Chapter 14

Epilogue

Abstract We identify some common threads and trends in the observations of hydrological responses to earthquakes. We suggest that seismic energy density is a useful metric for interpreting observations and relating different types of responses. We conclude with a summary of outstanding questions and new opportunities.

14.1 General Framework

The interaction between water and earthquakes vividly demonstrates the dynamic nature of the permeability of the uppermost crust, with implications for both earthquakes and groundwater transport. The processes of tectonic deformation and fluid movement are two-way coupled, as shown schematically in Fig. 14.1; i.e., changes in fluid pressure may alter stresses and hence can promote rock failure or accelerate slip on faults; at the same time, deformation and earthquakes may change pore pressure in the crust, causing changes of the water level in wells, discharge in streams, liquefaction of sediments, changes of groundwater temperature and chemical composition, and may even affect the eruptions of mud and magmatic volcanoes.

Figure 14.2 summarizes the magnitude of the reported permeability changes from lab experiments and field observations as a function of strain amplitude. It shows that, first, permeability usually increases after a disturbance, i.e., the ratio between the stimulated and the initial permeabilities is usually greater than 1; second, strain amplitudes as small as 10^{-6} can change permeability; third, permeability generally increases by less than a factor of ten unless new fractures form or their width increases significantly owing to pressurization of fractures; and fourth, there is no systematic dependence of the magnitude of the reported permeability changes on the strain amplitude, thus the change of permeability cannot be directly related to the applied strain. The results in Fig. 14.2 are also categorized by frequency, with filled boxes indicating frequencies greater than or equal to 10 Hz; everything else, except Faoro et al. (2012), has frequencies between 0.05 and 10 Hz, i.e., the range of seismic frequencies that cause the field responses. No obvious frequency-dependence is found either, but more experiments and observations are needed.

Fig. 14.1 Relationship between earthquakes and hydrology, and the processes through which interactions can occur. The + and – indicate the sign of the effect if it is known (from Manga and Wang 2007)

Fig. 14.2 Compilation of the permeability changes documented in the lab and field as a function of strain amplitude. Stippled boxes indicate field observations. Black filled boxes indicate experiments with frequencies ≥ 10 Hz. The dashed box indicates the strain amplitude and permeability changes for the pressurized fracture experiments presented in Faoro et al. (2012)—these are the only responses to non-oscillatory deformation shown in the compilation. Sources are as follows: bubble mobilization experiments (Li et al. 2005); pressure oscillation experiments (Elkhoury et al. 2011); axial stress oscillations in black (Roberts 2005) and in white (Liu and Manga 2009; Shmonov et al. 1999); well temperatures (Wang et al. 2012, 2013), with strain from Koizumi et al. (2004); springs (Manga and Rowland 2009); mud volcanoes (Rudolph and Manga 2010); wells (Elkhoury et al. 2006). For the bubble mobilization experiments of Beresnev et al. (2005), Li et al. (2005) we assumed a wave velocity of 3 km/s (from Manga et al. 2012)

The types of interactions shown in Figs. 14.1 and 14.2 may be extended to the evolution of permeability and groundwater flow in the deep crust. Rojstaczer et al. (2008) hypothesized that the permeability of the crust adjusts in a time-averaged sense so that it can accommodate recharge by precipitation and fluid released by internal forcing (metamorphism, tectonics, magmatism). If the pore pressure becomes large enough because the permeability is low, fracture may occur and will increase permeability. High permeability promotes groundwater flow, mineralization and ultimately permeability reduction. As a result, a balance is achieved in which the time-averaged permeability accommodates the transport of fluids provided to the crust, from below, within and above. Similar self-organizing feedbacks have been proposed for hydrothermal systems (e.g., Weis 2015) and deep fault zones (e.g., Lupi et al. 2011). Testing the Rojstaczer et al. (2008) hypothesis, however, is challenging because of the vast range of space and time scales involved in the processes that influence permeability and groundwater flow, even though the hypothesis is consistent with the mean permeability of the crust (Manning and Ingebritsen 1999). Other observational evidence supporting this idea includes mineral deposits that record transient, high permeability flow paths (e.g., Micklethwaite and Cox 2004) and short-lived high temperatures caused by transient flow in the lower crust (e.g., Camacho et al. 2005). Indeed, the permeability of disturbed crust, whether disturbed by tectonic events or manipulating the subsurface, can increase by a couple orders of magnitude highlighting that permeability is a dynamic physical property (Fig. 14.3).

