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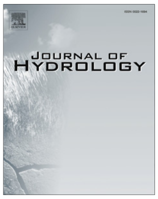

On the mechanism of earthquake induced groundwater flow

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SUMMARY

The Canterbury/Christchurch earthquakes and aftershocks of 2010–2011 generated groundwater level responses throughout New Zealand. However, the greater part of damage was sustained by the city of Christchurch which is built on a layered sequence of artesian aquifers. In a previous paper we analysed the earthquake induced groundwater responses. We quantified groundwater responses by fitting a simple statistical model which differentiated between immediate earthquake induced response (spike) and post-seismic change (offset). The most notable feature of this analysis was the consistency of responses between the earthquakes: deeper wells correlate with negative offset and shallower wells correlate with positive offset. In that paper we argued that this is consistent with the upwards vertical movement of water. In this paper we focus on the physical mechanisms, and consider a model that further explains and supports this hypothesis. We postulate a groundwater flow model in which storativity and aquitard permeability are modelled as time-varying shocks. We analyse the solutions for a range of non-dimensional parameters and obtain type curves that exhibit the same behaviour as the observed responses. Finally we consider data from the 2010 M_w7.1 Darfield (Canterbury) earthquake.

1. Introduction

Since the M_w7.1 Darfield (Canterbury) earthquake on 4 September 2010, 4.35 a.m. (local time), Christchurch and its environs experienced an intense sequence of earthquakes and aftershocks, the main destructive earthquakes being the M_w6.2 Christchurch earthquake on 22 February 2011 at 12.51 p.m. which resulted in 185 deaths, the M_w6.0 aftershock on 13 June 2011 at 2.20 p.m. and its M_w5.6 precursor at 1 p.m. (Cox et al., 2012; Gulley et al., 2013). Physical damage including land movement, subsidence and liquefaction was substantial and contributed to the degradation of infrastructure (water supply, sewage and power) as well as structural damage. In the central business district alone more than 1000 buildings were either destroyed or damaged beyond repair.

Christchurch is built on an extensive sequence of coastal confined aquifers, the 'Christchurch artesian aquifers', (Talbot et al., 1986), see also Fig. 1. Using the regional authority's groundwater database of 256 wells, Gulley et al. (2013) analysed groundwater responses to the main destructive earthquakes, the principal observation being the consistent pattern of responses to the earthquakes for wells in the Christchurch aquifers. For all wells with one exception (which was dominated by a tidal signal) the responses are shown schematically in Fig. 2: an earthquake induced jump followed by a post-seismic recession. Of particular interest is the offset marked in (a) and (b): a positive offset indicates a post-seismic elevated water level while a negative offset indicates a reduced water level. Most significantly they observed that offset correlates with well depth with shallow wells exhibiting a positive offset and deeper wells exhibiting a negative offset. We refer to Fig. 3 which is taken from (Gulley et al., 2013). It is clear that this is consistent with the upwards movement of water from deep to shallow aquifers. (We note that data was measured at 15 min intervals so there are no high frequency oscillations.)

Such post-seismic changes in groundwater levels have been observed elsewhere, see (Wang and Manga, 2010) and the references cited in (Gulley et al., 2013). Geballe et al. (2011) considered a model of the type shown in Fig. 4 and studied the implications of permeability change in the aquitard. However a permeability change alone cannot account for the observed phenomena, since the post-seismic head will be convex in one aquifer and concave in the other aquifer. Such approaches neglect consideration of aquifer compressibility.

A sudden reduction in storativity would explain the earthquake induced jumps shown in Fig. 2. Likewise a sudden increase in permeability of the aquitard would appear to be necessary to allow an accelerated passage of water from high pressure artesian aquifers to the shallow aquifers. In this paper we investigate a simple model of earthquake induced groundwater flow in which the storativity and permeability are modelled as shocks.

