POTENTIAL IMPACTS ON GROUNDWATER QUALITY DUE TO VERTICAL ENHACEMENT OF AQUIFER PERMEABILITY CAUSED BY EARTHQUAKES

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ABSTRACT

Following recent major earthquakes in New Zealand there has been concern about possible groundwater quality changes due to the infiltration of pollutants from the soil or ground surface. Various lines of evidence have pointed towards the possibility of recharge or sub-vertical flow following recent New Zealand earthquakes including:

- Increased turbidity
- Changes in water chemistry
- E Coli or total coliform detections
- Increased nitrate concentrations
- Changes in groundwater level pressure between multi-level piezometers

Artificial pathways may develop due to damage to well heads, infrastructure, and casing that could account for some of the observations. Earthquake-induced breaching of aquitards could also result in deeper aquifers becoming hydraulically connected to shallow aquifers. Wang et al (2016) found evidence for co-seismic breaching of aquitards in around 10% of the wells analysed after the 1999 Chi Chi earthquake in Taiwan. Evidence from our studies, including the convergence of groundwater pressures in multi-level piezometers, and modelling results that suggest leakage between layers[1] supports earthquake induced vertical permeability enhancement.

Of particular concern is where there is evidence of contamination of aquifers by pathogens. Environment Canterbury reported that some wells in the Christchurch shallow aquifers had positive detections of E Coli and Total Coliforms following the Canterbury earthquakes. Wellington Water Limited observed an increase in Total Coliforms and also E Coli in three of their supply bores located within the Waiwhetu aquifer in Lower Hutt after the Kaikōura earthquake in November 2016. This increase in bacterial detection was also accompanied by increase in turbidity in some wells, and initial work suggested that this may have been a result of breaching of the confining aquitards. Further evidence of the disturbance of the aquitards is through the changes in groundwater level fluctuations in the underlying Taita Alluvium located just below confining layers, which changed from muted fluctuations to full tidally induced ones, more similar to the productive aquifer.

Breaching of aquitards and damage to wells and well heads by earthquakes could have significant implications for security of groundwater resources for potable water supply, as it has the potential to allow rapid transport of solutes and microbes from the surface to depth. Given the reliance of New Zealand on groundwater for municipal supply, it is important to consider that preferential flow paths could develop following large earthquakes. Further research is needed to answer key questions, such as: How do breaches occur? How often do they occur? How long do the increases in vertical permeability last for? Is there are simple measure to monitor or detect the occurrence of aquitard breaching?

KEYWORDS

Earthquake impacts; vertical permeability

PRESENTER PROFILE

Dr Helen Rutter is a Senior Hydrogeologist with Aqualinc Research Ltd, having over 25 years' experience working in hydrogeology in the UK, Botswana, and New Zealand. She has in-depth understanding of physical hydrogeology, including resource assessment, recharge processes, groundwater flooding, catchment characterisation, geology and geochemistry. She has carried out extensive research into the hydrogeological impacts of the Canterbury Earthquake Sequence, including a Marsden-funded research project.

1 INTRODUCTION

Horizontal changes in permeability following earthquakes have been suggested by numerous authors. Changes in vertical permeability have been less well researched, though Wang et al. (2004) inferred this from increases in streamflow. More recently, Wang et al. (2015) describe an increase in permeability and disruption of aquifer confinement after the 1999 Chi-Chi earthquake in Taiwan. We consider whether similar increases in vertical permeability could have occurred following the Canterbury and Kaikōura earthquakes in New Zealand.

The hypothesis for an increase in vertical leakage has been based on a number of lines of evidence, including chemical/microbial changes, water level changes, and modelling of water level responses. This paper describes the evidence for increased connection between aquifer layers as a result of seismic events.

2 BACKGROUND TO THE AREAS AND EARTHQUAKES

2.1 CANTERBURY PLAINS

The Canterbury Plains lie along the eastern South Island of New Zealand. They comprise gravel alluvium and glacial outwash deposits that are around 300-600 m thick, sitting on basement. The alluvium was deposited by braided glacial melt-water rivers. Close to the coast, westward transgression of the sea during interglacial periods, resulted in a coastal zone where estuarine and shallow marine sediments are inter-bedded with the alluvial gravels. These fine-grained marine/estuarine sediments are now found up to 15 km inland of the present-day shoreline.

