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Hydrological effects of the M_W 7.1 Darfield (Canterbury) earthquake, 4 September 2010, New Zealand[1]

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The M_W7.1 Darfield (Canterbury) earthquake on 4 September 2010 generated widespread hydrological effects ranging from near-instantaneous coseismic liquefaction and changes of groundwater levels in boreholes, to more sustained (days to weeks) post-seismic changes in spring flow, river discharge and groundwater piezometric levels, to longer term shifts in groundwater level one year after the earthquake. Groundwater piezometric responses include local groundwater level increases of >20 m around the Greendale Fault, particularly in deep aquifers (>80 m), whereas decreases occurred in coastal confined aquifers beneath Christchurch city. Increases of up to 5 m persisted within 20 km of the fault 12 h after the earthquake. Groundwater levels and springs were affected throughout New Zealand, from >350 km away in Southland to nearly 1000 km away in Northland, even where shaking intensities were less than Modified Mercalli Intensity (MM) 3–4 (weak to largely observed) and peak ground acceleration was much <0.01 g. Release of artesian groundwater pressure and groundwater flow are postulated to have played pivotal roles in Christchurch liquefaction.

Keywords: earthquake; groundwater; piezometric level; artesian; aquifer; liquefaction

Introduction

Hydrological effects such as liquefaction, increased stream flow, the formation of new springs and eruption of mud volcanoes have been documented following large earthquakes for thousands of years. Such phenomena, together with changes in fluid pressure in the subsurface, are now being closely examined for the unique insight they provide into tectonic processes at scales in space and time that are otherwise difficult to study (Wang & Manga 2010a). On 4 September 2010, a series of faults hidden beneath the Canterbury Plains Pleistocene glacial outwash surface ruptured in a complex sequence to produce the c. 30 km Greendale Fault trace and accompanying M_W7.1 earthquake (Fig. 1; Beavan et al. 2010; Quigley et al. 2010, 2012; Gledhill et al. 2011). The earthquake and associated aftershocks, particularly that of 22 February M_W6.2, caused 185 fatalities (NZ Police 2011) and damage to Christchurch city and its environs will cost in excess of NZ$15 billion (8% of nominal GDP; NZ Reserve Bank 2011). Much residential property damage was caused by the unprecedented amounts of liquefaction, settling and lateral spreading (Cubrinovski & Green 2010; Orense et al. 2011; Kaiser et al. 2012), which can ultimately be attributed to the combination of shaking intensity, weak ground conditions and groundwater behaviour (Seed & Lee 1966; National Research Council 1985). Repeated liquefaction and differential movement were the principal reasons large suburban areas have had to be abandoned.

In this contribution, we describe the widespread hydrological effects of the M_W7.1 Darfield earthquake. The scale and nature of response at any one locality for the most part reflect proximity to the Greendale Fault and its ground deformation, ground acceleration and the degree of ground shaking. Observations are described in a context of near- (<50 km), intermediate- (50–100 km) and far-field (>100 km) distances from the earthquake epicentre. Major aftershocks in 2011 also induced groundwater changes and caused more-widespread liquefaction, but also caused some damage to the hydrological monitoring network (Environment Canterbury 2011a,b,c; Orense et al. 2011). Consequently, this investigation is focused on hydrological effects associated with the first damaging event, the main M_W7.1 Darfield earthquake on 4 September 2010, so that any observed responses carry only the influence of one (the first) earthquake. Fortuitously, for this hydrological investigation, Canterbury Plains received little precipitation in the 48 h before the earthquake, with <10 mm recorded at sites in Christchurch city and on the Canterbury Plains (NIWA 2011). Rainfall developed in the mountain headwaters c. 30 h after the earthquake, but held off on the Canterbury Plains

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until 6 September (NIWA 2011). The M_W7.1 earthquake also occurred just at the end of winter recharge, when aquifers were at near-maximum annual storage and before summer irrigation started to influence groundwater levels.

Hydrogeological setting

The Canterbury Plains are composed of gravel alluvium c. 300–600 m thick that was deposited in a complex of coalesced floodplains during the Pleistocene. The gravel sits on basement rocks of Permian–Jurassic Torlesse greywacke and locally a 0–1.5 km-thick sequence of late Cretaceous–Tertiary sedimentary rock (Fig. 1A; Forsyth et al. 2008). The gravels were formed by braided glacial melt-water rivers carrying detritus eroded from the uplifting Southern Alps. Changes of sea level of c. 200 m and westward transgression of the sea during interglacial periods resulted in estuarine and shallow marine sediments interbedded with alluvial gravels near the coast. These fine-grained marine/estuarine sediments are now found up to 15 km inland from the present-day shoreline. The Port Hills and Banks Peninsula, a Late Miocene volcanic complex that became extinct c. 6 Ma, may once have been an island. Faults with late Quaternary scarps, or folds and warps that buckle the ground surface, are found all along the western margin of the Canterbury Plains and within the Southern Alps (Forsyth et al. 2008). They are part of a distributed plate boundary deformation zone in which slip is mostly focused on the Alpine Fault along the west side of the Southern Alps. Following rupture of the Greendale Fault, there is now clear evidence that distributed plate boundary deformation occurs east of the upthrown range front. Other active faults or folds are probably buried beneath the Canterbury Plains (Cox & Barrell 2007; Forsyth et al. 2008).

The Canterbury groundwater resource is one of New Zealand's most important, providing 80% of the region's drinking supply and 50% of the water used for agriculture (Brown & Weeber 1992; Brown 2001). Fan and alluvial gravel sequences form aquifers, whereas the marine/estuarine sediments of silt, clay, peat and shelly sand act as aquitards (Fig. 1B). An artesian system with confined to semi-confined aquifers occurs in the coastal region where marine/estuarine sediments are interlayered with gravels. Confined aquifers and positive artesian groundwater pressures generally occur where fine-grained sediments exceed 3 m thick (Fig. 1A), but the transition is irregular due to depositional variation and erosion. Further inland, the layered structure of the coastal confined aquifers is less obvious and groundwater is semi-confined to unconfined. Groundwater occurs in better-sorted, more-permeable gravels that have been re-worked by alluvial processes, which are separated by poorly sorted less-permeable gravel. There is commonly a shallow unconfined aquifer with a water table in hydraulic connection with any nearby surface water courses, then intermediate and deeper aquifer zones at depths of 30–80 m and >80 m, respectively.

Regional piezometric contours indicate groundwater beneath the Canterbury Plains flows in a southeastward direction from the foothills towards the coast, generally seaward down the topographic gradient (Fig. 1A). Recharge from rivers and rainfall flows through the unconfined aquifers to the confined aquifers (Fig. 1B; Stewart et al. 2002). At the boundary where unconfined aquifers become

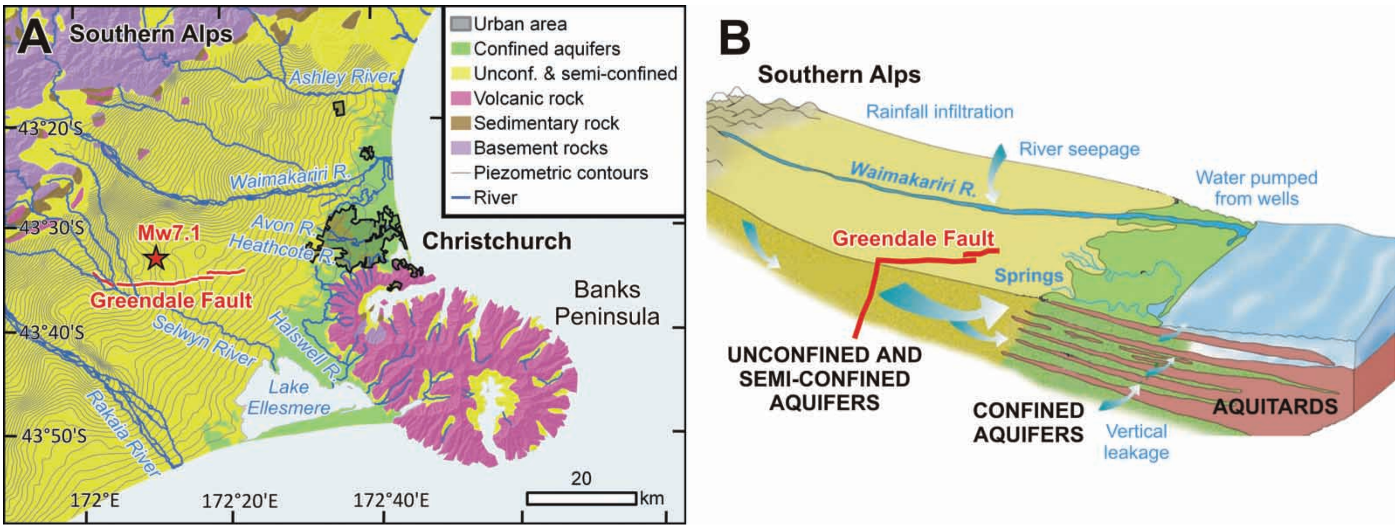

Figure 1 Location diagram. **A**, Map showing Canterbury Plains, Greendale Fault, the M_W7.1 Darfield (Canterbury) earthquake epicentreand the main river systems. The area of coastal confined aquifers (green) is distinguished from unconfined and semi-confined gravels of inland Canterbury Plains (yellow). A thickness of 3 m has been mapped to represent confidence in a continuous layer of surface fine-grained sediments which acts as the aquifer confining layer (after Talbot et al. 1986; Brown & Weeber 1992). **B**, Schematic cross-section showing Canterbury aquifers and groundwater (adapted from figure by Environment Canterbury, J. Weeber).

confined, groundwater either flows into near-surface gravel channels as springs which provide base flow of the Avon, Heathcote and Halswell rivers, or flows into confined aquifers.

