Title
Increased stream discharge after the 3 September 2016 Mw 5.8 Pawnee, Oklahoma earthquake

Journal
Geophysical Research Letters, 43(22)

ISSN
0094-8276

Authors
Manga, Michael
Wang, Chi-Yuen
Shirzaei, Manoochehr

Publication Date
2016-11-28

DOI
10.1002/2016gl071268

Peer reviewed

Increased stream discharge after the 3 September 2016 M_w 5.8 Pawnee, Oklahoma earthquake

Michael Manga

Chi-Yuen Wang

Manoochehr Shirzaei
First published: 22 November 2016

https://doi.org/10.1002/2016GL071268

Abstract

Earthquakes influence hydrogeological processes and properties in Earth's crust, some of which affect surface waters. We document increased discharge in a stream after the 3 September 2016 M_w 5.8 earthquake near Pawnee, Oklahoma, an event likely induced by underground wastewater disposal. Discharge increased by an order of magnitude and remained elevated until the change was obscured by rain 1 week later. Given the earthquake magnitude and distance from the stream, by comparison with previous examples of responses to earthquakes, increased discharge after this earthquake is expected. While the mechanism increasing discharge cannot be confirmed, the observations require changes in physical properties of the subsurface. Fluid injection may thus influence hydrogeological properties of shallow groundwater systems and aquifers indirectly by inducing seismicity, if the induced seismic events are large enough.

1 Introduction

Seismicity induced by deep disposal of wastewater is now abundantly documented [e.g., *Frohlich*, 2012; *Keranen et al.*, 2013; *Hornbach et al.*, 2015; *Weingarten et al.*, 2015]. While the earthquakes are typically modest in size, mostly less than magnitude 4, there is widespread concern about the rapid increase in their frequency in recent years [e.g., *Ellsworth*, 2013; *McGarr et al.*, 2015] and the possibility that seismic risk may continue to increase even after injection ends owing to continued pore pressure diffusion [e.g., *Shirzaei et al*., 2016]. Beyond the seismicity induced by injection, there is also concern that injected fluids can migrate vertically and contaminate more shallow aquifers [e.g., *Vidic et al*., 2013]. Studies, to date, have generally not documented impacts from deep injection on shallow aquifers [e.g., *Darrah et al*., 2014], but the issue remains controversial [e.g., *Vengosh et al*., 2014].

Earthquakes induce a range of hydrological responses, including changes in water level in wells and changes (usually increases) in stream discharge. The latter may have many origins including volumetric strains in the crust [e.g., *Muir-Wood and King*, 1993], changes in permeability [e.g., *Rojstaczer et al*., 1995; *Wang et al*., 2004; *Wang and Manga*, 2015], and water liberated from consolidation of soils [e.g., *Manga et al*., 2003; *Montgomery et al*., 2003; *Mohr et al.*, 2012] or mobilized from the unsaturated zone [*Manga and Rowland*, 2009; *Mohr et al*., 2015]. These changes have been documented globally and for nearly 2000 years [Pliny, first century A.D.]. Regardless of the mechanism or mechanisms that change stream discharge, a compilation of global reports reveals that there is a magnitude-distance threshold for the possible occurrence of changes in stream discharge [e.g., *Wang and Manga*, 2010].

Here we report an increase in stream discharge after a magnitude 5.8 earthquake in Oklahoma, USA (Figure 1). This event is likely an example of an induced earthquake given that it occurred in a region with numerous large volume class II injection wells and seismicity increased in Oklahoma after waste water disposal expanded in earnest [e.g., *Keranen et al*., 2014; *Walsh and Zoback*, 2015]. If it was an induced earthquake, the 3 September 2016 event is the largest to date caused by fluid injection. Given the magnitude of the earthquake, we show that near-surface hydrogeological responses not only occurred but were also expected.