On 4 September 2010 a 7.1 M_w earthquake occurred near Darfield, Canterbury in the South Island of New Zealand. The previously unknown Greendale Fault ruptured through an inland area of unconfined and semi-confined alluvial aquifers. There was a prolonged series of aftershocks, the biggest being the 6.2 M_w earthquake on February 22 2011, which had devastating consequences. Similar to many other studies, a series of short- to medium-term hydrological responses were observed within the first hours, days, and up to one year following the earthquake (Cox et al., 2012), including: a ‘spike’ pressure change; a positive step offset in piezometric level (that is, an instantaneous positive change); a negative step offset in piezometric level; combinations of spike and offset changes; changes in the rate of recharge or recession; and lack of a recession.

2.2 KAIKŌURA

The Kaikōura earthquake occurred on November 14 2016 at 12.02 am. It initiated in the Waiau Plains in northern Canterbury, New Zealand, on an oblique thrust at a depth of ~15 km. It propagated upwards and northwards, forming a complex rupture along a ~180 km zone that involved at least 21 faults (Langridge et al., 2016; Holden et al., 2017), producing widespread shaking, and reaching maximum Modified Mercalli Intensity of IX.

Again a wide range of hydrogeological responses were observed, including changes in groundwater levels, stream flow and turbidity.

3 EVIDENCE FOR INCREASED CONNECTION BETWEEN AQUIFER LAYERS

It is important to understand the difference between hydraulic responses, and transport. A water level response can simply be due to increased pressure at one end of the system having a ‘piston flow’ type pressure response at a location downgradient. In terms of earthquakes, increased pore pressure caused by shaking could result in a change in groundwater levels. Similarly, any consolidation of aquifer material, could lead to an increase in groundwater levels up-gradient, due to a pressure response.

However, a change in water chemistry or (to a large extent) temperature must be a result of transport of the water molecules that have the altered temperature or different chemistry. Pressure responses can be immediate; changes due to transport usually take a period of time.

Water chemistry, turbidity and microbial changes can all provide evidence for mixing of waters from different sources, or for increased recharge from the land surface. In the following sections we examine the evidence both for increased transport and a change in hydraulic connection, as a result of earthquakes.

3.1 CHANGES IN E COLI OR TOTAL COLIFORMS

Total coliforms are a group of bacteria that are predominantly associated with the human or mammalian gut and hence faecal matter, but can also occur in the environment associated with plant and soil material. Total coliforms in a groundwater supply provide warning that soil or surface bacteria have entered the well source water. While E. coli indicate faecal contamination, the presence of total coliforms in a groundwater supply indicates that a pathway exists for surface or near-surface pathogen entry into the source water. This can include from surface sources, but may also be from infrastructure, such as sewer pipes or septic tanks.

Following on from the Canterbury earthquakes, particularly the February 2011 aftershock, both ECan and Christchurch City Council (CCC) carried out sampling to assess if there was any evidence of faecal contamination. In particular, CCC collected 2,503 samples for indicator organisms (total coliforms and E.coli) from water supply wells, pump stations and reservoirs around the city following the 22 February 2011 earthquake. Of these 2,503 water samples, E.coli was absent in 99.2% and total coliforms were absent in 92.3%. 21 samples tested positive for E.coli and 192 samples were positive for total coliforms. Most positive detections of bacteria in samples occurred in the first four weeks after the 22 February 2011 earthquake.

ECan suggested that it was likely that any bacteria contamination in the water supplies was related to damaged pipes or well casings, rather than contamination of the aquifer. They considered that the low percentage of samples affected by bacterial contamination was consistent with this conclusion.

In Wellington, changes in microbial water quality from the Waterloo wellfield were observed from December 2016 onwards (Close et al., 2017). There was a long record of sampling for this wellfield: every second day for three years prior to the earthquake and daily from September 2016 onwards there was quantitative water sampling and testing for total coliforms and E. coli directly from each well in the wellfield. Prior to the earthquake there were positive detections for total coliforms in less than 1.5% of samples. Following the Kaikōura earthquake, there were marked increases in total coliforms in many of the Waterloo wellfield bores, with a particularly marked increase at the Willoughby Street South bore from March 2017 onwards. There were also E Coli detections at two bores.

The increase in total coliforms suggested that something happened to worsen any existing contamination, or enhanced a previously minor contaminant flow pathway. Given the relatively wide spread of the affected bores, it was considered to be unlikely to be just one localised source but is a reasonably pervasive source. Wellington Water (2017) suggested possible sources of contamination could include discrete pathways enabling water to travel into the aquifer from the surface, issues with the bore casing, or buried services leaking contaminated water/sewerage into groundwater.

