The Impacts of Geothermal Operations on Groundwater

Jody C. Robins

National Renewable Energy Laboratory

Keywords

Geothermal, groundwater, Raft River, Long Valley Caldera, Steamboat Springs, NREL, BLM

ABSTRACT

In 2018, the Bureau of Land Management's (BLM's) National Renewable Energy Coordination Office, through its Geothermal Program, funded the National Renewable Energy Laboratory (NREL) to review existing literature for potential cases in which geothermal wells contributed to groundwater contamination. NREL conducted an extensive literature review but was unable to find any cases of groundwater contamination resulting from geothermal operations. This paper includes cases in which wellbore failures did not affect groundwater and areas where geothermal operations may have affected other resources, such as hot springs and geysers.

1. Introduction

Recent publications have demonstrated the vast, interconnected nature of regional groundwater flow systems in the western United States—for example, the 100- to 200-mile radius Death Valley regional flow system characterized by Belcher et al. (2017) and the 13,500 mi2 area of eastern Nevada and western Utah studied by Welch et al. (2007). With the identification of the far-reaching nature of groundwater flow effects, a complementary concern has been raised in recent years that questions the safety of geothermal development and its role in protecting the integrity of the groundwater system as a whole.

The goal of this paper is to identify previous instances of groundwater contamination caused by geothermal wellbore failures and examine how that might affect the expansive regional groundwater systems found in the western United States. Of particular concern—because of the tectonically active nature of many geothermal fields—is the possibility of wellbores being sheared by movement along a fault. Also of interest are secondary effects such as reduced geyser and hot water spring activity.

We conducted a wide-ranging literature review, but found no instances of groundwater contamination caused by geothermal wellbore failures. In fact, we found no instances of groundwater contamination resulting from geothermal operations in general. This search included papers in, but not limited to, the following databases: the IGA Geothermal Paper Database, the Geothermal Data Repository, the National Geothermal Data System, One Petro,

OpenEI, ScienceDirect, and the U.S. Department of Energy Office of Scientific and Technical Information (OSTI.gov).

Previous studies also came to the same conclusion. In the 2007 report, "A Guide to Geothermal Energy and the Environment," Kagel et al. found no groundwater contamination resulting from geothermal activity in the United States. The report cites well casing, cement, the Environmental Protection Agency Underground Injection Control Program, the Bureau of Land Management (BLM) and state well construction requirements, and geothermal industry efforts as factors in minimizing the effects of geothermal development on local water regimes and surface features.

In addition, of the 886 geothermal wells the BLM has on file across Nevada, New Mexico, Oregon, Utah, and California, none have been found sheared because of fault movement. This can probably be attributed to two primary factors. First, geothermal wells have strict well casing and cementing requirements that must be adhered to, which provides each well with significant structural integrity. Second, operators conduct shallow hazard surveys before deciding on wellbore locations to avoid crossing shallow faults and all the operational difficulties those faults could cause.

It does seem, however, that geothermal operations can influence geothermal surface manifestations, such as geysers, hot springs, and fumaroles. These surface geothermic features have experienced decreases in activity near some geothermal plant developments. Although there is evidence that the geothermal plant activity contributed to these declines, local decreases in precipitation and increases in domestic consumption (i.e., population growth) are also significant factors.

The following sections of this report detail three geothermal fields in three different states and geologic settings. All three have a significant system of monitoring wells to provide data and have been the subject of study both before and after geothermal development. Two of the three have also had wellbore failures of different degrees that, as of yet, have not contributed to groundwater contamination.

2. Raft River, Idaho

The Raft River geothermal field is located in southern Idaho (Figure 1). The field was initially developed by the U.S. Department of Energy (DOE) between 1974 and 1982. Development consisted of drilling five production wells, two injection wells, and installing the world's first binary geothermal power plant. However, in 1982, DOE ended the project because of poor economics and sold the plant to a project developer in Nevada (NREL 2005). U.S. Geothermal Inc. acquired the project in 2002, began construction on the Raft River Unit 1 power plant in 2006, and brought the 13-megawatt (MW) power plant online in 2008 (Clutter 2009). In 2018, Ormat purchased U.S. Geothermal and, by extension, the Raft River plant.

The Idaho Department of Water Resources (IDWR) designated the Raft River area a Critical Groundwater Area in 1963 because of groundwater level decline caused by large-scale pumping for irrigation that began in the 1950s. As a result, there have been many groundwater and geothermal water monitoring programs in the Raft River area preceding DOE geothermal operations. Sampling indicated that irrigation caused groundwater levels to decline from the 1950s through the late 1970s. The 1980s saw more precipitation, and during that time water

