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Studies of mechanism for water level changes induced by teleseismic waves

--Manuscript Draft--

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Abstract:	The 8.0 Wenchuan earthquake of May 12, 2008 induces large-amplitude water level changes at intermediate and far fields (epicentral distance >1.5 fault rupture length) in Chinese mainland. Although many hydrologic changes induced by teleseismic waves have been reported, the mechanisms responsible for the changes still remain unclear. We invoke Skempton's coefficient B in this paper to explain those co-seismic water level changes documented in the intermediate and far fields. Some of those abrupt coseismic water level changes, for which the variation of the co-seismic water level, Skempton's coefficient B and the effective pressure preserve uniformity (all increase or all decrease) are found to favor the consolidation/dilatation induced by the shaking of teleseismic waves. While the other part of those coseismic water level changes, especially the more gradual water level changes in this area, can be explained with the enhanced permeability caused by fracture clearing or overcoming the capillary entrapment in porous channels of the aquifer induced by the shaking of teleseismic waves.
Author Comments:	Although coseismic water level changes induced by teleseismic waves have been widely studied, the mechanism responsible for the changes are usually obscure. We invoke the Skempton's coefficient B in this paper to explore the mechanism.
Suggested Reviewers:	Chi-yuen Wang chiyuen@berkeley.edu He is an expert in the region we studied in this paper, and several of his papers have been the references of this manuscript.
Opposed Reviewers:	Yaowei Liu he has a conflict with one of the author

Ref.: Ms. No. BSSA-D-12-00178
Studies of mechanism for water level changes induced by teleseismic waves
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Dear Yan Zhang,

Your paper has been reviewed for publication in the Bulletin. I enclose two reviews by anonymous referees. I also enclose comments by the associate editor. There is a consensus that your paper has significant technical problems. The editorial board has evaluated the reviews and decided that the current version of the paper must be rejected for publication. We have removed it from the review process. Please note that your manuscript needs significant improvement of its English grammar before it is submitted again. We urge you to find a colleague who is a native speaker of English to assist you with this process.

We are willing to consider a revised version in which you have addressed the issues raised by the referees and the associate editor. Any revision will be considered as a new submission but must be accompanied by a letter detailing the changes made in response to these reviews. The reason for taking this approach, rather than requesting revisions, is that we believe the required changes will result in essentially a new work and that the conclusions may change significantly.

Thank you for your interest in the Bulletin.

Sincerely

Diane I. Doser, PhD
Editor-in-Chief

Reviewers' and Editorial comments:

AE's comments: This is a resubmission of the manuscript BSSA-D-12-00070. While it addressed some of the previous raised comments, both reviewers found that the current version still needs significant improvement to improve English grammar, spelling, and organization. In particular, the results and discussions are mixed together in Sections 4 and 5. Instead, the results needed to be presented first without interpretation, followed by a detailed discussion section. In addition, both reviewers have many additional comments that needed to be addressed. Finally, the direct use of figures (**Figure 3a**) from other recent publications may not be appropriate, and is not really useful. If the authors felt that they are absolutely needed here, proper credit should be given, and in the current paper, the citations are not adequate. Sentences must be added to both figure captions indicating exactly what material has been obtained (for example, "Figure 3a is reprinted with [or modified with] permission from authors, article title, journal title, volume number, page number(s), year.)

Reply: I have modified a lot according to the suggestions of the two reviewers. For details, please see below.

In viewing these difficulties, I would recommend another reject/resubmit so that the authors will have enough time to revise. The authors needed to seriously seek improving the English and structures of this paper before resubmitting it again.

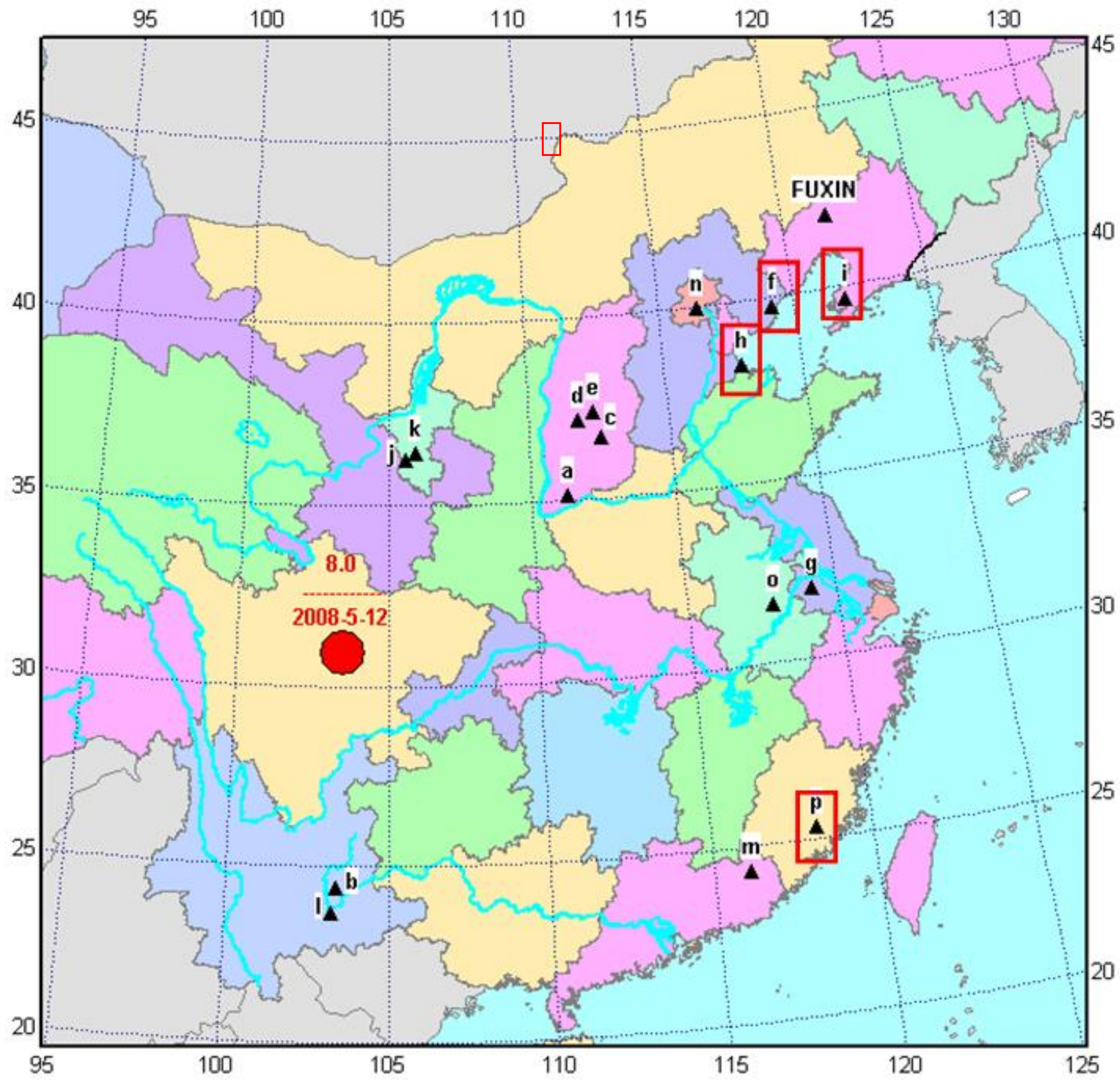
Reviewer #1: The manuscript needs to be edited extensively to improve English grammar, spelling, and organization. There are typographic and grammatical errors in almost every sentence of the paper. The discussion section of the paper currently spans sections 4 and 5. I would like to see this re-organized so that results are presented first with no interpretation, followed by one discussion section. In the discussion, when you compare each well's response with laboratory experiments, you should make this comparison quantitative by comparing your inferred changes in effective stress and B with the experimental results - is there quantitative agreement in addition to qualitative agreement? When you appeal to mechanisms involving increases or decreases in porosity (p. 10 and p. 13 for instance), you can also make quantitative statements about how much change in porosity is needed, and whether these changes are reasonable given that they must occur repeatedly following many earthquakes.

Reply: This is a good suggestion, and I have re-organized the paper according to your advice, see

"**Intermediate and Far Field Analysis**", "**Mechanism analysis** ", "**Discussion**".

I have use the quantitative analysis instead of the qualitative analysis, see Table 2, Table3 and Figure 4.

In addition, as indicated by reviewer2, we didn't take into account the oceanic tides that have been known to have an effect several tens of kilometers away from the seashore (Berger and Beaumont, 1975). The deformation caused by ocean tide loading is difficult to calculate, these tides appear with the same frequencies as the solid earth effects (Shfaqat and Hans-Georg, 2003), and the tides are strongly affected by the complicated topography around the seashore (Roy and Derke, 2001), so we can't simply to calculate the ocean tides by theory models. Besides, there are no public software to calculate the China national offshore ocean tides, so we have to deleted those wells (well: f, h, i and p in the old picture, which is show below) which may be influenced by the ocean tides obviously (<100km, 1 degree equals to about 111.195 km, the distances from well: f, h, i , p to the offshore are smaller than 1 degree). Well n --Zuojiazhuang has been deleted because there is a pumping well 200 meters away, which may influence the observation of Zuojiazhuang, and the well numbers have been rearranged see the new Figure 1.



Old figure1, the wells in red squares are deleted and well numbers have been rearranged.

A few specific comments and questions:

Table 1: Add the Fuxin well that you refer to repeatedly in the text.

Reply: I have already added Fuxin well in the picture. See Figure 1.

Figure 1: Remove faults so that well locations and letters can be easily read. Add location of Fuxin well.

Reply: I have already added Fuxin well in the picture, and removed wells f, h, i and p form the old picture and old Table 1, because those wells are near the sea, according to reviewer 2, the water level in those wells will be influenced by the ocean tide, and we may not calculate Skempton's coefficient B just with the calculated theoretical solid tide. The well numbers have been rearranged (Figure 1, Table 1).

Figure 3a is directly copied from Blocher 2009. I do not think that this is necessary and in any case the attribution needs to be made more clearly and permission must be sought.