3.2 CHANGES IN NITRATE CONCENTRATIONS

Another study being carried out at the time of the Canterbury earthquakes was a study of groundwater level changes and nitrate nitrogen concentration in shallow groundwater bores located in the Selwyn District – Canterbury Plains (Aqualinc, 2011). This work also suggested there could be changes in nitrates and water levels in some bores in response to seismic activity.

In one bore, L36/2304, following the September 2010 earthquake, nitrate concentrations almost doubled from those prior. L36/2304 is 48m deep, and considerably deeper than the other bores being sampled at the same time, which varied from 6.5 to 30 m. Concentrations were high when sampling was carried out in September and October, then decreased to 13 mg/l, close to the pre-earthquake concentration. Further sampling since, in 2012, has shown that nitrate concentrations have continued at similar levels. The groundwater was also tested for E Coli and total coliforms, resulting a positive result. The results of this work suggest that there was nitrate and possibly bacterial contamination of the groundwater at up to 48m depth following the September 2010 earthquake, but that the high nitrates were resolved within a couple of months. The source exact could not be determined, though may have been caused by a rupture or spill from a septic tank; however, the increased nitrates and E Coli must have been a result of enhanced recharge/leakage, with nitrates and bacteria being transported from the near surface to depth.

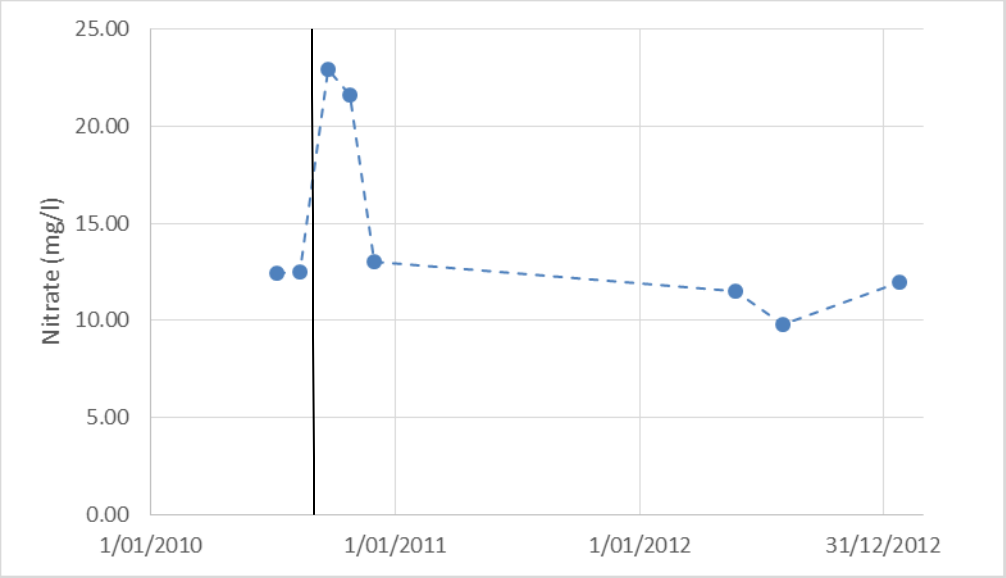

Figure 1. Spike in nitrate concentrations in L36/2304 following the September 2010 earthquake

3.3 CHANGES IN WATER CHEMISTRY

Minor changes in water chemistry appear to be commonplace following earthquakes. ECan sampled 35 bores following the September 2010 (Darfield) and February 2011 (Christchurch) earthquakes and found that for twenty bores, there was some evidence of a change in water chemistry, often with between one and three parameters (from a total of 21) where the post-earthquake value was slightly outside the range of what had been measured previously. The parameters that were exceeded were not the same for all bores.

From sampling post- Kaikōura earthquake in Wellington, there were generally only minor differences (some concentration spikes) in groundwater chemistry between the pre-and post-earthquake period (Close et al., 2017). Small increases in fluoride, magnesium, calcium, and sodium were also identified. In general, subsequent monitoring of the bores showed that the groundwater chemistry of the wellfield more or less returned to within the normal range expected within a year.

Whilst changes in water chemistry could have been caused by movement of water between aquifers or from the land surface, the changes could also have been due to natural variation, or sampling or analytical error. Increased manganese and iron could also possibly be a result of erosion of the coating of individual clasts within the aquifer. These coatings develop with time, and are often iron- or manganese-rich. If the movement of clasts during a seismic event resulted in movement of one clast against another, some of the coatings could potentially become suspended or dissolved in the groundwater.

