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Can We Use the North Texas Earthquake History to Predict the Next Earthquake?

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ABSTRACT

Since about 1860, there were no reported earthquakes in North Texas until the Dallas, Texas area began to shake in 2008 with the first felt earthquake (magnitude 3 or larger). Earthquakes of magnitude 3 (M3) and larger are significant because they can be felt by residents and can cause injuries plus property damage, so this report will focus on M3 and larger earthquakes. The first earthquake to be felt within the Fort Worth Basin occurred near the Dallas–Fort Worth International (DFW) airport just weeks after wastewater injection began at a salt water disposal (SWD) well on the DFW airport property. This correlation has led many researchers to look to oil industry practices relating to wastewater injection for an explanation of the seismicity in the Dallas area. Practices such as horizontal drilling and hydrofracturing are used to increase production from unconventional resource plays. SWD wells have long been used to dispose of hydrofracturing flow back water and brine water (a byproduct of hydrocarbon production). Studies have shown that an earthquake can be triggered if fluid injection occurs near a critically stressed fault. The subsurface pore pressure changes caused by wastewater injection can result in induced seismicity of various magnitudes. Wastewater injection in the Fort Worth Basin and the associated seismicity continued from October 2008 through May 2018. During this period there were times of seismic activity and times when few to no earthquakes were felt in the North Texas area despite ongoing wastewater injection. Until now there is no explanation for these seismically quiet periods. The Dallas area experienced a heavy rainfall in May 2015, creating floods and filling area lakes. After this event, no earthquakes were felt in 2016. Recently, the DFW area has received normal rainfall and earthquake occurrence has dramatically decreased. Conversely, during extreme drought conditions in 2014 and early 2015 the number of monthly M3+ earthquakes increased to as many as five per month. The results of this study suggest that subsurface moisture content reflected in lake levels might relate to the earthquake occurrence, magnitude and possibly help to predict when to expect the next North Texas earthquake.

INTRODUCTION

The Fort Worth Basin is known for gas production from the Barnett Shale. Permeability (ability for gas/fluid to flow) is very low in shale, and is the main target for hydrocarbon production in unconventional resource plays. Enhanced production methods, horizontal drilling and hydrofracturing (fracking), have successfully increased production from this formation by increasing the permeability of the productive interval. This process has been used in the Fort Worth Basin since 2003 for Barnett Shale gas production, and to date the fracking process has not caused any felt earthquakes in this area (Frohlich et al., 2016). A large amount of water is required for fracking horizontal wells that drill a longer section of the productive interval. This water is recovered as wastewater (frack flow back water) when the well starts production. Disposal of wastewater is done at salt water disposal (SWD) wells specifically drilled to reverse the process (Fig. 1) and flow wastewater back down a wellbore and inject into a deep non-productive interval under pressure.

The fracking process is not the only source of wastewater. In the normal course of producing oil and gas, water (trapped in the pore space with the hydrocarbons) is produced with the oil and gas. This water tends to be highly saline and is generally disposed of using SWD wells. The injection of wastewater alters subsurface pressures. If this happens near a critically stressed fault, the increased fluid pressure can trigger fault movement and cause an earthquake (Ellsworth, 2013; Frohlich et al., 2016; Hornbach et al., 2015). In the Fort Worth Basin, the large number of gas wells producing associated brine water and the wastewater from fracking operations supply the large volume that is injected into the Ellenburger formation. The association of injection depths of SWD wells being from 1.25 to 2.5 mi (2 to 4 km) depth and earthquake focal depth average 3.1 mi (<5 km) depth also support the assertion that this process has induced the seismicity that has occurred around the Dallas–Forth Worth area (Frohlich et al., 2016; Hornbach et al., 2015).

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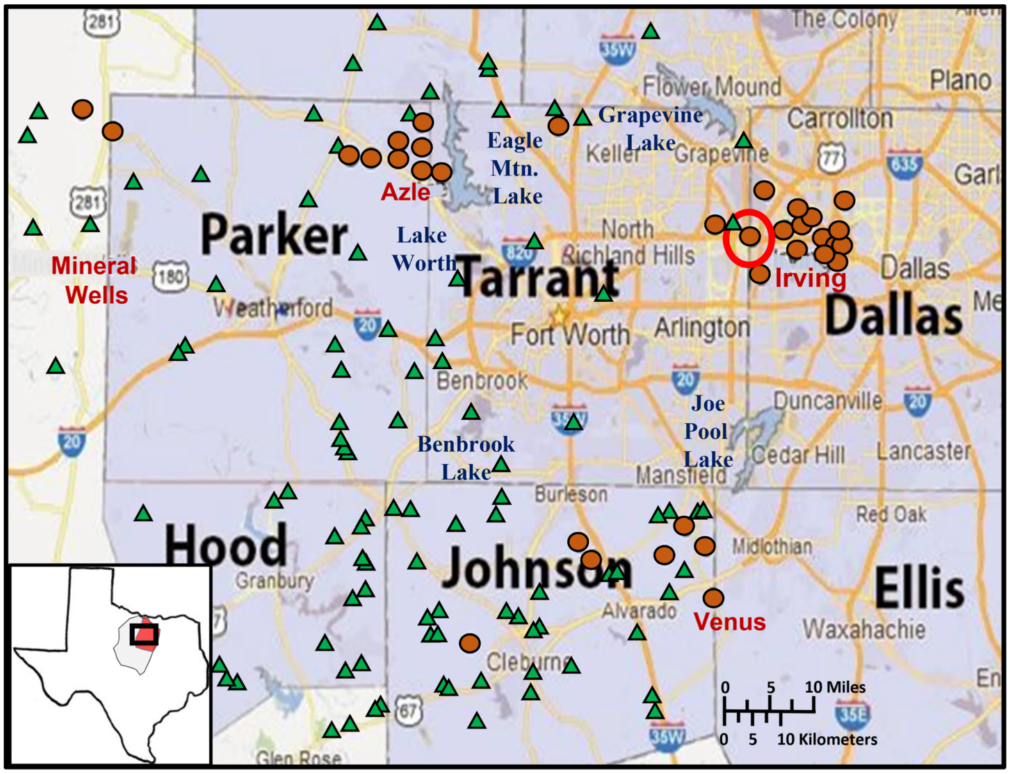

