste and the migration of groundwater pollutants [2].

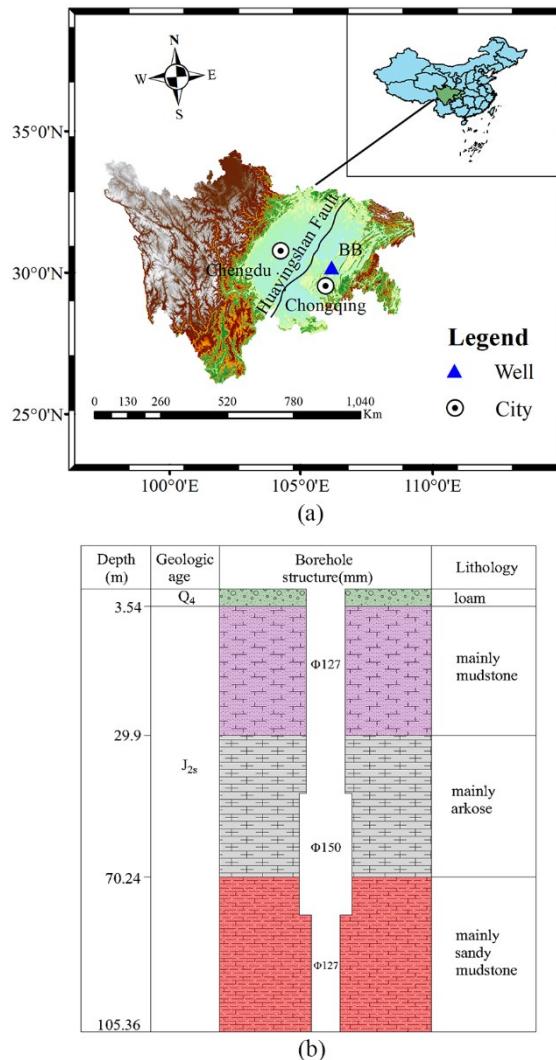
Groundwater level dynamics is an important observation reflecting the crustal activity, which is often affected by many factors, such as barometric pressure [3–5], earth tide [6,7], seismic wave propagation [8–10] and fault activity [11,12], so the response of well water level to these factors provides a feasible method for determining the aquifer hydraulic parameters. Cooper et al. [8] established a model for the response of well water level to periodic loading, and proposed that the response amplitude of well water level to pore pressure mainly depends on the dimensions of the well, the transmissivity and storage coefficient ( $S$ ) of the aquifer. Hsieh et al. [7] and Rojstaczer [13] estimated the hydraulic parameters of an aquifer by using the response models of well water level to barometric pressure and earth tide. Following Roeloffs [14], Doan & Brodsky [15] developed a tutorial to estimate the poroelastic parameters and the permeability of the reservoir by analyzing the amplitude and phase of the tidal response. Wang et al. [16,17] established a mixed flow model for the tidal response of groundwater in the aquifer, with the model gave the expressions of the  $T$  and  $\sigma$ , and they provided an important supplement to the previous tidal analysis model. Based on the analysis of changes in groundwater response to earth tide and barometric pressure, Wang and Manga [18]

reviewed the latest research progress on the effects of earthquakes on aquifer parameters, and stressed the importance of real-time and continuous monitoring of groundwater. The above models have been widely used in the study of co-seismic water level response [19–21], strain sensitivity assessment of well-aquifer systems [22,23], changes in shallow crustal permeability caused by earthquakes [24–26], and inversion of aquifer permeability parameters [27–30]. Among them, Sun et al. [31] calculated the hydraulic parameters of a confined aquifer based on the response of groundwater levels to seismic Rayleigh waves based on the model of Cooper et al. [8].

Previous studies could only calculate the permeability ( $T$ ) or leakage capacity ( $\sigma$ ) of an aquifer using the horizontal flow model or the vertical flow model separately [7,26]. Yang et al. [30,32,33] used the tides  $M_2$  and  $O_1$  responses in a least squares inversion of the unknown parameters in the leaky aquifer model, with three inputs used to obtain three parameters ( $S$ ,  $T$  and  $\sigma$ ) simultaneously. This method is suitable for situations where the phase shift of tide  $O_1$  is greater than that of tide  $M_2$ . Zhang et al. supplemented the method in the subsequent articles [32,33]. And to alleviate the problem of the large dependence of the results on the initial values, the aquifer lithology and the aquitard lithology are set as limitation conditions during the fitting processes. However, the problem of multiple solutions still exists, and the instability of tidal  $O_1$  results in relatively large errors [30,32,33]. And due to the complexity of hydrogeological conditions and the diversity of water level characteristics of wells, this algorithm is not suitable for all wells [18]. Here, taking well BB near Huayingshan fault as an example, through the tidal analysis of the well water level, we found that the tide  $M_2$  phase shift is greater than the tide  $O_1$  phase shift, it is challenging to get relatively precise solutions ( $T$  and  $\sigma$ ) using the above methods. Therefore, this paper attempts to explore the way of obtaining the time series changes of aquifer hydraulic parameters in this case by synthesizing the barometric pressure and earth tide effect of the well water level, and discusses the accuracy, applicability, advantages and disadvantages of the solution process, so as to achieve the purpose of explaining the changes of aquifer hydraulic characteristics caused by seismic activities.

