July 12, 2012

To the Editor of Hydrology and Earth System Sciences

Subject: Regarding revision of the HESS manuscript (**hess-2012-18**)

Thank you very much for reviewing carefully our manuscript, entitled "**Characterization of Spatial Coseismic Response of Groundwater Levels in Shallow and Deep Parts of an Alluvial Plain to Different Earthquakes**" by Mahmuda PARVIN, Naoyuki TADAKUMA, Hisafumi ASAUE and Katsuaki KOIKE published in HESSD. We are submitting the replies to the queries of the honorable reviewers.

We are very grateful to the reviewers' constructive, valuable, and preferable comments, and appreciate deeply the reviewers' hard works on critical reading of our manuscript. We checked carefully all the comments and revised the manuscript accordingly. The comments were very helpful to improve the clarity and quality of the paper. Detailed responses to the reviewers' comments including changes that have been made to the original manuscript are written in the attached sheets.

We wish to sincerely thank you and the reviewers again for editing and reviewing our manuscript. If there are still inappropriate points before acceptance, we are pleased to revise them as soon as possible.

Sincerely yours,

Mahmuda Parvin
Department of Civil and Environmental Engineering
Uttara University, Uttara Model Town
Dhaka 230, Bangladesh
E-mail: mahmudaalam@yahoo.com

[You can contact also] Katsuaki Koike (Professor)
Graduate School of Engineering, Kyoto University, Kyoto 615-8540
Tel: +81-75-383-3314, Fax: +81-75-383-3318, E-mail: koike.katsuski.5x@kyoto-u.ac.jp

Replies to Reviewer's comments (1)

We wish to reply to the valuable and constructive comments raised by the reviewer 1 as follows. The portions revised following the comments and suggestions by the reviewers are shown on the revised manuscript by red letters. The comments are copied by blue italic letters below.

General comments:

• What is the most important outcome of this study? How does this work explicitly contribute to the knowledge of earthquake related hydrological phenomena? What is the newly gained knowledge? This should be better pointed out by the authors.

We appreciate this correct comment. In accordance with this comment, we revised Abstract and Introduction to describe more clearly the most important outcome, contribution to earthquake hydrology, and the newly gained knowledge as our replies to the following comments.

Originality of this study is summarized by the following four points. One new approach is to investigate the responses of the groundwater levels in an alluvial plain to several earthquakes, which differed in magnitude and hypocenter ~~epicenter~~ distance, and clarify similarity and dissimilarity of the spatial patters of the level changes. Second point is to compare the level changes between shallow and deep groundwater. Preceding studies on clarifying the difference of groundwater level changes with the location are seen in several literatures, listed after, but our improvement is to map level changes more in detailed by considering the aquifer depth and using an interpolation technique. Third important point is to find the effect of a local geology, the Togawa lava (porous andesite), on the groundwater level change: levels in the Togawa lava area tended to change more in magnitude, and more quickly, with a shorter recovery time, than levels measured in the area outside the lava. Forth point is to develop a conceptual model to explain the mechanism of groundwater level change to explain the similarity and dissimilarity of the spatial patters of the level changes induced by different earthquakes between the shallow and deep groundwater.

• Some sections should be reorganized in order to clarify the paper's outline:
Abstract: what is the main outcome of this study? Neither the results, methods, interpretation/discussion nor conclusions do explicitly appear. I suggest reshaping the abstract completely.

In accordance with this comment, we revised Abstract as follows.

[Original] Coseismic changes in groundwater levels have been investigated in many places throughout the world, but most studies have focused on the effects of one large earthquake. Few studies have looked at the spatial patterns of level changes in response to several earthquakes, or at the relationship of the patterns to shallow and deep groundwater in the same area. The aim of this study was to investigate these patterns and to construct a model of hydraulic responses. We selected the Kumamoto City area in southwest Japan, a region with one of the richest groundwater resources in Japan, as our study site. Data from hourly measurements of groundwater levels in 54 wells were used to characterize the coseismic spatial responses to four large earthquakes that occurred in 2000, 2001, 2005, and 2008. Although the distance to the epicenter (12 to 2573 km), and seismic energy (Mw = 4.8 to 8.0) of these earthquakes varied, systematic groundwater level changes were observed in the range of 0.01 to 0.67 m. The zones where coseismic rises were observed were generally wider for deep groundwater than for shallow groundwater. We observed general trends in the changes in groundwater levels, and calculated pressure changes, in the deep groundwater, but the coseismic increases or decreases in compressive stress in the shallow groundwater were variable, depending on the distance to the earthquake epicenter. We developed a conceptual model of the mechanism underlying this phenomenon and also investigated the importance of Togawa lava, consisting of porous andesite and forming a main aquifer, in determining the pattern of groundwater level change.

