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Shaking water out of soil

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Abstract

Moderate to large earthquakes can increase the amount of water flowing in streams. Previous interpretations and models assume that the extra water originates in the saturated zone. Here we show that earthquakes may also release water from the unsaturated zone when the seismic energy is sufficient to overcome the threshold of soil water retention. Soil water may then be released into aquifers, increasing streamflow. After the M8.8 Maule, Chile, earthquake, the discharge in some headwater catchments of the Chilean coastal range increased, and the amount of extra water in the discharge was similar to the total amount of water available for release from the unsaturated zone. Assuming rapid recharge of this water to the water table, a groundwater flow model that accounts for evapotranspiration and water released from soils can reproduce the increase in discharge as well as the enhanced diurnal discharge variations observed after the earthquake. Thus the unsaturated zone may play a previously unappreciated, and potentially significant, role in shallow hydrological responses to earthquakes.

INTRODUCTION

Earthquakes induce a wide range of responses in both surface water and groundwater. Increased stream discharge is one of the most interesting examples because the response can be observed directly, can persist for days to months, and can be large, with discharge increasing more than 20-fold (Rojstaczer and Wolf, 1992). The excess water discharged after earthquakes has been attributed to (1) expulsion of water from compressed aquifers (Muir-Wood and King, 1993), (2) increasing permeability (Rojstaczer and Wolf, 1992; Wang et al., 2004a), (3) consolidation and liquefaction of sediment (Manga, 2001; Wang et al., 2001), or (4) rupturing of geothermal reservoirs (Wang et al., 2004b) or opening of deep fractures (Sibson and Rowland, 2003). While these mechanisms differ substantially from each other, they all assume saturated groundwater flow conditions.

There are several reasons why these three mechanisms may not fully explain responses in small headwater catchments: (1) discharge can increase even where earthquakes cause aquifers to expand (Manga et al., 2003); (2) the rate of decrease of streamflow after a rainfall event is not affected by earthquakes, implying no change in horizontal permeability (Manga, 2001) but potentially changes in vertical permeability (Wang et al., 2004a); and (3) the magnitude of consolidation needed to explain the observed streamflow increase is sometimes so large that it would have caused appreciable subsidence, but previous studies found no spatial relationship between the occurrence of liquefaction and increased streamflow (Montgomery et al., 2003; Wang et al., 2004a).

Here we analyze data from a small headwater catchment and its response to the A.D. 2010 Maule (Chile) earthquake. In contrast to a previous analysis that proposed that the increase in discharge was caused by consolidation of water-saturated materials (Mohr et al., 2012), we show that the water may have also originated from the unsaturated zone. To this end, we develop a one-dimensional model that couples groundwater flow (Manga, 2001) and recharge (Wang et al., 2004a) with evapotranspiration fluxes (Kirchner, 2009) to quantify streamflow and evapotranspiration responses to the earthquake by simulating diurnal streamflow oscillations.

The study may be relevant for a better understanding of earthquake impact on biological activity. While earthquakes usually have a negative impact on biology (Allen et al., 1999; Jacoby et al., 1997; Galassi et al., 2014), we show in this study that in some situations earthquakes may transiently promote root-water uptake on very short time scales.

STUDY AREA AND OBSERVATIONS

The magnitude 8.8 Maule earthquake (27 February 2010) caused intense ground shaking for ~150 s. This shock induced streamflow responses across south-central Chile including discharge increases (e.g., Rio Claro, Bío Bío Region, central valley), decreases (e.g., Huiri, Bío Bío Region, Andes), or a combination of both (e.g., Estero Quilque, Bío Bío Region, central valley). In most cases, the data from around the time of the earthquake are incomplete (Dirección General de Aguas, http://dgasatel.mop.cl/filtro_paramxestac.asp, 20 August 2014) which complicates a reliable analysis of the observed streamflow changes on a regional scale.

