Plain-scale sustained changes in well water levels following a large earthquake: possible evidence of permeability decrease in a shallow groundwater system

Xin Liao[1, 2, *], Guangcai Wang[1], and Zheming Shi[1]
1 China University of Geosciences, Beijing, China
2 Institute of Disaster Prevention, Beijing, China
* Corresponding authors: liaoxin19851224@126.com.

Key points:

- Plain-scale sustained changes occurred in well water levels in the Canterbury Plain after the Darfield earthquake.
- These sustained changes indicate that there should be plain-scale permeability decreases in the shallow groundwater system.
- The permeability decreases could be attributed to the consolidation of sediment in the Canterbury Plain.

Abstract: Observation of earthquake-induced changes in well water levels provides an opportunity to study the effects of seismic activity on the groundwater system. In this study, we used data from a plain-scale well network in the alluvial Canterbury Plain of New Zealand's South Island to document sustained and complex changes in well water levels, following the 2010 Darfield earthquake. We interpret that the sustained increases in well water levels in the midstream area, as well as sustained decreases in the downstream area, resulted from decreases in plain-scale permeability. These decreases in permeability were caused by the consolidation of the liquefied sediments following the earthquake. These results may provide a better understanding of the effects of large earthquakes on groundwater systems and resources, especially in liquefaction areas.

Keywords: earthquake; well water levels; permeability decrease; liquefaction; consolidation; New Zealand

Plain Language Summary

The Mw 7.1 Darfield earthquake that occurred in the eastern part of New Zealand's South Island on September 4th, 2010. It generated widespread hydrological responses in the Canterbury Plain, such as changes in well water levels. Although many studies have focused on coseismic hydrological responses to earthquakes, few have studied the effects of large earthquake on the sustained change in groundwater systems. In this study, we analyze data from a plain-scale well network, and propose a new model to explain the sustained changes observed in well water levels after the earthquake. In this model, the decrease in permeability of the shallow groundwater system was induced by seismic sediment consolidation in the Canterbury Plain. This in turn resulted in sustained changes in the hydraulic gradient of the shallow groundwater system, which increased groundwater resources in midstream areas but showed a decrease in downstream areas.

1. Introduction

The change in groundwater level, a widespread hydrogeological phenomenon that occurs during and after earthquakes, is of interest because it allows for the study of the potential effects of earthquakes on hydrological systems and groundwater resources. Several research studies show that earthquakes, especially large ones, can cause changes in well water levels by changing the pore pressure and hydrogeologic parameters of the groundwater system through static stress changes and seismic waves (dynamic stress) during the earthquakes (e.g., Brodsky et al., 2003; Cox et al., 2012; Gulley et al., 2013; Roeloffs et al., 1998; Shi et al., 2018; Shi & Wang, 2017; Wang & Manga, 2015). Coseismic changes in the well water level have been studied extensively by many hydrogeologists and geophysicists since the 1960s. Several mechanisms such as static strain (Ge and Stover, 2000; Jonsson et al., 2003; Roeloffs, 1996; Wakita, 1975), consolidation (Cox et al., 2012; Wang et al., 2001; Wang and Chia, 2008), new additional recharge (Wang et al., 2004; 2015), and permeability increase (Brodsky et al., 2003; Roeloffs et al., 1998) were proposed to explain this hydrological phenomenon. However, there are currently few research studies on the sustained changes in well water levels after earthquakes.

The Greendale Fault in New Zealand has produced a series of earthquakes from 2010 through the present. This includes the Mw 7.1 Darfield earthquake (main shock) on September 4, 2010, which affected well water levels in the Canterbury Plain (Cox et al., 2012). A detailed analysis of the coseismic changes in well water levels in the Canterbury Plain was performed by Cox et al. (2012). They showed that the groundwater levels increased coseismically via the consolidation of unconsolidated sediments during the earthquake. In this study, we revisited the Darfield earthquake and focused on the sustained changes in well water level following the earthquake. An analysis of summer irrigation on the shallow groundwater system in the Canterbury Plain showed that it had no effect on groundwater levels. This event allows for the investigation of permeability changes in the shallow groundwater systems, as well as their effects on well water levels following earthquake-induced consolidation and liquefaction of sediments in the Canterbury Plains.