3.4 CHANGES IN TURBIDITY

Changes in turbidity of groundwater are a well known consequence of seismic activity. Bores across Canterbury were pumping water with high suspended sediment for prolonged periods of time following the September 2010 and February 2011 earthquakes. However, most observations are anecdotal, and the recording of turbidity in earthquake-affected bores is relatively uncommon.

Turbidity changes were recorded in four municipal water supply bores in Marlborough following the Kaikōura earthquake in November 2016. In these bores, there had been some issues with turbidity pre-earthquake, but there was a marked increase after the earthquake. Initially, turbidity was measured at around 10 NTU following the earthquake. The spikes in turbidity tend to follow an exponential decay as pumping was continued. Weaver (In Prep) estimated the decay constants associated with each spike pre- and post-earthquake, and identified a change in decay constants after the earthquake. This may have resulted from a change in the aquifer or bore conditions. Weaver (In Prep) observed that this preliminary analysis required further assessment to understand the turbidity changes.

Wellington Water also sampled various wells following the Kaikōura earthquake in November 2016 (Close, 2017). High turbidity readings occurred at two sources in Wellington; in this case these corresponded with the occurrence of high total coliforms in these bores. The fact that total coliforms were also elevated indicated the possible ingress of contaminated surface water into the aquifer, or potentially inflows through cracked well casing. The significant increases occurred after the earthquake and were still occurring in mid-2017, and it was felt that it was unlikely that they were due to short-term disturbance of any microbial biofilm around the bore or casing, but indicated the increase in turbidity might be a sign of ingress of surface water.

3.5 CHANGES IN TEMPERATURE

The ECan report also noted that there were small changes in groundwater temperature at a number of wells which could be related to the earthquakes. A change in temperature must be a result of transport processes, and as a result, temperature can be used as a tracer. Most of the changes were small, though they could be up to 2 or 3 ^{0}C.

Temperature changes have also been observed in some wells with transducers installed. The high resolution data shows that temperature changes often show a similar pattern to the water level changes that are induced by seismic events, and can exhibit a range of responses, including spikes and offsets, as well as more gradual changes. Such changes have not been investigated in great detail, but could indicate direct recharge from the surface, or a change in groundwater flow paths. They could also be related to a damaged well casing allowing the entry of water from a different depth, with a different temperature.

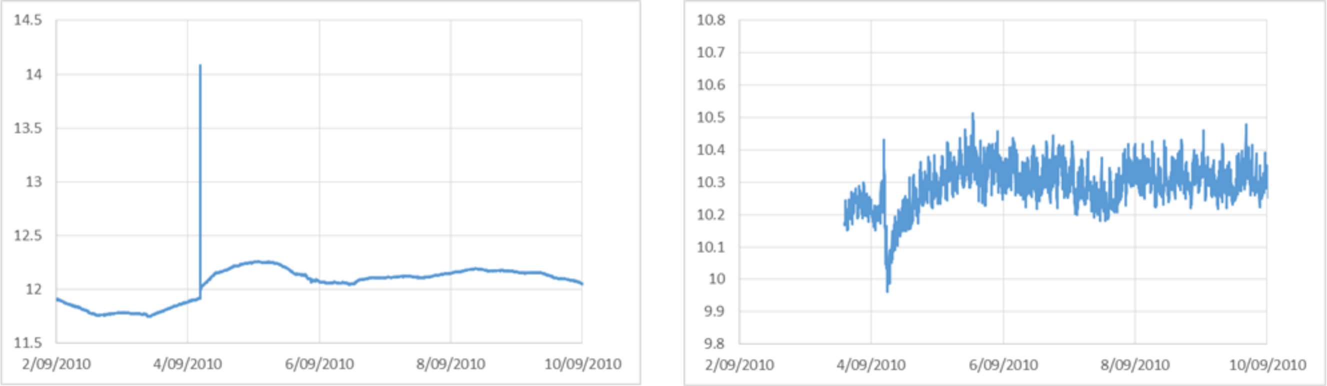

Figure 2. M36/0425 (left) and L36/2082 (right) temperature responses to the September 2010 earthquake (temperature in 0C)

3.6 EVIDENCE FOR INCREASED HYDRAULIC CONNECTION BETWEEN LAYERS

In the years following the September 2010 Darfield earthquake, groundwater levels in deeper inland wells appeared to be sustained at a higher level than pre-earthquake. Investigation of the changes suggested they were not driven by recharge or abstraction, but were a real effect resulting from the earthquake.

