GRC *Transactions*, Vol. 31, 2007

Resource Exploitation at Steamboat, Nevada: What it takes to Document and Understand the Reservoir/Groundwater/Community Interaction

Christopher W. Klein[1], Stuart Johnson[2], and Paul Spielman[2]

[1]GeothermEx, Inc., Richmond CA, USA
[2]Ormat Nevada, Reno NV, USA
cwk@geothermex.com • SDJohnson@ormat.com • pSpielman@ormat.com

Keywords

Steamboat, geothermal, Nevada, reservoir discharge, monitor wells, Na/K temperatures, injection permits, groundwater, conceptual model

ABSTRACT

Under operating permit regulations, groundwater wells near the Steamboat geothermal field have been monitored since the early 1980s to detect changes that may be caused by injection of spent geothermal fluids back into the reservoir. The phreatic aquifer to the NW, N and NE of the geothermal field is underlain by a native plume of variably cooled and chemically re-equilibrated outflow from the geothermal system. There is evidence that these two aquifers are separated by an aquitard, and the hydraulic head decreases downwards, yielding downflow from the phreatic zone into the geothermal zone except when the phreatic zone suffers extreme drawdown (decreased recharge or increased groundwater production) and the head reverses. Chemical changes that include increasing (and decreasing) Cl have occurred at groundwater monitor wells, but in all cases these appear to be the result of changes in the hydraulic head of the groundwater aquifer. Subsurface discharge from the Steamboat reservoir occurs principally in the N and NW, there is some evidence that this discharge occurs across relatively broad low permeability barriers (not within a few confined pathways), and there is evidence that the rate of discharge from the geothermal reservoir has decreased since the onset of commercial production. Monitor wells just N of the geothermal field appear to be more closely connected to deep upflow and to Upper Steamboat than to waters of Lower Steamboat. Ormat is now making improvements and additions to Steamboat which are intended to take the electricity generated from ~47 MW to 76 MW. This is enough to supply the households of the greater Reno area, and all but ~10 MW are essentially emissions-free. To ensure the comfort of the community with this expansion, it is important to continue to study and monitor the interaction of reservoir and groundwater. Better understanding of the interaction is being sought through a planned tracer test, re-design of the monitoring program, and drilling a new monitor well (or wells).

Introduction

For more than 60 years there has been considerable interest in the Steamboat geothermal system, on the part of government and academic research, small-scale resort/spa development, and larger-scale development for generating electricity (see References). The U.S. Geological Survey (USGS) carried out detailed studies from the late 1940s into the 1960s. Commercial exploration of the resource and surroundings for its electrification potential started in the late 1970s. Power generation started in January 1986, when the Steamboat 1/1A power plant (~7 MW) came on-line in the northern (“Lower”) Steamboat area. Power generation from the southern (“Upper”) Steamboat area started a year later (~10 MW), and Lower Steamboat was expanded by an additional ~30 MW when the Steamboat 2/3 power production system came on-line in January 1993.

Numerous commercial entities (legal and financial) have been involved in this history of exploration and development. In the simplest terms: (a) initial large-scale commercial exploration was carried out by Phillips Petroleum Co. (Lower Steamboat) and Chevron Resources Co. (Upper Steamboat); (b) initial development of the lower area was carried out by a division of Ormat, which sold its interest there to Far West Capital (Far West) in 1990; (c) the Yankee-Caithness Joint Venture Limited Partnership (YCJVLP) developed the upper area, and; (d) both Far West and YCJVLP sold their interests to Ormat Nevada, Inc. (Ormat), during 2004.

Since its purchase of the entire geothermal field, Ormat has started to carry out improvements and additions to the power plants and wellfield. When complete by the end of 2007, total electricity generation is expected to be about 76 MW, enough to supply all of the residential needs of the greater Reno area. Except for the gas and condensate loss at a cooling tower in the Upper Steamboat area, the power generation is entirely a