We have also seen that the various hydrologic responses are, to a first degree of approximation, scaled by earthquake magnitude M and hypocenter distance r

Fig. 14.3 Permeability as a function of depth. Curve for geothermal-metamorphic is based on the compilation of data in Manning and Ingebritsen (1999), Ingebritsen and Manning (2002). The disturbed crust curve is from Ingebritsen and Manning (2010). The arrows above the plot show the processes that dominate at different permeabilities (from Manga et al. 2012)

Fig. 14.4 Distribution of earthquake-induced hydrologic changes as functions of earthquake magnitude and epicentral distance. Data include an earlier global dataset from Wang and Manga (2010), water level data for Devils Hole from Weingarten and Ge (2014) and for China from Sun et al. (2018) and Zhang et al. (2019a), and liquefaction data for New Zealand from Simon Cox (personal communication). Also plotted are the contours of constant seismic energy density e (Eq. 6.10; Wang 2007). Note that the new data for liquefaction from New Zealand provides further support to the liquefaction limit (highlighted green line), especially at small earthquakes from $M = 4$ to 5. The orange line shows typical fault length as a function of magnitude. Note also that new water-level data from Devils Hole and China significantly extend the threshold of seismic energy density for water-level response from 10^{-4} J/m^3 (Wang and Manga 2010) to $< 10^{-6} \text{ J/m}^3$

and may thus be plotted together, as in Fig. 14.4. The data are compiled from an earlier global dataset (Wang and Manga 2010), new water-level data from Devil Hole, Nevada (Weingarten and Ge 2014) and China (Yan et al. 2014; Sun et al. 2018; Zhang et al. 2019a), and new liquefaction data from New Zealand (Simon Cox, personal communication).

We have also used an empirical relation among the seismic energy density e , the earthquake magnitude M , and the epicentral distance r (Eq. 6.10) as a reference to compare the different hydrologic responses:

$$\log_{10} e = -3 \log_{10} r + 1.44M - 4.62, \quad (14.1)$$

where r is in km and e in J/m^3 . We stress that this relation was constructed on the basis of ground motion data for southern California (Wang 2007) and is thus region-specific and may not apply to other areas such as New Zealand (Weaver et al. 2020).

It is not made for other regions only because there is a lack of available strong motion data for other specific regions.

Despite of the uncertainty in this relation, we use it here as a common reference to the global hydrological responses (Fig. 14.4). The figure shows that some hydrologic responses require much greater seismic energy density (e.g., liquefaction, mud volcanoes) than others (e.g., water level changes in wells, earthquake triggering). Part of the difference may be due to differences in the regional geology. Part of the difference may be a result of incomplete data. On the other hand, most other data summarized in Fig. 14.4 are abundant, come from a wide range of geological settings, and thus the differences in the threshold energy among the different hydrologic responses may be significant. Scatter in the hydrologic responses is expected for two reasons. First, if triggering of a particular hydrological response is a threshold process, then we might expect triggering to be possible for all distances up to the threshold. Second, because the hydro-mechanical properties of rocks and sediments are highly variable, less seismic energy density is required for a specific response at sites underlain by sediments or rocks more sensitive to seismic disturbances than at sites underlain by less sensitive rocks or sediments.

