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Hydrology and Earth System Sciences Discussions

Interactive comment on "Anomalous frequency characteristics of groundwater levels before major earthquakes in Taiwan" *by* C.-H. Chen et al.

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Reply to Anonymous Referee #1

(1) Both short (3 years) and long (13 years) precipitation records are presented in Fig. 2 and Fig. 5a, respectively. The bottom panel in Fig. 2 shows the annual precipitation of Taiwan covering the year before and after the Chi-Chi earthquake (i.e. from 1988 to 2000). The annual average precipitation in Taiwan is approximately 2500mm (page 6980, line 23) with large fluctuation. In general, the annual precipitation of 1998 is close to the long-term mean. The year 1999 and 2000 are about 20% and 40% lower than that of long-term mean. However, unusual decrease of groundwater level is only observed in 1999 for monitoring wells (for example, HT, TW and HR that are located

far away from recharge area) of the study area; no similar phenomena can be found in 2000 that is the year with less precipitation. If the unusual drop of groundwater level is caused by the precipitation decrease, then the feature should be prominent in 2000 rather than in 1999. For monitoring wells that are located near the recharging area (for example, TH and HH), the unusual decrease and annual water level variation yield in-phase changes (Fig. 5a). Even in this situation, the amplitude of annual water level changes is larger in 1999 than that of 2000. To mitigate the influence of annual variation from unusual decrease feature of groundwater level (such as the cases in TH and HH), the frequency dependent filter is adopted in this study. Only signals that have been removed from factors of air-pressure, tidal change, artificial noise and precipitation input in the unusual decrease (2 – 4 meter) records are used for earthquake-related analyses. Our observation and assumption are rigorously tested through a 13-year record of monitoring wells. Analytical results clearly show that observed anomalous phenomena (high amplitude ratio) are highly related with major earthquakes in Taiwan (events of R, C and M in Fig. 5b).

(2) The change of aquifer permeability after a major earthquake is an important topic. The major point is: Could the former earthquake affect the latter one in terms of permeability change? The answer depends on many factors, such as the magnitude of earthquake, time interval between two earthquakes, hydrogeological setting etc. In our case, the event R (1998/7/17, M=6.2) had no effect on the permeability of Choshuichi Alluvial Fan when event C (Chi-Chi earthquake) occurred one year later. The Chi-Chi earthquake (1999/9/20, M=7.6) did carry significant disturbance of groundwater level due to permeability change for the following Chia-Yi earthquake (1999/10/22, M=6.4; an aftershock of Chi-Chi), thus we eliminate the Chia-Yi earthquake from our analyses. In addition, the Hilbert-Huang Transform (HHT) has the advantage to analyze nonlinear and non-stationary features and remove the periodic and cyclic signals (such as seasonal variation) in the time-series record (please see references Chen et al., 2010b and Chen et al., 2011). This is the salient part of HHT relative to traditional methods. Fig. 5b shows that enhanced amplitude ratios did stand out before earthquake

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events of R, C and M after data filtering through HHT (i.e. 3 peaks relate with 3 major earthquakes). The authors further to respond the reviewer's comment "In fact the biggest changes occur at 0.06 1/day, 600 days before the earthquake" and computed the amplitude ratio at the frequency band of 0.05-0.07 1/day in the period without any anomalous changes in time domain. The amplitude ratio at the frequency band of 0.05-0.07 1/day in the records of HH, HT and TH stations are shown as bash line in Fig. A (below). It is clear that the amplitude ratio derived from 0.05-0.07 1/day often stays at the low stage (< 2%) during the 13-year period, except for a few days before the Chi-Chi earthquake. Enhanced amplitude at the 0.05-0.07 1/day, which suggested by the reviewer, can only be closely related with the Chi-Chi earthquake but not with Rei-Li (R) and Ming-Jain (M) events. Thus, the enhanced amplitude at the frequency band suggested by the reviewer would be dependent on the very strong earthquake magnitude (M > 7). Only one Chi-Chi earthquake falls into this range during the 13-year period. The authors determine the frequency band at 0.02-0.04 1/day in period based on the unusual decrease phase shown in Fig. 4. The determined period is further applied to the 13-year groundwater data in our study area as shown in Fig. 5. We assume that the enhanced amplitude derived from the record of unusual decrease is related with the subsequent earthquake and test the assumption to the other two earthquakes during the 13-year data record. The analytical results suggest that the enhanced amplitude at the frequency band of 0.02-0.04 1/day in period can be repeatedly observed in all 3 major earthquakes in Taiwan. Therefore, this assumption from the observation during the Chi-Chi earthquake can be checked with forthcoming strong earthquake in addition of the Rei-Li and Mein-Jain earthquakes in this study.