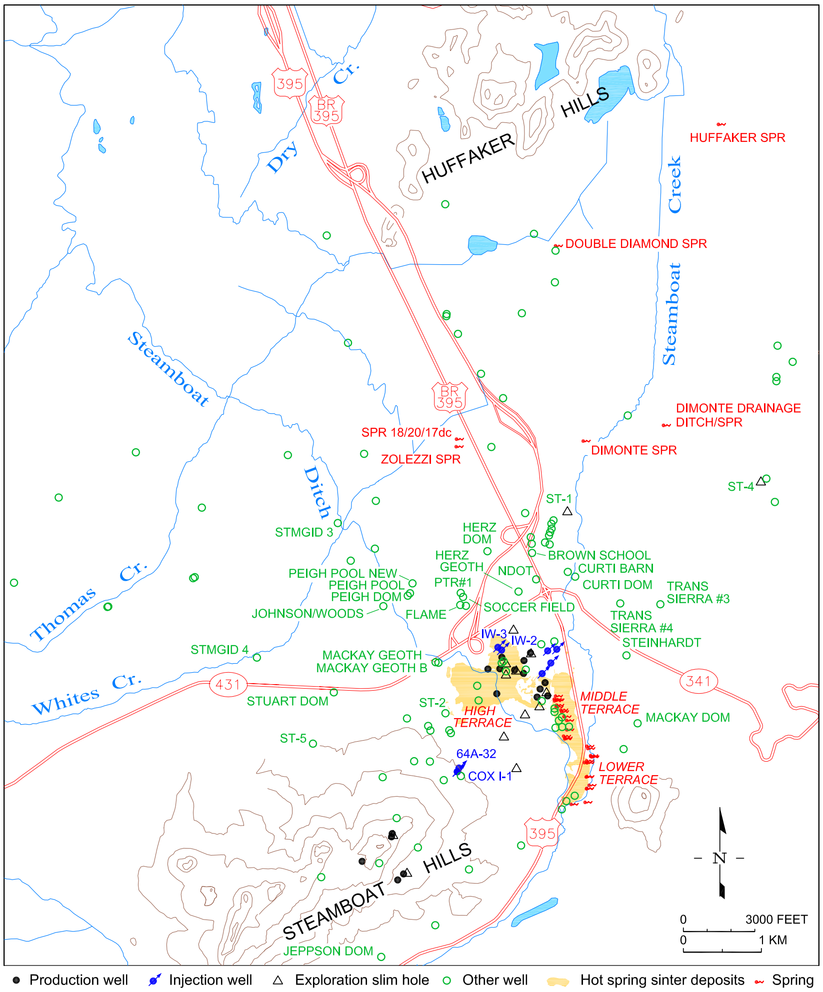

Figure 1. Map showing production wells, injection wells, commercial monitor wells, exploration wells, and the historically most-significant groundwater monitoring wells in the Steamboat geothermal field and adjacent S Truckee Meadows area.

closed-loop system, with no emissions of any sort to the ground surface or atmosphere.

Production of geothermal electricity at the Steamboat reservoir thus depends upon injecting cooled geothermal production waters back underground. This injection is subject to certain permits which have been issued by the Nevada Division of Environmental Protection (NDEP, Carson City NV) to the historic operators of the geothermal field, and now to Ormat. These permits require that groundwaters surrounding the geothermal area be monitored, to detect and investigate any effects of the geothermal injection activities. The monitoring program comprises periodically measuring water level and collecting and analyzing water samples at certain groundwater wells outside the commercial reservoir zone, and at production wells, injection wells and monitor wells within it (Figure 1). The monitoring has been done continuously since about 1984.

The injection wells covered by these permits comprise Cox I-1 (since abandoned) and 64A-32 (replacement), which receives all Upper Steamboat injection, and several injection wells in Lower Steamboat (see Figure 1). In the interest of long-term reservoir management, injection at the Cox I-1 / 64A-32 site is designed to be deep (well below Lower Steamboat production), and Cox I-1 was abandoned when discovered to have a shallower casing leak. During November 2006 a shallow leak also developed in 64A-32. This resulted in a 3-month-long shut-in of Upper Steamboat while the well was repaired, and during this period a program of weekly sample collection and downhole pressure measurement at a few of the monitor wells was carried out. (The initial chemical data from this period showed no effect of the shut-in and the pressure data were not yet available at the time this document was prepared.)

The groundwater monitoring program has experienced irregularities and discontinuities caused by the fact that almost all of the wells in-use have been privately-owned. (Municipal water supply wells have not been drilled close to the geothermal field because groundwater in this area is contaminated by natural (pre-exploitation) subsurface discharge from the geothermal system (more below).) Over time, many of the privately-owned groundwater wells eventually changed ownership, with subsequent denial of access. Others suffered mechanical problems which forced abandonment. At some sites it was possible to substitute an alternate pre-existing well, while at others there were no alternatives. At several sites there was one pumped well used for water sampling, and an adjacent idle well was used for water level measurement. Rampant commercial and housing development in S Truckee meadows and along the Mt. Rose highway has further complicated the issue.

Accordingly, and because Ormat would like to increase production and injection, NDEP has requested Ormat to re-design the groundwater monitoring program and to review the historic groundwater monitoring data to assist this process. Ormat is also planning (June 2007) to drill new monitor wells as needed, to be located on public lands and administered in such a way that future access should not be a problem. This report represents a study of the historic data, conducted on Ormat's behalf by GeothermEx, Inc. (GeothermEx), and further refined by GeothermEx and Ormat.

To accomplish this task in the most comprehensive way possible, it was necessary to compile chemical and water level data from various sources into a single database (MS-Access) which could be vetted thoroughly to achieve consistent formatting, remove errors and resolve historic uncertainties in the identities of many of the data points. The sources used have included spreadsheet files of production, injection and monitoring data separately compiled by Far West and YCJVLP, water level and chemistry records obtained from the Washoe County Department of Water Resources (DWR), and historic well and spring data included in numerous publications by the U.S. Geological Survey and others. Earlier studies of the groundwater and geothermal systems by GeothermEx and by other consultants to the geothermal operators and to DWR have also been consulted in detail (see References).

The result is a set of 197 data points (wells, springs, other point sources) that is represented by about 11,000 data re-

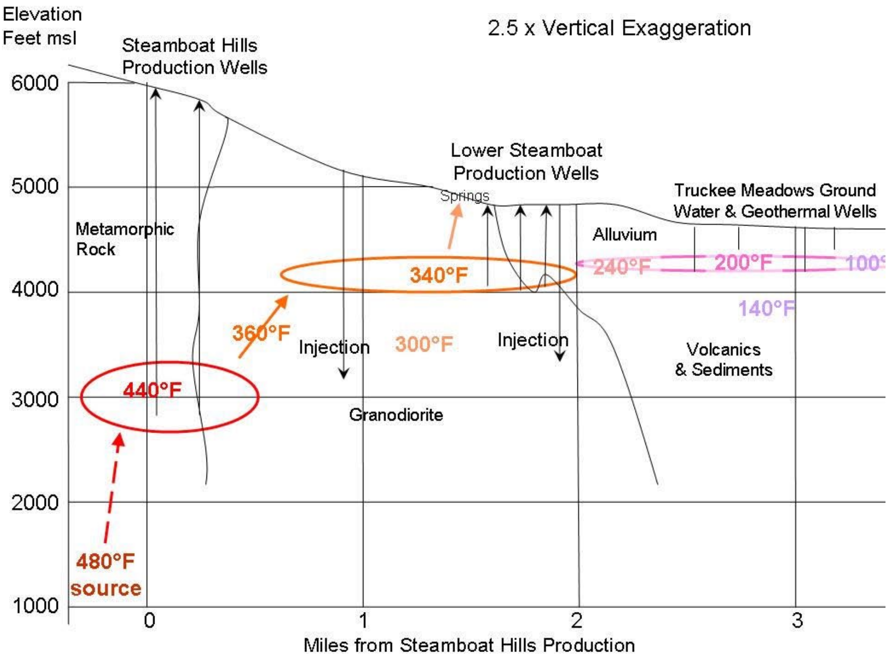

Figure 2. Example of detailed monitor well summary graph, showing data from three different wells.

cords (water level measurements and chemical analyses), approximately one-half of which are believed to be partial duplicates. As of February 2007, the database contained up-to-date chemical analyses and water level measurements until November 2006.

