Manuscript Number: BSSA-D-10-00104

Title: Intermediate Field Water Level Changes Observed From the Wenchuan Earthquake

Article Type: Article

Section/Category: Regular Issue

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Abstract: Water level changes at different monitoring stations are observed during the Wenchuan earthquake (Ms8.0) in the Chinese mainland. Our analysis of the data suggests that in the intermediate field, the size of the water level change is mostly related to the value of Skempton's coefficient B. Verification of this fact comes from analyzing the water level changes from the wells with constant epicentral distance. Therefore we conclude that, unlike other earthquakes for the intermediate field, the size of the water level change is not only related to the earthquake magnitude and epicentral distance, but also connected to the extent of the confinement of the aquifer (which is related to Skempton's coefficient B). Thus we also prove the applicability of poroelastic theory for the intermediate field coseismic water level changes from the Wenchuan earthquake.

Suggested Reviewers:

Opposed Reviewers:

Andrew J. Michael
Editor
Bulletin of the Seismological Society of America

Reviewers' and Editorial comments:

Associate Editor: This paper addresses the relationship between water level changes in wells and coseismic strains induced by the 2008 Wenchuan earthquake, and concludes that in the intermediate distance range from the quake the two are closely correlated. In the paper the authors first estimated the Skempton's coefficient B of each well using preseismic tidal strains and the associated water level changes. They then compared amplitudes of earthquake included water level changes with the Skempton's coefficients, and claimed to have found a good match between the two, suggesting that poroelasticity was the primary mechanism for water level change at this distance range. The data are interesting and the research is on the right track, but as pointed out by the two reviewers, the paper has numerous problems, some of which are major. The authors need to address the issues raised by the reviewers fully and make a substantial revision before the paper can be considered for
publication at BSSA. Major concerns include:

1. The data. A data section needs to be added. The authors didn't give a proper presentation of the data they used, except offering one line of claim that the data are classified information. It is not for us to ask how much information about the data could be disclosed, but to have the paper published at BSSA, some basic information about the dataset has to be provided, such as approximate locations of the wells (shown in a map), stratigraphy of the sites, and mean water levels, etc. Only with such information available to the readers can the paper be properly evaluated about its scientific rationale, content, and conclusions.

We have added a map (Figure 3) show the locations and stratigraphy of Wenchuan and those stations.

2. Result. A result section is needed. The paragraphs in the "Theory and Methods" section describing analysis result should be moved out of that section and put into the Result section.

A result section has been added.

3. Skempton's coefficient estimation using tidal strains. This part needs to be strengthened substantially. About the in situ tidal strains, how are they evaluated? Based on local strainmeter recordings or a theoretical model? My opinion is that it

should be OK to evaluate tidal strains using a theoretical model, as long as the model is verified. The verifications can be from results of previous studies or tests done by the authors, demonstrating that the model predictions do represent the real tidal strains. For that case the authors need to elaborate on the model (and/or code) they have used, and whether ocean tides are also incorporated in the model. About their data fitting strategy, I don't understand why M2 mode needs to be singled out for modeling, they can fit the data with all the (except some very long period and DC) tidal components in, to avoid any unnecessary distortion in data fitting. They should also show some examples of data fitting, and provide model fitting statistics, since these model fitting statistics are important indicators about how the poroelastic model explains the local deformation and water change in a normal quiescent time period.

We use the software --MAPSEIS to calculate the theoretical tidal strain, and it has been used by many other authors, and the software is programmed by Li shengle. The ocean tides are not incorporated in the model.

M2 wave is hardly influenced by the atmospheric pressure, thus use this factor we can avoid the disturbance of the atmospheric pressure. Besides the frequency domain analysis show that tidal strain and water level have good corelationships in the M2 wave frequency domain rather than other tidal components (Figure 1). Besides, the wavelength of the M2 wave is much large than the size of the well aquifer system, and the effect of M2 wave in the crust can meet with the undrained condition. Thus, M2 mode needs to be singled out for modeling. And during the data processing, we have deleted the boundary data after filtering to avoid the impact of the boundary effects. The detail is explained in my last paper (Zhang, 2009)

We have explained the calculation process in detail in the “Theory and methods” part now. (Figure 2)

4. Comparison with coseismic stress change. I agree with both reviewers that without presenting calculated coseismic stress change at the sites it's not a rigorous comparison. There were compressional and dilatational regions corresponding to the coseismic stress change, did the water levels in these regions also go up and down accordingly? Do the amplitudes of the water level changes match the strain changes according to eqn (4), using B values obtained previously? Give some statistical numbers of model fitting to make the result and conclusion more quantitative. Also explain if the 24 wells shown in Figs. 1 and 2 are all the wells observed in the intermediate range-have data from some other sites been removed due to their poor data fitting to the model?

We have added the coseismic strain change in Table 2, which is already calculated by Fuqiong Huang in her PhD Dissertation with Okada’s dislocation model (Huang, 2009).

Most water levels changes in these regions are consistent with the volume strain change. That means, when the volume strain change is positive (dilatational) the water level decrease, and when the volume strain change is negative (compressional) the water level increase. However, among those 27 wells the water level changes of 8 wells(well: 13,15,16,17, 19, 21, 22, 25) are not consistent with the volume strain change, and those wells are distributed in different areas in the Chinese Mainland (Figure 3). There are several faults between those regions and the epicenter, so the medium is not uniform. The Okada's dislocation model is based on the assumption that the whole land is isotropic and homogeneous, and does not consider about the geology conditions, thus the volume strain change got from this model will definitely have some differences from the real condition. B governs the magnitude of water level changes due to an applied stress, When the aquifer is confined (B-values are high), the applied stress is mostly transferred into changing pore pressure, which leads to relatively large changes in water level. When an aquifer is unconfined (B-values are low), the applied stress can be easily transferred outside the aquifer system without increasing the pore pressure resulting in small water level changes (Sil, 2006). Thus, in the same group with the similar epicentral distance, even the volume strain change is large as calculated from the Okada's dislocation model, when the B values are low the height of the water level change may be small (Table 2).

You can see, in Table 2, the water level changes are not well related to the volume strain change, but do connected with the B value. ---- we get the value of the quotient of the co-seismic water level changes and the Skempton's coefficient B. We can see the value of $\Delta h / B$ is between -5 to +5, and is relative stable, As Figure 6 shows.

We just use the pre-earthquake data of water level and tidal strain to get the value of B, while the change of the water level is the co-seismic value, thus they have no directly relationship as for the equation (4).

Just one group do not agree with "large pre-earthquake B value lead to large co-seismic water level change" (group d), and we had removed them from the table earlier, but now we add them into Table 2. As we can see in group d, the water level of well 8 rise and well 7 fall, the conflict may be caused by the gravity, otherwise may have something to do with the unascertained local structure environment near the well. The conflict needs to be clarified in further study.

Besides, we deleted a well (Weinanshuangwang) since we can not confirm the range of the shear modulus of it's rock (Sand clay). And we have added two wells into Table2 (group L), whose epicentral distance are a little large than 1000km, and can be roughly attributed to the intermediate field.

