The Effects of Earthquakes on Groundwater in Santa Clara County

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Abstract

The potential effect of a large earthquake on groundwater in Santa Clara County in California, United States is assessed. This paper will assess the types of ecosystems as well as the cities that will be affected, and will determine how to best manage the human health and public access issues that may arise as groundwater is affected after an earthquake. A large earthquake is expected to occur in the Bay Area, yet the reaction of groundwater to an earthquake in the region is not known with any great certainty. Through assessment of examples from other earthquakes that have occurred in California and in the County, possible groundwater reactions to an earthquake can be drawn. Using these examples, there is a high likelihood of groundwater levels rising within Santa Clara County after an earthquake. However, more research needs to be conducted on groundwater and how it reacts to structural changes for specific sites since each site is different than any other. In the case of groundwater rising in a contaminated area of the county, well water may not be safe to consume. Cities will need to create plans concerning groundwater in the event of an earthquake to ensure a water supply for the people of the city and its ecosystems.
Introduction

Groundwater is contained within geologic structures that allow water molecules to move through porous rock and material. Groundwater feeds ecosystems such as wetlands and provides support for river systems, which in turn provide for the flora and fauna found in ecosystems. Groundwater can also be pumped up to the surface for use during droughts or to supplement surface water for use in cities or irrigation for farmers. However, when too much groundwater is pumped up with nothing being pumped back in, the water table is lowered and accessing the groundwater becomes difficult along with other adverse effects.

Certain materials that contain limestone allow for greater freedom of movement of water, as opposed to those that contain clays. In cases of disturbance, this movement of groundwater can be affected. Disturbances such as earthquakes may cause the water table to rise or be lowered either temporarily or permanently. Earthquakes and their effects on groundwater have been recorded and studied in various cities across the globe, but there is still some uncertainty about the mechanisms that cause changes. There have not been many region-specific studies focusing on what may occur and how to handle groundwater changes after an earthquake. The focus of this paper is on the potential effect of a large earthquake on groundwater in Santa Clara County in California, United States. This paper will assess the types of ecosystems as well as the cities that will be affected, and will determine how to best manage the human health and public access issues that may arise as groundwater is affected after an earthquake.

This analysis is important due to the high likelihood of the Bay Area experiencing a strong earthquake (Johnson, 2007). The San Andreas fault has a major earthquake about every 150 years, but the southern stretch has not had an earthquake in over 300 years. This fault is expected to produce what is often referred to as the “Big One”, an earthquake that shakes stronger and longer than the most recent large earthquakes from 100 years ago (Johnson, 2007). However, it has been estimated more recently that in the next 30 years, the Hayward fault will be the most likely fault to rupture in the Bay
A Brief Background of Santa Clara County

In the past, the Santa Clara Valley was heavily used to grow fruits and vegetables for the first part of the century (Ingebritsen and Jones, 1999). Now the Valley is home to a growing urban population. Both the agricultural and urban water needs were supported primarily by groundwater and supplemented by surface water. A great deal of subsidence occurred in the valley due to consistent pumping of groundwater, about 13 feet on portions of the land in the first half of the 20th century (Moran et al., 2014). Subsidence is when the water in porous rocks and materials are taken out and not filled with more water, causing the pores to become smaller and eventually close up all together under gravitational pressure from the surface. This affects recharge rates, since once land has subsided and the pores have closed, the ability of water to flow is severely diminished. Subsidence has been relatively halted across the valley since 1969 and is closely monitored and managed, especially during periods of drought (Ingebritsen and Jones, 1999).

The Bay Area consists of nine counties. The county of Santa Clara is the largest of the counties, has great ecological diversity with many natural attractions, and is located at the southern edge of the San Francisco Bay (Reymers et al., 2001). There are 15 cities in Santa Clara County (figure 1).

**watersheds**

Five major watersheds that Santa Clara Valley encompasses are: Coyote, Uvas/Llagas, Guadalupe, West Valley, and the Lower Peninsula (Figure 2). Santa Clara County, however, crosses six smaller watersheds: Coyote, San Francisco Bay, Tomales-Drake Bays, San Lorenzo-Soquel, Pajaro, Panoche-San Luis Reservoir (USEPAb, 2014). In these watersheds, there are more than 800 miles of rivers and creeks (Santa Clara Valley Water District, 2014).