The regional groundwater flow produces large vertical hydraulic gradients within the Christchurch confined aquifer system (Talbot et al. 1986; Lough & Williams 2009). Groundwater in confined aquifers beneath Christchurch city's eastern suburbs is under high pressure, with static heads in boreholes 100 m deep reaching >10 m above sea level (Talbot et al. 1986). Piezometric levels are significantly deeper below the inland Canterbury Plains, reaching as much as 70 m below ground level in unconfined and semi-confined aquifers near Darfield. Groundwater yields tend to vary laterally over short distances beneath inland Canterbury Plains, suggesting that localised channels of more-permeable gravel are a significant feature of the flow regime (Bal 1996; White et al. 2007a; Lough & Williams 2009).

The pattern of flow in deeper aquifers is probably also southeastward then upward (e.g., Taylor 1996). Flow in deep confined aquifers may discharge to springs or continue some distance offshore, discharging on the continental shelf, or may continue only a relatively short distance east of the coast, with groundwater becoming entrapped by changes in grainsize and/or the presence of less-permeable Banks Peninsula volcanic rocks (Brown & Weeber 1992, 1994; Stewart et al. 2002). The confined aquifers have little capacity for extra storage so small changes in storage, for example, caused by the passage of seismic waves, can result in relatively large changes in piezometric levels. Confined and semi-confined aquifer storativity is typically 10^{-3} to 10^{-5}, whereas for unconfined aquifers drainable porosity (specific yield) can be as high as 0.1 (Brown & Weeber 1992). Seasonal fluctuation in groundwater levels is as much as 15 m in the unconfined and semi-confined aquifers of inland Canterbury, but <6 m in coastal confined aquifers, and c. 1 m for the shallow water table perched above the coastal confined aquifers (Bowden et al. 1983; Beca 2005). Around 30,000 irrigation and domestic supply wells are consented for groundwater abstraction, which amounts to c. 1250 million m^3 yr^{-1} (Environment Canterbury 2011d).

Data

The hydrological effects of the M_W7.1 Darfield earthquake were recorded by large networks of recorders in almost every region of New Zealand. The Canterbury monitoring network is operated by the Canterbury Regional Council (Environment Canterbury) with 125 local monitoring boreholes recording at 15-min intervals at depths ranging from 5 to 405 m, including a number of piezometer 'clusters' where boreholes in close proximity monitor water levels at differing depths. Confined artesian aquifers are mostly monitored with pressure transducers installed below the lowest expected groundwater level, some of which also record temperature. The pressure transducers have a limited operating range, so there is potential for particularly large shifts beyond this range to be missed. Alternatively, floats and counterweights attached to pulley-driven encoders and data loggers are used for many unconfined aquifers. These tend to be less reliable when groundwater levels change very rapidly, for example, as can occur as a result of an earthquake. Unfortunately, the M_W7.1 Darfield earthquake, or its aftershocks in particular, have damaged some recorder installations (Environment Canterbury 2011a,c). Around 214 boreholes are measured manually on a monthly basis, from which any earthquake-induced departure from long-term averages can also be defined. Anecdotal observations of local irrigation and domestic supply wells are available from a large number of users in Canterbury. The National Institute of Water and Atmospheric Sciences (NIWA) and Environment Canterbury also measure rainfall and make continuous stream and river recordings at c. 40 sites in Canterbury. Other types of piezometric data (some of it recorded at a sub-2-min sampling interval) have also been collected, including at sites where aquifer testing was being carried out, for example, from Selwyn District Council groundwater supply wells and observations from private users. Farther afield, piezometric data were obtained from Environment Southland, Otago Regional Council, Marlborough District Council, Hawke's Bay Regional Council, Northland Regional Council, Tasman District Council and Contact Energy. These organisations generally process and check data with some form of quality control, make barometric pressure corrections where appropriate, and then add them to long-term monitoring databases – some of which are published online. In this study we drew upon groundwater level observations from throughout New Zealand, including 166 monitoring boreholes and 5 local irrigation wells. Of these, 98 are from the near-field (<50 km) and 73 from the far-field (>100 km) (Table 1). Earthquake-related responses were recorded in 120 of the boreholes and wells examined, while 51 had no observable response.

Short- to medium-term groundwater response

Classification and examples

Nine types of response were recognised in data collected during the two months immediately following the M_W7.1 Darfield earthquake, which reflect a range from short transient changes to medium-term and potentially permanent changes in groundwater level. Selected examples of hydrographs from Environment Canterbury monitoring sites are presented in Figs 2A–2C. A colour-coded classification scheme was used to describe and aid recognition of response types (Fig. 2D, Table 1). The different styles probably reflect varying influences of: (1) aquifer properties and groundwater movement in the aquifer; (2) borehole damage, for example, depth changes due to sediment inflow; (3) uplift-related changes in land surface and/or borehole

Table 1 Outline of short- to medium-term borehole response types, distinguished also on the basis of: near-field (< 50 km) vs. far-field (> 100 km) distance from the M_W7.1 Darfield earthquake epicentre; shallow, intermediate and deep boreholes for all of New Zealand; and in the near-field area for shallow-intermediate (0-80 m) vs deep (> 80 m) boreholes. See also Fig. 2D and Supplementary file.

		Location		Depth			Near-field	
Type	Total	Near-field < 50 km	Far-field > 50 km	0–30 m	31–80 m	> 80 m	0–80 m	> 80 m
Red, slope change + ve	9	9	0	0	2	7	2	7
Pink, slope change − ve	1	1	0	0	1	0	1	0
Yellow, step offset + ve	13	11	2	4	3	6	7	4
Blue, step offset − ve	17	6	11	10	1	6	4	2
Green, spike offset + ve	24	22	2	10	5	9	14	8
Brown, spike offset − ve	16	15	1	6	5	5	10	5
Orange, spike + ve	31	28	3	18	4	9	4	9
Orange, spike − ve	9	4	5	7	1	1	19	0
White, no response	51	2	49	44	6	1	2	0
Total	171	98	73	99	28	44	63	35

elevation; (4) sampling frequencies with respect to the rate of groundwater level oscillations; and (5) the characteristics of boreholes, such as diameter and completion method.

To describe hydrological responses, we adopt the terms 'coseismic' for changes observed in the first 12 h after the earthquake and 'post-seismic' for changes in the period 12–24 h after the earthquakes. After 6 weeks it was generally no longer possible to distinguish earthquake-induced effects from other piezometric fluctuations, particularly as the late-spring irrigation abstraction and seasonal variations in precipitation became important influences on groundwater levels. One year after the Darfield M_W7.1 earthquake there are some sites at which groundwater levels have deviated from long-term average seasonal trends (see Aquifer Properties section below). No clear precursory responses have been identified in the data, although there are some fluctuations that occurred prior to the expected arrival times of seismic waves and anecdotal observations from the public that warrant further, more careful, investigation and explanation in a later study.

By far the most common hydrological response to the earthquake was a short coseismic spike, either positive or negative, followed by a return to pre-earthquake levels within a relatively short period of 30–60 min (orange spike positive, or orange spike negative; e.g., Fig. 2A, M35/1878). Also common were changes involving a coseismic spike followed by a post-seismic shift to a new higher level (spike-offset positive = green; e.g., Fig. 2A, Fig. 2B, M35/0931, M36/4633) or to a lower level (spike-offset negative = brown; e.g., Fig. 2B, M36/4634, M35/6107). A borehole at Puriri Park in Whangarei, Northland, had a spike-offset negative response (see below), but its unusually sensitive 2-min sampling rate showed the shift to a lower level involved numerous positive and negative oscillations in the first 30 min. Such oscillations may not be fully recorded by monitoring at the 15-min sampling interval generally adopted by regional councils throughout New Zealand. Rapid step changes to new piezometric levels, either positive (yellow) or negative (blue; e.g., Fig. 2A, K36/0493), may have involved < 10-min spikes or other high-frequency oscillations that were simply not recorded at 15-min sample intervals. The responses which potentially reflect permanent changes to aquifers are those where the hydrographs changed slope at the time of the earthquake, which are interpreted to represent a change to the recharge or discharge rate of the aquifer as a whole. Such a response, assigned the name 'slope-change' can have either a positive (red) or a negative (pink) value and was observed primarily in the deeper boreholes. A number of 'slope-change' responses occurred with no clear short-term spike, meaning that any fluctuations must have been restricted to a period < 15 min. Elsewhere, multilevel piezometers show large piezometric responses at depth which lasted days, whereas shallower level responses involved only small, relatively subdued, short-term spikes (e.g., Fig. 2C). Where responses involved both spike oscillations and slope changes (e.g., Fig. 2A, L36/1226), the longer term response type was assigned to the borehole. If no change was observed, the lack of groundwater level response was recorded and coded white.