## 2. Observation background and data

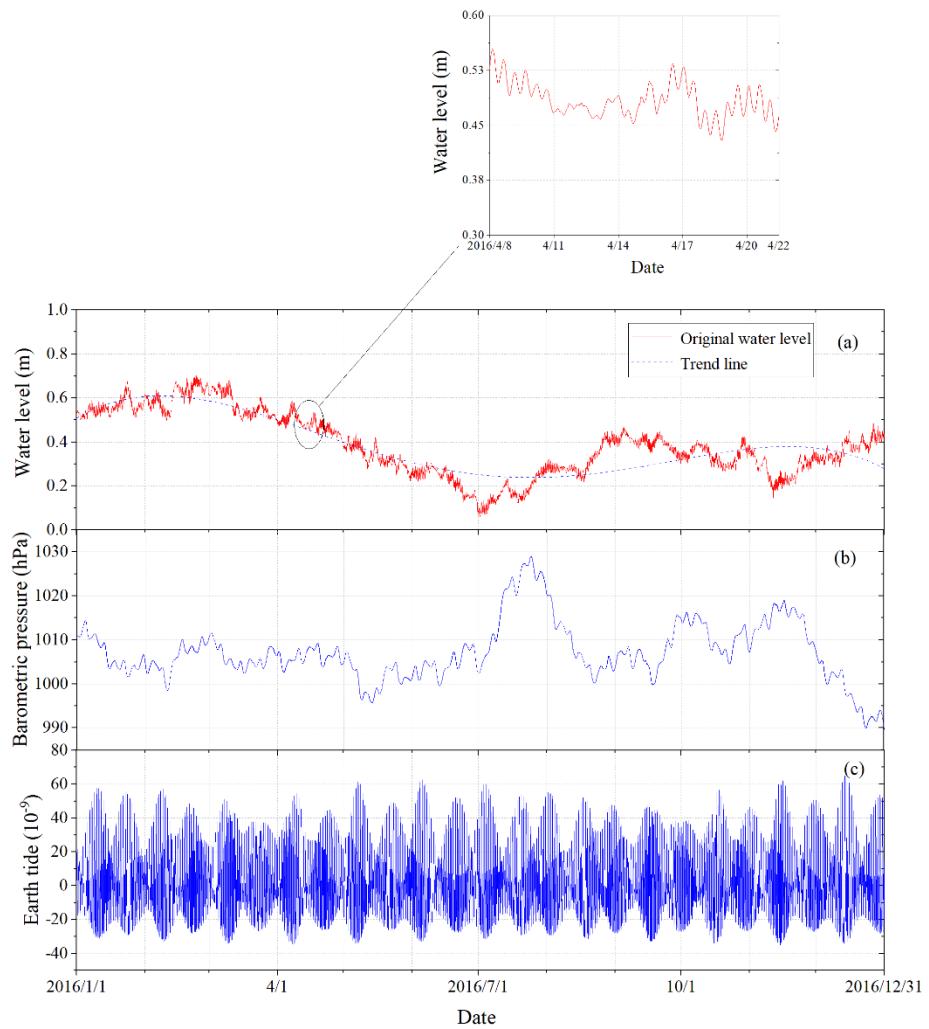
Huayingshan fault is located in southwest China and is a type of dextral strike slip reverse fault with about 460 km long. It is a boundary fault between the block-type fold belt in eastern Sichuan and the gentle structure of central Sichuan. Well BB is located within 10 km of Huayingshan fault zone (Figure 1a) (Table S1), which is a typical "red bed" area in Sichuan basin, that is to say, the main exposed strata in this area are interbeds of purplish red mudstone and gray white arkose. The underground aquifer is mainly composed of feldspathic sandstone with a thickness of about 10~50 m. The upper and lower water bearing sandstones are sandwiched by relatively impermeable mudstones. This type of aquifer is widespread and has numerous hydraulic connections. The confined water in this area's red bed is recharged primarily by precipitation in the outcrop area, followed by vertical infiltration of the surface water and partial leakage of adjacent aquifers. The precipitation and surface water infiltrate the aquifer through the exposed cracked near the surface, and runoff or vertical leakage occurs along the river bed or along the sandstone fissure. When the aquifer is depleted, groundwater is discharged into the surface water or spring, and it can also be discharged through the adjacent aquifers.



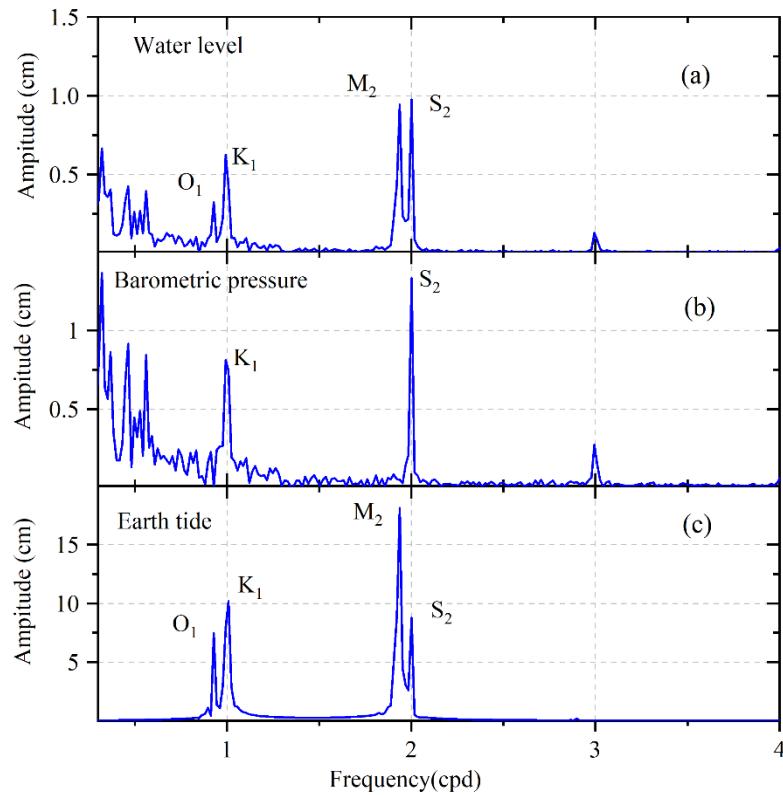
**Figure 1.** (a) The locations of Sichuan and Chongqing in southwest China. The basemap was downloaded from the Natural Earth at <http://www.naturalearthdata.com/>. Well BB is subordinate to Chongqing. (b) The stratigraphy of well BB.

