Chapter 1
Introduction

"… The waters that seem to have been cut off on the land of all communion with the sea, the springs, the lakes, were in extraordinary agitation in many distant lands at the same time. Most of the lakes in Switzerland, the lake at Templin in the Marches, some lakes in Norway and Sweden, took on a swirling motion that was far more tumultuous than a storm, and the air was at the same time calm. The lake at Neuchâtel, if one can rely on the news, went into hidden crevices, and the one at Meiningen did the same, but soon returned. In just these minutes, the mineral water at Töplitz in Bohemia suddenly stopped and returned to blood red. The force with which the water had drifted had widened its old course, and it got thereby a stronger inflow. The inhabitants of this city had to sing *te deum laudamus*, … In the Kingdom of Fez in Africa, a subterranean force split a mountain and poured blood-red streams out of its mouth. At Angoulême in France, there was an underground roar, and a deep crypt opened up on the plain, holding in itself unfathomable water. At Gçmenos in Provence, a spring suddenly became muddy and turned red. The surrounding areas reported similar changes of their sources. All this happened in the same minutes as the earthquake devastated the coasts of Portugal. Every now and then in just these short times some earth tremors in far-off countries were perceived. Amost all happened close to the seacoast. At Cork in Ireland, as in Glückstadt, and at some other places lying on the seas, there were slight changes. Milan is perhaps the place that has been shaken at the furthest distance from the shore of the lake on the very same day. Just this morning at 8 o'clock Vesuvius raged at Neapolis, and was silent again the time when the shock came to Portugal. …" von Kant (1756), translated by Christian Mohr, University of Potsdam.

For thousands of years, hydrologic changes have been documented following earthquakes. Examples include increased stream discharge, changes in groundwater level, changes in the temperature and chemical composition of groundwater, formation of new springs, disappearance of previously active springs, the liquefaction of sediments, and changes in the activities of mud volcanoes and geysers. The introductory quotation from Kant, for example, describes responses throughout Europe

C. Wang and M. Manga, *Water and Earthquakes*,
Lecture Notes in Earth System Sciences,
https://doi.org/10.1007/978-3-030-64308-9_1

Fig. 1.1 Well in Meizhou County, Guangdong, China, responding to the December 26, 2004, M 9.2 Sumatra earthquake 3200 km away, 2 days after the Sumatra earthquake. The fountain was 50–60 m high when it was first sighted 1 day after the earthquake. Picture taken by Hou Banghua, Earthquake Office of Meizhou County

to the 1755 great Lisbon earthquake. It is not unexpected that earthquakes can cause hydrologic changes because the stresses created by earthquakes can be large. What is surprising are the large amplitudes of hydrologic responses and the great distances over which these changes occur. Following the 2004 M9.2 Sumatra earthquake, for example, groundwater erupted in southern China, 3200 km away from the epicenter, and the water fountain shown in Fig. 1.1 reached a height of 50–60 m above the ground surface when it was first sighted. Because earthquakes and water interact with each other through changes in both stress and physical properties of rocks, understanding the origin of hydrological responses can provide unique insight into hydrogeologic and tectonic processes at spatial and temporal scales that otherwise could not be studied.

Earthquakes cause both static and dynamic changes of the stresses in the crust. Both types of stress change decrease with increasing distance from the earthquake, but at different rates. Figure 1.2, from Kilb et al. (2002), illustrates how static and dynamic stress change with increasing distance from the epicenter. The dynamic component of the Coulomb stress change, Δ CFS(t), as defined in the caption of Fig. 1.2, is the time-dependent change in the Coulomb failure stress resolved onto a possible failure plane. The static stress change, denoted by Δ CFS, diminishes much more rapidly with distance than the transient, dynamic change. Thus, at close distances the ratio (peak Δ CFS(t))/Δ CFS is approximately inversely proportional to the source-receiver distance, r^{-1}, and at larger distances proportional to r^{-2} (Aki and Richards 1980). At distances up to $\sim$1 ruptured fault length, the static and the peak dynamic changes are comparable in magnitude, while at distances greater than