Near-field piezometric responses in Canterbury

Short- to medium-term response-types in the near-field, < 50 km from the epicentre, show a considerable degree of spatial variability with depth (Table 1) so that patterns of behaviour are not immediately obvious in map-view (Fig. 3). Red (slope-change positive) responses occurred in intermediate and deep boreholes to the west of the Greendale Fault; blue (step offset negative) responses occurred in the periphery of the near-field area, mostly > 20 km from the fault; brown (spike-offset negative) responses occurred in the area of shallow confined aquifers along the coast, beneath Christchurch city and some deep semi-confined aquifers near Lake Ellesmere (see Fig. 2B); yellow (step offset positive) and green (spike-offset positive) responses occurred in semi-confined and unconfined aquifers beneath Canterbury Plains

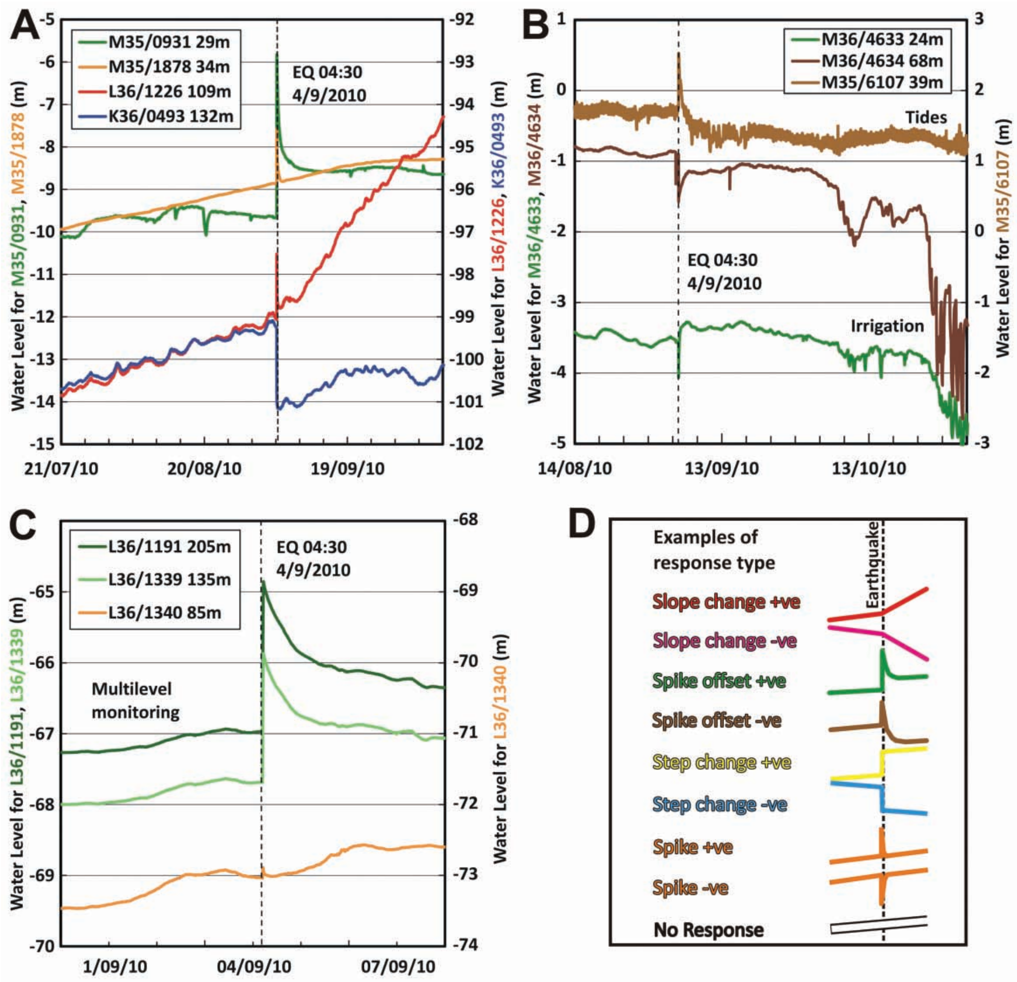

Figure 2 Selected response examples of groundwater level changes in monitoring boreholes. See Fig. 3 for the location of these boreholes. **A**, Responses from M35/0931 M35/1878 (intermediate depth) and L36/1226, K36/0439 (deep). **B**, M36/4633 (green) and M36/4634 (brown) from the same site, in aquifers at 24 and 68 m depth, respectively, show opposite changes in groundwater level reflecting transfer from the deeper aquifer where pressures are near-artesian, to the lower pressure shallower aquifer. The effect of tidal oscillations (M35/6107) and groundwater abstraction (M36/4633, M36/4634) are also evident in these hydrographs. **C**, Multilevel piezometers L36/1191 (205 m) and L36/1339 (139 m) show spike offset positive (green) responses in deepest aquifers, but a minor short-term spike response in L36/1340 at 85 m. **D**, Classification scheme of borehole responses based on the shape of hydrographs, ordered from potentially permanent (top) to transient and no observed response (upper). The colour codes are used throughout this paper.

(see Fig. 2C) and immediately adjacent to the Port Hills; orange spike positive and spike negative responses are found throughout the near-field region. There were no consistent patterns in the type of response when separated into deep (>80 m), intermediate (30–80 m) and shallow (<30 m) intervals (Table 1). Where multilevel piezometers recorded the responses at different depths for the same location, those in confined or semi-confined aquifers at greater depth tended to show more significant responses (e.g., Fig. 2C).

Piezometric changes in the deep (>80 m) and shallow–intermediate (0–80 m) boreholes were separated into coseismic (0–12 h) and post-seismic (12–24 h) categories, gridded and contoured using the natural neighbours function (Sibson 1981) in ArcGIS (Fig. 4). The maximum sized responses occurred immediately adjacent to the Greendale Fault, where irrigation boreholes within 2 km of the trace became artesian for c. 12 h after the earthquake, bringing turbid groundwater to the surface where the piezometric surface is normally c. 20–50 m below ground level.

The pattern of coseismic groundwater level shifts in deep aquifers is strongly centred on the Greendale Fault, with most of the boreholes recording a positive groundwater-level change and only three boreholes having groundwater-level decreases (Fig. 4A, blue crosses). A striking anomalous zone was present in deep aquifers within 20 km of the fault (Fig. 4A). Once coseismic oscillations had settled, the remaining piezometric response was much less pronounced, peaking at +5 m, but had spread outwards away from the fault (e.g., compare +2 m contour in Figs 4A, 4C).