Here we focus on the response of a small stream in the Chilean coastal range (Fig. 1A). The studied catchment is geologically homogeneous and topographically simple (Mohr et al., 2012) compared to previous study sites for hydrological responses to large-magnitude earthquakes (Wang and Manga, 2010a). With an area of 413 ha (Fig. 1B), it is the largest member of a network of 11 experimental catchments in the uplands of the Chilean coastal range. We measured streamflow using a flume equipped with a custom-built water-stage recorder with an accuracy of 2 mm. At the time of the earthquake, a 2-yr-old *Eucalyptus* spp. plantation with shallow roots not exceeding 100 cm in depth covered most of the catchment. Deeper-rooting native species (>200 cm on average), e.g., arrayán (*Luma apiculata* DC. Burret), boldo (*Peumus boldus* Mol.), and roble (*Nothofagus obliqua* Mirb), are found in a 45 ha riparian buffer strip along the main stream and its steep tributaries (Mohr et al., 2012) (Fig. 1B). Between 19 February and 5 May 2010, no significant rainfall was recorded, leading to low base-flow conditions and enabling us to identify the streamflow response to the earthquake.

We identify three distinct responses after the main shock. First, streamflow increased (Fig. 2): the excess discharge, integrated over time and divided by the area of the watershed, was 8–9 mm (Mohr et al., 2012). Second, diurnal streamflow oscillations were amplified (Fig. 2). Such amplification was recorded only in this specific case and only in the largest catchment of the network. In some adjacent, smaller catchments we see a third type of response, a short-lived drop in streamflow preceding the post-seismic streamflow increase (Mohr et al., 2012).

MODEL APPLICATION

We assume that water released from the unsaturated zone recharges an unconfined aquifer and that flow is described by the linearized Boussinesq equation and Darcy's equation,

$$S_y \frac{\partial h}{\partial t} = T \frac{\partial^2 h}{\partial x^2} + E_t(x,t) + A(x,t)$$

$$\text{with } Q = -\frac{\partial h}{\partial x} * K * D_t, \qquad (1)$$

where S_y is specific yield, h is hydraulic head, T is transmissivity, E_t is the evapotranspiration rate per unit width as a function of space (x) and time (t), A is the rate of water recharge per unit width released from the unsaturated zone, Q is discharge, K is hydraulic conductivity, and D_t is the cross-sectional area of the aquifer. We consider only horizontal groundwater flow and assume for simplicity that E_t and A are constant in space over the basin. We assume a small change in hydraulic head, as indicated by the few millimeters of excess water observed after the earthquake, and assume that discharge occurs from saturated flow and hence that Darcian flow applies. A detailed model description and a conceptual illustration are provided in the GSA Data Repository[1].

The aquifer extends from $x = 0$ at the catchment divide to $x = L$ at the stream. Boundary conditions are

$$h(L,t) = 0 \text{ and } \frac{\partial h(0,t)}{\partial x} = 0, \qquad (2)$$

while the initial condition is

$$h(x,0) = h_0(x) \text{ with } 0 \le x \le L. \qquad (3)$$

Seismic waves create time-varying ground motions that impart to the soil a combination of kinetic energy and potential energy. We treat the shaking (seismic energy) as a positive contribution to the matric potential that otherwise retains water in pores. If large enough, the shaking will then allow soil water to drain.

To quantify the effect of shaking, we use the empirical formula in Wang (2007) that relates seismic energy density to earthquake magnitude and epicentral distance (see the Data Repository). We estimate that the seismic energy density is ~10^2−10^3 J/m^3 in our watersheds. If we superimpose the seismic energy on the matric potential during the earthquake, the water retention threshold increases by 10^2−10^3 Pa. For the sandy subsoil in the catchments (Mohr et al., 2012), soil water contents between 33% and 36% may then be released during shaking (Fig. 3A). Soil moisture measurements before the earthquake show dry topsoil but near-saturated conditions in the deeper soil (soil depth >180 cm) where there is enough available soil water to account for the post-seismic excess streamflow discharge (Mohr et al., 2012). The water released from 180–250 cm depth during shaking would equal up to 20 mm of excess flow and would be available to recharge the underlying aquifer (Fig. 3B).

