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,

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Replies to Reviewer’s comments (2)

We wish to reply to the valuable and constructive comments raised by the reviewer 2 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.

• On the other hand, their claimed correlation between water level change and the Sichuan earthquake (SCE), shown in Figure 7, is not at all convincing. Not only are the signals extremely noisy, but also changes of similar magnitude occurred in the water-level records long before the earthquake.

It is a fact that the groundwater levels in our study area were affected by SCE as shown in Fig. 9 although the changes were smaller than those induced by near earthquakes. The affects of SCE on the groundwater levels and the temperatures of hot springs were reported in several areas in Japan such as in the Tottori, Okayama, and Shimane areas, west Japan (http://unit.aist.go.jp/actfault-eq/tectonohydr/topics/yochiren/2008/178/yo0808718tottori.pdf) and the Tono region in Gifu, central Japan (Asai, Y. et al, Geophysical Bulletin of Hokkaido University, No. 72, March 2009, pp. 247-256: http://hdl.handle.net/2115/38157). The distances between the epicenter and these areas are longer than the distance of our study area.

For the comment “*Not only are the signals extremely noisy, but also changes of similar magnitude occurred in the water-level records long before the earthquake*”, we checked the meteorological data before the coseismic analysis of the four earthquakes, and confirmed that there was no rainfall and marked change in atmospheric pressure around the occurrence time of each earthquake. No pumping effect was observed, and earth tide loadings did not change significantly during the study periods. Consequently, our water-level changes were induced by the earthquakes almost certainly.
Although the changes of almost similar magnitude may have been occurred in the water-level records by events irrelevant to earthquakes, the largest level changes were observed in the wells 18A and 19C during the occurrence day of SCE.

• More important problems occur in the interpretation of observation. Earthquake hydrology has advanced rapidly in the past decade. However, the authors appear unaware of some of the advances. Much of the cited material is out of date; even the cited review by Manga and Wang (2007) has been superseded by more recent reviews. The exception Parvin et al. (2011)

was their own paper.

In accordance with this comment, we added the following recent papers and included the recent results in Introduction. We revised Introduction largely to describe our purpose, different points from the previous studies, and contribution of this study to earthquake hydrology more clearly. We showed the revised Introduction below.

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

Manga, M., Beresnev, I., Brodsky, E. E., Elkhoury, J. E., Elsworth, D., Ingebritsen, S. E., Mays, D. C., Wang, C.-Y.: Changes in permeability caused by transient stresses: Field observations, experiments, and mechanisms, Rev. Geophys., 50, RG2004, 2012.

• Another example is the authors' assumption of poroelasticity as the mechanism in their interpretation of the observed water level changes. It has been pointed out time and again that the magnitude of static stress change due to distant earthquake, such as the Sichuan earthquake (SCE), is simply too small to cause any perceptible water level changes in the studied area.

This comment and the first comments are related and connected. Please see our reply to the first comment.

• The authors also made some misleading statements: At the beginning of Introduction (line 25-26), for example, they misquoted Roeloffs (1988) in stating that "groundwater fluctuations : : : can contribute a pre-warning system for earthquake disasters." Roeloffs (1988) was more careful not to make such misleading statement.

Considering this comment and the above comments, we corrected our misleading and revised Introduction largely as follows.

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.

- *Also, at the bottom of p. 5333, the authors stated: "decreases in compressive stress were observed :increases of compressive stress were observed" In fact, only water-level changes were observed. The supposed change in compressive stress was calculated based upon the unproven hypothesis that poroelasticity was the causing mechanism*

Yes, we observed the water-level changes only and the changes of stresses were just calculation based on the poroelasticity. However, our study area is composed chiefly of unconsolidated deposits and porous lave (the Togawa lava), and does not contain distinct fault like an active fault. In this case, the poroelasticity has been used widely as a reasonable theory to explain groundwater-level changes in alluvial plains over the world as our reply to the next comment. This is a reason why we relied on the poroelasticity for our study case.

- *Finally, two minor comments:*

1) The authors spent three full pages (p.5321- 5323) discussing poroelasticity, but did not calculate the elastic stress or strain in the studied area for any of the earthquakes. It begs the question why is this repetition of details but omission of the essential?

The sub-section "2.2 Poroelastic theory for pressure change" is essential to this paper, because we used all equations (equations 1- 6) to calculate pore pressure (equation 4) using the stress that has a relation to strain in equation 1. The strain can be calculated from equations 2 and 3. The pressure change can be related to the hydraulic-head change (i.e., groundwater-level change) by equations 5 and 6. Therefore, we think that this sub-section cannot be omitted and should be retained.
In connection with this comment, we added explanation on a reason to adopt the poroelastic theory as follows.

[Addition] We assumed that the groundwater flow system in the study area behaved as a poroelastic medium, and that the matrix deformation caused by the release of elastic strain energy during an earthquake induced a proportional undrained change in the water level. This assumption relies on a fact that the spatial distribution of the groundwater level change in an alluvial fan during the Chi-Chi earthquake was accounted for partly by a poroelastic model (Lee et al., 2002; Chia et al., 2008) except for the liquefied zones, probably consisting of loose sands. That geological condition is similar to our study area in that both are covered widely by unconsolidated sediments. Besides, no liquefaction due to the studied earthquakes was reported.

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(17), 1824, 2002.

Chia….

2) The model presented in section 4.6 is totally speculative without justification. As such, statements such as "For close earthquakes, the deep groundwater is strongly compressed" become meaningless and can only confuse the readers.

As our reply to the scientific issues and questions raised by the reviewer 1, we changed "the deep groundwater is strongly compressed" to "the deep aquifer is strongly compressed". In addition, we revised the portion pointed out as follows, and added explanation to supplement the model in sub-section 5.3 (original sub-section 4.6).

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 generation of dilatational volumetric strain that can release pore pressure, 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.