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Regional changes in streamflow after a megathrust earthquake

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ABSTRACT

Moderate to large earthquakes can increase the amount of water feeding stream flows, mobilizing excess water from deep groundwater, shallow groundwater, or the vadose zone. Here we examine the regional pattern of streamflow response to the Maule M8.8 earthquake across Chile's diverse topographic and hydro-climatic gradients. We combine streamflow analyses with groundwater flow modeling and a random forest classifier, and find that, after the earthquake, at least 85 streams had a change in flow. Discharge mostly increased ($n = 78$) shortly after the earthquake, liberating an excess water volume of >1.1 km^3, which is the largest ever reported following an earthquake. Several catchments had increased discharge of >50 mm, locally exceeding seasonal streamflow discharge under undisturbed conditions. Our modeling results favor enhanced vertical permeability induced by dynamic strain as the most probable process explaining the observed changes at the regional scale. Supporting this interpretation, our random forest classification identifies peak ground velocity and elevation extremes as most important for predicting streamflow response. Given the mean recurrence interval of $\sim$25 yr for $>$M8.0 earthquakes along the Peru–Chile Trench, our observations highlight the role of earthquakes in the regional water cycle, especially in arid environments.

1. Introduction

Hydrological changes after earthquakes have been documented for millennia (e.g., Pliny, ca. AD 77–79), including changing water levels in wells, liquefaction of soils, altered activity of mud volcanoes and geysers, and the formation and disappearance of springs (Muir-Wood and King, 1993; Rojstaczer et al., 1995; Wang and Manga, 2010a). Streamflow responses include co- and post-seismic increases (Montgomery et al., 2003), decreases (Wang et al., 2004a), or both (Mohr et al., 2012), as earthquakes change crustal stresses, hydraulic heads, and physical properties such as the permeability of the subsurface, all controlling water flux. Altered stream discharge following earthquakes have been observed in the near- and intermediate field (Rojstaczer et al., 1995). The near field is defined as the area within one fault length of the rupture, whereas the intermediate field enfolds an area within several fault lengths. Seismically triggered streamflow changes are more than curiosities, and provide rare opportunities to study the water cycle under pulsed disturbances. Hence, earthquakes may provide important insights into the regional hydrological cycle and near-surface hydro-seismological processes that are difficult, if not impossible, to study otherwise. Understanding earthquake hydrology may reveal details about hydrocarbon migration (Beresnev and Johnson, 1994), the dynamics of geothermal systems (Manga et al., 2012), the security of water supplies (Chen and Wang, 2009), the integrity of waste repositories (Carrigan et al., 1991), and biological activity, such as modified invertebrate fauna in streams affected by post-seismic changes in streamflow and hydrochemistry (Galassi et al., 2014).

Earthquakes cause static and dynamic strain, which directly affect streamflow via increases in pore pressure caused by static strain (Muir-Wood and King, 1993), consolidation (up to liquefaction) by dynamic strain (Manga, 2001; Montgomery et al., 2003), increased permeability (Rojstaczer et al., 1995; Wang et al., 2004a), or the release of vadose zone water by dynamic strain (Manga and Rowland, 2009; Mohr et al., 2015). Each of these mechanisms is physically plausible and might explain the observed streamflow responses, though detailed studies have drawn conflicting conclusions about the dominant mechanism. For example, the isotopic composition of excess water emerging in previously dry streams pointed to a groundwater source after the 2014 Mw6.0 South Napa earthquake (Wang and Manga, 2015). In contrast, modeling for headwater streams in south-central Chile, an area that is comparable to northern California in terms of its hydro-climatic conditions, indicated that water was shaken out of the vadose

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zone after the 2010 Maule M8.8 earthquake (Mohr et al., 2015). The hypothesis that strong ground shaking enhances permeability (Rojstaczer et al., 1995; Wang et al., 2004a) is consistent with lowered water temperatures (Wang et al., 2012) and altered electrical conductivity (Charmoille et al., 2005), but incompatible with unchanged recession constants after earthquakes (Manga, 2001; Montgomery et al., 2003). Recession constants are widely used to describe the hydraulic permeability at the catchment scale (Blume et al., 2007). Groundwater flow is governed by Darcy's law, so if permeability does not change, the hydraulic head has to increase instead. Accordingly, Manga (2001) and Montgomery et al. (2003) proposed that coseismic consolidation of saturated deposits increased the hydraulic head. Another hypothesis is that the vertical permeability was enhanced by earthquakes, which increased the base flow feeding streams (Fleeger and Goode, 1999; Wang et al., 2004a, 2004b; Wang and Manga, 2015).

Why do catchments respond in such different ways to earthquakes even under comparable environmental conditions? What are the underlying controls? Guided by these research questions, our objectives are (a) to identify regional patterns in streamflow responses to the M8.8 2010 Maule earthquake, Chile, (b) to identify environmental controls on the observed streamflow anomalies, and (c) to reconcile these anomalies with a groundwater flow model. To this end, we combine random forest classification of potential predictors of streamflow changes with physics-based 1D-groundwater modeling for catchments showing altered discharges following the Maule earthquake.