[Revision] Coseismic changes in groundwater levels have been investigated throughout the world, but most studies have focused on the effects of one large earthquake. The aim of this study was to elucidate the spatial patterns of level changes in response to several earthquakes, and the relationship of the patterns to shallow and deep groundwater in the same area. We selected the Kumamoto City area in southwest Japan, a region with one of the richest groundwater resources in Japan, as our study site. Data from hourly measurements of groundwater levels in 54 wells were used to characterize the coseismic responses to four large earthquakes that occurred in 2000, 2001, 2005, and 2008. Although the distance to the epicenter (12 to 2573 km), and seismic energy (Mw = 4.8 to 8.0) of these earthquakes varied, systematic groundwater level changes were observed in the range of 0.01 to 0.67 m. Spatial patters of the level changes were clarified by interpolating the point data by a spline method. The zones where coseismic rises were observed were generally wider for deep groundwater than for shallow groundwater, probably as a result of an increase in compressive stress. General trends in the changes in groundwater levels, and calculated pressure changes, were clarified to be consistent in the deep groundwater, but the coseismic increases or decreases in compressive stress in the shallow groundwater were variable, depending on the distance to the earthquake epicenter. We developed a conceptual model of the mechanism underlying this phenomenon by assuming uniformity or concentration of the seismic forces acting over the depth range. In addition, the importance of local geology was indentified, because levels in the area of Togawa lava (a porous andesite) tended to change more in magnitude, and more quickly, with a shorter recovery time, than levels measured in the area outside the lava.

Introduction: It is mentioned that further investigation of groundwater response to earthquake is needed. However, the authors do not explain why their study is important to address these issues and how they contribute to further understanding of seismo-hydrological processes? This should be complemented in order to point out the study's relevance.

In accordance with comment, we revised Introduction largely to describe our purpose, different points from the previous studies, and contribution of this study to earthquake hydrology more clearly.

1. Introduction

Groundwater levels are influenced by barometric pressure, precipitation, earth tide, and earthquakes. The effect of earthquakes has been a focus of research because the correlation between groundwater level fluctuations and earthquakes can contribute to find out signatures of the crustal response to tectonic deformation (e.g., Davis et al., 2001). Understanding the origin of the correlation can provide new insights into the spatio-temporal variability of hydrological properties and processes at pores to continents scales (Montgomery and Manga, 2003; Wang and Manga, 2010). Besides, it is significant from an aspect of groundwater resource management, because water-level changes can affect water supplies (Chen and Wang, 2009) and decrease water quality by causing water turbid. Groundwater levels respond rapidly to an earthquake, particularly in seismically active areas, and begin to change during ground shaking (coseismic), and continue to change after ground shaking ceases (post-seismic). These immediate and delayed responses are caused by different mechanisms including proximity to the epicenter, geological structure, and hydraulic properties (Montgomery and Manga, 2003). This study focuses on coseismic changes because they are generally much larger than post-seismic changes.

The coseismic groundwater-level changes in wells are typically classified into three types by Roeloffs (1998) using records from a single well that responded to multiple earthquakes: step-like increase for the near field of epicenter, gradual and persisted changes for hours to weeks for the intermediate field, and only transient oscillations in the far field (Manga et al., 2012). Redistribution of static stress or the strain field induced by fault displacement is probably associated with the generation of persistent coseismic changes in the near field (Roeloffs, 1996; Chia et al., 2008). Strain changes fluid pressure and alters hydrogeological properties such as permeability (Manga and Wang, 2007). Change of permeability has been of particular interest as a common cause for affecting various hydrological systems (Elkhoury et al., 2006; Manga et al., 2012).

Various mechanisms have been proposed to explain groundwater level changes in wells during earthquakes including permeability change at the site (e.g., Montgomery and Manga, 2003; see Fig. 1; Manga and Wang, 2007). Most studies have focused on level changes at several wells in a study area or for one large earthquake. For the groundwater resource management, detailed pattern of level changes in response to multiple earthquakes in a watershed using closely located monitoring wells needs to be clarified. Also the patterns may be different with proximity to the epicenter, local geological setting, and magnitude of earthquake. Such clarification is the most important to the area relying largely on groundwater. For this problem, we investigated the detailed spatial distribution of coseismic groundwater level changes over an unconsolidated sedimentary basin rich in groundwater resources. Persistent coseismic changes, which can be interpreted using the poroelastic theory, were our target. One new approach of this study was to compare the level changes between shallow and deep groundwater. Preceding studies on clarifying the difference of groundwater level changes with the location are Lee et al. (2002), Wang et al. (2001, 2004), Manga and Wang (2007), and Chia et al. (2008) by selecting a large alluvial fan in Taiwan for the Chi-Chi earthquake in 1999. Our improvement is to map level changes more in detailed by considering the aquifer depth and using an interpolation technique. Another was to construct a conceptual model for the mechanism of groundwater level changes by integrating the coseismic responses to multiple earthquakes.

Being part of the circum-Pacific seismic belt, Japan is one of the most seismically active regions in the world. Therefore, groundwater levels in Japan would be expected to change frequently in response to earthquakes. The Kumamoto City area in central Kyushu, southwest Japan (Fig. 2) is one of the best sites to conduct research on the spatial distribution of groundwater level changes, because all drinking water, and water used for agriculture and industry by the population of 700 000, is sourced from local groundwater. The systematic measurement of groundwater levels has been implemented at many wells to monitor the groundwater resource. We therefore selected the Kumamoto City area as our study site.