To facilitate detailed vetting and analysis, much of the information in the database has been illustrated on a set of detailed summary graphs, an abstracted example of which is shown as Figure 2 (the original graphs also include well completion profiles plotted against elevation). While densely illustrated graphs such as these are initially daunting, they contain a wealth of information that can be studied simultaneously. Thorough study of these graphs, of associated information from the monitor wells, and of previous geologic, geothermal and hydrologic studies at Steamboat has greatly improved our understanding of the nature of discharge from the Steamboat hydrothermal system and its interaction with surrounding groundwater.

In general, there is no compelling evidence that commercial exploitation of the geothermal system (and injection in particular) has affected the outlying groundwater system. Our confidence in this conclusion is high, but we also have a fairly good idea of what we don't know, and what is needed to continue the monitoring program into the future. Key findings are as follows.

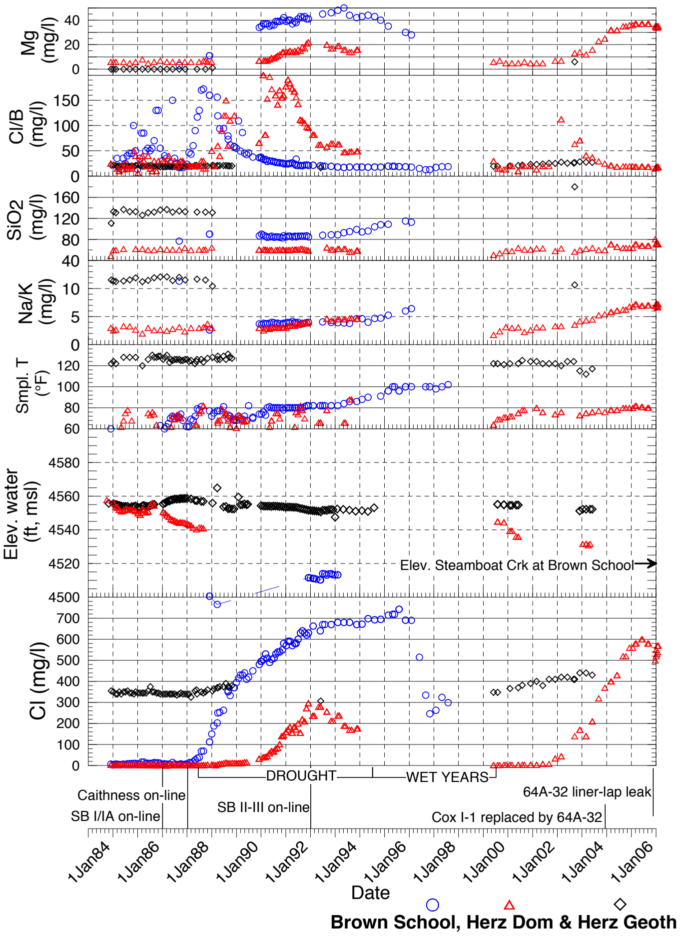

Figure 3. S to N cross-section through the Steamboat geothermal system and discharge zone.

Results

Conceptual Model of the Resource

The Steamboat reservoir is contained within metamorphic rocks of sedimentary and volcanic origin, and within granitic rocks that long-ago intruded the metamorphics. This complex is locally intruded and overlain by young (roughly 1 million-year-old) volcanic rocks, the deep roots of which are probably the heat source for the geothermal system. USGS studies have concluded that the geothermal system has been present for at least 3 million years, but an exact local heat source has never been determined.

In broad outline (Figure 3), hot water at about 480°F enters the reservoir deep beneath Upper Steamboat, on a steep ascent from E to W and carrying dissolved chloride (Cl) at about 820 mg/l. From there, the hot water flows to the NE at 4,000 to 4,200 ft msl, through the central part of the field and into Lower Steamboat, where the depth to production is only 600-800 ft. It finally rises to discharge at historic hot springs and into a shallow subsurface aquifer at a depth of about 200 ft (4,300 ft msl) that underlies Truckee Meadows and the lower slopes of adjacent alluvial fans.

In the Lower Steamboat area the resource is a horizontal layer of hot water that flows NE- and N-ward in a reservoir of fractured granodiorite. At most locations this shallow zone is effectively a tongue of hot water centered at about 4,100 ft msl, with sharply lower temperatures above (higher elevations are behind casing in most of the production wells) and slightly lower temperatures below (see Figure 4). The granodiorite of the aquifer lies beneath a layer of younger volcanic rocks (several distinct types and formations) which, in turn, are overlain by recently deposited sands, gravels and clays of varying thickness. The younger volcanic and sedimentary cover thickens to the N beneath Truckee Meadows.