From the diurnal discharge cycles, we estimate evapotranspiration (E_t) before and after the earthquake by “doing hydrology backward” as proposed by Kirchner (2009). We independently confirmed our estimates with the difference between discharge rates and a spline interpolation linking daily discharge maxima, and with maximum recharge rates during nighttime (White, 1932).

RESULTS AND DISCUSSION

We find a good fit to the observed discharge record without changing lateral hydraulic conductivity (Fig. 3) but instead by elevating hydraulic head by the release of additional water from the vadose zone. Our model fits the observations with ~12 mm of recharge, similar to the ~20 mm of available soil water. We also find a post-seismic increase in daily evapotranspiration of ~30%–60% for 5–10 days following the earthquake.

The amplitude of the diurnal streamflow cycles after the earthquake is similar to that during periods of similar mean streamflow during wetter times several months before the earthquake (Fig. DR2 in the Data Repository). This implies that the earthquake suddenly increased the availability of near-stream groundwater and soil water to both streamflow and evapotranspiration. How could the earthquake have caused this increase in water availability near the stream, and where did the water come from?

Under dry weather conditions, such as before and after the earthquake, diurnal streamflow cycling is caused by changes in groundwater storage in the riparian zone owing to daytime evapotranspiration (Hattermann et al., 2006). Evapotranspiration depends on soil water availability (Jhorar et al., 2004) and nighttime replenishment of depleted groundwater from upslope (Kirchner, 2009). We exclude diurnal changes in water viscosity causing discharge oscillations, as proposed elsewhere by Constantz et al. (1994), for two reasons. First, catchments that were recently clear-cut and, thus, experienced high insolation due to missing shading did not show diurnal cycling at all. However, we cannot exclude measurement artifacts considering the relatively low water stage across all smaller catchments and the limited accuracy of our water-stage recorders. Second, the stream is not losing water; instead it is being recharged by groundwater, and the water table adjacent to the streams is higher than the stream itself.

Changes in atmospheric conditions after the earthquake may be also excluded as a cause for the post-seismic increase because the potential evapotranspiration—a measure of the atmospheric demand driven by temperature, wind, and insolation—did not change substantially after the earthquake (Fig. 2).

Permeability Changes?

Increases in permeability are commonly invoked to explain increases in discharge after earthquakes (e.g., Rojstaczer and Wolf, 1992). That hypothesis can be assessed using two observations: increased discharge and evapotranspiration. Increases in horizontal permeability increase discharge, but would also lead to more rapid base-flow recession, and this is not the case following the Maule earthquake (Mohr et al., 2012). Wang et al. (2004a) proposed that increases in discharge are the result of increased vertical permeability, which would not affect base-flow recession. There are two possible scenarios.

First, permeability could increase everywhere by an amount proportional to its previous value. Tóth (1963) showed that recharge may take place in small upland catchments by lateral flow from nearby ridges. Assuming vertical permeability increases, the water table will adapt to a lower head gradient, and eventually time-averaged discharge will equal time-averaged recharge. The water levels are then expected to drop in the recharge areas (i.e., elevated areas such as close to the ridges) but rise close to the (local) discharge areas, i.e., close to the streams. This is consistent with the increase in the amplitude of diurnal fluctuations, which suggests higher water levels in at least some parts of the subsurface (and thus greater access to subsurface moisture by vegetation). If we treat E_t as a proxy for water level in the riparian zone, we expect higher E_t for a given discharge after permeability increased. However, E_t scales with discharge, and that relationship did not change after the earthquake (Fig. DR2).

Second, if instead permeability increased only in the regions away from the stream, water levels would decrease far away from the stream and increase closer to the stream (consistent with larger diurnal fluctuations), but the increase in discharge would potentially be delayed by a substantial fraction of the base-flow recession decay time. Manga (1996) showed that in groundwater-fed streams—as the case here—such time delays reach several days even in highly permeable rock. Instead, the observed increase in discharge peaked within less than a day, which requires a change in permeability over most of the aquifer, or at least close to the streams (Manga et al., 2003; Wang et al. 2004a).