Figure 1. Location map of 33 M3 and larger earthquakes (red dots) in the Dallas–Forth Worth area from January 2007 to January 2018. The inset map at lower left shows the study area in black box, estimated Barnett Shale extent as grey area and the approximate Newark East Field area in red. Earthquakes are focused in four counties, Parker, Tarrant, Dallas, and Johnson. The largest number of earthquakes occur in Dallas County. The cities of Venus, Azle, Mineral Wells, and Irving are highlighted in red and discussed in this report. Green triangles are SWD well locations. Location of the first North Texas earthquake is indicated by the red circle. Area lakes used in this report are also labeled.

Earthquake activity has been historically absent in North Texas (Frohlich et al., 2016). This changed when North Texas recorded its first 3.0 magnitude (M3) earthquake on 31 October 2008. Since starting in 2008, 33 M3 and larger earthquakes have occurred in the Dallas–Forth Worth area through January 2018, in Tarrant, Dallas, Parker, and Johnson counties (Fig. 1). Figure 1 shows that the events are concentrated around the cities of Venus, Azle, Mineral Wells and Irving Texas. The first felt earthquake occurred near the Dallas–Forth Worth International (DFW) airport just weeks after wastewater injection began at the DFW South SWD well on the airport property (Fig. 1). After that earthquake, investigations began into the cause and the influence of hydrocarbon operations. The publicly available seismograph data and data from temporary seismographs were the basis for research done at Southern Methodist University and the University of Texas at Austin. Frohlich et al. (2016) concluded that the DFW earthquakes were induced by human activity because of the lack of seismicity prior to injection, the injection well is located near a known fault, and the onset of seismicity occurred only six weeks after injection commenced at the DFW South SWD well.

The largest earthquake associated with the DFW location was M3.3 event on 16 May 2009. After the initial events, the DFW South SWD well stopped operations in August 2009, but seismicity continued for months. 33 M3 and larger earthquakes events have occurred in the Dallas–Fort Worth area from October 2008 to January 2018 (Fig. 2). This time period appears to be separated into seismically active and seismically inactive periods. A seismic quiet period (no earthquakes of M3.0 or larger) that started during 2010 continued into 2011 with only one event occurring in July 2011 (Fig. 2). Seismicity began to increase during mid and late 2012. Two events occurred in both June and September 2012. All previous North Texas earthquake studies have focused on the wastewater injection and associated pore pressure changes as cause of the earthquakes. However, gas production and wastewater injection continued during the seismic quiet periods when there were no felt earthquakes. Could there be another factor involved in the timing of the felt earthquakes?

In some areas, earthquakes occurred in a swarm or cluster. Multiple events (8) occurred near Azle, Texas (Fig. 1) from November 2013 to January 2014. Nine events were felt in the Irving, Texas area (Fig. 1) from November 2014 through May 2015. These M3 and larger earthquakes represent a seismically active period (Fig. 2). 2015 started out to be the most active year with nine events occurring before June. The previous most active year was 2013 with ten events recorded. The largest magnitude earthquake in the North Texas area was a M4.0 event in May 2015. A seismically inactive period, where no M3 or larger earthquakes occurred, was during 2016 and only one earthquake occurred during 2017. Figure 2 also suggests an increase in earthquake frequency and magnitude from 2012 to 2015 and few events from mid–2015 through the end of 2017. The oil price drop and the reduced drilling activity has been suggested as the reason for the reduced earthquake activity. However, a closer evaluation of natural environmental patterns in the Fort Worth Basin area shows a different correlation that matches both active earthquake periods and quiet periods. Low rainfall periods (drought) correlate with the active earthquake times and high rainfall periods with the quiet periods having few to no felt earthquakes. This report provides an explanation for this relationship and how it may help predict when to expect the next M3 or larger earthquake in the Dallas–Forth Worth area.