Rutter et al. (2016a) found two quite different types of responses, the difference being dominated by what occurred in the months following the earthquake. In the first group, there was little or no recession, and the hydrograph was effectively offset from the predicted groundwater response, for example **Error! Reference source not found.**. In the second group, the immediate offset was followed by a marked recession, usually with little or no recovery in the following year (**Error! Reference source not found.**).

Utilising Aqualinc's Canterbury groundwater flow model (Weir, 2008), we tested various possible scenarios that could have resulted from shaking of the sediments during the earthquake, including: a decrease in horizontal permeability; an input from bedrock; and an increase in vertical leakage. The model was already calibrated to pre-earthquake conditions. It was used to test different scenarios and assess whether the pattern of water level change could be explained through these scenarios. The results suggested that, at the eastern end and at greater distances from the fault, the measured groundwater level responses correlated closely with the modelled scenario for increased leakage. In particular, the immediate rise in groundwater levels followed by a marked recession in these wells could not be modelled with any of the scenarios other than an increase in vertical leakage (see Rutter et al.,2016b).

The possibility for increased vertical connectivity between aquifers, as a consequence of seismic activity, was also highlighted in Wellington following the Kaikōura 2016 earthquake. In the Lower Hutt area, the artesian Waitwhetu Gravels are overlain by the Taita Alluvium (T3) layer. Following the Kaikōura 2016 earthquake, the groundwater level responses in the overlying T3 alluvium changed, and became more similar to those in the Waiwhetu Gravels. This was taken to indicate a closer hydraulic connection between the aquifers.

3.6.1 CHANGES IN RELATIVE PRESSURE BETWEEN MULTI-LEVEL PIEZOMETERS

To further assess whether the model results were reflected in measured behaviour, we examined some of the multi-level piezometer clusters across the Canterbury Plains. These are clusters of piezometers (water level monitoring points) that are installed at different depths at the same location. They are used to assess the vertical hydraulic gradient, and the connection between different depths in the aquifer system. The mean depth to water for four years prior to the Darfield earthquake were plotted against the mean change in water level induced by the earthquake (**Error! Reference source not found.**). In all cases, the groundwater levels at different depths converged after the earthquake. This convergence was taken to indicate closer hydraulic connection between aquifer layers.

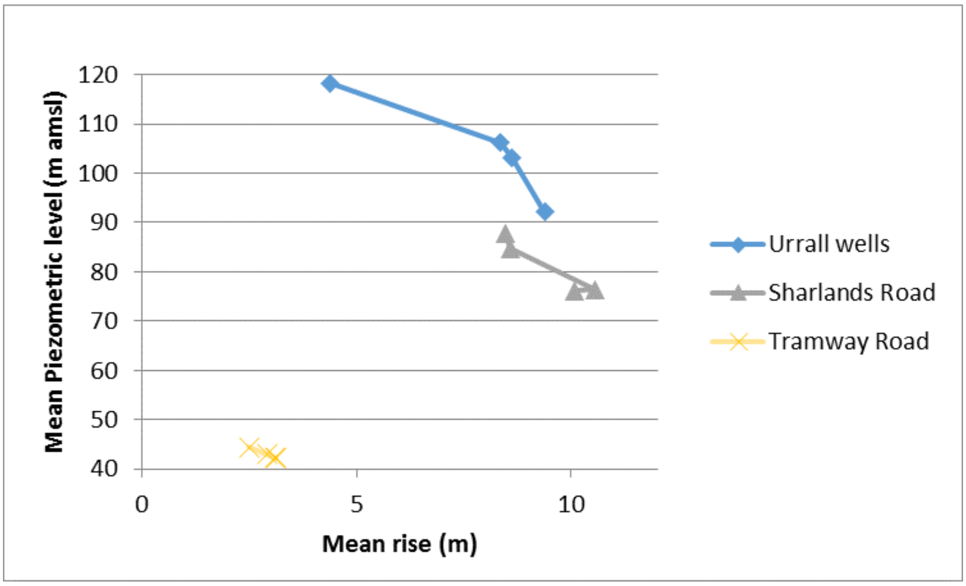

Figure 3: Mean depth to water (for the 4 years pre-EQ) against mean rise in groundwater level.

For the Urrall cluster, as a result of the September 2010 earthquake, K36/0493 showed a negative offset (around 2 m), whilst the others showed a positive offset (of over 2 m) (Figure 4). This exacerbated the effect of the convergence, and may be further evidence of an immediate pulse of water leaking from the upper aquifer to lower layers. The question has to be raised as to whether the convergence of piezometric levels is due to leakage between the installed piezometers, as opposed to increased leakage between aquifer layers. The differences between different hydrographs at each cluster were examined, and, although similar in shape, were sufficiently different that we considered that that leakage down, or damage to, the casing was not allowing direct hydraulic connection between layers.