The Santa Clara Valley Water District (SCVWD) uses water from all of these watersheds to provide water for the cities. The Santa Clara Valley water district provides water to the cities in the county and gets about 40% of its water from the delta (imported water that can come from hundreds of
miles away and is transported through rivers and uses the federal Central Valley Project, the State Water Project, and San Francisco’s Hetch Hetchy system), 40% from local surface water and groundwater, 15% from San Francisco Regional Water System, and 5% from recycled water (Santa Clara Valley Water District, 2014). The SCVWD monitors groundwater quality and elevation. They are responsible for monitoring groundwater quality, the quality of the water meant for recharge, and assessing the storage of groundwater (Santa Clara Valley Water District, 2014).

**water quality**

Water provided by the SCVWD has been treated at some stage before it reaches the consumer. Although most wells in Santa Clara County produce water that is safe to drink immediately, the presence of nitrates in several South County wells has been an increasing problem (Santa Clara Valley Water District 2014, Reymers et al. 2001, California Department of Water Resources 2004). Groundwater naturally has some minerals that have been dissolved as water percolates downward through the geologic structures (Moran et al., 2014) but the minerals are not toxic or harmful to drink so the water can be consumed immediately. Newhouse et al., (2004) stated that groundwater of the Santa Clara Valley has a small amount of dissolved solids and low chloride levels which indicates that the water is of good quality. While anthropogenic contaminants can get into the groundwater and contaminate the whole aquifer, there are numerous checks and balances in the system to keep locations and levels of contaminants from becoming a threat to the whole aquifer. Some of these balances include creating programs designed to create and destroy wells safely, wellhead protection programs, programs to oversee underground storage tanks that may be leaking, and toxic cleanup programs (Reymers et al., 2001). These programs can add an extra measure of protection to the groundwater of the region. Reymers et al., (2001) state that even though there are several Superfund sites in Santa Clara County, groundwater quality has been relatively unharmed: public wells do sometimes show trace amounts of volatile organic compounds. Water from this region overall is of great quality despite the Superfund sites.
**subbasins, treatment plants, and reservoirs**

The regional aquifer consists of both upper and lower aquifers. The upper aquifer provides the groundwater for drinking and other uses as well as a source of recharge for the lower aquifer (Hanson et al., 2004). The upper aquifer contains relatively young water, while the lower aquifer contains much older water that takes thousands of years to be recharged. In the Santa Clara region, recharge of groundwater occurs both naturally and artificially. Natural forms include precipitation and stream flow infiltration. Artificial recharge includes infiltration of imported water and leaks from pipes that transport water. Groundwater outflows from the system include pumpage from wells, regular stream flow, evaporation from streams and plants, and deep groundwater flow to the San Francisco Bay (Hanson et al., 2004). The county has three subbasins that allow rainfall and water from the recharge program of shallow aquifers to filter down into deeper aquifers. There are 18 major recharge facilities that the district operates and maintains (Reymers et al., 2001). These subbasins have a relatively large storage capacity which can be used for water storage in wet years and a reserve in dry years.

There are three subbasins within Santa Clara County: the Llagas Subbasin, the Santa Clara, and the Coyote (Figure 3). The Coyote is very small so it will not be discussed in much detail. The Diablo Range and the Santa Cruz Mountains border the subbasins, which together cover about 325 square miles (California Department of Water Resources 2004, Santa Clara Valley Water District 2014). The aquifers of the subbasins contain gravel, sand, and silty sand deposits. The aquifers reach a depth of over 1,000 feet in some places, yet only 500 feet in others. The two subbasins have confined zones and recharge areas that restrict groundwater flowing downward due to the clay and silt deposits that make for lower permeability. These lower permeability layers separate the shallow and deep aquifer zones, providing some protection from contaminants to the deeper layers (Santa Clara Valley Water District, 2014).