Reply: I have modified that portion enormously (just deleted the old Figure 3), and tried to make the description of the picture much more clearly, see "**Undrained Skempton's coefficient B as a function of effective pressure**".

Figure 4: Is this well called Fuxing or Fuxin? What is the arrow and label "s.o" in panel (c)?

Reply: It is called Fuxin, I have modified the name. The arrow and label is "8.0", which indicates the magnitude of the Wenchuan earthquake. I have plotted the label larger.

Page 5, last paragraph: The tidal analysis does not seem correct to me. I think that r should be Earth's radius, not the Earth-moon distance. Furthermore, the formula lambda = omega*r*T as you have stated could be simplified as omega = 2*pi/T, so you are just saying lambda = 2*pi*r.

Reply: Yes, this is really a problem. It is possible that, I need not to calculate the velocity with the angular frequency omega and the radius r (in reality, each kind of velocity is obtained through a definite assumption model with the definite medium), instead, just need to search the velocity of the M2 wave, and the velocity of the M2 wave is approximately equals to the velocity of the light in the vacuum space, so lambda = v*T=(3.0e*008) *(745.236*60)=13414000000 (km).

This modification is made in the paper, see p 5-6.

Page 8, section 4.2: "predicted with drilling" does not make sense to me. Are you referring to a theoretical prediction or an observation? A source needs to be cited or the data need to be presented. I do not understand what this sentence means:

"The depth of the extra high pressure is usually larger than 3000 m, the pressure will be normal when the depth is less than 3000 m, so we assume those results could be applied to these wells we studied?"

Reply: Because wells in Yingqiong Basin lack the records of porosities, we have replaced the figure and the well, we use the logging data of "W-1 well" in Yanchang Basin of Gansu province. See p10. and Figure 3. The content has been modified See "**Undrained Skempton's coefficient B as a function of effective pressure**", p9--10.

Page 9: Define pc and pf on first line. You use this phrase several times: "at the beginning of the first pressure cycle" but never explain what it means or its relevance to the problem that you study. I think that if you are going to address Blocher's experiments specifically, you should describe clearly in a couple of sentences what was done.

Reply: We have modified that portion enormously, and tried to make the description of the picture much more clearly, see "**Undrained Skempton's coefficient *B* as a function of effective pressure**", p9--10.

Page 12: Please use a specific rock type in place of whinstone.

Reply: We have use "basalt" instead of "whinstone". See " **Examples support far field water level increases induced by consolidation**" , p 13.

Page 15: <earthquake monitoring records of stations> needs to be removed and whatever you meant to put here needs to go in its place.

Reply: We have replaced it with <China earthquake monitoring records series>, see **"Wellbore storage effects"**, p15.

Reviewer #2: The authors study the disturbance of the 2008 Wenchuan earthquake on the behavior of water wells scattered in northeastern China.

Though the data seem very interesting, the draft lack convincing analysis for several reasons (see details below). Hence I suggest the authors to operate major revisions.

- The lithology of the rocks is not discussed. Is poroelasticity a valid theory to describe water level changes in granite ?

Reply: We discussed the lithology of the rocks in Table 1.

Granite and rocks of some other lithology are bedrocks of the well, the observation gauges are installed in these aquifers. The same as the other bedrocks, water level changes in the well with the granite bedrock can be assumed to fit for the poroelastic theory, because the linear poroelastic theory is an ideal assumption. Lots of scientific researches are properly resolved with Ideal hypothesis.

- The tidal analysis is very surprising: the *B* coefficient is extremely small (<0.1). For most usual rocks, its value is above 0.5 (see table C1 of Wang, 2000). Either it is related to specific geological features (to be discussed), an important water drainage effect, or it is related to the tidal analysis. It is difficult to assess the quality of the tidal analysis

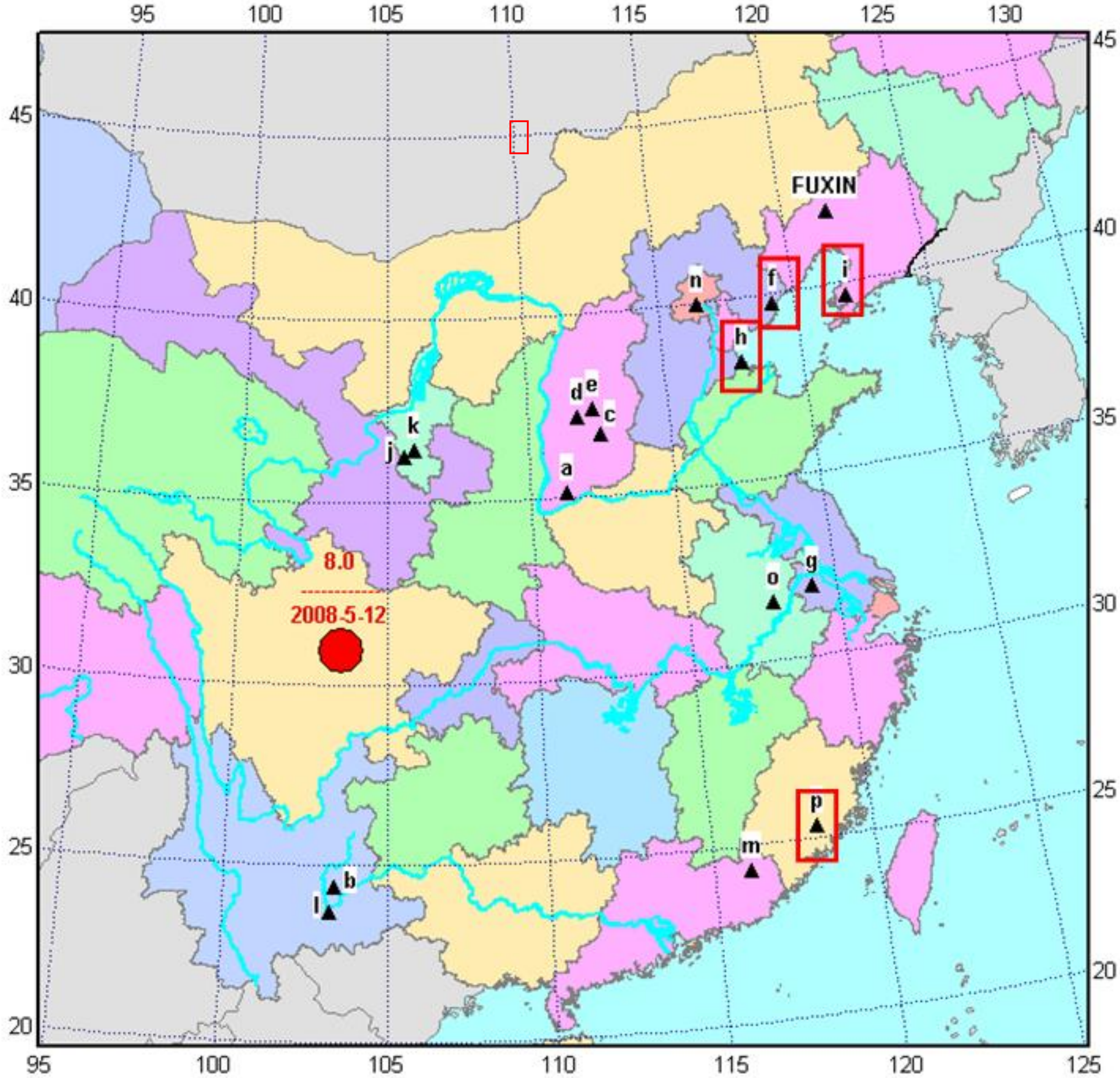
Reply: This is a good suggestion. I think the discrepancy can be explained: most of the *B* values are obtained from the laboratory rock physics experiments, those rocks may be obtained from a depth of several thousand kilometers, and most of them are well confined, so those *B* values are relatively high (above 0.5). However, our in-situ analysis is different from that, the wells (observation layers) are relatively shallow, and the aquifer may not be very well confined. In addition, the low values of the in-situ *B* are common, you can see low *B* values in several papers: 1) '**Short Note Transient Changes in Well-Water Level in Bore Wells in Western India Due to the 2004 Mw 9.3 Sumatra Earthquake**'(Bulletin of the Seismological Society of America, Vol. 98, No. 5, pp. 2553–2558). 2) '**Well water level changes in Fairbanks, Alaska, due to the great Sumatra-Andaman earthquake**' (*Earth Planets Space*, **58**, 181–184, 2006).

The tidal analysis is very accurate, the solid tide are calculated from a software in CENC (China Earthquake Networks Center) programmed by Shengle Li. And according to your suggestion, I have deleted those wells which may be influenced by the ocean tide.

o The strain computing program is not accessible. Hence it is difficult to verify its quality and its model. Does it take into account the oceanic tides that has been known to have an effect several tens of kilometers away from the seashore (Berger and Beaumont, 1975)?

Reply: The tidal analysis is very accurate, the solid tide is calculated from the MAPSEIS software in CENC (China Earthquake Networks Center) programmed by Shengle Li, which doesn't take into account the oceanic tides.

We didn't take into account the oceanic tides that has been known to have an effect several tens of kilometers away from the seashore (Berger and Beaumont, 1975). The deformation caused by ocean tide loading is difficult to calculate, these tides appear with the same frequencies as the solid earth effects (Shfaqat and Hans-Georg, 2003), and the tides are strongly affected by the complicated topography around the seashore (Roy and Derke, 2001), so we can't simply to calculate the ocean tides by theory models. Besides, there are no public software to calculate the China national offshore ocean tides, so we have to deleted those wells (well: f, h, i and p in the old picture, which is show below) which may be influenced by the ocean tides obviously (<100km, 1 degree equals to about 111.195 km, the distances from well: f, h, i , p to the offshore are smaller than 1 degree). Well n --Zuojiazhuang has been deleted because there is a pumping well 200 meters away, which may influence the observation of Zuojiazhuang, and the well numbers have been rearranged, see the new Figure 1.