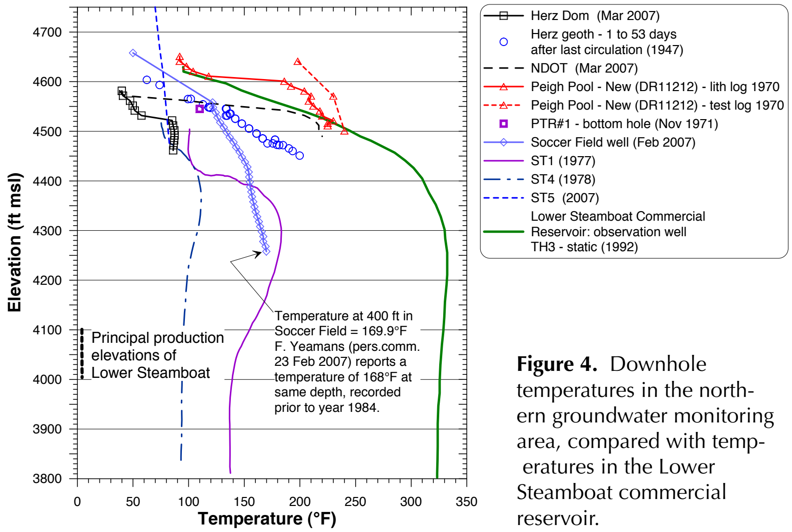

Figure 4. Downhole temperatures in the northern groundwater monitoring area, compared with temperatures in the Lower Steamboat commercial reservoir.

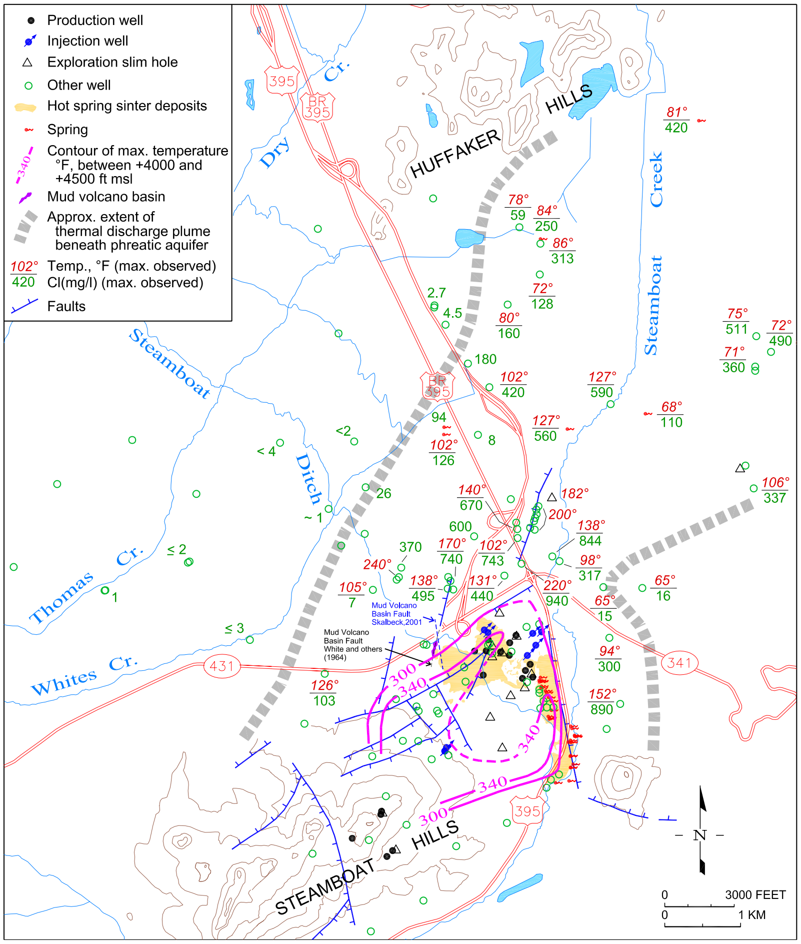

Figure 5. Map showing major faults and fracture zones, temperature distribution in the Lower Steamboat area, and temperature and chlorides in the discharge zone to the N.

Fracture permeability is pervasive in the granodiorite, but apparently enhanced in the vicinities of major fracture zones along the western and eastern sides of the reservoir. These have a strong degree of control on fluid flow in the Lower Steamboat area, as indicated by the temperature distribution at depth on Figure 5 (maximum subsurface temperatures within the elevation interval 4,000 to 4,500 ft msl). Highest temperatures occur along the western and eastern fracture zones, and a somewhat cooler area lies in-between. The eastern fracture zone, which dips to the E and is about 500 ft wide (White and others, 1964) is also known as the Steamboat Springs fault zone.

Measured downhole pressure profiles from the wells in the Lower Steamboat area are all very similar, which indicates that the lateral pressure gradient through the reservoir is insignificant. This implies that the overall permeability in the reservoir is very high, which has been confirmed by well testing.

Discharge from the Hydrothermal System

Total discharge from the geothermal system (surface and subsurface) has been measured several times since 1955, when White (1968) first estimated 1110 gpm by using a mass balance of spring and well discharges and Cl flux into Steamboat Creek and two associated irrigation ditches, measured as far north as Huffaker Hills (Figures 1 and 5). It appears that White (1968) inadvertently double-counted one component of his estimate (Mike Sorey, personal communication May 2007), and the true 1955 value was probably 810 gpm. Measurements in the early 1970s (Bateman and Schiebach, 1975) and early 1980s (Shump, 1985), all done before large-scale commercial exploitation, confirmed that the discharge rate was at least this amount or higher (to ~1,200 gpm).

R.J. Collar repeated White's (1968) process in 1988 and estimated 500 to 540 gpm (Huntley and others, 1988) and in 1989, estimating 660 gpm (Mike Sorey, personal communication May 2007). In April 2007 Sorey again repeated the process, and measured about 550 gpm, which is at least 30% lower than before commercial exploitation began. The values of 1988 and later all represent subsurface discharge to the Creek (and ditches), as the hot springs have gone dry. It is notable that there is a 440 gpm difference between average thermal outflow before and after 1987 (when the Upper Steamboat power plant went into production), and this is only slightly less than the 500 gpm difference between Upper Steamboat production and injection, caused by evaporation at the cooling tower).