DISCUSSION

Several studies conclude that the recent seismicity increase is not a natural phenomenon but is instead caused by oil and gas operations, primarily wastewater injection (Frohlich et al., 2016; Hornbach et al., 2015). The subsurface pore pressure changes caused by wastewater injection results in induced seismicity of various magnitudes. This report uses Texas Railroad Commission (TRC) public data for Barnett Shale production and injection volumes by county and by individual well. The North Texas

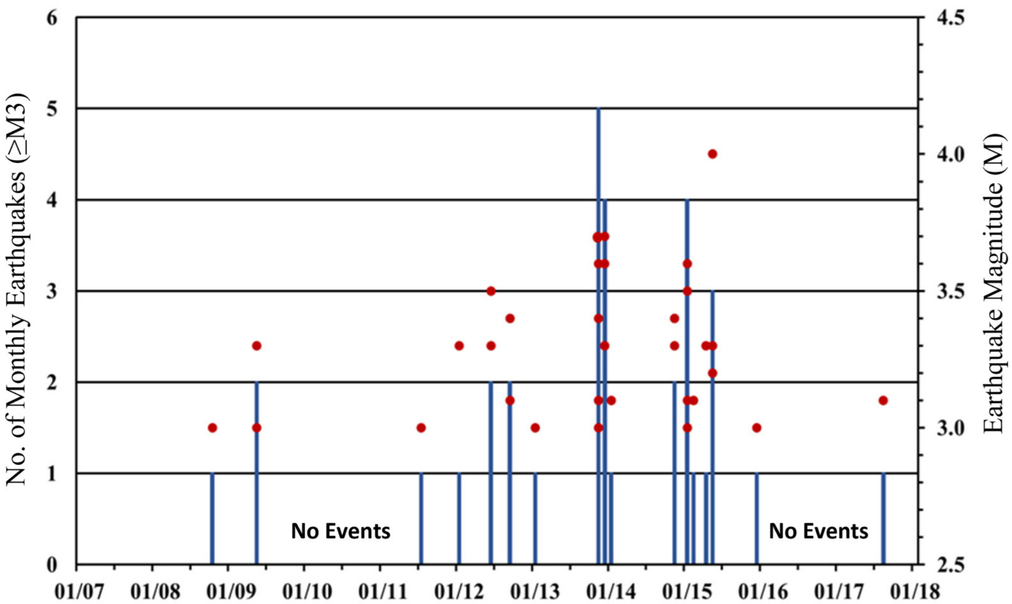

Figure 2. Blue bars represent the 33 North Texas earthquakes plotted by the number of earthquakes (M3 and larger) occurring each month with the associated magnitude of each event (red dots) for January 2007 to January 2018. No events are the extended times when there are no earthquakes of M3 or larger.

earthquake activity shows no correlation with the Barnett Shale gas production and wastewater injection volumes. Figure 3 shows monthly Barnett Shale gas production by county and number of North Texas earthquakes by month of occurrence. The main producing field from the Barnett Shale in the Fort Worth Basin is the Newark East Field (Fig. 1). Evaluating the production information, the Newark East Field was in decline beginning in late 2012; Johnson County production began declining in 2011; and Tarrant County production began declining in 2014. Dallas County only had minimal gas production between 2008 and 2018. There is no apparent correlation between production decline and earthquake occurrence or frequency during this period. Figure 4 shows injection volumes for each county with the earthquakes (M3 and larger) colored by county of occurrence to match county injection curve color.

Dallas County does not have any wastewater injection wells but has the greatest number of earthquakes of the four counties (Fig. 1). Wastewater injection wells in the Fort Worth Basin area have been operating since 2005 (Frohlich et al., 2016). For the four-county area, Johnson County had the most active SWD wells before January 2007. As production declined (Fig. 3), the produced wastewater also declined and injection volumes (Fig. 4) all show decreasing levels. Johnson and Parker counties had their highest injection volumes in 2008–2009, an earthquake-free period for both of those counties. In 2011, Johnson County increased the injection volume with one earthquake occurring in July 2011 and three events in 2012 (Fig. 4). This could point to a cause/effect relationship; however, Johnson County earthquakes continued in 2014, 2015, and as recently as May 2018 when injection volumes declined by over 50%. Johnson County injects the largest volume of wastewater of the three counties; however, the county experienced a two-year period with no felt earthquakes. Interpretation of this data does not show a reason for changes in macroseismicity (M3 and larger earthquakes). Seismologists have concluded that the North Texas earthquakes are induced because seismicity began after multiple counties started injecting wastewater into the Ellenburger formation and earthquake focal depths occurred near SWD well injection depths (Frohlich et al., 2016; Hornbach et al., 2015). However, is there an explanation for the induced earthquakes stopping and starting in the North Texas area?

The Irving area in Dallas County had numerous earthquake events occurring late 2014 through May 2015, but Dallas County had minimal gas production and no wastewater injection with the nearest injection well located over 8 mi (12.9 km) northwest of the Irving earthquake area. A study of wastewater injection (Hornbach et al., 2016) concluded that injection into the Ellenburger formation promotes seismicity by elevating formation fluid pressures, and seismicity could be expected to continue in Parker, Johnson, Tarrant, and Dallas counties. An explanation for the earthquakes in the Dallas/Irving area relied on this area residing over the Ellenburger's deepest point (Hornbach et al., 2016). Injection into the Ellenburger formation continued through the end of 2015 into 2016 and 2017; however, there were few to no felt earthquakes during this period. The oil price drop and the reduced drilling activity has been suggested as the reason for the reduced earthquake activity.