The Old figure1: the wells in red squares are deleted and well numbers have been rearranged.

o Does the band-pass filter described in figure 6 alter the signal (changing phase and amplitude) ?

Reply: Sorry ,there is no Figure 6 in the old paper, do you mean the process of the band-pass filter?

I have published a paper, which describes the method of *B* calculation in detail, because we have paied attention on the data dealing (include the boundary effects and so on) and the band-pass filter will not cause major influence on the original signal.

o What is the error related to the determination of *B* coefficient. Put differently, can you show that variation in the *B* coefficient due to the earthquake is significant relative to the uncertainty in *B* ?

Reply: we set Jurong well as an example, to show the variation in B due to the earthquake is significant relative to the uncertainty in *B*. For the details, please see **"Uncertainty of *B* coefficient"**, pp17.

- Figure 3a and its caption is taken straight ahead from (Blocher, 2009) ! It is better to cite, but not copy-paste information from another paper, especially for ethical and copyright issues. In this case, the figure is complex, from a complex experiment and the information provided is not complete, and it may not support what the authors argue. For instance, Blocher et al 2009 show that the *B* coefficient is dependent on the modulus of the porous medium (see their figure 8). Hence, it is not clear why the authors discard change in nu_u in the analysis, whereas it also contributes to the change tidal amplitude (see equation 4).

Reply: I have discarded Figure 3a, and as suggested by reviewer 1, I explain the conclusion of the experiment in detail. See "**Undrained Skempton's coefficient *B* as a function of effective pressure**", p9--10.

We suppose the undrained Poisson's ratio $\nu_u = 0.29$ both pre and after earthquake, and this kind of assumption is always used to simplify calculation issues of rocks near the crust (Zeng, 1984).

In addition, based on the poroelastic theory, and limited to isotropic conditions, Theo *et al.* (2002) aim to determine the elastic material constants of the solid matrix with two level of porosities. As it is not possible to experimentally determine the elastic material constants of the solid matrix at these levels, a theoretical approach is presented, based on experimental data taken from literature. They find different porosities lead to different values of elastic modulus. Their results indicate the variation extents of Skempton's coefficient *B* and the bulk modulus are much larger than the drained and undrained poisson's ratio (variation extents of *B*: 6.3% ; variation extents of K: 7.96% variation extents of ν_u: 0.3%), so we can approximately assume that, compared to the modulus of the porous medium (the bulk modulus and Skempton's coefficient *B*), the change of the undrained poisson's ratio can be neglected.

We have added these analysis into "Assumptions of shear modulus and Poisson's ratio "--pp. 6-7

- The discussion is very difficult to follow, as well as the conclusion. This is only partly due to language issues. Parts 4.3 and 4.4 are not well constructed. If I understand well, coseismic water level changes are attributed to permeability changes, that should be reflected by changes in B coefficient. In that case, a cross plot giving water level changes versus B changes would help a lot to summarize the data and support the discussion.

Reply: This is a good suggestion, and I have re-organized the paper according to your advice, see "**Intermediate and Far Field Analysis**", "**Mechanism analysis** ", "**Discussion**".

I have use the quantitative analysis instead of the qualitative analysis, see Table 2, Table 3 and Figure 4.

"plot giving water level changes versus *B* changes" is a good suggestion, and according to your suggestions, we have plotted Figure 4(effective pressure changes versus B changes, which is the same with pore pressure/water level changes versus B changes for those water level changes induced by consolidation or dilatation) , and it displays a linear relationship, see Figure 4.

- The authors focus on B variations during few days surrounding the B change. But how does it evolve later ? Does it recover to its initial values ? A study at larger scale should be given.

Reply: We can see the B value of Jurong well recover to its initial value after about 30 days (Figure 6).

The continuous of B will be influenced by lots of factors, such as power off, aftershocks, and so on, so B-value series at large time scale is not easy to obtain for each well. See **"Uncertainty of B coefficient"** pp17. We just set Jurong well as an example to show the recovery.

Typographic comments;

- The English is very poor and it needs to be reread by a native english speaker.

Reply: we have modified it carefully.

- in many cases, number are given by many unsignificant digits (see for instance, page 5: "The wavelength of the M2 wave is about 2,406,329 km")

Reply: we have modified those numbers.

- Figure 2 is difficult to read. The unit of the x-axis is not given (I assume it is day of the month).

Reply: we have modified the unit of the x-axis.

Studies of mechanism for water level changes induced by teleseismic waves

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Abstract

The M_s 8.0 Wenchuan earthquake of May 12, 2008 induces large-amplitude water level changes at intermediate and far fields (epicentral distance >1.5 fault rupture length) in Chinese mainland. Although many hydrologic changes induced by teleseismic waves have been reported, the mechanisms responsible for the changes still remain unclear. We invoke Skempton's coefficient *B* in this paper to explain those co-seismic water level changes documented in the intermediate and far fields. Some of those abrupt coseismic water level changes, for which the variation of the co-seismic water level, Skempton's coefficient *B* and the effective pressure preserve uniformity(all increase or all decrease)are found to favor the consolidation/dilatation induced by the shaking of teleseismic waves. While the other part of those coseismic water level changes, especially the more gradual water level changes in this area, can be explained with the enhanced permeability caused by fracture clearing or overcoming the capillary entrapment in porous channels of the aquifer induced by the

shaking of teleseismic waves.

Introduction

Various hydrologic responses to earthquakes have been documented, many occurred at great distances from the ruptured fault where static stress changes are extremely small (Liu and Manga, 2009; Wang and Manga, 2010). Hydrologic changes induced by teleseismic waves have been investigated in several studies of water wells (Roeloffs, 1998; Brodsky *et al.*, 2003; Elkhoury *et al.*, 2006; Geballe *et al.*, 2011). These studies indicate that significant water level changes can be driven at great distances by moderate-amplitude dynamic (time-varying) stresses (Liu and Manga, 2009).

Several mechanisms have been proposed to explain these co-seismic changes in water level. Fracture clearing and increased permeability caused by the earthquake-induced dynamic stress have been widely used to explain most documented water level changes (Brodsky *et al.*, 2003; Elkhoury *et al.*, 2006; Wang and Chia, 2008; Wang and Manga, 2010). Overcoming the capillary entrapment in porous channels is hypothesized to be one of the principal pore-scale mechanisms by which natural permeability is enhanced by the passage of elastic waves (Beresnev, 2011). Other proposed, but also unverified mechanisms include pore pressure increases caused by a mechanism 'akin to liquefaction' (Roeloffs, 1998), shaking-induced dilatancy (Bower and Heaton, 1978), or increasing pore pressure through seismically induced growth of bubbles (Linde *et al.*, 1994). In addition, Huang (2008) observed the co-seismic water level increase may be caused by the consolidation induced by the transmission of teleseismic waves. Experimental measurements of Liu and Manga (2009) indicate that permeability changes (either increases or decreases) owing to dynamic stresses are a reasonable explanation. In general, they find permeability decreases after shaking.

In the present study, we use the Skempton's coefficient *B*, the co-seismic water level and the inferred effective pressure to explain the co-seismic water level changes in the intermediate and far fields based on datasets from the Wenchuan earthquake in the Chinese mainland. Using a poroelastic relation between water level and solid tide (Zhang *et al.*, 2009), we calculate the in-situ Skempton's coefficient *B* both pre and post earthquake. From the research we find: Consolidation/dilatation induced by shaking of teleseismic waves, may account for the mechanism of those abrupt coseismic water level changes, for which the variation of the co-seismic water level, Skempton's coefficient *B* and the effective pressure preserve uniformity. While, the other part of those coseismic water level changes, especially the more gradual water level changes in this area, for which the co-seismic water level and the effective pressure change with inconformity may be explained with the increased permeability caused by teleseismic waves, which in turn lead to the redistribution of pore pressure.

An approach to Skempton's coefficient *B* based on the poroelastic theory

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 (they are the building blocks of the poroelastic theory):

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

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

Here $m - m_0$ 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 $m - m_0 = 0$ in equation (2) to obtain

$$p = -B\sigma_{kk}/3 \text{ or } \Delta p = -B\Delta\sigma_{kk}/3. \quad (3)$$

Equation (3) indicates that, in the 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. ($p = \rho gh$, where h is the water column height, g is the acceleration due to gravity and ρ 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 because 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. When B equals 0, there is no change in pore pressure after applying the stress. Thus a low value of B indicates the stiff rock matrix that supports the load with low coupling to the fluid (Nur and Byerlee, 1971). 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):

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

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:

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

With equation (5), we obtain 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 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 M_2 wave is about 13414200000 km ($\lambda = v \cdot T$, where $v = 3.0\times10^8$ (m/s) is the velocity of M_2 wave [the velocity of M2 wave is approximately equals to the velocity of the light in the vacuum space], T=745.236 min is the period of M_2 wave), this wavelength 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 M_2 wave in the crust can meet the undrained condition (Zhang *et al.*, 2009). In addition, those wells can record clear tidal strains and thus, because we calculate the phase lags between the water levels and the tidal strains are small, the wells can readily meet the undrained condition. In the M_2- wave frequency domain, the water level and the tidal strain show a good correlation; Furthermore, the M_2 wave is hardly influenced by atmospheric pressure. We therefore distill the frequency domain of the M_2 wave from the water level and the tidal strain by using band-pass filter (the frequency of the M_2 wave is $2.23636\times10^{-5}HZ$) to calculate the Skempton's coefficient *B*. By converting the frequency domain of the M_2 waves (obtained from the water level and the tidal strain), by inverse fast Fourier transform and adjusting their phases (using the least-square fit and putting the results into equation (5)), we can finally derive *B*. (More details of the method are explained in Zhang *et al.*, 2009). All the Water-level observations come from the sensor of water level, while tidal strain data are calculated via Mapseis software (see Data and Resources section).