5. Result presentation. Fig. 2 shows the same data as that in Fig. 1, the reason to plot the data twice, I guess, is blow up some parts of the overlapped data for better visualization. I suggest to replot Fig. 2 and put all the data in the same figure frame, but make axis corresponding to the sequential number of data points. As long as the same sequential numbers are listed in the data table, there will be no confusion in data identification.

This is a good suggestion, and we have Replotted this in Fig. 5 according to your suggestion.

Reviewer #1: This paper presents some interesting data and observations about the relation between water levels and coseismic strain in the intermediate distances from the Wenchuan China earthquake. The authors contend that water-level changes observed at these distances can be explained by variations in Skempton's coefficient, which really reflects the confining condition around the wells. The authors use an established method for estimating Skempton's coefficient using pre-earthquake tidal strains and associated water-level changes. The estimated value is then compared to water-level changes observed during the Wenchuan earthquake. I have two major concerns and one suggestion:

My first concern is that the paper has been submitted as a short note and is therefore limited in length. However, the paper, as such, lacks enough supporting evidence to convince the reader of the author's interpretations and conclusions. This supporting material should be included either by expanding the paper to a full-length article or by including an electronic supplement containing the data. Most important among the needed information are the following:

We have expanded the paper to a full-length article

1. A map showing the location of the Wenchuan earthquake (including the date.)(Perhaps this could replace the current Fig 1).

Fig 1 Has been Changed already in to Fig 3.

2. A map showing the calculated coseismic strain field plotted with the location of the observation wells, labeled to correspond to the information in Table 1 and Figure 2. One might speculate that the sign of water-level change would correspond to whether the well was located in an extensional or compressional field. If not, then it would emphasize that another mechanism was operating (e.g., confining conditions, compaction, etc.)

We have added Map 4 to show the calculated coseismic strain field plotted with the location of the observation wells.

Most water levels changes in these regions are consistent with the volume strain change. That means, when the volume strain change is positive (dilatational) the water level decrease, and when the volume strain change is negative (compressional) the water level increase. However, among those 27 wells the water level changes of 8 wells(well: 13,15,16,17, 19, 21, 22, 25) are not consistent with the volume strain change, and those wells are distributed in different areas in the Chinese Mainland (Figure 3). There are several faults between those regions and the epicenter, so the medium is not uniform. The Okada's dislocation model is based on the assumption that the whole land is isotropic and homogeneous, and does not consider about the geology conditions, thus the volume strain change got from this model will definitely have some differences from the real condition. B governs the magnitude of water level changes due to an applied stress, When the aquifer is confined (B-values are high), the applied stress is mostly transferred into changing pore pressure, which leads to relatively large changes in water level. When an aquifer is unconfined (B-values are low), the applied stress can be easily transferred outside the aquifer system without increasing the pore pressure resulting in small water level changes (Sil, 2006). Thus, in the same group with the similar epicentral distance, even the volume strain change is large as calculated from the Okada's dislocation model, when the B values are low the height of the water level change may be small (Table 2).

You can see, in Table 2, the water level changes are not well related to the volume strain change, but do connected with the B value. ---- we get the value of the quotient of the co-seismic water level changes and the Skempton's coefficient B. We can see the value of $\Delta h / B$ is between -5 to +5, and is relative stable, As Figure 6 shows.

3. Figure 2 should include the well names that are being plotted within each subplot. These should correspond to the Table 1 listing and the map (see #2).

We have replotted Figure 2, and now Figure 5 represents Figure 2. We use the Sequence number to correspond to Table 2 (Table 1 has been replaced by Table 2) listing and the map.

4. Some information on the stratigraphy at the wells should be included (like major regional aquifers being tapped by the wells and information on their confining conditions in the vicinity of each well). This is necessary to support the contention that higher B values correspond to areas with confined aquifers.

We added the stratigraphy information into Table2, and Fig3 shows the fault and geopolitical locations.

5. All the information contained in Figure 1 seems to be in Figure 2. Is Figure 1 really necessary?

We have Discarded Figure 1

My second concern focuses on the calculation of Skempton's coefficient. Although the background equations are provided, the actual method applied is not clearly explained (see p 5, first paragraph after equation (5)). The description of the method should be entirely rewritten for clarity. Define the M2 wave. Use SI units. What do you mean by "disposing the obtained frequency parts"?

The detail is explained in my last paper (Zhang, 2009). M2 wave is the tidal strain component (the period of M2 is 745.236 min equals to 12.42 hours). M2 wave is hardly influenced by the atmospheric pressure, thus use this factor we can avoid the disturbance of the atmospheric pressure. Besides the frequency domain analysis show that tidal strain and water level have good corelationships in the M2 wave frequency domain rather than other tidal components. Besides, the wavelength of the M2 wave is much large than the size of the well aquifer system, and the effect of M2 wave in the crust can meet with the undrained condition. Thus, M2 mode needs to be singled out for modeling. And during the data processing, we have deleted the boundary data after filtering to avoid the impact of the boundary effects. The detail is explained in my last paper (Zhang, 2009)

According to your suggestion, we have explained the calculation process in detail in the “Theory and methods” part now.

My suggestion to the authors is that the discussion of the far-field effects and possible explanations be eliminated. It detracts from the main focus of the paper (intermediate field response) and is very poorly supported by data.

According to your suggestion, we have eliminated the discussion of the far-field effects and possible explanations

Reviewer #2: Strength: The paper is an attempt to include rock physics in interpreting water-level response to earthquakes.

Major weaknesses:

1. The authors used a relation between water-level changes and tidal strain to determine Skempton's coefficient and showed that a correlation exists between the values of Skempton's coefficient and the coseismic water-level changes at the studied wells. However, they did not discuss how the tidal strains at the wells were determined. In their earlier study (Zhang et al., 2009) of the tidal response of the Changping well, the tidal strain was measured by using a strain meter at the bottom of the well. Given that the measurement of tidal strains in wells is a relatively rare undertaking, I would be

surprised if all the wells in the present study are equipped with strain gages. If they are indeed, the authors should give a full account of all the gages, such as their sentitivity, etc. If they are not, then how did the authors determine the tidal strains at the wells?

In our earlier study (Zhang et al., 2009) of the tidal response of the Changping well, the tidal strain was not measured by using a strain meter at the bottom of the well but calculated by the MAPSEIS software, which evaluate tidal strains using a theoretical model, and the model predictions do represent the real tidal strains. The software is programmed by Shengle Li, and the ocean tides are not incorporated in the model.

In this paper, we still use the software --MAPSEIS to calculate the theoretical tidal strain, and it has been used by many other authors earlier.

2. In determining the value of Skempton's coefficient, the authors arbitrarily chose a shear modulus of 6 GPa for all the wells. Considering that the wells likely tap different aquifers, the shear moduli must be different from well to well. This is important for the determination of the Skempton's coefficient and must be measured individually by independent field experiment. The suggestion that the authors' choice of a shear modulus of 6 GPa was 'arbitrary' is supported by the fact that they used a different modulus in their previous paper (Zhang et al., 2009) which is smaller by a factor of 2 than the present value. Thus the uncertainties in the Skempton coefficients they 'estimated' for the aquifers must be at least 100%, and the correlation they claimed would break down. Given these observations, I cannot trust the results in this paper and cannot recommend its publication in BSSA.