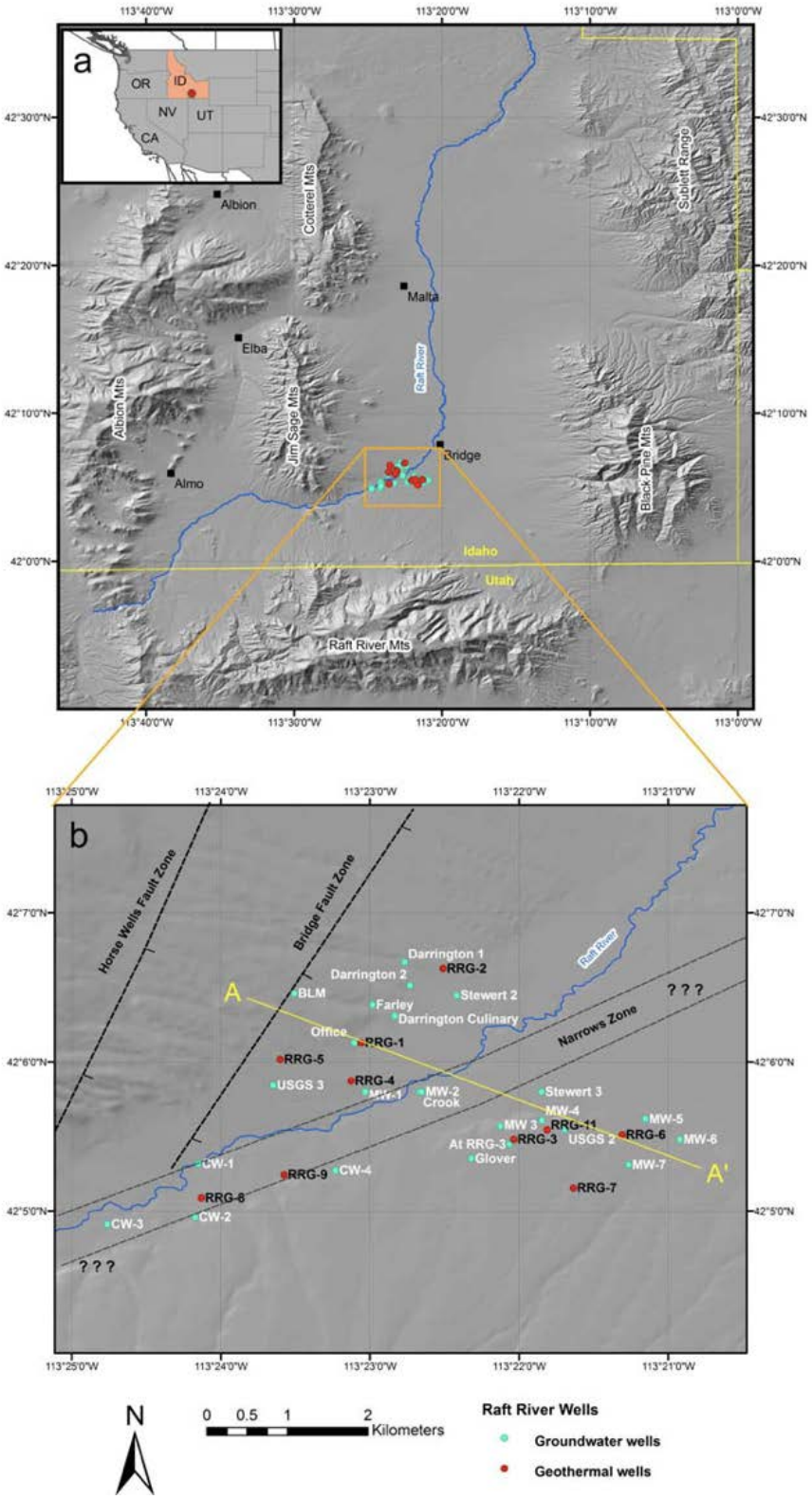

Figure 1. (a) Location of Raft River geothermal field (b) Locations of the geothermal and groundwater wells (Ayling et al. 2011).

levels were stable or rising. However, the declines resumed in the late 1980s through the present (Harrington and Bendixsen 1999). Interestingly, within the boundaries of the Raft River geothermal field, the shallow groundwater aquifer has remained stable and even shown slight improvements in groundwater recharge (Nichols 2019).

In the early 1970s, local hot springs and geothermal wells were sampled, which established the beginning aquifer temperatures and total dissolved solids for the geothermal resource (Young and Mitchell 1973). Additional groundwater monitoring around the Raft River field was initiated by the Idaho Department of Water Resources in 1974. This consisted of semiannual sampling of 22 nearby irrigation wells. Although the collection methods were not ideal, these samples did provide a useful geochemical baseline and discovered that the groundwater zones extended to a depth of 600 ft (Allman et al. 1979). Importantly, this early testing showed that geothermal and groundwater mixed naturally. This was most directly demonstrated by elevated concentrations of silica, chloride total dissolved solids, and fluoride in the groundwater (Nathenson et al. 1980).

After purchasing the geothermal field, U.S. Geothermal initiated its own monitoring program in 2004. This included taking samples from the geothermal wells (RRG-1, 2, 3, 4, 6, 7, 9, 11) and monitoring wells (MW-2, 3, 4, 5, 6, 7) in the field, as well as nearby shallow geothermal wells (BLM, USGS-1, 2, 3) and groundwater wells (CW-1, 2, 3, 4, Darrington Culinary, Stewert-2, -3, Crook, Farley, Glover). The location of these wells can be seen in Figure 1b. The data collected from these wells indicate that the fluid geochemistry in the field is variable and complex, with two distinct geothermal fluid types and two groundwater fluid types (Figure 2). These differences indicate that there are complex structural boundaries that influence the fluid pathways and compartmentalize the fluids but allow some limited mixing between them (Ayling et al. 2011). This finding matched the earlier conclusion that there is a natural mixing of groundwater and geothermal water. These proposed flow pathways (Figure 3) were confirmed by a series of geothermal injection and tracer tests conducted by the Idaho National Laboratory, the University of Utah Geoscience Center, and Lawrence Berkley National Laboratory (Bradford et al. 2015).

The Raft River geothermal power plant currently utilizes eight geothermal wells deeper than 5,000 ft, with four used for production (RRG-1, RRG-2, RRG-4, RRG-7) and four for reinjection (RRG-3, RRG-6, RRG-9, RRG-11). Geothermal water production averages 5,000 gallons per minute at 140°C (Ayling et al. 2011). The RRG-9 was part of a DOE enhanced geothermal system (EGS) demonstration project and is now used to reinject water (Bradford et al. 2015).

In addition to the geothermal water used to generate electricity, 250–300 million gallons of groundwater per month are used as cooling water for the Raft River plant. The spent cooling water is distributed across three hydraulic management units: two groundwater management zones fed by a sprinkler system in the summer and a holding pond in the winter. It is important to note that the cooling water is not geothermal brine, but groundwater. These operations are monitored by the IDWR and the Idaho Department of Environmental Quality (IDEQ). Before this system's implementation in 2007, IDWR and IDEQ recognized that this system could lead to a localized increase in total dissolved solids, chloride, fluoride, and/or silica, so as part of the IDEQ-approved water discharge plan, the IDWR developed a well monitoring program to assess any negative impacts. The monitoring plan includes six monitoring wells surrounding the hydraulic management units. Additionally, soil sampling is conducted annually each spring.

After five years, the IDEQ and IDWR concluded that geothermal operations and the cooling water disposal system

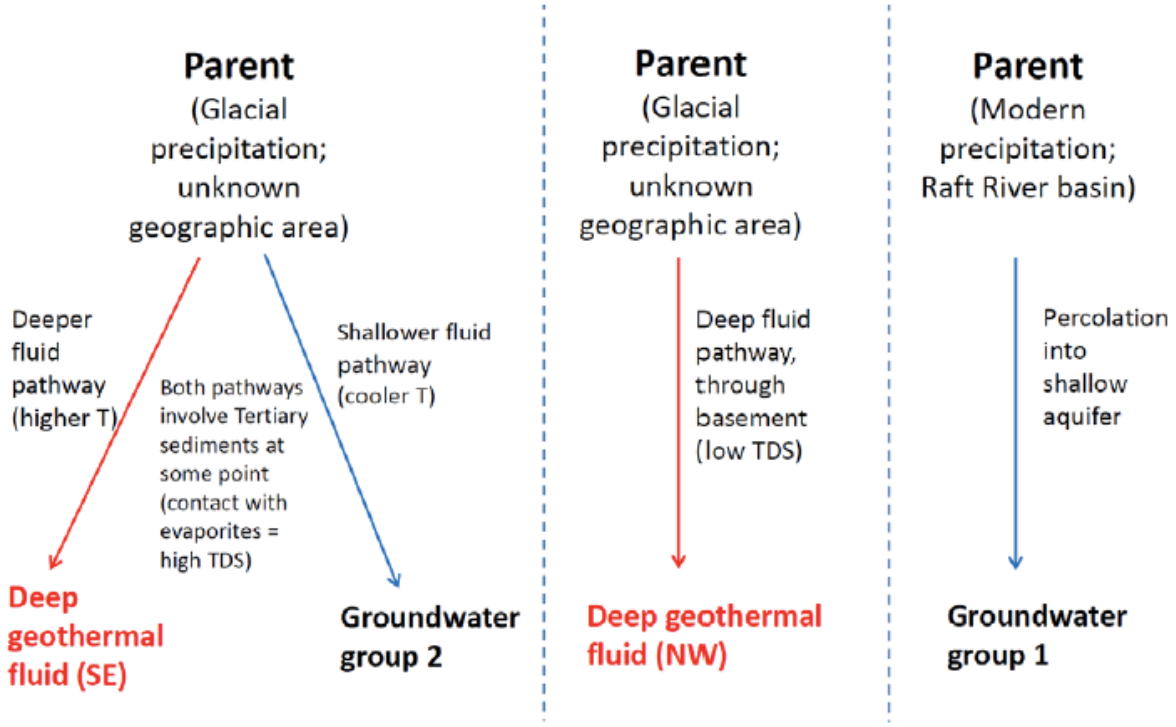

Figure 2. Schematic diagram representing sources and possible fluid pathways that are consistent with the observed water chemistry at Raft River (Ayling et al. 2011).