Results: Results, observations and discussion are merged into one section. From my point of view, this makes the interpretation complicated. It is very hard to differentiate between the results/findings and the authors' personal interpretation. I'd suggest separating the distinct sections clearly in order to avoid mixing of observations, results which may lead to misinterpretation. Moreover, it facilitates the reader to follow the thoughts of the authors. Even though the interpretation seems to be reasonable in cases, the interpretation remains unsupported by any proof (e.g., page 5328, lines 4-8).

In accordance with the former comments, we divided the section of the results into two sections on the result and discussion, as our reply to the next comment. For the latter comment on the descriptions "The magnitude of the rise was similar in wells 13A and 14B (0.13 m and 0.14 m, respectively) and the rise patterns were also similar although the well depths differed by 35 m. This similarity may have been caused by a hydraulic connection between two permeable layers with similar pore compressibility", similar phenomenon and interpretation are noted by Chia et al. (2008). We added this reference to support our interpretation as follows.

Line 285-290

[Addition] The magnitude of the rise was similar in wells 13A and 14B (0.13 m and 0.14 m, respectively) and the rise patterns were also similar although the well depths differed by 35 m. This similarity may have been caused by a hydraulic connection between two permeable layers with similar pore compressibility. Similar phenomenon and interpretation are described by Chia et al. (2008) for the case of Chi-Chi earthquake.

Chia, Y., Chiu, J. J., Chiang, Y.-H., Lee, T.-P., Wu, Y.-M. and Horng, M.-J.: Implications of coseismic groundwater level changes observed at multiple-well monitoring stations, Geophys. J. Int., 172, 293-301, 2008.

- *The distinct hydrological responses to the earthquakes and their magnitude are mentioned in section 3.2. However, they rather belong to the results section where they should be removed to. In general, I think, the results section should be reshaped up to a substantial extent and a discussion section should be added.*

In accordance with the former comment, the latter part of sub-section 3.2 was revised and moved to a new sub-section "**4.1 Range of groundwater level changes**" in the next section on the results.

4.1 Range of groundwater level changes

The range of groundwater level changes observed over one hour around the time of the earthquake, are shown in Table 1. For example, if an earthquake occurred at 9:30, groundwater levels at 9:00 and 10:00 were recorded to determine if there had been a sudden drop or rise.

Although the KME was the smallest in seismic energy (M_w = 4.8), a strong effect was observed on the groundwater level. The changes observed ranged from −0.2 m (a 0.2 m coseismic drop in the level) to +0.67 m (a 0.67 m coseismic rise) among the 54 wells. This large effect can be attributed to the short distance of the hypocenter from the study area. The effect of the GYE on levels was smaller because of the greater distance to the hypocenter, while the FOE had the second strongest effect on groundwater levels because it was centered at the second shortest distance from the study area. A small effect was detected for the SCE, one of the most destructive earthquakes in recent time, even though it was centered more than 2500 km from the study area.

Moreover, in accordance with the latter comment, we made a discussion section by separating the latter part of result into a discussion section as follows.

[Original] **4.4 Spatial characteristics of pressure changes**
4.5 Effect of Togawa lava
4.6 Conceptual model for level change mechanism
5. Conclusions

[Revision] **5. Discussion of groundwater level changes**
5.1 Spatial characteristics of pressure changes
5.2 Effect of Togawa lava
5.3 Conceptual model for level change mechanism
6. Conclusions

- *The distinct mechanism (communicating aquifers; increasing hydraulic head vs. indicated permeability change by coseismic (dilitant?) fissures) are presented over simplistic and a critical assessment is missing. The anisotropic permeability change, as proposed for the Chi-Chi earthquake response in Taiwan is not considered as a potential mechanisms though the geological/topographical setting of the greater study area here seems to be comparable.*

This study focused on the similarity or dissimilarity of the spatial patterns of groundwater level changes induced by different earthquakes, and relation of the spatial patterns between the shallow and deep parts. Clarifying a detailed mechanism controlling the spatial patterns is our next step, because the hydraulic data such as permeability and storage coefficient are not sufficient at present. Although the descriptions of mechanism are simple, these are the best ones which we can interpret using the present data and information. But, considering the suggestion, we added words and revised the text as follows.

Line 403: a strong anisotropy of the hydraulic structure such as permeability

Line 499-501:

[Original] For close earthquakes, the deep groundwater is strongly compressed because of the large seismic force, which causes relatively large rises in groundwater level.

[Revision] For close earthquakes, the deep aquifer is strongly compressed because of the large seismic force, which causes relatively large rises in groundwater level.

Line 504-509:

[Original] New fractures or fissures result in a release of pressure, and consequently the levels of shallow groundwater fall, as seen for the KME and the FOE, and illustrated in Fig. 10.

[Revision] New fractures or fissures may result in forming fracture-related anisotropic permeability such that only the vertical permeability of the groundwater system is enhanced, while the horizontal permeability remains nearly constant (Wang et al., 2004). This can release pore pressure and induce downward flow, and consequently the levels of shallow groundwater fall, as seen for the KME and the FOE, and illustrated in Fig. 10.

Wang, C.-Y., Wang, C.-H., Manga, M. (2004) Coseismic release of water from mountains: Evidence from the 1999 (Mw=7.5) Chi-Chi, Taiwan, earthquake, Geology, v. 32, no. 9, pp.769-772.