The new water-level data from Devils Hole, Nevada (Weingarten and Ge 2014) and China (Sun et al. 2018; Zhang et al. 2019a) significantly extend the threshold of seismic energy density for water-level response from 10^{-4} J/m³ (Wang and Manga 2010) to 10^{-6} J/m³ or lower. It is likely that this boundary may even be further extended when more data becomes available. On the other hand, the liquefaction limit proposed by Wang (2007; highlighted in green in Fig. 14.4) is supported by the new liquefaction data from New Zealand (Simon Cox, personal communication, 2020), especially at small earthquake magnitudes of $M = 4$ to 5.

Without a priori knowledge of the seismic sensitivity of the rocks and sediments at most of the documented sites, we simplify the comparison by focusing on the threshold seismic energy density, i.e., the lower bound of the seismic energy density required to initiate a specific type of hydrological response in the most sensitive sediments or rocks. Thus liquefaction, some mud volcanoes and streamflow increases are bounded by the contour with $e \sim 10^{-1}$ J/m³, while groundwater level may respond to $e < 10^{-6}$ J/m³. It is important to note that the examples for mud volcano eruptions shown in Fig. 14.4 include only clearly identified triggered eruptions. Geysers have long been known to be sensitive to earthquakes, as manifested by changes in the time interval between eruptions (Ingebritsen and Rojstaczer 1993), and some geysers in the Yellowstone National Park have responded to $e \sim 10^{-3}$ J/m³ from the Denali earthquake (Fig. 14.4; Husen et al. 2004). Given the limited number of data, however, we are unable to confirm whether this may be representative for other geysers and it is worth highlighting that most Yellowstone geysers did not obviously respond to the Denali earthquake. Triggered seismicity also appears to be especially sensitive to seismic disturbances and may respond to e as small as 10^{-4} J/m³ (Fig. 14.4; Brodsky and Prejean 2005; Hill and Prejean 2007). It is, however, important to highlight that the question whether triggered seismicity is a hydrological phenomenon is a matter of active debate (e.g., Hill 2008) and it is likely that some triggered earthquakes are not caused by earthquake-induced re-distribution of pore pressure. Regardless of a

clear hydrologic connection, triggered earthquakes by large ($M > 9$) earthquakes may be global (e.g., West et al. 2005; Velasco et al. 2008)—consistent with the threshold limit for triggered earthquakes shown in Fig. 14.4.

Beyond the near field, dynamic strain must be invoked because the static poroelastic strain is either too small or has the wrong sign to account for the coseismic changes in groundwater systems. Dynamic strain by itself cannot lead to sustained hydrologic changes, but it can dislodge blockage from fractures to enhance permeability (Mogi et al. 1989; Roeloffs 1998; Brodsky et al. 2003; Wang and Chia 2008). Roeloffs (1998) noticed that, at a given well, the amplitude of the sustained groundwater-level change increases in proportion to the increased peak ground velocity (PGV), which is directly related to the seismic energy density. Based on the analysis of groundwater response to Earth tides, Elkhoury et al. (2006) first showed that seismic waves enhance the permeability of shallow crust and the magnitude of this enhancement increases with increased peak ground velocity, and thus with increased seismic energy density. Wong and Wang (2007) found that PGV is a much better predictor for water level changes and liquefaction than peak ground acceleration (PGA). Mohr et al. (2017) also found that PGV was the best ground motion predictor of streamflow changes. Weaver et al. (2020) further found that PGV is better correlated with water level changes in wells than other measures of ground motion. Taken together, it appears that earthquake-enhanced permeability in the shallow crust may be closely related to the seismic energy density and may explain a broad spectrum of hydrologic responses that occur in the intermediate and far fields.

14.2 Future Research

An important theme throughout this book is that much remains to be learned about the interactions between water and earthquakes. We highlight below several unsolved problems that we consider important, and may be fruitful for future research to advance our understanding of the interaction between water and earthquakes.