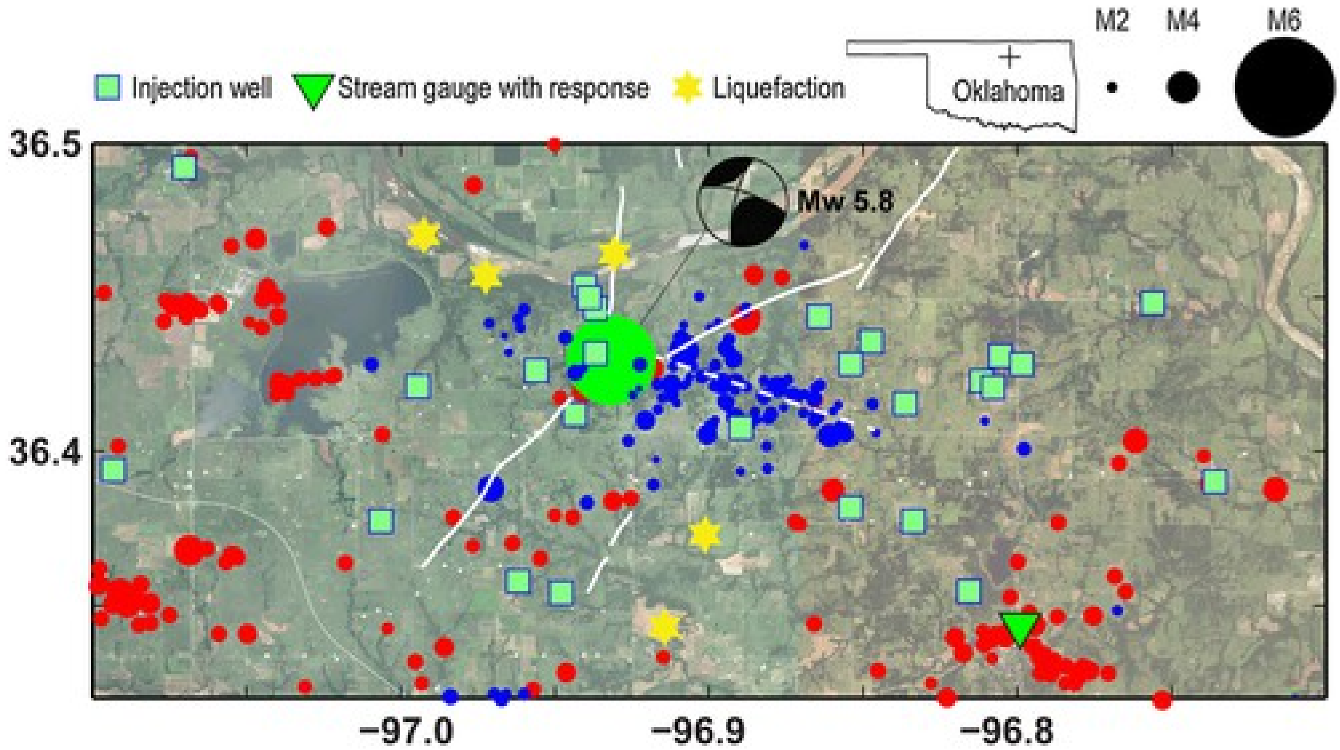

Figure 1

Open in figure viewerPowerPoint

Map showing the location of the stream gauge (green triangle) that documented an earthquake-induced change in stream discharge, the epicenter of the 3 September 2016, M_w5.8 Pawnee, Oklahoma earthquake (large green circle), and its aftershocks (smaller blue circles). Red circles show earlier earthquakes in the area. Squares show the location of injection wells. Yellow stars show the location of reported liquefaction (E. Atekwana, personal communication, 2016). White solid lines are known faults and the dashed line is the new unknown fault that ruptured in this event. See index map on the upper right for the location of this map and scale for earthquake magnitude.

