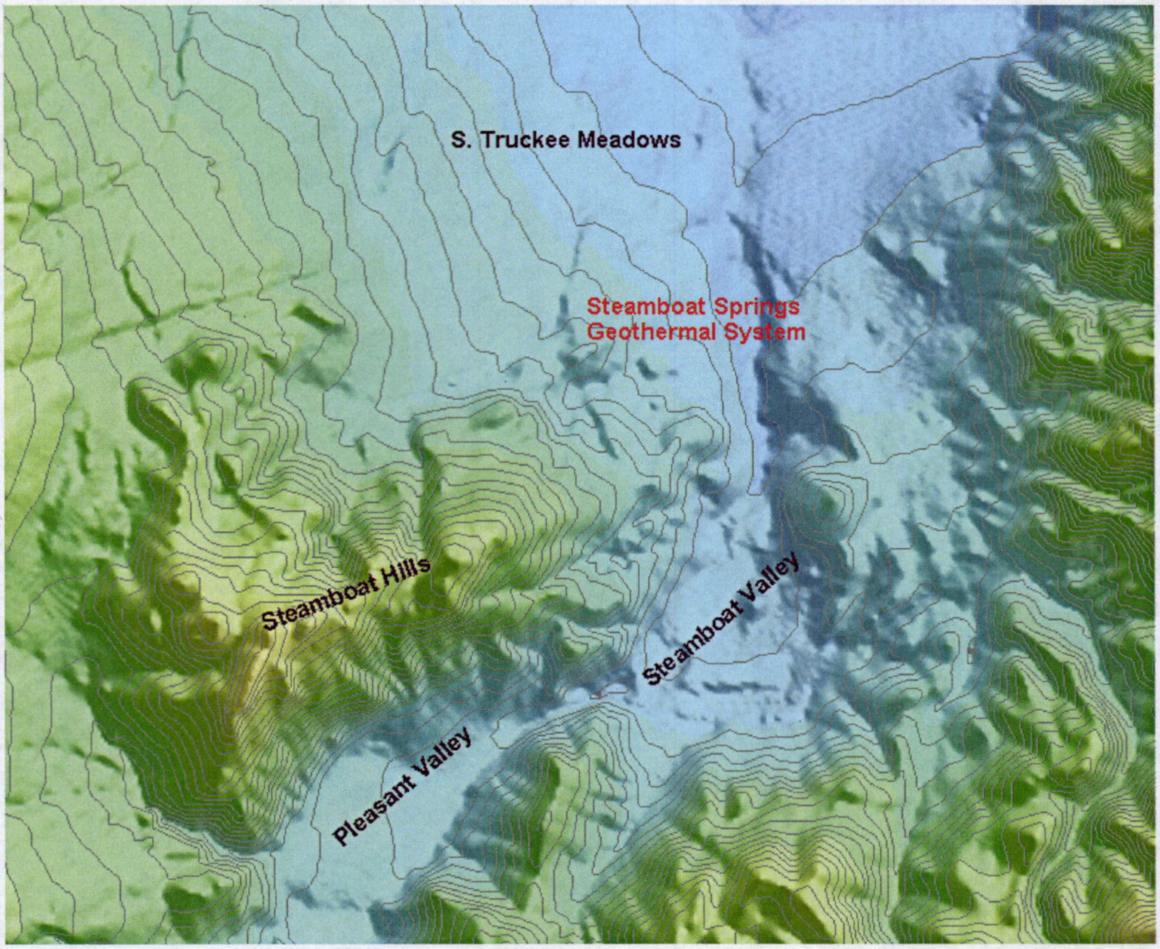
Analysis of ground water level and water quality changes in the vicinity of the Steamboat Springs Geothermal Area, Washoe County, Nevada



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INTRODUCTION

Recently, Frank Yeamans (2006) was contracted by Washoe County to present, analyze and report on water chemistry changes found near the Steamboat Springs Geothermal area. The Yeamans report used monitoring data collected by geothermal operators over a period of 1984 to present. This current report is considered a companion that presents, analyzes and reports on changes in the potentiometric surface (water table elevations) and water quality of the fresh water aquifer within the same area and over the same period of time. Washoe County and the geothermal operators collected the data for this report.

It has been recognized that changes in the ground water chemistry near the Steamboat Springs Geothermal area can be affected by the rise and fall of the potentiometric surface. Changes in the potentiometric surface come from changes in municipal and domestic pumping, geothermal production and injection[1], irrigation practices, and annual precipitation/recharge events. However, increasing geothermal injection and resultant discharge can also play a role in changing the chemistry of the fresh water aquifers.

It is interesting to know that the development of the geothermal resource for power generation coincided exactly with the large-scale development of the fresh water aquifers for municipal water supply. Also coincident with the developments, a long-term drought occurred (1988-1994) and irrigation practices within the area of concern diminished. These last two events reduced the amount of recharge to the fresh water aquifers. Consequently, identifying the major cause of water quality change is clouded by all four of these simultaneous events.

Purpose and Scope

The major purpose of this report is to present an analysis of possible impacts the potentiometric surface may have had on the changes in water chemistry reported on by Yeamans (2006). How the potentiometric surface has changed over the years is also addressed, albeit in a somewhat elementary manner. Some of the analysis is studied for reasons of completeness and to answer the "what if" questions that have surfaced over the last several years. The impetus for this investigation is to resolve some of the questions as to the impact the geothermal power generation projects may have on the non-thermal aquifers. The water level data used encompasses an area south of the Huffaker Hills, west and east of the Virginia and Carson Ranges, respectively, and north of Washoe Valley. Figure 1 is a display of this area. However, lack of data within this broad area, particularly within the geothermal reservoir, limits the completeness of the analysis. A focus is placed upon the area immediately north of the geothermal system.

BACKGROUND

Regional ground water occurrence and movement

Washoe County has a very large database of water level measurements taken from both dedicated monitor wells and domestic wells. This database dates back to 1979. Therefore, the fundamental understanding of the occurrence and movement of groundwater is well documented.

[1] As discussed later, pressure changes in the geothermal system that reach the ground water system will not create or be recognized as pressure-hydraulic head changes in the ground water potentiometric surface.

Recharge to the alluvial aquifers begins in the Carson Range and is generated mostly as snowmelt that percolates into the hard rock formations, granodiorite and mafic volcanic rocks. Recharge also occurs from streambed leakance beneath Galena, Whites and Thomas creeks. This is particularly true with respect to Galena Creek as the soils are primarily of decomposed granite that provides excellent infiltration. The reader is directed to Katzer (et al, 1984) for a review of Galena Creek's interaction with infiltration. Contrary to this, Whites and Thomas creeks do not necessarily lend themselves to large infiltration rates due the streambeds being composed of volcanic silts and clays.

Figure 1 is the 1982 potentiometric surface and shows that ground water emanates from the Carson Range flowing easterly and northeasterly. Flow towards Steamboat Hills has been estimated to flow around these Hills (Katzer, 1984) or both around and through the Hills. Where the Steamboat Geothermal System is actually recharged is not understood, but is likely from snowmelt within the 6900 feet elevation of the Carson Range (Nehring, 1980). Recharge could certainly occur through fault structures (not shown) on the Galena alluvial fan to the magma chamber, estimated at 10,000 feet below the Hills (White, 1964 and Skalbeck, 2001).

The regional ground water gradient is towards the South Truckee Meadows valley floor. Ground water discharges to Steamboat Creek (Shump, 1984) and as evapotranspiration. Estimates of the mountain front recharge, are 12,000 to 16,000 acre-feet (AF) per year (Widmer, 1991; HydroSearch, 1991; Eco:Logic, 2002). Ground water movement also occurs northward from Pleasant and Steamboat valleys towards the South Truckee Meadows valley floor. It is estimated that only a small proportion of ground water recharge occurs from the Virginia Range due to the relatively low annual precipitation.

The map shows that a "flat" gradient exists within the Galena Fan, a steep gradient upon the mid-alluvial fan, and a flattening gradient towards the valley floor. This is a classic form depicting the recharge zone at the highest elevations, a discharge zone at the valley floor, and a transition zone in between. The vertical gradients within these zones are mostly downward, horizontal and upward, respectively. It is of note that the steep gradient at mid-fan is reflective of the Steamboat Hills (where there is little data to support the gradient depicted), but also of the alluvial aquifer to the immediate north. Within the geothermal area, the gradient appears flat.

Historical irrigation practices have played a major role in "secondarily" recharging the fresh water aquifers below Steamboat ditch. Widmer (1991) estimated that the amount of surface importation in 1983 was nearly 9,000 AF. Irrigation has largely diminished throughout the area and has probably been reduced by as much as 75%. The rate reduction began in 1985 (Federal Water master records). Irrigated lands began to diminish after 1984, north of the Steamboat Geothermal area. Yeamans (1987) discusses the lack of "secondary" recharge due to this cessation. It is certain that the effects of "drying up" historically irrigated lands have impacted water level elevations.

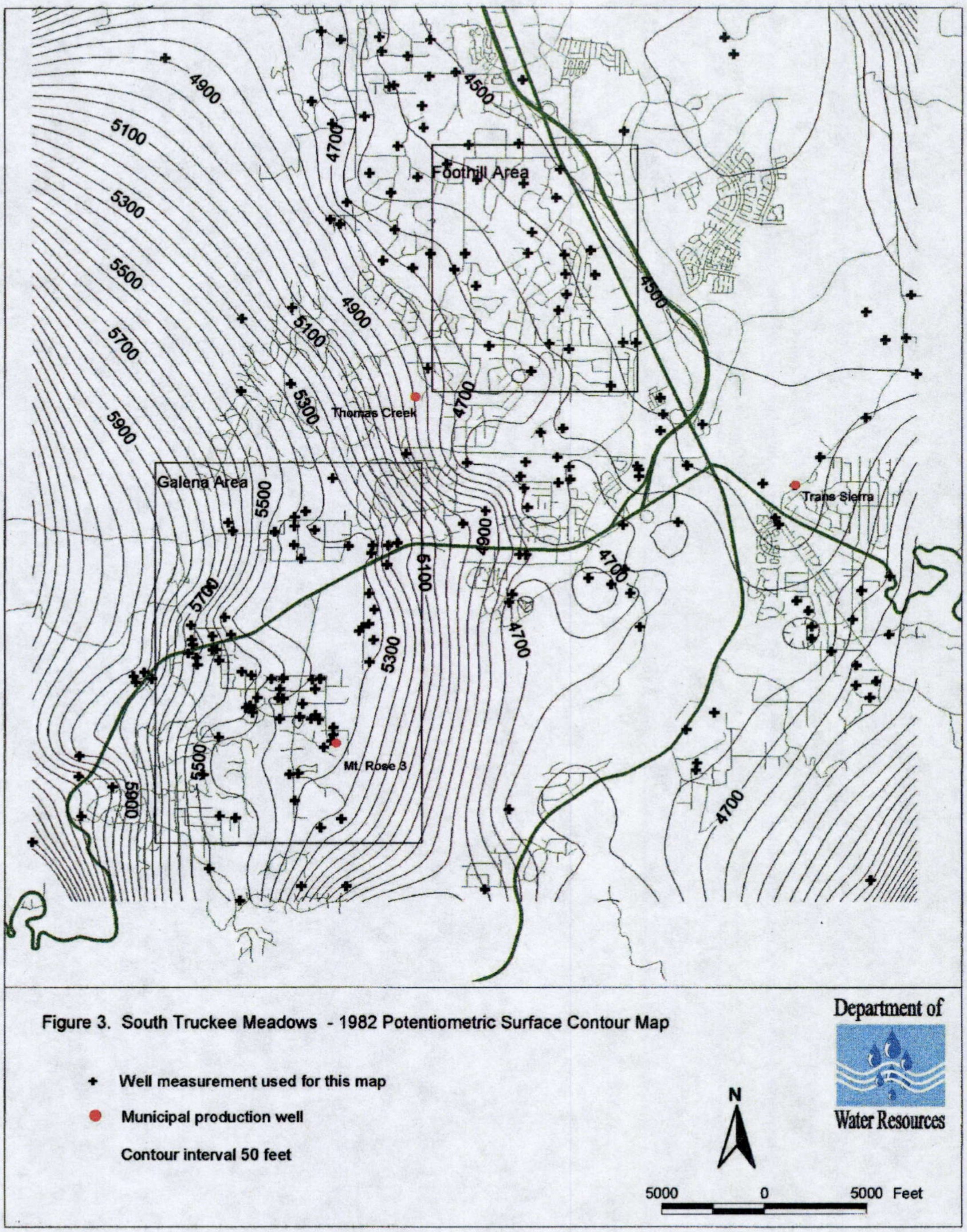

Figure 1. Reproduction of Felling's (2002) Figure 3 of South Truckee Meadows 1982 potentiometric surface contour map.

The natural geothermal discharge has been discussed by White (1964), Bateman and Scheibach (1975), and by Widmer (2006). White estimated the annual geothermal discharge at 1,100 gpm or 1,800 AF based upon chloride techniques. This paper assumes that most of this discharge is subsurface and occurs north and east within a two-mile area adjacent to the geothermal springs proper. However, geothermal discharge has been identified several miles to the northeast and associated with the Steamboat system. It is assumed that this discharge is upwelling along north trending faults.

Washoe County municipal production wellfield and pumping

Due to housing and commercial demands, Washoe County began developing the ground water resource in 1982. This primarily began as a replacement wellfield for the Trans Sierra Water Company, that had been recently purchased by the South Truckee Meadows General Improvement District (STMGID). Wellfield development increased with time as other subdivision development occurred. Today, both the South Truckee Meadows and the Galena Fan wellfields are largely complete although a "secondary" wellfield is being developed at the north central portion of the valley floor. This wellfield will be pumped during late summers and during drought periods, but will require water quality treatment to reduce arsenic levels.

Figure 2a displays the current wellfield. Municipal well development occurred in tandem with residential development. Wells were constructed within the subdivision they were to serve. The Mt. Rose Highway generally divides the two hydrographic basins of the South Truckee Meadows (STM) from the Pleasant Valley where the Mount Rose (MR) wellfield is located. Figure 2b displays the relative location map of the three geothermal power plants, their production (red) and injection (green) wells and the monitor wells (blue) discussed in this report.

Figure 3 displays the historical pumping of both the STM and MR wellfields. The Mt. Rose wells are located within the Pleasant Valley Hydrographic Basins. Full pumping of these wellfields is estimated at 2,400 mga by the year 2020. Current pumping is at 1,731 mga (2005).

Domestic pumping also affects the potentiometric surface. Within two hydrographic basins there are an estimated 2,000 domestic wells (2004 estimate). Washoe County estimates that each domestic well pumps an average of 0.15 to 0.4 mga. This amounts to approximately 600 mga.

Four STMGID production wells are relatively close to the geothermal monitoring sites. If municipal wells are responsible for affecting water levels in the geothermal monitor wells, these are likely to be the ones responsible. Figure 4 shows the total annual pumping of these wells. Inspection of the Figure shows that since 1987 the wells have pumped from 250 to 400 mga, increasing incrementally by approximately 50-75 mga. From 1995-2005 these wells have pumped an average of 314 mga. And since 1999, the rate of annual pumping has actually decreased.