2. Observation

The Canterbury Plain includes a large (~2,000 km^2) alluvial fan extending from the eastern margin of the Southern Alps to the South Pacific Ocean (Fig. 1a). This alluvial plain is composed of Quaternary glacial outwash from the Southern Alps; it overlies late Cretaceous-Tertiary sediments and a Permian-Jurassic Torlesse greywacke basement (Cox et al., 2012; Rutter et al., 2016). The groundwater system in this region consists of thick (300–600 m), unconfined or semiconfined gravel aquifers in the proximal area, as well as confined aquifers of gravel beds interlayered with estuarine and shallow marine beds near the coast (Fig. 1b). Groundwater in the unconfined and semiconfined aquifers flows southeastward from the foothills toward the coast. In the confined aquifers, groundwater flows upward and is discharged through springs along the coast and offshore, as a result of the vertical hydraulic gradient (Cox et al., 2012).

A large-scale network of hydrological monitoring wells was built for monitoring the groundwater resources, and continuously monitored throughout the plain by the Canterbury Regional Council of New Zealand (Environment Canterbury) (Fig. 1a). We obtained water level data, collected from 2009 to 2012, by pressure transducers for 112 wells from the Environment Canterbury website (https://ecan.govt.nz/). Data used in this study were obtained from wells monitored at 15-min intervals at depths ranging from 5 to 405 m. All data were corrected for barometric pressure such that the data reflected the water pressure, and manual measurements were taken in the field and adjusted where required to remove instrument errors.