The lithology of borehole BB is shown in Figure 1b. The depth of well BB is 105.36 m, the diameter of 127 mm casing is lowered to 42.1 m, and the casing is cemented and sealed with cement. Purple mudstone at 3.54~29.90 m. The main aquifer is located at 29.90~70.24 m, and the borehole lithology is light grayish white medium-coarse-grained thick-bedded arkose of middle Jurassic. 70.24~105.36 m is mainly purplish-red sandy mudstone with purplish-gray siltstone bands. The well water level is observed by static water with a LN-3A digital piezometer, with a sampling interval of 1 min, an accuracy of 1 cm, and a resolution of 1 mm (Table S2).

As shown in Figure 2, the daily dynamic fluctuations in the water level in well BB are stable, with a typical change amplitude of about 6 cm. And it has clear tidal variation characteristics of two peaks and two valleys, which is negatively correlated with the barometric pressure. Spectrum analysis of water level, barometric pressure and earth tide data was performed using the calculation package *Matlab*® (Mathworks Inc., Natick, Minnesota), with spectrum analysis power plotted according to period (days/period) (Figure 3). According to the spectrum analysis results of well BB, the main tidal components of well water level are tides O<sub>1</sub>, K<sub>1</sub>, M<sub>2</sub> and S<sub>2</sub>, and is affected by both barometric pressure and earth tide. Considering that tides S<sub>2</sub> and K<sub>1</sub> are affected by barometric pressure and have small signal-to-noise ratios, the tides O<sub>1</sub> and M<sub>2</sub> are mainly used in well water level tidal analysis to reduce calculation errors. Among them, the tide M<sub>2</sub> water level data typically has a significant amplitude and a modest amount of errors.



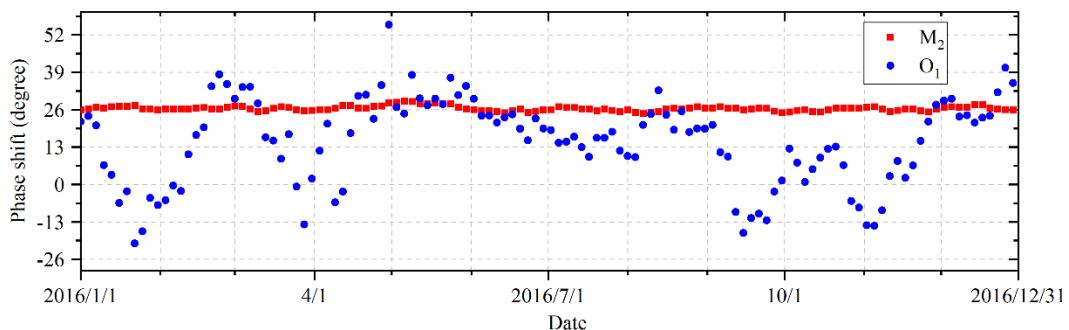
**Figure 2.** (a) Water level, (b) barometric pressure and (c) theoretical tidal volumetric strain of well BB in 2016. The data of water level and barometric pressure were obtained from the China Earthquake Precursor Monitoring Network, the theoretical tidal volumetric strain was obtained using the software *EIS2000*.



**Figure 3.** Results of spectrum analysis of the well BB's hourly values of (a) water level, (b) barometric pressure and (c) earth tide in 2016.

### 3. Methods

To solve the unknown parameters in the mixed flow model proposed by Wang et al. [16], tidal analysis of well water level should be performed first. Through the tidal analysis of the well BB's hourly values of water level in 2016 (Figure 4), it can be found that the M<sub>2</sub> phase shift (the average is 26.435°) is greater than the O<sub>1</sub> phase shift (the average is 14.92°), which is not matching the standards of the literature [30]. And due to the unstable phase shift of the tide O<sub>1</sub>, it is challenging for us to get time series and relatively precise solutions using Yang et al.'s method for calculations. While the tide M<sub>2</sub> has the advantages of having sufficient amplitude, being easy extraction and not being affected by barometric pressure [34,35]. Therefore, here, only the response of well water level to tide M<sub>2</sub> was used to estimate the  $T$  and  $\sigma$  of aquifer near well BB. Based on the mixed flow model of aquifer proposed by Wang et al. [16], there are four unknowns ( $S$ ,  $T$ ,  $\sigma$  and  $BK_u$ ) in the analytical expressions of the tidal factor ( $A'$ ) and the phase shift ( $\eta$ ).  $S$  and  $BK_u$  were determined beforehand based on the barometric influence and tidal effect of well water level, then the numerical solutions of  $T$  and  $\sigma$  were solved simultaneously using the least square method.



**Figure 4.** Phase shift of the tides M<sub>2</sub> and O<sub>1</sub> obtained through tidal analysis using the Baytap08 program [36], with the time window of 30 days and the running step of 3 days.