1. Recent advances in space technology such as InSAR have allowed continuous monitoring of ground deformation, which opens the door to investigate the interactions among groundwater processes, crustal deformation and earthquakes. While studies in this direction are still in their initial stage (e.g., Shirzaei et al. 2016; Johnson et al. 2017; Shi et al. 2020), the combination of space-monitoring of ground deformation and groundwater processes has the potential to provide insight to the interaction between water and earthquake processes, and its promise for future research cannot be over-emphasized.
2. Estimates of the hydraulic parameters have been increasingly made using the water-level response to the oscillatory changes of the crustal strain in response to the tidal, barometric and seismic wave forcing. But the transmissivity estimated

- from the different kinds of forcing can be different by several orders of magnitude (Sun et al. 2020). These authors attributed such differences to the different frequencies among the different kinds of forcing. But how transmissivity may depend on the forcing frequency and what are the mechanisms that may produce such dependence are largely unknown. Recent advances in instrumentation and data storage have allowed the documentation of water level data from yearly to seismic frequencies (Shih 2009; Sun et al. 2018; Zhang et al. 2019b), and thus have greatly extended the time scale for quantitative analysis. This opens the door for investigating the frequency dependence of aquitard impedance.
3. Tidal analysis has increasingly been used in studies of the water-level response to earthquakes. However, due to the absence of strain measurements near most wells, tidal analyses have largely relied on theoretical tides for the analysis of the water-level response. Such simplification may lead to errors in the inferred phase shift (Harrison 1974; Beaumont and Berger 1975) and thus in the inferred response to earthquakes. This uncertainty needs to be corrected, if possible, or at least considered and discussed in order to avoid drawing misleading conclusions.
 4. Mohr et al. (2015) proposed that pore water was released from the unsaturated zone during the 2010 M8.8 Maule earthquake to explain the increased discharge of some streams in the Chilean coast ranges. This mechanism may also explain the rapid responses of stream flow (Manga et al. 2016) and water level (Wang et al. 2017) to the induced earthquakes in the flat mid-continental USA, such as Oklahoma, where no immediate sources of extra water are evident on Earth's surface. Breen et al. (2020) used a laboratory experiment to verify this hypothesis; but more experiments and field data are needed to better understand the effects of earthquakes on the unsaturated zone.
 5. Field observation that liquefaction occurs at distances far beyond the near field and is bounded by the liquefaction limit on a magnitude versus hypocenter distance diagram (green contour in Figs. 11.8 and 14.3; Wang 2007) is inconsistent with the notion of most earthquake engineers that liquefaction occurs only in the near field (blue contour in Fig. 11.8). Nor is it consistent with the results of laboratory studies that show that liquefaction is preceded by undrained consolidation. This inconsistency is curious but not understood. It is thus important, particularly for the mitigation of liquefaction damage, to understand why the threshold seismic energy for triggering liquefaction by earthquakes is so much lower than that in the near field and in laboratory studies.
 6. The mechanism leading to enhanced permeability is not entirely clear. Brodsky et al. (2003) suggested that seismic vibrations may unclog fractures by mobilizing colloidal particles in the fracture. Others have suggested that seismic vibrations may dislodge gas bubbles from the throats that connect pores (e.g., Beresnev and Johnson 1994; Beresnev et al. 2005; Deng and Cardenas 2013). At low flow velocity, clay particles suspended in water may form flocculated deposits which may effectively fill fractures, blocking flow, and such fluids are non-Newtonian and have a yield strength equivalent to a threshold energy density of 10^{-3} J/m³ at a few percent solid fraction for different clays (Coussot 1995). The 2002 M7.9 Denali earthquake enhanced groundwater flow in Iowa,