2 The Magnitude 5.8 Oklahoma Earthquake

A moment magnitude 5.8 strike-slip earthquake occurred on 3 September 2016 at 12:02:44 UTC, with depth 5.4 km and epicenter N36.43°, W96.93°. It was followed by 22 aftershocks with magnitude >3 over the next 12 days (Figure 1). The earthquake probably ruptured a previously unmapped northwest-southeast trending fault given the distribution of aftershocks (Figure 1).

The geology of the study area (Pawnee County, OK) is dominated by sequences of thick shale beds alternating with Permian limestones and Pennsylvanian sandstones [*Johnson et al*., 1972]. Quaternary sand, silt, clay, and gravel occur in flood plains and over terraces along river valleys (Figure 1). While the region is away from any large mountains, dipping sandstone and limestone layers in the sedimentary sequences form cuestas that rise above broad shale plains (topographic map in Figure S1 in the supporting information).

The occurrence of earthquakes with magnitude > 3 in Oklahoma has now exceeded that in California [e.g., *McGarr et al*., 2015]. Most of the larger events with $M > 5$ are caused by the deep injection disposal of contaminated water produced during hydrocarbon extraction [e.g., *Ellsworth*, 2013]. Similar to many other induced events in Oklahoma [*McNamara et al*., 2015], it was a strike-slip earthquake on a NW-SE trending fault. Given the focal mechanism and fault orientation of the Pawnee event and other induced earthquakes in Oklahoma, it is reasonable to assume that increases in pore pressure may induce earthquakes on critically stressed faults. At the present time, however, it is not confirmed by detailed modeling that this particular earthquake was induced by the 26 wastewater disposal wells in the vicinity, within 20 km (Figure 1). Nevertheless, the Oklahoma Corporation Commission responded immediately and wells that inject into formations in contact with basement ceased operations and others were required to reduce disposal volumes. If the 3 September event is induced, it is the largest earthquake caused by wastewater injection to date, greater than the 2011 M_w 5.7 Prague, Oklahoma earthquake, though it is smaller than some earthquakes attributed to water impoundment in reservoirs [e.g., *Gupta*, 1992; *Ge et al*., 2009].

3 Stream Discharge Responses

USGS stream gauge 07153000 on Black Bear Creek, the closest USGS gauge to the epicenter at a distance of 15 km, recorded an increase in discharge that began within a few hours after the earthquake (Figure 2). The increase on 3 September continued broadly and lasted for many days until heavy precipitation after 10 September overwhelmed the response we attribute to the earthquake. An apparent local precipitation event on 3 September was a recorder malfunction caused by the earthquake and is not plotted in Figure 2. There was no damage to the dam at Pawnee Lake, upstream of the gauge, and changes in slope (Figures S2 and S3 in the supporting information) are too small ($<10^{-4}$°) to change discharge. The increase in discharge thus originates in the subsurface. The form of the hydrograph after the earthquake looks qualitatively similar to responses seen in other streams after other earthquakes [e.g., *Muir-Wood and King*, 1993]. We could not identify any other excursions similar to that after the earthquake—hydrograph responses to precipitation have sharp increases and gradual decreases such as the events on 26 August and 10 September shown in Figure 2.