The proposed decrease in drilling activity would not have significant impact on injection volumes since fracking flow back water volume is not a large percentage of wastewater injected into the Ellenburger formation. In 2011, the TRC required companies operating SWD wells to report percentages of salt water and frack flow back water injected during each 12 mo reporting period (H–10 forms). Most SWD wells near earthquake activity reported <20% frack flow back water. Salt water from normal gas production was the largest percentage by volume of the injected fluid. Only one SWD well (American Petroleum Institute [API] 25132450) in Johnson County, near the city of Venus, Texas, had frack flow back water percentage exceeding reported salt water injection percentage. Therefore, it is unlikely that flow back water from fracking was the majority of the water being injected into the Ellenburger formation (Hornbach et al., 2016). Any drop in new well completions would decrease the frack flow back water volume but not significantly impact the wastewater volume being injected. Figures 3 and 4 show no significant change in production or injection volumes that would demonstrate a change in oil industry activity at that time.

While living in Dallas during a seismically active period, I recognized that seismic activity ceased after a large rainfall and associated flooding in May 2015. This spurred my investigation of a rainfall/earthquake correlation in and around Dallas. Dallas and Mineral Wells had complete monthly rainfall data near the earthquake activity, and other cities in the Fort Worth area all followed the same Dallas rainfall pattern. Review of the rainfall data indicated that there were several periods that had below normal rainfall amounts (Fig. 5). These dry periods were followed

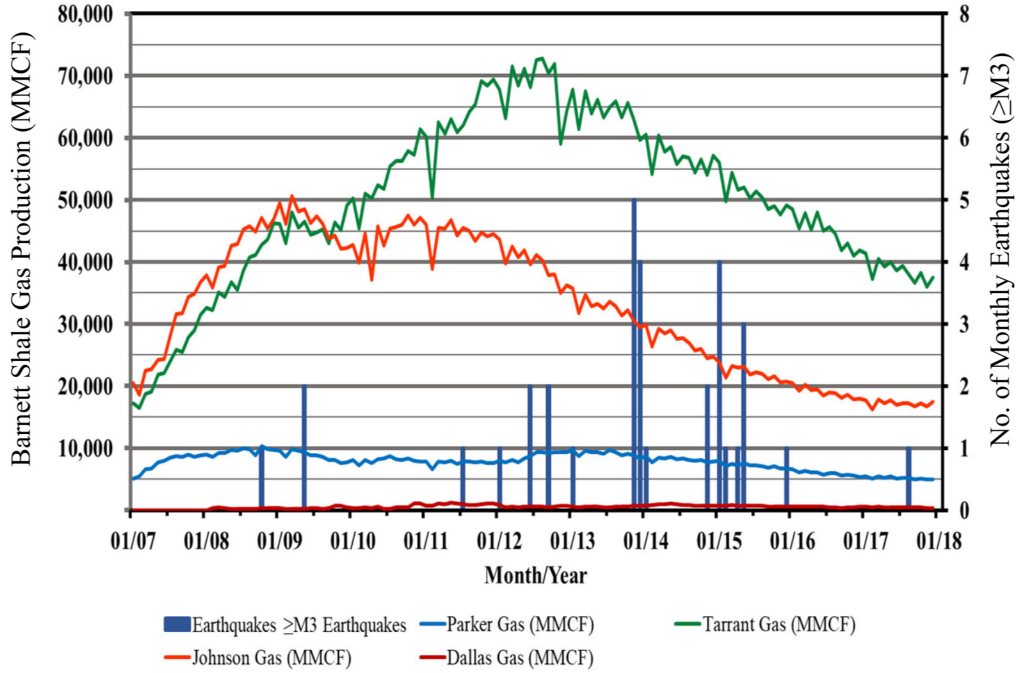

Figure 3. The 33 North Texas earthquakes and monthly Barnett Shale gas production. Curves are monthly Barnett Shale gas production for Parker (blue), Tarrant (green), and Johnson (orange) counties for January 2007 to January 2018. Dallas County (brown) had minimal gas production. Blue bars are the number of felt earthquakes for the month of occurrence for the North Texas area. Production decreases with time indicating the Newark East Field (Fig. 1) in these counties is in decline.