This natural discharge is best envisioned as a sort of spillage that occurs over the rim of a "tub" of fractured rock (the geothermal reservoir), within a zone of low permeability between the rim and overlying cap rock (see more below). Generally low permeability in the discharge zone(s) is required to explain the fact that hot springs at the eastern edge of the geothermal system lie at elevations higher than groundwater outside the discharge zone to the N.

Historically (until the springs dried out), about 5% of this discharge appeared at the hot springs, and 95% traveled in the subsurface, discharging from the NW, N and NE edges of the geothermal area, and thence moving northward under Truckee Meadows at a depth of about 200 ft and up into Steamboat creek at certain (poorly constrained) locations. Figure 5 shows the minimum area in which shallow dilute groundwater is underlain by water of thermal origin, and related data on chloride and temperature.

Groundwater Declines

Groundwater levels have declined since the on-set of production and injection in 1984, both above the commercial reservoir and to the NW, N and NE (Figure 6), as a result of drought, over-production and a decrease of irrigation recharge during the rapid development of the area for housing and commerce since the early 1980s.

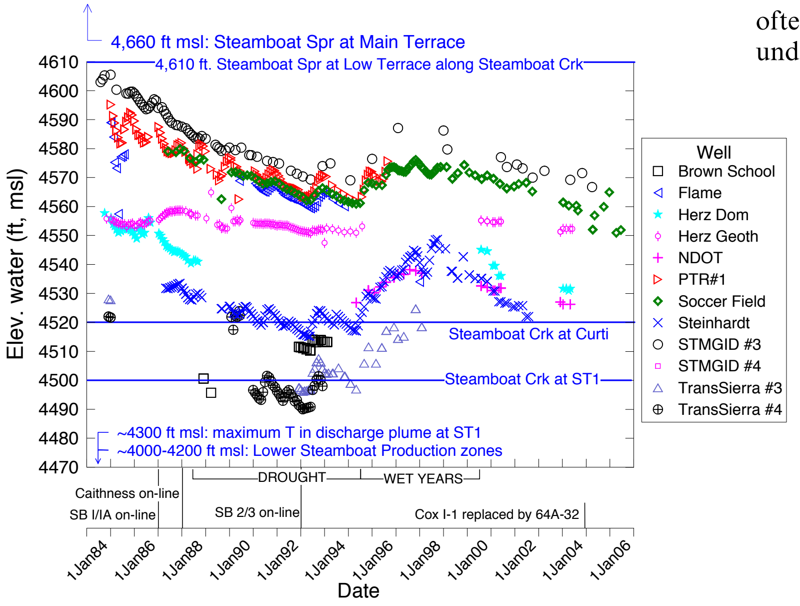

Figure 6. Water level elevations vs. time at monitor wells to the N of the Steamboat geothermal field.

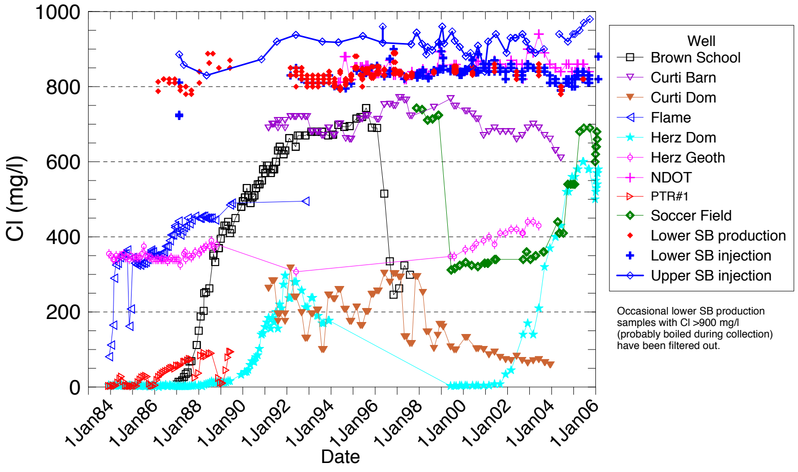

Figure 7. History of Cl in selected monitor wells to the N of the Steamboat geothermal field.

Pressures in monitor wells that penetrate into the commercial reservoir have also declined (slightly), probably due to cooling and because commercial extraction exceeds injection due to the 500 gpm evaporation of steam condensate in the Upper Steamboat cooling tower. An exception occurs around injection wells IW-2 and IW-3 (Figure 1), where a small mound of higher pressures and elevated water surface has developed during the period of exploitation. It might seem that this mound would cause an increase of discharge from the reservoir, to the N, but fluids chemistry data place this into doubt (see below).

As groundwater levels have declined, the deepest groundwater wells close to the geothermal field have shown increases of chloride (Cl; Figure 7) and changes of other chemistry (and often temperature) that indicate increased production of the underlying geothermal water. Water samples collected before 1986 and historic data on temperature, silica (SiO_2), chloride, the ratio of chloride to boron (Cl/B), magnesium (Mg) and the ratio Na/K combine to indicate that the geothermal component at most of the monitor wells has underlain the area for a long time.

There is evidence at several locations W of Truckee Meadows (Herz Geoth well, Flame-PTR#1-Soccer Field wells, Peigh wells) that the shallower groundwater zone and the deeper geothermal discharge zone are separated by an aquitard (limited vertical permeability) and that the hydraulic head in the upper zone exceeds that of the lower zone, leading to downflow (where possible), except during times of extreme drawdown in the upper zone, when the potentials may reverse. Wells drilled in the Meadows tend to be artesian.