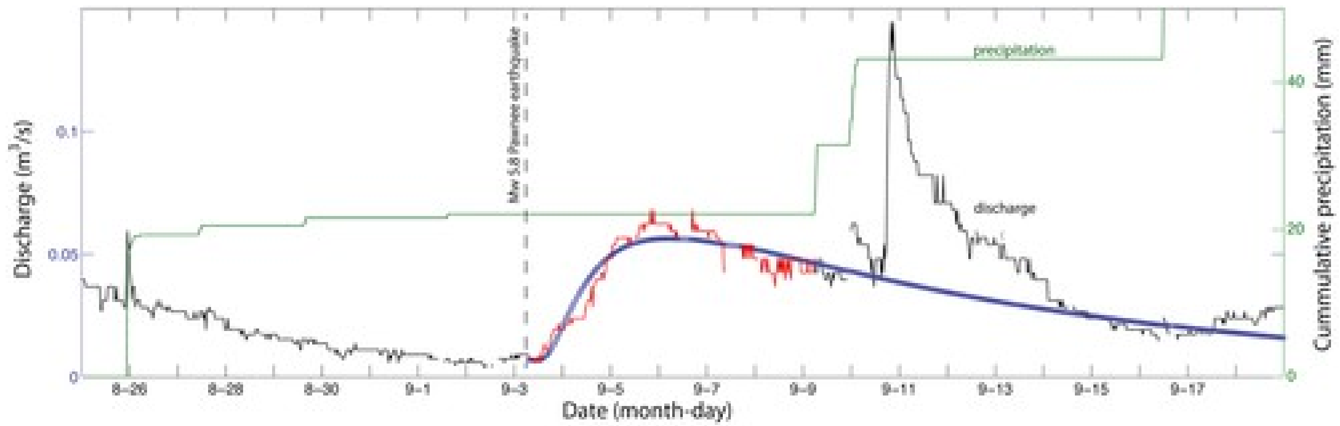

Figure 2

[Open in figure viewerPowerPoint]

USGS stream gauge record from Black Bear Creek, Pawnee County, OK (black curve), together with precipitation (green curve). The vertical dashed line shows the time of the M_w 5.8 earthquake. Simulated increase of discharge after the earthquake is shown with the overlapping blue circles and the data used to fit the model is shown in red. USGS data downloaded on 23 October 2016.

One other gauge recorded an increasing discharge that began after the earthquake: the Cimarron River near Guthrie, gauge 07160000. The area of this watershed is very large, 33,500 km^2. If we look at other gauges on the Cimarron River farther upstream, gauges 07159100 and 07161450, we see a pulse of discharge before the earthquake that occurs progressively earlier as we move farther upstream; the hydrograph also resembles that for other precipitation events. We thus attribute the increased discharge at Guthrie to increased discharge earlier than the earthquake and upstream of the gauge.

4 Discussion

We begin by assessing the earthquake-generated strains responsible for the change in discharge. We then attempt to identify the mechanism by which discharge increased and use a groundwater flow model to quantify the volume of excess water released after the earthquake. We end by putting this particular response to an earthquake in the context of a global compilation of stream responses to earthquakes.

Changes in stream discharge have been attributed to either coseismic volumetric strains (static strains) produced by slip on the ruptured fault or the passage of seismic waves (dynamic strains). The latter are temporary, and thus, they must initiate a process that leads to permanent changes in hydraulic heads or transport properties of the subsurface. We first assess which type of strain is most likely responsible for the increase in discharge.

The focal mechanism of the Pawnee earthquake (Figure 1) shows that the stream gauge that recorded the increased discharge is located in a dilatational quadrant, and most of the drainage basin experienced dilatation as well. Figure 3a shows the computed volumetric strain at a depth of 10 m for the USGS focal mechanism and assuming a northwest-southeast striking fault. The calculation is done using a square dislocation model buried in an elastic half space [*Okada*, 1992] with shear modulus of 30 GPa and Poisson ratio of 0.25. We also consider a stress drop of 30 bars and compute the slip on the fault using an empirical relationship [*Kanamori and Anderson*, 1975]. Given this pattern of volumetric strain, the increased stream discharge is unlikely due to coseismic compression associated with fault displacement, one of the earliest hypotheses for the origin of increased stream discharge [e.g., *Muir-Wood and King*, 1993]. Changes in permeability from strains of 10^{-6} are also likely far too small to change discharge by the observed amount. Instead, the dynamic strains from the passage of seismic waves are more likely responsible for changes in the subsurface that in turn cause changes in stream discharge.