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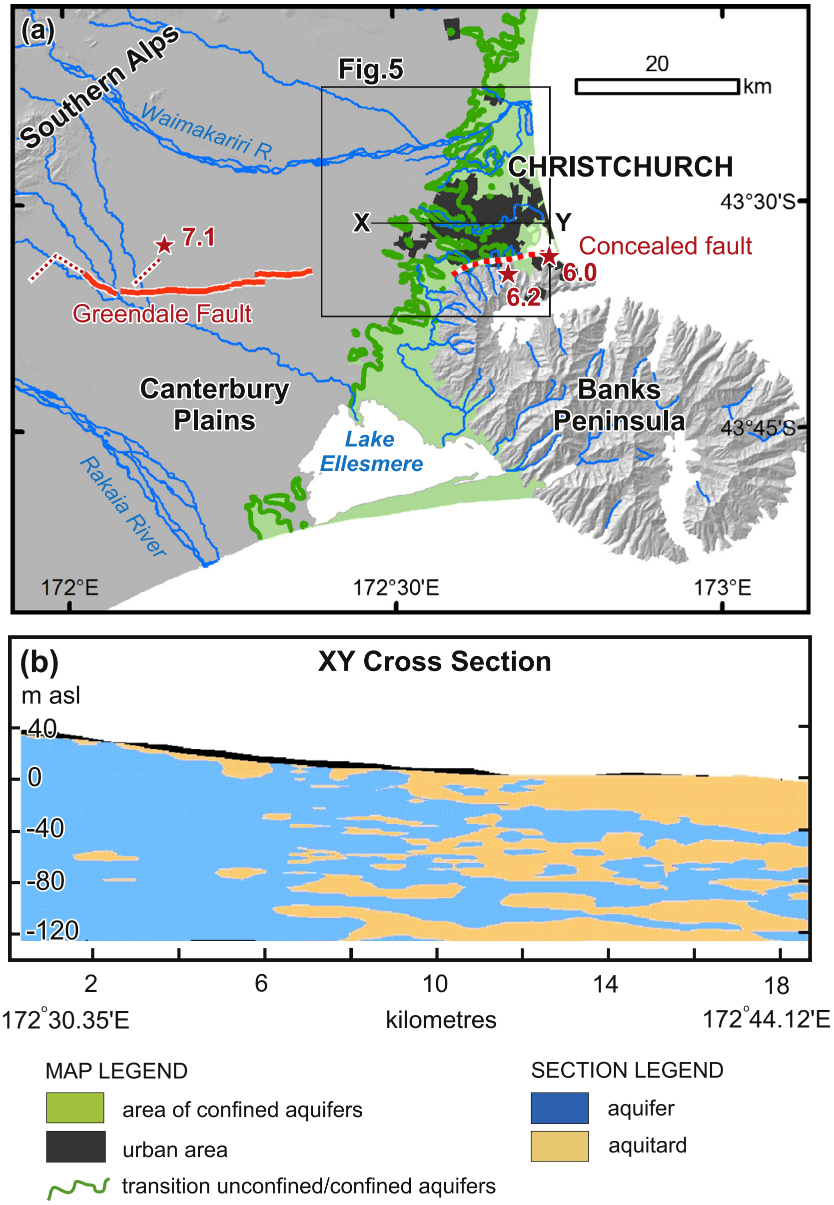

Fig. 1. Location diagram. Plot (a) shows the mid-Canterbury region, the broken red curves indicate the location of concealed fault lines underneath the gravels, the red curve denotes the Greendale fault and the stars indicate the epicentres of the main earthquakes. The green curve indicates the transition zone between unconfined and confined conditions to the west and east respectively, while the green shading denotes the coastal confined (artesian) aquifers. Urban areas are marked by black shading. Plot (b) shows a section through the Christchurch artesian aquifers, where blue indicates aquifer and brown aquitard. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Geological and seismic setting

Brief details are given here, more information is given in (Gulley et al., 2013) from where the current account is taken. The central Canterbury Plains are bounded by the Southern Alps to the west, to the north and south by the Waimakiriri and Raikaia rivers respectively, and to the east by Christchurch and Banks Penninsula (Fig. 1(a)). They are composed of gravel alluvium, around 300–500 m thick, deposited in a complex of coalesced floodplains during the Quaternary, and underlain by basement rocks of Permian–Jurassic Torlesse greywacke and locally a 0–1.5 km thick sequence of late Cretaceous–Tertiary sedimentary rock. The gravel aquifers were formed from eastwards flowing braided glacial meltwater rivers carrying detritus eroded from the uplifting Southern Alps. Changes in sea level of around 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 of the present-day shoreline. An artesian system with confined to semi-confined aquifers occurs in the coastal region where marine/estuarine sediments are interlayered with gravels, see Fig. 1. The green curve in (a) marks the approximate transition from unconfined/semi-confined to confined conditions.

The M_w7.1 (Darfield) September 2010 earthquake produced a surface rupture of 30 km, now termed the Greendale Fault, Fig. 1 (a), which tore an east–west trending rupture through semi-confined inland aquifers of central Canterbury Plains. The ensuing aftershock sequence occurred dominantly to the east, on concealed faults below the coastal confined aquifer system, but did not result in any surface rupture. The M_w6.2 (Christchurch) February 2011 earthquake occurred on an oblique thrust fault near the contact