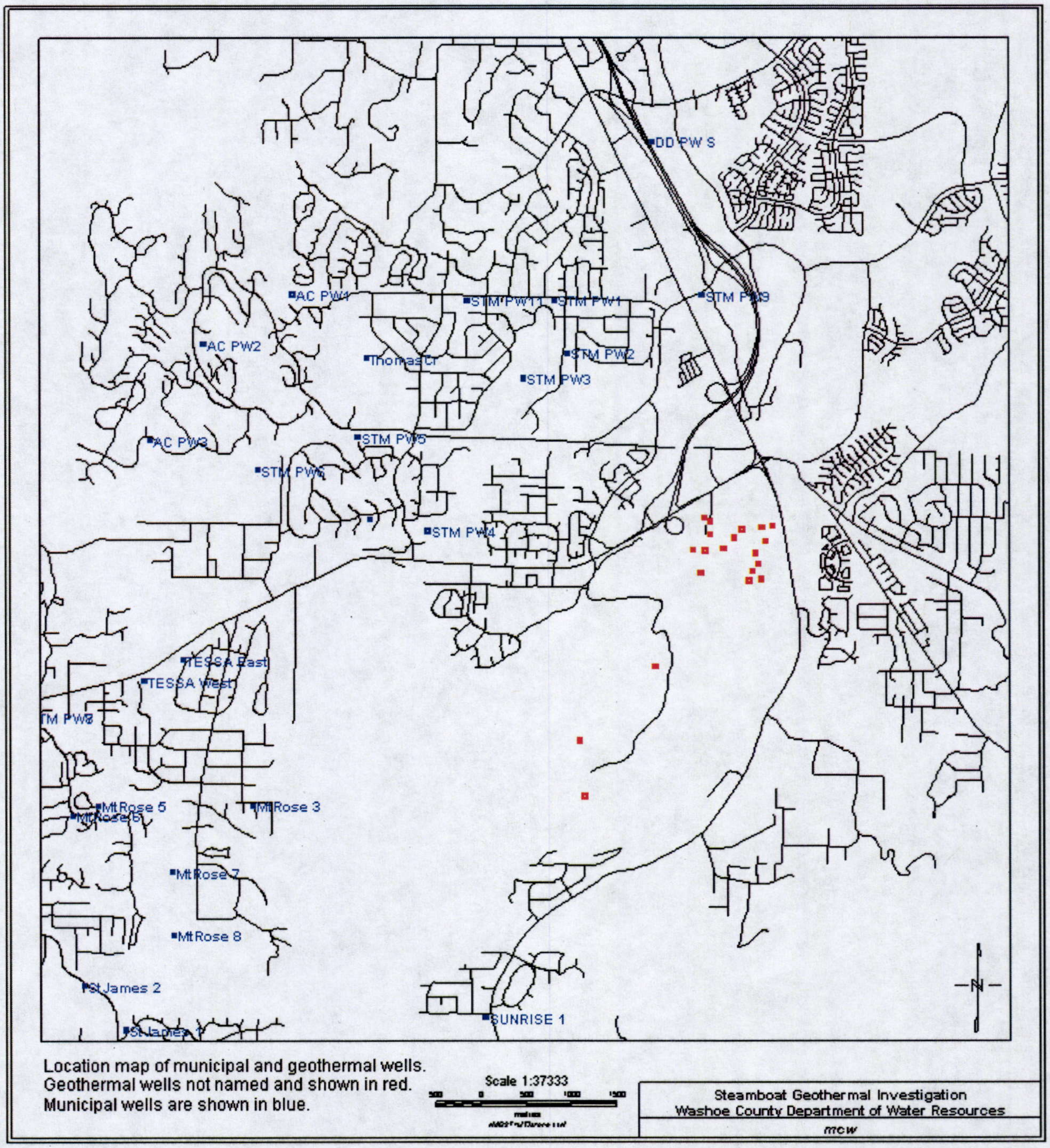

Figure 2a. Municipal and geothermal wells of the South Truckee Meadows.

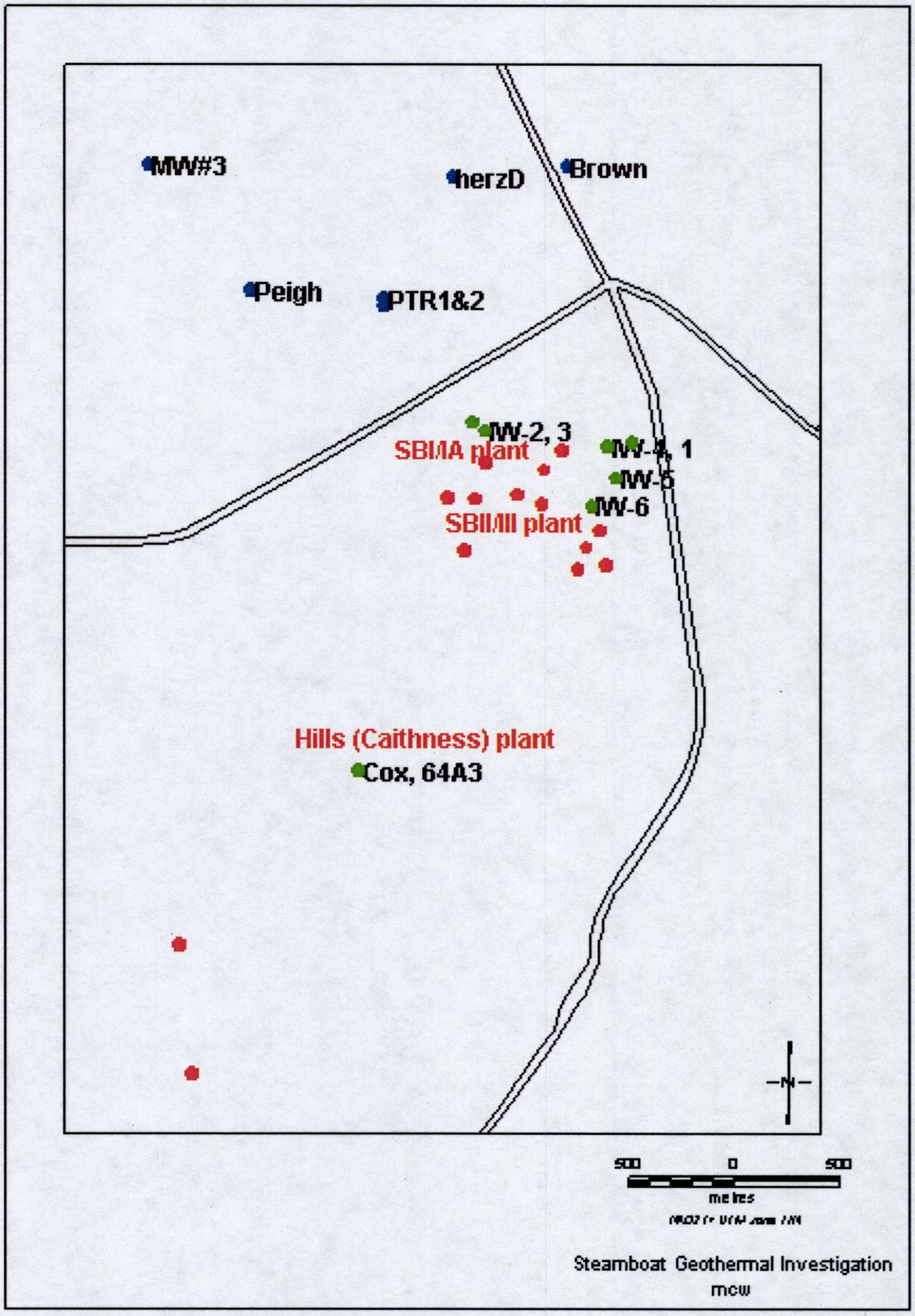

Figure 2b. Relative location map of the three geothermal power plants, their production (red) and injection (green) wells and monitor wells (blue). Only the monitor wells discussed in this report are shown. Production wells are not labeled for clarity.

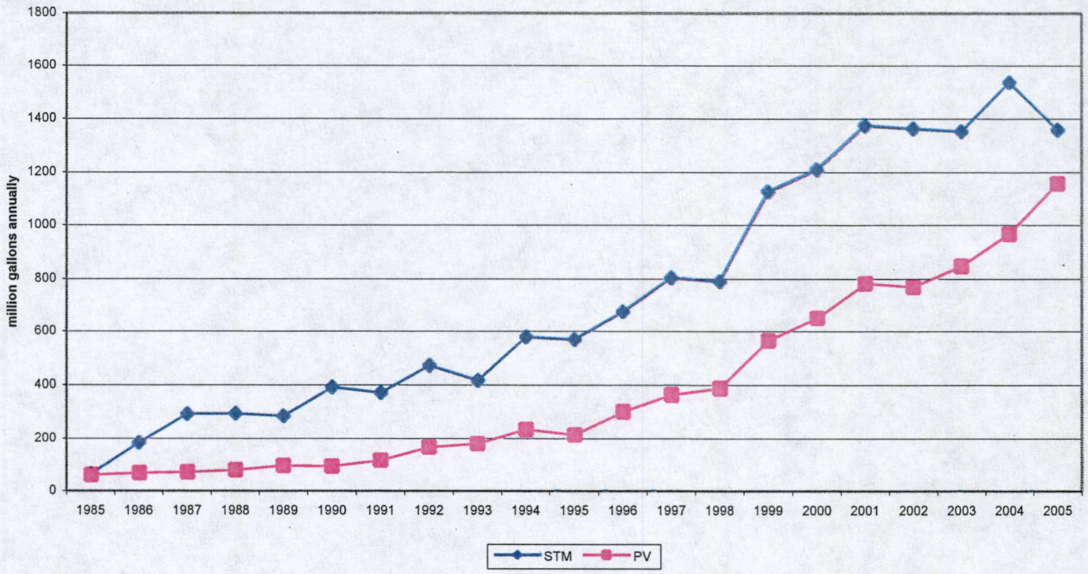

Figure 3. Washoe County municipal pumping (note PR= Mount Rose water system).

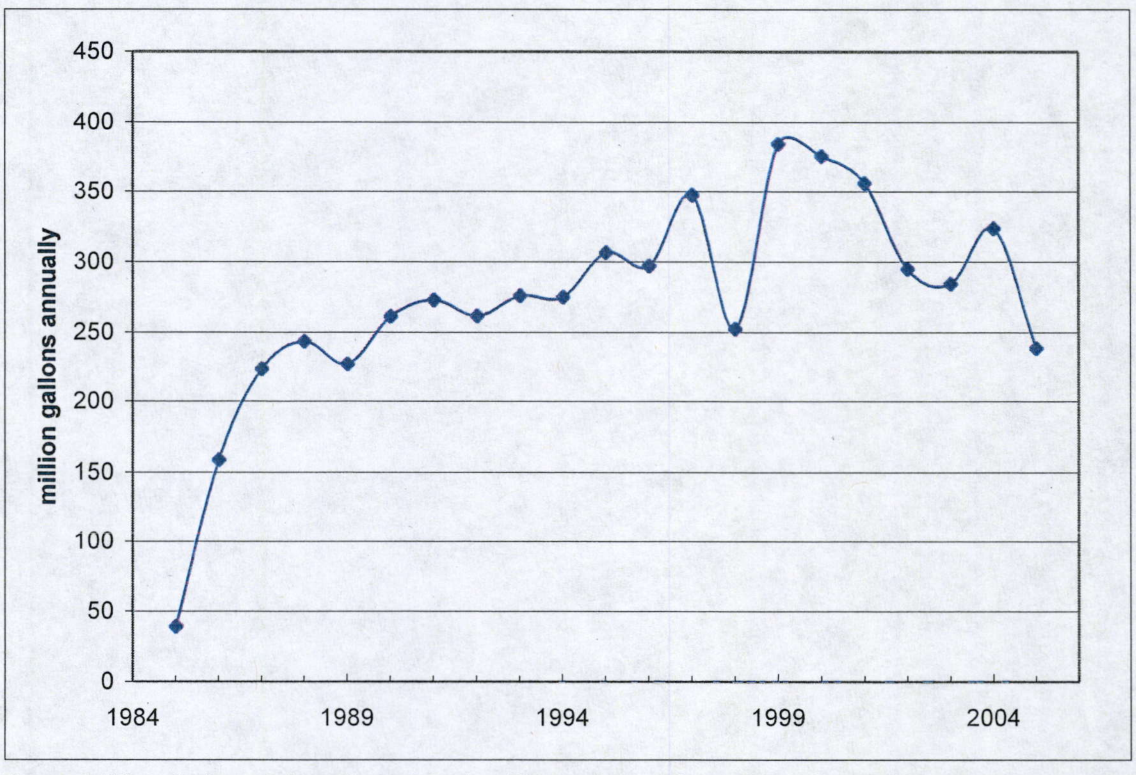

Figure 4. Historical pumping of municipal wells nearby geothermal monitor wells

Previous investigations

In 1978, the USGS collected two years of water level data on the upper portions of the Mt. Rose and Galena fans. Washoe County began collecting water level data in 1982. The 1982 survey serves as the baseline datum for water level changes due to municipal pumping. No other regional survey exists prior to this survey. Washoe County conducted full-scale surveys again in 1991 and 1996. Since 1996, full-scale surveys have been conducted annually and often semi-annually until the present. Unpublished reports on two of these surveys can be found in Kanbergs (1996) and Felling (2002). Of note are the changes in water levels during five, ten and twenty year time frames.

Groundwater models were constructed in 1985 (Widmer, 1991) and in 1991 (HydroSearch, 1991). The HydroSearch model has been updated several times, most recently in 2002 (Felling, 2002). Predictions were made of the effects of full scale municipal pumping upon the potentiometric surface.

In the Felling report, water level declines are expected to range from 0 feet several miles from production wells, to 100 feet in the immediate vicinity of the pumping wells. His model predicted 10 feet of water level decline due to municipal and domestic pumping (1985-2001) for the Herz Domestic well (see his Figure 24) by 2001. Actual water level changes during this time period were 30 feet (Washoe County data base). This model prediction was based upon average annual groundwater recharge, without secondary recharge from irrigation, and in the absence of geothermal pumping. Under the 2023 pumping prediction, 20 feet of water level decline due to municipal and domestic pumping was predicted for the area of the Herz Domestic well.

DATA COLLECTION, DATABASES AND METHODOLGY

The following describes the various databases and their collection methods. The methodology of gridding the water level data is discussed.

Water level data bases

Washoe County collects and maintains a ground water level database that consists of greater than 5,500 data points, mostly from domestic wells. These are generally within the South Truckee Meadows and the Galena Fan. A Pleasant Valley (proper) database consists of approximately 100 data points that began in 2002. Since 1996 the annual and semi-annual surveys attempt to measure the same wells, approximately 200 in number. In 2004 the number of wells was reduced to 125 because of manpower constraints.

Water levels are measured with electric sounders or steel tapes to the nearest 100th foot. The database is maintained in an Excel ™ spreadsheet. Each well has been located with a survey grade GPS unit or estimated from electronic orthophoto maps to the nearest 2 feet, horizontal, and 1foot vertical resolution. The wells are coordinated in Nevada State Plane feet, NAD 83.

The geothermal monitoring data is collected by geothermal operator staff. Data is reported to the Nevada Division of Environmental Protection and Washoe County. An electronic database is also maintained by Washoe County. Because several different geothermal operators have collected the data, there is no consistency in reporting. Often, data is not collected or reported. Methods of data collection are not described. Regardless, the database has a large record that extends from 1984 to present. The data consists of production and injection volumes and their pressures, rates and chemistry.

Monitor wells are also included with water levels and/or chemistry. This data was used in the Yeamans report (2006).

Precipitation records

Three sets of precipitation records are used to document the regional climate changes over the last 25 years. The date was provided by the Western Regional Climate Center and consist of gauge records collected from the Reno-Tahoe International Airport (Reno), the Washoe County Galena Park (Galena) and a Verdi (Verdi) residence. These gauges are read on a daily basis.

Figure 5 displays the precipitation records for these gauges. The data points are for calendar years of precipitation. Inspection shows that the records are similar, but the Galena gauge shows much more fluctuation in the pattern. All three datasets describe a major drought (1987-1994), a very wet period (1995-1999), and again a dry period (2000-2004).

Because ground water recharge is largely impossible to measure directly, annual precipitation is used as a proxy for the measurement of the relative magnitude of annual recharge. The Galena record is used in this analysis as a measure of ground water recharge to the regional ground water aquifers. Precipitation from this gauge ranges from 48 inches during very wet winters to 10 inches during drought years. Average precipitation for the period of record is 23.6 inches.

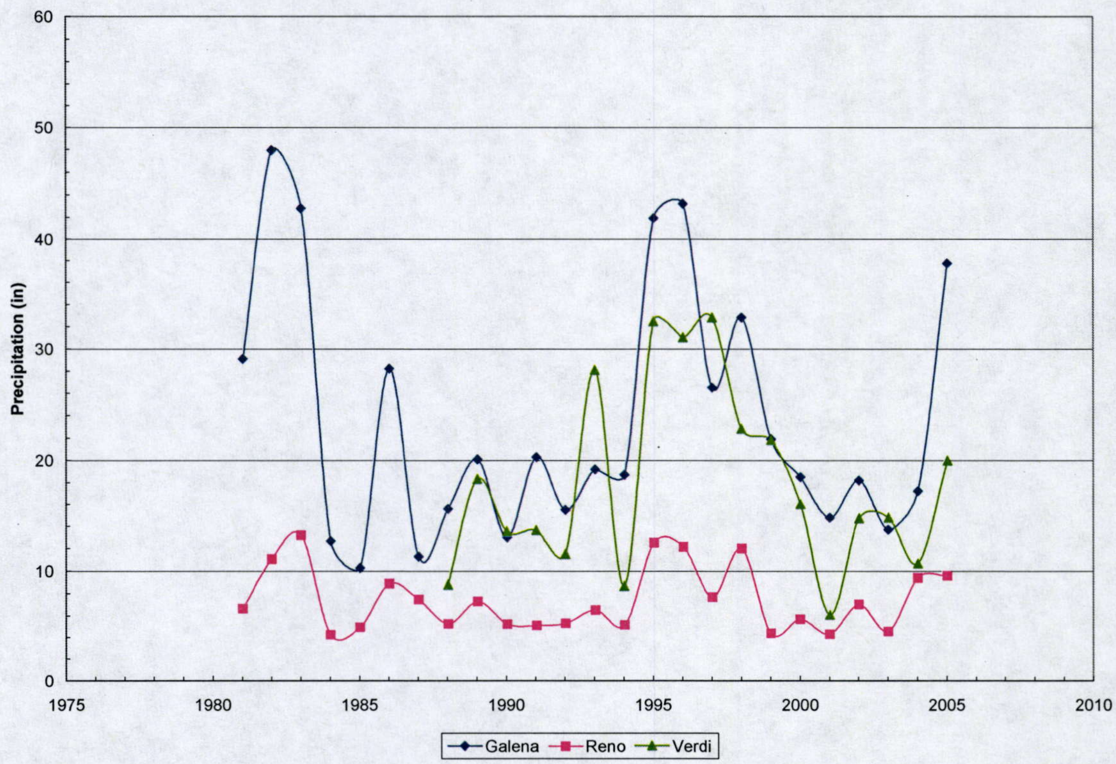

Figure 5. Annual precipitation for the Reno, Galena and Verdi gages.