This is really a big weakness, and we have tried our best to get the relatively precise shear modulus value of each well.

Since the shear modulus will change with the change of the stress, we can hardly get the in suit value of the shear modulus of those wells by experiment, which is as hard as getting the in suit Skempton’s coefficient B.

We have investigated the geology of each well and referred to the Rock Mass Mechanism (Yourong Liu and Huiming Tang, 1998), using the dynamic elastic modulus and dynamic Poisson’s ratio to estimate the range of the shear modulus of those rocks, and approximately choose the intermediate shear modulus value. As shown in Table 1.

We calculate the range of the Dynamic shear modulus according to the formula $G=\frac{E}{2(1+\sigma)}$, and estimate the rough G value. Approximately, we choose the mean value of G, and if we choose other values during the G value region the result—-large pre-earthquake B value come with large co-seismic water level change will also be ture.

There are many other weaknesses in the paper, but the above two major problems must be addressed before further comments on the paper are warranted.

Even though I do not recommend the publication of this paper in its present state, I must say that the authors' work is in the right direction. In order to make their results believable, however, the authors must measure tidal strain and shear modulus at each of their wells. This additional work, though laborious, would make their paper the first in the field that ties rock physics to coseismic water-level changes.

Intermediate Field Water Level Changes Observed From the Wenchuan Earthquake

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Abstract

Water level changes at different monitoring stations are observed during the Wenchuan earthquake (Ms8.0) in the Chinese mainland. Our analysis of the data suggests that in the intermediate field, the size of the water level change is mostly related to the value of Skempton's coefficient B. Verification of this fact comes from analyzing the water level changes from the wells with constant epicentral distance. Therefore we conclude that, unlike other earthquakes for the intermediate field, the size of the water level change is not only related to the earthquake magnitude and epicentral distance, but also connected to the extent of the confinement of the aquifer (which is related to Skempton's coefficient B). Thus we also prove the applicability of poroelastic theory for the intermediate field coseismic water level changes from the Wenchuan earthquake.

Introduction

Several types of earthquake induced groundwater level changes and corresponding mechanisms have been recognized for decades. In the near field (generally, epicentral distance D between 0-100 km), most documented water level shows abrupt (step-like) coseismic changes (Wakita 1975; Quilty and Roeloffs, 1997; Wang et al., 2001, 2004; Chia et al., 2001; Wang and Chia, 2008). Undrained dilatation and consolidation of the sediments may be responsible for the step-like water level changes in the near field, and can often be quantitatively related to the poroelastic response to the earthquake’s static strain. In the intermediate field (epicentral distance D between 100-1000 km), most documented changes are gradual and can persist for days or weeks. These are coined by Roeloffs (1998) as the ‘sustained’ water level changes, and an earthquake-enhanced permeability may be responsible for this intermediate field phenomenon (Wang and Chia, 2008). At even greater distance (the far field, epicentral distance D larger than 1000 km), only transient oscillations of the water level have been documented. There are several existing models for far-field coseismic pore pressure changes: mobilization of gas bubbles, (Roeloffs, 1998), shaking induced dilatancy (Bower and Heaton, 1978), fracture of an impermeable fault (King et al., 1999), fracture clearing (Brodsky et al., 2003), and shaking induced by surface waves (West et al., 2005; Sil and Freymueller, 2006).

Investigation of coseismic water level changes has been of scientific interest for decades (Wang and Manga, 2010). Groundwater level changes following earthquakes can affect water supply; seismic waves can affect oil well production, and it has been suggested that in some cases the induced seismicity can stimulate oil production (Beresnev and Johnson, 1994). Earthquake-induced fluid pressure changes are hypothesized to control the timing and/or location of the aftershocks and trigger seismicity (Hill et al., 1995; Gomberg, 1996). Finally, these groundwater level changes could also be related to the hydrologic earthquake precursors (Roeloffs, 1998).

In this paper we calculate Skempton's coefficient B from the poroelastic relationship between water level changes and tidal strain using data prior to the earthquake. Further analysis of the water level data from the Groundwater Monitoring Network (GMN) (see Data and Resources Section) is done during the Wenchuan earthquake for far and intermediate fields. A relation between the amplitude of the water level and the earthquake magnitude and distance is developed by Roeloffs (1998) for the "sustained" water level changes. To develop this relationship, different intermediate field earthquakes are used. Several authors have obtained similar empirical relations between water level change, epicentral distance, and the earthquake magnitude (Matsumoto et al., 2003; Yang et al., 2005; Sil and Freymueller, 2006). In addition to the above observation, we find that the size of the water level change at GMN stations in the intermediate field is not only related to the earthquake magnitude and the epicentral distance, but also related to the value of Skempton's coefficient B. We choose those wells with similar epicentral distance in the intermediate field, and find large B-values come with large changes of water level. B governs the magnitude of water level changes due to an applied stress, thus in the same group with the similar epicentral distance, even the volume strain change is large as calculated from the Okada's dislocation model, when the B values are low the height of the water level change may be small. Therefore, we conclude that water level changes induced by the Wenchuan earthquake in the intermediate field are related to both the epicentral distance and the Skempton's coefficient B. And undrained dilatation and consolidation of sediments may be responsible for the water level changes in the intermediate field for the Wenchuan earthquake.

Theory and Methods

Skempton's coefficient B is a significant pore-fluid parameter in poroelastic theory. A poroelastic material consists of an elastic matrix containing interconnected fluid saturated pores. Fluid saturated crust behaves as a poroelastic material to a good degree of approximation.

Rice and Cleary (1976) summarized the following equations for a linearly elastic isotropic porous medium, which are the building blocks of the poroelastic theory:

$$2G\varepsilon_{ij} = \sigma_{ij} - \frac{\nu}{1+\nu}\sigma_{kk}\delta_{ij} + \frac{3(\nu_u - \nu)}{B(1+\nu)(1+\nu_u)} p\delta_{ij}, \tag{1}$$

$$m - m_0 = \frac{3\rho(\nu_u - \nu)(\sigma_{kk} + 3p/B)}{2GB(1+\nu)(1+\nu_u)}. \tag{2}$$

Here m-m_o is the change of the fluid mass, ε_{ij} is the strain tensor, σ_{ij} is the stress tensor, δ_{ij} is the Kronecker delta function, G is the shear modulus, ρ is the density of the fluid, B is the Skempton's coefficient, p is the pore pressure, ν is the Poisson's ratio, and ν_u is the "undrained" Poisson's ratio. Rice and Cleary (1976) describe equation 1 as a stress balance equation and equation 2 as a mass balance equation.