- *The written English should be improved.*

Before submission, this manuscript was edited and revised by an English editing company in Japan (Edanz), which has collaborate with Springer, AIP, etc.

- *Important and recent references are missing: e.g., latest overview: Wang and Manga, (2010): Earthquakes and water; Permeability: Elkhoury et al. (2006) Nature, Alluvial fan response: Wang et al., (2001) Geology; Anisotropic permeability change: Wang et al., (2004)* *Geology; Groundwater of different depth: Wang et al., (2012) Geology.*

We appreciate this instruction. All important and recent references suggested have been included in the revised text.

- *The authors stress the lack of studies focussing on multiple earthquake responses and to groundwater tables of different depth though studies of comparable settings exist. However, the hydrological responses and their spatial patterns of the Chi-Chi earthquake may provide a valuable comparison for this study here. In addition, Montgomery et al, 2003 does also deal with hydrologic effects of an earthquake on an alluvial fan.*

We appreciate this suggestion. Considering the comment, we added descriptions on the preceding studies in Introduction by red letters as follows.

[Addition] One new approach of this study was to compare the level changes between shallow and deep groundwater. Preceding studies on clarifying the difference of groundwater level changes with the location are Lee et al. (2002), Wang et al. (2001, 2004), Manga and Wang (2007), and Chia et al. (2008) by selecting a large alluvial fan in Taiwan for the Chi-Chi earthquake in 1999. Our improvement is to map level changes more in detailed by considering the aquifer depth and using an interpolation technique.

Lee, M., Liu, T.-K., Ma, K.-F., Chang, Y.-M.: Coseismic hydrological changes associated with dislocation of the September 21, 1999 Chichi earthquake, Taiwan, Geophys. Res. Lett., 29, 1824, 2002.

Wang, C.-Y., Cheng, L.-H., Chin, C.-V., Yu, S.-B.: Coseismic hydrologic response of an alluvial fan to the 1999 Chi-Chi earthquake, Taiwan, Geology, 29, 831-834, 2001.

Wang, C.-Y., Wang, C.-H., Manga, M.: Coseismic release of water from mountains: Evidence from the 1999 (Mw=7.5) Chi-Chi, Taiwan, earthquake, Geology, 32, 769-772, 2004.

In addition, we checked the reference of Montgomery and Manga (2003, *Science*). This reference focused on the distance from epicenter versus earthquake magnitude for locations reported to have exhibited seismically induced changes in groundwater levels. The relationship must be significant, and multiple earthquake responses in a fixed area may be included there, but the relation to our study is weak.

- *The authors often refer to "patterns" but do not explicitly explain what kind of patterns they* *refer to? Spatial? Temporal? Please clarify this consistently.*

As we described “spatial patterns” in Abstract, we focus on spatial pattern. But, in the section “4. Results”, we used the term “pattern” as the shape of level change with the time. To avoid such confusion, we changed the term “pattern” to “shape” as follows.

Line 286: the rise patterns -> the rise shapes
Line 330: **4.2 Variation in the shape of coseismic change patterns -> 4.2 Variation in the shape of coseismic changes**
Line 331: There are four types of pattern -> There are four types
Line 336: Representative patterns for each type -> Representative data for each type
Line 338: The typical ‘up-down’ pattern -> The typical ‘up-down’ shape
Line 346: The ‘up-up’ pattern type -> The ‘up-up’ type
Line 349: This pattern of change -> This temporal change
Line 351: The remaining two pattern types -> The remaining two types
Line 352: The level change pattern -> The level change
Line 356: In summary, the ‘up’ pattern types -> In summary, the ‘up’ types
Line 357: while the ‘down’ pattern types -> while the ‘down’ types
Line 430: the magnitude and pattern -> the magnitude and spatial pattern
Figure 8: Representative coseismic change patterns -> Representative coseismic change data

- *From my personal opinion, the geological impact of Togawa lava is the most interesting feature of this study and should be expanded in analysis and discussion.*

We appreciate this approval. As our above reply, we moved the sub-section “**Effect of Togawa lava**” to the new discussion section and added information on the porosity of Togawa lava. Also, we added description that supplements our interpretation to the end of this sub-section by red letters as follows.

[Original] A possible cause of this phenomenon is that impact of the slow load of the seismic force with a long wavelength on the lava may have brought out its elastic property.

[Revision] Manga and Wang (2007) suggested that sustained changes in well water levels in the far field must be caused by the interactions between the aquifer and seismic waves. P and S waves attenuate largely with increasing propagation distance. In the far field, only Rayleigh waves that involve changes in volumetric strain can cause water-level changes (Liu et al., 1989). Therefore, a possible cause of the above phenomenon is that the interactions between Rayleigh waves and the Togawa lava may have brought out elastic property of the lava. Another possible cause is that mechanical response of the Togawa lava to Rayleigh waves is different from the other elastic waves. More observations and testing on the hydraulic properties of the Togawa lave are indispensable to validate these hypotheses.

Liu, L.-B., Roeloffs, E., Zheng, X.-Y.: Seismically induced water level fluctuations in the Wali well, Beijing, China. J. Geophys. Res., 94, 9453–9462, 1989.

