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COMMENTARY
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Key Points:
- Earthquakes affect groundwater by changing properties of aquifers and their ability to transmit fluids
- Monitoring how water levels in wells respond to tides and atmospheric pressure provides an inexpensive way to monitor changes in aquifers
- Properties of aquifers are not static but change over time

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Earthquake Hydrogeology

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Abstract Hydrologic responses to earthquakes such as streamflow increases, water-level changes, and changes in geyser eruption frequency often reflect changes in permeability caused by seismic waves. The dynamic nature of permeability, as revealed by coseismic hydrologic phenomena, holds implications for groundwater systems, geothermal resources, mineral resources, and geologic hazards. Analysis of water-level responses to solid Earth tides and changes in atmospheric pressure provides a passive way to continuously monitor changes in permeability and storage properties in tectonically active regions.

Plain Language Summary Earthquakes affect groundwater by changing properties of aquifers and their ability to transmit fluids. Monitoring how water levels in wells respond to tides and atmospheric pressure provides an inexpensive way to monitor changes in aquifers. Properties of aquifers are not static but change over time.

1. Introduction

Permeability is not a static property. On long time scales, geochemical processes such as mineral precipitation and dissolution can decrease and increase permeability, respectively. Stresses can also change permeability through compaction and fracturing. On shorter time scales, stress changes from earthquakes and seismic waves also influence hydrogeological properties. Characterizing temporal changes of permeability has received relatively limited attention compared to spatial variations, in part because the latter are so large.

Earthquake-related hydrologic changes have been recorded for millennia (Pliny, 79 AD). Water-level changes in wells were widely observed following the Great Alaska Earthquake of 1964, and, more recently, “earthquake hydrology” has been the subject of a growing number of quantitative studies. The ongoing increase in quantitative analysis owes both to the growing availability of suitable seismic and hydrologic data and to a realization that earthquake responses can provide new insights into hydrologic and mechanical properties of the crust.

Zhang et al. (2019) use coseismic and postseismic changes in the water-level response to Earth tides and atmospheric pressure to estimate earthquake-caused increases in aquifer and aquitard permeabilities. To the best of our knowledge, this is the first time that coseismic aquifer and aquitard responses have been separately distinguished, as well as the first application of wavelet analysis to this problem. In our commentary, we place the innovative Zhang et al. paper in the broader context of recent research on earthquake hydrology, briefly summarize some implications of this body of work for groundwater systems and other subsurface resources, and suggest opportunities for future research and monitoring.

2. Coseismic Changes in Streamflow, Water Levels, and Other Hydrologic Phenomena

Perhaps the most conspicuous coseismic and postseismic hydrologic responses are increases in streamflow. These are often widespread, with typically rapid increases followed by quasi-exponential decay (Figure 1). The *M*8.8 Maule, Chile, earthquake released an excess streamflow volume of >1.1 km^3, the largest yet reported, over an affected area of ~2 × 10^5 km^2 (Mohr et al., 2017). After the Maule event, at least 85 monitored streams exhibited changes in flow, mainly positive (n = 78). Several catchments had excess discharge corresponding to >50-mm water depth over the contributing area, in some cases equivalent to more than a month of average discharge. Many other similar—though smaller—coseismic increases in streamflow have been well documented globally.

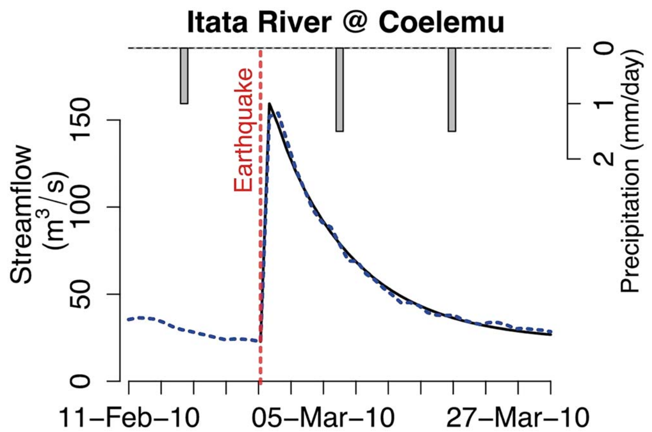

Figure 1. One of 78 examples of increased streamflow recorded after the *M*8.8 Maule, Chile, earthquake, from Mohr et al. (2017). Streamflow rapidly increased about sixfold above preearthquake values before decaying toward the preearthquake baseline over a period of about 3 weeks. The watershed area above Coelemu is about 1×10^4 km^2, and the transient streamflow increase equates to 16-mm water depth over that contributing area.