Assumptions of shear modulus and Poisson's ratio

Calculations are performed using $\rho=1000kg/m^3$, $g=9.8m/s^2$, and $\nu_u=0.29$ according to equation (5). We suppose the undrained Poisson's ratio $\nu_u=0.29$ both pre and after earthquake, and this kind of assumption is always used to simplify calculation issues of rocks near the crust (Zeng, 1984). In addition, based on the poroelastic theory, and limited to isotropic conditions, Theo *et al*.(2002) aim to determine the elastic material constants of the solid matrix with two level of porosities. As it is not possible to experimentally determine the elastic material constants of the solid matrix at these levels, a theoretical approach is presented, based on experimental data taken from literature. They find different porosities lead to different values of elastic modulus. Their results indicate that the variation extents of Skempton's coefficient *B* and the bulk modulus are much larger than the drained and undrained poisson's ratios (variation extent of *B*: 6.3% ; variation extent of K: 7.96% variation extent of ν_u: 0.3%). So we can approximately assume that compared to the variations of the porous medium modulus (the bulk modulus and Skempton's coefficient *B*), the change of the undrained poisson's ratio can be neglected before and after the earthquake.

Gassmann (1951) predicted that the effective shear modulus would be independent of the saturating fluid properties (the shear modulus is a constant) in the undrained isotropic poroelastic media. As studied by Berryman (1999) and Berryman and Wang (2001), the theory applies at very low frequencies. At high enough frequencies (especially in the ultrasonic frequencies), as the numerical simulation of Berryman and Wang (2001) shows (based on the effective medium theory, and use a complete set of poroelastic constants for drained Trafalgar shale), with the increase of Skempton's coefficient *B*, the bulk modulus changes by as much as 100% in this example, whereas the shear modulus changes by less than 10%, and other rock examples also show similar results (Berryman and Wang, 2001).

As discussed above, we can know: It is obvious that the change of shear modulus G is extremely tiny, and even can be neglected (both in the drained or undrained cases) as compared with the change of Skempton's coefficient *B*. In this paper we suppose, shear modulus of well aquifer systems will not change after affected by the seismic waves (the frequencies of seismic waves are much lower than the ultrasonic frequencies, so the change of the shear modulus will just be neglectable compared to the change in *B* value).

Intermediate and Far Field Analysis

Calculation

Large numbers of stations with co-seismic water level changes induced by M_s 8.0 Wenchuan earthquake have been collected in the intermediate and far fields (>1.5 fault-rupture lengths). Most of those water level changes in this area can not be induced by the change of the static strains, which are extremely tiny (Zhang and Huang, 2011). We selected those co-seismic water level changes with distinct amplitude (tiny or obscured co-seismic water level changes have been excluded). In order to calculate the pre- and post- earthquake *B* values, water level data in stations should not be long-time missing or be influenced by other factors, such as pumping or other disturbances, and the data should be long enough (at least with a 10-day continuous data before and after the earthquake respectively), so that we can use the least-square fit to calculate *B*. In addition, we didn't take into account the oceanic tides that has been known to have an effect several tens of kilometers away from the seashore (Beaumont and Berger, 1975). The deformation caused by ocean tide loading is difficult to calculate, these tides appear with the same frequencies as the solid earth effects (Khan and Scherneck, 2003), and the tides are strongly affected by the complicated topography around the seashore (Walters and Goring, 2001), so we can't simply to calculate the ocean tides by theory models. Besides, there are no public software to calculate the China national offshore ocean tides, so we have to delete those wells (4 wells: Hejiazhuang, Huanghua, Wafangdianloufang amd Yongchun) which may be influenced by the ocean tides seriously. Bearing those rules in mind, we find 11 stations (well a to well k (Figure 1)) can be chosen during the Wenchuan earthquake (Table 1).

We apply the above method to those well-picked stations. The pre-and post-earthquake *B* values are respectively obtained from May 1, 2008 to May 11, 2008, and from May 13, 2008 to May 24, 2008 (Figure 2).

Undrained Skempton's coefficient *B* as a function of effective pressure

When the aquifer be consolidated, the effective pressure (effective pressure = confining pressure - pore pressure) will increase, while a dilation is in accordance to the decrease of effective pressure. Blocher *et al.* (2009) measured the relationship between Skempton's coefficient *B* and effective pressure based on the laboratory experiment. The in-situ aquifer of those wells (well a～k) we studied are under lithostatic pressures for a long time and also be affected by the transmission of seismic waves for countless times, the situation is much similar to those well bedrocks be applied on repeated pressure cycles. So the situation will be much similar to the last several ramps (apply more than once pressure cycles on the rock) rather than the first ramp (apply the first pressure cycle on the rock, during which a possible dissolution of gas in the fluid of an incompletely saturated sample happened) in the experiment of Blocher *et al.* (2009), and the isotropic Skempton's coefficient *B* will increase/decrease with the increase/decrease of effective pressure (when the effective pressure is less than ～4 Mpa), while *B* will decrease with the increase of effective pressure (when the effective pressure is larger than ～4 Mpa). Although these results obtained from sandstone, because of the lack of the laboratory experiment study of those specific rocks, we assume the results can be applied to the bedrock of all those wells studied in this paper.

In order to compare with the experiment results, we have to estimate the effective pressure of each well. Pore pressure response to gravitational loading is similar to tectonic loading and can also be treated as a poroelastic problem (Green and Wang, 1986). Depth of those wells are show in Table 1, all of which are less than 1km. W-1 well lies in Yanchang basin of Gansu province,Yanchang basin is a deep basin with Paleozoic sediments (Wu *et al.*, 2010). The "pressure - depth" relation of well W-1 (Figure 3a) is similar to other wells in the Chinese mainland. So we assume those results could be applied to these wells we studied (well a～k) since we lack the "pressure-depth" predictions of these wells. We calculate the effective pressure of W-1 well (effective pressure approximately equals to lithostatic pressure minus pore fluid pressure) (Figure 3b), and estimate the range of the effective pressure of these wells we studied according to the well-depth (Table 1).

We calculated the change of pore pressure in each well ($\Delta P_p = \rho g \Delta h$), together with the range of the effective pressure, the variation trend of Skempton's coefficient *B*, and the *B*-effective pressure relation obtained by the experiment of Blocher *et al.* (2009), we can infer the variation of the effective pressure in each well (Table 2, Table 3). When the range of the effective pressure lies in 0-3 Mpa (most of the wells), the increase/decrease of *B* accompanied with the increase/decrease of effective pressure. When the range of effective pressure >5 Mpa, the increase/decrease of *B* accompanied with the decrease/increase of effective pressure Blocher *et al.* (2009), only the effective pressure of Jurong well (well f) lies in this range (Table 3).

Mechanism analysis

Coseismic water level change induced by consolidation or dilatation

Water level increase/decrease accompanied with the increase/decrease of

Skempton's coefficient *B* and the increase/decrease of effective pressure in well a, b, c, d, g, j, and k (Table 2). To our understanding, when the aquifer be consolidated/ dilatated and the pressure not exceed a limitation (the fissures not be closed), the mean fracture width (the porosity and permeability) may decrease/increase with the increase/decrease of the effective pressure, then the stiff rock matrix that supports the load could with a higher/lower coupling to the fluid (Nur and Byerlee, 1971), and the value of *B* increase/decrease. Which indicating shaking induced by the transmission of teleseismic waves may cause consolidation/dilatation of the aquifer, and lead to the increase/decrease of the water level (effective pressure). Figure 4 shows the relation between the change of Skempton's coefficient *B* and the change of effective pressure (pore pressure/water level) in well a, b, c, d, g, j, and k . Approximately, it displays a linear relation.

Coseismic water level change induced by increased permeability

Water level decrease/increase accompanied with the increase/decrease of Skempton's coefficient *B* and the increases/decrease of effective pressure in well e, h, and i (Table 3). Fracture clearing (unclogging) and increased permeability may be used to explain this phenomenon. Since pore-pressure heterogeneity may be the norm in the field, an enhancement of permeability among sites of different pore pressure may cause pore pressure to spread (Roeloffs, 1998; Brodsky *et al.*, 2003; Wang, 2007; Wang and Manga, 2010). Pore-pressure of those wells may be higher/lower than other places before the earthquake, an enhancement of permeability incured by overcoming the capillary entrapment in porous channels induced by the passage of elastic waves will decrease/increase the pore-pressure in those wells (the pore-pressure will shift to/shift from other places), and water level will decrease/increase. Then the effective pressure will increase/decrease accompanied with the decrease/increase of pore-pressure, so the Skempton's coefficient *B* increase (which indicates the stiff rock matrix could with a higher coupling to the fluid) in well e, and decrease (which indicates the stiff rock matrix could with a lower coupling to the fluid) in well h and i (Table 3).

The depth of well f (889.18 m) is larger than other wells, and the effective pressure range of this depth is 8～10 MPa (Table 3). Effective pressure decreases accompanied with the Skempton's coefficient *B* increases in this range (Blocher *et al.*, 2009). So water level increases with the decreases of effective pressure in this well, and this should be explained with the increased permeability. Pore-pressure of well f may be lower than other places before the earthquake, an enhancement of permeability will increase the pore-pressure in this well (the pore-pressure may shift from other places), and water level will increase. Then the effective pressure will decrease accompanied with the increase of pore-pressure, so the Skempton's coefficient *B* increase.

Examples support far field water level increases induced by consolidation

The spreading of shear waves may cause dilatation of the aquifer medium, which can broaden the porosities and give birth to new fractures, and the effective pressure will reduce (in wells: g, j and k, the effective pressure range is 0～3 MPa) leading to the decrease of Skempton's coefficient *B*. This explanation is similar to the mechanism of shaking-induced dilatancy (Bower and Heaton, 1978). So it may be easier to understand weater level decreases in the far field induced by the transmission of teleseismic waves. However, water level increases induced by consolidation in the far field is not the mainstream view. Since many cases support the theory of the increased permeability, it is necessary to give some examples which can support far field water level increases induced by consolidation.

Permeability will increase/decrease, which is mostly related to the increase/decrease of porosity (Xue, 1986). As explained by rock mechanics the same porosity always corresponding to the same effective pressure (Terzaghi, 1925; Magara, 1978). From that we can know porosity and permeability are all directly connected with effective pressure, and they will decrease with the increase of the effective pressure (Blocher *et al.*, 2009).