For the undrained condition, the poroelastic effect on the crust can be obtained by putting m-m_o =0 in equation 2, and therefore we obtain:

$$P = -B\sigma_{kk}/3 \text{ or } \Delta p = -B\Delta\sigma_{kk}/3. \tag{3}$$

Equation 3 says under "undrained" condition, the change in fluid pressure (Δp) is proportional to the change in mean stress ($\Delta\sigma_{kk}$ /3). This is the mechanism of water level changes for poroelastic material. (p= ρ g h, where h is the water column height, g is the acceleration due to gravity and □ is the density of water).

According to equation 3, Skempton's coefficient *B* can be qualitatively defined: In the "undrained" condition, *B* is the ratio of the induced pore pressure divided by the change in mean stress (Wang, 2000). *B* governs the magnitude of water level changes due to an applied stress since pore pressure is directly proportional to water level. The value of *B* is always between 0 and 1. When *B* is 1, the applied stress is completely transferred into changing pore pressure. *B* equals 0 indicates no change in pore pressure after applying the stress. When an aquifer is not confined, an applied stress can be easily transferred outside the aquifer system without increasing the pore pressure. Thus a low value of *B* indicates a poorly confined aquifer system (Sil, 2006). Laboratory studies indicate the value of *B* depends upon the fluid saturated pore volume of the sample (Wang, 2000).

Equation 3 can be expressed in terms of tidal strain as well (Roeloffs, 1996):

$$\Delta h = -\frac{2GB(1+\nu_u)}{3\rho g(1-2\nu_u)}\Delta\varepsilon_t \;. \qquad (4)$$

Equation 4 shows that water level changes proportionally in a poroelastic material under the influence of tidal strain (ε_t). Here Δh is the change in height of water level, and $\Delta\varepsilon_t$ is the corresponding tidal strain change (Sil, 2006).

From equation 4 we obtain:

$$B = -\frac{3\rho g(1-2\nu_\mathrm{u})}{2G(1+\nu_\mathrm{u})}\frac{\Delta h}{\Delta\varepsilon_t}. \qquad (5)$$

With equation (5) we can get the value of *B* with water level and tidal strain. However, the calculation must be on the strict premise of the undrained condition, the good correlation ship between the water level and the tidal strain and should not be influenced by the other factors.

For the effect of the solid tide on the crust, when the wavelength of the tidal strain is much larger than the size of the aquifer, we can suppose the aquifer system is undrained (Huang, 2008). The wavelength of the M2 wave is about 2 406 329 km ($\lambda=\omega\times r\times T$, $\omega=1.4\times10-4/s$ is the angular frequency of M2 wave, r=384 400 km is the distance from the earth to the moon, T=745.236 min is the period of the M2 wave), which is much larger than the size of the radius of the Earth, and is definitely much larger than the thickness of the aquifer systems of those wells. Thus, the effect of the M2 wave in the crust can meet with the undrained condition (Zhang et. al, 2009). Besides, those wells can record clear tidal strains and as we calculate the phase lags between the water levels and the tidal strains are small, thus the wells can meet with the undrained condition well. In the M2 wave frequency domain the water level and the tidal strain have a good correlationship, we just set the Changping station as an example to see the correlationship clearly (Figure 1). We can see in the M2 wave frequency domain the correlationship between the tidal strain and the water level approaches 1, which means a good correlationship between them. Besides, the M2 wave is hardly influenced by atmospheric pressure. Since that, we distill the frequency domain of the M2 wave from the water level and the tidal strain by using band-pass filter (the frequency of the M2 wave is $0.0805114\,h^{-1}$) to calculate the Skempton's coefficient B. Disposing the obtained frequency domain of the M2 wave by IFFT (inverse fast Fourier transform) and adjusting their phase (Figure 2), through the least square fit and putting the results into equation (5), we can finally derive *B*. More details of the method are explained by the paper "Research on Skempton's coefficient *B* based on the observation of groundwater of Changping station" (Zhang et. al, 2009). All the Water level observations come from the sensor of water level, while tidal strain data are calculated via Mapsis software, which is programmed by Shengle Li.

We apply the above method to the wells where earthquake induced water level changes are observed. Pre-earthquake analysis is carried out using data from May 2, 2008 to May 10, 2008 to obtain the pre-earthquake *B* values. Calculation is performed using

$\rho = 1000kg/m^3$, $g = 9.8m/s^2$, and $\nu_u = 0.29$. Since the shear modulus will change with the change of the stress, we can hardly get the in suit value of the shear modulus of those wells by experiment, which is as hard as getting the in suit Skempton's coefficient *B*. We have investigated the geology of each well and referred to the Rock Mass Mechanism (Yourong Liu and Huiming Tang, 1998), using the dynamic elastic modulus and dynamic Poisson's ratio to estimate the range of the shear modulus of those rocks, and approximately choose the mean value (Table 1).

Result

Our co-seismic analysis shows that for the wells with similar epicentral distances (within a range of less than 0.15 degrees or 16.68 km), large pre-earthquake *B* values correspond to large magnitude of co-seismic water level changes, this phenomenon mainly exists in the intermediate field. Note that B values are calculated using pre-earthquake data.

We only find 27 wells which can form groups that have the similar epicentral distance in the intermediate field of mainland China (Figure 3). One well (Weinanshuangwang) has been deleted since we can not confirm the range of the shear modulus of it's lithology (Sand clay). We divided those 27 wells into twelve groups (group a to group l), each group has a specific range of epicentral distance and contains two to three wells (Table 2). The co-seismic volume strain changes are also contained in Table 2, which is already calculated by Fuqiong Huang in her PhD Dissertation with Okada's dislocation model (Huang, 2009). We have also plotted those wells with the spatial distribution of the static volume strain change of Wenchuan earthquake (Figure 4). Figure 5 helps us to see the relationship between water level change and Skempton's coefficient B obviously. Just one group does not agree with "large pre-earthquake *B* value leads to large co-seismic water level change" (group d). As show in table 2, the water level of well 8 rise and well 7 fall, the conflict may be caused by the gravity, otherwise may have something to do with the unascertained local structure environment near the well. The conflict needs to be clarified in further study.

As Figure 6 shows: we get the value of the quotient of the co-seismic water level changes and the Skempton's coefficient B. We can see the value of $\Delta h / B$ is between -5 to +5, and is relative stable.

Earlier, Cua (2004) use 30,000 strong-motion records for Southern California earthquakes, and derived empirical relations between the peak ground velocity with distance from the earthquake sources. From these Wang et al. (2006) derived e(r) =A/r3 for soil sites, where e(r) is the seismic energy density at a hypocentral distance r and A is an empirical constant. Although strictly valid only for southern California, we assume it may be applied elsewhere in the absence of similar relations. With the similar epicentral distance, wells in each group will have the similar seismic energy density and the similar change of stress. Since B governs the magnitude of water level change due to an applied stress, in the same group even the volume strain change is large as calculated from the Okada's dislocation model, the height of the water level change may be small (Table 2).