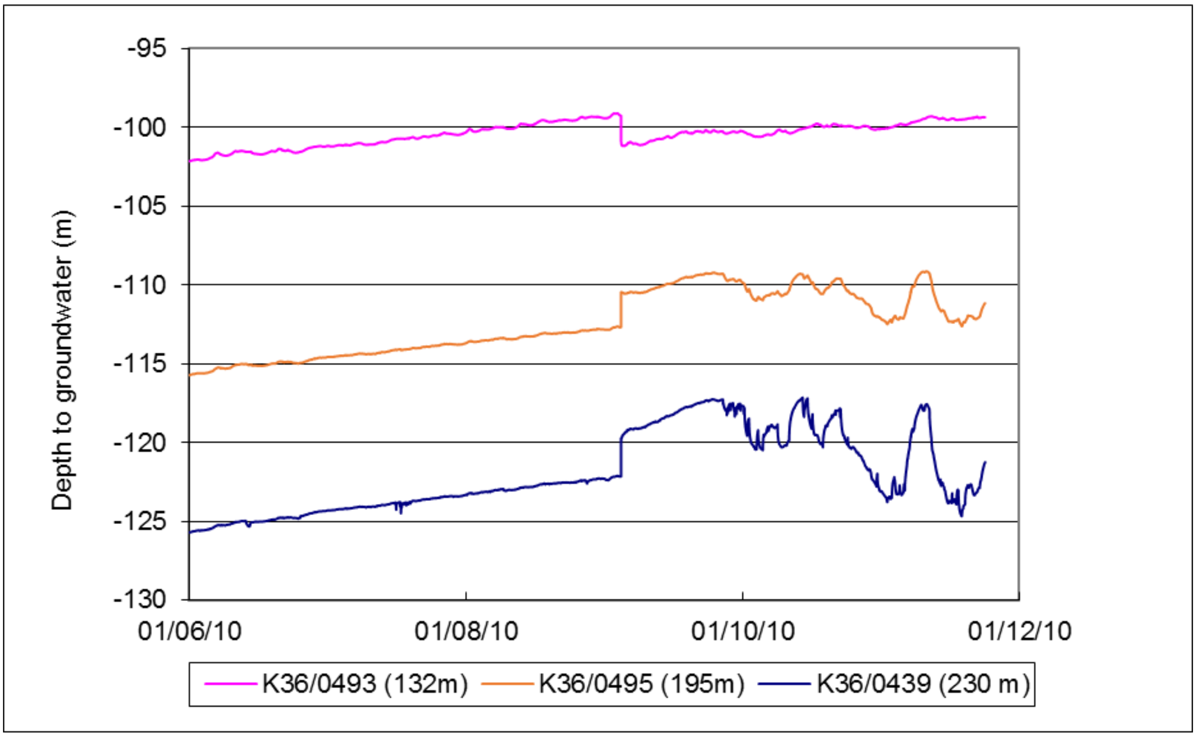

Figure 4: Convergence of groundwater levels in the Urall cluster

The Urrall cluster was investigated in further detail to assess whether the difference in piezometric levels between the piezometers was maintained over the years following the earthquake. The responses between different depths show a reasonable amount of variability, but generally suggest that piezometric levels have converged, and have not returned to pre-earthquake values (Figures 7,8), suggesting that the ‘healing’ observed by Wang et al (2016) has not occurred here.

