Hydrogeological Responses to the Canterbury Earthquakes
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ABSTRACT: Hydrologic responses to the 4 September 2010 M\textsubscript{w} 7.1 and 22 February 2011 M\textsubscript{w} 6.2 Canterbury earthquakes ranged from near instantaneous co-seismic liquefaction and changes in groundwater levels, to more sustained (days to months) changes in river discharge, spring flow and groundwater level. There was some indication of a sustained change in aquifer properties.

This paper presents some of the hydrographs from the September and February events, and compares the response to each event, briefly taking into account the location of the bore relative to each earthquake, together with other factors such as borehole depth.

Over the months following the September earthquake, a pattern emerged of relatively short-term responses in the shallow aquifers and in the confined aquifer system, close to the coast. A longer term response appears to have occurred in inland, deep bores, where water levels 12 months after the September event were (in some cases) up to 20 metres higher than would have been expected based on simple modelling (see Figure 3). Some examples of these are highlighted.

1. INTRODUCTION

The Canterbury region is the largest region in New Zealand with an area of 45,346 km\textsuperscript{2}. It is located towards the middle of South Island. The region is bounded in the north by the Conway River and to the west by the Southern Alps. The southern boundary is the Waitaki River. The coast forms the eastern boundary (Figure 1).

The 4 September 2010 M\textsubscript{w} 7.1 earthquake in Canterbury was the result of a series of faults hidden beneath the Canterbury Plains which ruptured in a complex sequence. The earthquake has been followed by over 10,000 aftershocks, including the M\textsubscript{w} 6.2 event on February 22 2011, and other major aftershocks in June and December 2011.

We describe the widespread hydrogeological effects of the M\textsubscript{w} 7.1 Darfield earthquake, and briefly examine the different responses to the September 2010 and February 2011 events. With each major aftershock there has been increased damage to the hydrological monitoring network, and as a consequence, investigation of the different responses to the earthquakes is limited.

1.1 Hydrogeological setting

The Canterbury Plains are composed of several hundreds of metres of gravel alluvium. Towards the coast, due to changes of sea level during interglacial periods, and the resulting inland transgression of the sea, the gravels alternate with fine-grained estuarine and marine deposits, and a more defined sequence of aquifers and aquitards has developed. Groundwater beneath the Plains flows in a south-eastward direction from the Southern Alps foothills towards the coast. Where the aquifers become confined around the Christchurch area, groundwater is confined under high pressure, with piezometric levels of up to around 10m above sea level (Talbot et al. 1986).
The Canterbury groundwater resource is one of New Zealand’s most important, providing 80% of the region’s drinking supply and 50% of water for agriculture (Brown & Weeber 1992; Brown 2001). Around 30,000 irrigation and domestic supply wells are consented for groundwater abstraction which is around 1250 million m$^3$/year (Environment Canterbury 2011a). Localised high permeability channels of re-worked gravels are a significant feature of the flow regime (Bal 1996).

1.2 Data

The effects of the earthquakes on piezometric levels were observed in a number of bores. The main source of data was from the Canterbury Regional Council (Environment Canterbury) with 125 local monitoring bores recording at 15 minute intervals at depths ranging from 5 to 405 m, including a number of multi-level piezometers (Cox et al., in press). An additional 214 bores were measured manually on a monthly basis, and were useful to assess any departure from water levels in the longer term. Other types of piezometric data (some of it at a sub-2 minute interval) were also available, including aquifer test data and observations from private users.

2. GROUNDWATER HYDROGEOLOGICAL RESPONSES

2.1 Response to the September event

Groundwater level data from September 2010 were assessed in a number of ways, including assessment of the amount of offset before and after the earthquakes, change in recovery rates (slope change), changes in recession rates through the following summer compared to previous years, and changes relative to borehole depth. In all, nine types of response were observed, which are presented in Figure 2.
Figure 2. Earthquake response type examples

An initial investigation of the piezometric responses to the earthquakes did not reveal a convincing pattern (Figure 3). Further work by Cox et al (2011) separated responses into bores of less than 80m depth and greater than 80m depth, and this suggested there was a more systematic response than what had initially been seen (Figure 3).