From the analysis above, we may gain an equation between the water level change Δh , the earthquake magnitude M, the Skempton's coefficient B and the epicentral distance r.

$$\Delta h = f(M, r, B) \qquad (6)$$

Discussion

Most water level changes in these regions are consistent with the volume strain changes. That means, when the volume strain change is positive (dilatational) the water level decrease, and when the volume strain change is negative (compressional) the water level increase (Table 2). However, among those 27 wells the water level change of 8 wells are not consistent with the volume strain change (well: 13,15,16,17, 19, 21, 22, 25), and those wells are distributed in different areas in the Chinese Mainland (Figure3). There are several faults between those regions and the epicenter, so the medium is not uniform. The Okada's dislocation model is based on the assumption that the whole land is isotropic and homogeneous, and does not consider about the geology conditions, thus the volume strain change got from this model will definitely have some differences from the real condition (Figure 2).

In each group different wells have different geology conditions, wells with large value of co-seismic volume strain change calculated from the Okada's dislocation model are not always along with large size of water level change, but do related to the Skempton's coefficient B (Table 2). Large *B*-values come with large changes in water level. This phenomenon is in accordance with the poro-elastic theory. When the aquifer is confined (*B*-values are high), the applied stress is mostly transferred into changing pore pressure, which leads to relatively large changes in water level. When an aquifer is unconfined (B-values are low), the applied stress can be easily transferred outside the aquifer system without increasing the pore pressure resulting in small water level changes (Sil, 2006). From that, we can see undrained dilatation and consolidation of sediments may be responsible for the water level changes in the intermediate field, and those results can prove that the poroelastic theory is appropriate for the intermediate field at least for this earthquake of relatively high magnitude.

For intermediate distance earthquakes, several authors previously obtained similar empirical equations (shown below) relating water level change, epicentral distance, and magnitude of the earthquakes (Roeloffs, 1998; Matsumoto et al., 2003; Yang et al., 2005; Sil and Freymueller, 2006). And this empirical equation is based on the mechanism of shaking induced water level change. They attribute the magnitude of the water level change to two major impact factors:

earthquake magnitude and epicentral distance. The empirical relation found by them can be written as:

$$\log_{10} \Delta h_i = w_1 M + w_2 \log_{10} D + w_3 . \qquad (7)$$

In this equation w_1 , w_2 , and w_3 are constants, Δh_i is the size of the water level change in centimeters, M is the earthquake magnitude, and D is the well- hypocenter distance in kilometers (Roeloffs, 1998). The importance of equation 6 is that, for intermediate distances, it can explain earthquake induced water level changes, where poroelastic theory generally is not applicable.

But in our case, from Table 2, we can see that, for the intermediate field for wells with similar epicentral distances, the size of the water level changes are totally different, most of them are related to the value of the Skempton’s coefficient B. Thus we can know the mechanism of the shaking induced water level change is invalid here, while this again proves the poro-elastic theory is appropriate on the other side, since approximately there are two main kinds of water level change mechanisms: the poro-elastic theory and the shaking induced water level changes (Sil, 2006).

We couldn’t find data from near field wells with the similar epicentral distance during the Wenchuan earthquake. While, in the relatively far field, we obtain seven groups of wells. However, among those seven groups, three groups of wells do not show any relationship between *B* values and water level changes.

Magnitude of the Wenchuan earthquake is relatively large (Ms 8). Therefore, even without computing, we can expect that the static strain field from the earthquake will affect a relatively large area. Thus we assume that our observation is not contradicting any existing theory of earthquake induced water level changes.

Conclusions

The present study indicates that the magnitude of the water level changes at GMN stations in the intermediate field are related to the earthquake magnitude, the epicentral distance and Skempton's coefficient *B*. For different wells with similar epicentral distance, their energy density and the change of their stress are approximately the same, but the co-seismic water level changes are absolutely different, and connected with the confinement of the well aquifer, which reflected by the Skempton's coefficient *B*. *B* governs the magnitude of water level changes due to an applied stress, in the same group with the similar epicentral distance, even the volume strain change is large as calculated from the Okada's dislocation model, when the B values are low the height of the water level change may be small (Table 2). We can also conclude that the poroelastic theory may play an important role in the intermediate field water level changes, at least for the high magnitude Wenchuan earthquake.

Data and Resources

Data used in this paper were collected from a classified source (Mapseis) of the China Earthquake Networks Center for restricted use only.

Acknowledgement:

This research is supported by National Natural Science Foundation of China (40674024 and 40374019). The authors sincerely acknowledge Samik Sil and Tom Lovitz for checking the manuscript.

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Figure Captions:

Table 1. Dynamic deformation parameters of rocks. The range of the dynamic elastic modulus and

dynamic Poisson’s ratio are referred to Rock Mass Mechanism (Yourong Liu and Huiming Tang, 1998). From those parameters we calculate the range of the Dynamic shear modulus according to the formula $G = \frac{E}{2(1+\sigma)}$, and estimate the rough value of the dynamic shear modulus. Approximately, we choose the mean value.

Table 2. Epicentral Distances, Water Level Changes, Volume Strain Changes, Lithology, Shear Modulus and B Values for the stations separated into 12 groups (group a to group l). The difference of the epicentral distances of wells in each group is less than 16.68 kilometers (0.15 degrees). The volume strain change is calculated according to Okada’s dislocation model (Huang, 2009). “-” means water level decrease in the water level change column and means compression in the volume strain change column.

Figure 1. Correlation coefficient of water level with solid tide, barometric pressure and volume strain for Changping station from January 1, 2008 to May 11, 2008 in the frequency-domain (Lai et al, 2009).

Figure 2. Raw hourly water level data and tidal strain data (a); Water level and the tidal strain after removing linear trend (b); Frequency domain analysis of the water level and the tidal strain (c); Distilled frequency of M2 wave from the water level and the tidal strain (d) (Zhang et. al, 2009).

Figure 3. Those 27 wells which can form groups that have the similar epicentral distance in mainland China. The serial number is in accordance with the number listed in table 2. The base map comes from the Mapseis software programmed by Shengle Li and the fault is plotted by Qidong Deng.

Figure 4. The spatial distribution of the static volume strain change of Wenchuan earthquake, which is calculated according to elastic half-space dislocation model (Okada, 1992). The solid line indicates inflation, while the dashed line represents compression. The pentagram is the epicenter of the Wenchuan earthquake , and the triangles represent the distributed 27 stations. Parameters of the focal mechanism: trend, 229°; angle of inclination, 43°; angle of slide,123°; depth, 15km; rupture length, 141km; width, 40km; slide range, 447cm.

Figure 5. Water level changes and B values plotted according to the serial number of those 27 wells, and they can be separated into 12 groups in accordance with the serial number of table 2. In each group, large pre-earthquake B values come with large co-seismic water level changes, except group d (well 7 and well 8).