The hottest and chemically least evolved geothermal component is found close to the northern tip of the reservoir at the NDOT and Curti wells around the intersection of highways 431 and old 395, and at the Peigh wells in the NW corner of Sec. 29 (see data on Figures 4 and 5; no deep water has been sampled at the Peigh wells, but a temperature of 240°F has been recorded). However, there have been no changes at any of these wells or any other groundwater monitor that can be confidently and unambiguously associated with commercial injection activities.

Cl/B Ratios

Cl/B in the Steamboat geothermal water is about 23 and similar values characterize high Cl warm springs and several high Cl groundwater exploration holes that have been drilled in the central area of Truckee Meadows. In contrast, samples from the Brown School and Herz Dom wells (Figure 2) both show patterns of mixing before 1995-6 with higher Cl/B water that has Cl at about 150 mg/l, which in turn may be a mixed water with one component that carries yet higher Cl and lower B. Similar waters (Cl to ~500 mg/l or higher and Cl/B at 250~1000) have been sampled from wells in the northern part of Truckee Meadows and along the eastern edge. These waters are either old Steamboat discharge which has lost B into clay minerals, or they represent a separate (and otherwise hidden) geothermal system that perhaps discharges along the eastern edge of the Meadows.

Na/K Ratios

Interestingly, even the hottest monitor wells with consistently highest Cl (NDOT at 850 mg/l, Curti Barn at ~700 mg/l) have not shown a historic increase of ion ratio Na/K (caused by cooling) that has been observed in the Lower Steamboat commercial reservoir (Figure 8).

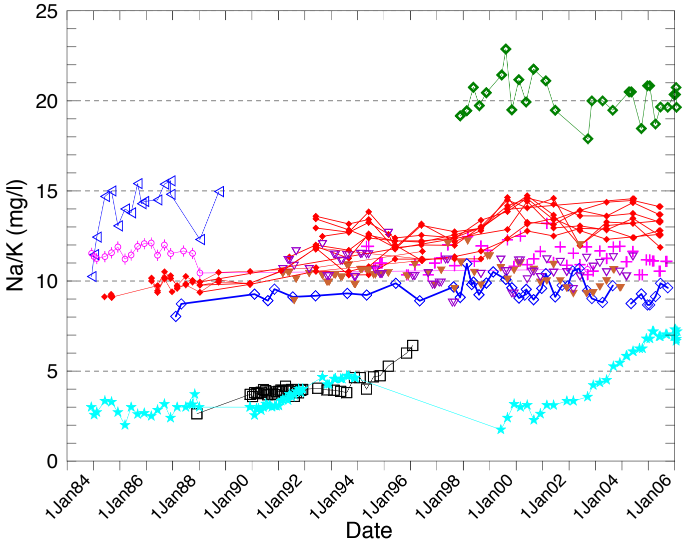

Figure 8. History of Na/K in waters of the Steamboat geothermal field and in monitor wells to the N. (See key to data points at Figure 7).

Na/K values of about 2 to 7 characterize dilute, cool groundwaters in the area and mixtures of these with small amounts of the geothermal water. Values greater than about 8 characterize the Steamboat geothermal water and are lowest at the highest temperatures and increase as the water cools as a function of ion exchange between the thermal water and feldspar minerals in the granodiorite and volcanic rocks. Upper Steamboat injection (an average of production) has a value of 9 to 10 which has remained constant over time. Lower Steamboat SB1/1A production (and therefore also injection) initially had Na/K values of 9.5 to 10, which increased to 10.5-11.5 by early 1993. At this time the SB2/3 production wells came on-line and displayed initial values of 12-13 (slightly cooler water) which subsequently declined (slightly hotter water) into the entire Lower Steamboat range of 11-13 during the late 1990s. By year 2000 the Lower Steamboat production Na/K had increased to 12.5-14.5 (average about 13) and it has remained stable since that time.

Curti Barn, Curti Domestic and NDOT all have displayed historically stable Na/K at the level which characterized Lower Steamboat in the early 1990s: *i.e. they show no sign of the cooling (increasing Na/K) that has affected the Lower Steamboat production (and injection) water*. Signs of cooling are also absent among the more limited data from Herz Geoth and Steinhardt wells.

To the NW of the field, Flame well (195 ft deep) showed values of 13-15 in the late 1980s, which indicated some cooling from the initial Lower Steamboat range, and Soccer Field (400 ft deep and 169°F at the bottom, which is relatively cool for the area) has an even cooler Na/K signature. There has been no shift of Na/K at Soccer Field, even during a recent strong increase of Cl that we attribute to excessive drawdown. At the Herz Dom and Brown School wells, Na/K has historically increased from groundwater background levels towards geothermal values during periods of increasing Cl. The increase of Na/K and Cl at Herz Dom since late 2002 projects to Na/K about 9 at 850 mg/l Cl, but also with elevated Mg, which is a signature of cooling.

Discharge Pathways

Skalbeck (2001) and Skalbeck and others (2002) studied mixing of thermal discharge waters with overlying groundwaters in the Steamboat area, and concluded that certain N-S-trending faults are "hydrologically significant" as conduits for the discharge of thermal water from the reservoir to the N. One of the faults which they describe is the Mud Volcano Basin fault (Figure 4), although the exact location of this feature is appears to be poorly constrained. Other faults on Figure 4 are from GeothermEx areal photo interpretation of mapping by White and others (1964). Another, similar fault set from Bonham, H.F., Jr. and D.K. Rogers (1983) is not shown herein, to keep the map from being too dense.