From the laboratory experiment, Liu and Manga (2009) find that: in general, permeability decreases after shaking. They measured the evolution of permeability in fractured sandstone in response to repeated shaking under undrained conditions, and set the frequency and amplitude of the imposed shaking to be representative of those that cause distant hydrological responses. As they explained: Dynamic strains cause time varying fluid flow that can redistribute particles within fractures or porespaces, and can allow particles to move away from regions where they hold pore spaces open, and are expected to accumulate and get trapped at the narrowest constrictions along flow paths, and hence allow a consolidation (contraction) of the sample. Their result just supports our mechanism analysis. It implies that teleseismic waves can cause a consolidation of well aquifer and cause the increase of effective pressure, which is in accordance with the increase of co-seismic water level changes accompanied with the increase of Skempton's coefficient *B* in wells: a, b, c, d (effective pressure range 0 ~ 3 MPa).

In addition, Huang (2008) find that: the water level increase in Fuxin well

(1409.98 km away from Wenchuan, the well depth is 60.74 m , stiff Granite with a little basalt is the bedrock and we assume the shear modulus = 60 Gpa) is induced by the increase of volume strain (consolidation) (Figure 5a). In the Chinese mainland, Fuxin is the only well in which there are observations of volume strain and water level in a specific aquifer medium, and both of them show obvious co-seismic responses to Wenchuan earthquake. There are clear and obvious effects of tidal strain and atmospheric pressure in the water level and volume strain, which indicates Fuxin is a terrific artesian well. This well has not be chosen in the above analysis because there is an abrupt large-amplitude increase in the water level, which starts from 11 p.m. May 22, 2008 (we can not find any interference of this abrupt increase according to the daily records of Fuxin station), and we can just use a shorter time period to calculate the post-earthquake *B* value, which may cause a little impact on the precise of *B*. The calculation is performed based on the M_2 wave distilled from the water level and the tidal strain (pre-earthquake: from May 1, 2008 to May 11, 2008, post-earthquake: from May 13, 2008 to May 22, 2008 (Figure 5b)). (The large-step abrupt water level increase starts from 09 p.m. May 22, 2008 (Figure 5c), which may cause large impact on the detrend process and influence the calculation result, so we just discard these data). From Figure 5a, we can see the co-seismic water level increase is induced by the change of the volume strain, which indicates the well aquifer has been consolidated. The depth of Fuxin well is 60.74 m, and we can assume the range of the effective pressure is 0 ~ 3Mpa (Table 3), from the change of the pre- and post- earthquake *B* (Figure 5b), we may infer the consolidation may be very extreme, accompanied with the coseismic water level increase it could cause an extra pressure, which just overcomes the capillary entrapment in porous channels of the aquifer or incures a fracture clearing and bring in the increase of the permeability, then water flow in from other places with a higher pressure, which lead to the decrease of the Skempton's coefficient *B* with the decrease of the effective pressure, and the water level increases more gradually. Finally with the further enhancement of the permeability (increase of the porosity), a permanent deformation could be induced, so there is an abrupt increase in the water level in 22 May, and remain in a relatively high level for several months(Figure 5c). From the picture we can see it may be in a drained condition after the abrupt large-amplitude water level increase, because the water level fluctuates irregularly.

So we argue that water level increase induced by the consolidation incurred by transmission of teleseismic waves is reasonable, and a consolidation with large enough energy may also lead to an enhanced permeability by overcoming the capillary entrapment in porous channels.

Wellbore storage effects

Tidal phase lags are caused by wellbore storage. "Wellbore storage" is the term used to describe a lag of piezometer water level behind aquifer pressure resulting from the need for water to flow into the borehole in order to equilibrate water level with aquifer pressure. Wellbore storage effects increase (phase lags increase) as the transmissivity (and permeability) of the formation decreases (Roeloffs, 1996; Doan *et al.*, 2006).

Most of those wells can record clear tidal strain and atmospheric pressure, and according to the <China earthquake monitoring records series> (which is written by different Subordinate units (earthquake administration of each provinces and different institutions) of China Earthquake Administration, and published in Beijing in different years by Seismological Press (in Chinese)) they are well confined. From

Table 1 we can see the phase difference of water level and tidal strain of most wells are 0, which mean good correlations between the water levels and the tidal strains, and those wells are well confined and under the undrained condition. Because we use the hourly data, we can not identify the phase difference when it is less than 1 hour, and we just neglected the wellbore storage effects in those wells. Before and after the earthquake, if phase lags remain the same, it indicates the permeability of the well aquifer keeps the same or just changes a little (the phase difference may be lees than 1 hour). Phase lags ≧ 1 hour in well: b, c, e, and Fuxin, and most of them are small, except well b, which may be semi-confined. Thus, the validity of the calculated *B* values in well b may be a little questionable. The phase lag of Fuxin well decreases after the earthquake (L1=2 hours, L2=1 hour), which indicates the permeability increases after the shakig of the earthquake, this is in accordance with the mechanism analysis of the co-seismic water level increase in Fuxin well.

Discussion

The variation of porosity

Figure 3c shows, in general, the porosity decreases with the increase of depth, however, when reach 3000m the effective pressure turns much larger (approximately equals to 35 Mpa) than that in the depth of those wells (well a～k), the porosity still persists relatively large, and changes with different depth. From Table 2 we can see, the variation of effective pressure of well a, b, c, d, g, j and k is less than 0.01Mpa, and from Figure 3b we know, variation of 0.01Mpa in effective pressure approximately equals to variation of 1 meter in depth, as Figure 3c shows, the variation of porosity is tiny during variation of 1 meter in depth. So this variation extent of effective pressure is hard to induce permanent deformation of porosity. However, in reality, the change of porosity may also connected with the formation and the state of the rock matrix.

Furthermore, phase lags of well a, b, c, d, g, j and k keep constant before and after the earthquake (change less than 1 hour) (Table (1)), so we can infer, the porosity (permeability) change little after the earthquake. Because the phase lags increase/decrease (wellbore storage effects increase/decrease) as the permeability (porosity) of the formation decreases/increase (Roeloffs, 1996; Doan *et al.*, 2006).

So we can infer, the porosity of well a, b, c, d, g, j and k can persist despite being reduced/enlarged due to the consolidation/dilatation induced by the passage of teleseismic waves of M_s 8.0 Wenchuan earthquake.

Uncertainty of *B* coefficient

In order to study the uncertainty of *B* coefficient (error related to the determination of *B* coefficient), we use Jurong well to show the variation of *B* during a relatively long – time span (50 days before and after the Wenchuan earthquake) (Figure 6). Skempton's coefficient *B* will change with the change of time. Because we use the least square fit to calculate *B*, the value may be a little different when we use diffenent length of data , but the change tendency (increase or decrease of *B*) before and after the earthquake will be constant. Furthermore, we can see the *B* value of Jurong well recover to its initial value after about 30 days (Figure 6).

So, compared with the uncertainty in *B* value, variation of *B* due to the earthquake is significant. The continuous of *B* will be influenced by lots of factors, such as power off, aftershocks, and so on, so *B*-value series at large time scale is not easy to obtain for each well.

The variation value of effective pressure

We calculated the change of pore pressure ($\Delta p_p = \rho g \Delta h$), and we can use the critical state to help us to analyze the variation value of effective pressure in each well.

When the aquifer be consolidated/dilated, in the critical state, the pore pressure keeps constant, the confinging pressure increase /decrease, then the effective pressure increase/decrease, and at last transfer into the increase/decrease of pore pressure (water level increase/decrease), and the system come into an equilibrem state. So the change of pore pressure can be attributed to the change of the effective pressure.

When the permeability increase, in the critical state, the confining pressure keeps constant, the pore pressure (water level) increase (the well in a relatively low pressure region before the earthquake) /decrease (the well in a relatively high pressure region before the earthquake), then the effective pressure decrease/increase, so the change of the effective pressure can be attributed to the change of pore pressure.

However , the variation value of the effective pressure of each well may be different from the value we calculate, because the critical state is an assumption ideal state, and the transfer of stress may also relate with the formation and state of the aquifer.

Conclusion

Together with the variation of Skempton's coefficient *B*, the change of pore pressure and the inferred variation of effective pressure in each well, we can infer the mechanism of the co-seismic water level changes. From the study we can conclude: consolidation/dilatation induced by shaking of teleseismic waves, may account for the mechanism of those abrupt coseismic water level changes, for which the variation tendency of the co-seismic water level, Skempton's coefficient B and the effective pressure keep the same (all increase or all decrease). While, fracture clearing and increased permeability may be used to explain the other part of those coseismic water level changes, especially the more gradual water level changes in this area, for which the co-seismic water level, and the effective pressure change with inconformity. Our analysis is not conflict with any of those existing theories. Although those water level changes happened in the intermediate and far fields, most of those water levels present abrupt and obvious co-seismic changes owing to the huge energy of M_s 8.0 Wenchuan earthquake.

From the analysis of Fuxin well, we can see a consolidation with large enough energy may also incur an enhanced permeability by overcoming the capillary entrapment in porous channels or by fracture clearing. So as discussed by Liu and Manga (2009), permeability changes (either increases or decreases) owing to dynamic stresses are reasonable explanations for earthquake-induced hydrologic responses. The mechanisms analyzed in this paper are similar to the experiment results of Liu and Manga (2009), and our in-situ analysis may complement the limitation of the initial condition of their laboratory experiments.

In reality, the shear modulus G and the undrained Poisson's ratio ν_u would change slightly after the shaking of seismic waves, and the discussed "undrained" condition can hardly last for a long time, as long as the fluid flow exists, the undrained condition will disrupt and be replaced by the drained condition soon. We assume the results get from sandstone can be applied to all those bedrocks in those wells (Figure 3), however this is not very precise. As described by Wang (1993) nonlinear compaction effects can be significant and they are not incorporated in the linear theory presented here, because the well aquifers are under lithostatic pressures for a long time and withstand large numbers of seismic shaking, the irreversible deformations and the nonlinear effects have been minimized (In the laboratory experiment, in order to reduce the irreversible deformation and to minimize the nonlinear effects, repeated pressure cycles are always applied on rock samples as preconditions (Blocher *et al.*, 2009). Discard all those ideal assumptions, things may be different.