### 3.1. Determination of storage coefficient

The specific storativity ( $S_s$ ) is a parameter that describes the water release capacity of an aquifer [ $L^{-1}$ ]. Assuming that the change of aquifer porosity is equal to the change of aquifer volume, the  $S_s$  of confined aquifer can be expressed as [37,38]:

$$S_s = \rho_w g \left( \frac{1}{K} + \frac{n}{K_w} \right) = \frac{gn\rho_w}{K_w} = -\frac{\varepsilon_{kk}}{h} = \frac{1}{A'} \quad (1)$$

$$S = S_s \times M \quad (2)$$

where  $\rho_w$  refers to the density of water [ $L^{-3}M$ ],  $n$  refers to the porosity of the entire aquifer,  $A'$  is tidal factor, which refers to the ratio of measured amplitude of the tide to the theoretical amplitude of the earth tide [L],  $M$  refers to the aquifer thickness [L], and  $K$  and  $K_w$  refer to the bulk modulus of the aquifer and water [ $LM^{-1}T^{-2}$ ], respectively.

To obtain the  $A'$  in the aquifer, the tidal analysis data by Baytap08 program was used [36], which uses Akaike's Bayesian information criterion. The following sections are presumptively possible for a time series [15,36,39]:

$$y_i = \sum_{m=1}^M (\alpha_m C_{mi} + \beta_m S_{mi}) + \sum_{k=0}^K b_k x_{i-k} + d_i + e_i \quad (3)$$

The tidal component is the first term on the right-hand side:  $C_{mi}$  and  $S_{mi}$  are theoretically computed values for the  $m$ th group of tidal elements, and  $\alpha_m$  and  $\beta_m$  are the tidal response constants to be established in the statistical model. The barometric response element is established as  $\sum_{k=0}^K b_k x_{i-k}$ , where  $x_{i-k}$  is the observed barometric pressure and  $b_k$  is the response coefficient,  $d_i$  is the long-term trend and  $e_i$  is the noise. The Akaike Bayesian information criterion is established from Equation (3), and this program features a Bayesian inversion procedure that enables the parameters  $\alpha_m$  and  $\beta_m$  to be calculated and subsequently evaluated. The result of the Baytap08 analysis provides the  $A'$  and  $\eta$  for each tide group [40].

### 3.2. Determination of $BK_u$

$BK_u$  represents the elasticity of the rock ( $B$  is the Skempton coefficient,  $K_u$  is the undrained bulk modulus [41]), which is related to the bulk modulus of porous media ( $K$ ), the bulk modulus of solids ( $K_s$ ), the bulk modulus of fluids ( $K_w$ ), and the porosity ( $n$ ) of porous media. The calculation equations for  $K_u$  are shown in Table 1 [42–44].

**Table 1.** Calculation equations of  $BK_u$  and related physical quantities.

	$K$	$\alpha$	$N$	$B$	$K_u$
<b>Equation</b>	$\frac{1}{K} = \frac{1-n}{K_s} + \frac{n}{K_w}$	$1 - K/K_s$	$\frac{1}{(\alpha/K_s) + n(1/K_w - 1/K_s)}$	$\frac{1/K - 1/K_s}{(1/K - 1/K_s) + n(1/K_w - 1/K_s)}$	$K + \alpha^2 N$

\* $\alpha$  is Biot coefficient,  $N$  is Biot modulus. The aquifer lithology of well BB is grayish white medium-coarse grained thick bedded arkose, and the solid skeleton bulk modulus is empirical value, i.e.  $K_s=3.6 \times 10^4$  MPa.

In this calculation, the aquifer porosity is determined by the response of well water level to barometric pressure [45]:

$$n = \frac{B_e S_s K_w}{\rho g} \quad (4)$$

where  $K_w=2.065 \times 10^3$  MPa,  $\rho g=9.8 \times 10^{-3}$  MPa/m.  $B_e$  is the barometric efficiency (dimensionless), it is a key index to directly reflect the barometric effect of well water level. Here, in order to eliminate the

influence of earth tide, the daily series values of water level and barometric pressure were selected to obtain  $B_e$ . Well water level ( $H(t)$ ) is mainly composed of trend term ( $H^0(t)$ ), response to barometric pressure ( $B_e P(t)$ ) and rainfall ( $H'(t)$ ):

$$H(t) = H^0(t) + H'(t) + B_e P(t) \quad (5)$$

The first-order difference is performed on Equation 5 to eliminate the influence of the trend term, so that the value of  $B_e$  is calculated:

$$\Delta H(t) = \Delta H'(t) + B_e \Delta P(t) \quad (6)$$

Where  $\Delta H(t)$  is the change value of well water level,  $\Delta P(t)$  represents the water column height corresponding to the change values of the barometric pressure. The barometric efficiency obtained by the first-order difference method can eliminate the influence of trend change factors on water level. It is worth noting that the signs of  $\Delta H(t)$  and  $\Delta P(t)$  are both positive or negative at the same time, and  $\Delta H(t)/\Delta P(t) < 1$ , all these can avoid the interference of rainfall ( $\Delta H'(t)$ ) to the well water level.

### 3.3. Calculation theory of horizontal transmissivity and leakage coefficient

Based on the mixed flow model proposed by Wang et al. [16], the analytical expressions of the  $A'$  and  $\eta$  are as follows:

$$\begin{cases} A' = \text{abs} \left( \frac{i\omega S}{(i\omega S + (K'/b'))\zeta} \right) * \frac{BK_u}{\rho g} \\ \eta = \arg \left( \frac{i\omega S}{(i\omega S + (K'/b'))\zeta} \right) \end{cases} \quad (7)$$

$$\zeta = 1 + \left( \frac{r_c}{r_w} \right)^2 \frac{i\omega r_w K_0(\beta r_w)}{2T\beta K_1(\beta r_w)} \quad (8)$$