However, there is no satisfactory evidence to indicate that discrete and hydrologically significant faults or fractures (such as the Mud Volcano Basin fault and others postulated by Skalbeck and others, 2002) connect the commercial geothermal reservoir with the shallower groundwater aquifer to the NW, N and NE. A pressure-interference test conducted in 1988 failed to detect any connection between Lower Steamboat injection and two different monitor wells (PTR#1 and Herz Geothermal). Temperatures measured in the Soccer Field well (Figure 3) show that area to be relatively cool, even at depths which approach the levels of commercial production to the S. If any fault or relatively narrow and confined fault zone were to conduct fluid from an injection well N-ward to the shallow aquifer at wells such as PTR#1 and Soccer Field, these shallow wells would be affected in a matter of weeks or months, by the spent geothermal water being injected. Such a fault would also be expected to create a heterogeneous permeability distribution and affect production wells in the Lower Steamboat area in ways that have not been observed. In contrast, the horizontal permeability distribution throughout Lower Steamboat is generally quite high and uniform.

Although N-S-trending faults do transect the area, the evidence suggests that these have been sealed by hydrothermal mineral deposits (silica, carbonates) and are relatively impermeable. Except at NDOT, the levels of silica at all of the monitor wells are much lower than silica in the reservoir, which requires that deposits of amorphous silica and/or chalcedony tend to seal off their own conduits. It is clear that there are significant levels of subsurface geothermal discharge from S to N that occur to the W and E of the Soccer Field area, but it remains to be established whether this discharge flows along particular structures, or within a more evenly distributed permeability.

Sorey and Colvard (1992) found that springs of the Steamboat Main Terrace were responding to production/injection practices in Upper Steamboat, but not to production and injection at Lower Steamboat 1/1A. It follows from this that the hydrologic connection between Upper and Lower Steamboat may be limited relative to the connection between Upper Steamboat and the Main Terrace springs, and therefore that injection into Upper Steamboat is not likely to be preferentially directed to the N (unless perhaps discharging to the NW and avoiding Lower Steamboat entirely).

A fourteen day interference test was conducted in 1988, during which an upper Steamboat well was produced and the residual water was injected at Cox I-1. This caused a small (one psi) pressure *decline* at reservoir observation well ST-2, which lies just outside the SW corner of the Lower Steamboat wellfield. This response could be modeled with radial flow as the result of steam loss to the atmosphere and a reservoir conductivity-thickness of 462 darcy-ft (1380 ft^2/day). The pressure decline observed during the 1988 test has continued, and during 1989 - 2006 the water level in well ST-2 (computed from pressure) declined by about 40 ft.

The 1988 test result (high permeability) is perhaps at odds with the findings of Sorey and Colvard (1992), but also indicates that injection at Cox I-1 is not likely to be directed preferentially into the groundwater aquifer N of the geothermal reservoir.

Interestingly, and in possible connection with the findings of Sorey and Colvard (1992), the Na/K data discussed above suggest that the portion of the reservoir discharge plume that reaches the NDOT, Curti Barn, Curti Dom, Herz Geoth and Steinhardt wells is more directly fed by flow that has a deep-seated connection to Upper Steamboat than by flow connected directly to Lower Steamboat, *in spite* of the proximity of these monitor wells to the Lower Steamboat area. This flow path probably has something to do with permeability along the Steamboat Creek fault zone. Upflow beneath Upper Steamboat comes from a deep-seated source that is located somewhat to the E of the Upper Steamboat production wells, and the Steamboat Creek fault zone is also believed to dip steeply to the E. Perhaps, then, Upper Steamboat, the hot springs, and the discharge plume in the area of the monitor wells in question are all better-connected to the source of deep upwelling than is the Lower Steamboat commercial aquifer (or, at least, the portion of Lower Steamboat that has cooled).

It is not possible that the Lower Steamboat aquifer is isolated from thermal recharge and outflow, because this part of the system must be dynamic to have maintained temperature over geologic time. However, this idea (that discharge may be better-connected to the spring area than to the commercially exploited area in Lower Steamboat) merits consideration during future studies. The most important fact here is the lack of response of Na/K at the monitor wells to production-injection-produced cooling in the Lower Steamboat aquifer. This strongly implies that the cooled Lower Steamboat water is not entering the discharge plume that reaches these monitor wells.

Summary and Conclusions

Complete documentation of all monitor well data from the region to the NW, N and NE of Steamboat reservoir (not possible herein) shows numerous instances when some change of Cl concentration at some well coincides approximately in time with some change of commercial activity, such as the onset of production or a shift of injection practice. However, in all such cases there are ambiguities and extenuating circumstances (drawdown, behavior of temperature and other chemical components) that prevent concluding that any specific commercial activity has been the cause. Nevertheless, there is no question that a natural subsurface discharge from the reservoir occurs, and it is essential to continue the monitoring program, especially in light of Ormat's desire to make certain changes to and increase the amount of injection.

At the present time it appears that most discharge occurs in two areas, at the northern tip of the Lower Steamboat area (but fed by flow along the eastern edge of the system), and from the NW side (NW of the Cox I-1 location), with a relatively cool and dead zone (around Soccer Field) in-between. It appears that the rate of total discharge has decreased since the on-set of commercial production. It also appears that faults and fracture zones which are somewhat significant within the reservoir (and which control the locations of historic hot springs on the E side) tend to be sealed (probably by silica) moving to the N, and that discharge occurs less along discrete faults than within zones of more widely distributed and not very high permeability. This may be more true in the NW and less true at the N tip. Hopefully, the re-designed monitoring program, new monitoring well(s) that will be drilled in 2007, and new data collected in the future, will help to better resolve these issues.

Acknowledgements

This study would not have been possible without assistance from Mike Widmer of the DWR, who provided both digitized data and a wealth of knowledge concerning the groundwater system and its historical development and testing. It has also benefited from conversations with and feedback from Russ Land of NDEP, with Mike Sorey (U.S.G.S., retired) and the support and contributions of other individuals at GeothermEx and at Ormat.