Formation of grids

Central to analyzing the changes in the potentiometric surface is the use of difference grids. Water level data is interpolated through a grid routine in order to generate a gradient surface throughout the study area. These grids represent a snapshot in time of the surface. These grids can be subtracted from each other to generate a third surface- a difference grid that, once contoured, shows the changes in the potentiometric surface between those two end points in time.

This gridded data must use the same data points for a clear picture of water level change. Not doing so will render artificial changes that are artifacts of the grid interpolation routine. This presents problems with an incomplete data set. As a result it is often times necessary to insert "dummy" data points in order to control the grid routine. These dummy values must always be distinguished in the mapping of the data. However, missing data points that are critical to data analysis over a particular time period can be estimated from nearby data points. This is an acceptable process, but again, should be noted.

Within this study area water level data consists of wells constructed in hard rock aquifers and in alluvial aquifers. Generally, this can sometimes compare hydraulic head data that is physically unrelated. That is, the hydraulic heads measured in the rock aquifers are not communicative with heads measured in alluvial aquifers. The data should be reviewed to ascertain if comparing the two data sets is appropriate.

In previous reports geothermal reservoir wells were used in combination with the alluvial wells when the reservoir wells have a completion depth of less than 1000 feet. Several reservoir wells are within this range and indeed are approximately 600 feet in depth. The justification for comparing the "hard rock" data with "alluvial" data is that the hard rock levels correspond very well with the alluvial levels that surround the reservoir. And these hard rock levels respond to drought in the same time frame as the alluvial levels. It is hypothesized (Nehring, 1980) that the geothermal reservoir is recharged from the same source area as the alluvial aquifer is and the assumption is made that the two systems are not isolated, but in good communication. The geothermal system also discharges to the alluvial system with heads indicative of good communication with the alluvial system. White (1964) provides additional insight to this assumption.

WATER LEVEL CHANGES SINCE 1982

Potentiometric surface difference maps

The reader is directed to the Washoe County reports of Kanbergs (1996) and Felling (2002) for details in the generation of potentiometric difference maps displayed herein. For this report, the difference maps are used from Felling (2002) and consist of changes from 1982 to 1992 (Figure 6), 1992 to 2002 (Figure 7), and 1982 to 2002 (Figure 8). The reader is also directed to Figure 1 in this report for a review of the 1982 potentiometric surface.

Felling used the ST 2, ST 5, ST 7, and ST 9 wells in these difference maps. As discussed above, this may not be appropriate, but Felling used them in order to control the contouring to the grids. Their use may be justified however and in this section of this report the main discussion will be with the regional trends observed.

Figure 6 shows the differences in the potentiometric surface from 1982 to 1992. Please note that a mistake is shown in that the ArrowCreek wells were not in use during this time frame. Within the upper fan area water levels were generally flat in terms of change. The biggest change was within the area of STMGID PW1, 2 and 3 where water level declines of 20-30 feet are documented. This corresponds to the initial production of these wells. A 30 feet water level decline is also found in the Holcomb Lane area probably due to the Truckee Meadows Water Authority production well, however the drawdown is not widespread. Finally, the largest decline (60') is found in the geothermal area supported by the measurements of the ST 5 and ST 2 wells, at least reflecting the impact of the geothermal pumping.

Figure 7 shows the differences in the potentiometric surface from 1992 to 2002. A water level depression is found centered at STMGID PW5 and PW6. The decline is nearly 40 feet at STMGID PW6 reflecting the impact this well has had on the aquifer. On the Galena Fan the changes range from a decline of less than 10 feet to a rise of 10 feet. The other anomaly is again within the geothermal area where 40 feet of decline is observed, centered at ST 9. It is interesting to note that a ten feet rise is observed within the SBI/IA geothermal wellfield, just south of the Mt. Rose Highway. Other than the changes discussed, most of the area showed little change over this ten-year period.

Figure 8 shows the difference in the potentiometric surface from 1982 to 2002. The depressions due to the STMGID PW5 and PW6 are shown at 40 feet. On the Galena Fan, only the previously discussed ten feet depression is noted and the rise in the potentiometric surface. Clearly the STMGID pumping has had an effect over this twenty-year time frame, but appears mostly limited to 20 to 40 feet within a 1-2 mile radius of the production wells. The Figure shows the largest decline due to the geothermal pumping, centered on the ST 2 well. It is unfortunate the Felling report did not incorporate more of the geothermal database into this analysis. This will be addressed later in this report. It should be clear as to the impact the two municipal wellfields had on the alluvial aquifers.

In order to preserve proper gridding techniques, a second data set of water levels was generated for the area centered over the geothermal reservoir. This data set makes use of the geothermal wells and data generated since 1996. Figure 9 displays the potentiometric surface during the spring of 1996 using the wells indicated by red dots on the Figure. A general west to east gradient is observed. Figure 10 shows the potentiometric surface during the spring of 2005. Here a depression has developed over the SBI/IA wellfield, supported by the OW-2 and OW-3 wells. It is interesting that the TH-1, 2 and 3 do not support the depression. Figure 11 is a difference map of these two potentiometric surfaces. The depression is approximately 180 feet of pressure head from the nearby TH-1, 2 and 3

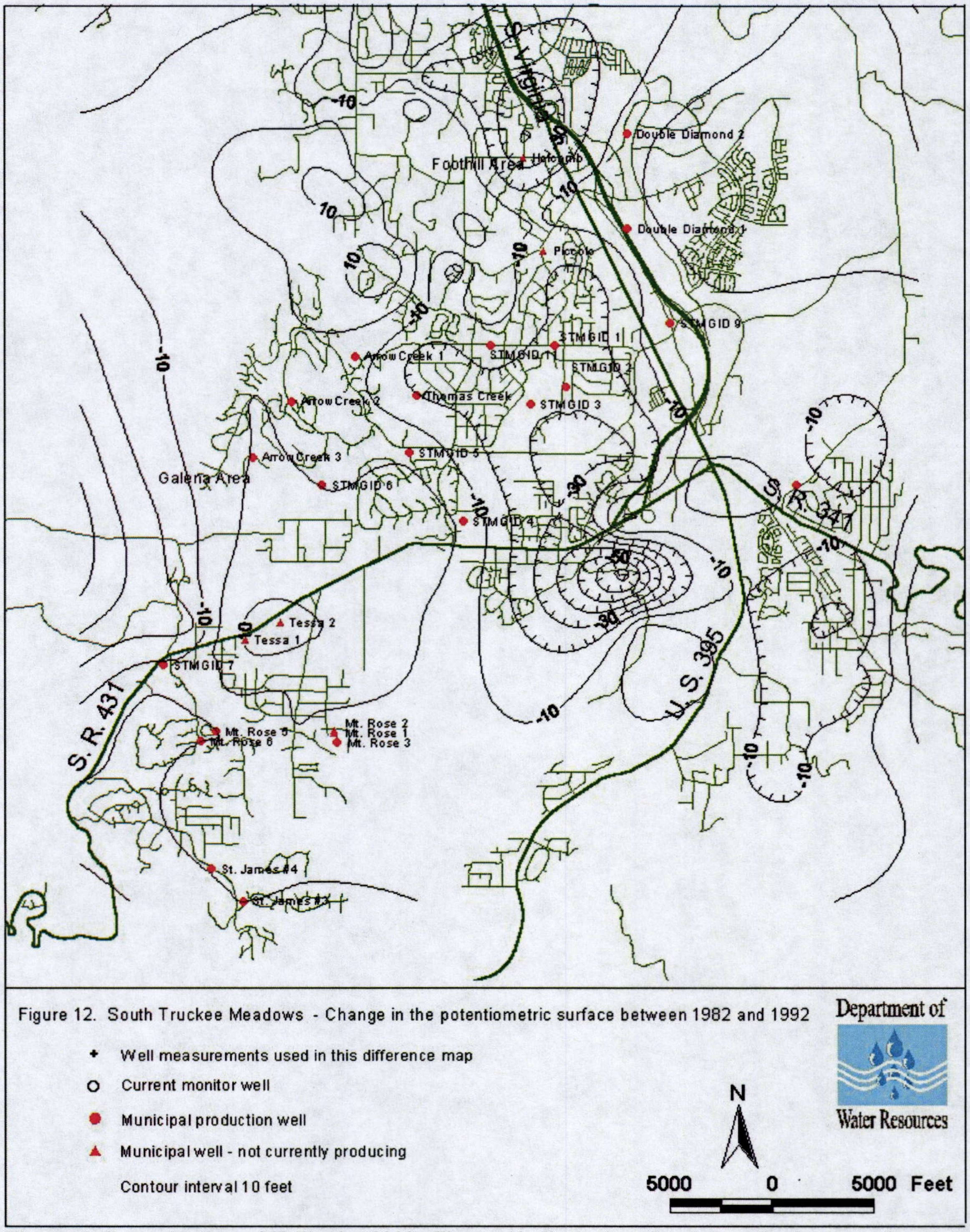

Figure 6. Reproduction of Felling's (2002) Figure 12 displaying the change in the potentiometric surface from 1982 to 1992.

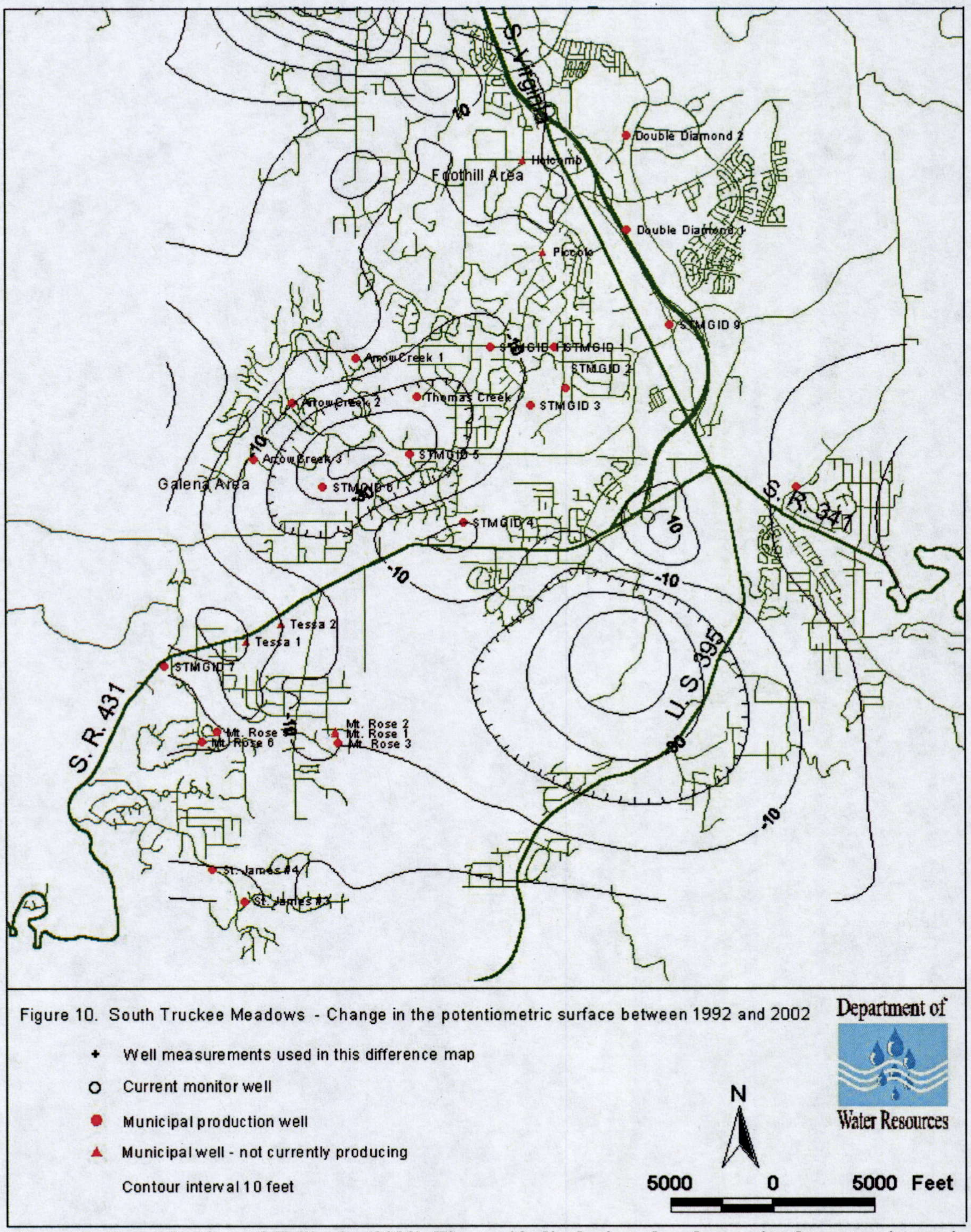

Figure 7. Reproduction of Felling's (2002) Figure 10 displaying the change in the potentiometric surface from 1992 to 2002.

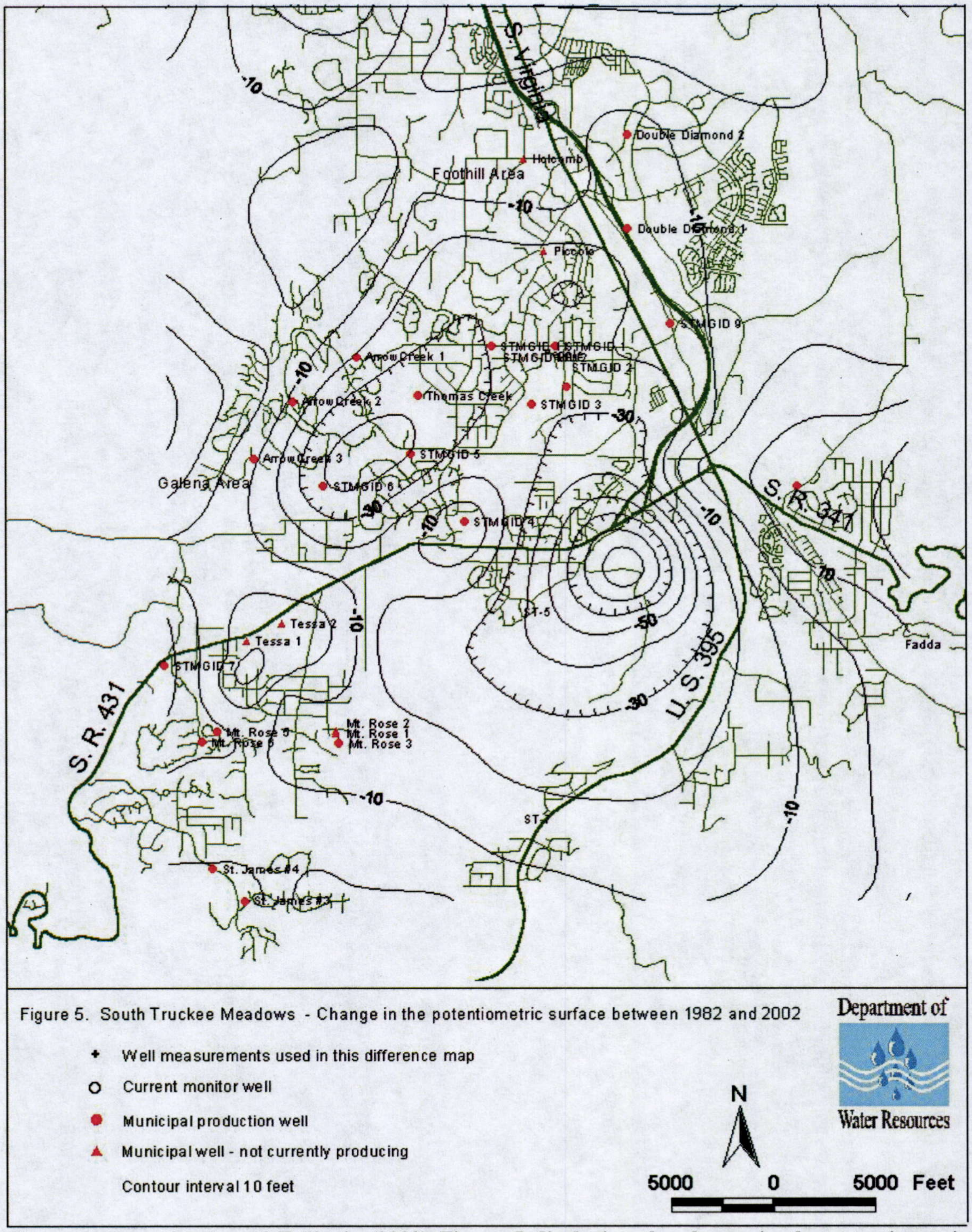

Figure 8. Reproduction of Felling's (2002) Figure 5 displaying the change in the potentiometric surface from 1982 to 2002.