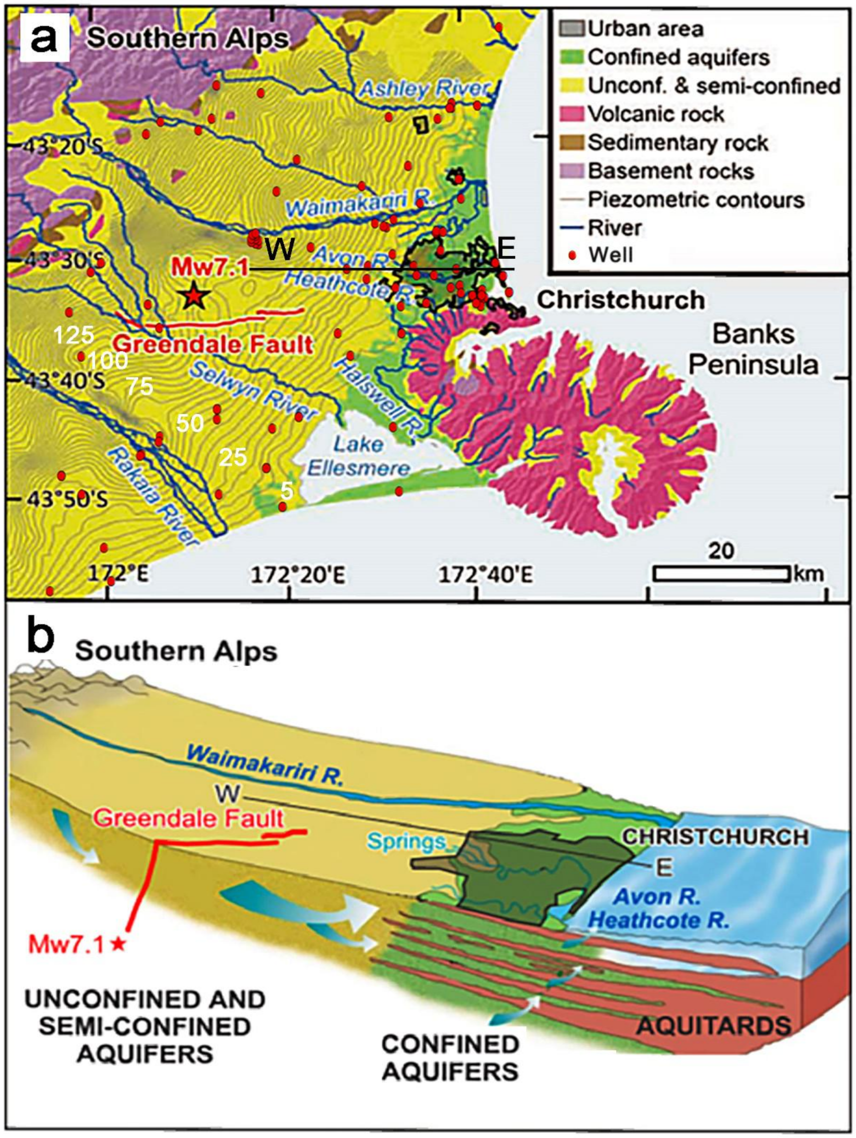

Fig. 1. Hydrogeology of the study area (modified from Cox et al., 2012 & Rutter et al., 2016). (a) Distribution of observational wells in the Canterbury Plain. Piezometric contours indicate groundwater flow from the foothills to the coast. The shallow groundwater system in the alluvial plain is divided into the following areas: downstream

(piezometric head < 25 m), midstream (25 m < piezometric head < 125 m), and upstream (piezometric head > 125 m), according to hydrogeological conditions. (b) Simplified cross-section along line W-E (Fig. 1a). Blue arrows indicate the direction of groundwater flow in the shallow groundwater system.

3. Results

We used three-day data to plot **Fig. 2** as the water levels in these wells returned to new ‘balanced’ levels after several days. Additionally, this makes it easier to indicate the changes caused by the Darfield earthquake in a short-term time sequence. Changes in water levels in these observational wells, including coseismic change, post-seismic change, and sustained change, were quantified based on the following definitions: coseismic change is a step-like change in water levels during the earthquake; post-seismic change is the change in water levels from the time of the earthquake to when water levels reach their new post-seismic levels; and finally, a sustained change is the total change in water levels caused by the earthquake. The sustained change is the sum of the coseismic change and the post-seismic change. Additionally, if these changes were smaller than the amplitude of the tidal response, the wells were recorded as “no response,” whereas if there was no data or the data was considered anomalous during and after the earthquake, the wells were recorded as “no data.”