Data and Resources

Data used in this paper were collected using a classified network (Groundwater Monitoring Network, GMN) of the China Earthquake Networks Center and cannot be released to the public. We use the Mapseis software (Lu *et al.*, 2002) to calculate the tidal strain data.

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Table 1. Basic information of well a ~ k.

Station	Epicentral Distance /km	Δh/m	Pre/Post-Earthquake *B*	Lithology	G*/Gpa	Phase lag/hour	Well Depth/m	Range of P_{eff}/MPa
(a) Xiaxian	465.9465	0.106	0.0123/0.0149	Gneiss	40	L1=L2=0	168	3
(b) Mile	726.4589	0.579	0.0872/0.1103	Limestone	20	L1=L2=-6	614	5
(c) Qinxianmanshui	983.8517	0.172	0.0557/0.0653	Sandstone	8	L1=L2=-2	240.05	3
(d) Xiaoyi	1062.0768	0.398	0.1493/0.186	Sandstone	8	L1=L2=0	502.47	3
(e) Qixian	1152.6034	0.831	0.0906/0.0153	Limestone	20	L1=0 L2=-3	410	3
(f) Jurong	1750.2357	0.263	0.0472/0.0519	Sandstone	8	L1=L2=0	889.18	
(g) Haiyuanganyanchi	606.402	-0.036	0.0407/0.0395	Sandstone	8	L1=L2=0	306.73	3
(h) Guyuanzhenqi	638.7904	-0.026	0.0026/0.0047	Sandstone	8	L1=L2=0	618.39	5
(i) Kaiyuan	805.4263	-0.155	0.0724/0.077	Limestone	20	L1=L2=0	224	3
(j) Meizhou	1345.951	-0.075	0.0873/0.0823	Quartzite	20	L1=L2=0	338.86	3
(k) Chaohu	1587.6013	-0.455	0.091/0.0798	Limestone	20	L1=L2=0	331	3
Fuxin	1409.9764	0.121	0.5761/0.5145	Granite & Basalt	60	L1=-2 L2=-1	60.74	3

Epicentral Distances, Water Level Changes, Pre- and Post- Earthquake *B* Values, Lithology of the bedrocks, Shear Modulus, Phase Lags, Well Depths and Range of Effective pressures of those well-picked stations. L1 and L2 represent the pre- and post- earthquake phase lags (the lag of piezometer water level behind the tidal strain induced aquifer pressure) separately.

Shear modulus G* see Yan Zhang and Fuqiong Huang (2011).

Table 2. Coseismic water level changes induced by consolidation or dilatation.

Station	Δh/m	ΔB	ΔP_p/MPa	ΔP_{eff}/MPa	Well Depth/m	Range of P_{eff}/MPa
(a) Xiaxian	0.106	**0.0026**	0.0010	**0.001**	168	3
(b) Mile	0.579	**0.0231**	0.0057	**0.0057**	614	5
(c) Qinxianmanshui	0.172	**0.0096**	0.0017	**0.0017**	240.05	3
(d) Xiaoyi	0.398	**0.0367**	0.0039	**0.0039**	502.47	3
(g) Haiyuanganyanchi	-0.036	**-0.001**	-0.0004	**-0.0004**	306.73	3
(j) Meizhou	-0.075	**-0.005**	-0.0007	**-0.0007**	338.86	3
(k) Chaohu	-0.455	**-0.011**	-0.0045	**-0.0045**	331	3

Water Level Changes, Changes of *B* Value, Calculated Changes of Pore-Pressure ΔP_p, inferred Changes of Effective Pressure ΔP_{eff}, Well Depths and Ranges of Effective pressure of those wells.

Table 3. Coseismic water level changes induced by increased permeability.

Station	Δh/m	Δ*B*	ΔP_p/MPa	ΔP_{eff}/MPa	Well Depth/m	Range of P_{eff}/MPa
(e) Qixian	0.831	**-0.075**	0.0081	**-0.0081**	410	3
(f) Jurong	0.263	**0.0047**	0.0026	**-0.0026**	889.18	
(h) Guyuanzhenqi	-0.026	**0.0021**	-0.0003	**0.0003**	618.39	5
(i) Kaiyuan	-0.155	**0.0046**	-0.0015	**0.0015**	224	3
Fuxin	0.121	**-0.0616**	0.0012	**-0.0012**	60.74	3

Water Level Changes, Changes of *B* Value, Calculated Changes of Pore-Pressure ΔP_p, inferred Changes of Effective Pressure ΔP_{eff}, Well Depths and Ranges of Effective pressure of those wells.

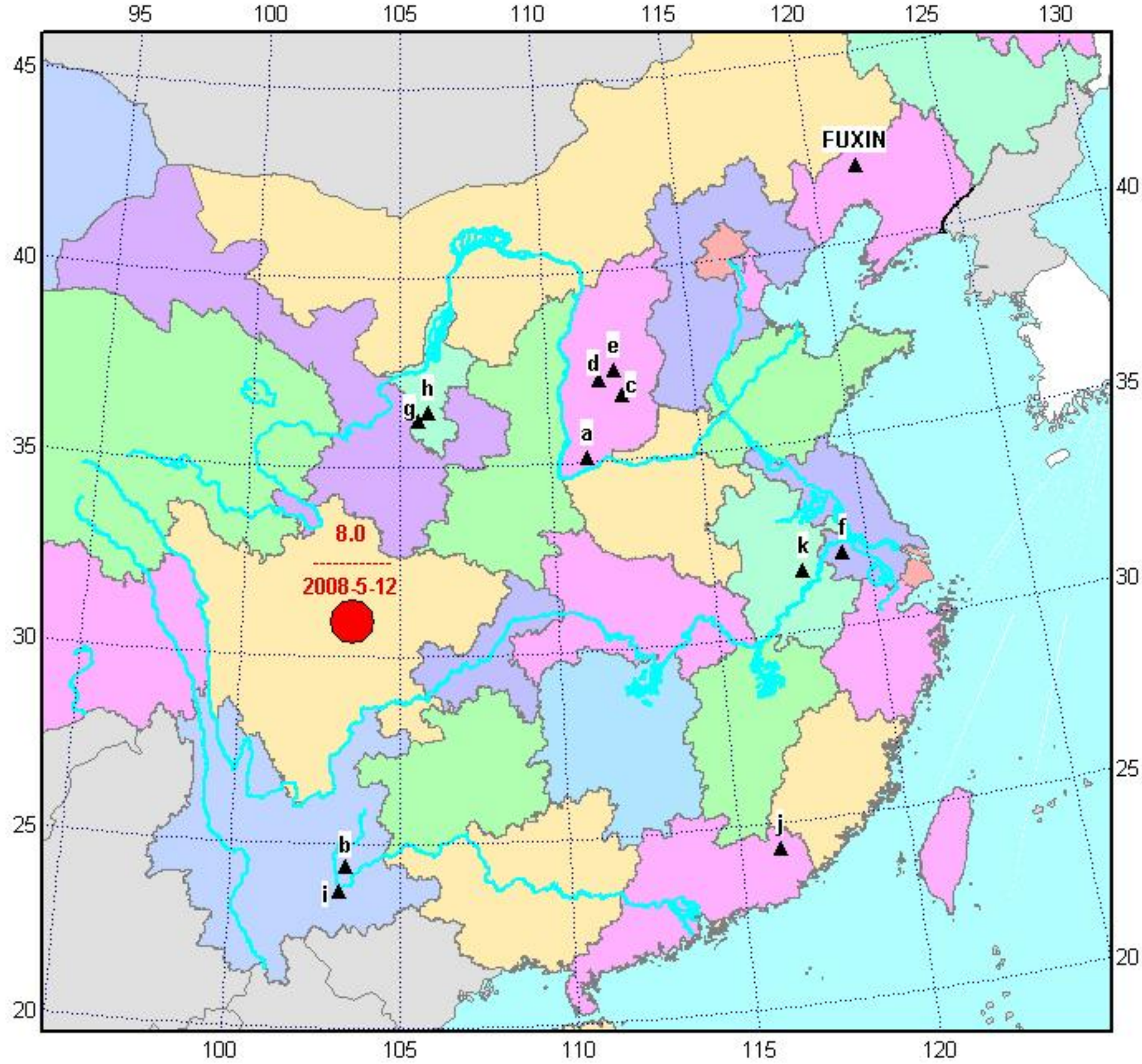


Figure 1. The selected 12 stations with distinct amplitude co-seismic water level changes during the Wenchuan earthquake in mainland China. The well numbers are in accordance with the numbers listed in Table 1.