Manga, M., Wang, C.-Y.: Earthquake hydrology. In: Earthquake Seismology (Ed. Kanamori H), Vol. 4 of Treatise on Geophysics. Elsevier, Amsterdam, Ch. 4.10, 293–320, 2007.

Scientific issues and questions:

1) What is the exactly the underlying process? Is it a co-seismic change in hydraulic head, modified connectivity or permeability of the geological units? In the abstract, the importance of hydraulic head increase is mentioned. In the conceptual model, however, the impact of permeability change due to fissuring is also indicated. Is it a mix of both processes? In order to facilitate the discussion, the present day's understanding of seismo-hydrological processes can be shortly reviewed in the introduction/model section.

In accordance with this suggestion, we added short review on the recent understanding of seismo-hydrological processes at the beginning of the sub-section on a conceptual model for level change mechanism as follows.

[Addition] 5.3 **Conceptual model for level change mechanism**

As a result of the observations on changes in streamflow and groundwater levels, Montgomery and Manga (2003) summarized plausible mechanisms concerning hydrological responses to earthquakes. These changes have been attributed mainly to expulsion of fluids from the seismogenic zone, pore-pressure diffusion after coseismic elastic strain occurs in the upper crust, compression of shallow aquifers, increased permeability of surficial materials resulting from either shaking of near surface deposits or opening of bedrock fractures, and decreased permeability resulting from consolidation of surficial loose sediments. Other possible factors are coseismic liquefaction and ruptured subsurface reservoirs (Wang et al., 2004;

Manga and Wang, 2007). Of those, elastic strain, compression of aquifers, and enhanced permeability are most feasible for the present case, because liquefaction was not observed during the four earthquakes. This signifies that the surficial sediments in the study area are dense to a certain degree.

Elastic strain and compression can cause the rise of water level, while enhanced permeability can cause both the rise and fall depending on the condition of water pressure. If the pressure is small as a condition in unconfined, shallow aquifer, the increase may enhance downward flow and consequently, the water level falls. As one interpretation of the level and pressure changes shown in Figs. 10 and 11, a conceptual model for the mechanism of groundwater level changes resulting from close and distant earthquakes is shown in Fig. 13. In this model, we use the above three feasible factors and assume that the shallow and deep aquifers are partly connected by fractures, or the absence of aquicludes between the aquifers, as described by Parvin et al. (2011). Mt. Kinpo is used as an impermeable boundary. For close earthquakes, the deep aquifer is strongly compressed because of the large seismic force, which causes relatively large rises in groundwater level. Because of the propagation of the strong pressure toward the shallow aquifer, or the large seismic force at shallow depths, new fractures or fissures may be generated around the shallow aquifer. This is an important factor contributing to changes of permeability and groundwater level, as shown in Fig. 1. New fractures or fissures result in forming fracture-related anisotropic permeability such that only the vertical permeability of the groundwater system is enhanced, while the horizontal permeability remains nearly constant (Wang et al., 2004). This can release pore pressure and induce downward flow and consequently the levels of shallow groundwater fall, as seen for the KME and the FOE, and illustrated in Fig. 10.

On the other hand, for distant earthquakes, the seismic forces may be uniform over the depth range, leading to increases in compressive stress in both the shallow and deep aquifers. However, if the forces are not strong enough to generate fractures or fissures, the level changes will be small. As a result, rises in groundwater levels and increases in compressive stress would occur most frequently in the zones in which the stresses are concentrated in the shallow and deep aquifers. Alternatively, interactions between Rayleigh waves and those aquifers may cause small rises in level as described in the previous section.

Manga, M., Wang, C.-Y. : Earthquake Hydrology in Schubert, G. ed., Treatise on Geophysics, 1-11., 293-320, 2007.

Montgomery, D. R., Manga, M.: Streamflow and water well responses to earthquakes, *Science*, 300, 2047-2049, 2003.

Wang, C.-Y., Wang, C.-H., Manga, M.: Coseismic release of water from mountains: Evidence from the 1999 (Mw=7.5) Chi-Chi, Taiwan, earthquake, Geology, 32, 769-772, 2004.

2) What is the accuracy of the groundwater level measurements? By what means has the groundwater levels been measured? How are the uncertainties? Uncertainties are not quantified or even mentioned in this manuscript. Please be more critical about the measurements in terms of assessing the quality of the measurements (In fact, an increase of ~1 cm is hard to measure). Does water temperature data exist in order to support your interpretation?

We apologize that we did not describe the measurement system of groundwater level. There were two systems using float recording water gauge and hydrostatic head level gauge. Their accuracies are reported to be within 0.01 m. Therefore, we checked severely the 0.01 m level change described after, whether it was originated from noise or coseismic event, by investigating the waveform of level data. A continuous recording system of water temperature has not been installed, but abnormal rise of water temperature induced by earthquake has not been reported in our study area. In accordance with this comment, we added explanations on the measurement system and accuracy as follows.