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Rock	**Dynamic Elastic Modulus (Gpa)** E*	**Dynamic Poisson's Ratio** σ *	**Dynamic Shear Modulus (Gpa) G**	**Rough value of dynamic Shear Modulus (Gpa)**
Sandstone	5.3 ~ 37.9	0.20 ~ 0.22	2.17 ~ 15.79	8
Graniton	63.4 ~ 114.8	0.20 ~ 0.21	26.20 ~ 47.83	36
Quartzite	20.4 ~ 76.3	0.23 ~ 0.26	8.10 ~ 31.02	20
Limestone	12.1 ~ 88.3	0.24 ~ 0.25	4.84 ~ 35.60	20
Gneiss	76.0 ~ 129.1	0.22 ~ 0.24	30.65 ~ 52.91	40
Granite	37.0 ~ 106.0	0.24 ~ 0.31	14.12 ~ 42.74	28
Whinstone	53.1 ~ 162.8	0.10 ~ 0.22	21.76 ~ 74.00	48
Diorite	52.8 ~ 96.2	0.23 ~ 0.34	19.7 ~ 39.11	30
Psephite	3.4 ~ 16	0.19 ~ 0.22	1.39 ~ 6.723	4

*see Liu, Y. R., and H. M. Tang (1998). Rock Mass Mechanics, Press of China University of Geosciences, Beijing, 112.

Table2

Table 2. Epicentral Distances, Water Level Changes, Volume Strain Changes, Lithology, Shear Modulus and *B* Values for the stations separated into 12 groups (group a to group l). The difference of the epicentral distances of wells in each group is less than 16.68 kilometers (0.15 degrees). The volume strain change is calculated according to Okada's dislocation model (Huang, 2009). "-" means water level decrease in the water level change column and means compression in the volume strain change column.

Serial Number	**Group**	**Station**	**Epicentral Distance (km)**	**Water Level Change (m)**	**Volume Strain Change /10-9**	**Lithology**	**Shear Modulus G (Gpa)**	**B**
1	a	Dazu	185.4687	-0.587	100.4	Sandstone	8	0.331
2	a	Rongchang	186.4838	-0.052	135.5	Sandstone	8	0.062
3	b	Beibei	209.4532	-0.945	54.06	Sandstone	8	0.273
4	b	Nanxi	217.7074	-0.75	163.6	Sandstone	8	0.197
5	c	Xichang03	342.2935	0.03	-32.35	Graniton	36	0.084
6	c	Xichangtaih	350.68	0.119	-27.9	Graniton	36	0.087
7	d	Shangrao	379.473	-0.133	0.3169	Quartzite	20	0.0275
8	d	Luguhu	384.256	0.022	-27.28	Limestone	20	0.1862
9	e	Qingshuiwe	425.681	0.02	-19.62	Sandstone	8	0.087
10	e	Jinyangkouz	430.448	0.835	-9.153	Limestone	20	0.1856
11	f	Xiaxian	465.8363	0.106	-3.503	Gneiss	40	0.0339
12	f	Luonan	473.9955	0.07	-6.082	Limestone	20	0.0296
13	g	Linxia	521.5619	-0.153	-0.7463	Psephite	4	0.4116
14	g	Panzhihua	527.4969	0.068	-9.513	Diorite	30	0.0412
15	h	Haiyuan	606.2586	-0.036	-6.952	Sandstone	8	0.1117
16	h	Jiujiang	623.3212	0.072	0.3121	Sandstone	8	0.1193
17	h	Guyuanzhen	638.6394	-0.026	-6.383	Sandstone	8	0.00731
18	h	Kunming	650.7373	0.072	-1.245	Limestone	20	0.0992
19	h	Lasa	661.047	0.005	0.3116	Granite	28	0.0074
20	i	Baoshan	793.4069	0.0410	-4.915	Sandstone	8	0.018
21	i	Kaiyuan	799.662	-0.155	-0.08346	Limestone	20	0.1977
22	j	Huangmeidu	848.861	0.124	0.2208	Sandstone	8	0.0748
23	j	Lingwudaqu	856.022	0.053	-2.723	Sandstone	8	0.0605
24	k	Guigangdon	899.981	-0.014	1.943	Sandstone	8	0.0722
25	k	Guiping	900.8791	0.575	2.068	Sandstone	8	0.1768
26	l	Jining	1131.181	0.012	-0.8496	Whinstone	48	0.0087
27	l	Qixian	1146.9055	0.831	-1.944	Limestone	20	0.2462

Figure1

Figure 1. Correlation coefficient of water level with solid tide, barometric pressure and volume strain for Changping station from January 1, 2008 to May 11, 2008 in the frequency-domain (Lai et al, 2009).