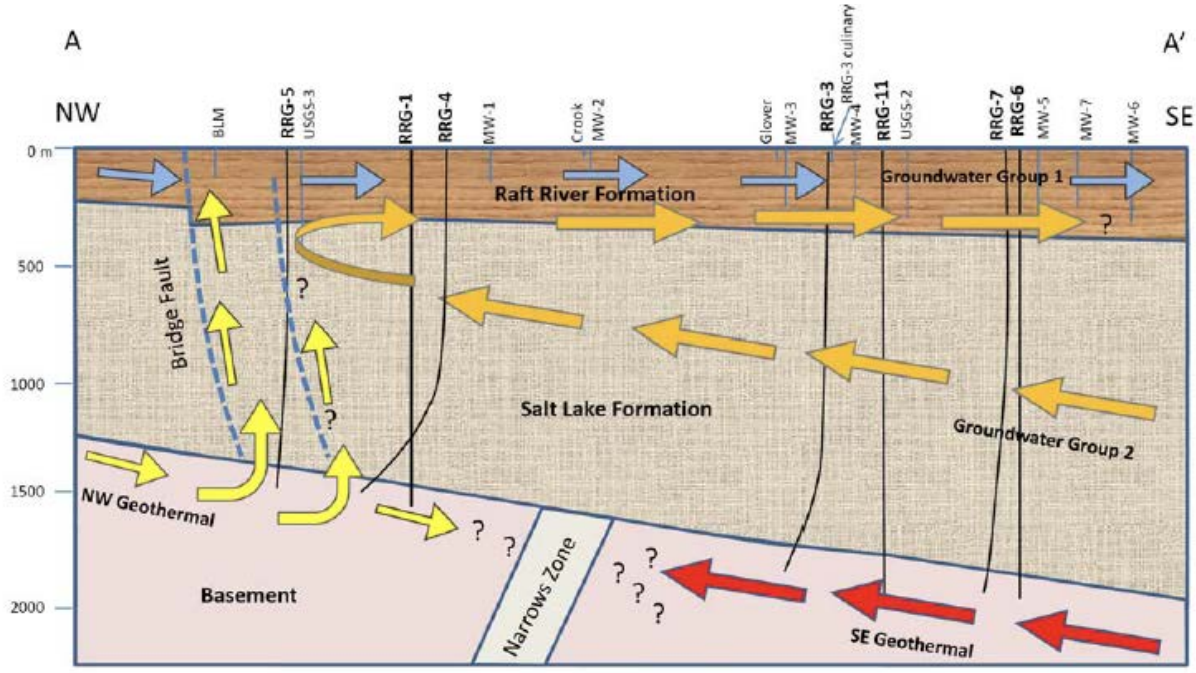

Figure 3. Speculative fluid pathways for the four fluid types at Raft River indicated on a simplified NW-SE cross section through the field (refer to Figure 1b for cross section location) (Ayling et al. 2011).

had not negatively impacted the surface or groundwater. In fact, to date there has been no upward trend in total dissolved solids, fluoride, or chloride concentrations at all (Nichols 2019).

Since the Raft River plant began operations, there have been two wellbore failures. The first was RRG-2. In June of 2010, a leak in the 13-3/8-in casing was discovered by a change in production temperature and subsequent pressure test. To resolve the problem, 585 ft of the 13-3/8-in casing was removed and replaced (OpenEI 2015). The RRG-2 well was returned to production on January 6, 2012. The second, and more substantial, failure was the RRG-7 (Geothermal Resources Group [GRG] 2017). In September of 2017, the casing head and 20-ft conductor pipe it was welded to subsided 12 in into the cellar, rendering production operations impossible. Following the initial attempt to repair the well, geothermal water began to flow uncontrollably out of the well, into the cellar and off location via a drainage ditch (Figure 4). The flow of geothermal water continued for seven days during kill operations. Once the well was dead, it was discovered that though the 13-3/8-in casing was in good shape, the 20-in conductor casing had become severely corroded and was unusable. The well was repaired by adding a casing head to the 13-3/8-in casing and replacing the top 37 ft of 20-in casing with 26 in and cement. The RRG-7 well was returned to production in January 2018.

Figure 4. Geothermal water filling the cellar during RRG-7 blowout. Photo courtesy of Ormat (GRG 2017).

These two wellbore failures are among the worst-case scenarios for geothermal wells. Importantly, in both cases, the redundant safety features of the wellbore design prevented any groundwater contamination. In the RRG-2 well, although the production casing failed, the surface casing did not, preventing contamination of the groundwater. In the RRG-7 well,

although the surface casing failed, the production casing did not, again preventing any contamination of the groundwater (GRG 2017). So, despite both wellbore failures being significant, no indication of groundwater contamination has been observed in any of the surrounding monitoring wells.

3. Long Valley Caldera, California

The Long Valley caldera is located in California on the eastern slope of the Sierra Nevada mountains (Figure 5). Within the caldera sits the Casa Diablo geothermal field, about three miles east of the town Mammoth Lakes. Initial geothermal exploration wells were drilled in the 1950s and 1960s by Magma Power Company. In addition, 11 temperature gradient test wells were drilled by the U.S. Geological Survey (USGS) to better understand the geothermal potential of the area (Sorey et al. 1978). Several more geothermal exploration wells were drilled in the 1970s and 1980s, leading to the construction of the first 10-MW binary power plant in 1985. Two more 15-MW binary power plants followed in 1990, giving the geothermal field, also known as the Mammoth complex, a combined capacity of 40 MW (Campbell 2000). The Mammoth complex is currently owned by Ormat Technologies, Inc. (Ormat), which has plans to add another 40 MW of geothermal capacity in 2020 (Howle et al. 2019).