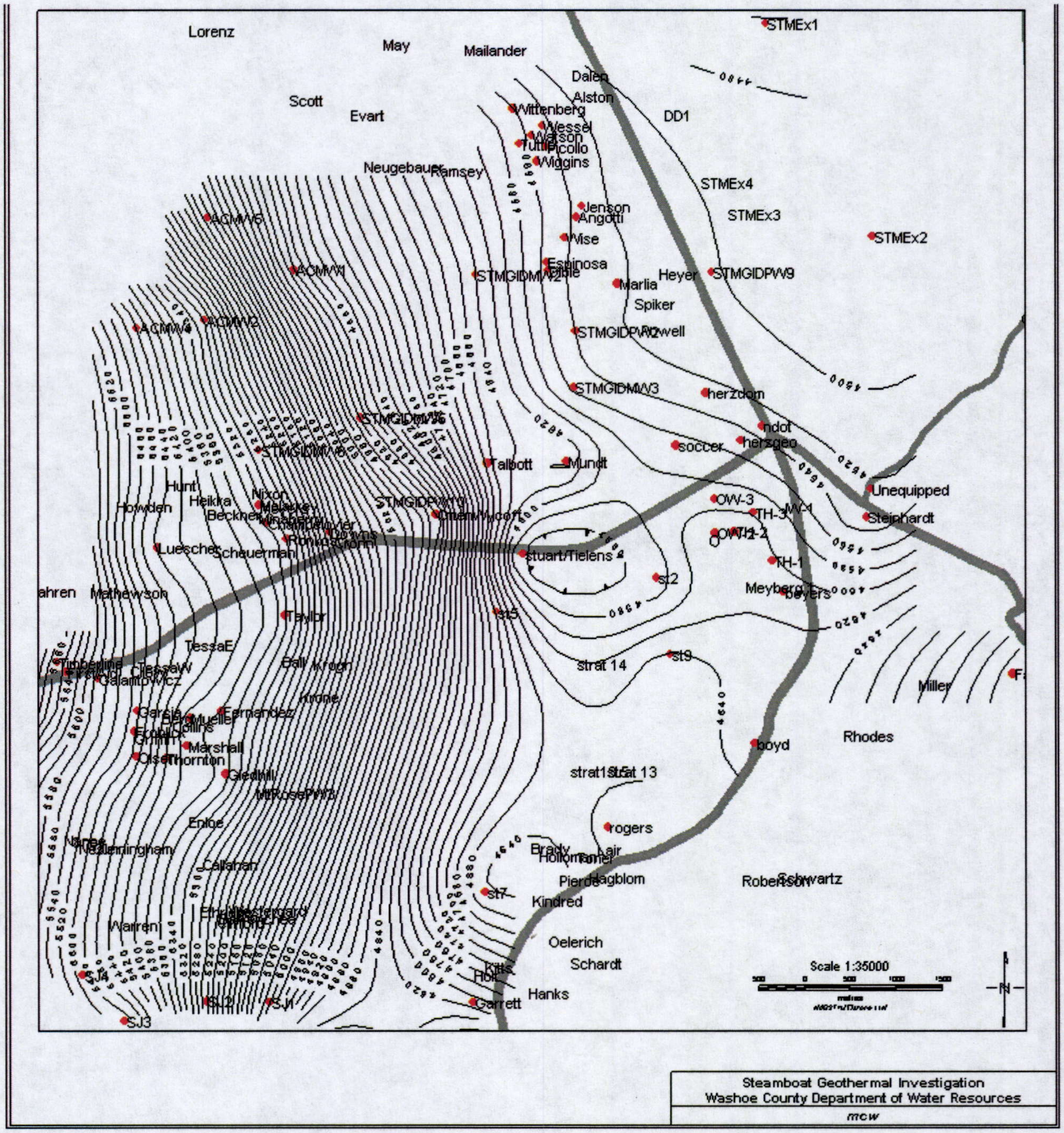

Figure 9. Potentiometric surface in spring of 1996. Contour interval is 20 feet. Red dots indicate data points used in gridding of data.

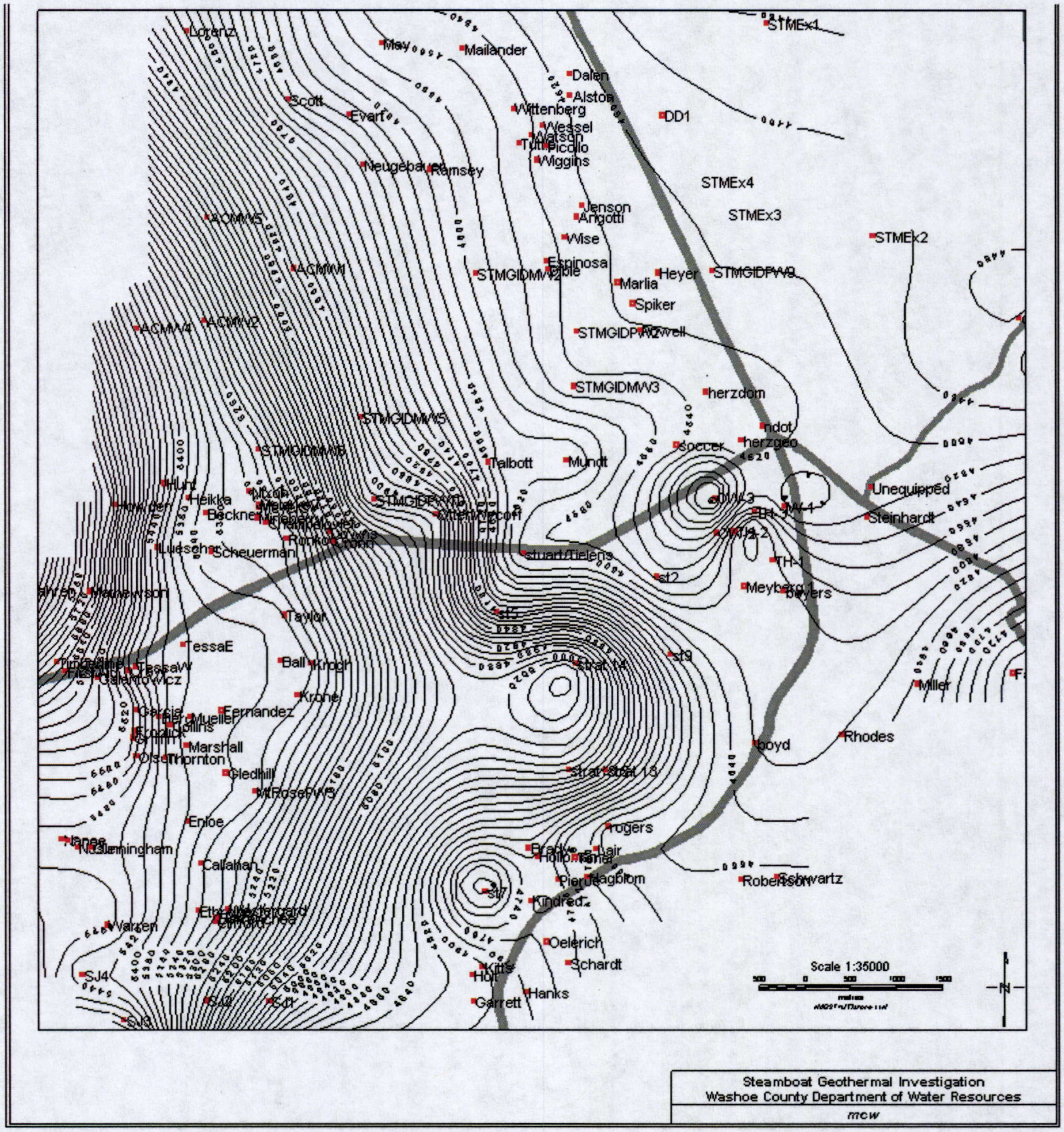

Figure 10. Potentiometric surface in spring of 2005. Contour interval is 20 feet. Red dots indicate data points used in gridding of data.

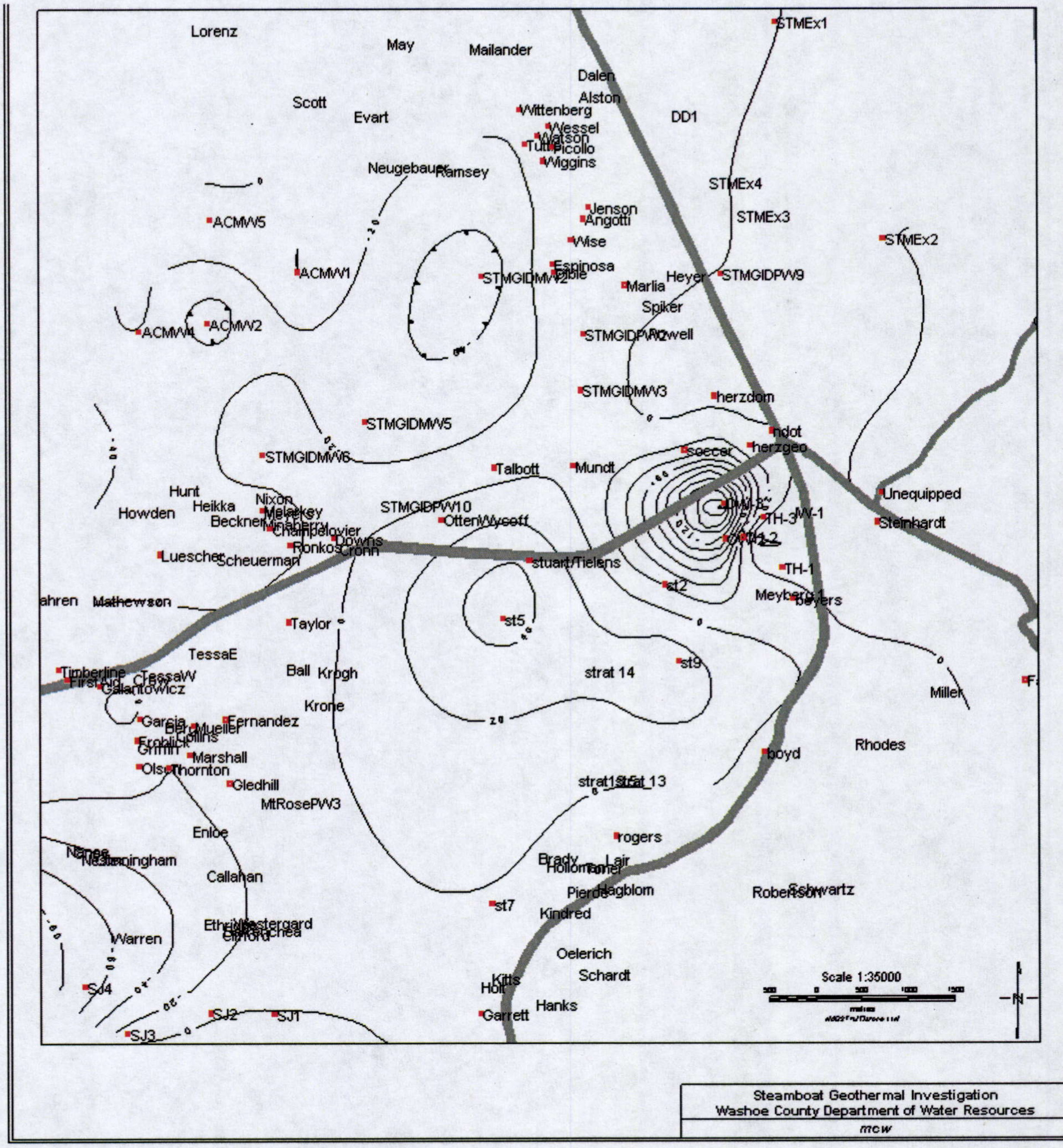

Figure 11. Difference map of the potentiometric surfaces from spring of 1996 to spring of 2005. Contour interval is 20 feet. Red dots indicate data points used in gridding of data.

wells. A rise in the potentiometric surface is noted atop the Steamboat Hills of as much as 40 feet of head, supported by ST9, ST5 and the Stuart/Tielens wells. Also, 20-40 feet of head has been removed from the STMGID wellfield during this eleven-year time frame.

Various hydrograph responses to precipitation rates

It is well understood, from previous studies (Felling, personnel communication; various Washoe County records), of the influence that annual precipitation has on water levels throughout the study area. And while municipal pumping has certainly played a major role in regional water level declines, drought also has a profound effect. A good example is found in Figure 12 where a domestic well, rarely used and not influenced by municipal pumping, is compared to precipitation records. The 1988-1994 drought is clearly seen and its effect upon the water level in the well, a steady rate of decline. The above average precipitation (wet years) from 1995 to 1998 cause an abrupt rise in the water level. This is then followed by below average precipitation (1999-2004) causing a decline in the water level. The response from the monitor well during above average precipitation (2004-2005) does not appear to have much of an effect although an abrupt rise is seen in the last data point (Sept 9, 2006, not shown).

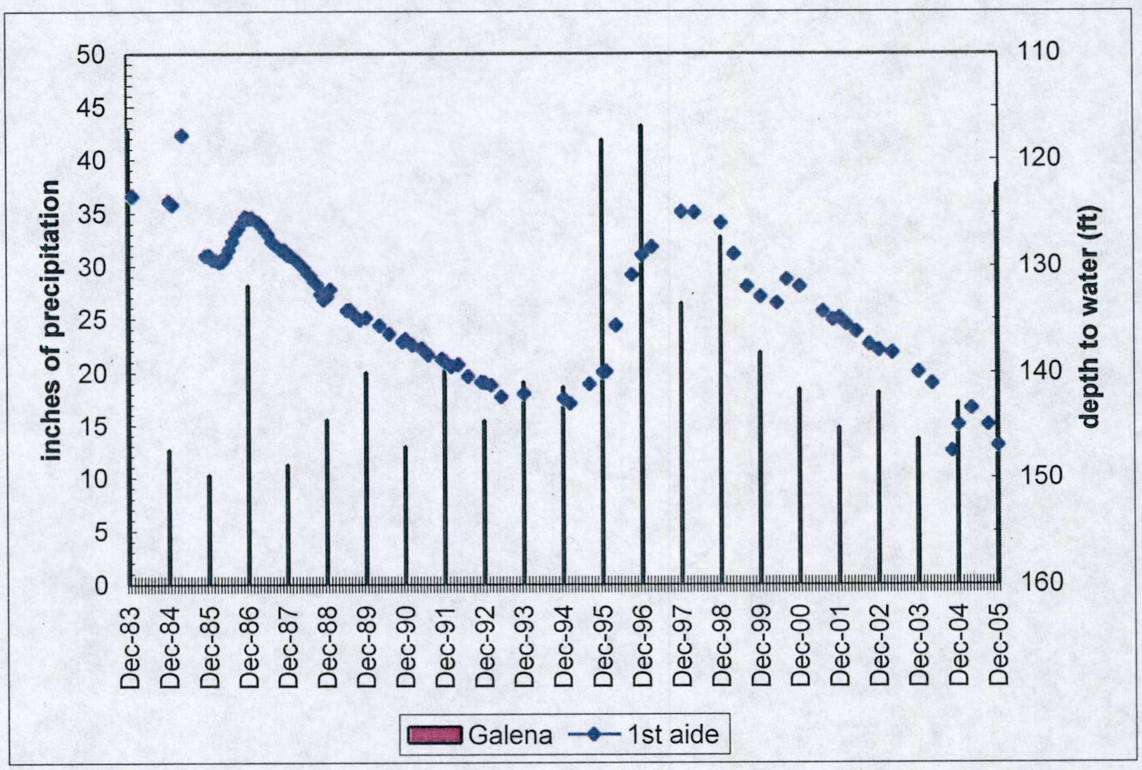

Figure 12. Comparison of annual precipitation to the 1st Aide well hydrograph.