$$\beta = \left( \frac{K'}{Tb'} + \frac{i\omega S}{T} \right)^{1/2} \quad (9)$$

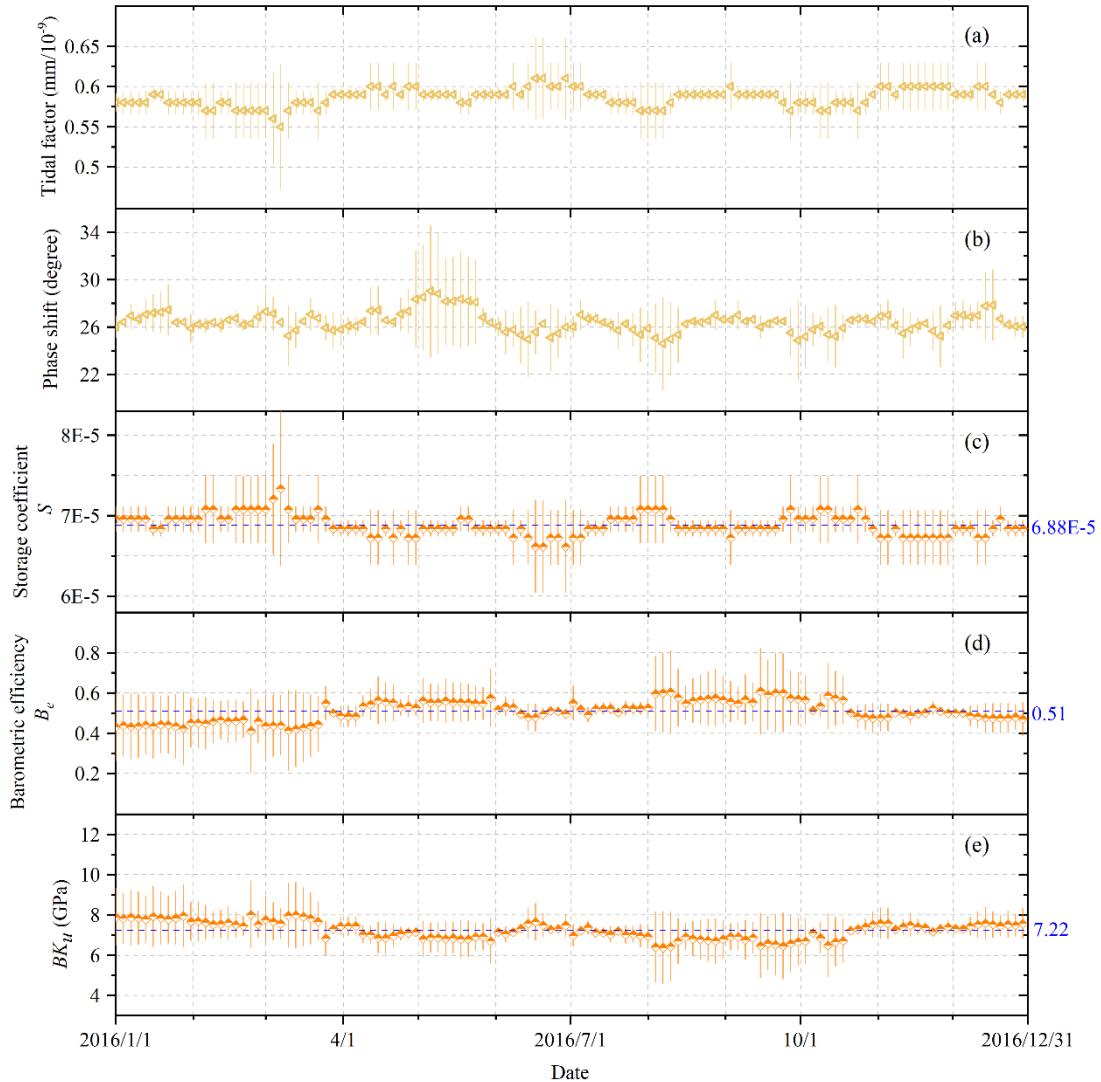
$$A' = A * \frac{BK_u}{\rho g} \quad (10)$$

where  $A'$  and  $\eta$  can be obtained through tidal analysis by Baytap08 program [36],  $A$  is the amplitude ratio (amplitude ratio of well water level to pressure head fluctuation),  $\omega$  is the tidal wave frequency,  $K_n$  is the second kind of modified Bessel function (BesselK function) with order  $n$ , aquifer leakage coefficient  $\sigma = K'/b'$ ,  $r_w$  and  $r_c$  represent the well radius and the case radius. When  $S$ ,  $BK_u$ ,  $A'$  and  $\eta$  are known, Equations. 7 can be used to simultaneously obtain the  $T$  and  $\sigma$ .

## 4. Results

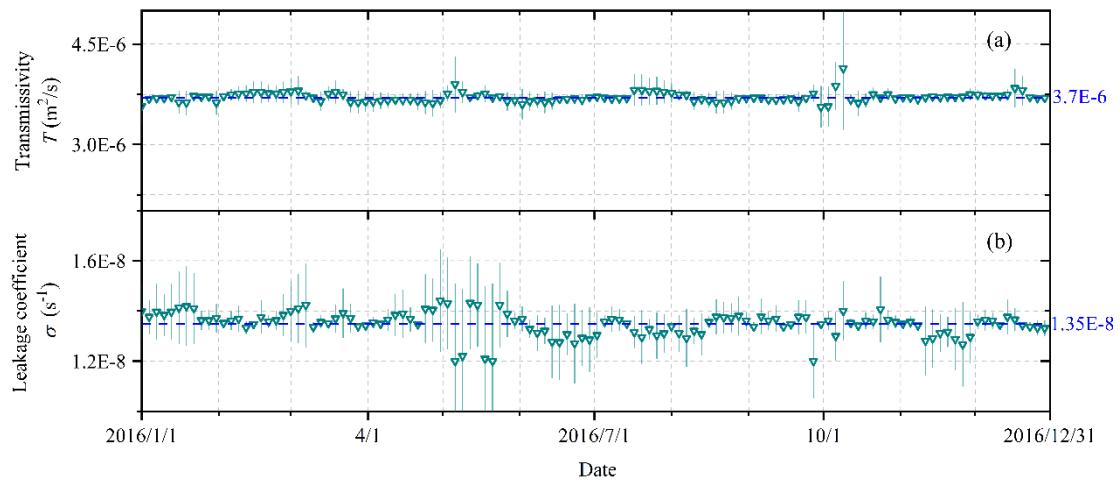
Considering that there are no major earthquakes in Sichuan-chongqing area in 2016, and the characteristics of well water level are not interfered by human factors, the information of well water level of well BB in 2016 are collected for research. Tidal analysis was performed on the hourly water levels of well BB with the time window of 30 days and the running step of 3 days (Figure 5a and b), then the dynamic change of  $S$  (Figure 5c) was obtained according to the  $A'$  (Equations 1 and 2). Based