Line 197 - 201

[Addition] A groundwater level monitoring system was established at the beginning of 2000 in the Kumamoto City area. This system measures levels on the hour, from 0:00 to 23:00, at the 54 groundwater well sites shown in Fig. 2. The levels were measured by two gauges of float recording water and hydrostatic head level. Their accuracies are reported to be within 0.01 m. Therefore, we checked severely the 0.01 m level change described after, whether it was originated from noise or coseismic event, by investigating the waveform of level data.

3) The Magnitude of the earthquakes is mentioned and seismic energy appears several times throughout the manuscript. The local seismic energy (density) can be estimated according to Wang and Manga (2010), Geofluids, or Wang (2007), SRL, which could be used to evaluate concurring mechanisms within the near- and far- field as different hydro-seismological mechanisms are related to threshold values of seismic energy density. The earthquake mechanism is not mentioned. Are all earthquakes comparable in terms of rupture mechanisms? Moreover, the ground shaking can be assessed by available ground velocity/ acceleration data (e.g., see http://earthquake.usgs.gov/) in order to compare the impact of each earthquake within the study area. Finally, the duration of the distinct earthquakes *should be considered since they may be crucial for some processes, e.g. undrained consolidation (probably up to liquefaction).*

We appreciate truly these valuable comments. For the former comment on the local seismic energy (density), we checked two references Wang (2007) and Wang and Manga (2010), as suggested, and calculated the local seismic energy density. The table below shows the calculation result. By compiling many groundwater-level data observed in the USA, Japan, and Taiwan, most sustained groundwater-level changes were revealed to be induced by the local seismic energy larger than 10^{-3} J m^{-3} (Wang and Manga, 2010). All our data are larger than this threshold. Therefore, the coseismic responses detected by this study are meaningful. As for the focal mechanism of the four earthquakes, the mechanisms were not the same as shown in the table. Although we must investigate the relationship between the spatial pattern of groundwater-level changes and the focal mechanism in detail as our next work, we didn't find any significant relation between them. As shown in Figs. 10 and 11, the spatial patterns are similar common to the four earthquakes. In accordance with the comment, we added descriptions on the seismic energy and focal mechanism to the sub-section 3.2 and Table 1 as follows.

Earthquake name	Seismic energy (J m^{-3})	Focal mechanism
Kumamoto earthquake (KME)	7.9×10^{-2}	Right-lateral slip type with NW-SE principal axis of tension
Geiyo earthquake (GYE)	2.0×10^{-2}	Normal-fault type with N-S principal axis of tension
Fukuoka west offshore Earthquake (FOE)	5.0×10^{-1}	Left-lateral slip type with ENE-WSW principal axis of compression
Sichuan earthquake (SCE)	1.2×10^{-3}	Reverse-fault type with WNW-ESE principal axis of compression

[Addition]…distance range between the hypocenter and groundwater wells, and focal mechanism, are summarized in Table 1. The focal mechanism of the four earthquakes is different each, but this did not affect the spatial characteristics of coseismic level changes conspicuously.

Wang (2007) and Wang and Manga (2010) proposed a concept of seismic energy density to relate the M_w and the distance d (km) with the various hydrologic responses by a parameter e. The e can be estimated from the following density empirical relation.

$$\log d = 0.48M_w - 0.33\log e - 1.4 \quad (10)$$

where *e* is in J m^{-3}. The *e* values of the four earthquakes are shown in Table 1. By compiling many groundwater level data observed in the USA, Japan, and Taiwan, most sustained groundwater-level changes were revealed to be induced by the *e* greater than 10^{-3} J m^{-3} (Wang and Manga, 2010). Although the *e* of SCE is small, the four *e* values exceed this threshold. Therefore, the coseismic responses to all earthquakes can be appeared in the study area.

Wang, C.-Y.: Liquefaction beyond the near field, Seismological Research Letters, 78, 512–517, 2007.

Wang, C.-Y., Manga, M.: Hydrologic responses to earthquakes and a general metric, Geofluids, 10, 206–216, 2010.

The latter comment on the ground shaking and the duration must be appreciated, but we don’t have enough data on the local three earthquakes, KME, GYE, and FOE. The prime objective of this study is to characterize the spatial patterns of water-level changes. We keep this comment in mind for our next step to clarify more detailed mechanism of water-level change in our study area.

4) Several times throughout the manuscript, “large earthquake” is mentioned. However, how are they defined in this case?

The magnitudes of the four earthquakes studied ranged from 4.8 to 8.0. Since the definition of “large” is ambiguous as this comment, we deleted this term from the related two portions as follows.

Line 9: four large earthquakes that occurred… -> four earthquakes that occurred
Line 225: four large earthquakes that had recognizable effects on… -> four earthquakes that had recognizable effects on…

5) The applied interpolation technique seems to be suitable for such a kind of data set. However, the geological setting differs substantially across the study site and I am wondering if spline-based interpolation does account for that? Moreover, please specify how many samples are included into the spatial analysis. Are all wells (n=56) included into this spatial analysis? What is the uncertainty of the spline-interpolation?

Spline does not account for the difference of geological setting over the study area, because the principle of spline is to produce a smooth surface. If our water level data are influenced generally by the geological setting, the data must have a spatial correlation structure and we can draw a clear variogram curve that increases largely with increasing lag distance. This is because our study area can be divided roughly into two regions, the regions covered by pyroclastic flow deposits and the Togawa lava. Such extent of the same geological unit must yield a clear spatial correlation of the water-level changes. Although our data set is not enough to conclude the presence or absence of the geological control on the spatial correlation, and the general trends in the water-level changes are different between the two regions, we think that the geological effect is too weak to be applicable to kriging-based interpolation.