Figure 13 displays the same precipitation record, plotted against the hydrograph for the PTR#1 well. The data set shows a very similar pattern during the drought, the above average precipitation years (1995-1999), the ensuing dry years (2000-2004) and the same delay during the last two years (2004-2005).

A review of Yeamans' (2006) Figure 17 shows the water level data for the geothermal monitor wells north and the Mt. Rose Highway and the record is very incomplete. However, similarities can be drawn from well to well with respect to the precipitation record and the PTR#1 record. Please note the PTR#1 and Soccer (PTR#2) water level records are combined for this current study. This is reasonable as the wells were located within 100 feet of each other, at similar elevations, and had similar static water elevations noted on their well logs.

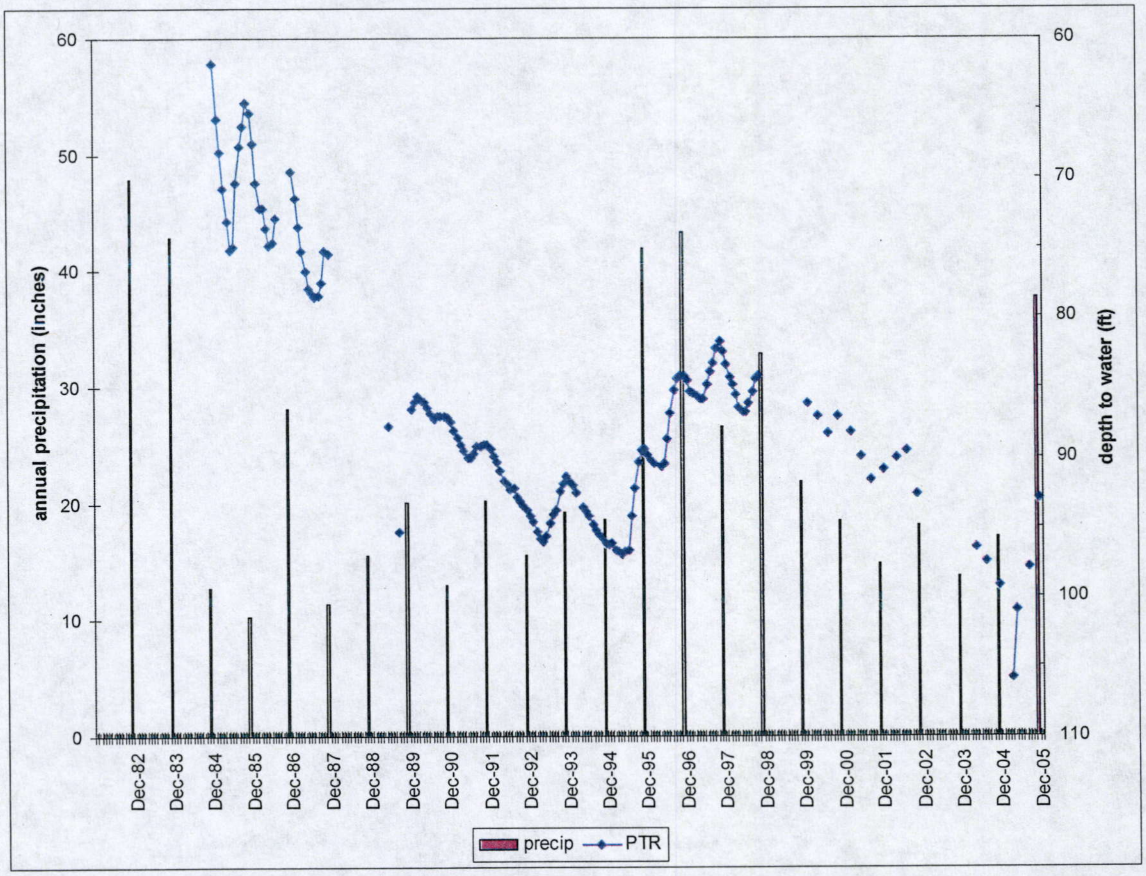

Figure 13. Comparison of annual precipitation (Galena) to the PTR#1 well hydrograph.

The STMGID MW#3 well has a record from 1984 to the present. Water levels and the precipitation record are shown in Figure14. Once again, the correlation of water levels to the precipitation is duplicated as seen in the two previous figures.

Comparison of ground water levels to municipal pumping

From Figure 2, four STMGID production wells (1, 2, 3, and 4) are assumed to have had the most affect upon the geothermal monitor wells. From Figure 4, these rates have been plotted against the water level record for the STMGID MW#3 and the PTR#1 wells. Figure 15 shows the data for the STMGID MW#3. The early start-up of production began in 1985 and within 1987 had reached 225 mga. However, as previously discussed the water level declines began during this time frame and maintained a constant rate of decline. The decline continued at this rate until 1993. The pumping rate increase after 1987 was slight until 1995. From this portion of the Figure it is difficult to relate the water level decline strictly to municipal pumping although common sense would offer that the pumping must have had some effect.

From 1994 until 1999, the annual pumping rate increases to 350 mga. During this time frame the water level in the MW#3 rises and this is probably due to the above average precipitation. So it is interesting that until at least 1998 the rise in the water level goes

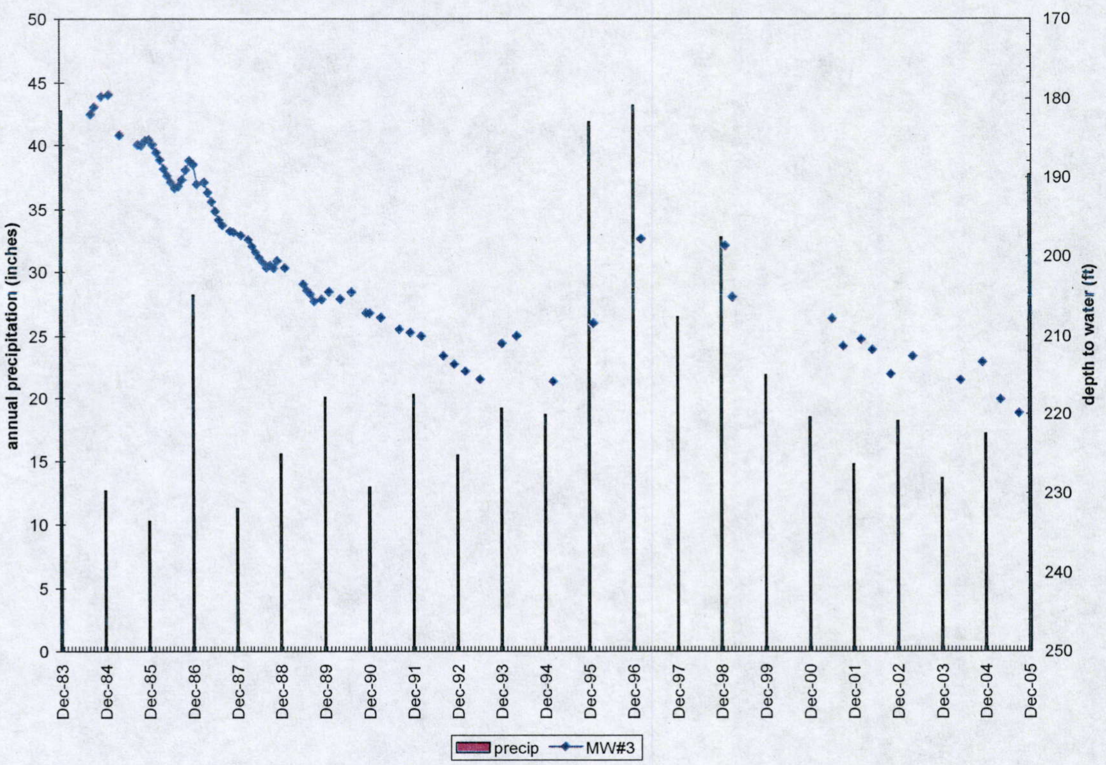

Figure 14. Comparison of STMGID MW#3 and the precipitation record (Galena).

against the increase in municipal pumping. Again, clearly the effects of pumping are not easily discernable. From the years 2000 to present, the rate of municipal pumping decreases while the water levels also decline. This relationship is also key to the understanding of the impacts of municipal pumping to this well.

Figure 16 shows the same municipal pumping as compared to the PTR#1 hydrograph. The relationship is very similar to the STMGID MW#3 well. However, water levels rise during 2004. It would appear that the effects of municipal pumping are much less than the effects of precipitation- the proxy for ground water recharge to the area.

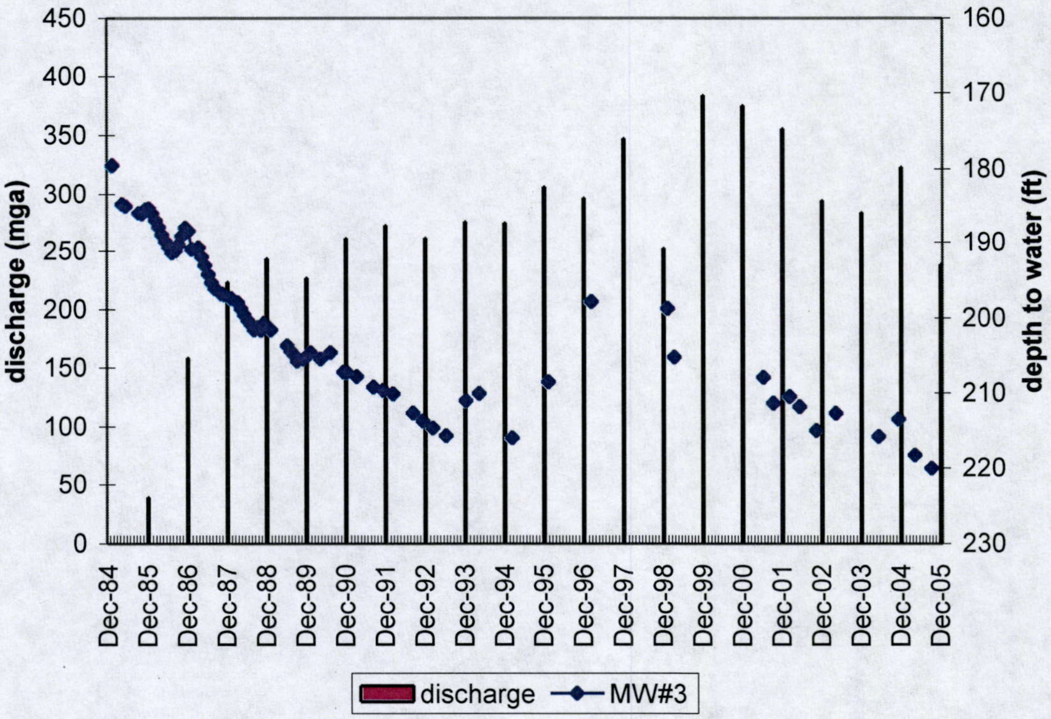

Figure 15. Comparison of STMDGID pumping to the MW#3 hydrograph.

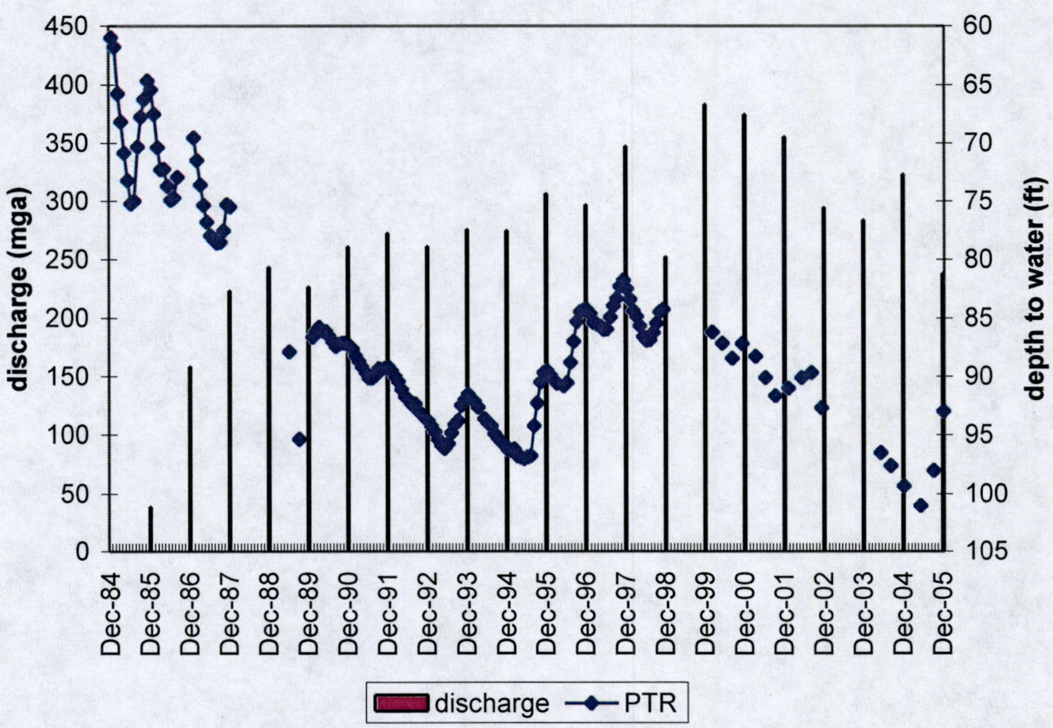

Figure 16. Comparison of the STMGID pumping to the PTR#1 hydrograph.

Ground water recharge from irrigation practices

Yeamans (1987) recognized the "secondary" recharge to the alluvial aquifer from irrigation. This is a result of flood-irrigated waters percolating beneath the root zone and migrating downward to the water table. Cohen and Loeltz (1964) stated that the water table could rise as much as six feet from this recharge down gradient from the Last Chance Ditch, located two miles north of the geothermal area. Yeamans also states that seven feet of water table rise was recorded in the PTR#1 well from irrigation and its proximity down gradient from the Steamboat Ditch. The amount will be a function of the irrigation application rate, the soil moisture content, and the infiltration rate of the particular soil.

Figure 17 is a reproduced map from the Yeamans and Broadhead report (1988) showing a portion of the flood-irrigated lands of the South Truckee Meadows during 1979, 1984 and 1987. Cessation of this irrigation began in 1985 and today has been reduced to a portion of section 22 (T18N R20E) east of US 395 (the Damonte Ranch) and the area around Thomas Creek north and west of Foothill Road. In particular, the Pine Tree Ranch ceased irrigation during the last have of the 1980s. All secondary recharge was slowly reduced due to the reduction in irrigation deliveries (Water Master records for irrigation ditches) and the reduction in irrigated lands. Commercial and residential development has all but replaced these irrigated lands. This most certainly has had an effect upon the ground water levels in the aforementioned geothermal monitor wells.

It is interesting to note the fluctuation in the water level at the PTR#1 well (Figure 16) during the years of 1984 to 1988. It is observed that the annual fluctuation is approximately 10 feet. This may coincide with recharge from irrigation and ditch practices. This magnitude of fluctuation is not observed today.

Geothermal production and injection influences

As with the municipal pumping, the production from the two Steamboat (I/IA and II/III) geothermal plants are reviewed for any correlation to the geothermal monitor well historical water levels. And as with the previous charts, the PTR wells are used to reflect the changes in the potentiometric surface immediately north of the geothermal system. Figure 18 shows the changes as compared to the Steamboat production and the Caithness production in Figure 19. Note that the annual pumping is plotted at December of each year.

The Steamboat I/IA plant averaged approximately 1.5 to 1.8 billion gallons of annual production from 1988 through 1993. During this time frame water levels dropped in the PTR wells and follow the same trend prior to plant startup. During 1993 the SBII/III plant began operations when total production from both plants increased significantly to 11 billion gallons and quickly increased to approximately 12 billion gallons through 2003. During this time frame the PTR water levels continued to drop through 1995 and then rose through 1998. Since that time the levels dropped to below 100 feet until 2005 where they began to rise. Overall, there is not a convincing trend such as the hydrographs for PTR with annual precipitation. Also, plotting just the SBI/IA production against the water levels for PTR did not provide a correlation.