on the first-order difference method to solve the  $B_e$ , the time series change of  $B_e$  was obtained by taking 30 days as a group and sliding for 3 days at a time (Figure 5d). And then the aquifer  $n$  was obtained according to the corresponding equation (Equation 4), and finally the  $BK_u$  values of the aquifer were obtained (Table 1; Figure 5e). The mean values of  $S$  and  $BK_u$  are  $6.88 \times 10^{-5}$  and 7.22 GPa, respectively.



**Figure 5.** The change characteristics of (a) tidal factor, (b) phase shift, (c) storage coefficient, (d) Barometric efficiency and (d)  $BK_u$  in 2016. Here the error bars are three times the standard deviation, the blue lines represent the mean of the data set.

According to Equations. 7, when the values of  $S$  and  $BK_u$  are determined, Equations. 7 has two equations with two unknowns ( $T$  and  $\sigma$ ). Based on the least square method to solve the equations, input the corresponding parameters ( $S$ ,  $BK_u$ ,  $A'$  and  $\eta$ ) in *Matlab* program, the time series changes of the aquifer hydraulic parameters near well BB (Figure 6) can be obtained. The mean values of  $T$  and  $\sigma$  are  $3.7 \times 10^{-6}$  m<sup>2</sup>/s and  $1.35 \times 10^{-8}$  s<sup>-1</sup>, respectively. The hydraulic parameters are relatively stable as a whole because of the aquifer near well BB is not disturbed significantly in 2016.



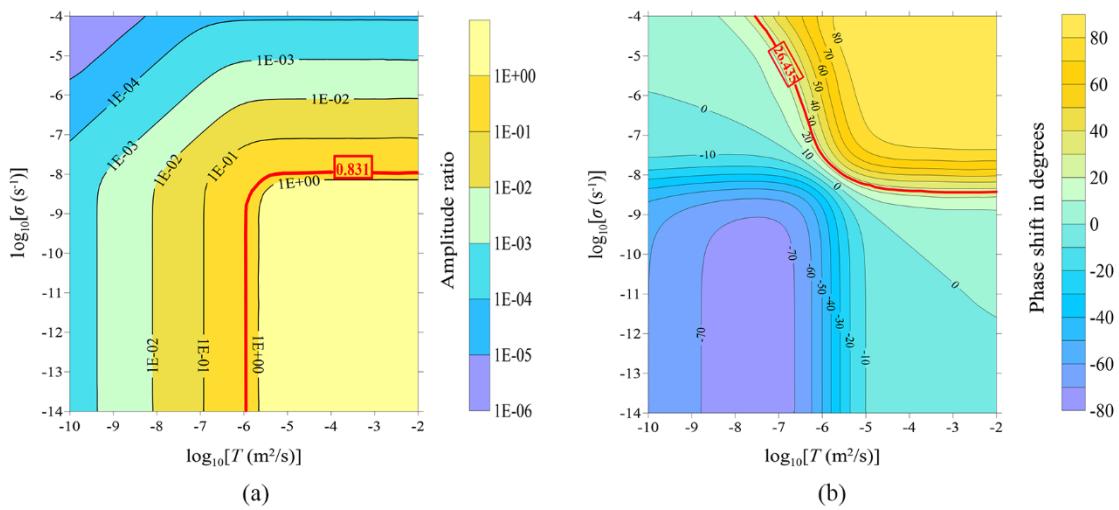
**Figure 6.** The changes of aquifer parameters near well BB in 2016, including (a) transmissivity and (b) leakage coefficient. The blue lines represent the mean of the data set.

## 5. Discussion

### 5.1. Verification of results

Since there are always inconsistencies between the assumed conditions established by the theoretical equations and the actual site conditions, certain errors will inevitably occur in the process of solving. In this calculation, the variation of aquifer  $n$  near well BB ranges from 15.6% to 22% (Figure S3). The main lithology of well BB aquifer is sandstone, according to Zhou et al.'s survey and laboratory test of the sandstone reservoir in the area where well BB is located [46–49], the  $n$  of the sandstone reservoir in this area ranges from 5% to 30%.

The previous pumping test showed that the  $T$  of the aquifer in the observed section of the well was  $6.94 \times 10^{-6} \text{ m}^2/\text{s}$ , which is close to the current calculation (Figure 6a). In order to further verify the calculation results of aquifer parameters of well BB, the methods of Sun et al. [50] and Yang et al. [30] were cited and calculated based on the tidal analysis results. Based on the method of Sun et al. [50], the relationship between the hydraulic parameters of aquifer ( $T$  and  $\sigma$ ) and the tidal parameters ( $A'$  and  $\eta$ ) of well BB was calculated and established in Figure 7. When  $A$  and  $\eta$  were 0.831 and 26.435° (point data, the mean of tidal analysis results of well BB in 2016), the variation curves of  $T$  and  $\sigma$  could be obtained and cross-solved to establish them as  $3.76 \times 10^{-6} \text{ m}^2/\text{s}$  and  $1.38 \times 10^{-8} \text{ s}^{-1}$ . Although Yang et al.'s method [30] is challenging to obtain time series changes in parameters of the aquifer near the well BB, it can be used to obtain point values to validate the results of this paper. All the results of the above methods are shown in Table 2, which indicates that the calculation results of the aquifer parameters near well BB in this paper is reliable.