The Santa Clara subbasin runs from the northern edge of the county boundary to a groundwater divide close to Morgan Hill. The Valley in the middle drains Coyote Creek, Los Gatos Creek, and the
Guadalupe River into the San Francisco Bay. Groundwater in the Llagas subbasin tends to flow in the opposite direction (southeast) (Santa Clara Valley Water District 2014, California Department of Water Resources 2004). An aquifer susceptibility assessment concluded that the most vulnerable areas of the main subbasin in the county are the unconfined portions immediately before the Bay due to rapid groundwater recharge times (Moran et al., 2004). With these rapid recharge rates, any contaminants that enter the system will contaminate those portions rapidly. Areas that are less at risk for rapid contamination are areas that have had groundwater isolated from surface sources for more than 50 years such as the large confined portions of the subbasin close to the Bay (Moran et al., 2004).

The Santa Clara Valley Water District directs three water treatment plants in the county: Penitencia, Rinconada, and Santa Teresa (Santa Clara Valley Water District, 2014). Five major water bearing pipes connect all three of these plants as well as two water conduits from the Central Valley Project and the State Water Project (Reymers et al., 2001). The interconnectedness of the three plants is essential in the event an earthquake breaks one or two conduits. With one or two broken, water could still be re-routed to the plants.

Local runoff is another important factor to consider when assessing water supply. Local runoff is captured in these district reservoirs (Figure 4) that have a capacity of about 169,000 acre-feet (Reymers et al., 2001). The water contained in these reservoirs can be used in case of emergencies, but public access could be challenging if pipes broke.

Assessment of Groundwater Reaction to an Earthquake in Santa Clara County

*earthquakes, groundwater, and geology*

Earthquakes occur along fault lines so it is crucial to know the major faults of the county. There are several small faults in Santa Clara County, such as those named along the Foothills thrust belt: Monte Vista and Berrocal Faults (USGS, 2006). The main faults that run through the county are the San Andreas, Calaveras, Greenville, and Hayward faults (Association of Bay Area Governments Resilience Program 2014, USGS 2006).
Groundwater is affected by seismic waves in two main ways: permanent offsets and oscillations (Roeloffs, 2012). Both effects have been known for some time and are not new, and both refer to groundwater levels. Oscillations are understood to be caused by surface waves that have long periods. Oscillation theory is based on the idea that pressure changes can occur among pores due to fluctuations of the aquifer by seismic waves (Roeloffs, 2012). Offsets are mostly caused by the permanent contraction or expansion of the rocks in the close vicinity of the quake. These offsets are noticed less as the distance increases. Some offsets can begin immediately (from minute to minute changes) and some may start quickly but take days or weeks to reach the maximum or minimum point. The offsets are experienced at both shallow and deep depths and are usually dependent on distance and the magnitude of the earthquake.

If the quake occurs near a confined aquifer, this confined aquifer may be subject to more permanent underground changes with similar implications for change for groundwater. These underground changes only cause a change in groundwater until the water tables equalizes itself. This equalization could take anywhere from a few minutes to a few months. Exactly how the water table equalizes is still unknown so there is a great deal of uncertainty as to how long it may take for any given hydrologic system to recover (Roeloffs, 2012). This implies that site specific geologic data should be gathered when an area is being assessed for the potential of liquefaction or other hydrological responses. These changes in the pressure of the groundwater can lead to liquefaction and lead to great damage to buildings and infrastructure (Wang and Manga, 2010). Infrastructure includes wells and pipes used for pumping and carrying water.

Local geological structure controls what happens to the groundwater in the upper crust (Zhou and Burbey, 2014). For this reason it is important to know the geological structure of the Santa Clara area. Deeper into the crust, confined aquifers react immediately to a sudden slip in the fault. Strike slip faults, or transform faults, tend to have less dramatic water level changes as opposed to normal or reverse/thrust faults (Zhou and Burbey, 2014). Faults found in Santa Clara county such as the San...
Andreas, Hayward, and Calaveras faults are transform faults. Therefore, it seems any change in groundwater will be less than it would be if the earthquake was along a normal or reverse fault.

The geologic formations that contain the groundwater found in the Santa Clara subbasin include unconsolidated to semi-unconsolidated clay, silt, sand, and gravel (California Department of Water Resources, 2004). Using well monitoring sites completed by the USGS, Newhouse et al. (2004) noted that the fine grained layers of the aquifers were thinner than previously thought and that there are extensive coarse-grained water-bearing zones. These formations allow for relatively easy groundwater flow. This easy flow can be beneficial for purposes relating to groundwater recharge, but bad when considering any contaminants entering the system.