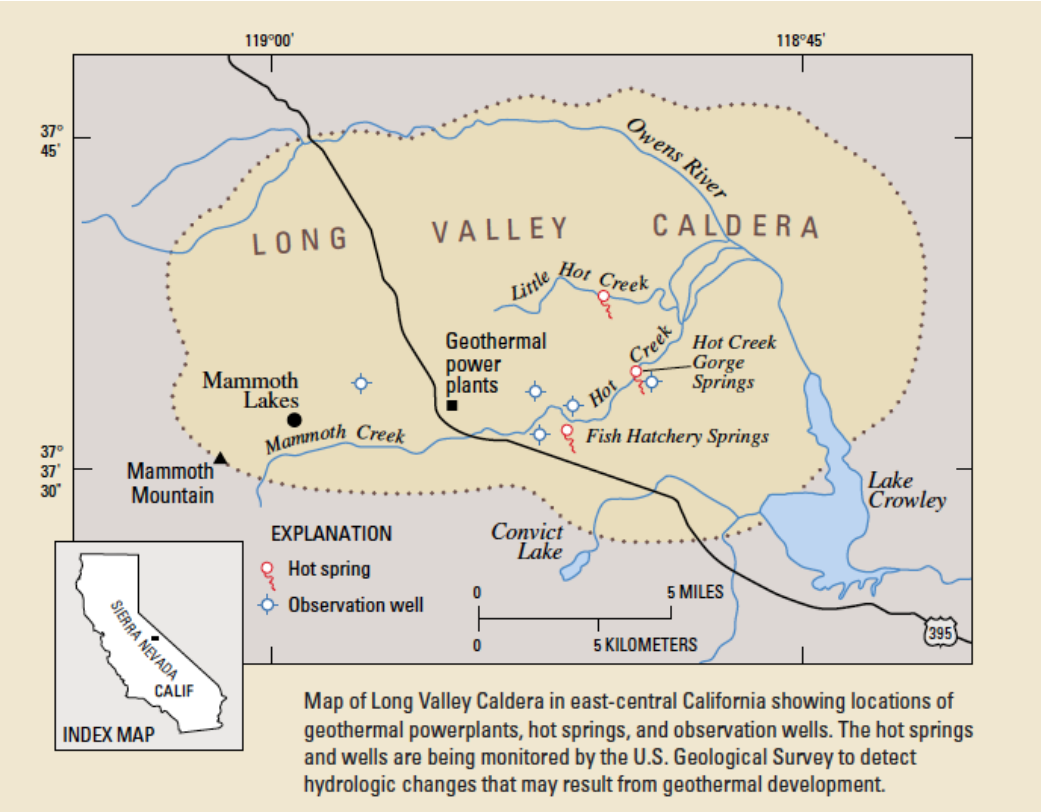

Figure 5. Map of Long Valley caldera (Duffield and Sass 2003).

This geothermal system has been studied extensively since drilling in the area began. All evidence points to a scenario in which the geothermal reservoir is charged by precipitation on the caldera's western rim. As the geothermal reservoir is heated, the geothermal water flows upward

and eastward into the Casa Diablo geothermal well field. The geothermal water is gradually diluted by groundwater as it continues its eastward flow and is finally discharged from a series of springs on the eastern side of the caldera (Howle et al. 2019).

Because of increasing demand on the region's hydrologic resources—both from the geothermal plants and the growing resort town of Mammoth Lakes—the Long Valley Hydrologic Advisory Committee (LVHAC) was created in 1987. The LVHAC is composed of representatives of federal, state, county, and local government agencies as well as Ormat. It oversees the hydrologic monitoring of geothermic features such as fumaroles, hot springs, streams, and wells. The monitoring program is designed to detect changes that could be caused by geothermal production or local land development (Figure 6). The committee would then advise permitting agencies of the changes and possibly recommend mitigation actions to minimize or reverse the changes. The advice and recommendations of the LVHAC are not legally binding, but they inform the regulatory decisions of the U.S. Forest Service, BLM, and the Mono County government (Duffield and Sass 2003).

Since 1987, the USGS has been responsible for conducting the LVHAC's hydrologic monitoring program. The program consists of monitoring fluid pressure, flow rates, water levels, water chemistry, and temperature in the shallow cold-water and deeper geothermal aquifers in and surrounding the Casa Diablo geothermal field (Howle et al. 2019). In addition, Ormat collects similar data from their production and injection wells and daily pressure measurements from a series of monitor wells. The Mammoth Community Water District also monitors the water chemistry of their water wells (Figure 7). Results from these monitoring programs are reported to the LVHAC on a quarterly basis (Duffield and Sass 2003). Together, these monitoring programs provide a comprehensive picture of the condition of the geothermal and groundwater aquifers in the Long Valley caldera.

The shallow nonthermal groundwater system has a very different temperature and fluid chemistry than the deeper, hotter geothermal system. It is also found in shallower depths and different geologic formations. The nonthermal groundwater in the Mammoth groundwater basin is colder (45–48°F), shallower, lower in total dissolved solids, and found primarily in geologic layers consisting of glacial till, basalt, and or alluvium/colluvium, all of which overlie the geothermal reservoir. These layers are separated from the hotter geothermal systems by low-permeability layers of hydrothermally altered Early Rhyolite in the western and south-central part of the caldera, near Mammoth Lakes and the Casa Diablo field. This separation does not exist in the southeastern caldera, where the geothermal system and shallow groundwater systems mix before discharging at the surface in springs and creeks (EGS 2012).

The chemistries of the shallow groundwater and deeper geothermal fluids are quite different, so evidence of mixing should be readily apparent in monitoring wells. To date, samples from shallow groundwater wells in the Mammoth Groundwater Basin have not shown any chemical evidence of mixing with geothermal water. Well P-17 (Figure 7) exhibits very low concentration of chloride and could indicate a very small (1%–2%) constituency of geothermal fluid; however, that chloride concentration is small enough to be near the minimum level of accurate reporting of laboratory measurements, which renders it inconclusive. In addition, well P-17 is not near any geothermal wells, potentially indicating that if there is any geothermal mixing, the source is the deeper geothermal aquifer (EGS 2012).