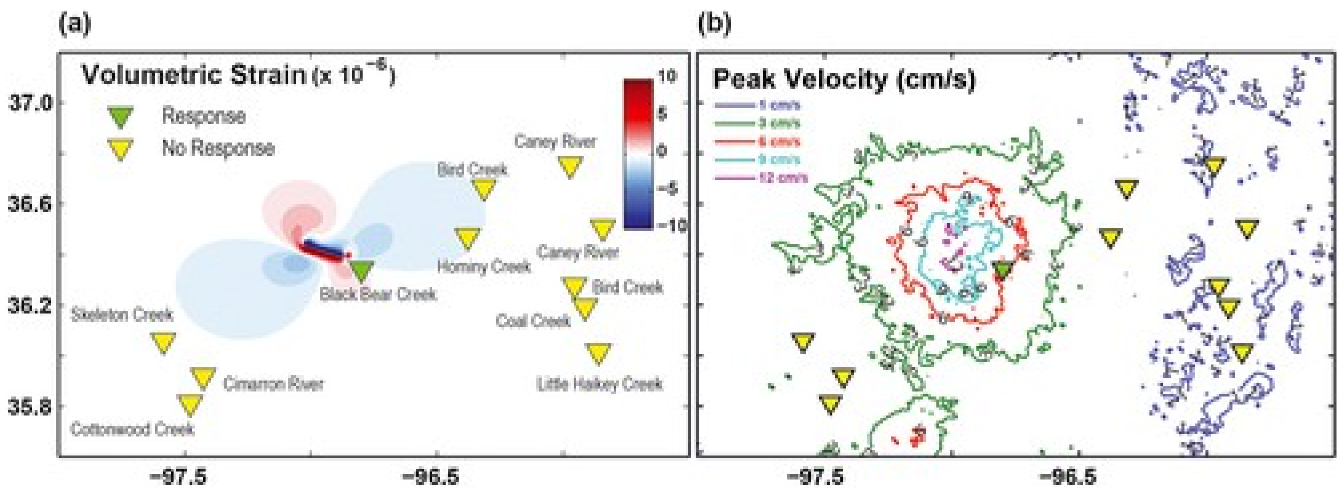

Figure 3

Open in figure viewerPowerPoint

(a) Static volumetric strain (positive is expansion). Dip, rate, and strike are based on the USGS moment tensor solution. (b) Peak Ground Velocity (PGV) from the USGS ShakeMap. Both panels show the location of stream gauges with and without responses. All gauges are shown except the Arkansas River which drains such a large area and has such a large discharge that any response to the earthquake would be noise.

The reason seismic waves (dynamic strains) increase discharge is uncertain, and three possibilities have been hypothesized in the literature. First, water may be mobilized from the unsaturated zone [e.g., *Mohr et al*., 2015]. Second, unconsolidated sediment may compact and increase hydraulic head and then discharge [e.g., *Manga et al*., 2003; *Montgomery et al*., 2003]. Third, permeability and hence discharge may increase [e.g., *Rojstaczer et al*., 1995; *Fleeger and Goode*, 1999; *Wang et al*., 2004] and seismic waves can increase permeability [e.g., *Elkhoury et* *al*., 2006], possibly by mobilizing colloidal particles that otherwise impede fluid flow [e.g., *Candela et al*., 2014]. Because base flow recession is not affected by the earthquake (Figure 2) (see also *Manga* [2001], *Montgomery et al*. [2003], and *Wang et al*. [2004]) for this third explanation, it is often assumed that vertical permeability is enhanced, allowing water to drain downward [*Wang and Manga*, 2015]. Conceptually, in all three cases hydraulic head increases in the aquifers providing groundwater discharge to the stream. Continuous water level data from nested monitoring wells sampling different depths could in principle distinguish between these hypotheses using some combination of tidal analysis and water level changes [*Wang et al*., 2016], but no suitable well data are available.