The soil types found in the Santa Clara area are mainly sandstones, mudstones, silts, and muds (Table 1). The soil types from the Quaternary, Upper Tertiary, and the Lower Tertiary are found in the more mountainous areas while the second Quaternary soils listed are found in the lower elevation areas. These lower elevations are more susceptible to significant amplification of shaking due to their softer soil types. This will be important when considering the possibility of liquefaction for Santa Clara County.

**earthquake after-effects and implications**

The Loma Prieta earthquake had a magnitude of 6.9, occurred October 17, 1989 at 5:04 pm, with the epicenter located in the Santa Cruz Mountains near Loma Prieta peak (USGS, 2014). The Loma Prieta earthquake occurred during a dry season in California, and a large amount of extra water was found flowing in the streams after the quake (Manga, 2001). Other quakes during wet seasons showed little excess water joining the streams. This seasonal difference could be a very important factor; if an earthquake were to occur during a dry season, more water would be seen at a time when drought might be prevalent. If a quake occurs in the wet seasons, dams may be taxed with any extra flow, but will likely cause no noticeable difference to landscapes or people. When there is a decrease in the amount of water in wells from the higher edges of the watershed, this is evidence for the extra
groundwater coming from a shallow source. When the water temperature is lower in streams and springs that are experiencing extra groundwater, this is also an indicator of a shallow source for additional water. This cooler temperature of water was experienced after the Loma Prieta earthquake and helped to identify the origin of the extra water as shallow groundwater (Manga, 2001). During the water year 1990 after the Loma Prieta earthquake, about 87 cubic hectometres of shallow groundwater that had been stored was released in the rivers along the sides of the Santa Cruz Mountains (Curry et al., 1994).

Near the Alum Rock springs, California, which is close to San Jose, an earthquake occurred on October 30, 2007 with a magnitude of 5.5 (Manga and Rowland, 2009). There was a large increase in discharge from the springs within a day after the earthquake and over a year the levels slowly decreased back to pre-earthquake amounts. Manga and Rowland (2009) determined that the extra groundwater flowing from the springs was of shallow origin. The extra water available was deemed to have little if any significant change in composition from the surrounding surface water.

In California, a 6.0 earthquake occurred in Napa County August 24, 2014 at 3:20 am (Jensen, 2014). For at least two weeks after the quake, the Napa River and many of its tributaries showed an increased flow. Some areas experienced rapid change in the amount of water in the river, while others noticed changes that took up to three days to appear after the earthquake. Some wells were not able to get any water, while some others saw an increase in the water they could pump. These results are usually temporary but shifts in rocks and sediments could make some effects permanent. For example, a possible positive effect could be the reconnection of a deep aquifer to a shallower one to allow for recharge.

Wang et al. (2004) studied groundwater changes after the 1999 Chi-Chi earthquake of 7.5 magnitude in central Taiwan and characterized the responses into four different types: rise then a consistent decline of groundwater level, a fall then a continuous groundwater level rise, a drop then slow decline, a rise then stay the same for a time before slowly declining. These different types of
responses varied based on what material they occurred on. The first type occurred on the Choshui River fan with unconsolidated sediments. The second and third type occurred near the fault in the foothills that had ruptured on top of the fractured and deformed sedimentary rocks. The fourth occurred along the coastal unconsolidated sediments of central Taiwan (Wang et al., 2004). This characterization of the responses could be loosely used for other regions with similar geologic formations. For instance, it seems likely that Santa Clara County would experience a mix of type one and type two responses due to the unconsolidated and coastal unconsolidated sediments that can be found in the County. From other accounts of earthquakes and subsequent groundwater reactions in California, it seems that the county would experience type four.

The above examples of previous earthquakes and groundwater reactions now point to the likelihood of shallow water percolating upwards and flowing out after a moderate to strong earthquake in Santa Clara County and that this water will likely be safe to drink with little if any cleaning straight out of the ground. This increase in water level will likely be temporary.