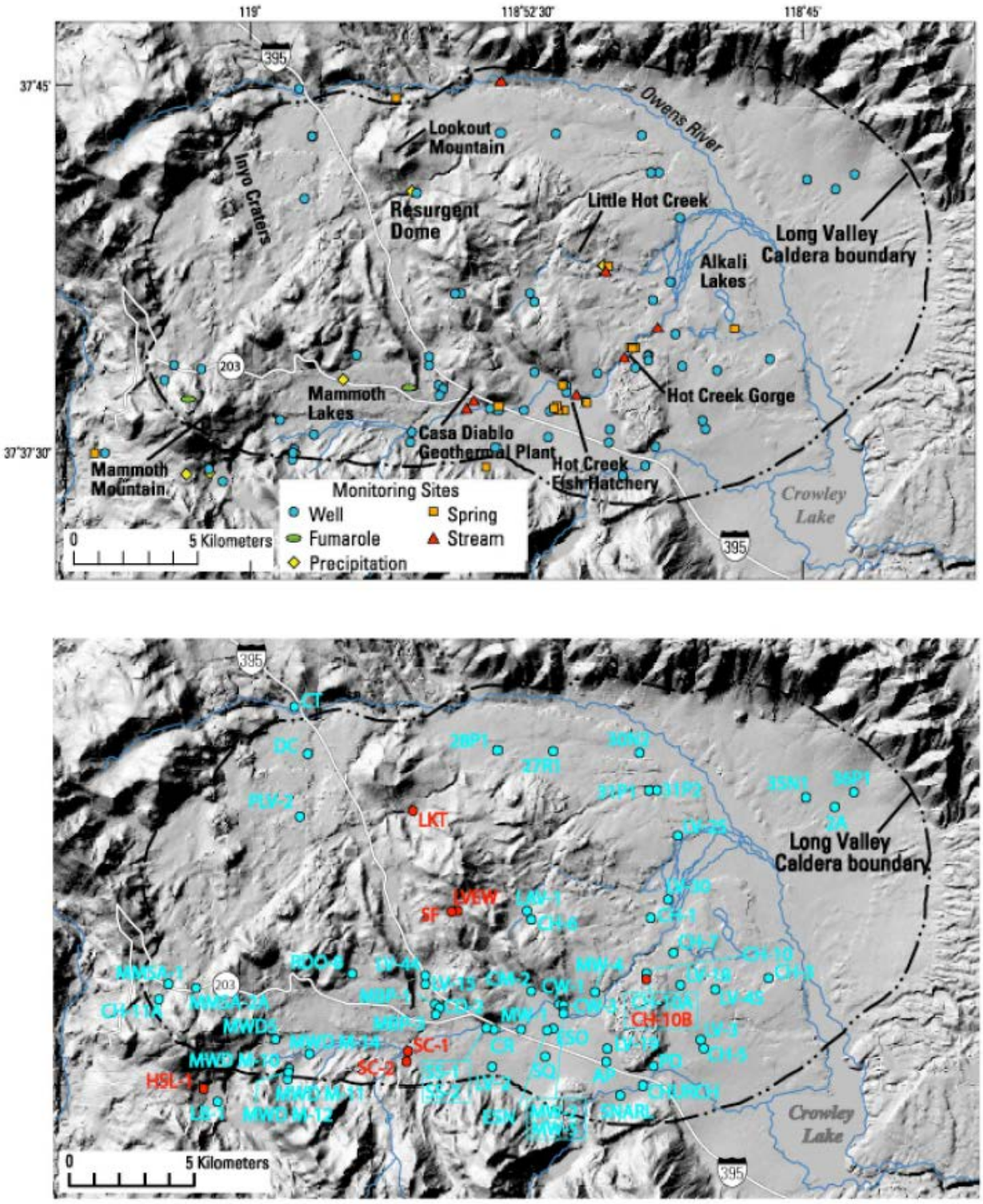

Figure 6. USGS hydrologic monitoring points in Long Valley (EGS 2012)

Results from working fluid leaks from the power plants also indicate no groundwater contamination by deeper geothermal water. The power plants in the Mammoth field use isobutane as the working fluid, which is a low-solubility nontoxic gas that easily vaporizes at

atmospheric conditions (Wilhelm et al. 1977). Leaks, while rare, have been used as an inadvertent tracer test when the fluid is injected into the geothermal system below the shallow groundwater (Evans et al. 2004). To date, isobutane has been detected in geothermal wells, fumaroles, hot bubbling pools, and hot springs, but not groundwater wells. In short, it appears that there is a high degree of lateral continuity within the geothermal system, but there is no evidence that the geothermal system is contaminating the shallow Mammoth groundwater basin (EGS 2012).

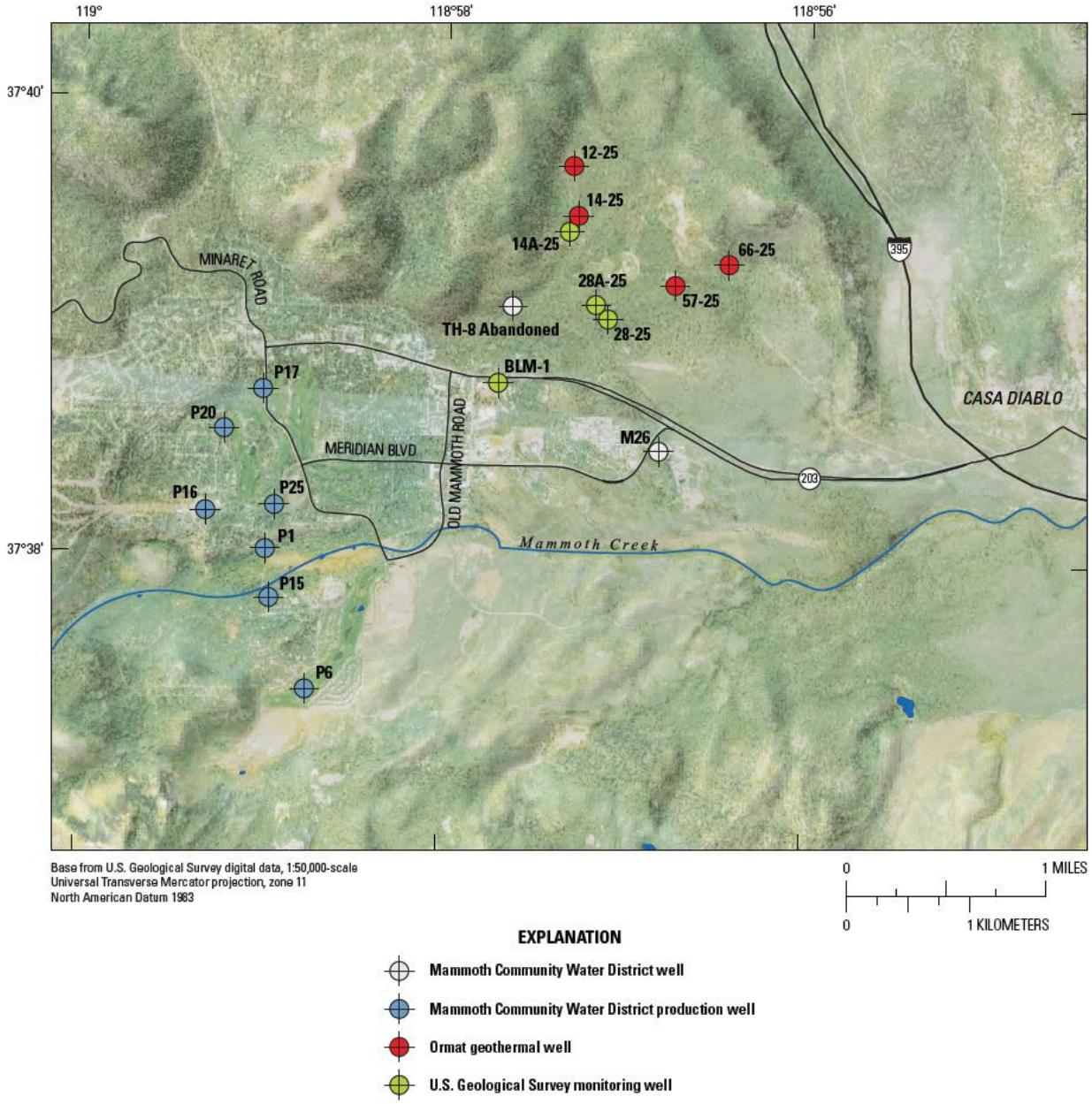

Figure 7. Mammoth Lakes area, California, showing the location of monitoring sites and other features (Howle et al. (2019).