In wells, permeability changes are documented for smaller energy densities than the one observed here. In general these are in units through which there is little flow due to low permeability (Wang and Manga, 2010a). We thus do not favor increased permeability as the single mechanism to explain this particular set of observations.

Consolidation?

A previous analysis attributed the increased discharge to subsurface consolidation of loose materials, which decreases pore volume and increases hydraulic head (Mohr et al., 2012). The location of the watersheds is close enough to the earthquake for consolidation and even liquefaction to occur (Wang, 2007). However, no liquefaction or signs of settlement that would accompany consolidation were observed in the catchments.

An Origin in the Unsaturated Zone?

We now consider the possibility that seismic shaking could have released water held in the unsaturated zone. One previous study also suggested that the increased discharge may originate from the unsaturated zone, based on subtle changes in the isotopic and hydrogeochemical properties of stream water (Manga and Rowland, 2009).

We propose that, just as a sponge releases water when shaken, water can be mobilized from an unsaturated soil whenever the energy imparted by seismic waves exceeds the matric potential holding the water in place. The magnitude of basin-averaged excess discharge is typically a few millimeters to a few centimeters (Manga, 2001), similar to that in the present study, and similar to what we suggest can be mobilized from soils (Fig. 3B).

Though the duration of shaking is relatively short, we suggest that it lasts long enough to potentially transfer vadose zone water to groundwater, for the following reasons. First, fast vertical drainage along preferential flow paths, such as root channels or soil cracks, is common in this study area (Mohr et al., 2013). Second, transient stresses from seismic waves can clear clogged (macro-) pores, which would enhance downward drainage (Candela et al., 2014; Manga et al., 2012). Third, near-surface cracking by co-seismic dilatancy may additionally promote vertical connectivity (Wang et al., 2004a). Dilatancy describes the increase of porosity owing to shear stress (Scholz, 2010). Based on data from Taiwan (Wang et al., 2004a), an estimated seismic energy density of 530 J/m^3 is sufficient to initiate (dilatant) crack formation promoting aquifer recharge. The Maule earthquake generated similar energy densities in our catchment, and indeed, surface cracks were observed on ridges or road fillings after the earthquake. Assuming co-seismic dilatancy, water is expected to redistribute from the saturated pores into the newly formed and unsaturated cracks. As a consequence, the hydraulic head declines and streamflow is temporarily disrupted. Such decreases are in fact seen. However, short initial drops in streamflow are observable only in the smallest catchments, presumably because merging of tributaries and dispersion along channels in larger catchments averages out these short-lived decreases. Consequently, our observations are consistent with two distinct mechanisms operating at the same time: (1) increased vertical permeability improving connectivity between the vadose and groundwater zones due to co-seismic dilatancy, while (2) ground shaking released vadose zone water.

As the water released from the unsaturated zone recharges groundwater, the groundwater table rises, enlarging the “active zone” of high evapotranspiration. We define the active zone as the region where the water table is shallow enough that water uptake is not limited by water availability. Thus, the increase in evapotranspiration suggests a spatial expansion of the active zone after the groundwater level and capillary fringe rise, even if evapotranspiration rates may remain the same. Importantly for interpreting the streamflow observations, water lost to evapotranspiration must be connected to groundwater in order to be recorded by streamflow.

CONCLUSIONS

Changes in discharge are normally attributed to changes in permeability, which affect a range of subsurface processes that involve heat and solute transport. Our results show that water released from the unsaturated zone may be quantitatively sufficient, under plausible conditions, to account for the observed streamflow response and the inferred increase in evapotranspiration following the Maule M8.8 earthquake. To this end, our study suggests that seismo-hydrological processes can occur in the unsaturated zone, a zone that is essential for understanding root-water uptake (e.g., Hattermann et al., 2006; Krause and Bronstert, 2007). Against this background, we see temporary enhancement of root-water uptake.