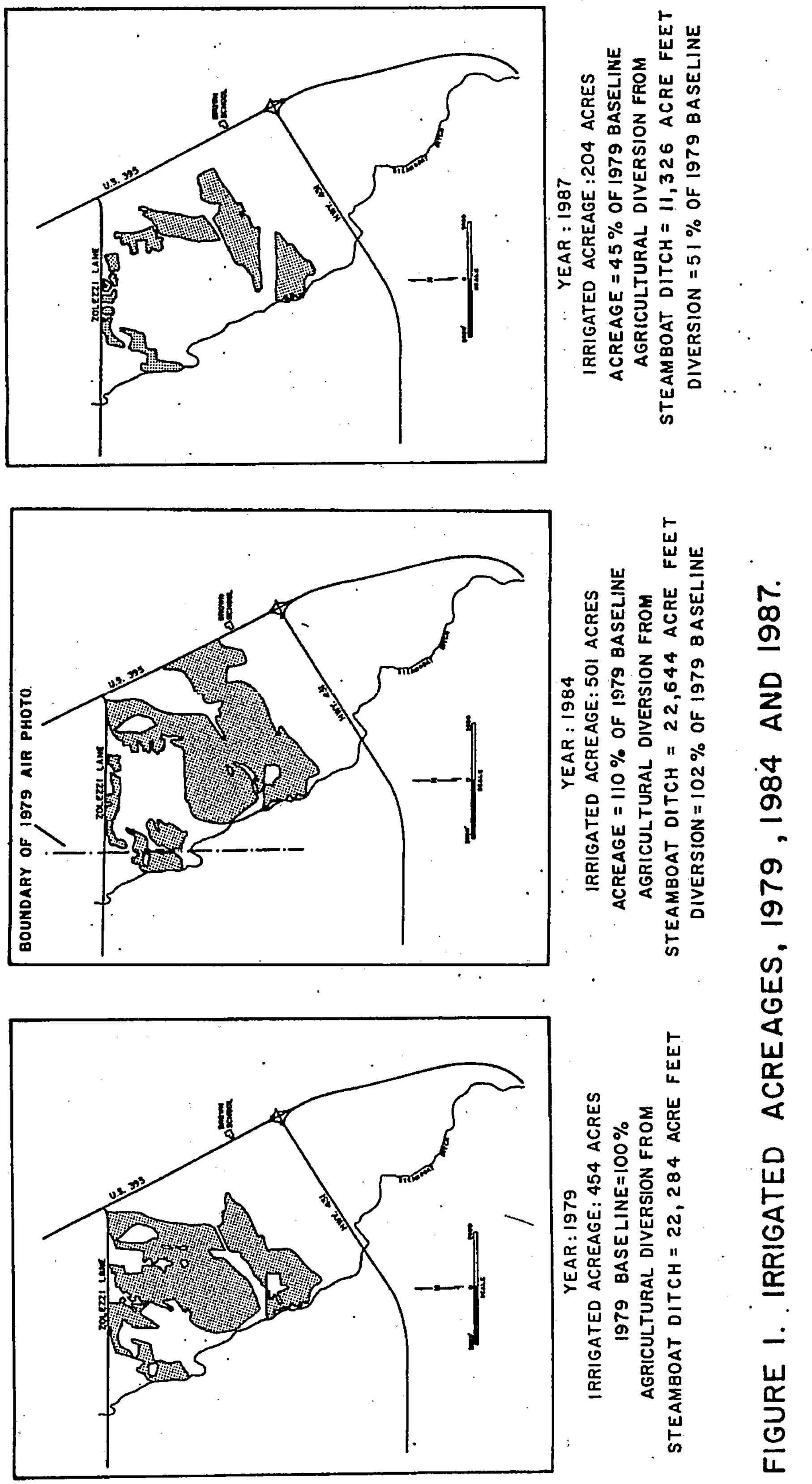

Figure 17. Yeaman's (1987) Figure 1 of the irrigated acreage in years 1978, 1984 and 1987.

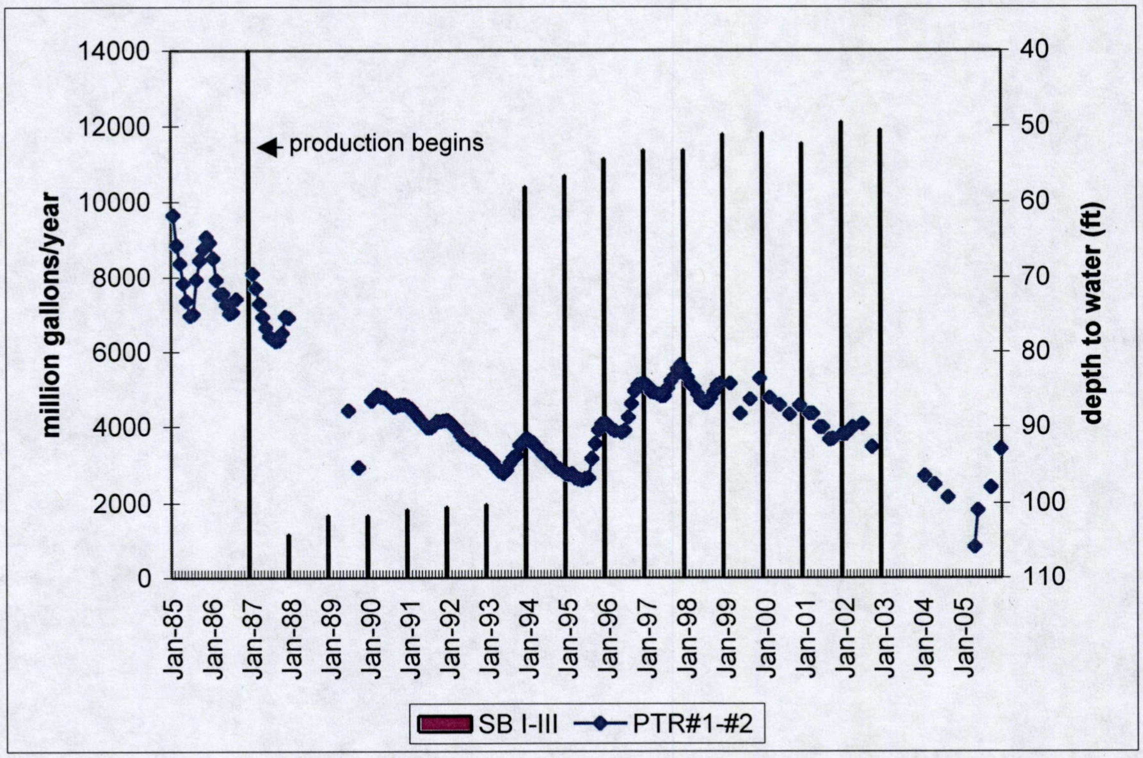

Figure 18. PTR#1-#2 water levels compared to Steamboat production

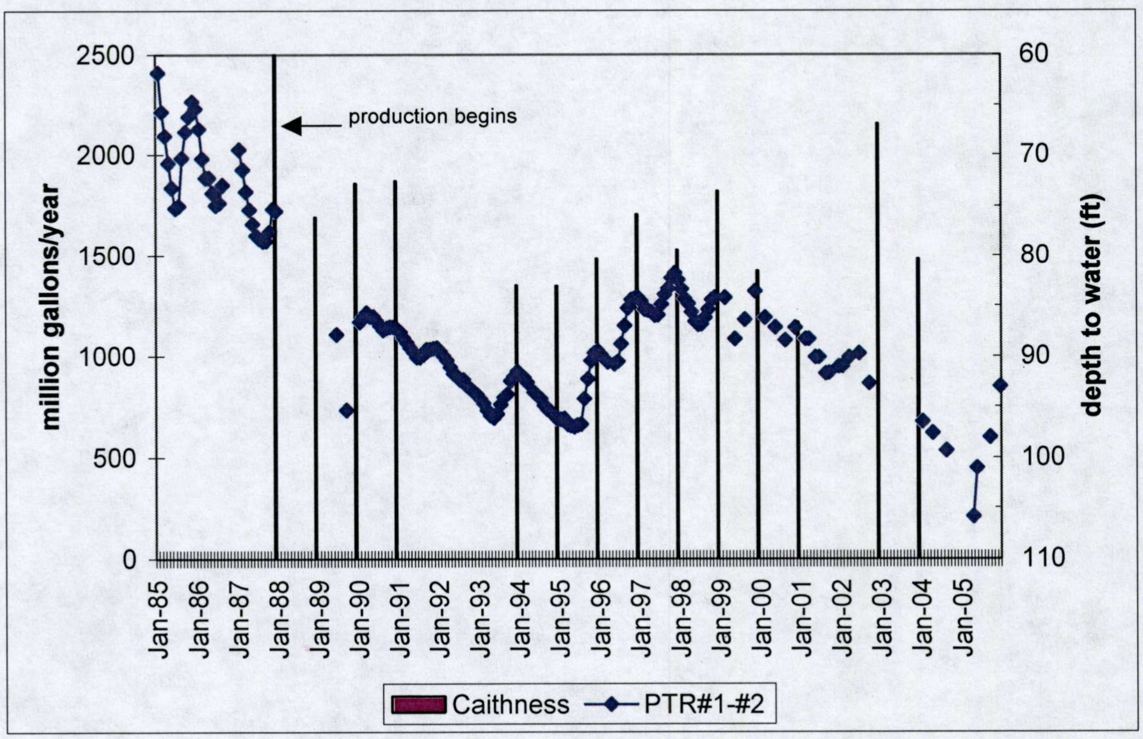

Figure 19. PTR#1-#2 water levels compared to Caithness production

In comparison to the Caithness (Steamboat Hills) plant's production, there is a correlation during the years 1987 through 1995 (note missing data from 1991-92), but then an inverse correlation until 1999. This also does not provide a trend that would indicate a direct relationship to geothermal production and water levels in the PTR wells.

Injection was also compared to the PTR wells' water levels. Figure 20 displays the Caithness injection pressures to the PTR water level. Again there is not a clear relationship of these two data sets, the thinking that injection pressures might cause a rise in water levels.

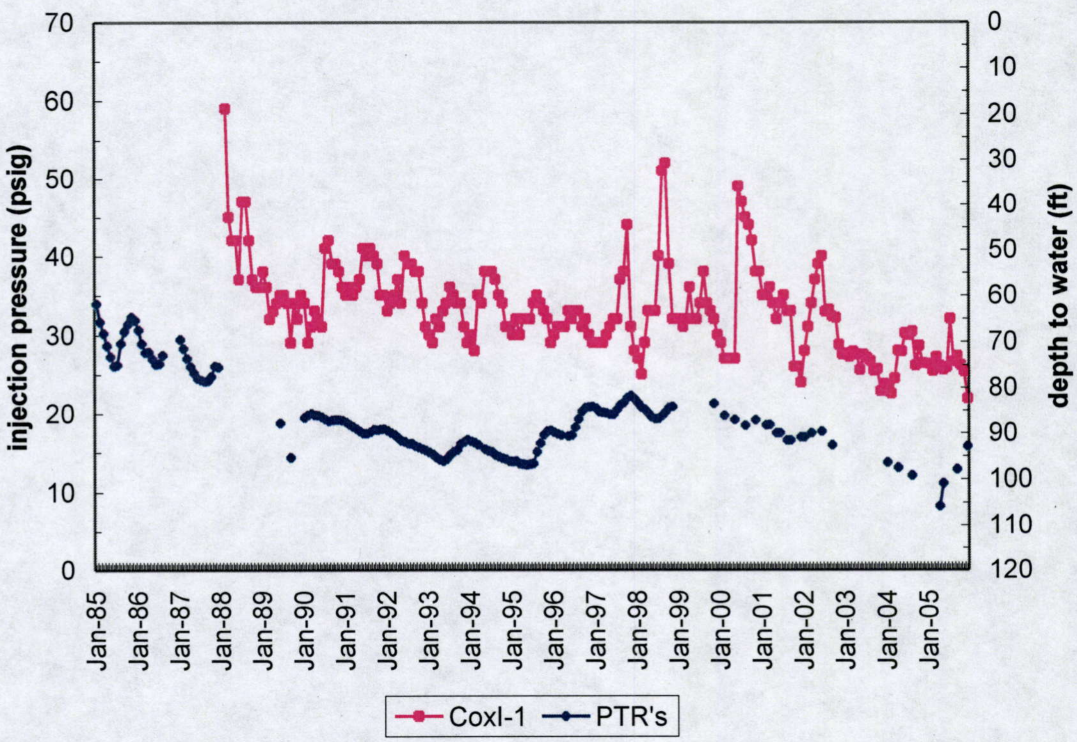

Figure 20. PTR#1-#2 water levels vs. CoxI-1 injection well pressures.

ANALYSIS OF WATER QUALITY CHANGES IN MONITOR WELLS

This portion of the report further details the changes is water quality that Yeamans discussed. The changes in well water quality is related to annual precipitation and water level declines as discussed earlier and shown to have a direct effect on the geothermal monitor wells. The water level declines are also indicative of the influence from municipal production, although the impact appears to be less than from precipitation and cessation of irrigation. The well water chemistries are further compared to geothermal injection rates.

Comparison of climate and potentiometric changes to water quality

Figure 21 displays the chloride concentration found in the Herz Domestic, Brown School and PTR#1 wells, with time, plotted against the annual precipitation record. Also shown are the time periods of the geothermal operations. At the Herz well, the chloride concentration begins to increase in 1989, two years after the SBI/IA startup and one year after the Caithness startup. As Yeamans pointed out (2006), there appears to be a lag period of one to two years between the increase in chloride and geothermal injection. As the drought continues, the chloride concentration increases until SBII/III

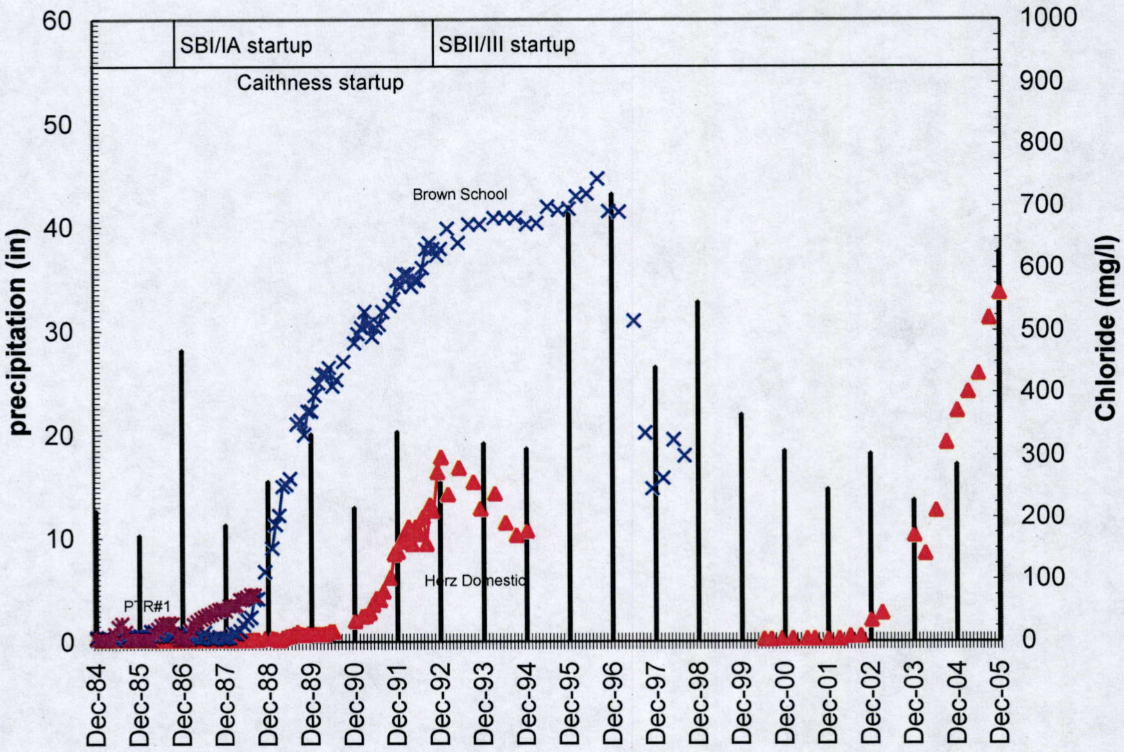

Figure 21. Comparison of annual precipitation to Herz Domestic, PTR#1, Brown School chloride

begins operations where it then decreases. This is curious because the drought continues, but December 1992-January 1993 were very wet months. For the next two years the concentration decreases through 1994 and monitor data is missing. Data collection continues in 1999 and chloride concentrations are at background levels. This appears to be reflected by the above average precipitation years of 1995-1998 if the two-three year lag period is in effect. As several more years of below average precipitation occur, the chloride concentration increases. The last two years of above average precipitation do little to change the rate of increase.