Changes in stream discharge after earthquakes are often modeled with one-dimensional groundwater flow equations, because the solutions fit the data well and the equations account for changes in hydrogeological properties in the model, if not the geometric complexity of the groundwater systems [e.g., *Rojstaczer et al*., 1995; *Roeloffs*, 1998; *Sato et al*., 2000; *Manga*, 2001; *Mohr et al*., 2015; *Wang and Manga*, 2015]. We assume that increased vertical permeability or water released either from the saturated or unsaturated zone increase hydraulic head and thus horizontal flows in the aquifers discharging groundwater into the streams. The linearized Boussinesq equation for the evolution with time t of the increase in hydraulic head h in unconfined aquifers and that for groundwater flow in confined aquifers is given by

$$\frac{\partial h}{\partial t} = D\frac{\partial^2 h}{\partial x^2} + A(x,t) \quad (1)$$

with

$$Q = -KD_t\frac{\partial h}{\partial x}, \quad (2)$$

where A is the rate of seismically induced head change per unit width in the release zone, Q is discharge, x is horizontal position, K is the horizontal hydraulic conductivity, D is the hydraulic diffusivity, and D_t is the cross-sectional area of the aquifer. We assume that discharge is derived from saturated flow and hence that Darcy flow applies. The aquifer extends from $x = 0$ at the catchment divide to $x = L$ at the channel. Boundary conditions are

$$h(L,t) = 0 \quad (3)$$

and

$$\frac{\partial h(0,t)}{\partial x} = 0. \quad (4)$$

where recharge occurs over $0 < x < L'$. At the time of the earthquake ($t = 0$) discharge is Q_0. The solution [*Wang and Manga*, 2015] is

$$Q(t) = Q_0 e^{-\pi D t/4L^2} + \frac{2DQ_t}{LL'} \sum_{r=1}^{\infty} (-1)^{r-1} \sin\frac{(2r-1)\pi L'}{2L} e^{-\frac{(2r-1)\pi^2 D}{4L^2}t}, \quad (5)$$

where $Q(t)$ is total water discharged by the earthquake at time t, the first term on the right-hand side describes the base flow recession in the absence of an earthquake, and the second term on the right-hand side is the excess discharge caused by the earthquake. We fit equation 5 to data using three parameters L'/L, D/L^2, and Q_t using the nonlinear least squares Marquardt-Levenberg algorithm.

Figure 2b compares the increased discharge in Black Bear Creek with the simulated discharge. The best fitting parameters for this model are $L'/L = 0.4$ (assumed), $D/L^2 = 0.0454 \pm 0.0007$ day^{-1} and $Q_t = 5.22 \pm 0.09 \times 10^4$ m^3. The good fit of the simulation to the data shows that the observed increase of discharge in Black Bear Creek is consistent with earthquake-induced recharge providing the increased discharge. However, the model cannot reveal the source of water and hence on its own is not sufficient to distinguish between the three hypotheses about the mechanism responsible for the changes.

Figure 3b shows the peak ground velocity (PGV) produced by the earthquake (calculation from the USGS ShakeMap). Streamflow increased in the region with greatest PGV, with a value of ~6.2 cm/s at the stream gauge. The surface area with PGV greater than this value is 1800 km^2. This PGV is consistent with those that are correlated with increased discharge elsewhere after other earthquakes [e.g., *Manga et al.*, 2003]. Assuming a shear velocity of 200 m/s, appropriate for unconsolidated sediment, peak strain is $>3 \times 10^{-4}$, which is large enough to initiate consolidation [*Vucetic*, 1994]. Indeed, liquefaction has been reported after this earthquake (Figure 1) (E. Atekwana, personal communication, 2016). None of our observations can distinguish between the three proposed hypotheses, but we note that where the needed geochemical [*Rojstaczer et al.*, 1995], isotopic [*Wang and Manga*, 2015] of water level [*Fleeger and Goode*, 1999] data were available to test these three hypotheses, the mechanism of permeability increase was favored.