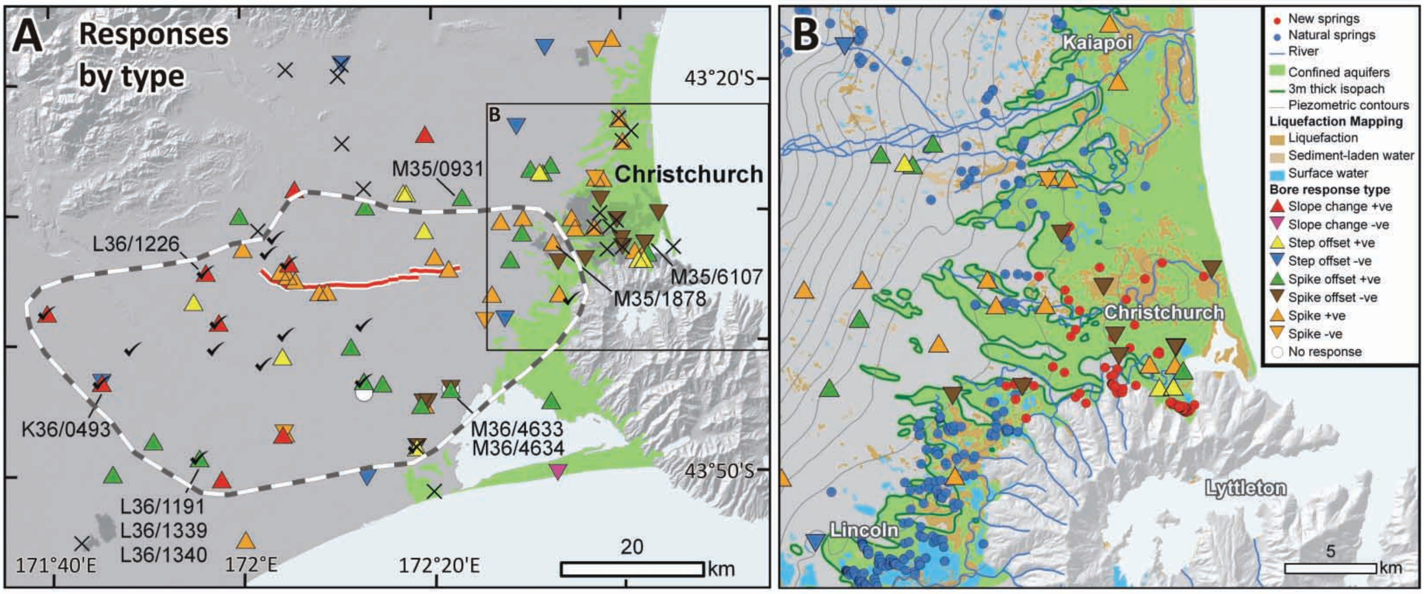

Figure 3 Near-field responses. **A**, Map of borehole groundwater responses over the Canterbury region. Symbols are colour-coded according to different response types (see Fig. 2D). Coastal confined aquifers (light green area) and the Greendale Fault (red line) are also shown. Selected example or important boreholes (Figs 2A–2C) are individually labelled. Ticks represent boreholes (some measured monthly) where abnormally high groundwater levels were still present in October 2011, with the region highlighted by a dashed white/dark grey line. Crosses show where groundwater levels returned to normal. **B**, Enlargement of the Christchurch urban area, also showing borehole responses, isopiezometric contours and new springs (red circles) that emerged following the M_W7.1 Darfield earthquake, compared with the location of seasonally influenced 'natural' springs (blue circles) documented by Environment Canterbury to be present prior to (and presumably after) the earthquake. Mapping of liquefaction, sediment-laden water and ponded surface water following the earthquake is from aerial and satellite images, but with limited ground truthing (Unpublished work carried out by GNS Science, Canterbury University and Tonkin & Taylor. Dougal Townsend, pers. comm.).

The geographic distribution of boreholes in shallow–intermediate (0–80 m) aquifers is different from those in deep aquifers. There are few shallow–intermediate boreholes to the west and north of the Greendale Fault, where groundwater levels tend to be relatively deep, and this may cause some bias to the map-view pattern of responses around the fault. Shallow–intermediate boreholes showed some coherent areas of piezometric level falls, as well as piezometric level rises around the Greendale Fault which were similar but smaller than the deep borehole responses. In the coseismic interval, changes of -0.2 to -0.7 m were recorded in the west but the largest fall (-4.7 m) was recorded 10 km southeast of the fault in the Selwyn District Council groundwater supply well at Springston (M36/8178; Fig. 4B). A pronounced change occurred in shallow–intermediate aquifers beneath Christchurch, where initial increases were followed by a decrease in piezometric levels during the post-seismic interval, corresponding to responses classified as spike-offset negative (brown; Fig. 3). A northeast–southwest trending corridor of pressure decrease c. 7-km wide follows the boundary between semi-confined and coastal confined aquifers (Fig. 4D). We suggest that either groundwater pressures fell as the confining layers have been breached, and/or groundwater was forced out of the aquifers up onto the surface (Fig. 3B, see surface water). Note that coseismic (Figs 4A, 4B) vs post-seismic (Figs 4C, 4D) responses are illustrated with different colour ranges in Fig. 4 to accentuate the subtleties of these smaller changes away from the Greendale Fault (although the same colour scale is used within each time interval). By integrating level changes across the grid areas and assuming a uniform storativity of 10^{-4}, we estimate that the coseismic responses represent a 1.1×10^6 m^3-equivalent volume of groundwater, with a smaller 0.3×10^6 m^3 post-seismic response. Both these values are only a small fraction of the annual 1250×10^6 m^3 consented groundwater allocation (Environment Canterbury 2011d).

Greendale Fault motion was dominated by right-lateral strike slip (max. 5.3 ± 0.5 m, average 2.5 ± 0.1 m), but locally included up to 1.4 ± 2 m of vertical displacement (Quigley et al. 2012) and uplift/subsidence of up to 100 mm was measured geodetically within 10 km either side of the fault (Beavan et al. 2010). Responses shown in Fig. 4 were not corrected for vertical ground motion (e.g., Beavan et al. 2010), as both coseismic and post-seismic groundwater level shifts are at least an order of magnitude larger than the local ground motion at the borehole sites. Clearly there is little expression of the vertical displacement in groundwater levels, such as might be caused by offset aquifers, an offset piezometric surface or wider changes in borehole elevation

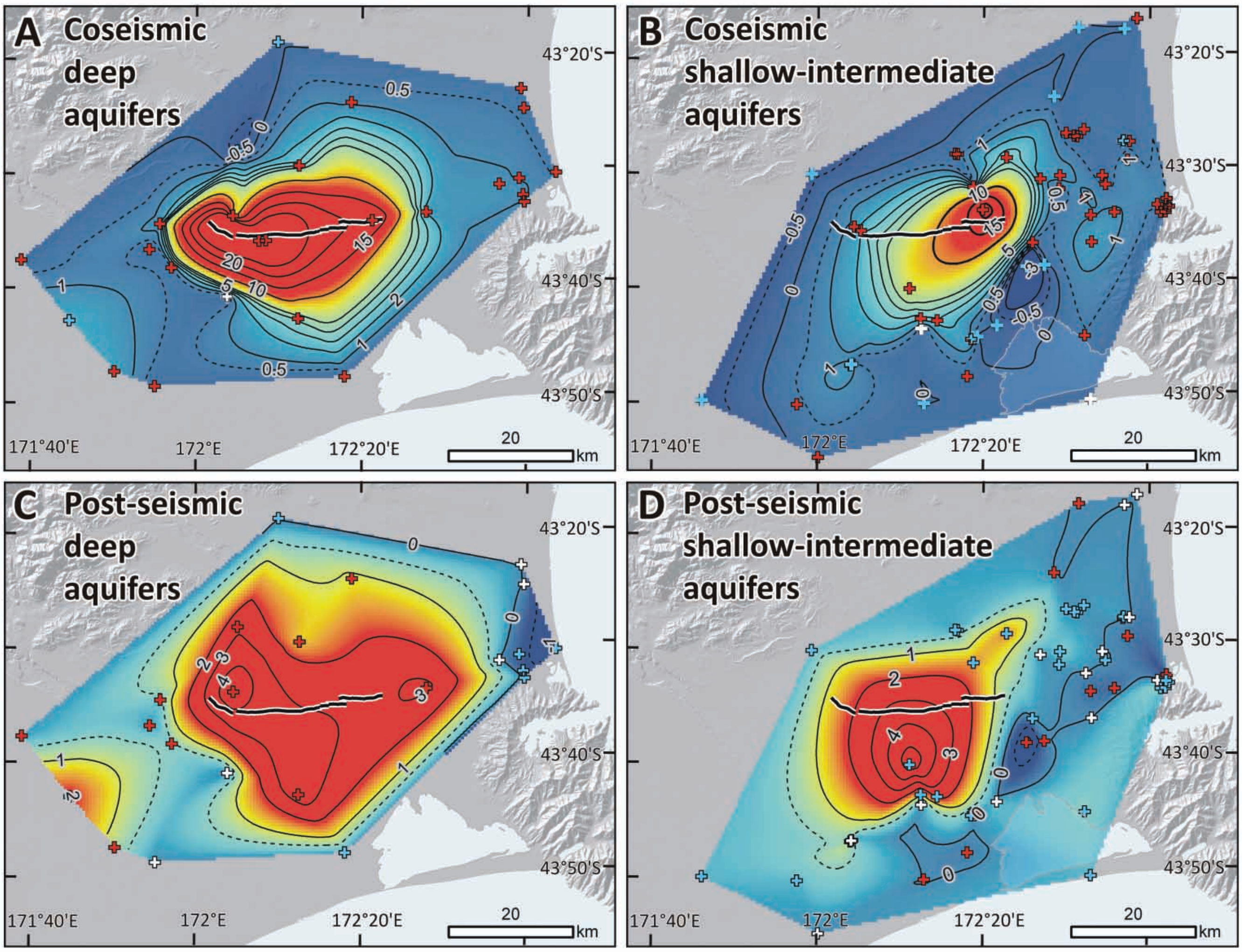

Figure 4 Canterbury groundwater responses as contour maps and coloured grid models. **A**, Coseismic (0–12 h) response in deep (>80 m) boreholes. **B**, Coseismic response in shallow–intermediate (<80 m) boreholes. **C**, Post-seismic response (12–24 h) in deep boreholes. **D**, Post-seismic response in shallow–intermediate boreholes. Contour intervals at 0, 0.5, 1, 2, 3, 4, 5, 10, 15, 20, 25 m and negative equivalents map increases and decreases in borehole peizometric levels. Note the data point distribution (crosses) is colour coded differently from other diagrams (red = increase, white = no change, blue = decrease) and the range of the colour palette is different between the coseismic and post-seismic intervals.

by uplift/subsidence, which would generate asymmetry with level increases on the downthrown northern side.

Far-field responses

Short- to medium-term changes in piezometric levels occurred throughout New Zealand (Fig. 5), although many monitored boreholes in the far-field (>100 km from the earthquake epicentre) showed no response to the M_W7.1 Darfield earthquake. Observed far-field changes were either coseismic spikes (orange), step offset changes (blue or yellow) or a combination spike and step offset (brown or green) and nearly all involved changes of <1 m (Table 1). Step offsets to sustained lower levels (blue response) were by far the most common type of change, being recorded at nearly half of the far-field boreholes. No slope-change response styles (red or pink) were observed in the far-field.