As for the comment on the number of data used for the interpolation, we used all data at 54 wells by assigning the value of zero to no response well data. It is very difficult to quantify the uncertainty involved in the spline interpolation, because we can’t know true values at unsampled points. However, we believe that the spline interpolation can minimize the uncertainty based on its principle that a spline surface minimizes the overall surface curvature and passes through the data points. This surface becomes smooth essentially by preventing oscillation, but this smoothness can minimize the uncertainty when a spatial correlation is absent in the data set. Considering the comment, we added the number of data used and the uncertainty to the sub-section “**Spline for point-data interpolation**” as follows.

[Addition] The spatial correlations between Δh and Δp were unclear in our data; therefore we used a spline for their interpolation. All data at the 54 wells were used in the interpolation by assigning a value zero to the site of no response well.

A spline estimates values between sample points using a mathematical function that minimizes the overall surface curvature and passes through the data points. This smoothness constraint may minimize the uncertainty involved in the spline interpolation by preventing unfounded oscillation of the surface when a spatial correlation is absent in the data set.

6) The andesite seems to differ from the alluvial deposits mostly in terms of porosity. Can the porosity of both geological units be quantified?

It is very difficult to quantify the porosity of alluvial deposits because their facies and grain sizes are variable from clay-rich sediment to gravel-rich sediments. Therefore, the porosity is also variable largely. On the other hand, the porosity in the most porous part of Togawa lava is known to be around 40% (Mizuta et al., 1990). We added this porosity and the reference as follows.

[Addition] The upper and lower parts of the lava are porous with around 40 % porosity at most, as shown in Fig. 3, while the middle is dense and contains fresh andesite with sparse joints.

Mizuta, T., Obata, M., Egami, K.: Morphology and distribution of vesicles in the Togawa andesitic lava, Bulletin of the Volcanological Society of Japan, 35, 2, 249-262, 1990 (in Japanese with English abst.).

7) Short-term dilatation is mentioned in the introduction section. However, dilatation/dilatancy excludes increased hydraulic head as a potential mechanism since dilatation/dilatancy increases the porosity by secondary dilatation cracks/fissures which in turn decrease the hydraulic head.

We appreciate this thoughtful suggestion. But in the revised manuscript, we deleted the sub-section “2.1 Two types of coseismic change” because this section does not have essential relationship with the main content of this study.

8) Are there any significant tectonic faults crossing the area? And if so: Is there a spatial relation between responses and the tectonic setting?

The Futagawa fault is running in the a few km south of the southern boundary of the study area and approximately along the boundary. This fault trends along NE and SW with about 24 km in length, and is mostly reverse with slight right lateral displacements. The displacement velocity averaged over the late Quaternary is estimated as 0.1-1 mm/year. The Futagawa fault does not cross the study area. We checked the correlation of the groundwater level change due to earthquake with the distance between the fault and observation well, and found no correlation between them.

Considering this comment, we added explanation on the active fault to the end of section 3.1 as follows.

[Addition] There is an active fault (Futagawa fault) running in the a few km south of the southern boundary of the study area. This fault trends along NE-SW with 24 km in length. Since the well sites are distant from the fault, no substantial effect of the fault on the groundwater level changes was found.

9) The more detailed analyzed wells (2 each geological unit/ earthquake) are all located in the recharge area of the flats, right? Does data from the discharge area of the foothills exist?

Almost yes, because only the wells 31a and 32b are located near the foot of terrace. The data at the wells 37a, 38b, 45b, 39a, 40b, and 45b are located in the discharge area. These sites are covered mainly by paddy fields and overlain thickly by the post-glacial clay (Ariake clay). The groundwater level changes at these wells were not sensitive to the earthquakes. This may be caused by that the groundwater tables at these sites are located in the clay layer.

10) The conceptual model postulates a strong compressibility of groundwater. However, compressibility of water is very small, isn't it?

We don't assume a strong compressibility of groundwater. Our model is based on the mechanical condition of aquifers, i.e., compression of shallow and deep aquifers and formation of new fractures or fissures in aquifers by the large seismic force. But the description "the deep groundwater is strongly compressed" causes misunderstanding to be a strong compressibility of groundwater. We revised the description as follows.

[Original] For close earthquakes, the deep groundwater is strongly compressed
[Revision] For close earthquakes, the deep aquifer is strongly compressed

Technical corrections/ suggestions

• What is the undrained Poisson's ratio (page 5322; line: 4)? What describes the Kronecker delta (page: 5322; line: 5) and the Skempton's coefficient (page 5322; line: 18)? A short explanation would benefit to the understanding of the study.

We appreciate this careful check. In accordance with this comment, we added short explanations on the undrained Poisson's ratio, the Kronecker delta, and the Skempton's coefficient to the section "2.2 Poroelastic theory for pressure change" by red letters as follows.