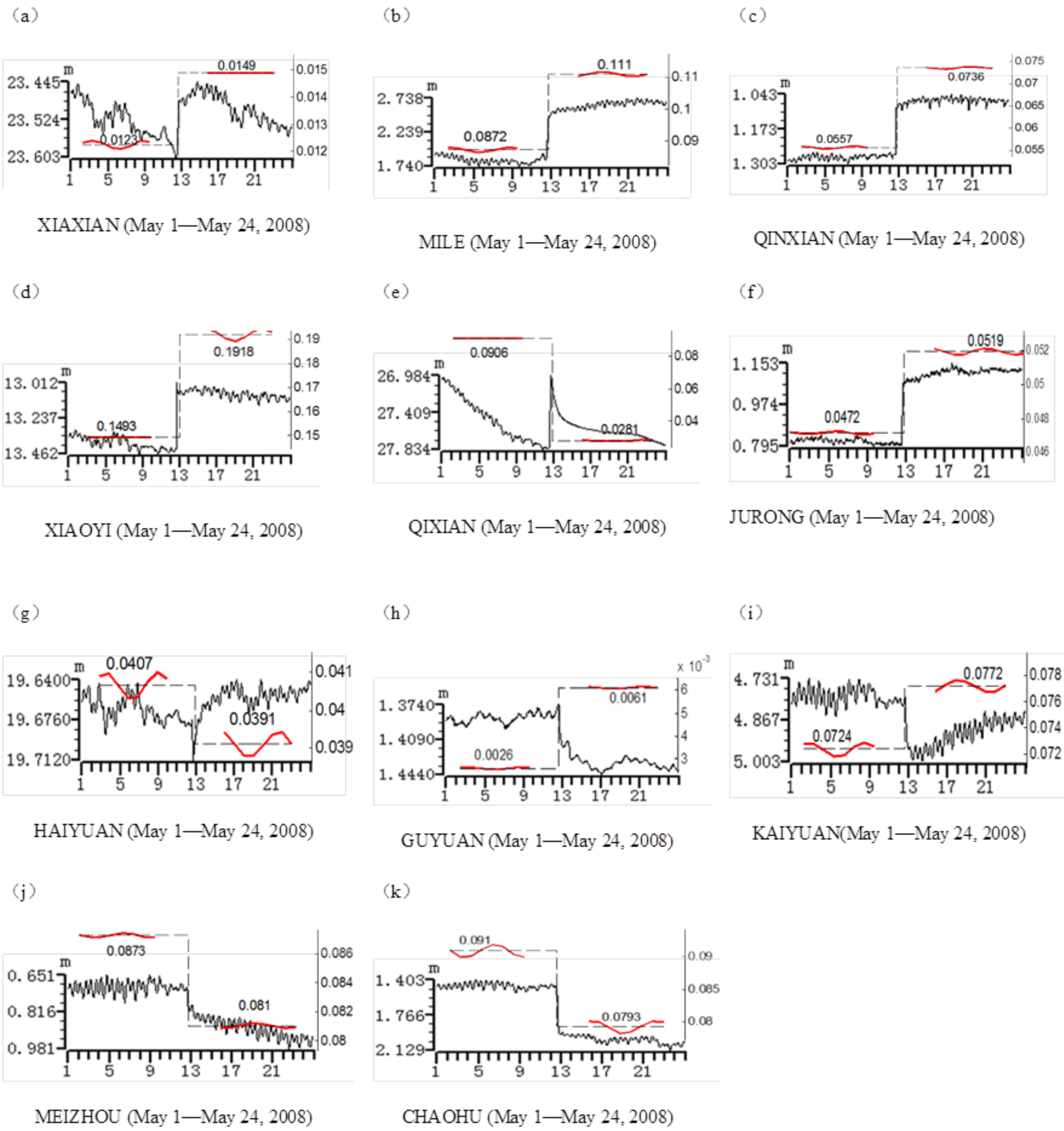


Figure 2. (a) Left y-coordinate: original water levels, the sequential number of y-coordinate depends on the type of the well, “sequential number increase from low to

high” indicates an artesian well, the coordinate value means the height from the free water surface to the artesian discharge point or to the ground. “Sequential number decrease from low to high” indicates a non-artesian well, and the coordinate value means the depth from the free water surface to the ground. All the ascendant/ descendent patterns in the picture indicate water level ascending/ descending. (b) Right y-coordinate: the calculated Skempton’s coefficient *B*. The dashed lines indicate the mean *B* values, which are clearly shown in numbers. While the curves along the dashed lines indicate the continuous *B* values both pre- and post-earthquake.

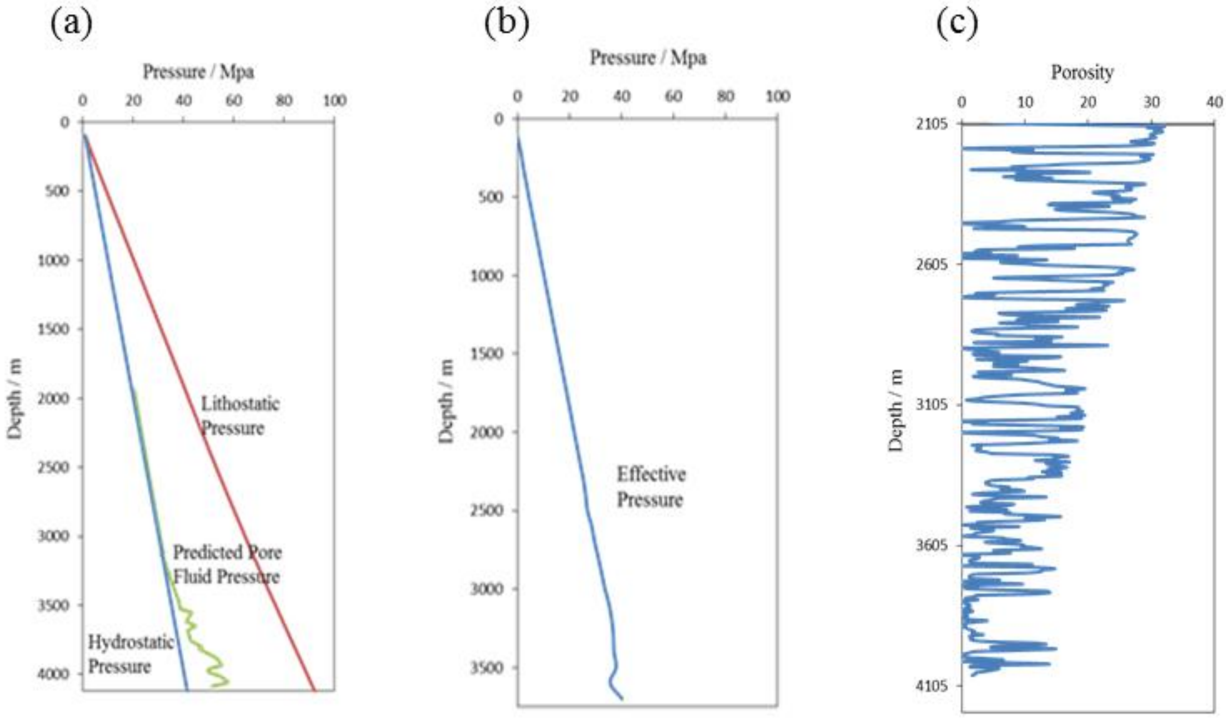


Figure 3. (a) Pressure section of W-1 well in Yanchang basin, the bedrock of W-1 well is sandstone. (b) Effective pressure section of W-1 well, we just show the depth above 3500m, so as to see the value in shallow depth more clearly. (c) Porosity section of W-1 well. The porosity records approximately starts from 2100 m, there are no records above this depth.

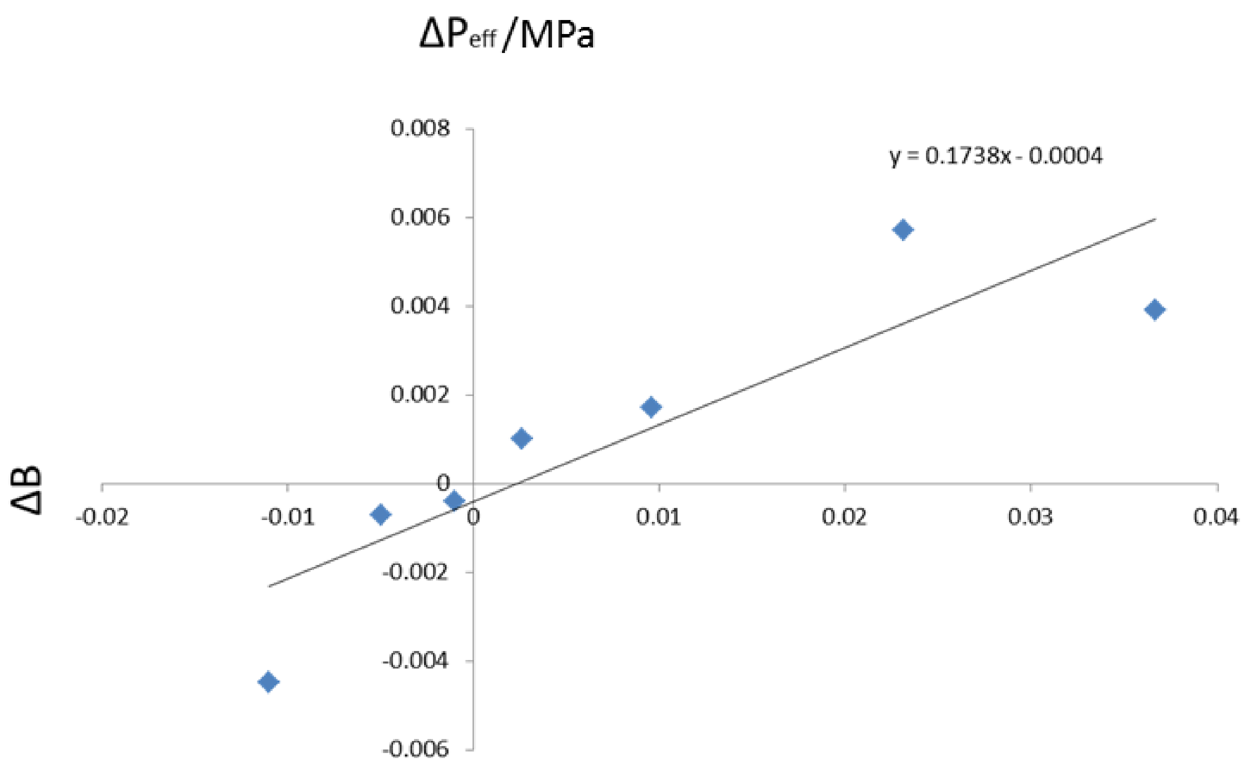
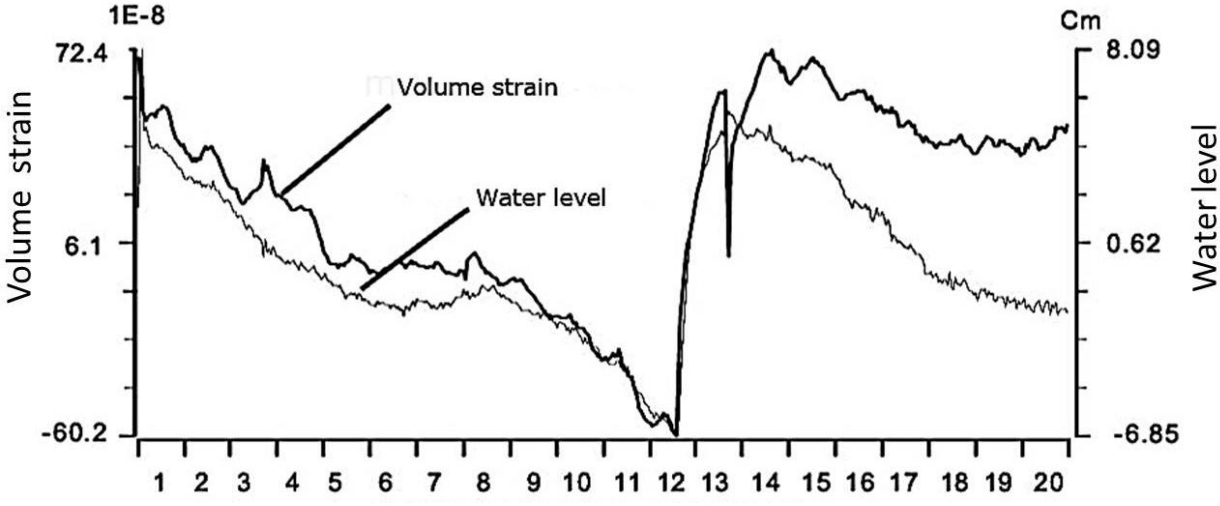