A thermal spring at Copland valley, located in the Southern Alps 175 km from the epicentre (Fig. 5), cooled by 1.1 ± 0.2 °C from normal background temperatures of c. 57 °C, with the start of cooling delayed around 140 ± 15 min after arrival of seismic waves. At the time, monitoring was being carried out by GNS Science using a submerged Hobo U12-015 logger (relative precision ±0.04 °C, accuracy ±0.4 °C) (Cox & Strong 2009). The seismic waves are interpreted to have changed the fracture permeability of the schist mountains adjacent to the spring, opening fractures and allowing greater quantities of cool surface groundwater to mix with upwelling hot groundwater (Cox et al. 2010).

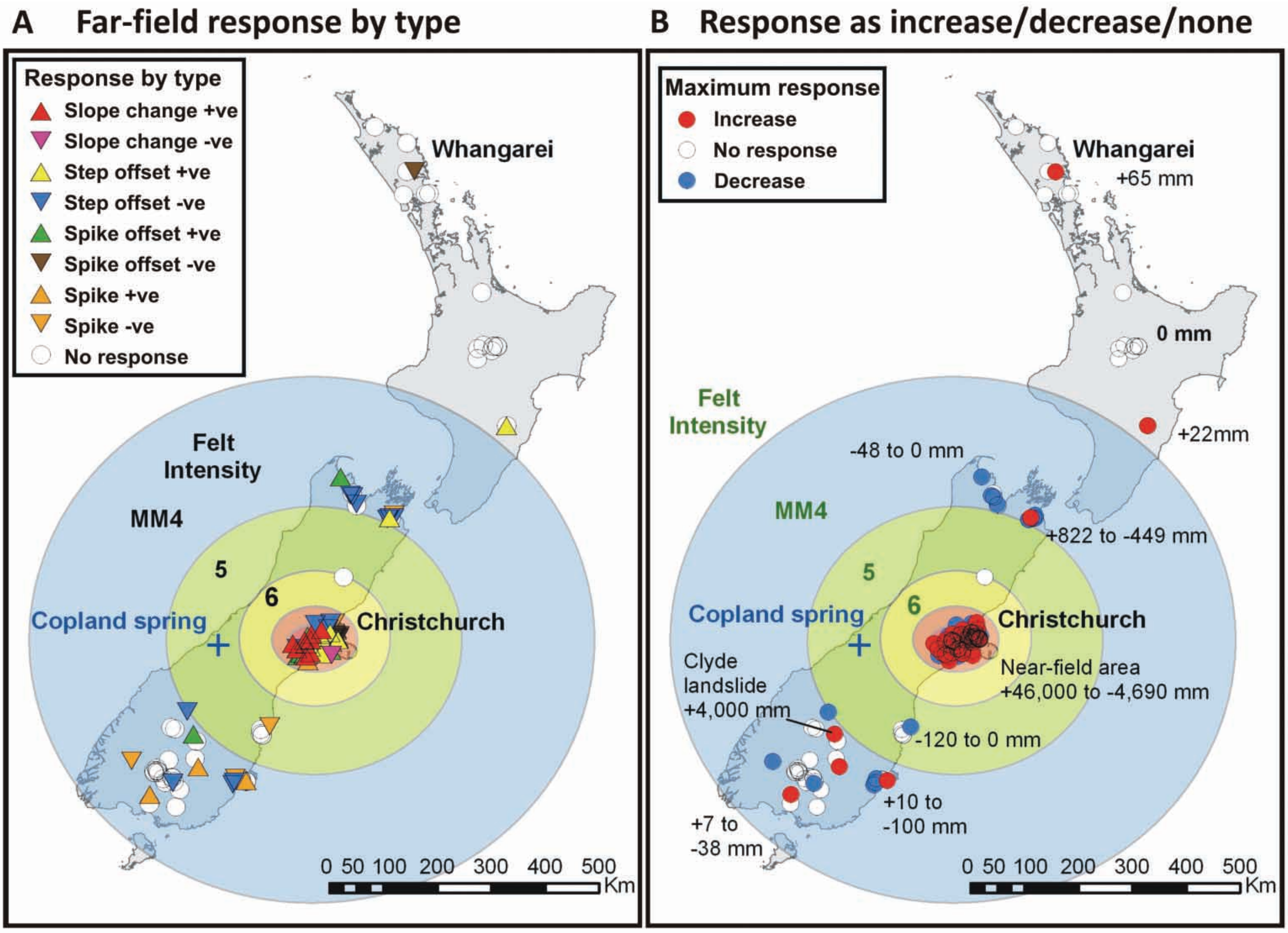

Figure 5 Far-field groundwater responses throughout New Zealand overlain on isoseismal map of shaking intensity (GeoNet 2010). **A**, Distribution of different response types as outlined in Fig. 2D. **B**, The maximum coseismic or post-seismic response. The location of Copland warm spring, Whangarei and Clyde landslide (DL/545) are also shown. The figure illustrates the large distances over which responses have occurred, the distribution of data and places where responses have/have not been observed, and that far-field responses include both transient (orange) and medium-term (brown, green, blue, yellow) changes.

The largest far-field response occurred in the Nine Mile landslide near Clyde, central Otago, where Contact Energy monitor an extensive network of piezometers and tunnel-flow weirs above a hydroelectric dam. Landslides in schist rock present a safety hazard to the impounded lake, now mitigated by tunnels and boreholes draining compartmentalised groundwater (Gillon & Hancox 1992; Macfarlane et al. 1992). The large +4 m response in borehole DL/545 following the M_W7.1 Darfield earthquake reflects movement of groundwater through perched aquifers of the landslide (Fig. 6A). Drainage-depressed piezometric pressures appear to be re-equilibrating towards their more natural level at c. 340m asl. DL/545 piezometric levels have lifted by 2–5 m on at least five previous occasions in response to earthquakes in Fiordland, including the 2009 Dusky Sound M_W7.8, but in each case have recovery over recession periods of 200–300 days. Nearby sesimographs recorded peak ground accelerations (PGA) <0.01 g (1 $g=9.8$ ms^{-2}) for all of these earthquakes (GeoNet 2010). The pressure response and hence volume of fluid associated with each earthquake seems relatively uniform given the variation in earthquake magnitude and the local intensities of shaking. It is also interesting to note how groundwater levels in the landslide are slowly rising as, for example, mineral precipitation and clay weathering slowly decreases the overall efficiency of the drainage system.

Groundwater levels in a borehole in basalt at Puriri Park, Whangarei, regularly respond to large earthquakes located at great distances. Having recorded the M_W7.8 Dusky Sound (Fiordland) earthquake at 15-min intervals, the Northland Regional Council reset the sampling rate to 1-min intervals (Fig. 6B). The record of the M_W7.1 Darfield earthquake clearly shows the greater degree of fluctuations that can be observed with higher sampling frequency, potentially missed in other networks and classification of responses. Responding equally to PGA of 5×10^{-5} g