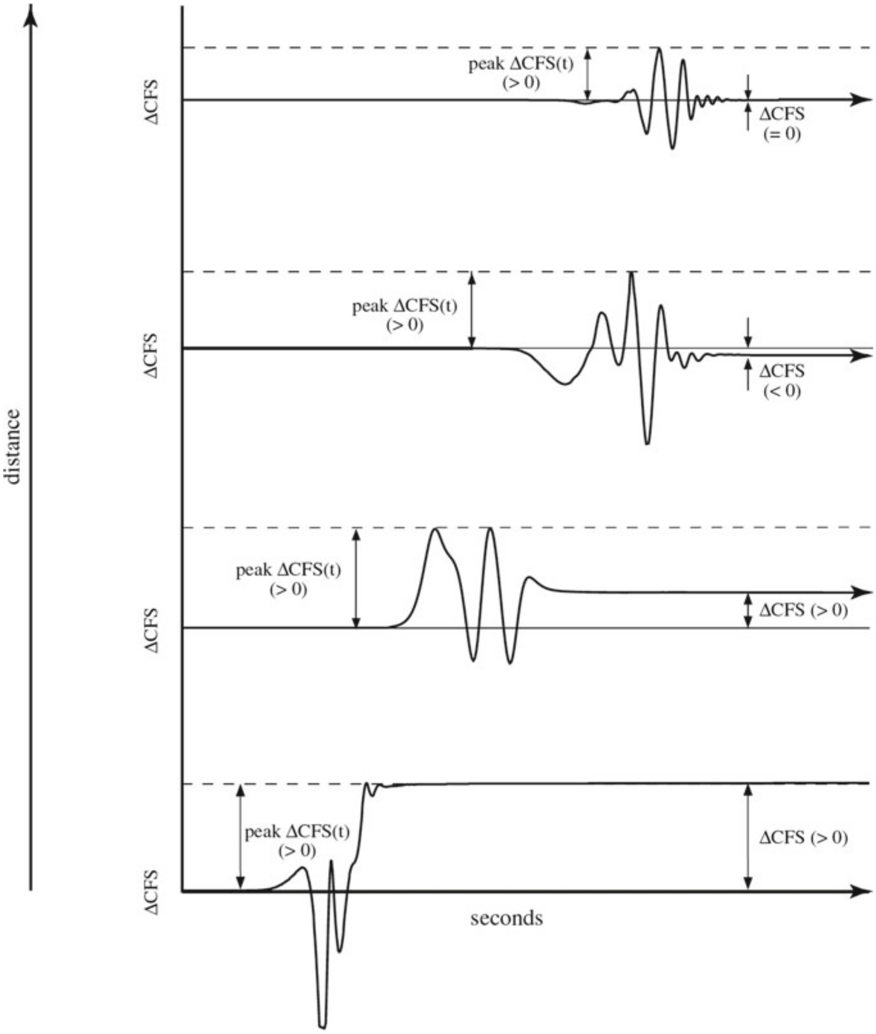

Fig. 1.2 Cartoon illustrating the peak dynamic Coulomb stress change (peak Δ CFS(t)) and static Coulomb stress change (Δ CFS), and their variation with distance from the ruptured fault. Δ CFS(t) $\equiv \Delta\tau(t) - \mu\ [\Delta\sigma(t) - \Delta P(t)]$, where τ is shear stress on the fault, σn is the stress normal to the fault, P is the pore pressure, and μ is the coefficient of friction. In the far field, peak dynamic stresses, Δ CFS(t), are far greater than the static change, Δ CFS, but in the near field, both are comparable in magnitude. Modified from Kilb et al. (2002)

several ruptured fault lengths, the peak dynamic change is much greater than the static change. As discussed in later chapters, the relative magnitude of the static and dynamic stresses is reflected in the hydrologic responses to earthquakes and is critical to understanding the origin of hydrological changes. We thus hereafter use the expression 'near field' to denote distances within about one ruptured fault length, ‘far field’ to denote distances many times greater than the fault length, and ‘intermediate field’ for distances in between.