Although the groundwater has not been contaminated, there have been some negative consequences of geothermal production, mainly expanding tree-kill areas. Casa Diablo binary

power plants allow most of the produced geothermal water to be conserved and reinjected, but the injection depths are deeper than the production depths. Reinjecting the geothermal water into a deeper formation prevents thermal breakthrough, but also results in a reduction of pressure support in the geothermal production zones. This reduction has led to increased boiling in the geothermal system and increase up-flow of steam, producing areas of hot ground on the surface. Since two additional production wells (57-25 and 66-25, Figure 7) were added in 2006, the areal extent of thermal ground, vegetation die-off, and carbon dioxide (CO2) emissions has enlarged significantly (Bergfeld et al. 2015). At the same time, hydrogen sulfide (H2S) emissions were found at the nearby Shady Rest fumarole (Howle et al. 2019). The presence of this gas may signal an increased drawdown of water levels by the nearby geothermal production wells.

4. Steamboat Springs, Nevada

The Steamboat Springs geothermal field is located approximately nine miles south of Reno, Nevada (Figure 8). Historically, this area included numerous hot springs and geysers, which prompted a study of the geothermal system by USGS between 1945 and 1952. This included drilling eight wells to test the resource and better understand the system (White 1968). In 1975,

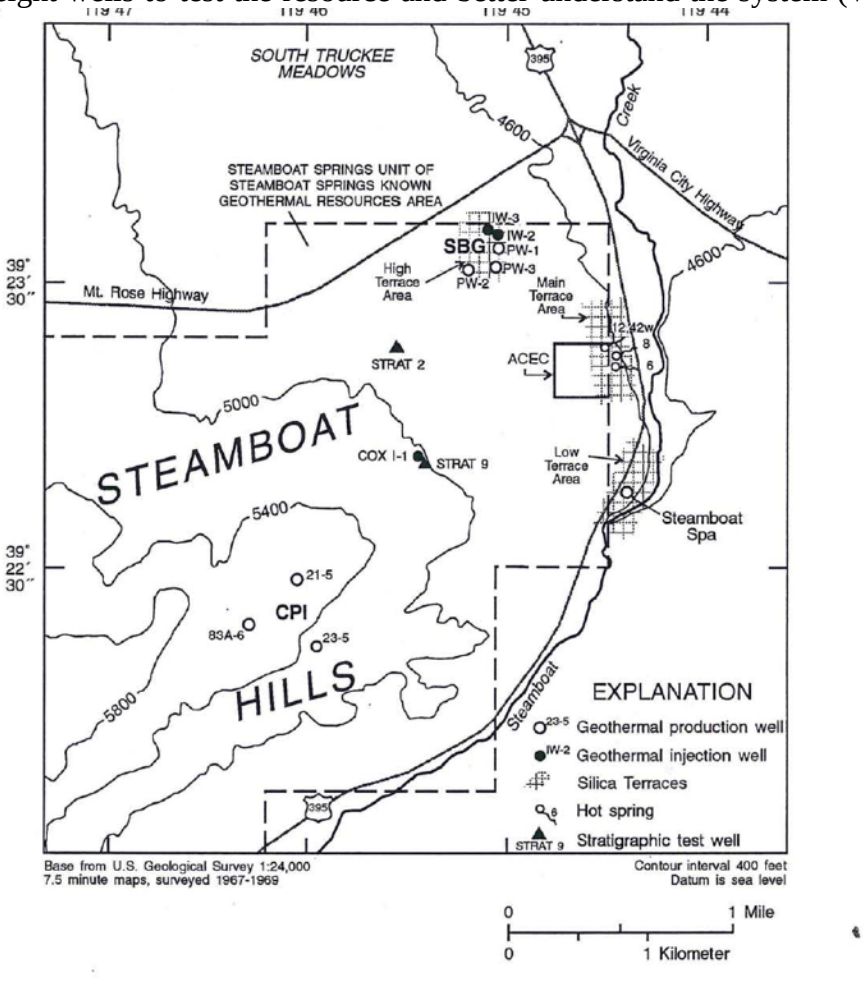

Figure 8. Location of Steamboat Springs Area of Critical Environmental Concern (ACEC) within the Steamboat Springs unit of the Steamboat Springs KGRA, which includes the Caithness Power, Inc. (CPI) and SB GEO, Inc. (SBG) geothermal well fields (Sorrey and Colvard 1992).

delineation of the Steamboat Springs Known Geothermal Resources Area prompted the exploration for and development of geothermal resources by both petroleum and geothermal companies such as Phillips Petroleum, Chevron, Caithness Power, and Ormat (Figure 8). Out of concern for the geothermal features in the area, a 40-acre plot of public land encompassing the majority of the geologic features was designated an Area of Critical Environmental Concern in 1983 by BLM (Figure 8) (Sorey and Colvard 1992).

In March 1986, Caithness Power, Inc. constructed and began operation of a flash-type geothermal power plant in the field (Figure 8). In January 1987, a binary power plant owned by SB Geo, Inc. began operation near the Area of Critical Environmental Concern (Figure 9) (Collar and Huntley 1990). There have since been six more binary geothermal plants built in the Steamboat Springs field, and the entire complex is now owned by Ormat (Sorey and Spielman 2017).