Coseismic and postseismic changes in water levels in wells are also common and generally fall in four categories: (1) Large (as much as 20 m), persistent, near-field (perhaps <50 km from the epicenter) water-level declines that have been attributed to near-surface permeability enhancement due to ground motion (e.g., Rojstaczer & Wolf, 1994); (2) transient water-level changes at distances of up to a few hundred kilometers from the epicenter that can sometimes be directly related to the magnitude of the crustal strain produced by fault slip (e.g., Roeloffs, 1988); (3) smaller (e.g., centimeter to decimeter scale) long-lived water-level changes initiated by earthquakes thousands of kilometers from the well (e.g., Shi et al., 2015); and (4) coseismic water-level oscillations caused by the resonant coupling of flow in the well and aquifer that amplifies seismic strain (e.g., Cooper et al., 1965). Coseismic water level oscillations associated with the great (*M*9.25) Alaskan earthquake in 1964 attracted scientific attention after large water-level fluctuations were measured at far-distant wells in eastern Canada, the central and eastern United States, and Puerto Rico.

Other hydrologic responses to earthquakes, such as changes in geyser eruption frequency (e.g., Hurwitz et al., 2014) and groundwater temperatures (e.g., Wang et al., 2013), have been well documented. Such observations are intriguing and offer complementary insights into water level and streamflow changes, but comparatively fewer time series exist to permit formal analysis.

3. Permeability Change as a Causative Mechanism

The large majority of hydrologic responses to earthquakes have been explained in terms of permeability changes, which, at least in tectonically active areas, challenges the standard hydrogeologic notion of permeability as a static or slowly evolving property. For instance, widespread streamflow increases associated with the *M*7.1 Loma Prieta, California, earthquake were modeled as being the consequence of an approximately tenfold increase in the "bulk" permeability of shallow rock in the contributing watersheds (Rojstaczer et al., 1995). Applying this simple model to the *M*8.8 Maule, Chile, earthquake, a sixfold streamflow increase like that shown in Figure 1 is caused by an approximately sixfold increase in permeability; the subsequent decay owes to reequilibration of driving-force gradients with the increased permeability.

Additional research on both the Loma Prieta event and the similarly well documented *M*7.5 Chi-Chi, Taiwan, earthquake revealed an important caveat. The characteristics of baseflow, or groundwater contribution to stream discharge, generally appeared unaffected by the earthquakes (e.g., Manga, 2001; Montgomery et al., 2003). Consistent preearthquake and postearthquake recession characteristics—both for Loma Prieta and Chi-Chi—seem to argue against earthquake-induced changes in shallow hydraulic diffusivity and, therefore, against significant changes in permeability. Wang et al. (2004) resolved this apparent dilemma by invoking hydraulic anisotropy. They proposed that the Chi-Chi earthquake enhanced vertical permeability in the mountains, thereby releasing water to streams; they further suggested that the recession characteristics are mainly controlled by horizontal permeability, which remained nearly constant.

The hypothesis of enhanced *vertical* permeability to explain streamflow increases survives comparison with the major observational data sets. Other prominently discussed hypotheses, such as expulsion of water from great depths (Muir-Wood & King, 1993) and liquefaction (e.g., Manga, 2001), fare less well. The regional pattern of the streamflow responses, in most instances, does not mimic the distribution of earthquake-caused volumetric strain (expansion or contraction) nor are streamflow increases confined to areas underlain by liquefaction-prone sediments (e.g., Mohr et al., 2017).

Whereas watershed-scale permeability increases can be roughly estimated from the magnitude of streamflow increases, local-scale permeability changes can be more directly and precisely estimated from coseismic changes in the tidal response of wells, as in the Zhang et al. example that motivates this commentary. A particularly useful example, from the Pinon Flat Observatory in the California Coast Ranges, involved the response of two different wells to a series of regional earthquakes (Elkhoury et al., 2006). At Pinon Flat, the observed permeability increases were linearly proportional to peak ground velocity for peak ground velocities ranging up to >2 cm/s.

Another intriguing aspect of the Pinon Flat data is the fact that permeability repeatedly returns to similar background values over the months to years following coseismic permeability enhancement. One potential explanation for both the permeability increases and subsequent recovery is mobilization of fracture-blocking colloidal particles or bubbles, followed by a gradual resettling (e.g., Manga et al., 2012).

While permeability changes are commonly invoked to explain hydrological responses to earthquakes, a systematic analysis of water-level responses in a large network of monitoring wells in China reveals that changes likely have multiple mechanisms (Yan et al., 2014). These authors noted that a minority of wells with water-level changes also had detectable changes in the response to Earth tides, a signature of permeability change. They found no clear correlation of responses with well depth or lithology, concluding that responses are complex and that more detailed studies are needed to reveal the multiple mechanisms that cause hydrological responses to earthquakes.

4. Implications for Groundwater and Other Subsurface Resources

The dynamic nature of permeability as revealed by coseismic hydrologic phenomena holds implications for groundwater systems, geothermal resources, mineral resources, and geologic hazards. Consider, for instance, the following:

1. Water quality may be impacted by postseismic leakage of contaminants or by large increases in hydrothermal outflow;
2. Geothermal fluid production is generally associated with recently active faults, where seismic activity episodically regenerates permeability that is otherwise lost to hydrothermal alteration; and
3. Many mineral deposits are associated with fault stepovers, bends, splays, and tips—locations where permeability is created repeatedly by small earthquakes.