For the Browns School well, the concentration increases a year after SBI/IA startup and at the same year as the Caithness startup. The concentration continues to increase through the drought and then decreases quickly after two above average precipitation years. The well was abandoned in 1998. For the PTR#1 well, chlorides fluctuate based upon the amount of irrigation and precipitation (Yeamans, 2006). Chlorides rise in 1987 when the

SBI/IA plant begins and continues to rise after the Caithness startup. This occurs after an above average year (1986) and an average year of precipitation (1987).

Figure 22 displays the chloride content for these wells, but compared to water levels in the MW#3 well (Washoe County). The water level is used as a proxy for the decline in the potentiometric surface displayed in previous figures. The water level begins to decline in late 1984 (minimal municipal pumping during 1985) and continues until June of 1993. During this time frame the chloride levels rise for all three monitor wells, however there appears to be a two to four year lag period for the PTR#1, Browns School and Herz Domestic wells, respectively. Water levels remain stable through 1994 and then rise with the ensuing wet years of 1995–1998. Data is missing for the Herz Domestic for this period and the PTR#1 well was abandoned in 1998, but not sampled after 1988.

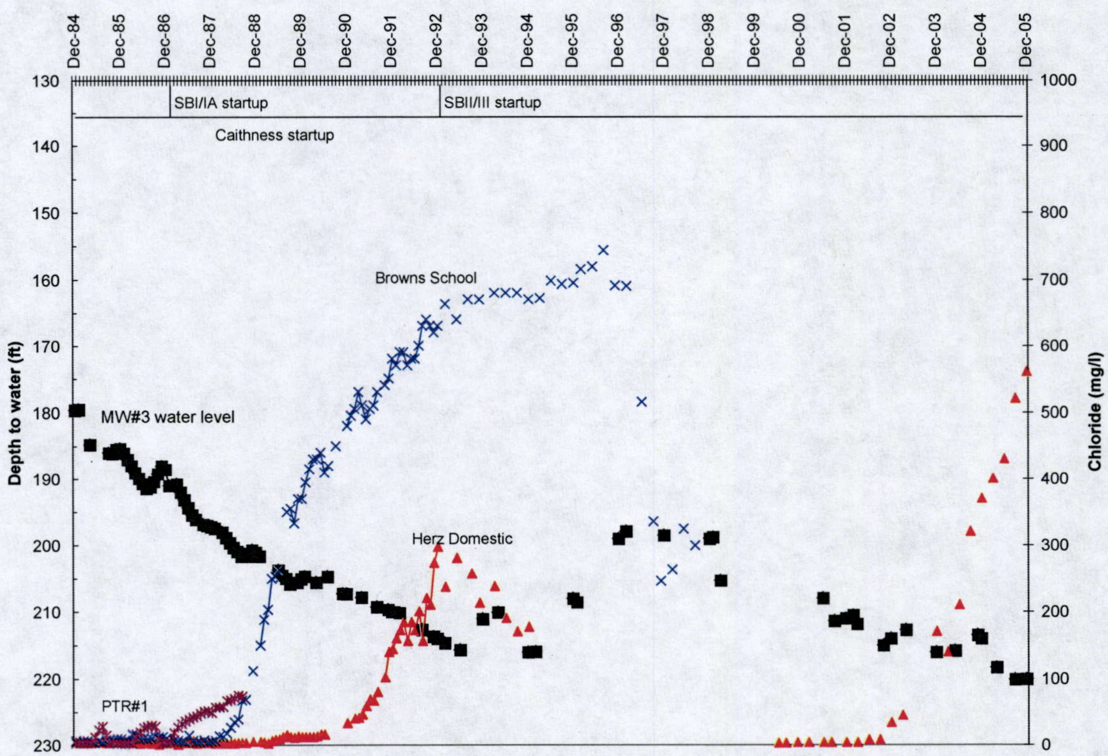

Figure 22. Comparison of Washoe Co. MW#3 water levels to Herz Domestic, PTR#1, Brown School wells chloride history.

The Brown School chloride concentration decreases dramatically during this time, abandoned thereafter. After the wet period 1995-1999, monitoring of the Herz continues and the concentration is at 1984 background levels until 2003 when the concentration increases significantly. This increase appears to correlate with the lowering of the potentiometric surface as shown with the MW#3 levels.

Comparison of geothermal production to changes in water quality

Figure 23 compares the same chloride levels with geothermal production. Please note that missing production data was estimated, particularly for the years 2003-2005. The annual production is shown for the Caithness (plotted in October), SB I/IA (plotted in November) and SBII/III (plotted in December). This Figure would indicate that the PTR well began to respond to the SBI/IA production in 1987. The Brown School well responded to production in 1988 when Caithness was also in production. The Herz Domestic well began to respond, slightly, in 1988 and more significantly in 1991.

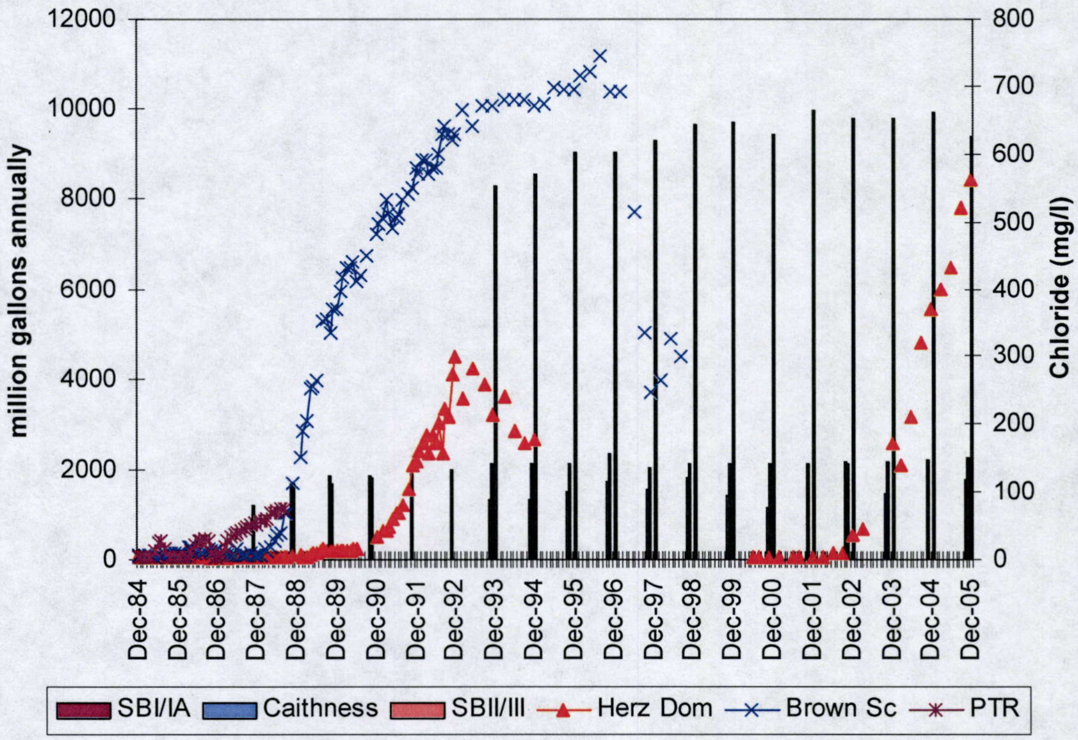

Figure 23. Comparison of monitor well chloride values to total geothermal production.

SBII/III production did not appear to affect the Herz Domestic well, but may have elevated the Brown School water chemistry. However, the decline in chloride concentration that began in 1997 decorrelates with this production. The lowering of the concentration when sampling began in 2000, consequent rise in 2002 and significant rise to date is not explained in this Figure.

Comparison of geothermal injection to changes in water chemistry

Individual power plant injection pressures were analyzed with respect to the rising chloride levels in the previous monitor wells. The thought is that the injection pressure would increase the migration of geothermal fluids through fault structures that affect these wells (Yeamans, 1987 and 2006). The injection pressures have shown a fluctuation in patterns as compared to production rates.

At SBI/IA the IW-3 was used almost exclusively for plant injection where IW-1 was never used (?) and IW-2 was used intermittently. At SBII/III, four individual injection wells are in use. The pressures used in this analysis reflect that of the plant. At the Caithness operation, the CoxI-1 well was the only injection well used until it was replaced in 2005 by 64A-32.

Figure 24 displays the SBI/IA injection pressures and rates compared to the chloride concentrations sampled in the Brown School and Herz Domestic wells. Overall the injection rates (displayed as gpm/10) increase with time from ~3,000 gpm to 4,600 gpm. In this Figure the individual pressures are not shown well, but most of the outline reflects IW3. Throughout the life of this plant, IW3 was mostly used for injection. At the startup of operations, IW3 pressures were approximately 30 psig gradually increasing to 90 psig by 2000 and then a gradual reduction to 30 psig today. IW2 pressures reached a maximum of 215 psig during 1996 (shown as the anomaly), then reduced in 1997 to ~25 psig and gradually to 5psig today. It is unknown why pressures were so high in 1995-96.

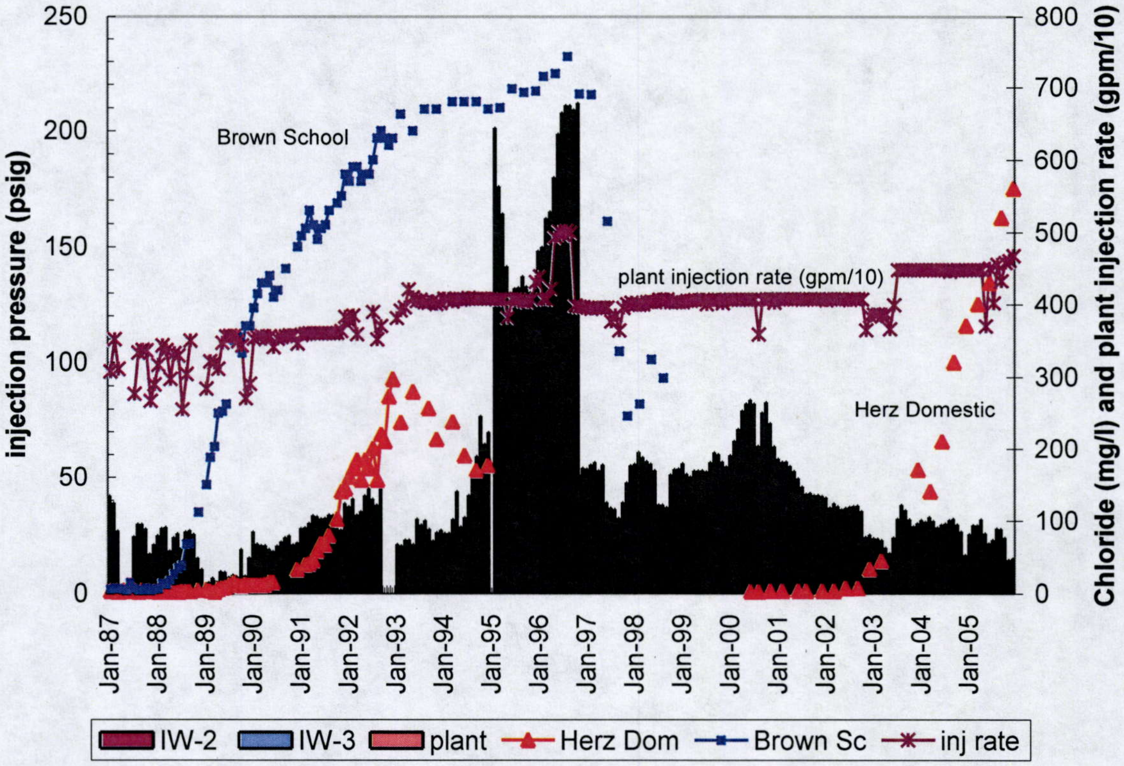

Figure 24. Chloride concentrations of monitor wells vs. SBI/IA injection pressures and rates.

These pressures appear to affect the chemistry of the monitor wells with the startup, particularly the PTR well (not shown). If this is true, an apparent time delay is seen in the Brown School well and the Herz Domestic well in terms of their chloride response to the injection. The Brown School well chloride increase can be correlated to the increase in injection pressures from 1989 through 1992. During 1993-94, pressures dropped to less than 30 psig and the chloride levels remain constant at under 700 mg/l. In 1995 the IW2 pressures increased to 130-210 psig and this may reflect the increase in chloride to above 700 mg/l. In late 1996 IW2 was shut in (?) and IW3 pressures fluctuated around 50 psig. The Brown School chloride concentration dropped significantly to less than 100 mg/l. The same pattern is better correlated in the Herz Domestic well through 1994, but the concentrations of chloride from the year 2000 onward are not explained by the injection pressures, but may correlate to the increase of production.

Figure 25. displays the injection pressures from the SBII/III plant (poor data support individual well pressures) against the chloride concentrations of the same monitor wells. Chloride values were already elevated prior to the start up of the SBII/III plant. It is curious to note that upon startup, the chloride concentrations in the Herz Domestic decrease. Also, the Brown School chloride concentrations begin to level out at this point in time as well, but near the pure geothermal content of 800 mg/l. When the pressures drop during 1995, no response is seen in the Brown School concentrations until 1997. Without an apparent change in injection operations in 2003, the Herz Domestic well concentrations increase significantly.

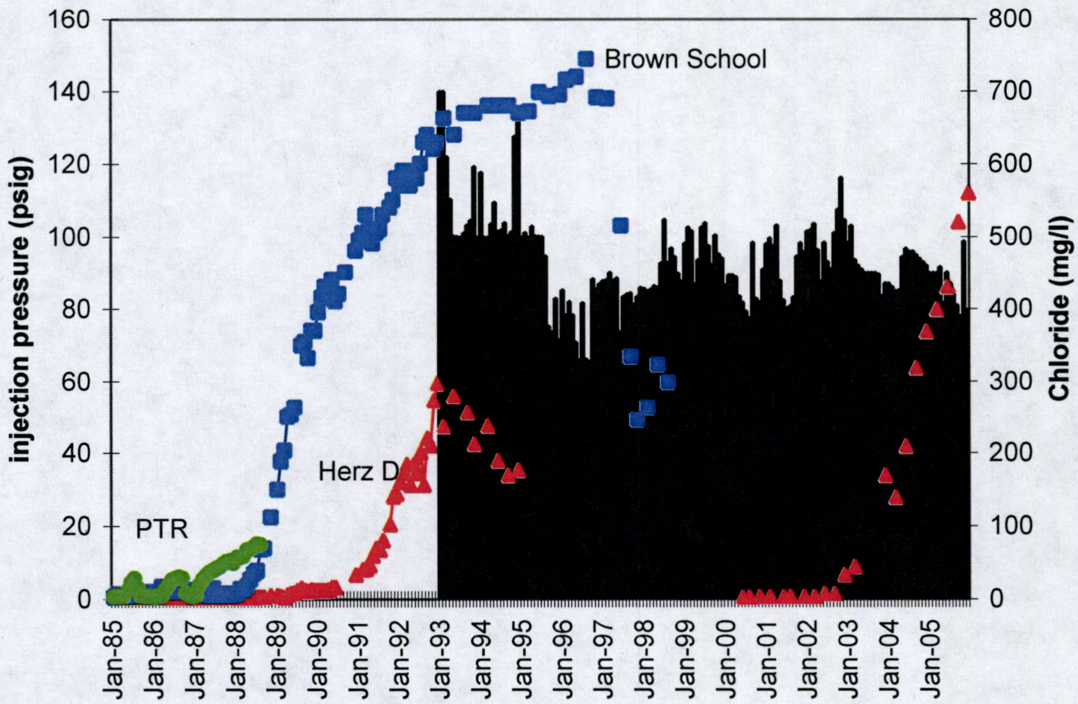

Figure 25. Chloride concentrations of monitor wells vs. SBII/III injection pressures.

A review of the individual injection rates (gpm) for the four injection wells were made to determine if any correlation could be made between individual wells and chloride increases or decreases as seen in Figure 25. Reports made available to Washoe County only list individual well injection rates as of 1997. Little can be drawn from this data in regards to the Brown School chloride concentration. Changes in wellfield injection operations indicate (from the data provided) that the rate of injection in IW-1 decreased over time (~4,000 gpm to 2,500 gpm), IW-5 had relatively constant injection rates until 2002 when the rate was decreased substantially (from ~8,000 gpm to ~3,000 gpm), IW-6 had a rate increase in 2002 (from ~2,500 gpm to ~7,000 gpm), and IW-4 had a relatively constant rate of injection (~6,000 gpm). Then all that can be surmised is that the increase of IW-6 injection may have caused the increase in chloride concentration seen in the Herz Domestic well from 2002 to present.