The most spatially widespread changes in stream discharge follow the largest earthquakes. Other shallow earthquakes with magnitudes similar to the Oklahoma earthquake have also caused changes in stream and spring discharge: M_w 4.5 1989 and M_w 5.3 1988 Alum Rock, California, and M_w 5.7 1986 Mount Lewis, California [*King et al.*, 1994]; *M* 5.1 2004 Besancon, France [*Charmoille et al.*, 2005]; M 5.2 1998 Pymatuning Reservoir, Pennsylvania [*Fleeger and Goode*, 1999]; M_w 5.5 2007 Alum Rock, California [*Manga and Rowland*, 2009]; M_w 6.0 2014 Napa, California [*Wang and Manga*, 2015]; and M_w 6.3 L'Aquila, Italy [*Amoruso et al.*, 2011].

Figure 4 shows the distance between the epicenter and the stream gauges for streams that did and did not respond to the Oklahoma earthquake. It also shows a global compilation of other examples of increased streamflow after other earthquakes. Hot springs, hydrothermal systems, and geysers are more sensitive to earthquakes [e.g., *Husen et al*., 2004; *Ingebritsen et al*., 2015] and are not included in this comparison. For reference, we show two sets of curves whose intent is to help us interpolate and extrapolate. First are contours for seismic energy density, based on a California attenuation model, a quantity that was proposed to have a correlation with a number of hydrological responses to earthquakes [*Wang and Manga*, 2010]. Second is a relationship between magnitude *M* and distance *d* (in cm)

$$M = -0.44 + 3 \times 10^{-8} d + 0.98 \log_{10} d, \quad (6)$$

which was originally proposed as a limit for liquefaction by *Papadopoulos and Lefkopoulos*[1993] and we use it here simply as an empirical guide for the distance over which streamflow responses might be expected. We note that more recent global compilations of liquefaction include examples at distances beyond the predictions of equation 6 (e.g., Figure 2 in the review by *Manga and Wang* [2015]). Figure 4 shows that the distance over which streams responded to the Oklahoma earthquake is consistent with responses by other streams to earthquakes elsewhere.