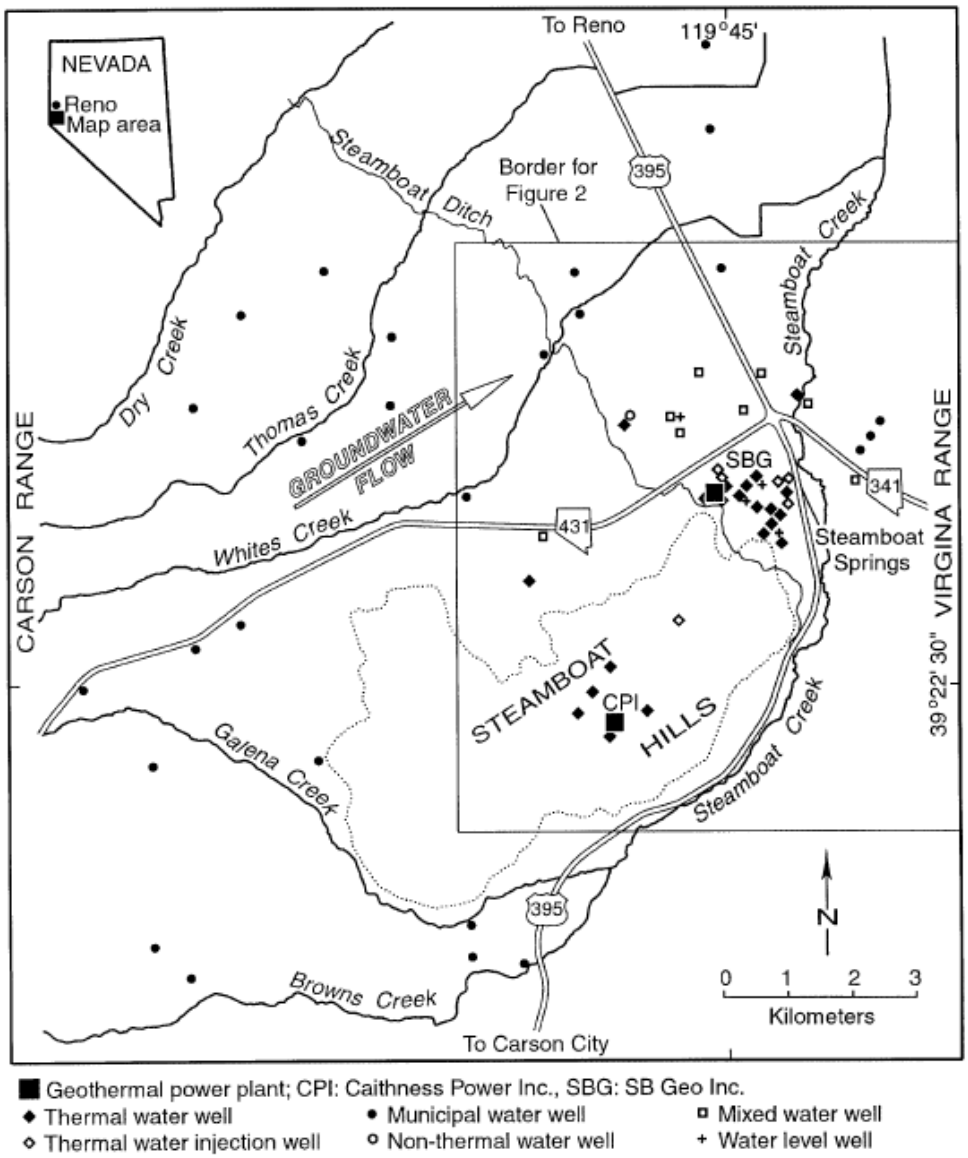

Figure 9. Location map of the Steamboat Hills area, Nevada (Skalbeck et al. 2002).

Historically, hot springs and geyser activity in the Steamboat Springs field was second only to Yellowstone National Park in the continental United States. However, geothermal activity began to decline in the Area of Critical Environmental Concern in late 1986, soon after Caithness Power, Inc.'s flash-type geothermal plant had begun operation. As a result, BLM commissioned a study of the Steamboat Springs field by USGS and San Diego State University. To meet study objectives, the following data was collected and analyzed: a history of hot spring and geyser activity, aerial photography, geologic mapping, barometric pressure, precipitation records, stream discharge and chloride concentration measurements, water level measurements in hot spring vents, and water level and pressure measurements in observation wells in the vicinity of the springs and geothermal well fields. After SB Geo, Inc's binary plant came online in early 1987, geothermal activity continued to decrease until all spring and geyser activity ceased in early 1988. The cessation of activity coincided with a decrease in geothermal water levels in nearby observation wells. The authors of the study (Collar and Huntley 1990) believed that the decline in water levels was largely caused by the net water loss from the flash plant.

A few years later, Sorey and Colvard (1992) showed that the principal factor inducing the reduction in geothermal activity was a reduction in shallow nongeothermal groundwater levels caused by increased domestic consumption and decreased groundwater recharge associated with successive years of below-average precipitation. Sorey and Colvard estimated that the shallow groundwater system water level decline caused 80%–95% of the geothermal activity decline, with the flash plant and associated geothermal water use responsible for the remaining 5%–20% decline. The binary plant was thought to have a minimal effect, as nearly 100% of the geothermal water used for power is reinjected (Sorey and Colvard 1992). Interestingly, although geothermal water levels have declined in places, the total geothermal water discharge from the Steamboat geothermal field into Steamboat Creek to the east and northeast of the field does not appear to have changed significantly over the past 60 years (Sorey and Spielman 2008).

Although geothermal water production likely contributed to the cessation of hot spring and geyser activity, it does not appear to have affected the shallow groundwater quality. Groundwater monitoring in Steamboat Hills began in 1985, with a large number of monitoring wells installed over a wide area in the Steamboat Hills field (Figure 10). 21 of these wells, representing shallow groundwater, geothermal, and mixed waters, were analyzed for variations in boron (B) and chloride (Cl) concentrations, water levels, and temperature. The geochemical data indicate that although there is some mixing between the geothermal reservoir and the shallow groundwater system, it is a result of fault-controlled groundwater flow and not geothermal well operations. An analysis of B versus Cl values over time shows strong mixing along prominent north-trending faults that appear to connect the geothermal reservoir to the groundwater aquifer (Figure 10). A study of temperature and water level data versus time indicates that the primary causes of mixing are: 1) lowering of shallow groundwater levels because of increased municipal groundwater production; 2) lowering of shallow groundwater level because of a reduction in recharge via decreases in precipitation and irrigation runoff; and 3) to a lesser extent, reinjection of geothermal waters into geothermal reservoir areas that may have greater connectivity to the groundwater aquifers than the production areas (Skalbeck et al. 2002).