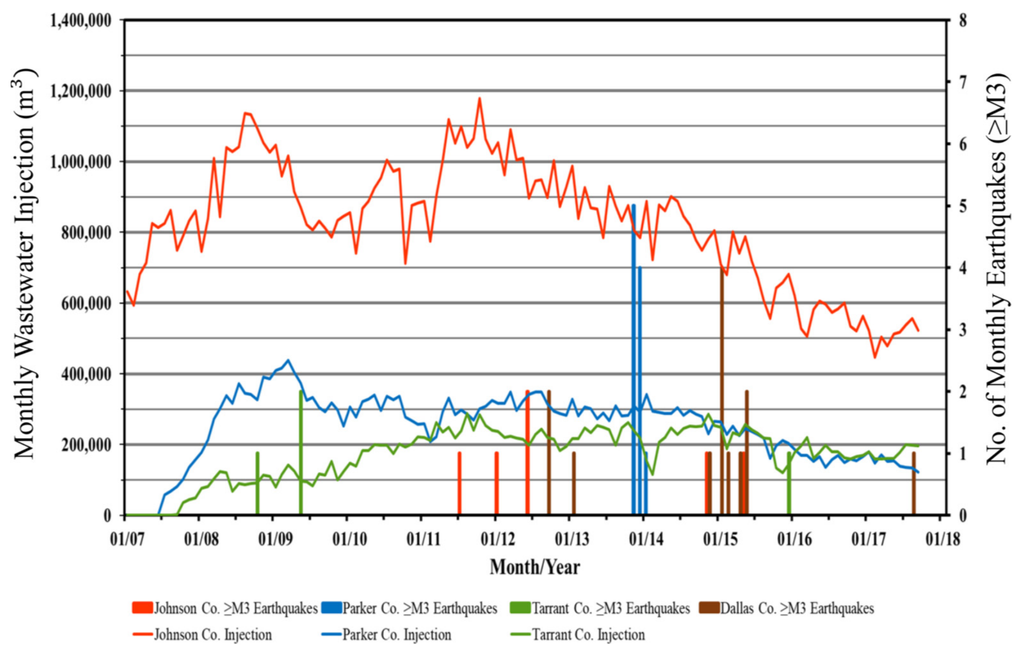

Figure 4. Number of monthly North Texas earthquakes and monthly wastewater injection volumes (m^3). Curves are monthly wastewater injection volumes for Johnson (orange), Parker (blue), and Tarrant (green) counties for January 2007 to January 2018. Dallas County does not have any SWD wells. Bars represent the 33 North Texas earthquakes (M3 and greater) and are colored to the county of occurrence and show the number of events in each month. Dallas County earthquakes (brown bars) are included; even though there are no SWD wells in Dallas County. As gas production decreased (Fig. 3), injected wastewater volumes also declined. There is no apparent relationship of wastewater injection volume to the seismicity. 200,000 m^3 = ~1.26 million barrels.

by average or above average rainfall. Figure 5, when broken out by months for both rainfall and earthquakes, shows an obvious pattern between the two datasets. Dallas yearly average rainfall recorded at DFW airport is approximately 36 in (0.9 m). This equates to 3 in (7.6 cm) per month which is represented by the purple line in Figure 5. The Dallas rainfall cycles are annotated to indicate times of low (below avg.) and high (above avg.) rainfall. These are labeled dry periods for low rainfall and wet periods for high rainfall. These rainfall cycles have an apparent correlation with the North Texas earthquake events.

The cyclic nature of the monthly rainfall for Dallas and Mineral Wells in Figure 5 makes it difficult to determine the impact of long periods of low rainfall. Since low rainfall periods can happen over a period of months to years, a better way to visualize the impact is on area lake levels (Fig. 1). Because lakes vary by areal size and depth, percent fill is a factor that can be used for evaluating conditions at area lakes. Lake levels were plotted as percent fill monthly for the lake data available in the four county area (Fig. 6). The accumulation of low rainfall years is evident in decreased lake level fill. As the drought continues, the lake level progressively drops (fill decreases). This is seen in the four lakes in the North Texas earthquake area.

Figure 6 best demonstrates the wet and drought periods for January 2007 to January 2018. The first drought period began in early 2008 and continued through late 2009 when a wet period began. This wet period continued into late 2010 with lake levels never dropping below 90% fill. A drought period began in 2011 as lake levels all dropped. The dry years 2011–2015 in Figure 6,

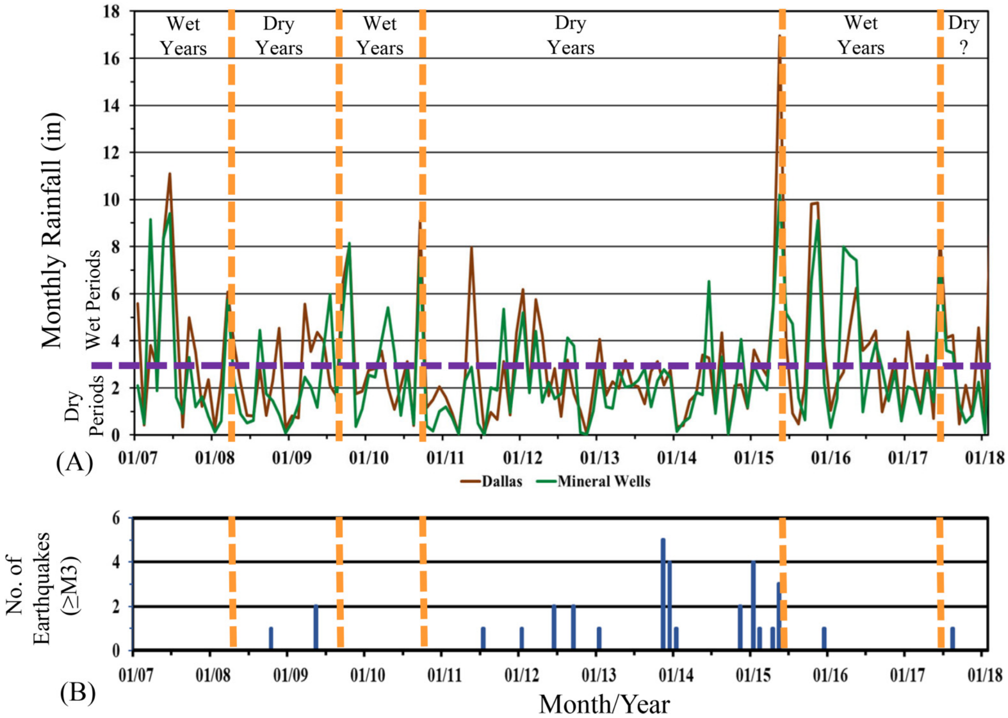

Figure 5. The 33 North Texas earthquakes and monthly rainfall (in) for January 2007 to January 2018. (A) Monthly rainfall (curves) for Dallas (brown) and Mineral Wells (green). Purple line is the average monthly rainfall (~3 in/mo [~7.6 cm/mo]) for Dallas. The line separates the monthly rainfall into wet periods and dry periods. Dry years are labeled for times when multiple months of rainfall fall below the purple line. Wet years are when multiple months of rainfall are at or above the purple line. 2 in = ~5.1 cm. (B) Blue bars represent the 33 North Texas earthquakes plotted by the number of earthquakes occurring each month. Earthquakes appear to line up with periods of low rainfall.