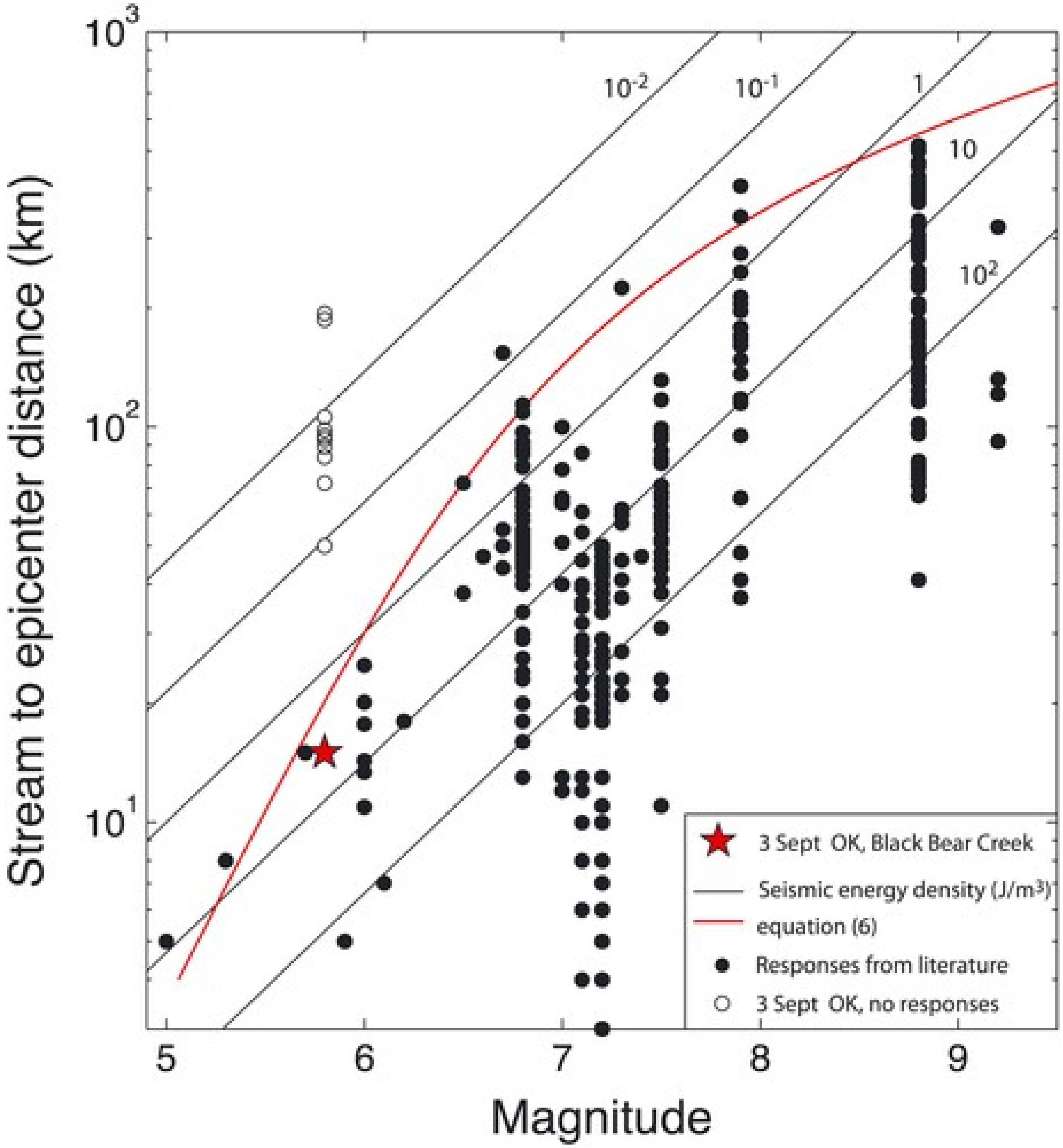

Figure 4

Open in figure viewerPowerPoint

Magnitude-distance relationship for streams that responded to earthquakes. The red star corresponds to Black Bear Creek, and the open circles show streams that did not respond to the 3 September 2016 Pawnee, Oklahoma earthquake. For this earthquake, we plot the distance between the stream gauge and the epicenter. Literature examples were compiled in *Manga and Wang* [2015] and updated to include responses to the M_w 6.0 Napa, California earthquake [*Wang and Manga*, 2015] and the M_w 8.8 Maule, Chile earthquake [*Mohr et al*., 2016]. For reference, the sloping black lines are lines of constant seismic energy density [*Wang and Manga*, 2010]. The red curve is an empirical bound, equation 6.

5 Conclusions

The changes in discharge after this earthquake and after other earthquakes are usually small compared to the annual water budget and hence of little consequence for water supplies and availability. Rather, the significance of the observed responses is that they provide evidence that deep fluid injection, through induced seismicity, can influence shallow groundwater systems. If the magnitude of induced events continues to increase, then based on Figure 4 we should expect more widespread shallow hydrogeological responses. Continued and expanded stream gauging, especially in small unregulated catchments, and complementary water level monitoring in nested wells that sample different depths will allow for both better documentation of responses and may permit the testing of hypotheses about the origin of any responses.

Acknowledgments

This paper is supported by NSF grant EAR1344424 to M.M., C.Y.W., and M.S. We thank the U.S. Geological Survey for operating the network on gauging stations and making the hydrological and seismic data and data products readily available and in real time. We thank Jason Lewis, William Andrews, Brad Sewell, and staff in the city of Pawnee for answering queries about the responses and possible confounding processes, and Estella Atekwana for sharing the locations where liquefaction occurred. We thank the reviewers and Editor for constructive comments and suggestions. Data used to generate the figures are available from the authors upon request. The USGS discharge and precipitation data are available from http://waterdata.usgs.gov/nwis.