References

Bateman, R.L. and Scheibach, R.B. (1945). Evaluation of geothermal activity in the Truckee Meadows, Washoe County, Nevada: Nev. Bur. Mines and Geology Rpt. No 25, 38p.

Bonham, H.F., Jr. and D.K. Rogers (1983). Mt. Rose Quadrangle Geologic Map. Nevada Bureau of Mines and Geology Map 48g. Scale 1:24,000.

Cohen, Phillip and Loeltz, O.J. (1964). Evaluation of hydrogeology and hydrogeochemistry of the Truckee Meadows area, Washoe County, Nevada, in U.S. Geol. Survey Water-Supply Paper 1779-S, 63p.

Felling, R. A. (2002). Groundwater Level Status, South Truckee Meadows, Washoe County, Nevada. Washoe County Department of Water Resources, July 2002. (Copies available from Washoe County

Department of Water Resources Utility Services Division, 4930 Energy Way, Reno, NV 89502.)

GeothermEx (1989). Interpretation of Geochemical Monitoring and Pressure Interference Data, Ormat Geothermal Project, Steamboat Springs, Nevada. For: Ormat Energy Systems, Inc., Sparks, Nevada. By: GeothermEx, Inc., Richmond, CA. July 1989. 17 p. plus tables and figures.

GeothermEx (2005). Potential Impact of the Development of the Galena II Project on Potable Water Wells in the Steamboat Springs Geothermal Area, Washoe County, Nevada. For: ORMAT NEVADA, Inc., Sparks, NV. By: GeothermEx, Inc., Richmond, CA, USA., December 2005.

Goranson, C. (1993). Far West Capital, Inc., Steamboat Hills Geothermal Field Lease Area Data Package. Prepared for Far West Capital, Inc. and Steamboat Development Corp., July 1993.

Huntley, D., R.J. Collar and M.L. Sorey (1988). Preliminary Report on Hydrologic Monitoring at the Steamboat Springs, Nevada, Geothermal Area. November 1, 1988. 40 p.

Nehring, N.L. (1980). Geochemistry of Steamboat Springs, Nevada: U.S. Geol. Survey Open-File Report 80-887, 61p.

Skalbeck, John (2001). Geochemical Analysis and Geophysical Monitoring for Hydrogeologic Assessment of the Steamboat Hills and Southern Truckee Meadows area, Washoe County, Nevada. Washoe County Department of Water Resources, July 31, 2001. (Copies available from Washoe County Department of Water Resources, Resource Planning and Management Division, Post Office Box 11130, Reno, NV 89520-0027).

Skalbeck, John D., Shevenell, L., Widmer, M. (2002). Mixing of thermal and non-thermal waters in the Steamboat Hills area, Nevada, USA. Geothermics, vol. 31, pp. 69-90.

Sorey, M.L. and E.M. Colvard (1992). Factors Affecting the Decline in Hot-Spring Activity in the Steamboat Springs Area of Critical Environmental Concern, Washoe County, Nevada. U.S. Geological Survey Administrative Report for the Bureau of Land Management. Menlo Park, CA. 106 p.

Thompson, G.A. and D.E. White (1964). Regional Geology of the Steamboat Springs Area, Washoe County, Nevada. U.S. Geological Survey Professional Paper 458-A. 52 p. plus plates.

White, D.E., Thompson, G.A. Sandberg, C.H. (1964). Rocks, Structure and geologic history of the Steamboat Springs thermal system, Washoe County, Nevada: U.S. Geologic Survey Prof, Paper 458-B, 63 pp.

White, D.E. (1968). Hydrology, activity and heat flow of the Steamboat Springs thermal system, Washoe County, Nevada: U.S. Geologic Survey Prof. Paper 458-C, 109 pp.

Widmer, M. (2005). Letter to Christy Morris, Program Manager, Nevada Division of Minerals, from Michael Widmer, Senior Hydrogeologist, State of Nevada Department of Water Resources, August 18, 2005. Subject: Galena Geothermal Project.

Yeamans, F. (2006). An analysis of Ground Water Monitoring in the Steamboat Springs Geothermal Area. Prepared for the Washoe County Department of Water Resources. By: Frank Yeamans, Ground Water and Geothermal Hydrology, Sacramento, CA. October 15, 2006. 34 pp.

Widmer, M. C. (2006). Analysis of Ground Water Level and Water Quality Changes in the Vicinity of the Steamboat Springs Geothermal Area, Washoe County, Nevada. Washoe County Department of Water Resources, Reno, NV. December 13, 2006. 39 pp.

Widmer, M. C. (2006). Letter report on the airborne resistivity results of the Steamboat Springs area. Letter to Lisa Shevenell, Nv. Bur. Mines and Geology, from Michael C. Widmer, DWR. September 7, 2006. 2 pp plus figure.

Yeamans, Frank (1984). Hydrology of the Steamboat Springs geothermal system: unpublished report prepared for the Phillips Petroleum Company, 131 p.

Yeamans, Frank (1987). Results of the hot spring, ground water and surface water monitoring program. COX I-1 injection test, May-July 1987: a report prepared for the Chevron/Yankee Caithness Steamboat Joint Venture Geothermal Project Steamboat, Nevada, under the Nevada Division of Environmental Protection Injection Permit No. NEV 70016, 14 p.

Yeamans, Frank, and Broadhead, Roxanne (1988a). Hydrogeology and water chemistry in the vicinity of Brown School, Steamboat, Nevada: a report prepared for the Nevada Division of Environmental Protection and Ormat Energy Systems, Inc., 23 p.

Yeamans, Frank, L. (2006). An analysis of ground water monitoring data in the Steamboat Springs Geothermal Area. Consultant report prepared for Washoe County Department of Water Resources, Reno, Nevada. October 15, 2006. 34 p.