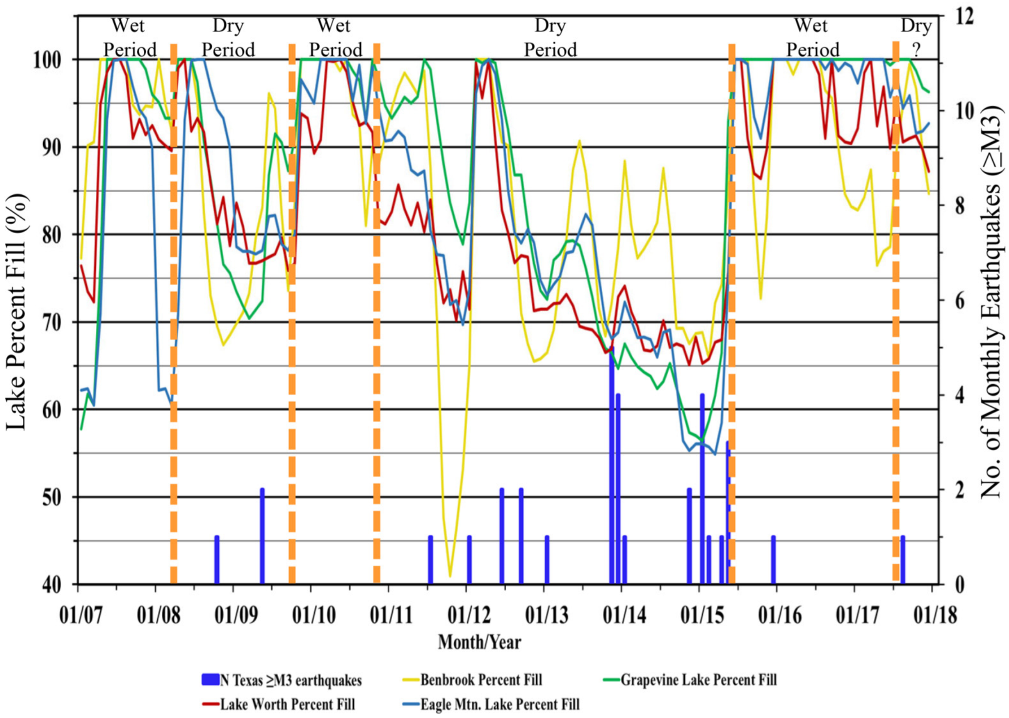

Figure 6. The 33 North Texas earthquakes and area lakes percent fill (%) for January 2007 to January 2018. Curves are percent fill for the four area lakes near the Dallas–Forth Worth area (Fig. 1); Benbrook (Yellow), Grapevine (green), Lake Worth (brown), and Eagle Mountain (blue). Joe Pool Lake is not included because the water level is managed by the U.S. Army Corp of Engineers to provide a source of drinking water to nearby cities. Blue bars represent the 33 North Texas earthquakes plotted by the number of earthquakes occurring each month. Dry/drought periods are labeled for times of lower lake levels (decreasing fill). Wet periods are defined by lake levels at or near 100% fill. Strong correlation of earthquake occurrence to drought (dry) periods. 31 of 33 North Texas events (94%) occurred during periods of drought.

indicate that as the lakes dry up (increasing drought) the earthquake frequency increases. 2015 had nine events in the first five months of the year at the time of extreme drought in the area. The drought may also have an impact on the magnitude of earthquakes, since the largest magnitude event was a M4.0 on 07 May 2015 (Fig. 2). This drought period continued till the end of May 2015, with one brief time in 2012 when the lakes recharged to 100% fill. No earthquakes occurred during this time from February to May 2012. North Texas experienced very heavy rainfall in late May 2015, filling area lakes to or near historic levels and the Trinity River surged above flood stage. After this major rainfall event all felt earthquakes nearly stopped for the next two years and most lake levels were above 90% fill. Tabulation of events occurring in dry and wet periods indicate that felt earthquakes predominately occur during dry/drought periods. Of the 33 earthquake events (M3 and larger), 31 earthquakes (94%) occurred during the drought periods and only two events during the wet periods.

Lake levels are used in this study only as an indicator of the subsurface moisture conditions, because lake water level has not been previously linked to either inducing earthquakes or stabilizing fault systems in the North Texas area. Hornbach et al. (2015) investigated whether the pressure change from a drop in the Eagle Mountain Lake level was sufficient to induce earthquakes in the Azle, Texas area (Fig. 1). He concluded that the changes were too small and can be ruled out as an important contributing factor to the Azle earthquakes. Thus, lake levels in this report are only used as a measure of the current state of the environmental conditions of the surrounding area. Therefore; wastewater injection creates the pore pressure changes that induced the North Texas earthquakes, but the environmental conditions appear to determine the timing and magnitude of the earthquake.