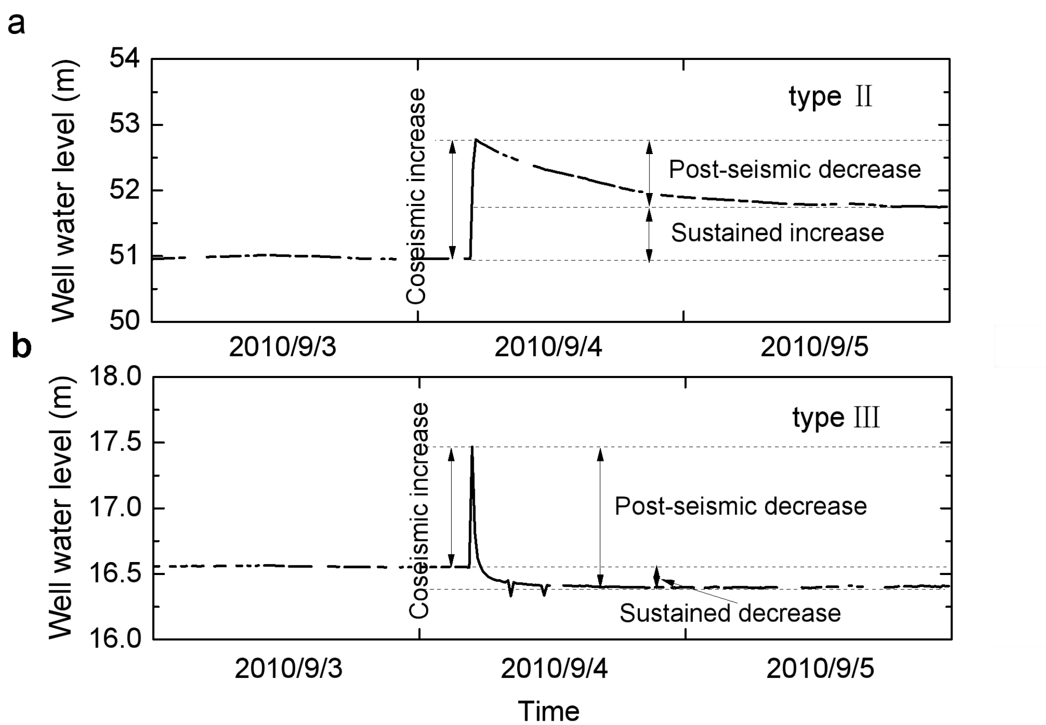

Fig. 2. Primary changes in water levels in two observation wells induced by the Darfield earthquake. The “coseismic step-like” increases in well water levels are followed by “post-seismic” decreases, as well as (a) a sustained higher water level and (b) sustained lower water level, which represent the typic types (types II and III, respectively) of changes shown in **Fig. 3**.

The well water levels in the Canterbury Plain changed during and after the Darfield earthquake. The water levels in 94 (not including the well in which the record of water level was missing during the earthquake) of the 112 studied wells increased abruptly during the earthquake, followed by a gradual decrease (Fig. 2). Most wells recovered to a level either above or below the pre-earthquake level after 2-3 days, indicating sustained changes in well water levels (Fig. 3). Sustained increases (type II) were more common in the central region of the plain, where well water levels (piezometric head) before the earthquake were > 25 m. Sustained decreases (type III) were common near the coast, where well water levels (piezometric head) before the earthquake were < 25 m.

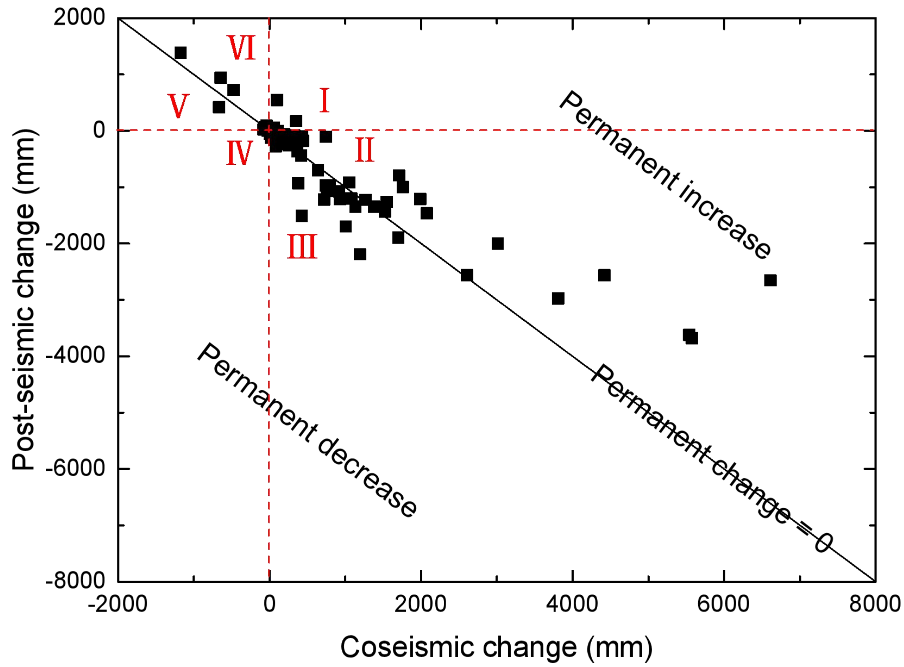

Fig. 3. Change in well water levels in the Canterbury Plain related to the 2010 Darfield earthquake**.** There are six typic patterns of sustained change in water levels with respect to coseismic, post-seismic, and sustained change.