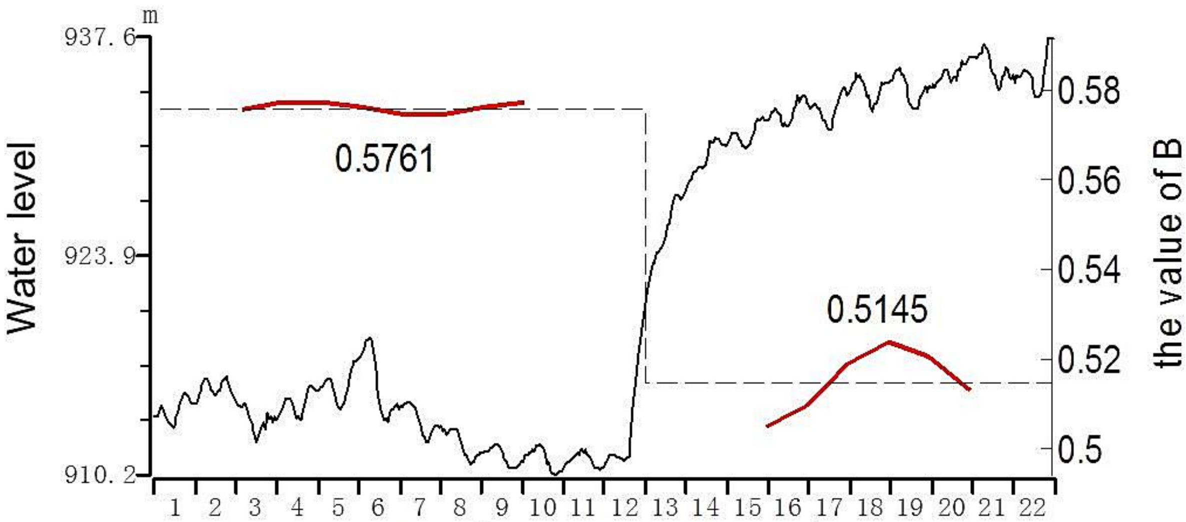
Figure 4. The relationship between the change of Skempton's coefficient *B* and the change of effective pressure Peff of those wells of which the coseismic water level changes can be explained by the consolidation or dilatation caused by teleseismic waves.

(a)



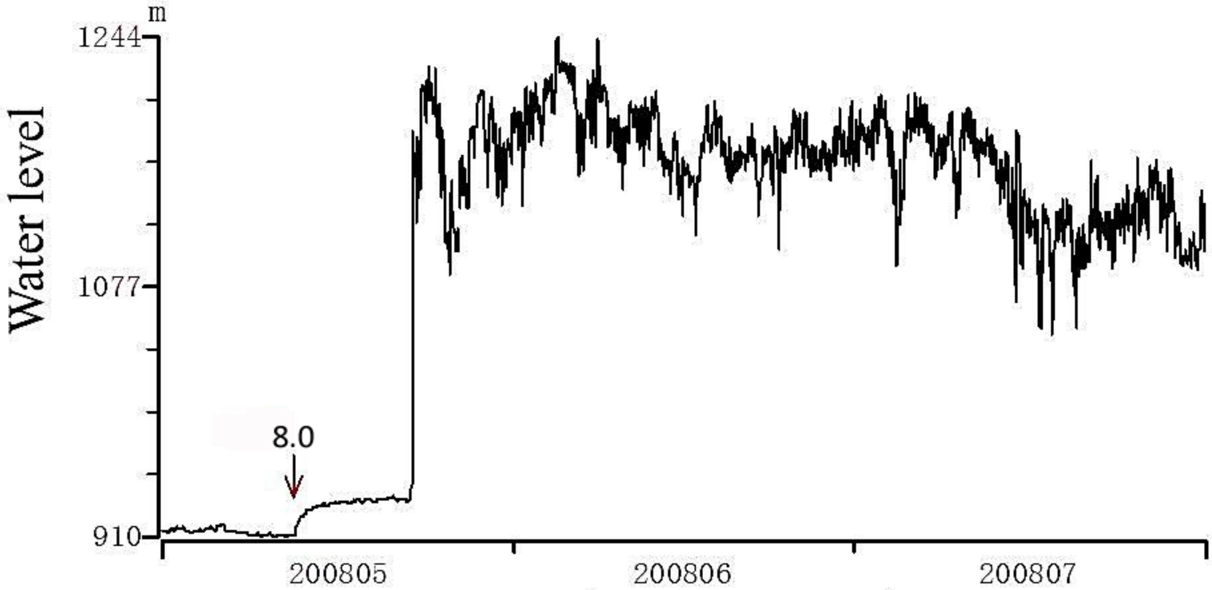
FUXIN (May 1—May 20, 2008)

(b)



FUXIN (May 1—May 22, 2008)

(c)

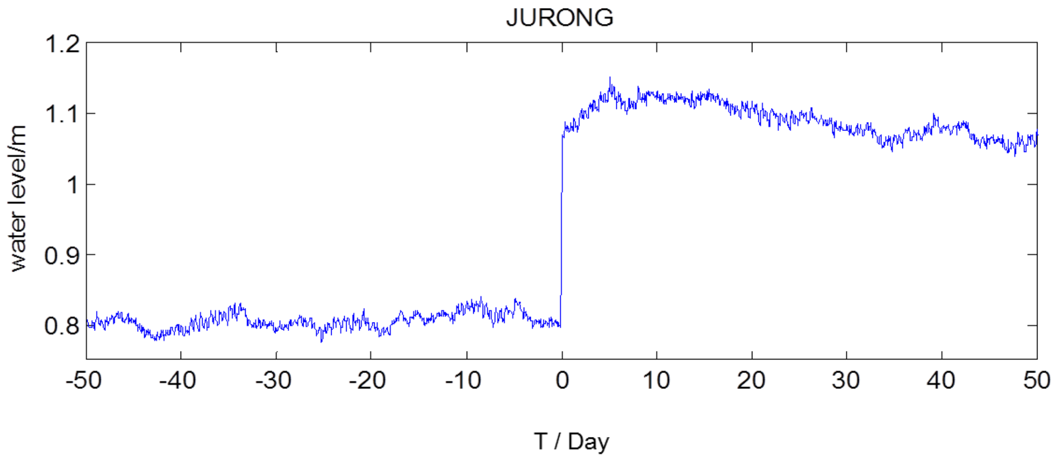


FUXIN (May 1—July 31, 2008)

Figure 5. Fuxin well (a) Corrected water level and volume strain after removing the influence of atmospheric pressure and tidal srain (based on the harmonic analysis method). In order to avoid the interfere of thunder, there is a power cut protection on 13 May, which is in accordance with the break point of the volume strain in the figure (Huang, 2008). (b) Original water level and the pre- and post- earthquak Skempton's

coefficient *B*. (c) Original water level of Fuxin well form May, 2008 to July 2008.

(a)



(b)

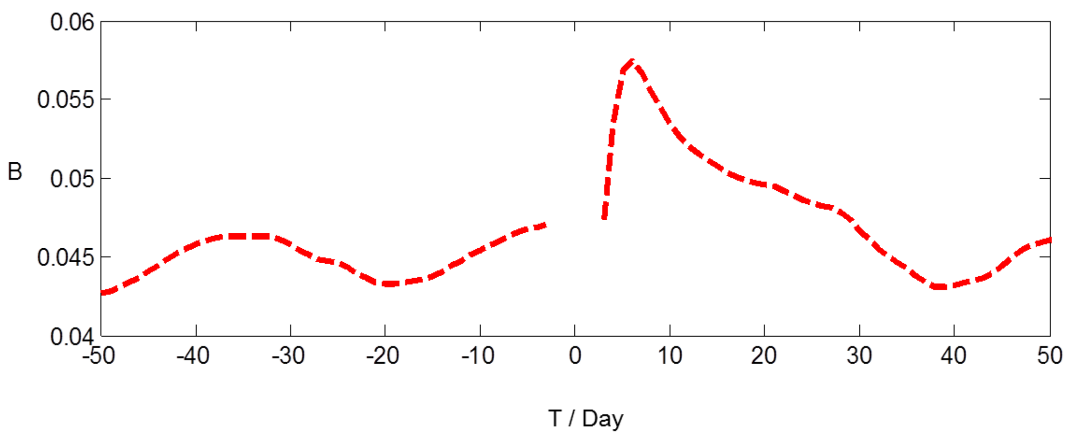


Figure 6. Jurong well (a) Original water level of Jurong station. (b) Continuous *B* value of Jurong station. ("0" depends the day when Wenchuan earthquake happened)

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