....The stress–strain relation for a porous elastic material is

$$\Delta\varepsilon_{ij} = \frac{1}{2G_u}\left[\Delta\sigma_{ij} - \frac{\gamma_u}{1+\gamma_u}\Delta\sigma_{kk}\delta_{ij}\right], \quad (1)$$

where $\Delta\varepsilon_{ij}$ is the difference in the strain tensor, G_u is the shear modulus (Pa), σ_{ij} and σ_{kk} are components of the stress tensor (Pa), γ_u is the Poisson's ratio, and δ_{ij} is the Kronecker delta (δ_{ij} = 1 at i = j or 0 at $i \neq j$). The G_u and γ_u are the values under an undrained condition, because the change of stress in the crust by an earthquake in a relatively short time can be induced generally under this condition (Roeloffs, 1996; Wang, 2000). In this study we used typical values for rocks, 2.3 × 10^4 MPa for G_u (Jaeger, 1969), and 0.25 for γ_u (Detournay and Cheng, 1993), and simplified the stress tensor as $\sigma_{ij} = \sigma_{kk}$, which allowed consideration of only one component, as a scalar. This simplification was adopted because it was difficult to correctly define the anisotropic behavior of the stress-strain field around an arbitrary study area.

The change in volume strain is accompanied by a change in the volume of solid material and a proportional undrained change in fluid pressures. This can be described by the next constitutive relationship, developed by Rice and Cleary (1976) based on the formulations of Biot (1941)

$$\Delta P = C \Delta \varepsilon_{ii}, \qquad (2)$$

where P is fluid pressure (Pa) and C is a proportionality coefficient. The C has a relationship with the G_u and γ_u

$$C = -BG_u \left[\frac{2(1+\gamma_u)}{3(1-2\gamma_u)} \right] = \frac{B}{\alpha}, \qquad (3)$$

where B is Skempton's coefficient with a value between 0 and 1, which is a ratio of the induced pore pressure to the change of stress loading under an undrained condition (Skempton, 1954; Wang, 2000), and α is bulk compressibility (Pa^{-1}). The variable B is related to the porosity of solid grains and saturated rock, and to the compressibilities of the pore fluid, and approaches 1 for unconsolidated sediments.

- *Poroelastic theory should be explained more clearly if mentioned, probably by adding 1-2 sentences.*

In accordance with this comment, we added the following two sentences on the Poroelastic theory to Line 107-111 in the text.

[Addition] Poroelasticity is a continuum theory for the analysis of a porous media consisting of an elastic matrix and interconnected fluid-saturated pores. Since the pores are fluid-filled, the presence of the fluid acts as a stiffener of the material and further, results in the flow of the pore fluid (diffusion) between the regions of higher and lower pore pressure (e.g., Cederbaum et al., 2000). According to the poroelastic theory (Biot, 1941; Roeloffs, 1996), stress, strain, pore pressure, and water content are related to each other.

Cederbaum, G., Li, L.-P., Schulgassor, K.: Poroelastic Structures, Elsevier, 2000.

- *Table 1: longitude of SCE earthquake is incorrect. This table could be expanded with additional earthquake features (e.g., type of earthquake mechanism, duration, surface velocity, ...).*

From the web-site of USGS (http://earthquake.usgs.gov/earthquakes/recenteqsww/Quakes/us2008ryan.php), the longitude of SCE is 103.364°E. This location is converted to 103°21’50”. In accordance with the comment, we corrected the longitude to it. The suggestion to add additional earthquake features must be appreciated, but this study focused on the location and magnitude of earthquake. This is because the distance and magnitude must be predominant factors on the groundwater level change. As our reply to the above comment 3), we added two features on the focal mechanism and the seismic energy density. Other features are not so accurate for all the earthquakes. Consequently, we wish to limit the earthquake features to the accurate ones shown in Table 1.

- *In Figure 2, 5, 9, 10 and 11appears a red line crossing the area. What is that red line exactly?*

As indicated by the letter “*R. Shirakawa*” in these figures, the red lines in Figure 2, 5, 9, 10 and 11 show the path of the Shirakawa River.

- *Figure 13: quite speculative and the model should be better explained*

As our reply to the first comment on **scientific issues and questions**, we added explanation to the model and revised the inadequacies.

- *Page 5331; Lines 23-25: This is an interesting finding and should be included into the abstract.*

In accordance with this comment, we added the following description pointed out to the abstract: “In addition, the importance of local geology was indentified, because levels in the area of Togawa lava (a porous andesite) tended to change more in magnitude, and more quickly, with a shorter recovery time, than levels measured in the area outside the lava.”

- *Page 5332; Line 10: where is mentioned twice in this line. The second should be changed to “were”*

This was our careless mistake. We changed the second “where” to “were” in the revised manuscript.

- *Page 5334: line 8: R^2 is here 0.63 but 0.62 in figure 12. Moreover, I was wondering if this relation is really resilient.*

The value in Fig. 12 was our mistake. We corrected it to $R^2 = 0.63$. For the latter comment, the linear correlation coefficient (R: $0 \leq |R| \leq 1$) is calculated as $R = 0.79$ from $R^2 = 0.63$. This value does not show a strong correlation, but can be used as a proof for the existence of a positive correlation in general.