Some patterns emerged from analysis of the September 2010 data:

- The groundwater level rise in the deeper bores tended to be larger in magnitude, and propagated over a wider area, possibly as a result of reduced storativity. Negative offsets tended to be more predominant in the shallower bores, particularly close to the coast;
- Changes in recovery rates comparing before to after the earthquake occurred, particularly in the deeper inland bores;
- There were possible changes in recession rates in some bores, most notable those that already showed a relatively high recession rate through summer months; and
- Shallow bores tended to exhibit a short short-term response.
2.2 Comparison of the September 2010 and February 2011 events

A comparison of the responses to the two main events (September 2010 and February 2011) have been investigated by Gulley et al (in prep). They concluded that the magnitude of the effect of each earthquake was different depending on location. They refer to an area called the ‘Christchurch Flat’, which roughly corresponds with the confined aquifer system. Significant responses to the February 2011 event occurred within and adjacent
to this area, with bores at greater distances showing little effect compared to the September 2010 event. Some bores in the ‘Christchurch Flat’ area showed not only a greater short-term spike, but also a distinct positive offset following the February 2011 event (for example M35/6107: Dyers Road, Figure 5).

The different responses spatially to the two events are highlighted in Figure 6 (based on provisional data from CRC) (Environment Canterbury, 2011b). This illustrates the increasing impact of the February event within the Christchurch area and adjacent, and the greater effects of the September earthquake on inland bores. The impact of the different earthquakes varied due to the changes in ground deformation, ground acceleration and the degree of ground shaking caused at each location.

Figure 5. Response at Dyers Road to the September and February events

Figure 6. Earthquake-induced level changes in September 2010 and February 2011
3. LONGER-TERM IMPACTS

Over the year following the September 2010 earthquake, a pattern emerged of relatively short-term responses in the shallow aquifers and in the confined aquifer system, close to the coast. However, anecdotal evidence suggested that piezometric levels in some inland, deep bores, were higher than might be normally expected, despite seasonal abstraction for irrigation being little different from previous years. In addition, in the summer of 2011 several of the bores failed to show the normal recession that usually begins around September or October each year.

Eigen modelling was used to assess whether the high groundwater levels were due to climatic influences, or whether there appeared to have been some change in aquifer properties. Eigen models can be used to predict either groundwater levels or total aquifer discharge (either natural or abstractive) for a given recharge input (Bidwell & Morgan, 2002; Bidwell, 2003). The approach involves calibration of the models to match a subset of pre-earthquake groundwater levels (given calculated recharge and abstraction), and prediction of post-earthquake groundwater levels based on post-earthquake calculated recharge and abstraction. The method is based on the assumption that the aquifer system is one large homogeneous aquifer with all the wells responding as a function of their position in the catchment. Simulations were run from 1967 to the present and were calibrated against available data up to the Mw 7.1 Darfield earthquake in September 2010. The results indicate that elevated piezometric levels through 2010 and 2011 were significantly above those that would be expected on the basis of historical data. L36/1226, which had showed a positive slope-change response in the medium-term (see Figure 7) is used to illustrate the results.

![Figure 7: Short-term response in L36/1226, illustrating the spike, small offset and positive slope change following the September 4 earthquake.](image)

The modelled and actual levels illustrated in Figure 8 for this bore show not only the departure from the calibrated model prediction, but also the lack of a seasonal recession. Given the fact that a sustained rise in piezometric surface is observed in numerous deep bores, the elevated water levels suggest a systematic response to the earthquake, and possibly reflects a decrease in storativity and/or transmissivity of the aquifer system in the vicinity of the fault rupture. The reason for the lack of a seasonal recession in some of the hydrographs cannot be easily explained.

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Figure 8. Preliminary eigen modelling results showing apparent change in behaviour after the September 2010 earthquake (groundwater levels in metres above mean sea level).

4. SUMMARY

Understanding the behaviour of groundwater systems during and after earthquakes is important in a seismically-active country that depends on groundwater for drinking water and agriculture. Whilst the monitoring network has been increasingly damaged by successive earthquakes, there is sufficient data to draw broad conclusions. These initial observations and modelling results highlight a number of areas of interest and raise questions as to how the earthquakes have affected the aquifer. The long term effect on piezometric levels that is suggested by the eigen modelling suggests there could be a change in aquifer properties: in order to assess this properly, further fieldwork and modelling would need to be carried out.

5. REFERENCES