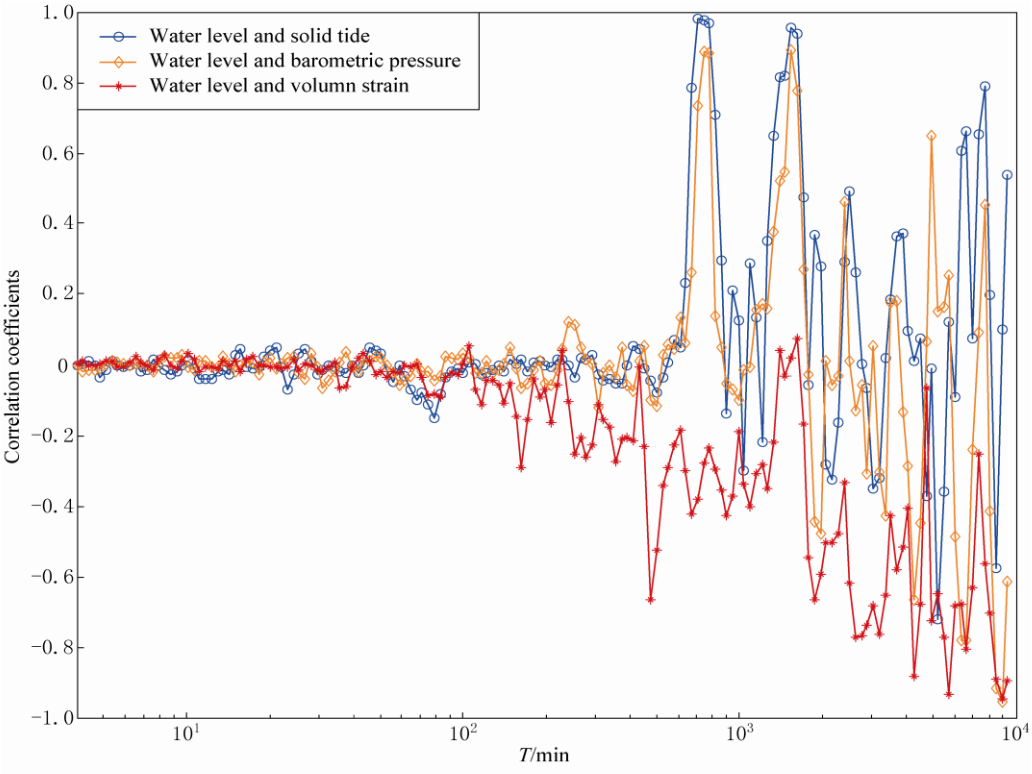

Figure2

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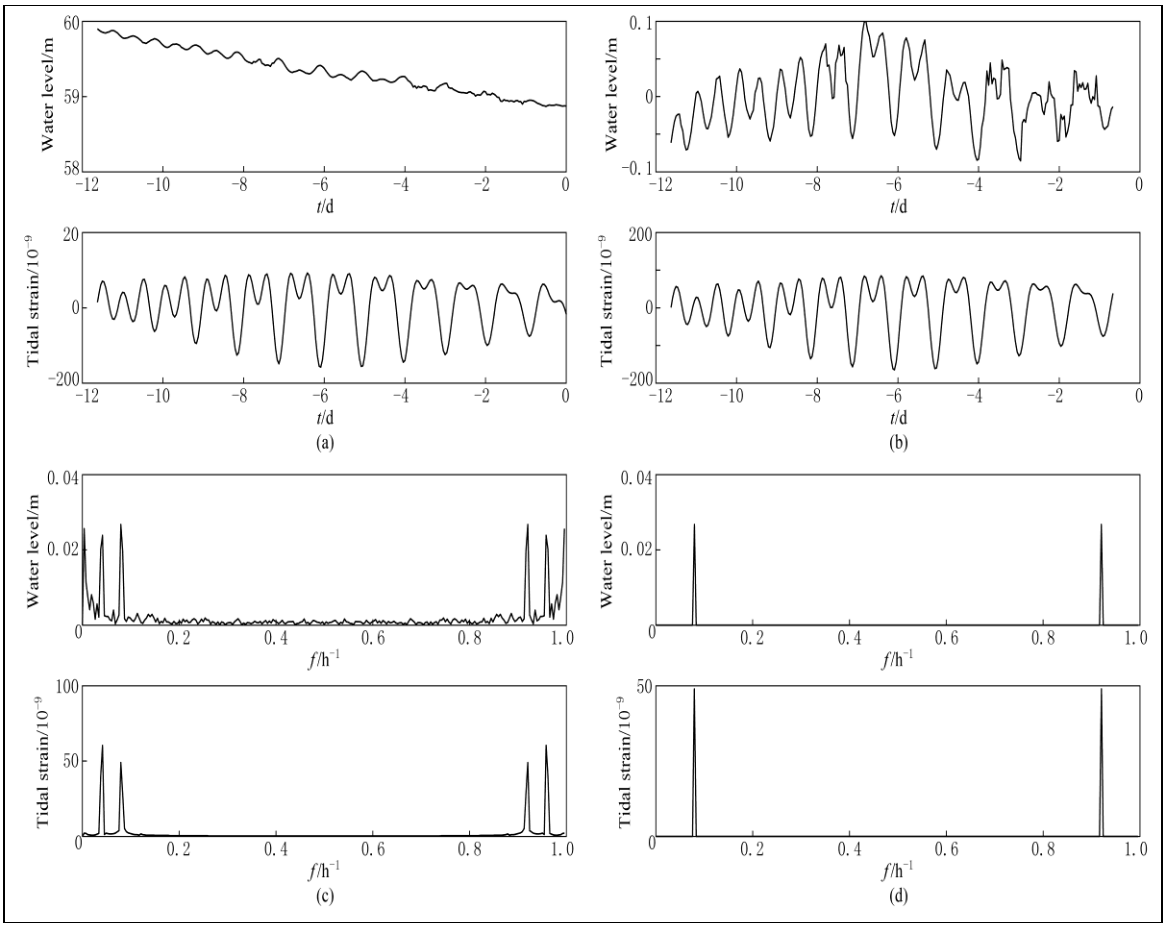

Figure3

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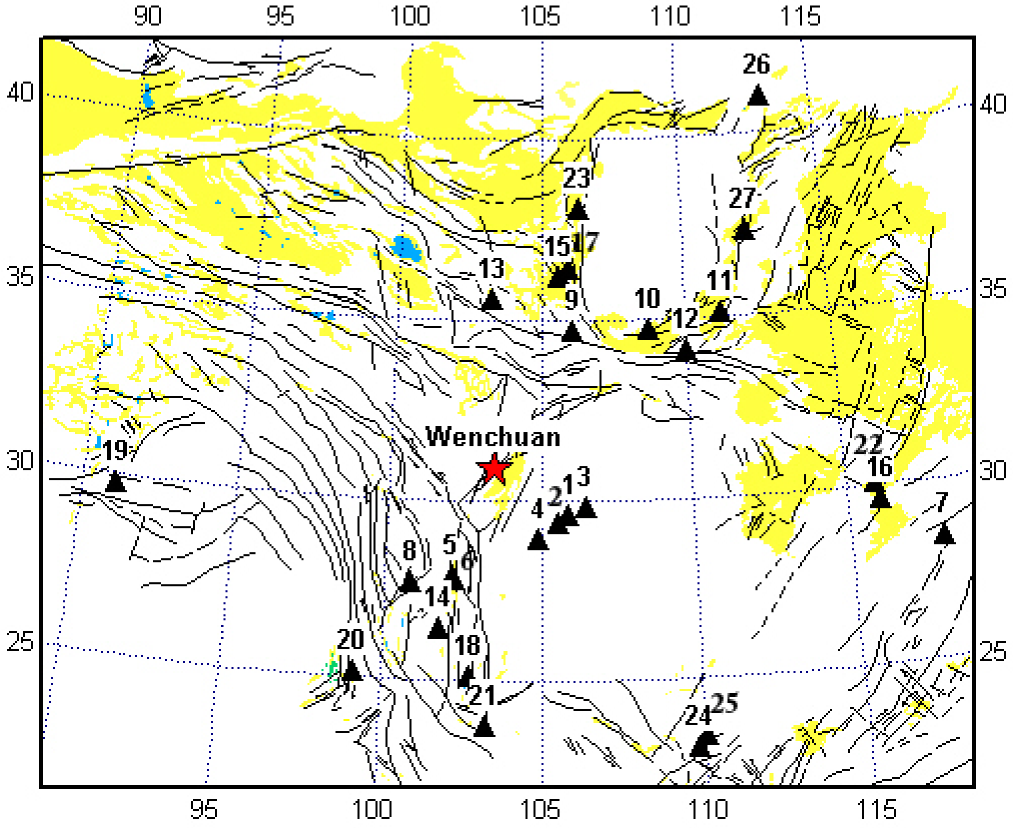