Becken et al. (2011) stated that rock water can act as a lubricant and plays an important role in earthquake onset. Diao and Espinosa-Marzal (2018) reported that experiments have shown that the presence of an aqueous solution can lead to a significant decrease of the friction strength compared to a dry condition. When they conducted frictional measurements in the absence of an aqueous solution, the frictional forces increased and emphasized the role of solutions in facilitating slip. When lake levels are low (drought) the subsurface moisture conditions would have reduced fluid present to lubricate the fault surfaces causing frictional lockup. During periods of high lake levels (wet periods) the subsurface moisture conditions would have more fluid present to lubricate fault surfaces reducing the frictional strength of the fault surface and facilitating early fault failure. The reduced frictional strength results from lubricating fault surfaces can be applied to multiple recent studies, involving rain induced earthquakes in the Swiss Alps (Husen et al., 2007; Miller, 2008) and another rain induced earthquake pattern in southeastern Germany (Hainzl et al., 2006; Kraft et al., 2006; Miller, 2008) and groundwater recharge at Mt. Hood, Oregon (Saar and Manga, 2003). All these areas are tectonically active. The faults in these areas are critically stressed and may be in a state of stress near failure (Saar and Manga, 2003).

Saar and Manga (2003) studied groundwater recharge at Mt. Hood, Oregon as the cause of the seasonal induced earthquakes. They calculated the pore pressure increase at depth caused by pore-fluid pressure diffusion to be ~1.45 psi (~0.01 MPa). There was a 151 d delay from the initiation of groundwater recharge to seismicity. The ~1.45 psi (~0.01 MPa) is at the lower end of pore-fluid pressure changes needed to induce earthquakes (Saar and Manga, 2003). The observed delay to seismicity may indicate the time for the groundwater to lubricate the fault surface and decrease the frictional strength enough that the low pressure change would result in fault failure, an earthquake. The majority of earthquakes recorded at Mt. Hood were less than M2.5 and at focal depths shallower than 2.8 mi (4.5 km). Saar and Manga (2003) suggested that the pressure changes due to groundwater recharge enhances the probability of earthquake occurrences, as opposed to generating them. A delay was also noticed in triggered seismicity in the central Swiss Alps following a large rainfall in 2005 (Husen et al., 2007). Their study plotted the focal depth versus time of rainfall. After a delay of 72 hr, earthquakes began and as time increased the focal depths increased to a maximum depth less than 3.1 mi (5 km). This again might illustrate the effect that wetting the fault surface has on reducing the fault frictional strength to a point where the pressure change induced by surface rainfall could cause fault failure. The aqueous lubrication allowed the faults to fail at small pressure changes and the resulting Swiss Alps earthquakes all had magnitudes less than M2.4. In these areas the ground moisture content was increased and small magnitude earthquake events were observed.

Kraft et al. (2006) and Hainzl et al. (2006) studied rainfall and increased seismicity at Mt. Hochstaufen, southeastern Germany. There was a 10 d delay from the start of rainfall to microseismic activity. 1171 earthquake events occurred after the 2002 heavy rainfall and all had magnitudes less than M2.4. The focal depths of the Mt. Hochstaufen events also migrated from very shallow to greater depth with time from the start of rainfall. The study also points out that the larger macroseismic events occurred before the maximum rainfall (Kraft et al., 2006). They concluded the larger earthquakes were likely to occur after the winter months. This is a time when any moisture is kept at the surface as snow. In the above studies a delay from an inducing event is noted, and only microseismic events were recorded after the delay, and focal depths increased with time. The timing of larger earthquakes before rain and many smaller events after the rain supports hypothesis that rain wets and lubricates the fault surface, thereby reducing friction strength, allowing the fault to slip and generate smaller magnitude earthquakes. In North Texas, earthquakes of magnitude less than 3 (microseismic) continued during the wet periods and larger magnitude earthquake events occurred during the drought periods. Frohlich (2012) studied a 2 yr period from November 2009 to September 2011. He identified over 60 events during this time with magnitudes between 1.4 and 3.0 and even more by using cross-correlation analysis that had even smaller average magnitudes. This time period is a seismic quiet period for North Texas (Fig. 2) with only one earthquake in July 2011. Area lake fill levels during this period have all lakes above 80% fill (Fig. 6). This highlights the presence of additional moisture to lubricate the faults allowing failure to occur at reduced stress and result in earthquakes of smaller magnitude. The fact that all the stress energy stored in the fault can be released as a series of less destructive lower intensity earthquakes during wet periods is a desired outcome.

The lack of a wetting solution causing frictional lockup is presented in a paper where over pumping of groundwater may have accentuated earthquake magnitudes (Al-Farraj, 2012). Arid conditions were evaluated by Al-Farraj (2012) in the northern United Arab Emirates (UAE). Overpumping of groundwater for consumption and farming has increased since the 1970s. The UAE normally experiences minor earthquakes not exceeding M4.4. Pumping of groundwater was so severe that in 2002 farmers in the northern UAE reported lack of groundwater on their farms. In the same time period, the northern UAE experienced multiple earthquakes greater than M5. Al-Farraj (2012) concluded that changes in the groundwater conditions due to overpumping may accentuate earthquake magnitudes. The reduced groundwater would mean less water to provide the lubrication to the faults, resulting in frictional lockup. Stress would continue to build and the resulting failure would release more energy in larger magnitude earthquakes. Over-pumping of groundwater would equate to the drought conditions in North Texas expressed in low lake levels and the occurrence of earthquakes of M3 and larger during this time period.