**Figure 7.** In the calculation, when  $S=6.88\times10^{-5}$ ,  $r_c=63.5$  mm,  $r_w=75$  mm,  $\tau=12.42$  hr, the relationship between the hydraulic parameters of aquifer ( $T$  and  $\sigma$ ) and the tidal parameters ( $A'$  and  $\eta$ ) of well BB. The red lines represent the mean tidal parameters for well BB in 2016, the  $T$  and  $\sigma$  can be obtained when they intersect.

**Table 2.** Comparison of hydraulic parameters calculated by various methods.

Method	Storage coefficient $S$	Horizontal transmissivity $T$ (m <sup>2</sup> /s)	Leakage coefficient $\sigma$ (s <sup>-1</sup> )
Pumping test	-	$6.94\times10^{-6}$	-
Yang et al. ' method cited*	$8.10\times10^{-5}$	$3.1\times10^{-6}$	$3.0\times10^{-8}$
Sun et al. ' method cited	$6.88\times10^{-5}$	$3.76\times10^{-6}$	$1.38\times10^{-8}$
this paper	$6.88\times10^{-5}$	$3.7\times10^{-6}$	$1.35\times10^{-8}$

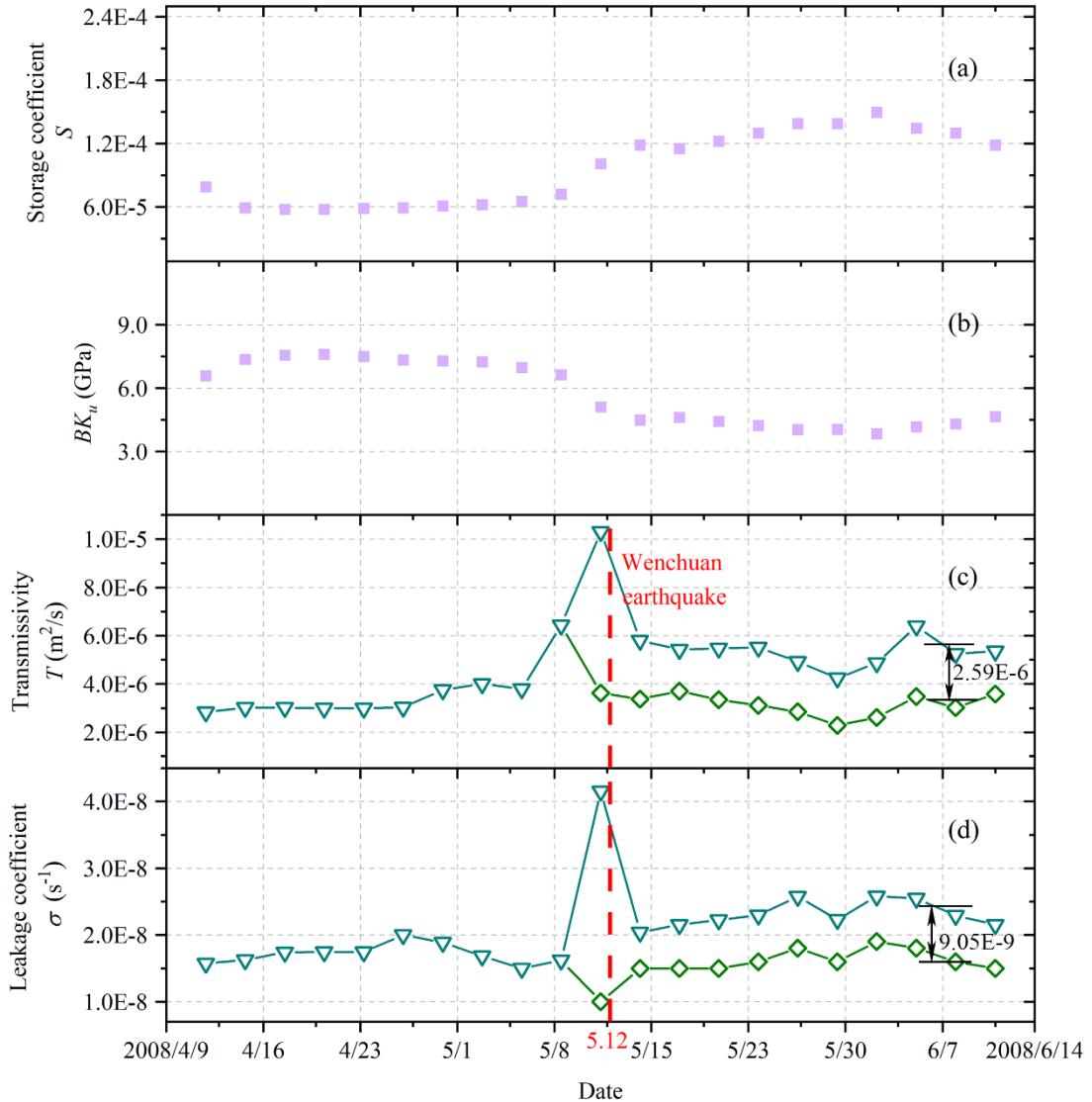
\* In Yang et al.'s method, the parameters of the tide  $M_2$  are  $A'=0.58$  mm/10<sup>-9</sup> and  $\eta=26.402^\circ$ , with the tide  $O_1$  are  $A'=0.59$  mm/10<sup>-9</sup> and  $\eta=23.799^\circ$  (point data, the mean of tidal analysis results of well BB in 2016).