Independent evidence from future earthquakes will be needed to determine whether this is an important hydrologic process in other catchments. If correct, the conclusions of our study challenge the conventional view that hydrological responses to earthquakes are restricted to the saturated zone.

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[1] GSA Data Repository item 2015074, supplementary information on the methods and modeling, modeled daily evaporanspiration rates, and supplemental Figures DR1 and DR2, is available online at www.geosociety.org/pubs/ft2015.htm, or on request from

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References

Allen, R.B., Bellingham, P.J., and Wiser, S.K., 1999, Immediate damage by an earthquake to a temperate montane forest: Ecology, v. 80, p. 708– 714, doi:10.1890/0012-9658(1999)080[0708 :IDBAET]2.0.CO;2.

Candela, T., Brodsky, E.E., Marone, C., and Elsworth, D., 2014, Laboratory evidence for particle mobilization as a mechanism for permeability enhancement via dynamic stressing: Earth and Planetary Science Letters, v. 392, p. 279–291, doi:10.1016/j.epsl.2014.02.025.

Constantz, J., Thomas, C.L., and Zellweger, G., 1994, Influence of diurnal variations in streamflow temperature on streamflow loss and groundwater recharge: Water Resources Research, v. 30, p. 3253–3264, doi:10.1029/94WR01968.

Galassi, D.M.P., Lombardo, P., Fiasca, B., Di Cioccio, A., Di Lorenzo, T., Petitta, M., and Di Carlo, P., 2014, Earthquakes trigger the loss of groundwater biodiversity: Scientific Reports, v. 4, 6273, doi:10.1038/srep06273.

Hattermann, F.F., Krysanova, V., Habeck, A., and Bronstert, A., 2006, Integrating wetlands and riparian zones in river basin modelling: Ecological Modelling, v. 199, p. 379–392, doi: 10.1016/j.ecolmodel.2005.06.012.

Jacoby, G.C., Bunker, D.E., and Benson, B.E., 1997, Tree-ring evidence for an A.D. 1700 Cascadia earthquake in Washington and northern Oregon: Geology, v. 25, p. 999–1002, doi:10.1130 /0091-7613(1997)0252.3 .CO;2.

Jhorar, R.K., van Dam, J.C., Bastiaanssen, W.G.M., and Feddes, R.A., 2004, Calibration of effective soil hydraulic parameters of heterogeneous soil profiles: Journal of Hydrology (Amsterdam), v. 285, p. 233–247, doi:10.1016/j.jhydrol.2003 .09.003.

Kirchner, J.W., 2009, Catchments as simple dynamical systems: Catchment characterization, rainfall-runoff modeling, and doing hydrology backward: Water Resources Research, v. 45, W02429, doi:10.1029/2008WR006912.

Krause, A., and Bronstert, A., 2007, The impact of groundwater–surface water interactions on the water balance of a mesoscale lowland river catchment in northeastern Germany: Hydrological Processes, v. 21, p. 169–184, doi:10.1002/hyp.6182.

Manga, M., 1996, Hydrology of spring-dominated streams in the Oregon Cascades: Water Resources Research, v. 32, p. 2435–2439, doi: 10.1029/96WR01238.

Manga, M., 2001, Origin of postseismic streamflow changes inferred from baseflow recession and magnitude-distance relations: Geophysical Research Letters, v. 28, p. 2133–2136, doi:10.1029/2000GL012481.

Manga, M., and Rowland, J.C., 2009, Response of Alum Rock springs to the October 30, 2007 Alum Rock earthquake and implications for the origin of increased discharge after earthquakes: Geofluids, v. 9, p. 237–250, doi:10.1111/j.1468 -8123.2009.00250.x.

Manga, M., Brodsky, E.E., and Boone, M., 2003, Response of streamflow to multiple earthquakes: Geophysical Research Letters, v. 30, 1214, doi:10.1029/2002GL016618.