Fault zone permeability controls the ability of surface water to transit down the fault surface. Faulkner et al. (2010) studied fluid flow of fault systems. Damaged zones within the fault core may provide a pathway for fluid flow (Faulkner et al., 2010). Hydrocarbon migration has used fault gouge as a pathway to flow from deep to shallow formations. Oil seeps indicate that permeability and flow can exist all the way to the surface. Miller (2008) discussed the nature of karst geology and the ability to channel water after intense rainfall down through the karst formation. This is a very effective method to deliver fluids to the fault network. The permeability of the various faults from Mt. Hochstaufen to the Swiss Alps could account for the various amount of delay from water sourced to start of seismicity. Brodsky and Kanamori (2001) stated that increased fluid pressure can deform the fault wall and modify geometry to increase effective lubrication and reduce the normal stress. The ability to supply an aqueous fluid to a fault surface, the resulting reduced frictional stress, the small pressure changes calculated at depth being at the low end of pressure changes necessary to generate fault failure, and the macroseismicity occurring before heavy rainfall all point to fault lubrication as an important method in allowing fault slippage or creep.

CONCLUSIONS

Some studies have tried to link rainfall to earthquakes that occur many kilometers below the surface. However, water content (saturation) present in the soil could be the key to understanding the North Texas earthquakes. Faults have a hydrologic link to near surface conditions. The subsurface water concentration during wet periods could lubricate the faults, allow critically stressed faults to slip early in the stress accumulation resulting in smaller magnitude earthquakes. This is observed in the studies of the Swiss Alps and Mt. Hochstaufen in southeastern Germany. Many low magnitude earthquakes (<M2.5) occurred after heavy rainfall and larger magnitude events preceded the heavy rain (Kraft et al., 2006). The calculated pore-pressure change, from the Swiss Alps heavy rainfall, at focal depths was at the low end of estimates needed to induce earthquakes. The lubrication of the fault surface reduces the frictional strength of the fault, allowing fault failure to occur at smaller pressure changes. Similarly, earthquakes of magnitude less than 3 were recorded by the U.S. Geological Survey (USGS) network during the wet periods in North Texas (Frohlich, 2012). In the northern UAE, the lack of groundwater increased the friction strength of the fault resulting in larger magnitude earthquakes. During North Texas drought periods, the lack of moisture to lubricate the faults results in frictional lockup and allows stress to build up in the fault resulting in larger magnitude earthquakes when this greater stress is suddenly released. Therefore, it is hypothesized that the combination of wastewater injection in times of drought/low rain when the ground is locked-up is what triggers larger earthquakes. The Venus, Texas M4.0 earthquake occurred following months of low rainfall. After a heavy rainfall, in late May 2015, no seismicity occurred in the Venus area until May 2018. In North Texas, the timing of M3 and larger events occurring during drought periods and microseismic events occurring during wet periods is an association that might allow for prediction of future earthquake events.

The Dallas–Fort Worth area is a highly populated area and there is concern that large earthquakes might cause injuries and property damage. Using the lake levels as an indication of drought conditions and the amount of aqueous solution available to lubricate the fault surfaces, it may be possible to predict when M3 and larger earthquakes could impact the North Texas area. These results show that larger seismic events could occur during drought conditions, marked by lake levels dropping below 90% fill. The fact that all the stress energy stored in the fault can be released as a series of smaller less destructive earthquakes during wet periods is a better outcome than having an earthquake of significant magnitude during a drought period. Predicting when earthquake magnitudes could reach dangerous levels, would allow additional monitoring to be installed during these periods and assist in locating and analyzing any seismicity that might occur in the area. The phenomena of lubricating fault surfaces could explain some of the results in the references cited in this paper. Likewise, applying these results could help in analyzing the timing and magnitude of earthquake patterns in other areas.

DATA AND RESOURCES

Earthquake data for felt earthquakes (magnitude 3 and greater) was obtained from the USGS public website for events in the Fort Worth Basin and confirmed with those of other studies (Frohlich et al., 2016). TRC public data was used for Barnett Shale production and injection volumes by county and by wells. The information can be broken down by county, field, or by individual well (including SWD well locations). The North Texas earthquakes occurred in four main counties, Dallas, Tarrant, Johnson, and Parker counties. Monthly data for production and injection was gathered for these counties. Dallas County does not have any wastewater injection wells. Rainfall data for Dallas was obtained from the weather.gov website. The rainfall data for other cities in the Fort Worth Basin came from the iweathernet.com website. Lake level information was found at waterdatafortexas.org. All the information was collected in monthly and annual data sets. Production volume information was in thousand cubic ft (mcf) units from TRC (converted to million cubic ft [mmcf] by dividing by 1000). Injection volumes units from TRC are in barrels but converted to m^3 (100 barrels = ~16 m^3). Since earthquakes began in 2008, data was gathered starting in January 2007 to capture any trend leading up to the first event. If available, data was collected through 31 December 2017. Missing monthly rainfall for some cities resulted in exclusion of that city or estimation of the missing value from other nearby cities that had recorded rainfall for that missing month.

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