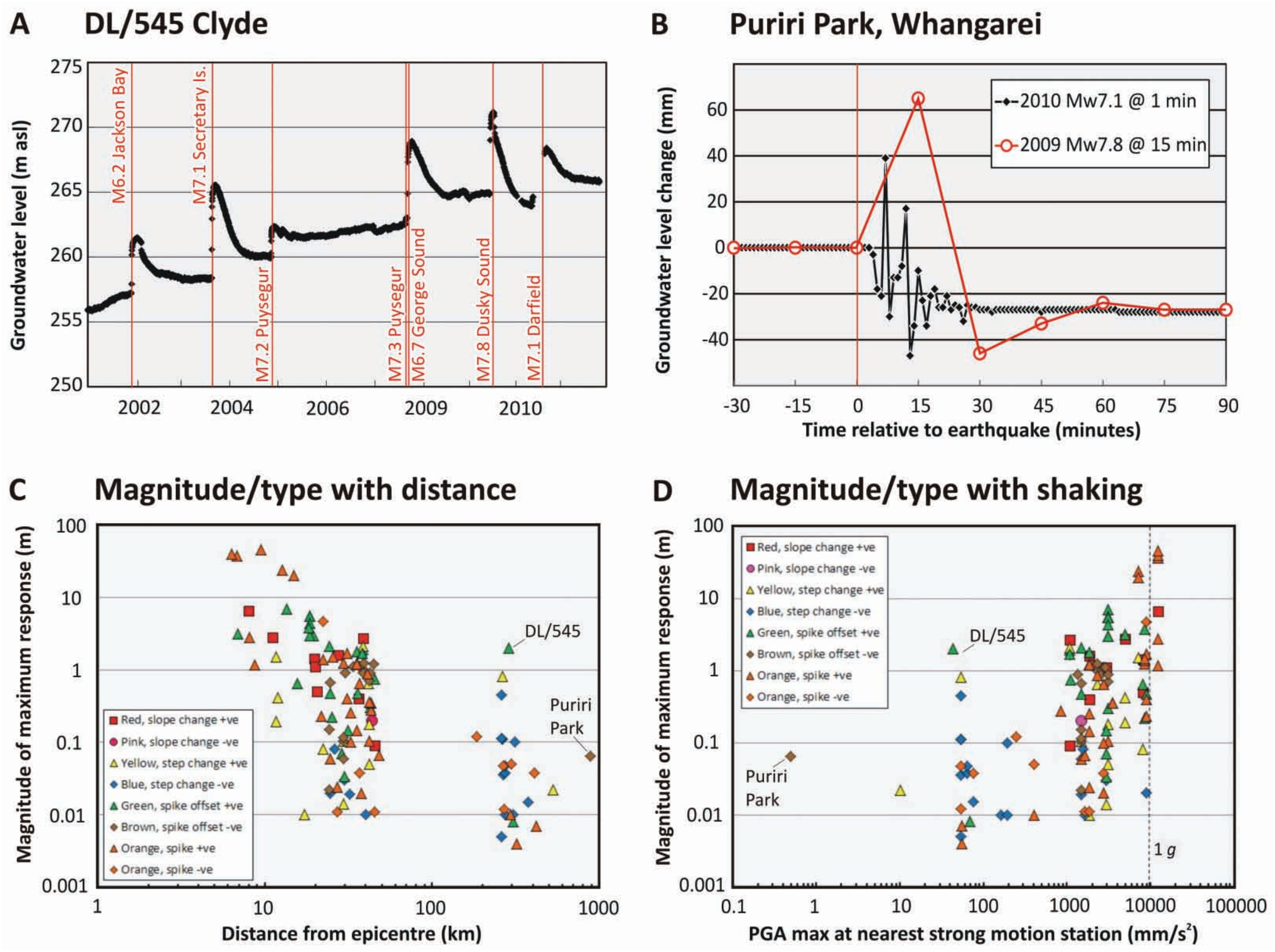

Figure 6 Far-field response style and magnitude. **A**, Ten-year history of responses in landslide monitoring borehole DL/545 at Clyde, central Otago, showing far-field effects of multiple earthquakes (mostly from Fiordland). **B**, Responses of Northland Regional Council monitoring borehole at Puriri Park, Whangarei. Note the earthquakes are recorded at different 15- and 1-min sampling intervals for the M_W7.8 Dusky Sound (Fiordland) 2009 and M_W7.1 Darfield (Canterbury) 2010, respectively. **C**, Graph showing the magnitude of groundwater response (absolute value of the maximum increase or decrease) with distance from the earthquake epicentre, with symbols coloured according to response type (as per Fig. 2D). **D**, Magnitude of response versus the peak ground acceleration (PGA) measured at the nearest GeoNet strong motion seismic station (GeoNet 2010).

(M_W7.1 Darfield earthquake) and $2 \times 10^{-3}g$ (M_W7.8 Dusky Sound earthquake), the borehole appears to have a characteristic –27 cm drop that takes 1 h. Similar responses were recorded to earthquakes in Sumatra M_W9.1 2004, Solomon Islands M_W8.1 2007, Samoa M_W8.1 2009, Chile M_W8.8 2010 and Japan M_W9.0 2011.

The magnitude of the maximum change in groundwater level (positive or negative, coseismic or post-seismic) shows a negative correlation with distance from the earthquake epicentre (Fig. 6C; see also Wang & Manga 2010b). To compare hydrologic responses with a measure of seismic shaking intensity, the magnitude of the maximum groundwater level change was plotted against the PGA measured at the nearest GeoNet strong motion seismometer (Fig. 6D; GeoNet 2010). In most cases seismometers are reasonably close, on average within 14 km of monitoring boreholes, although the nearest seismometer is over 45 km away for two boreholes (in Southland and Hawke's Bay at 376 and 530 km, respectively, from the epicentre). Unfortunately, since most seismometers are located on bedrock sites, there are some local differences in the ground strength conditions to the gravel aquifers in which many of the boreholes are sited (and hence shaking experienced). The comparison in Fig. 6D provides a simplified first approximation only, but highlights the wide range in responses at any given distance, the difference between near- and far-field responses, and the scale of responses that may be expected during future events. Minor groundwater level changes appear common at 400 km distances and occur up to 1000 km from earthquake epicentres, even though shaking intensities are less than Modified Mercalli Intensity (MM) 3–4 (weak to largely observed) and PGA much less than 0.01 *g*. It appears that boreholes sited in rocks with low storativity and permeability, such as DL/545 in the Clyde Dam schist landslide or the Puriri Park borehole in basalt, tend to be more sensitive to seismically induced groundwater level changes than those in Quaternary gravel aquifers.

New springs

Springs naturally emerge on the Canterbury Plains, either in northwest–southeast trending depressions where the Rakaia and Waimakariri alluvial fan complexes coalesce along the Selwyn and Ashley Rivers, or across the plains in a broadly northeast–southwest trending zone marking the transition from unconfined and semi-confined aquifers to the confined coastal aquifer zone (Fig. 3B; Talbot et al. 1986). Warm thermal springs also occur in the vicinity of the Port Hills, and these are thought to be meteoric and seawater warmed by deep circulation and upwelling, rather than volcanic activity (Brown & Weeber 1994; Reyes et al. 2010). Prior to the M_W7.1 Darfield earthquake, relatively few springs emerged through the Christchurch confined aquifers in the south and east of the city (White et al. 2007b), but immediately following the earthquake a series of new springs began to flow in this area (Fig. 3B). Some springs appear to have resulted from a breach of confining layers, perhaps by fracture or liquefaction, which allows artesian pressures to drive upwards flow to the surface. Such responses are consistent with spike-offset negative (brown) response styles in boreholes (as illustrated by M36/4634 in Fig. 2B). Flows in new springs immediately adjacent to the Port Hills appear to be caused by increased permeability and the development of new fracture-pathways through volcanic rocks (Rutter 2011), or leakage near the contact between Quaternary sediment and volcanic rock, producing a general rise in shallow groundwater levels and boreholes with step offset positive (yellow) responses (Fig. 3B). There has also been some reactivation of old, sealed boreholes through damage to casing or pipework at the surface, generating flows that can appear like 'natural' springs. Most springs are little more than seeps, but some have substantial flow (up to 10 L s^{-1}). The combined flow appears to be a minor proportion of total groundwater flow in the Christchurch area, so the loss does not pose any risk to sustainability of the groundwater resource (Environment Canterbury 2011c). Nonetheless, the springs have resulted in house foundations being inundated, with the concomitant risk of loss of strength and potential for movement of the dwellings, as well as issues concerning dampness (Rutter 2011). The emergence of springs at the base of the Port Hills and changing groundwater pressures in this region also raises the potential for increased landslide hazard.

Potential changes in aquifer properties

An important issue for groundwater users that arose immediately after the M_W7.1 Darfield earthquake was whether aquifer damage had occurred, either locally or regionally. Users initially reported three main observations: (i) increased turbidity; (ii) groundwater levels showed abrupt changes (as described above); and (iii) numerous boreholes showed a decline in yield. At the time of writing, one year after the event, it may seem premature to investigate longer term responses given that only one set of post-earthquake seasonal variations has been experienced. Nonetheless, given user concerns and the economic importance of irrigation, we present some preliminary observations and results. In this section, we describe approaches taken to assess whether groundwater level and yield changes represent a temporary response or a more permanent change in aquifer properties.

Hydraulic characteristics and well losses

It is difficult to assess changes in aquifer characteristics without carrying out constant rate aquifer tests on boreholes that had already been tested prior to the earthquakes. As a proxy, there are other, less direct, methods of assessing whether there have been any changes, including step-testing, and assessment of any changes in recession rates, or barometric or tidal efficiency. Step-drawdown tests (Eden & Hazel 1973) can be used to measure aquifer transmissivity. A borehole (M36/6998), situated only 150 m from the Greendale Fault trace, was tested a short time before the M_W7.1 earthquake (17 March 2010) and was tested again (24 September 2010) shortly after the event. The transmissivity estimates from both tests were c. 5000 m^2 d^{-1} but post-earthquake well losses were 86% compared with pre-earthquake well losses of 52%. Whilst this was a single test, and step-tests are not the most accurate means of determining transmissivity, it suggests some of the observed changes might be caused by local effects around the borehole, such as an increase in fine-sediment being carried into the screened interval of the borehole, rather than an impact on the whole aquifer. The testing does not, however, account for any potential changes in storativity.