- some 5000 km away, to such an extent that clay particles flushed from local aquifers discolored well waters. More experimental studies seem justified to test which of the suggested mechanisms actually occur in field settings and to identify telltale signatures of the process.
7. The empirical relation developed among seismic energy, earthquake magnitude and epicentral distance (Chap. 6; Wang 2007) is sometimes applied to different parts of the world to study the earthquake-induced hydrologic responses. As emphasized previously, this relation was developed specifically from the seismic data for southern California and its application to other regions, if not verified, may lead to error, such as in New Zealand (Weaver et al. 2020). Given the current availability of dense seismic networks in many parts of the world, the development of region-specific empirical relations between seismic energy density and responses may be worthwhile.
 8. As more data for the hydrologic responses to earthquakes are collected and the analysis of data becomes more refined, an important consideration in the interpretation of these responses is the effect of geology and rock properties on the measured seismic response. Earthquake engineers have long emphasized the importance of site geology on the distribution of seismic hazards. Similar considerations should be included in the interpretation of hydrologic responses to earthquakes.
 9. Identifying and understanding the interactions between earthquakes and water require data. Instruments, data storage, and data transmission are now much less expensive than ever before. Whereas sampling water level daily to hourly may have been standard practice, it is becoming feasible to sample every second, allowing wells to record hydroseismograms and enabling tidal and barometric analysis. High frequency data enables frequency-dependence of responses to be identified and used to monitor the evolution of properties (see item 1). Obtaining more data is not sufficient—ideally this data is made available so that researchers can test new models, look for correlations, and revisit past studies with new understanding. We applaud those nations, agencies, or individuals who share their data!

References

- Beaumont C, Berger J (1975) An analysis of tidal strain observations from the United States of America: I. The laterally homogeneous tide. *Bull Seismol Soc Am* 65(6):1613–1629
- Beresnev IA, Johnson PA (1994) Elastic wave stimulation of oil production: a review of methods and results. *Geophysics* 59:1000–1017
- Beresnev IA, Vigil RD, Li W et al (2005) Elastic waves push organic fluids from reservoir rock. *Geophys Res Letters* 32:L13303. <https://doi.org/10.1029/2005GL023123>
- Breen S, Zhang Z, Wang CY (2020) Shaking water out of sands: an experimental study. *Water Resour Res* 56: e2020WR028153. <https://doi.org/10.1029/2020WR028153>