2. Study area, data and methods

2.1. Study area

Chile is well suited for studying earthquake hydrology because of the country's distinct environmental contrasts. With some of the driest and wettest spots on Earth, Chile has a steep hydro-climatic gradient. Mean annual rainfall varies between less than 10 mm and more than 2000 mm (Hijmans et al., 2005), and potential evapotranspiration varies by more than an order of magnitude (Fig. 1). The trade-off between water supply and demand determines the effective aridity. Chile hosts some of the world's steepest topographic gradients, and the Andes reach ~7000 m asl, while the Coastal Mountain ranges are >3000 m asl in the north (Fig. 1). The country is also prone to frequent earthquake shaking. According to the ANSS earthquake catalogue (NCEDC, 2014), Chile has experienced >M8.0 earthquakes every 25 yr on average (Fig. 2).

2.2. Data

We examined time series of daily averaged discharge at 716 stream gauging stations, rainfall at 802 precipitation gauges, and air temperature at 75 meteorological stations, provided by the Dirección General de Aguas (DGA) (http://dgasatel.mop.cl/). The stations are spread across Chile from the Atacama Desert and Altiplano in the north to Tierra del Fuego in the south (Fig. 1), and sample headwater streams as well as larger catchments with multiple tributaries, including lowland rivers of the Central Valley.

For each catchment we compiled several attributes. We grouped the geological map of Chile (SERNAGEOMIN, 2003) into metamorphic, sedimentary, and igneous rocks, as well as unconsolidated sediments, and computed the fraction of each class within each catchment. We calculated the distance between the gauging stations and the nearest (mapped) fault, and estimated fault density (km/km^2) in each catchment. This density estimate includes all normal, reverse, and strike–slip faults mapped by SERNAGEOMIN (2003). We used annual precipitation data from the BIOCLIM data (Hijmans et al., 2005) for the period between 1950 and 2000 derived from summing monthly rainfall data. We used average annual rainfall to estimate how much water entered the catchments during a hydrological year. To account for rainfall prior to the earthquake, we also included the long-term (1950–2000) averaged February precipitation, as the earthquake occurred at the end of that month. We (re)classified the land-cover information in global mosaics of the standard MODIS land-cover type data product (MCD12Q1) at 500-m resolution (Channan et al., 2014; Friedl et al., 2010), and LANDSAT images (2000–2005) at 30-m resolution (Sexton et al., 2013). We used data on peak ground acceleration (PGA) and peak ground velocity (PGV) generated by the M8.8 Maule earthquake published by the USGS (http://earthquake.usgs.gov/earthquakes/shakemap/global/shake/2010tfan/#download), and modeled static strain within each catchment using Coulomb 3.3 (Lin and Stein, 2004; Toda et al., 2005), and model parameters provided by Chen Ji (University of California, Santa Barbara, http://www.geol.ucsb.edu/faculty/ji/big_earthquakes/2010/02/27/chile_2_27.html).

Some of the published gauge locations at catchment outlets seemed questionable. We thus estimated the most plausible location requiring that the distance to the published outlet location

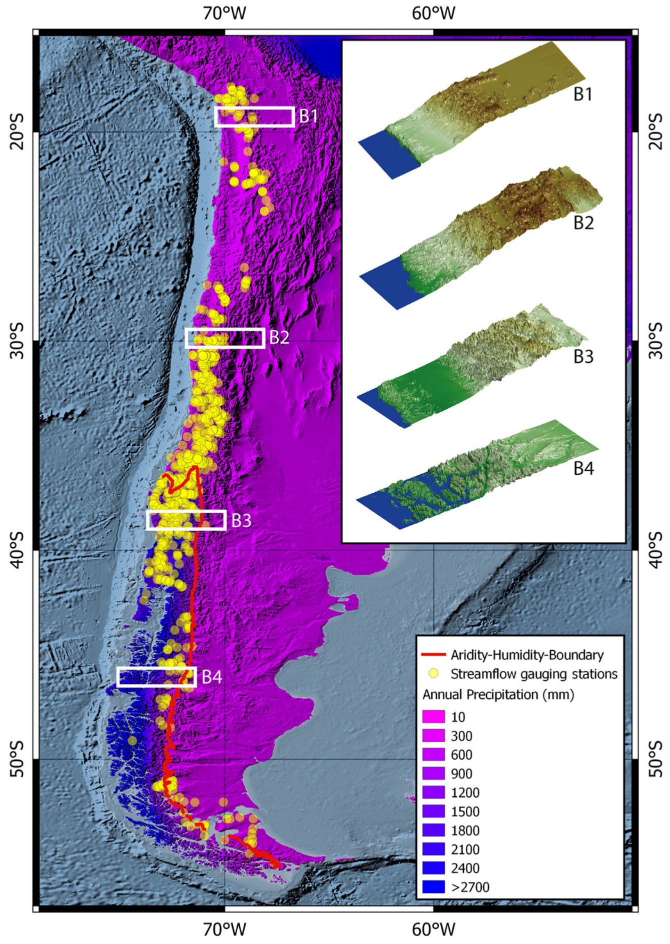

Fig. 1. Geographical setting. Average annual precipitation (mm) for the period between 1950–2000 based on BIOCLIM data (Hijmans et al., 2005) for Chile. Yellow circles show streamflow gauging stations operated by Chilean Direccion General de Aguas (DGA). Red line indicates the aridity–humidity boundary, i.e. the ratio of mean annual precipitation and mean annual potential evapotranspiration (Zorner et al., 2008). Topography is based on SRTM data (Jarvis et al., 2008), bathymetry comes from the ESRI World Ocean Baselayer. The inset shows 100-km wide topographic swath profiles based on SRTM data (Jarvis et al., 2008) to illustrate the topographic gradients across Chile. (http://services.arcgisonline.com/arcgis/rest/services/Ocean/World_Ocean_Base, accessed 05.06.2016.) (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

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