We also analysed recession rates in 10 shallow to intermediate level boreholes within the near-field area. Bores were chosen so as to provide an even geographic distribution across the region and based on the cleanness and appropriateness of their data. The slope of post-earthquake summer recession in late 2010–2011 was compared with the equivalent seasonal recession from 2000 to 2009 (Fig. 7B). Of 10 boreholes analysed, 5 showed no discernable change in recession rate. These include M35/1205, M35/4781, M36/0183, L35/0180, M35/6936 (the latter two are

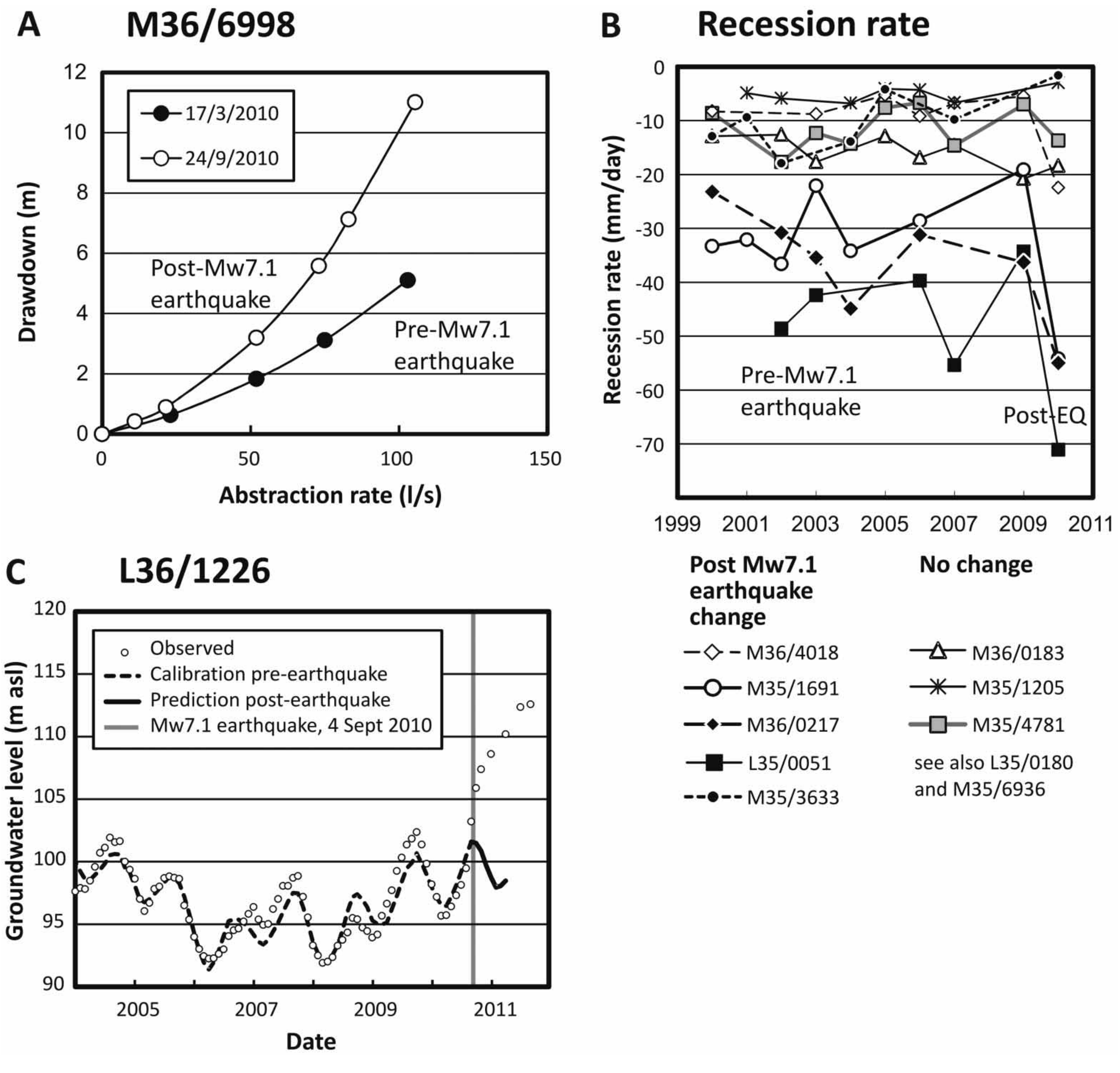

Figure 7 Aquifer properties and potential long-term effects. **A**, Step tests performed in M36/6998 on 17 March 2010 (pre-M_W7.1 Darfield earthquake) and 24 September 2010 (post-M_W7.1 Darfield earthquake). The borehole is only 150 m from the Greendale Fault. **B**, **C**, Observed and modelled groundwater levels in L36/1226 using an eigen model incorporating rainfall recharge. The borehole did not show the normal seasonal recession during spring–summer 2010 despite normal abstraction of groundwater for irrigation. The model was unable to reproduce the observations, suggesting there has been a significant change in aquifer properties.

omitted from Fig. 7B for clarity). Four boreholes (L35/0051, M35/1691, M36/0217, M36/4018) showed a probable increase in recession rate (i.e. groundwater levels recessed at a greater rate) and the rate in one borehole may have decreased (M35/3633). The changes were more pronounced in boreholes that had historically higher recession rates prior to the earthquake (>0.02 m d^{-1}), which might be expected if the initial head was higher or if aquifer storativity decreased/permeability increased. Further monitoring and assessment is needed to determine whether these are in fact long-term changes in aquifer properties, although this will not be meaningful where boreholes have been redeveloped or flushed. By contrast, assessment of barometric and tidal efficiency changes in 16 boreholes was inconclusive, showing a mixture of positive and negative changes, but commonly within the uncertainties of the method and data. The assessment is expected to be improved by future studies once a longer period of post-earthquake observations has been obtained.

Persistent changes in groundwater levels

Anecdotal evidence suggested that during the year following the M_W7.1 Darfield earthquake, piezometric levels in some inland, deep boreholes, were higher than might be normally expected despite seasonal abstraction for irrigation being little different from in previous years. This was confirmed by a review of Environment Canterbury monitoring data up to October 2011 in which a number of the deep inland boreholes, particularly those where groundwater levels showed positive slope-change (red) responses, were experiencing groundwater levels that were higher than normal, with some exceeding previous record levels. Places where sustained high groundwater levels were observed lie within a 70×40 km area around the Greendale Fault (Fig. 3A). Places where rises were not sustained have also been noted (Fig. 3A). Good examples of high levels are boreholes L35/0790, L35/0884, L36/0064 and L36/1226. In the summer of 2010–2011, several of these failed to show the normal recession that usually begins around September or October, as recharge decreases and irrigation abstraction begins (e.g., L36/1226, L35/0790 and K36/0495).

Eigen modelling was used to investigate whether the sustained high groundwater levels observed in several boreholes could be explained by unusual seasonal recharge, or were better explained by an earthquake-induced 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 the same abstraction scenario in the catchment (see also Sloan 2000; H Williams et al. 2008). The method is based on the assumption that the aquifer system is one large homogeneous aquifer with all the boreholes responding similarly, depending on their position in the catchment and groundwater recharge from rivers is constant. Annual simulations were for the years 1967 to 2011 and were calibrated against available data up to the M_W7.1 Darfield earthquake in September 2010. The results (Fig. 7B) 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 shows one of the more dramatic positive slope changes (red) responses in the medium-term (Figs 2A, 3), is used to illustrate the results. The modelled and actual levels illustrated in Fig. 7B for this borehole show not only the departure from the calibrated model prediction, but also the lack of a seasonal recession even though usual volumes of groundwater appear to have been abstracted for irrigation. Given that a sustained rise in piezometric surface is observed in numerous deep boreholes, this suggests 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 Greendale Fault.

Interpretation and synthesis

The Canterbury earthquake sequence produced extreme ground motions and radiated anomalously high levels of seismic energy (Cousins & McVerry 2010; Fry et al. 2011; Reyners 2011; Kaiser et al. 2012). The M_W7.1 Darfield earthquake had an energy magnitude (M_E) of 7.4, whereas the M_W6.2 February aftershock was M_E6.7 (Reyners 2011). Dynamic and static strains associated with the M_W7.1 earthquake were large enough that either might cause measureable hydrologic responses (Manga & Wang 2007; Wang & Manga 2010a,b). Some earthquakes generate patterns of groundwater level change that mimic the pattern of volumetric strain, such as an X-shaped pattern of rise and fall in compressional and dilational quadrants around a strike-slip fault (e.g., Jonsson et al. 2003). However an X-shaped pattern of rises and falls predicted by strike-slip Coulomb stress change models (e.g., CA Williams et al. 2011; Zhan et al. 2011) did not develop in groundwater levels around the right-lateral Greendale Fault. Instead, the symmetric O-shaped pattern centred on the fault (Fig. 4A) suggests the response is a consequence of dynamic strains rather than static strains. The area of the most significant hydrological response, within 20 km of the Greendale Fault, matches a region with anomalously low Vp/Vs seismic wave speeds at depths of 3–8 km (M Reyners & D Eberhart-Phillips, GNS Science, pers. comm.). One possibility is that the stress change from the earthquake and its rich aftershock swarm induced dilation of the rock mass at depth, generating fracture connectivity and permeability sufficient to produce a vertical flow zone. Strongly elevated pressures were recorded in the short- to medium-term (Fig. 4), but longer term effects in gravel aquifers are possibly driven by fluid-pressure and changes to flow-paths through greywacke basement at depth and/or nearby mountains. An alternative scenario of ruptured subsurface reservoirs (Manga & Wang 2007), such as from below Miocene volcanics in the buried late Cretaceous–Tertiary sequence, seems unlikely given the period of the longer term response, but cannot be ruled out with our data alone. Observations of turbid water in wells and rivers immediately following the M_W7.1 Darfield earthquake suggest the earthquake agitated fine silt- and clay-sized particles and must have, at least temporarily, changed the interconnectivity of pores and the flow of groundwater in the glacial outwash gravels. Potentially long-term slope change (red or pink) responses were only observed in the near-field region, coinciding approximately with the area where abnormally high groundwater levels were still present one year after the earthquake. The short-term spikes in groundwater level are probably caused by the seismic waves and their interaction with the boreholes and/or aquifers themselves (Cooper et al. 1965), but the temporal resolution of monitoring may not be high enough to exploit these observations for quantitative assessment.