Besides being a matter of academic interest, the study of earthquake-induced hydrologic changes also has important implications for water resources, hydrocarbon exploration and engineered systems. For example, groundwater level changes following earthquakes can affect water supplies (Chen and Wang 2009). The abandonment of Crete during the Late Minoan period has been attributed by some to a depletion of groundwater caused by earthquake (Gorokhovich 2005). In more recent times, it is sometimes necessary to evaluate the causative role of an earthquake in insurance claims for loss of water supply (Roeloffs 1998). Furthermore, earthquake-induced increase in crustal permeability (e.g., Rojstaczer et al. 1995; Roeloffs 1998; Brodsky et al. 2003; Wang et al. 2004; Elkhoury et al. 2006; Wang and Chia 2008; Zhang et al. 2019a, b) has important implications on hydrocarbon migration and recovery on the one hand, and contaminant transport on the other. Forensic earthquake hydrology was also applied to evaluate whether an earthquake may have played causative role in the 2006 mud eruption near the Indonesian city of Sidoarjo, in eastern Java, that led to massive destruction of property and evacuation of people (Tingay et al. 2018). Groundwater level changes following earthquakes may also put some underground waste repositories at risk (Carrigan et al. 1991; O’Brien 1992; Wang et al. 2018). Earthquake-induced fluid pressure changes can induce liquefaction of the ground that causes great damage to engineered structures (e.g., Seed and Lee 1966; National Research Council 2016), affect hydrocarbon production (Beresnev and Johnson 1994), and trigger seismicity (Hill and Prejean 2007; Guglielmi et al. 2015; Craig et al. 2017). Finally, measured changes of the pore pressure in rocks and/or the chemical composition of groundwater are sometimes taken as signatures of the crustal response to tectonic deformation (e.g., Davis et al. 2006) or even as earthquake precursors (e.g., Silver and Wakita 1996).

In the last two decades, there has been a rapid increase in the number and especially the quality of quantitative data documenting hydrological changes during and following earthquakes, largely due to the implementation of modern hydrological, seismological and geodetic monitoring systems around the globe. Research results on this topic, however, have been published in various journals and various fields (geoscience, hydrology, geotechnical engineering, petroleum geology). We felt it desirable to summarize the advances made so far in a single volume, both in terms of observations as well as their analysis and interpretation. Such a volume may serve on one hand as a convenient reference for researchers active in this area, and, on the other hand, as a starting point for students interested in this topic and may thus help to advance the studies of the interactions between water and earthquakes.

This volume does not address all possible interactions between water and earthquakes. Not covered are tsunamis, for example. We also do not address how the chemical properties of water affect faults and rock failure, and address only the physical effects of water on rock properties. Further, most studies of groundwater response to earthquakes tend to focus on the responses of groundwater systems that are directly detected and measured, such as the coseismic and post-seismic changes of water level in wells, discharge in streams, and changes in water temperature and composition. Others have considered the response of deep fluid systems, such as fluids released from metamorphic processes that occur at depths of several tens of km (e.g., Ingebritsen and Manning 2010), for which the response to earthquakes are not directly measured. In order to keep the book within a reasonable scope, we focus on processes that are directly measurable with available instruments, and are thus relatively shallow, even though deep metamorphic and magmatic processes are relevant and important for understanding both Earth's subsurface water cycle and the feedback between tectonics and fluids in the crust.

In keeping with the spirit of the series of Lecture Notes in Earth System Sciences, we prepared the chapters in the style of lecture notes; we also used some of these chapters in teaching a graduate course in the fall 2019 at the University of California, Berkeley. The basic principles for groundwater flow and transport and hydromechanical coupling are summarized in Chaps. 2 and 3. These chapters are provided as background for those new to the study of hydrogeology, and concepts and results from these chapters will be referred to when observations are discussed. In Chap. 4 we discuss induced seismicity, i.e., earthquakes influenced by water. In Chap. 5 we discuss the tidal and barometric responses of groundwater and how these responses can be used to monitor changes caused by earthquakes. In the later chapters we discuss separately the different types of hydrologic changes caused by earthquakes, including changes of groundwater level (Chap. 6), changes of stream flow (Chap. 7), changes of groundwater temperature (Chap. 8), changes of groundwater composition (Chap. 9), changes in geyser activity (Chap. 10), earthquake-induced liquefaction (Chap. 11), and the eruptions of mud and magmatic volcanoes (Chap. 12). We also summarize the current state of the art on detecting and interpreting hydrologic precursors before earthquakes in Chap. 13. The concepts of dynamic strain and seismic energy density are used interchangeably throughout the book. The latter is defined in Chap. 3 as the maximum seismic energy available to do work in a unit volume estimated from the earthquake magnitude and the distance from the earthquake source. It provides a convenient metric to relate and compare the different hydrologic responses and allows us to integrate and compare the various hydrologic responses in the last chapter (Chap. 14) and to provide a coherent picture for all these responses.