**ecosystems**

Groundwater-dependent ecosystems (GDEs) are ecosystems that rely on groundwater to maintain their wetness for extended amounts of time (Blevins and Aldous, 2011). These ecosystems include wetlands, springs, rivers, and lakes. GDEs are special due to relatively high amounts of minerals that appear in the groundwater from the underlying materials. Seasonal variations in amounts of groundwater available to the given ecosystem usually do not fluctuate in GDEs, and the temperature of the water is generally the same seasonally. This usually means that the groundwater is cooler in the summer and warmer in the winter than surface water. Figure 5 is a map of groundwater dependence at the highest hydrological unit scale for California. The scoring of none to high indicates how dependent the area is in total (the accumulation of groundwater dependent variables of groundwater dependent wetlands and matched vegetation connections, baseflow needs, and springs) (Howard and Merrifield, 2010).
California and a few other states have higher numbers of groundwater-dependent species than most states in the US (Figure 5) (Blevins and Aldous, 2011). These species would benefit greatly from concentrated conservation efforts and mindful planning of groundwater use, and they would be negatively impacted by any unusual fluctuation in groundwater. GDEs are smaller than most surface fed ecosystems since the groundwater discharge area can be rather small. These small ecosystems often are habitats for rare or endangered species, which makes them even more valuable. If groundwater rises, these habitats could be inundated from below with too much water. But if the water table falls then these ecosystems are in danger of disappearing completely, possibly permanently. However, it seems that in Santa Clara County at least, the groundwater will rise for a short amount of time and then fall so the inundation would not last overly long as seen in previous earthquakes.

**chemical concerns**

The watershed in this county that poses the most toxicological concern is the Guadalupe watershed. The Guadalupe watershed has mercury contamination from California gold rush mining (Santa Clara Valley Water District, 2014). Methylmercury is the most dangerous form of mercury. Fish and other organisms can ingest and accumulate this methylmercury, causing serious health problems for those who eat them. It affects the immune system and nervous system and stays in the body for a long amount of time. Mercury poisoning affects young children and pregnant women greatly. If groundwater were to rise in this area after an earthquake, as has been evidenced previously, then amounts of mercury/methylmercury could increase and cause fish to ingest more. Although, the increased discharge could help flush the area out a bit so when the flows recede there may be lower concentrations. More research would need to be done on this idea of flushing concentrations before it would be acceptable to allow people to use this water as an emergency source. Also of concern in the county are Superfund sites. There are at least 20 cleanup sites located within Santa Clara County on the EPA's list of cleanup sites in California, some are brownfields, but the majority are Superfund sites (USEPAa, 2014). If groundwater were to rise up and overflow streams, some of these areas could
contribute to pollution of the surrounding waterways. This sudden rise in groundwater levels is proven rather likely due to examples of other earthquakes in the region mentioned. This could result in flushing some of the chemicals from the ground. When the groundwater recedes, however, the chemicals may filter out partially, but end up contaminating the entire upper aquifer.

The same issue of flushing contaminants applies to overdraft concerns. Even if overdraft does occur and contaminants become concentrated into the remaining water, a rise in groundwater levels would likely help flush these contaminants. The extra water would allow for greater dilution of the contaminants and push some up and out of the aquifer. However, if this were to happen, then the water coming out of the ground should not be consumed until it is deemed safe again by those monitoring the water quality.

Monitoring and managing of groundwater by the SCVWD to prevent further subsidence will be important after an earthquake since some groundwater will flow up and out of the basin. If there is long-term, large scale pumping of groundwater after the earthquake, subsidence could become a concern once again. In the weeks following the earthquake, an increased amount of water may need to be allocated to recharge stations across the county.

**liquefaction**

When considering earthquakes and groundwater, liquefaction must be considered as well. Liquefaction occurs when wet sands and soils are shaken and become liquid-like. These conditions cause damage both above and below ground to infrastructure of all sorts. Figures 6, 7, and 8 are maps that show the probability of liquefaction occurring for each given scenario along each of the three faults identified. The communities of Campbell, Los Altos, Cupertino, Los Gatos, Mountain View, San Jose, Santa Clara, Palo Alto, Saratoga, Sunnyvale, and Milpitas are included. The values shown are due to the use of the lowest water table levels historically recorded, not the most recent groundwater conditions. If the current water table level is deeper, then there is less probability of liquefaction occurring in that area (USGSb, 2012).
Liquefaction hazard maps indicate that liquefaction is most likely in the Bay margins of the county with landslides more likely to occur in the Hills on the Eastern side of the county (Association of Bay Area Governments Resilience Program, 2014). It seems that the most liquefaction would occur after an earthquake along the San Andreas Fault above San Jose northwards to the Bay (Figure 6). For an earthquake along either the Calaveras or Hayward fault, the most liquefaction would occur in the same area from San Jose north to the Bay (Figures 7 and 8). Although, if groundwater levels were to rise slightly before an earthquake, as has been concluded previously, liquefaction may become more severe than these hazard maps have modeled. There has been some research conducted on predicting earthquakes by how groundwater behaves before an earthquake occurs, but the results were inconclusive considering different areas have different rocks and soils causing different reactions.