The graphical method proposed by Sun et al. [50] can guarantee the accuracy of the results, but only one set of  $T$  and  $\sigma$  can be calculated and obtained at a time, making it challenging to calculate the time series changes of aquifer parameters. Yang et al.'s method [30] can simultaneously obtain the  $S$ ,  $T$  and  $\sigma$  of the aquifer. The outcomes of the calculations using the least square optimal fitting method, however, also depend on the initial values of the parameters to a certain extent, and there will be various solutions. Considering that when it is applied to an aquifer such as well BB (phase shift of the tide  $M_2$  is greater than the tide  $O_1$ ), it is difficult to get a relatively correct solution even if a reasonable initial value is set. Here, firstly the barometric pressure and earth tide effects of well water level were introduced to solve the  $S$  and  $BK_u$ , and then only the relatively stable tide  $M_2$  was considered to solve Equations 7. By reducing the number of unknown parameters in the equations compared with the method of Yang et al.', the dependence of the results on the initial values is greatly reduced. In addition, when substituting the calculated values of horizontal transmissivity and leakage coefficient into Equations 7, and the error of each equation was less than  $1\times10^{-5}$ .

## 5.2. The effects of earthquake

Based on the above solving process, the effects of Ms8.0 Wenchuan earthquake on aquifer parameters near well BB is discussed. The values of  $S$  and  $BK_u$  of aquifer before and after (4/12-6/12) the Wenchuan earthquake were firstly calculated (Figure. 8a and b). The mean value of  $S$  caused by the earthquake increases from  $6.32\times10^{-5}$  before the earthquake to  $1.27\times10^{-4}$  after the earthquake, and the mean value of  $BK_u$  decreases from 7.21 GPa before the earthquake to 4.36 GPa after the

earthquake. The results showed that the  $T$  increased from  $3.59 \times 10^{-6} \text{ m}^2/\text{s}$  (mean value) to  $1.03 \times 10^{-5} \text{ m}^2/\text{s}$  (the maximum value after the earthquake) (Figure. 8c), and the  $\sigma$  increased from  $1.71 \times 10^{-8} \text{ s}^{-1}$  (mean value) to  $4.16 \times 10^{-8} \text{ s}^{-1}$  (the maximum value after the earthquake) (Figure. 8d). It can be inferred that the Wenchuan earthquake has led to the increase of the aquifer permeability. According to the changes of co-seismic pore volumetric strain proposed by Shi et al. [51] and Lai et al. [52] during the Wenchuan earthquake, the well BB was located in an expanding area and the aquifer permeability enhanced accordingly.



**Figure 8.** The time series changes of  $S$ ,  $BK_u$  and hydraulic parameters ( $T$  and  $\sigma$ ) of aquifer before and after the Wenchuan earthquake. The green lines (—◇—) represent the changes of hydraulic parameters after the earthquake using the mean values of  $S$  and  $BK_u$  one month before the earthquake as the input parameters.

Some scholars believe that the change of  $S$  has no obvious effect on  $T$  [22], if the mean values of  $S$  and  $BK_u$  ( $S=6.32 \times 10^{-5}$ ,  $BK_u=7.21 \text{ GPa}$ ) before the earthquake were used as input parameters to solve the aquifer after the earthquake (the tidal parameters were still post-earthquake), although it didn't make a big difference to the outcomes (the error of  $T$  is about  $2.59 \times 10^{-6} \text{ m}^2/\text{s}$ , and the error of  $\sigma$  is  $9.05 \times 10^{-9} \text{ s}^{-1}$ ), the variation interval of aquifer parameters (—◇—) will be the same as that before the earthquake. And the impact of the earthquake on the aquifer characteristics cannot be accurately reflected. Therefore, it is necessary to obtain the dynamic changes of  $S$  and  $BK_u$ , especially when the stratum is seriously disturbed.

## 6. Conclusions

Based on the response of well water level to barometric pressure and earth tide, the aquifer parameters near well BB are estimated in this paper with the help of mixed flow model. The evolution process and characteristics of aquifer parameters near well BB caused by the Wenchuan earthquake are also obtained. The calculation results are unique and continuous, and have little dependence on the initial values in the least square method and does not utilize the unstable tide  $O_1$ . The results have reference significance for the estimation of aquifer parameters near other wells. Due to the simplification and assumption of the mathematical model, there may be errors between the calculation results and the actual situation. And the more accurate determination of  $S$  and  $BK_u$  values can improve the accuracy of aquifer parameters estimation.

**Supplementary Materials:** The following supporting information can be downloaded at the website of this paper posted on Preprints.org. **Table S1.** Longitude and Latitude of well BB. **Table S2.** Water level of well BB. **Figure S3.** Dynamic change of aquifer  $n$  near well BB in 2016.

**Author Contributions:** Conceptualization, P.Q.; methodology, P.Q. resources, S.L.; data curation, H.G.; writing—original draft preparation, P.Q. and S.L.; writing—review and editing, P.Q., S.L. and H.G.; supervision, Z.M.; funding acquisition, S.L. All authors have read and agreed to the published version of the manuscript.

**Funding:** This study is funded by the Beijing Natural Science Foundation of China (8222003) and National Natural Science Foundation of China (41807180).

**Data Availability Statement:** Data can be requested from the corresponding author upon request.

**Conflicts of Interest:** The authors declare no conflict of interest.

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