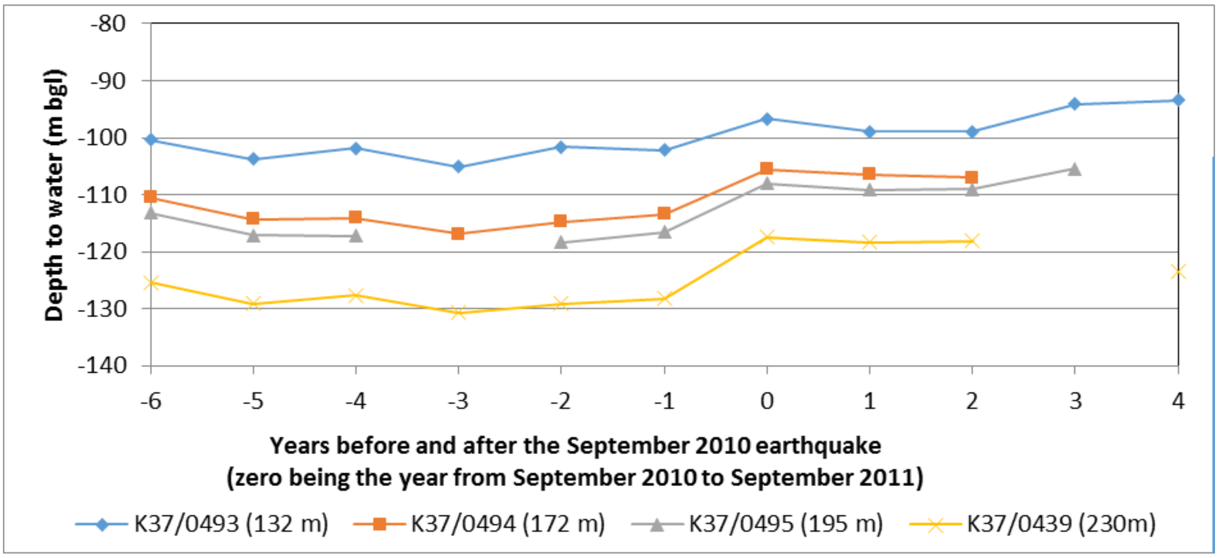

Figure 5: Annual average depth to groundwater in the Urrall piezometers

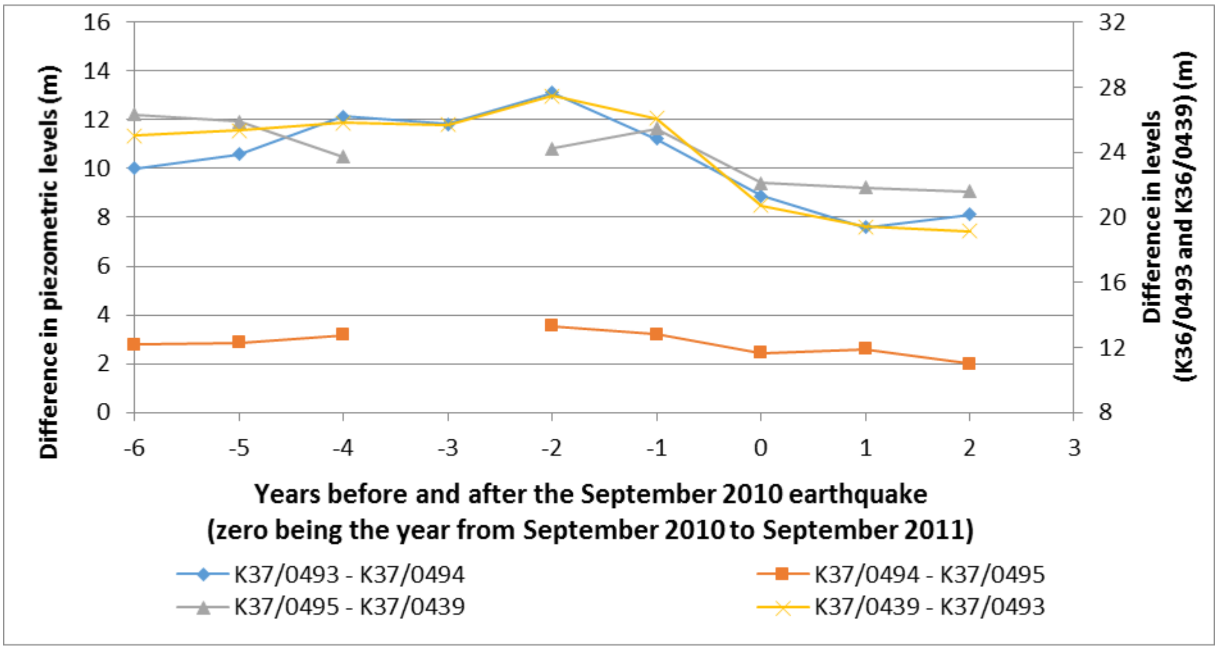

Figure 1: Piezometric level differences between the Urrall piezometers

4 DISCUSSION

Various lines of evidence provide evidence for increased connection between aquifer layers as a result of earthquakes. This includes evidence from changes in water chemistry, microbe detection, temperature, turbidity, and groundwater levels.