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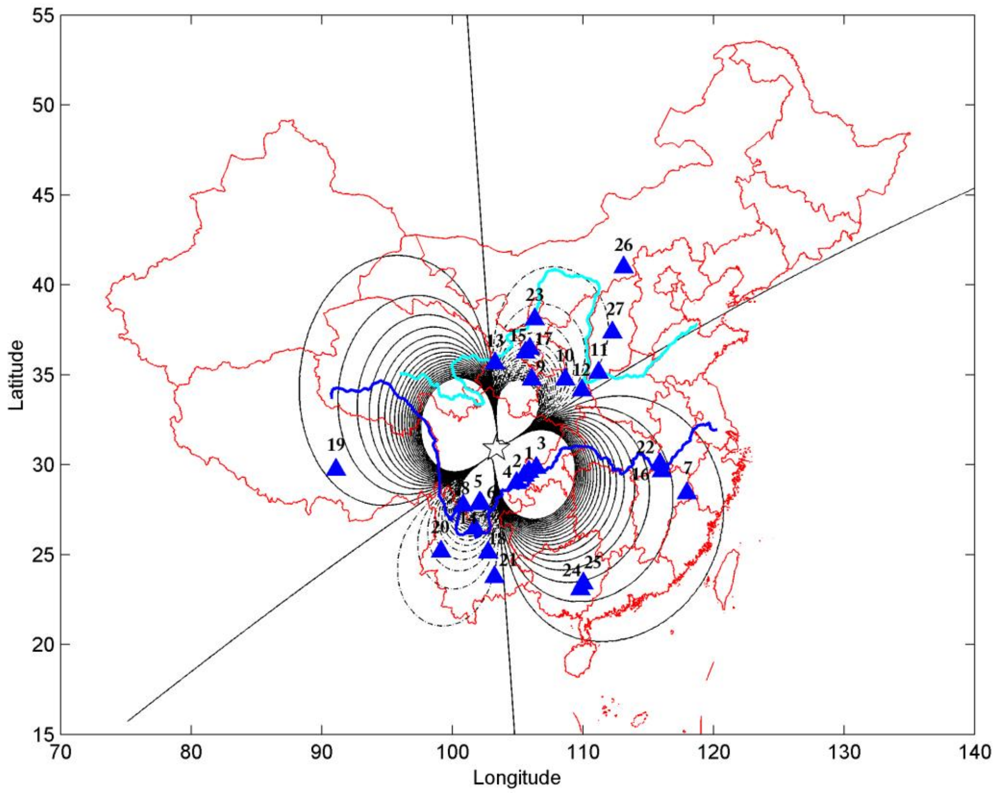

Figure5

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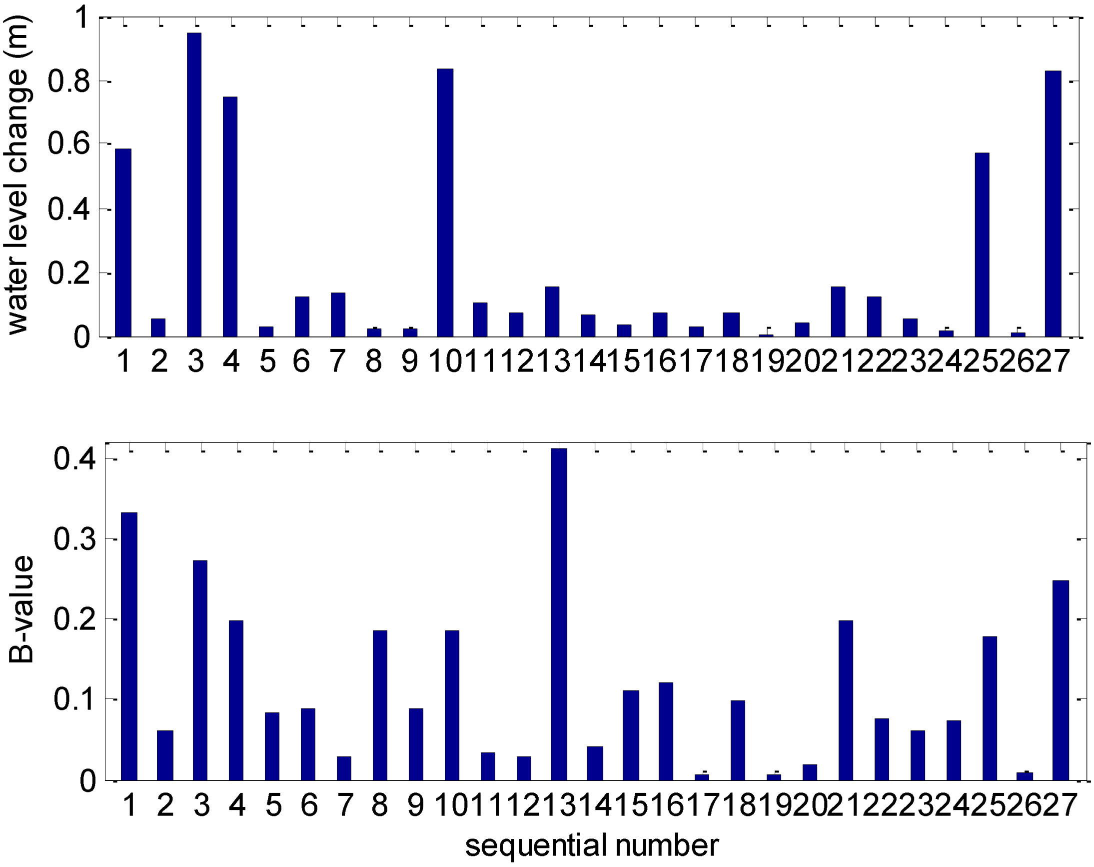

Figure6

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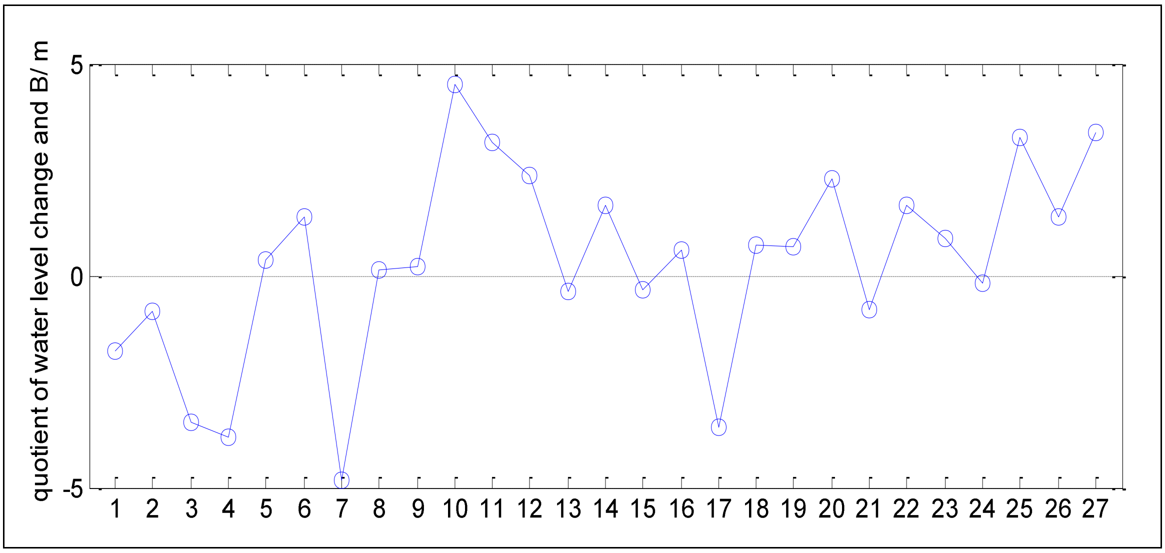

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