Well water levels in groundwater systems usually become higher with increased proximity to upstream areas. Therefore, the groundwater level data can be used to determine the part of whole groundwater system in which the observed well is present, and the change in well water level at different parts can be conveniently analyzed through the correlation between the change in well water level and well water level. As shown in Fig. 4, The maximum value of sustained increase in the midstream area was approximately 4 m, and the minimum value of sustained decrease in the downstream area was approximately -2 m. This indicates a sustained increase in the hydraulic gradient by as much as 5% between the midstream and the downstream areas of the shallow groundwater system.

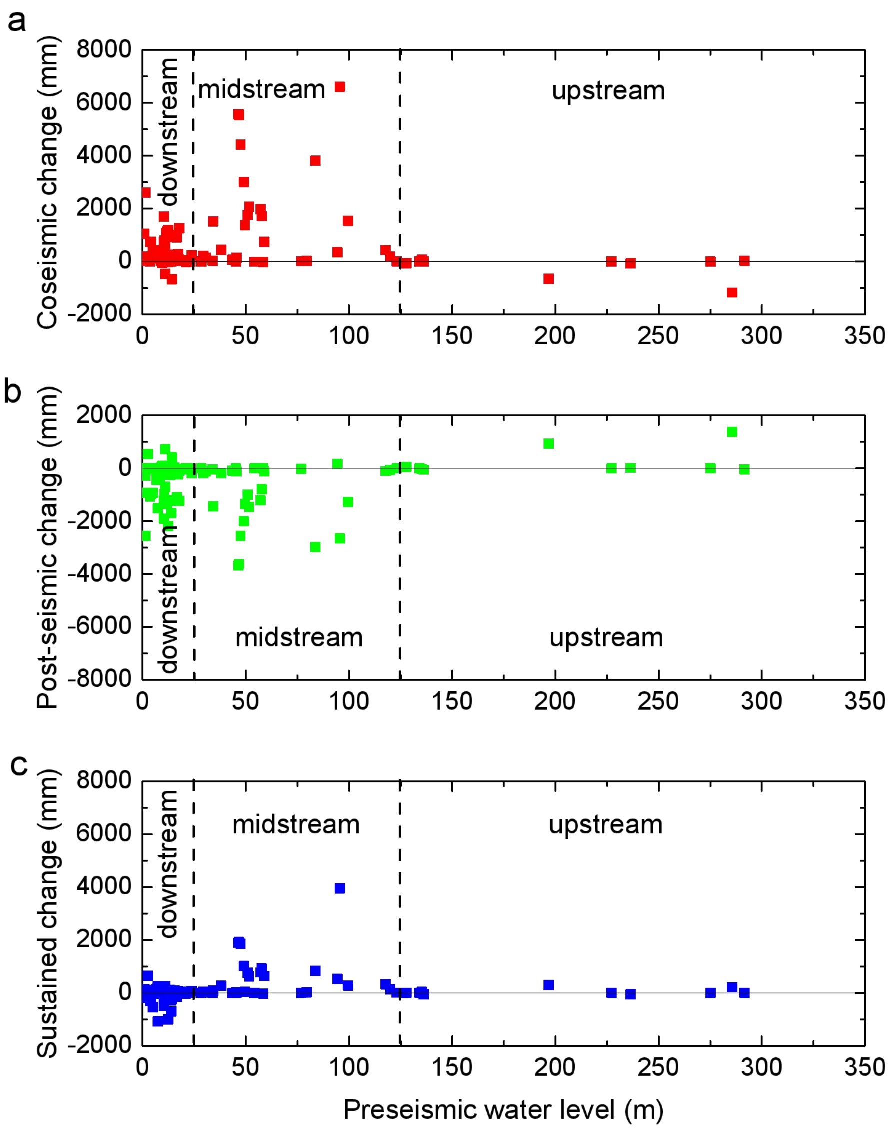

Fig. 4. Spatial and temporal changes in well water levels in the shallow groundwater system in the Canterbury Plain: (a) coseismic change, (b) post-seismic change, and (c) sustained change versus pre-seismic water levels in the upstream, midstream, and downstream area. It shows that there are sustained decreases in the well water level in the downstream area, sustained increases in the midstream area, and no changes in the upstream area.