References

Aki K, Richards PG (1980) Quantitative seismology. New York, W.H, Freeman and Company

Beresnev IA, Johnson PA (1994) Elastic wave stimulation of oil production: a review of methods and results. Geophysics 59:1000–1017

Brodsky EE, Roeloffs E, Woodcock D et al (2003) A mechanism for sustained groundwater pressure changes induced by distant earthquakes. J Geophys Res 108:2390. https://doi.org/10.1029/2002JB002321

Carrigan CR, King GCP, Barr GE et al (1991) Potential for water-table excursions induced by seismic events at Yucca Mountain, Nevada. Geology 19:1157–1160

Chen JS, Wang CY (2009) Rising springs along the Silk Road. Geology 37:243–246

Craig TJ, Chanard K, Calais E (2017) Hydrologically-driven crustal stresses and seismicity in the New Madrid Seismic Zone. Nat Commun 8:1–11

Davis EE, Becker K, Wang K et al (2006) A discrete episode of seismic and aseismic deformation of the Nankai trough subduction zone accretionary prism and incoming Philippine Sea plate. Earth Planet Sci Lett 242:73–84

Elkhoury JE, Brodsky EE, Agnew DC (2006) Seismic waves increase permeability. Nature 411:1135–1138

Gorokhovich Y (2005) Abandonment of Minoan palaces on Crete in relation to the earthquake induced changes in groundwater supply. J Archaeol Sci 32(2):217–222

Guglielmi Y, Cappa F, Avouac JP et al (2015) Seismicity triggered by fluid injection–induced aseismic slip. Science 348(6240):1224–1226

Hill DP, Prejean SG (2007) Dynamic triggering. In: Schubert G (ed) Treatise on geophysics, vol 4, p 257–292

Ingebritsen SE, Manning CE (2010) Permeability of the continental crust: dynamic variations inferred from seismicity and metamorphism. Geofluids 10:193–205

Kilb D, Gomberg J, Bodin P (2002) Aftershock triggering by complete Coulomb stress changes. J Geophys Res 107(B4):2060. https://doi.org/10.1029/2001JB000202

National Research Council (2016) State of the art and practice in the assessment of earthquake-induced soil liquefaction and its consequences. The National Academies Press, Washington DC. https://doi.org/10.17226/23474

O'Brien GM (1992) Earthquake-induced Water-level Fluctuations at Yucca Mountain, vol 92, Nevada. US Department of the Interior, US Geological Survey

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 S, Wolf S, Michel R (1995) Permeability enhancement in the shallow crust as a cause of earthquake-induced hydrological changes. Nature 373:237–239

Seed HB, Lee KL (1966) Liquefaction of saturated sands during cyclic loading. J Soil Mech Found Div 92:105–134

Silver PG, Wakita H (1996) A search for earthquake precursors. Science 273:77–78

Tingay M, Manga M, Rudolph ML et al (2018) An alternative review of facts, coincidences and past and future studies of the Lusi eruption. Mar Pet Geol 95:345–361

von Kant E (1756) Geschichte und Naturbeschreibung der merkwürdigsten Vorfälle des Erdbebens welches an dem Ende des 1755sten Jahres einen grossen Theil der Erde erschüttert hat, Konigberg, Hartung

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, Doan ML, Xue L et al (2018) Tidal response of groundwater in a leaky aquifer—application to Oklahoma. Water Resour Res 54:8019–8033. https://doi.org/10.1029/2018WR022793

Wang CY, Wang CH, Manga M (2004) Coseismic release of water from mountains: evidence from the 1999 (Mw=7.5) Chi-Chi earthquake. Geology 32:769–772

Zhang H, Shi Z, Wang G et al (2019) 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 (2019) Unexpected far-field hydrological response to a great earthquake. Earth Planet Sci Lett 519:202–212. https://doi.org/10.1016/j.epsl.2019.05.007