**What Plans are Currently in Place and What Else Should be Considered**

With the vast population in the Bay Area, the issue of water supply and groundwater quality after a natural disaster needs to be addressed. Groundwater management is a local responsibility in California as the California Legislature has decided. This means that California has no comprehensive statewide groundwater management system, unlike the other states in the US (Howard and Merrifield, 2010). This may be for the best in Santa Clara because when earthquakes occur, local responses will likely be the most efficient/effective. Plans that are in place currently focus mostly on large scale relief. More focus needs to be placed on a smaller scale, community based organization. Distribution of the water supply to the public after an earthquake would best be handled on a county level.

As O'brien and Milet, (1993) found in Santa Cruz and San Francisco Counties several days after the Loma Prieta earthquake, disaster brings communities together more than driving them apart. The more work that needed to be done in the community, the more the community members came together to solve problems. One of the largest problems the community would face after an earthquake would be finding a source of drinking water. If a neighbor has a well, then this source may be groundwater. Those who were victims after an earthquake have been shown to help other victims
significantly after the event and must be used as part of any recovery plan. However, the people of the community would need to know that they will be a part of the solution in advance. Also, increasing public awareness of how to be prepared in case of an earthquake may increase the number of people who will step forward to help others. Identifying those in the community who own a well in advance of an earthquake will not only relieve anxiety for individuals, but also stress on the city to ensure their citizens are taken care of.

After an earthquake, many people will be in need of food, shelter, and most importantly, water. Ideally, all residents would have an emergency pack prepared in case of an earthquake. Even if they only have a few small bottles of water, they can survive for a few days. Ted Johnson noted a good plan that involves Southern California creating a Potable Water Plan that describes to the general public how to use the water they have during the first few hours and days after the earthquake (Johnson, 2007). Rationing water as if the city will not be able to supply water for up to a week is the best option. However, donations to the various areas that were devastated tend to flow as fast as news travels. The regions hit by the earthquake devised a catastrophic earthquake donations management plan that details how various forms of donation should be handled (Regional Catastrophic Preparedness, 2011). This plan is essential, but should be implemented like a spider web as much as possible. The center of the county should be the center of the web, and each city that is a part of the county should be one of the main hubs to gain assistance such as materials or volunteers. From the city heads, the communities should have two or three leaders known in advance to group together everyone in their community. In this manner, it should become easier to account for those who are missing, and identify which communities were hit hardest.

When an earthquake does hit, major damage and breakage categories will likely include bridges, dams, buildings, downed power lines, roads and railways, water and sewer lines, and petroleum pipelines (Johnson, 2007). All of these systems could take months to repair back to full working condition. However, private wells would likely be intact and functional so a few of the population
could access fresh water immediately. For the rest of the population, the cities’ water supply system is what they will rely on. The most efficient way to plan ahead for the effects of an earthquake on the water supply system is to create a model. Tabucchi et al. (2010) created a model for the Los Angeles region to simulate the restoration of the water supply system. This model was created specifically for the Los Angeles region, however many of the factors used in the model apply to other cities as well. The model can be changed depending on the severity of the earthquake and predictions can then be made on how badly pipes and other water supply infrastructure may be damaged.

This particular model put out several useful outputs including restoration curves, spatial distribution of restoration, crew usage, and material usage. These factors will vary by area but the use of a model could be extremely beneficial for any city to aid in planning for the after-effects of an earthquake. More factors to consider would be how long it may take crews to even assess the damage, then get to the area to fix it and how long it will take to get portions of the city functional and connected to other functioning parts of the city. Another suggestion would be to have crews for other services go out together such as electricity and gas. That way it is known that once the crew is finished with that area then those functions should be operational. This would also save money and time for the city since crews would navigate the damaged landscape together and aid each other. One more important suggestion would be that the city leader needs to decide which portions of the city need to be taken care of first in case of large versus small earthquakes since these choices may differ based on the extent of the damage. On a larger scale for pipelines, a good backup plan for any city is for municipalities that are nearby to have some sort of interconnectedness in case of system failure of one municipality.