Why was hourly data down-sampled to a daily record?

This study shows that the consistent results can be derived from the daily record, thus substantially reduce the computing time and effort. The analytical method and results could be widely applied to and tested in different places and/or countries by using common groundwater monitoring systems without a high frequency sampling rate. If these

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results can be repeatedly observed in different countries and other places, source of anomalous changes would be directly related with seismogenic period. Otherwise, these phenomena would be related to subsurface structure prior to the earthquake due to local effect.

Figure Caption

Fig. A. Variations and the amplitude ratio (derived from the frequency band of 0.05-0.07 1/day in period) of groundwater levels at the HH, HT and TH stations from 1 August 1997 to 31 December 2009. Panel (a) presents the temporal variations. The shadow lines show variations of the 1-yr running average. Panel (b) reveals the amplitude ratio derived from the frequency band of 0.05-0.07 1/day in period. Vertical dash lines denote occurrence time of the Rei-Li (R), Chi-Chi (C), Ming-jian (M) earthquakes, respectively.

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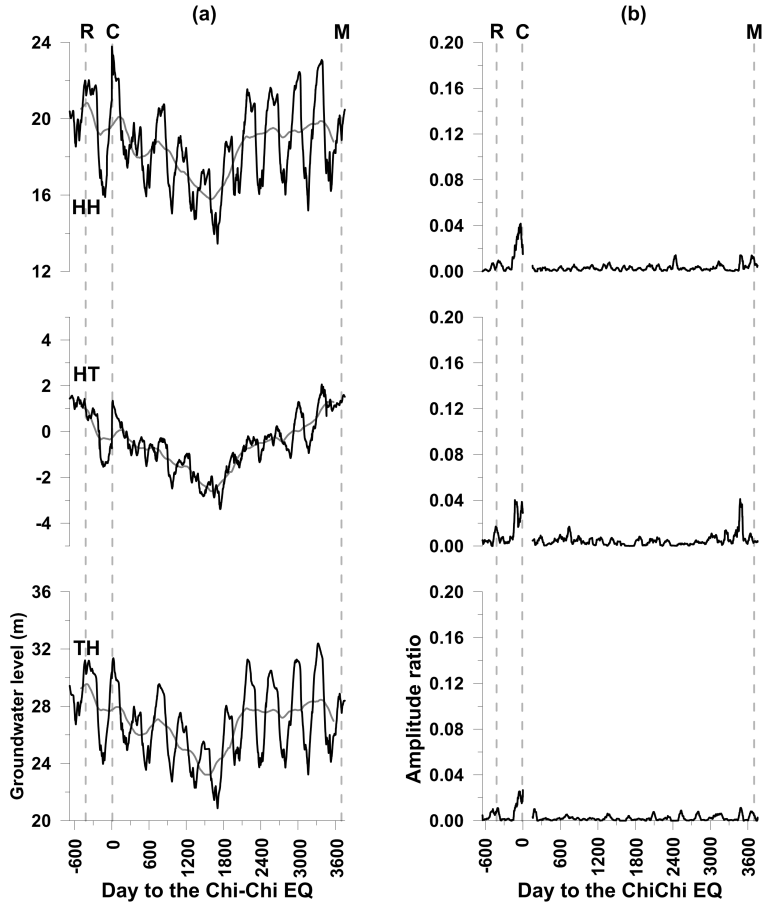

Fig. 1. Fig. A. Variations and the amplitude ratio (derived from the frequency band of 0.05-0.07 1/day in period) of groundwater levels at the HH, HT and TH stations from 1 August 1997 to 31 December 2009.

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Interactive Comment