Disruption of the sedimentary sequence during earthquakes could have feasibly increased vertical connection between aquifer layers. Wang et al. (2015) suggested that the postulated ‘fractures’ healed within 6 months of the earthquake. It is difficult to determine whether this is the case from the available evidence from the Canterbury earthquake sequence and the Kaikōura earthquake. Generally, the analysis and modelling of groundwater levels suggests that there is some evidence for long term increased connection between aquifer layers, though chemistry and temperature data suggest the effects may be short-lived. It may be that there is a semi-permanent increase in hydraulic connection between layers, but that this does not result in increased long-term risk of transport between layers. This may be reinforced by the fact that changes in chemistry, temperature and microbes appear somewhat sporadic, and these appear to return to background relatively quickly. So the increased risk of transport between land surface or other water bodies appears to be a local one, and of short duration. In contrast, the hydraulic response (as evidenced through water level analyses) may persist for some time.

However, this may not always be the case. In Wellington, continuing elevated total coliforms may raise the possibility of a permanent change in groundwater/recharge flow paths, allowing water from the near surface to access the aquifer at around 40 m depth. As the detections were predominantly total coliforms rather than E Coli, this is not necessarily indicative of faecal contamination, but could be due to contamination by soil or plant matter. However, this still raises the possibility of enhanced connection with the surface. The association of increased turbidity with higher readings of total coliforms also suggests that increased turbidity may be a symptom of increased transport from the near surface.

5 CONCLUSIONS

Based on the results of this work, the long term risks to aquifer water quality from earthquakes may be limited, but there is certainly evidence that earthquakes can disrupt aquitards and/or result in the development of new flow paths, such that groundwater quality could be affected. The ongoing issues with total coliform detections at the Waterloo Wellfield in Wellington suggest that, in some cases, the pathways that can develop during earthquakes can be maintained for a prolonged period of time. This may be a relatively unusual case, but given other observations, the potential for increased connectivity between aquifers and the surface/shallow subsurface should not be discounted following large earthquakes.

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REFERENCES

Aqualinc (2011). ***Error! Use the Home tab to apply RptTitle to the text that you want to appear here. Error! Use the Home tab to apply RptTitleSub to the text that you want to appear here.***. Report Number C10085.

Cox, S.C.; Rutter, H.K.; Sims, A.; Manga, M.; Weir, J.J.; Ezzy, T.; White, P.A.; Horton, T.W.; Scott, D. (2012): Hydrological Effects of the Mw7.1 Darfield (Canterbury) Earthquake, 4 September 2010, New Zealand. *New Zealand Journal of Geology and Geophysics*, DOI: 10. 1080/00288306.2012.68474. Published 3 September 2012.

Close, M; Banasiak, L; Weaver, L; van der Raaj, R; and Morgenstern, U. (2017). *Waiwhetu Aquifer Investigations*. ESR. Draft Report.

ECan (2011). *Earthquake impacts on groundwater: Update #2.* Environment Canterbury, Groundwater Resources Section.

Rutter, H. K.; Cox S. C.; Dudley Ward, N. F. and Weir, J.J. (2016a), Aquifer permeability change caused by a near-field earthquake, Canterbury, New Zealand, *Water Resour. Res.*, 52, 8861–8878, *doi:*10.1002/2015WR018524.

Rutter, H. K.; Cox, S. C.; Weir, JJ and Rajanayaka, C. (2016b) *Increase in vertical permeability after the m7.1 Darfield (Canterbury) earthquake [online].* In: 37th Hydrology & Water Resources Symposium 2016: Water, Infrastructure and the Environment. Barton, ACT: Engineers Australia, 2016: 491-498. Availability: https://search.informit.com.au/documentSummary;dn=689958736945484;res=IELENG> ISBN: 9781922107954.

Rutter, H. K.; Cox, S. C.; Weir, JJ and Rajanayaka, C. (2016b) *Increase in vertical permeability after the m7.1 Darfield (Canterbury) earthquake* [online]. In: 37th Hydrology & Water Resources Symposium 2016: Water, Infrastructure and the Environment. Barton, ACT: Engineers Australia, 2016: 491-498.

Rutter, H. K. and Cox, S.C (2015) *Long-term hydrogeological effects on the Canterbury Plains aquifer system from the Darfield 2010 earthquake*. 2015 New Zealand Hydrological Society Conference, Hamilton.

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

Wang C.-Y., Liao X., Wang L.-P., Wang C-H., and Manga, M. (2016), Large earthquakes create vertical permeability by breaching aquitards. *Water Resources Research*. 52 (8), 5923-5937

Weaver, K. C. *In preparation. Earthquake-induced hydrogeological changes in New Zealand*. PhD thesis, Victoria University of Wellington

Wellington Water 2017. *Waterloo Wellfield Water Quality Contamination Investigations. Part 1.* August 2017, 46 p.