- Brodsky EE, Roeloffs E, Woodcock D et al (2003) A mechanism for sustained water pressure changes induced by distant earthquakes. *J Geophys Res* 108:2390. <https://doi.org/10.1029/2002JB002321>
- Brodsky EE, Prejean SG (2005) New constraints on mechanisms of remotely triggered seismicity at Long Valley Caldera. *J Geophys Res* 110:B04302. <https://doi.org/10.1029/2004JB003211>
- Camacho A, Lee JK, Hensen BJ, Braun J (2005) Short-lived orogenic cycles and the eclogitization of cold crust by spasmodic hot fluids. *Nature* 435(7046):1191–1196
- Coussot P (1995) Structural similarity and transition from Newtonian to non-Newtonian behavior for clay-water suspensions. *Phys Rev Lett* 74:3971–3974
- Deng W, Cardenas MB (2013) Dynamics and dislodgment from pore constrictions of a trapped nonwetting droplet stimulated by seismic waves. *Water Resour Res* 49(7):4206–4218
- Elkhoury JE, Brodsky EE, Agnew DC (2006) Seismic waves increase permeability. *Nature* 441:1135–1138
- Elkhoury JE, Niemeijer A, Brodsky EE et al (2011) Laboratory observations of permeability enhancement by fluid pressure oscillation of in-situ fractured rock. *J Geophys Res* 116:B02311. <https://doi.org/10.1029/2010JB007759>
- Faoro I, Elsworth D, Marone C (2012) Permeability evolution during dynamic stressing of dual permeability media. *J Geophys Res* 117:B01310. <https://doi.org/10.1029/2011JB008635>
- Harrison JC (1974) Cavity and topography effects on the measurement of tilt and strain. *EOS Trans Am Geophys Union* 56:1151
- Hill DP (2008) Dynamic stresses, coulomb failure, and remote triggering. *Bull Seism Soc Am* 98:66–92
- Hill DP, Prejean SG (2007) Dynamic triggering. In: Schubert G (ed) *Treatise on geophysics*, vol 4, pp 293–320
- Husen S, Taylor R, Smith RB et al (2004) Changes in geyser eruption behavior and remotely triggered seismicity in Yellowstone. National park produced by the 2002 M 7.9 Denali fault earthquake Alaska. *Geology* 32:537–540
- Ingebritsen SE, Rojstaczer SA (1993) Controls on geyser periodicity. *Science* 262:889–892
- Ingebritsen SE, Manning CE (2002) Diffuse fluid flux through orogenic belts: implications for the world ocean. *Proc Natl Acad Sci USA* 99:9113–9116. <https://doi.org/10.1073/pnas.132275699>
- Ingebritsen SE, Manning CE (2010) Permeability of the continental crust: dynamic variations inferred from seismicity and metamorphism. *Geofluids* 10:193–205
- Johnson CW, Fu Y, Bürgmann R (2017) Seasonal water storage, stress modulation, and California seismicity. *Science* 356(6343):1161–1164
- Koizumi N, Lai WC, Kitagawa Y (2004) Comment on “Coseismic hydrological changes associated with dislocation of the September 21, 1999 Chichi earthquake, Taiwan” by Min Lee et al. *Geophys Res Lett* 31:L13603. <https://doi.org/10.1029/2004GL019897>
- Li W, Vigil RD, Beresnev IA et al (2005) Vibration-induced mobilization of trapped oil ganglia in porous media: experimental validation of a capillary-physics mechanism. *J Colloid Interface Sci* 289:193–199
- Liu W, Manga M (2009) Changes in permeability caused by dynamic stresses in fractured sandstone. *Geophys Res Lett* 36:L20307
- Lupi M, Geiger S, Graham CM (2011) Numerical simulations of seismicity-induced fluid flow in the Tjörnes Fracture Zone, Iceland. *J Geophys Res Solid Earth* 116(B7):B07101
- Manga M, Wang CY (2007) Earthquake hydrology. In: Schubert G (ed) *Treatise on geophysics*, vol 4, pp 293–320
- Manga M, Rowland JC (2009) Response of Alum Rock springs to the October 30, 2007 earthquake and implications for the origin of increased discharge after earthquakes. *Geofluids* 9:237–250
- Manga M, Beresnev I, Brodsky EE et al (2012) Changes in permeability caused by transient stresses: field observations, experiments, and mechanics. *Rev Geophys* 50:RG2004. <https://doi.org/10.1029/2011RG000382>