Hydrological responses in coastal confined aquifers differed from those in semi-confined and unconfined aquifers of inland Canterbury Plains. When consolidated sediments or sedimentary rocks are cyclically sheared beyond some critical threshold, microfracture and fracture may occur, leading to increased porosity and decreased pore pressure (Manga & Wang 2007). We propose this dynamic stress mechanism, rather than static stress, may best explain the initial increase, then decrease, of piezometric levels in coastal confined aquifers (brown response) causing fracture formation or unblocking and the appearance of some of the new springs in Christchurch. We postulate below that artesian pressure release and the behaviour of groundwater played a pivotal role in the damage caused to Christchurch city by recent earthquakes.

At far-field distances there are places where 'no response' was observed, but those responses that were observed were widespread, some of them sustained in the longer term (e.g., DL/545 at Clyde). At far-field distances, the static stress due to the earthquake is nearly zero so sustained changes in groundwater level must be caused by dynamic stress associated with passage of seismic waves (Manga & Wang 2007). The magnitude of responses we observed is variable, showing weak trends with epicentral distance or amplitude of ground acceleration, but the far-field shaking was insufficient to produce any slope change responses (red or pink). The boreholes and springs which have responded to multiple far-field earthquakes (e.g., DL/545 at Clyde, Puriri Park and Copland spring) appear to exhibit a characteristic response, interpreted to be due to far-field shaking-induced dilation and enhanced local permeability. Experience from previous earthquakes recorded at Copland spring (Cox et al. 2010) and DL/545 at Clyde suggest far-field recovery of groundwater to pre-earthquake conditions will take approximately one year.

Discussion

Understanding the behaviour of groundwater systems during earthquakes is important in a seismically active country that depends on groundwater for irrigation and drinking water. The M_W7.1 Darfield earthquake and its aftershocks appear to have had a relatively subtle, yet significant, impact on the Canterbury groundwater system. Damage in the subsurface, although less visible than damage to buildings, can be expected given the magnitude of the static stress change and dynamic stresses caused by the seismic waves. The emergence of springs and the vast quantity of liquefied sand and silt carried to the ground surface after the earthquakes are indicators of the subsurface change to the aquifer system. Studies elsewhere have suggested that the impacts of earthquakes on hydrogeological systems may be relatively short-lived (e.g., Geballe et al. 2011) although effects may last many months to a few years or more (e.g., Elkhoury et al. 2006; Claesson et al. 2007; Kitagawa et al. 2007; Manga & Rowland 2009; Rudolph & Manga 2010; Wang et al. 2012). The multiple earthquake responses recorded by DL/545 at Clyde appear to have groundwater-level offset and recovery times in the order of 200–300 d. At this stage, one year after the M_W7.1 Darfield earthquake, it is difficult to know the extent to which the hydrological impacts of the Canterbury earthquakes will be significant and/or long-term, although the preliminary eigen modelling motivates the hypothesis that there are certainly places in the near-field region experiencing significant longer term changes.

Perhaps of wider importance to New Zealand, as well as internationally, is the need to understand why the severity of liquefaction produced by the earthquakes has been so much greater than expected. Earthquake engineers commonly think of liquefaction in terms of Terzaghi's concept, whereby consolidation and densification of loose sediments temporarily increases the pore pressure and results in liquefaction (Seed & Lee 1966; National Research Council 1985; Terzaghi et al. 1996). While Terzaghi's mechanism may be valid in the near-field of an earthquake, it has been noticed that the energy of seismic waves may be too small to induce consolidation and explain occurrences of liquefaction at intermediate- and far-field distances (Wang 2007). This has led to the idea that redistribution of pore pressure by earthquake-enhanced permeability could be an important mechanism that is not accounted for, or replicated, in laboratory experiments (Wang 2007; Wang & Manga 2010a). In the near-field, such processes have potential to provide the additional increment of pore pressure needed to push highly stressed sediments over the critical state to be liquefied, or to initiate secondary liquefaction processes. Redistribution of pore pressure may enable lateral spreading to develop at a larger scale or continue for extended periods – longer than would otherwise be expected from shaking alone (e.g., Zhang et al. 2008).

Liquefaction susceptibility had been recognised for some time in Christchurch and mapped as a function of sediment/soil type distribution, soil strength and water table (e.g., Brown & Weeber 1992; CAE 1997; Beca 2004). Because liquefaction only occurs in unconsolidated (loose) soils that are saturated, water table depths are critical in predictive models. Seasonal variations, which reach c. 1 m in eastern Christchurch, are factored into some assessments (e.g., Beca 2005). However, while liquefaction models may include the position of the water table before an earthquake, they do not yet account for changes induced during/by shaking. Our study highlights that earthquakes are capable of substantially increasing local piezometric pressures, such as the

$>$20 m (200 kPa) rise centred on the Greendale Fault (Fig. 4). It is not clear why relatively small earthquakes and aftershocks (e.g., M_W4.8 of 19 October 2010) liquefied the ground in Christchurch, or whether ground subsidence (Beavan et al. 2010, 2011) is sufficient to account for the volume of ejected sediment and water flooding in the suburbs. We suspect, but have yet to fully test the hypothesis, that release of artesian pressures from the confined aquifers did play a key role in the Christchurch liquefaction process.

Our work shows that the M_W7.1 Darfield earthquake raised piezometric levels in the unconfined and semi-confined aquifers around the Greendale Fault, yet lowered groundwater pressures in confined aquifers beneath Christchurch city once coseismic fluctuations had passed (Fig. 4D). Our interpretation is that the increases centred on the Greendale Fault reflect a dynamic stress change associated with fault rupture, whereas decreases in the city (spike offset negative brown responses) are a more subtle result of the dynamic passage of seismic waves. Springs emerged where confining layers have been breached, liquefaction developed in areas of soft sediment and immediate coseismic pressure increases were then released post-seismically over a period of several days. We present the hypothesis that artesian pressures were transmitted from intermediate- and shallow-level aquifers through breached confining layers to the shallow near-surface water table above.

Although we have yet to examine the more-damaging February 2011 M_W6.2 aftershock in any detail, we suspect it had similar (or greater) effects at depth to the M_W7.1 Darfield earthquake, but with the pressure response (cf. Fig. 4A) centred directly beneath the artesian aquifers and Christchurch city (Environment Canterbury 2011a). Pressure release through the leaky artesian system may have amplified the local predisposition for liquefaction in the eastern suburbs caused by the character of shallow formations (strength, grain size, density, etc.), the shallow groundwater table and a basin geometry that locally amplified the shaking (as outlined by Brown & Weeber 1992; Cousins & McVerry 2010; Cubrinovski & Green 2010; Cubrinovski et al. 2011; Green et al. 2011; Guidotti et al. 2011). The M_W7.1 Darfield earthquake had a different sense of motion and stress characteristics from the major aftershocks in 2011 (22 February M_W6.2, 23 June M_W5.3 and M_W6.0), which resulted in very different local shaking intensities (Cousins & McVerry 2010; CA Williams et al. 2011; Fry et al. 2011). Comparison of their groundwater level changes, which ranged from at least -7 to $+8$ m beneath Christchurch city (Environment Canterbury 2011a), may eventually enable localised site-specific responses to be unravelled to derive information on recovery and response time, and sensitivity to seismic amplitude and frequency. Unfortunately it may prove difficult to define the groundwater behaviour during the aftershocks, which caused extreme ground motions and a relatively rare 'trampoline effect' (Fry et al. 2011), as many monitoring sites suffered damage (Environment Canterbury 2011a,c).

Is the hydrological and geological setting of Christchurch unique? Can lessons be learnt and applied to mitigating the liquefaction hazard in Christchurch city and elsewhere? Ground compaction is one of the more commonly applied methods used to mitigate liquefaction hazard. However, if the permeability change mechanism was important and artesian pressure release did play a role in Christchurch city liquefaction, compaction or other ground strengthening may have little long-term effect and may even exacerbate the issue elsewhere. It will be difficult to seal springs, deep fractures and newly developed upwards flow paths. Hazard mitigation would then need to look towards design solutions that reduce groundwater pressure, perhaps at depths of 30 m or greater. This might be achieved through abstraction or hydraulic isolation, or by promoting rapid dissipation of excess pore water pressure by installing drainage. A more positive corollary of our hypothesis is that liquefaction hazard in other urban centres may not be as great as that which affected Christchurch, where sediments are weak and saturated but artesian pressures absent.

Supplementary file

EQ hydrology data: METAdata description; and Database, 20 February 2012.

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