Whereas our emphasis here is the effect of seismicity on hydrologic systems, it is notable that, conversely, groundwater systems can modulate seismicity, potentially complicating interpretation of seismic monitoring motivated by geologic hazards. Seismicity induced by wastewater disposal in the U.S. midcontinent is one example (e.g., Ellsworth, 2013). In a recent and dramatic natural example, shallow seismicity in the Sierra Nevada near Long Valley Caldera, California—a high-threat volcanic area—was shown to be strongly modulated by snowmelt, with seismicity rates ~37 times higher during very wet periods versus very dry periods (Montgomery-Brown et al., 2019).

5. Research and Monitoring Opportunities

Controls on the magnitude of changes and subsequent evolution of permeability remain poorly documented, and even the mechanisms are uncertain. Some of the more comprehensive studies have shown that multiple mechanisms must be at play (e.g., Hosono et al., 2019; Yan et al., 2014). There are three clear pathways for making progress in understanding the temporal evolution of permeability.

First, tidal analysis is a relatively inexpensive way to monitor changes in permeability and storage properties but requires continuous, precise, and high-frequency water-level sampling and robust data archiving. It seems likely that many thousands of potentially useful time series, meeting the minimal requirements of hourly sampling and record lengths greater than one month, are generated globally. The U.S. Geological Survey alone currently maintains more than 1,900 real-time wells with water levels logged at intervals ranging from 1 min to 1 hr. Limits on the actual suitability of such records for tidal analysis include the fact that Earth tide responses are generally more pronounced in deep wells, owing to the generally lower compressibilities of deeper rocks (though shallow wells tapping artesian systems can also be sensitive); that both deep or shallow wells near coasts tend to be dominated by ocean loading and ocean tides; and that most monitoring wells are used for groundwater supply, which tends to target shallow horizons with high storativity, which reduces sensitivity to tides. Tidal analysis thus offers a biased sampling of the crust—biased to deep, low-compressibility rocks far from coastlines. Extensive networks of wells exist globally, including the network hosting the monitoring well considered by Zhang et al. (2019). The research

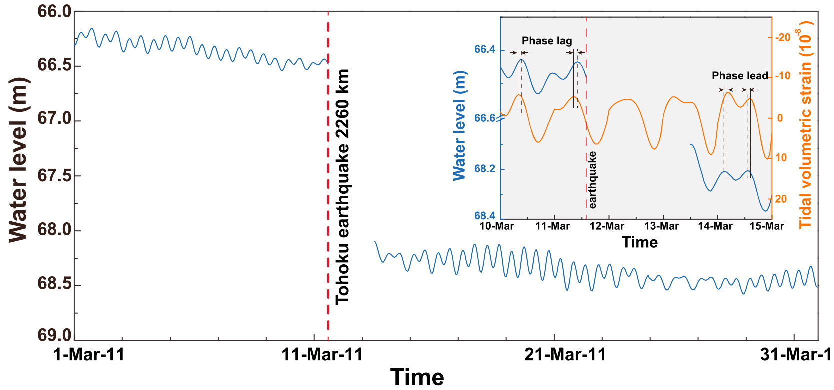

Figure 2. Expanded views of the water-level data analyzed by Zhang et al. (2019). The data are from a 2,605-m-deep well located 2,260 km from the epicenter of the *M*9.0 Tohoku earthquake. Postearthquake changes in the phase and amplitude of the tidal response are visible. Zhang et al. used both tides and barometric pressure changes to infer changes in horizontal and vertical permeability. A total of 73 monitoring wells, maintained by the China Earthquake Administration for the purposes of earthquake prediction, exhibited water-level responses to the Tohoku earthquake, fairly evenly distributed between increases and decreases (Yan et al., 2014). The data gap following the earthquake arose because the sensor was out of the water after the water level fell, and had to be repositioned.

community is best served if these data are freely shared and accessible, which is not the case for many nations or agencies that monitor wells.

Second, higher-frequency sampling, around 1 Hz, enables hydroseismograms to be recorded, and more faithfully records the magnitude of water level changes and duration of short-lived changes (e.g., Brodsky et al., 2003). Hydroseismograms provide a further constraint on hydrogeological properties at different spatial scales than tides (e.g., Shalev et al., 2016). Transient water level change may also be rapid (e.g., Geballe et al., 2011) and short-lived, and may not be captured by hourly sampling.

Third, quantitative insights from data come from using models to interpret that data. The novelty in Zhang et al. (2019) is that they consider both horizontal and vertical flow. The change in phase between water level and tidal strain from a phase lag to a phase lead (Figure 2) requires changes in vertical and horizontal permeability (Wang et al., 2018). By analyzing both barometric-pressure and tidal responses, Zhang et al. (2019) are able to quantitatively evaluate permeability changes in both aquifer and aquitard. The results show that small stress changes can have large effects on permeability. Permeability is not a static quantity, and, where suitable wells are available, monitoring it by such methods can be both inexpensive and informative.

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