4. Discussion

As mentioned in the **Introduction section**, four conceptual models are proposed as possible mechanisms for such effects. However, none of these models can explain the sustained increase in the hydraulic gradient observed after the Darfield earthquake. First, the pattern of well water levels sustained changes in the Canterbury Plain was not related to static stress change induced by the faulting of the Greendale Fault. This is because the change in static stress does not show such a pattern. Second, the changes cannot be explained purely by increased recharge, as that would imply that well water levels in the entire system should be higher than they were before the earthquake, which was clearly not the case. Third, the sustained changes cannot be attributed to an increase in permeability, as this would have caused the well water levels in the recharge area to decrease, whereas those in the discharge area to increase (Rojstaczer and Michel, 1995). Lastly, the sustained decrease in well water levels in the downstream area contradicts the hypothesis of permanent strain produced by consolidation. However, the coseismic increase in water levels in the alluvial plain, away from the coast, could be attributed to consolidation (Cox et al., 2012). Therefore, a new model is needed to properly explain the sustained increase in the hydraulic gradient shown by our data for the Canterbury Plain.

Coseismic, step-like increases in water levels occurred on a regional scale across the Canterbury Plain in the near field of the Darfield earthquake. Such increases are usually attributed to coseismic consolidation of unconsolidated sediments (Cox et al., 2012; Wang et al., 2001). Therefore, we hypothesize that the sustained increase in the hydraulic gradient between the downstream and midstream areas indicates a decrease in permeability. This decrease was caused by coseismic consolidation of the shallow groundwater system in the downstream and midstream area, which in turn reduced groundwater flow through the shallow groundwater system and produced the pattern of sustained changes in well water levels seen in our results.

By using pumping tests (Rutter et al., 2016) and the tidal response of well water levels to the earth tide (Weaver et al., 2019), studies have shown that earthquakes can decrease aquifer permeability near observational wells. However, field studies using these methods have only shown that permeability changes occur in the area surrounding the observational wells (usually <100 m). Currently, there is no evidence of permeability changes far from the wells (usually >100 m) during the earthquakes. The sustained changes in well water levels in the alluvial plain following the Darfield earthquake suggest the presence of plain-scale sustained permeability decreases in the shallow groundwater system.

However, a small number of confined wells in the downstream area (liquefaction area) have experienced sustained decrease in water levels, which cannot be explained by the decreased permeability. We suggest that this phenomenon may be caused by the liquefaction-induced disruption of the groundwater system. In the downstream area, due to failure of the weak permeable layer, the confined aquifer began to leak under the vertical hydraulic gradient, which eventually led to the decrease of water levels in these confined wells.

The change in well water levels, as well as changes in permeability, could be used to study the effects of changes in permeability on groundwater resources in the Canterbury Plain. Groundwater resources in the midstream area increased after the earthquake, as a result of decreased discharge to the downstream area. Meanwhile, groundwater resources in the downstream area decreased after the earthquake, because of decreased recharge from the midstream area. Further research is required to better understand the effect of the Darfield earthquake on groundwater resources in the Canterbury Plain.

5. Conclusions

In this study, we analyze data acquired from a large-scale well network and propose a new model to explain the sustained changes in the hydraulic gradient documented after the 2010 Mw 7.1 Canterbury earthquake. Our results show sustained increases in well water levels in the midstream area and sustained decreases in well water levels in the downstream area after the earthquake. The sustained increase in the pressure gradient indicates that there should be permeability decreases in the shallow groundwater system. This could possibly be attributed to the consolidation of sediment during the earthquake. The decrease in permeability is used to explain that the sustained changes in the hydraulic gradient had a positive effect on the groundwater resources in the midstream area but a negative effect in the downstream area. This study may provide a better understanding of the effects of large earthquakes on hydrological responses and groundwater resources, especially in liquefaction areas.

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