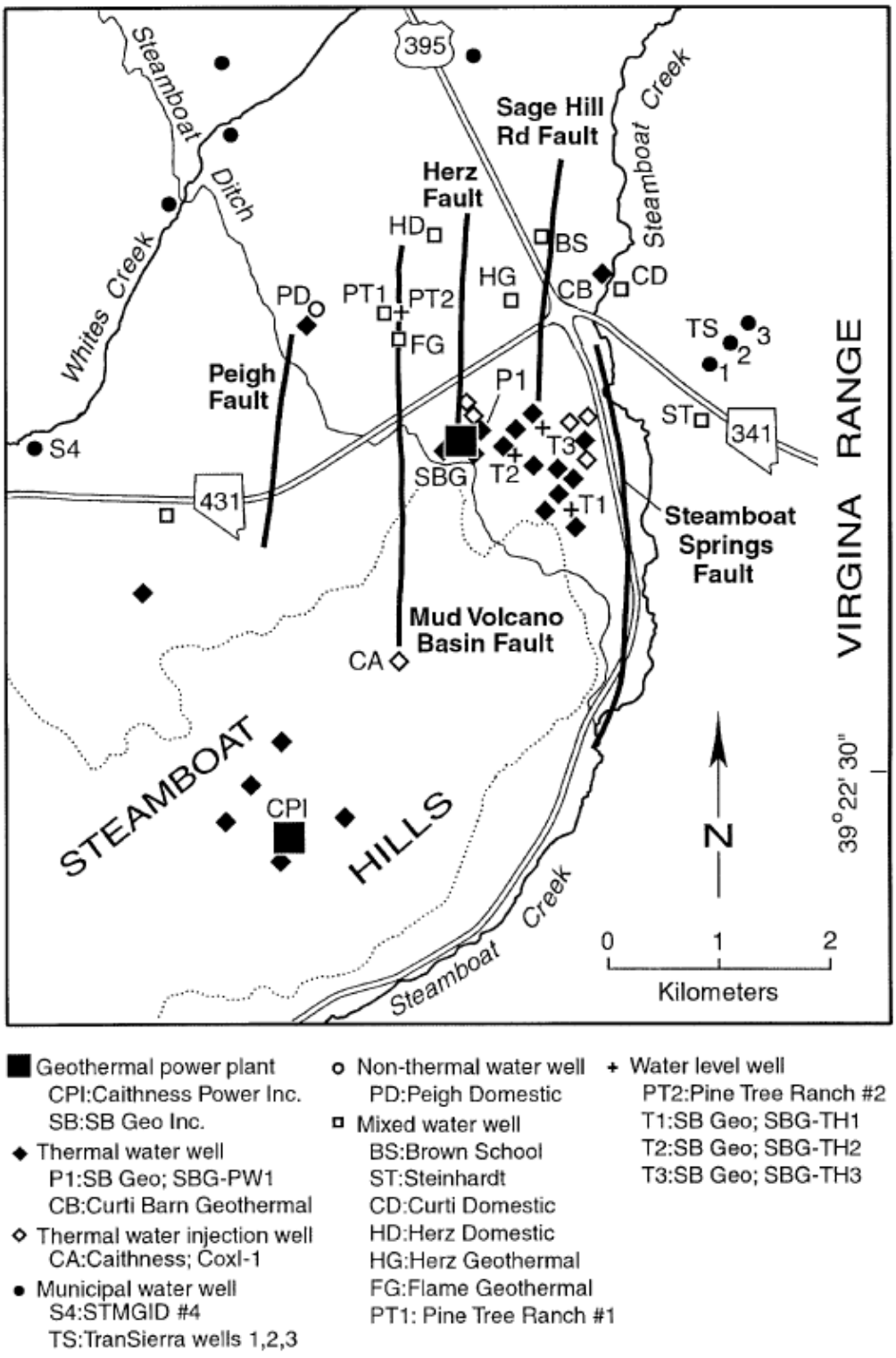

Figure 10. Study area location map. Geothermal, nonthermal, mixed water, and water level wells and hydrologically significant faults referenced in this study are labeled (Skalbeck et al. 2002).

In addition, there have been two wellbore failures, neither of which have appeared to contaminate the local groundwater. The Cox I-1 well (Figure 11), which originally received all of the Steamboat Hills power plant injection, was abandoned by Ormat in 2006 because of a shallow casing leak. Ormat replaced it with the 64A-32 well (Figure 10), which itself developed a shallow casing leak in 2006, and was shut-in for three months while repairs were made. During repair work, Ormat implemented a program of weekly sample collection and pressure measurement in the surrounding monitor wells. The data from this period showed no ill effects from the casing leak (Klein et al. 2007).

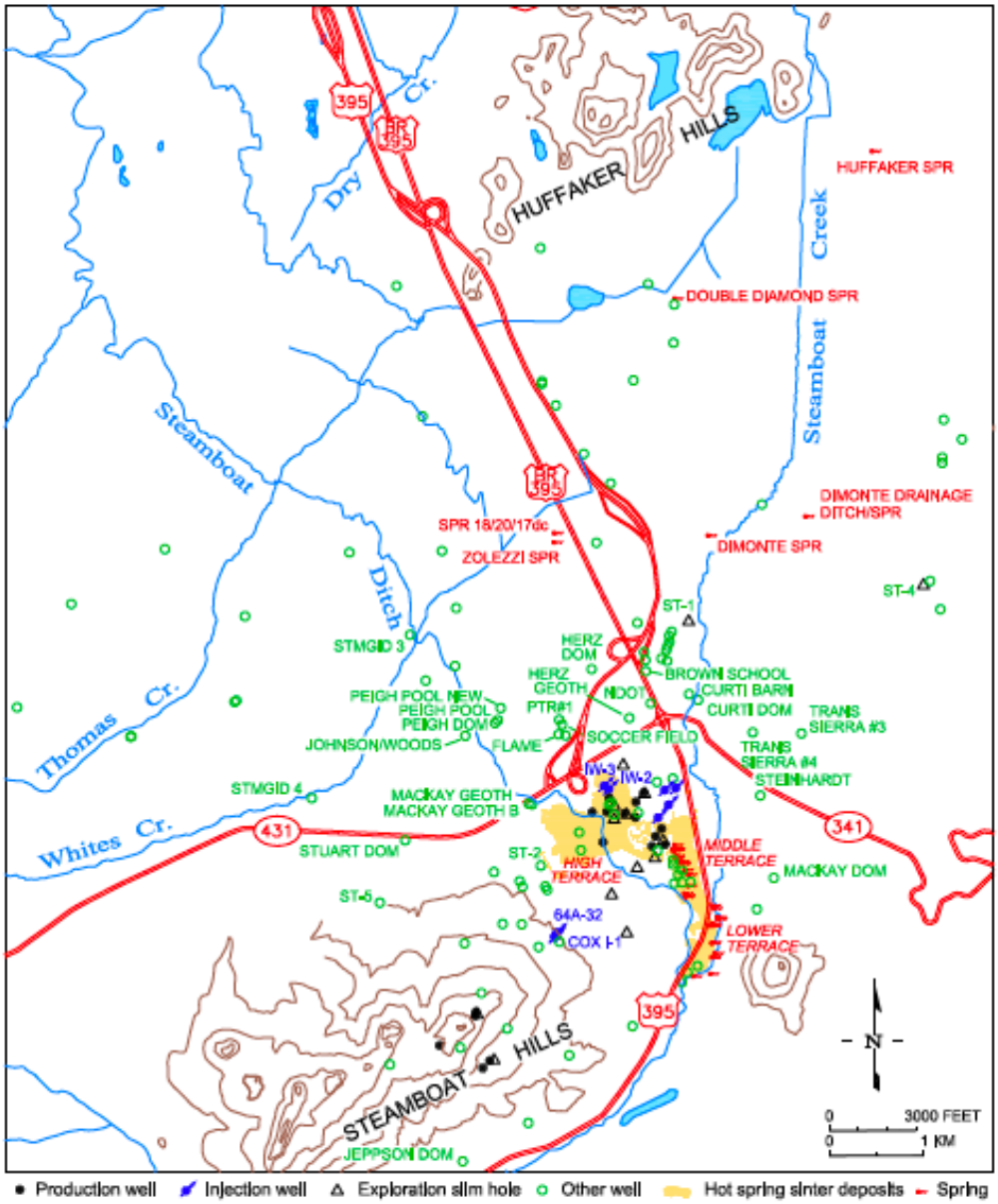

Figure 11. Map showing production, injection, and monitoring wells in the Steamboat geothermal field (Klein et al. 2007).

5. Conclusion

To date, there is no recorded instance of geothermal development contaminating shallow groundwater in the United States. Although wellbore failures can result in casing leaks and/or blowouts, these incidents are relatively rare and, to our knowledge, have never polluted local drinking water. There are some geothermal fields where the surface groundwater and geothermal resource mix in the subsurface, but this appears to be a natural occurrence. In geothermal fields where mixing occurs, a robust monitoring program should be maintained for data collection and study.

It appears likely that geothermal operations are affecting surface geothermal expressions in some fields. However, the extent of these effects is difficult to quantify because these areas have also been subject to increases in domestic consumption of groundwater and periods of drought.

Acknowledgements

This work was supported by U.S. Department of Interior Bureau of Land Management's Renewable Energy Coordination under contract L16PG00068 with the National Renewable Energy Laboratory (NREL). NREL is a national laboratory of the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy operated by the Alliance for Sustainable Energy, LLC. The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government.

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