- Manga M, Wang CY, Shirzaei M (2016) Increased stream discharge after the 3 September 2016 Mw 5.8 Pawnee. *Okla Earthq Geophys Res Lett* 43:11588–11594. <https://doi.org/10.1002/2016GL071268>
- Manning CE, Ingebritsen SE (1999) Permeability of the continental crust: the implications of geothermal data and metamorphic system. *Rev Geophys* 37:127–150
- Micklethwaite S, Cox SF (2004) Fault-segment rupture, aftershock-zone fluid flow, and mineralization. *Geology* 32(9):813–816
- Mohr CH, Manga M, Wang CY et al (2015) Shaking water out of soil. *Geology* 43(3):207–210
- Mohr CH, Manga M, Wang CY, et al, (2017) Regional changes in streamflow after a megathrust earthquake. *Earth Planet Sci Lett* 458:418–428
- Mogi K, Mochizuki H, Kurokawa Y (1989) Temperature changes in an artesian spring at Usami in the Izu Peninsula (Japan) and their relation to earthquakes. *Tectonophysics* 159:95–108
- Roberts PM (2005) Laboratory observations of altered porous fluid flow behavior in Berea sandstone induced by low-frequency dynamic stress stimulation. *Acoustical Phys* 51:S140–S148
- Roeloffs EA (1998) Persistent water level changes in a well near Parkfield, California, due to local and distant earthquakes. *J Geophys Res* 103:869–889
- Rojstaczer SA, Ingebritsen SE, Hayba DO (2008) Permeability of continental crust influenced by internal and external forcing. *Geofluids* 8:128–139
- Rudolph ML, Manga M (2010) Mud volcano response to the April 4, 2010 El Mayor-Cucapah earthquake. *J Geophys Res* 115:B12211. <https://doi.org/10.1029/2010JB007737>
- Shirzaei M, Ellsworth WL, Tiampo KF, González PJ, Manga M (2016) Surface uplift and time-dependent seismic hazard due to fluid injection in eastern Texas. *Science* 353:1416–1419
- Shi Z, Hu X, Wang CY (2020) Hydro-mechanical coupling in the shallow crust—insight from groundwater level and satellite radar imagery in a mining area (in review)
- Shih DCF (2009) Storage in confined aquifer: spectral analysis of ground-water responses to seismic Rayleigh waves. *J Hydrology* 374:83–91
- Shmonov VM, Vitovtova VM, Zharikov AV (1999) Experimental study of seismic oscillation effect on rock permeability under high temperature and pressure. *Int J Rock Mech Mining Sci* 36:405–412
- Sun X, Xiang Y, Shi Z (2018) Estimating the hydraulic parameters of a confined aquifer based on the response of groundwater levels to seismic Rayleigh waves. *Geophys J Int* 213:919–930
- Sun X, Shi Z, Xiang Y (2020) Frequency dependence of in-situ transmissivity estimation of well-aquifer systems from periodic loadings, *Water Resources Research* (in press)
- Velasco AA, Hernandez S, Parsons T et al (2008) Global ubiquity of dynamic earthquake triggering. *Nature Geosci* 1:375–379
- Wang CY (2007) Liquefaction beyond the near field. *Seismo Res Lett* 78:512–517
- Wang CY, Chia Y (2008) Mechanism of water-level changes during earthquakes: near field versus intermediate field. *Geophys Res Lett* 35:L12402. <https://doi.org/10.1029/2008GL034227>
- Wang CY and Manga M (2010) Earthquakes and water. Springer, Lecture notes in earth sciences, vol 114, 249pp
- Wang CY, Manga M, Wang CH et al (2012) Earthquakes and subsurface temperature changes near an active mountain front. *Geology* 40:119–122
- Wang CY, Wang LP, Manga M et al (2013) Basin-scale transport of heat and fluid induced by earthquakes. *Geophys Res Lett* 40:3893–3897
- Wang CY, Manga M, Shirzaei M et al (2017) Induced seismicity in Oklahoma affects shallow groundwater. *Seismol Res Lett* 88:956–962
- Weaver KC, Arnold R, Holden C et al (2020) A probabilistic model of aquifer susceptibility to earthquake-induced groundwater-level changes. *Bull Seismol Soc Am* 110:1046–1063
- Weingarten M, Ge S (2014) Insights into water level response to seismic waves: a 24 year high-fidelity record of global seismicity at Devils Hole. *Geophys Res Lett* 41:74–80. <https://doi.org/10.1002/2013GL058418>
- Weis P (2015) The dynamic interplay between saline fluid flow and rock permeability in magmatic-hydrothermal systems. *Geofluids* 15(1–2):350–371

- West M, Sanchez JJ, McNutt SR (2005) Periodically triggered seismicity at Mount Wrangell, Alaska, after the Sumatra earthquake. *Science* 308:1144–1146
- Wong A, Wang CY (2007) Field relations between the spectral composition of ground motion and hydrological effects during the 1999 Chi-Chi (Taiwan) earthquake. *J Geophys Res* 112:B10305. <https://doi.org/10.1029/2006JB004516>
- Yan R, Woith H, Wang R (2014) Groundwater level changes induced by the 2011 Tohoku earthquake in China mainland. *Geophys J Int* 199:533–548
- Zhang H, Shi Z, Wang G et al (2019a) Large earthquake reshapes the groundwater flow system: Insight from the water-level response to Earth tides and atmospheric pressure in a deep well. *Water Resour Res* 55:4207–4219. <https://doi.org/10.1029/2018WR024608>
- Zhang Y, Wang CY, Fu LY et al (2019b) Unexpected far-field hydrological response to a great earthquake. *Earth Planet Sci Lett* 519:202–212

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