Manga, M., Beresnev, I., Brodsky, E.E., Elkhoury, J.E., Elsworth, D., Ingebritsen, S.E., Mays, D.C., and Wang, C.Y., 2012, Changes in permeability caused by transient stresses: Field observations, experiments, and mechanisms: Reviews of Geophysics, v. 50, RG2004, doi:10.1029 /2011RG000382.

Mohr, C.H., Montgomery, D.R., Huber, A., Bronstert, A., and Iroumé, A., 2012, Streamflow response in small upland catchments in the Chilean coastal range to the MW 8.8 Maule earthquake on 27 February 2010: Journal of Geophysical Research, v. 117, F02032, doi:10.1029/2011JF002138.

Mohr, C.H., Coppus, R., Huber, A., Iroumé, A., and Bronstert, A., 2013, Runoff generation and soil erosion processes after clear cutting: Journal of Geophysical Research, v. 118, p. 814–831, doi:10.1002/jgrf.20047.

Montgomery, D.R., Greenberg, H.M., and Smith, D.T., 2003, Streamflow response to the Nisqually earthquake: Earth and Planetary Science Letters, v. 209, p. 19–28, doi:10.1016/S0012-821X (03)00074-8.

Muir-Wood, R., and King, G.C.P., 1993, Hydrological signatures of earthquake strain: Journal of Geophysical Research, v. 98, p. 22,035– 22,068, doi:10.1029/93JB02219.

Rojstaczer, S., and Wolf, S., 1992, Permeability changes associated with large earthquakes: An example from Loma Prieta, California: Geology, v. 20, p. 211–214, doi:10.1130/0091-7613 (1992)0202.3.CO;2.

Scholz, C.-H., 2010, The Mechanics of Earthquakes and Faulting: Cambridge, UK, Cambridge University Press, 471 p.

Sibson, R.H., and Rowland, J.V., 2003, Stress, fluid pressure and structural permeability in seismogenic crust, North Island, New Zealand: Geophysical Journal International, v. 154, p. 584– 594, doi:10.1046/j.1365-246X.2003.01965.x.

Tong, X.P., et al., 2010, The 2010 Maule, Chile earthquake: Downdip rupture limit revealed by space geodesy: Geophysical Research Letters, v. 37, L24311, doi:10.1029/2010GL045805.

Tóth, J., 1963, A theoretical analysis of groundwater flow in small drainage basins: Journal of Geophysical Research, v. 68, p. 4795–4812, doi: 10.1029/JZ068i016p04795.

Wang, C.Y., 2007, Liquefaction beyond the Near Field: Seismological Research Letters, v. 78, p. 512–517, doi:10.1785/gssrl.78.5.512.

Wang, C.Y., and Manga, M., 2010a, Earthquakes and Water: Heidelberg, Springer, 225 p.

Wang, C.Y., Cheng, L.H., Chin, C.V., and Yu, S.B., 2001, Coseismic hydrologic response of an alluvial fan to the 1999 Chi-Chi earthquake, Taiwan: Geology, v. 29, p. 831–834, doi:10.1130/0091 -7613(2001)0292.0.CO;2.

Wang, C.Y., Wang, C.H., and Manga, M., 2004a, Coseismic release of water from mountains: Evidence from the 1999 (MW=7.5) Chi-Chi, Taiwan, earthquake: Geology, v. 32, p. 769– 772, doi:10.1130/G20753.1.

Wang, C.Y., Manga, M., Dreger, D., and Wong, A., 2004b, Streamflow increase due to rupturing of hydrothermal reservoirs: Evidence from the 2003 San Simeon, California, earthquake: Geophysical Research Letters, v. 31, L10502, doi:10.1029/2004GL020124.

White, W.N., 1932, A method of estimating groundwater supplies based on discharge by plants and evaporation from soil—Results of investigations in Escalante Valley, Utah: U.S. Geological Survey Water Supply Paper 659-A, 105 p.

Wosten, J.H.M., Lilly, A., Nemes, A., and Le Bas, C., 1999, Development and use of a database of hydraulic properties of European soils: Geoderma, v. 90, p. 169–185, doi:10.1016/S0016 -7061(98)00132-3.