The SCVWD runs a groundwater elevation monitoring program that measures the depth to groundwater (Reymers et al., 2001). This program would be very useful after an earthquake to monitor groundwater levels. Utilizing the knowledge of where the sites that may be deeply contaminated are and the level of the groundwater table, notices can be sent to private well owners or companies to warn
them. The toxic cleanup program is also important since they oversee investigations and cleanup of non-fuel contaminated sites. They would be useful after an earthquake to determine which areas were a concern before and what the increase in groundwater level does to the contaminants. Reymers et al., (2001) noted that improvements still need to be made considering that the groundwater programs and activities tend to operate individually, while it would be more beneficial for them to become more integrated to operate efficiently. Greater integration would help response time after an earthquake as well as during normal operation times.

The Cities Association of Santa Clara County is a representative group of leaders from each city. A forum is provided by the association that allows organizations, the private sector, and non-city individuals to broach topics for the cities of Santa Clara County (Cities Association of Santa Clara County, 2014). Priorities of mutual interest are adopted by the board of directors of the association each year and members work together each year to achieve the priorities set out. At best every year, but if only for one year, it would be a good idea to make preparation for earthquakes a top priority. Perhaps also taking a year or two on the tail of earthquake preparation, focus on groundwater cleanliness and usability in the case of an earthquake to determine what gaps they have in their plans in action.

In the plans reviewed, groundwater storage is considered, but no mention is made about what might happen if an earthquake were to occur and a good portion of the water stored previously were to come out. A study of the possible reactions of water storage basins would be useful to determine what actions may need to be taken. It is possible that more water that was earmarked for public distribution will need to be diverted to recoup groundwater storage in the short term.

Another issue mentioned, but not discussed in much detail, is the issue of levees. During a moderate to strong earthquake, levees could shake and collapse causing possible saltwater intrusion. It may be possible that the extra groundwater flowing in the streams could help counteract this by causing joint increased flow from several tributary streams.
Conclusions

There is a high likelihood of a moderate to severe earthquake in the Bay Area. Earthquakes cause damage to infrastructure which can cause trouble for humans and potentially ecosystems. Groundwater dependent ecosystems will likely survive an earthquake that causes groundwater to fluctuate. Groundwater supply to cities will likely be disrupted for a time, but by identifying and creating plans in advance of an earthquake, negative effects may be mitigated.

For Santa Clara County, it seems certain that groundwater levels will raise at least a little and likely fall back to normal levels relatively quickly. This groundwater would come from the shallow aquifers and should be safe to use, but people should refrain from using the water as drinking water directly considering the presence of Superfund sites in Santa Clara County.

It is well known how earthquakes occur, but it is less well known how groundwater reacts to structural changes such as those that earthquakes sometimes bring about. More research needs to be conducted on groundwater and how it reacts to structural changes for specific sites since each site is different than any other.
Figure 1- The 15 cities in Santa Clara County (Cities Association of Santa Clara County, 2014).

Figure 2- The five major watersheds that Santa Clara Valley encompasses.
Figure 3- Subbasins of Santa Clara County. Both the Llagas and Santa Clara Valley subbasins are confined but not connected (Reymers et al., 2001).

Figure 4- Locations of the three Water Treatment Plants (WTP) and reservoirs of the county.
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<td>Lower Tertiary (24 to 64 million years old)</td>
<td>Mudstones, sandstones, Franciscan melange, and serpentinite</td>
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Table 1 - Soil types and their ages in Santa Clara County. Created using information from USGS (2012).
Figure 5- Ecosystem Groundwater dependence index (Howard and Merrifield, 2010).
Figure 6- San Andreas Fault M 7.8 scenario (USGSa, 2012).

Figure 7- Hayward fault M 6.7 scenario (USGSa, 2012).
Figure 8- Calaveras fault M 6.9 scenario (USGSa, 2012).
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