Figure 26 displays the CoxI-1 and 64A32 (Caithness operation) injection pressures during the period of record. Note that the CoxI-1 well was shut in on November 2004, replaced by 64A32. In 1988 an immediate response in the Brown School chloride concentration is noted. After mid-1992, injection pressures slightly decrease and the concentration in the Brown School well remains relatively constant at 700 mg/l until mid-1997. Then the concentrations drop to approximately 300 mg/l after which the well was abandoned.

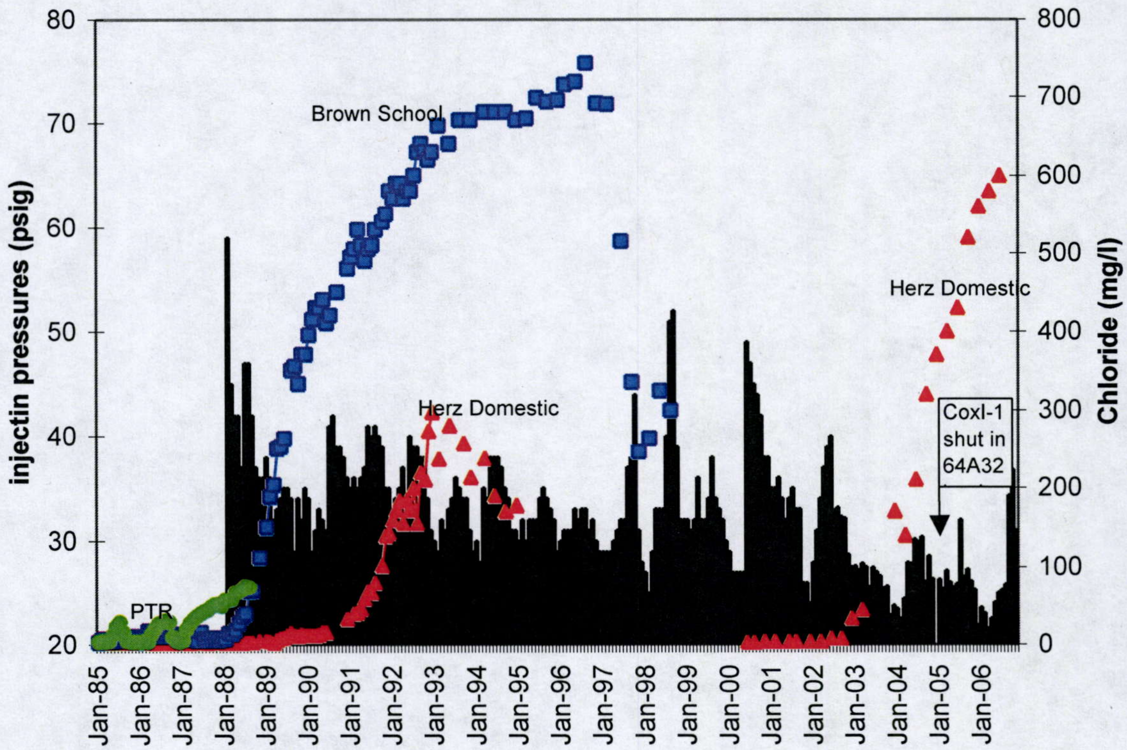

Figure 26. Chloride concentrations of monitor wells vs. CoxI-1 and 64A32 injection pressures.

The same pattern might be said of the Herz Domestic well although the concentrations did not significantly rise until 1991. There was a decrease in the concentration during 1993. When sampling continued in 2000, the concentrations increase from background in 2003 and continue to rise today.

Figure 27 displays the monthly average injection pumping rates (gpm) for the SBII/III plant. The top data set is the monthly average for all injection wells for this plant. Overall there is an increase in the rate from 15,000 gpm to 20,000 gpm in 2004. After this data, there is much data missing. Injection Well 4 shows a steady injection rate of approximately 6,500 gpm whereas Injection Well 1 shows a steady decline in the rate from nearly 5,000 gpm to 2,500 gpm over a period of eight years. In February 2002 the rates of injection at Injection Well 5 dropped from 8700 gpm to 3400 gpm while Injection Well 6 increased injection from 1,700 gpm to 7,000 gpm and these rates approximately persist today. This corresponds to the time that the chloride concentration in the Herz Domestic well rose dramatically from low background levels to 550 mg/l. Other correlations are not possible due to the lack of data.

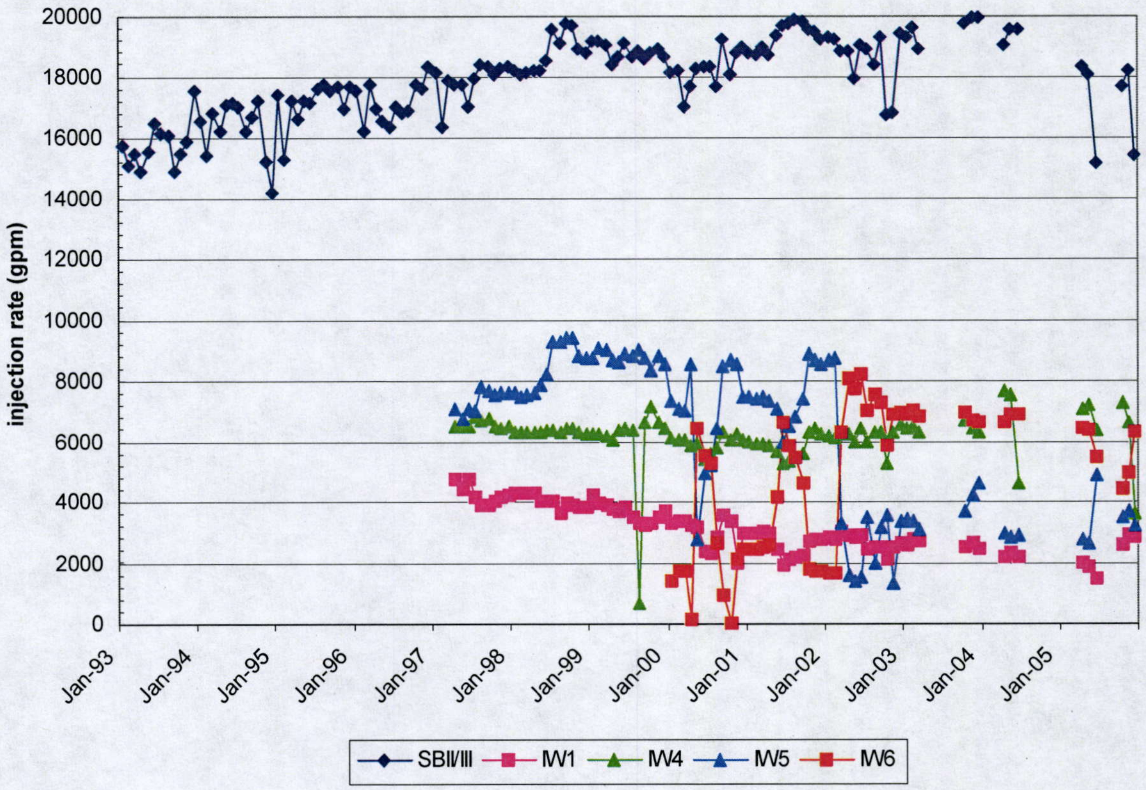

Figure 27. Monthly averages of injection pumpage for SBII/III wells including total for plant.

DISCUSSION

Changes in the potentiometric surface due to climate, irrigation and municipal production.

Figures 12-14 clearly illustrate the correlation of ground water levels and annual precipitation. These figures draw upon historical data from three distinct areas, far removed and up gradient from the geothermal and municipal pumping (first aide well), within the fringe of the two wellfields (STMGID MW#3), and within the geothermal discharge area (PTR). It should be recognized then that just climate, such as prolonged drought, will cause the potentiometric surface to decline. This has the effect of reducing the head upon the geothermal discharge areas allowing geothermal fluids to increase their effects on water chemistry.

Municipal pumping will also affect the potentiometric surface by causing a decline in ground water elevations. As shown in Figures 6-8 and 11, individual production wells or clusters of production wells have lowered this surface. However, after some period of time, the effects from pumping the individual wells will diminish as long as the pumping rate remains constant or decreases. This is the case in the STMGID production wells 1, 2, 3 and 4; the municipal wells most likely to effect the geothermal monitor wells as shown in Figures 15 and 16.

The effect of the diminished irrigation recharge upon the potentiometric surface has already been discussed by Yeamans (1987). It is clear that water quality degradation within the geothermal discharge area suffers because of it. Whether or not the lack of irrigation recharge will continue to affect a change is not readily apparent and will probably never be known. This is because the historical rate of irrigation and the gradual decrease has not been documented.

There is a very poor record of water level measurements for most of the geothermal monitor wells. The best record consists of combining the Pine Tree Ranch #1 and #2 wells. Used together, Figures 13 and 16 illustrate that annual precipitation (as a proxy to ground water recharge) most likely has a far greater impact on theses monitor well levels. The reduction in irrigation largely contributed to the water level decline seen in the years 1984 to 1994.

Changes in the potentiometric surface due to geothermal production and injection.

Geothermal production does not appear to have affected the potentiometric surface of the cold-water aquifers immediately north of the Mt. Rose Highway. Figures 18 and 19 show no correlation between production and water levels in the Pine Tree Ranch monitor wells. However, Figures 6, 7, and 11 do show potentiometric impacts from geothermal pumping.

Potentiometric changes in the geothermal reservoir are occurring. This can be seen in Figures 6, 7, and 8 from the Felling report. A depression is noted over the ST2 well that grew from 50 feet during 1982 to 1992, to 80 feet in 2002. These changes are support by ST5, ST7 and ST9 all deep hard rock wells. This change might be better described by the data set provided in Figure 11. Using the aforementioned wells plus the observation and test wells within the two lower power plants, the aforementioned depression is disputed. A larger anomaly is noted between the SBI/IA and SBII/III plants with head changes of over 150 feet. The aforementioned depression actually shows an increase in head, at least with respect to the Stuart, ST5 and ST9 wells. ST2 supports the depression associated with the lower plants. The depression should be confined to the hard rock aquifer, and not affecting the nearby Soccer Field well. An explanation for the depression can be made from the following.

The fracture system within the reservoir appears to have three sets of orientation and these sets may not interact with each other. From White (1964) the surface fracture traces are oriented north-north-west, north-east and north-west. It would appear that the depression is located in the fractures oriented north-north-east and the small potentiometric rise is located in the fractures oriented north-west. The SBI/IA production and injection is located on the former and the SBII/III plant over the later. It should be noted from the record that injection volumes from the SBI/IA plant do not equal the production in that some of the SBI/IA spent fluids are injected at the SBII/III wellfield. This imbalance of production and injection within the same fracture network may create the depression in a general sense. One must think of the fracture connectivity within a

family network of fractures. This additional injection at the SBII/III plant would also give an explanation for the small rise in the potentiometric surface noted in Figure 11.
There is also a net loss from the geothermal system from the Caithness (now Steamboat Hills) operation where some production is lost to evaporation during the power generation process. This loss is estimated at 15% to 20% and amounts to approximately 400 AF/yr. For the geothermal system to remain at equilibrium, additional recharge to the system would be needed. This demand might cause a potential depression located over the geothermal recharge source area. Viewing the aforementioned figures does not provide any clues if indeed this point is valid.

The rise in the potentiometric surface over the central portion of the Steamboat Hills is somewhat puzzling. It would appear that the injection at the CoxI-1 well might be the cause of this. However, little data exists or has been recognized that would lead to a proper analysis of this change in the potentiometric surface. Also, from Figure 20 there is no apparent correlation of the CoxI-1 injection pressure on the water level changes seen in the PTR wells.

In discussions, Yeamans points out that, "the water table/hydraulic head in the cold water aquifer is a varying boundary for the geothermal discharge. Transient pressures from the geothermal production and injection wells will not pass or be transmitted past this boundary, a murky zone at depth where the geothermal fluids and pressures exit the geothermal system and are subsumed into the water table potentiometric surface. Production and injection pressures/rates can be compared with changes in the cold water chemistry (with or without time lags as determined to be appropriate), but there will not be hydrostatic pressure responses in the water table from geothermal operations."

Changes in water chemistry due to climate and potentiometric changes

A good correlation exists between below normal precipitation (again a proxy for regional ground water recharge) and the rise in the Herz Domestic chloride concentration. The drop in concentration that began in early 1993 might be explained by the exceptional wet months of December 1992, January and February of 1993. However, very little precipitation fell until November of 1994. The rise in the chloride concentration at the Browns School well to 700 mg/l nearly reaches the geothermal content of 820 mg/l from December 1992 until well after the drought ended in 1995. The concentration did not begin to decrease until mid 1997. Either this represents a lag period with precipitation or that the high levels of chloride were supported by the geothermal operations.

In the former case, viewing Figure 22 shows that the potentiometric surface (illustrated by the MW#3 levels) might support a pressure head that holds the chloride concentration below 200 mg/l in the Herz Domestic well. This pressure head might be represented as a depth to water of 215 feet in MW#3. If the water level drops below this elevation, the chloride concentration appears to rise above 200 mg/l. When the water level rises above this level (<215 feet) the concentrations fall in both the Herz Domestic and the Browns School wells. This might explain the sudden rise in the chloride concentration at the Herz Domestic after 2004 when the water level in the MW#3 drops below 215 feet.

In the later case, the Brown School well chloride concentration drops in 1997. This might be due to the change in injection pressures during 1995-96 shown in Figures 25 and 26. If a lag period for pressures to change in faults near the Brown Scholl well, this plant operation change might explain the sudden drop in chloride concentration. However, a clearer correlation for the Browns School well's behavior in 1997 is the relationship to the above average precipitation shown in Figure 21.

Felling plots a large potentiometric depression occurring over the ST2 well during periods from 1982 onward. As shown in the Figure 6-8, this could have the effect of lowering the water levels north of the Mt. Rose Highway and affecting water chemistry. Figures 9-11 also support a depression over the eastern portion of the geothermal reservoir. However, the depression is most likely confined to the hard rock aquifer within the geothermal reservoir otherwise it is difficult to account for the rise in chemistry of the monitor wells is pressures are reduced. And as shown in Figure 11, the depression appears only over the SBI/IA operation.

Changes in water chemistry due to geothermal production and injection

From the various figures shown in this report and from Yeamans (2006) it is clear that the geothermal operations have caused water quality changes in nearby monitor wells. Most likely this is due to injection practices and not production. Figure 23 illustrates that production is not clearly linked to the chemistry changes seen, over the 19 years of operations.

The injection pattern from SBI/IA is best linked in time with the rise in chemistry for the PTR well. The Brown School well's chemistry is better linked to the startup from the Caithness operation. With the increase in pressures from the SBI/IA plant during 1990, the Herz Domestic well shows a link with respect to time. This is also seen when pressures are reduced at this plant in 1993 where the chloride concentration decreases at the Herz Domestic well. Startup at the SBII/III plant supports the 700 mg/l chloride concentration at the Brown School well with respect to time.

There have been as many as eight injection wells used between the three power plants where pressures and injection rates have been variable with time. Consequently, there are no clear and instant patterns linked between the injection wells and the changes seen in the monitor wells over time. Added to this is the influence that the cold water aquifer has on these wells given the fluctuation in potentiometric surface due to the fluctuating sources of recharge and to some extent, municipal pumping. This cold water "cap" can only control the extent of vertical movement and rate of geothermal fluids and consequent "mixed" water quality measured in monitor wells. The geothermal discharge will always occur regardless of the power plant operations and the fluctuations of the "water table".

Because the geothermal wellfields operate in faulted and fractured rock, the injection patterns that are manifested in the alluvial aquifer are also fault controlled (Yeamans, 2006, 1987, 1984; Widmer, 2006). Injection pressures in faults within the geothermal wellfield are, to some degree, dissipated with distance from the wellfield. Because the geothermal discharge has always occurred at distance from the reservoir, changes in the hydraulic nature of the reservoir will change and effect the pressure distribution within and outside of the reservoir. Depending upon the permeability and connectivity of these faults and fractures, some lag time is required for the injectate to migrate northward and eastward from the reservoir. The changes in the water quality at the monitor wells reflect this lag period. Despite the incompleteness of geothermal monitoring data, an analysis of fault structure and their relation to all geothermal wells is important to better understand water quality changes noted to date.

Skalbeck's Mixing Line

Skalbeck et al, (2000) derived a geothermal mixing line for the Steamboat Geothermal System that illustrated boron and chloride concentrations to mixed thermal and non-thermal water. Figure 28 shows this mixing line and displays the Herz Domestic well data. Most of the early data is shown in the lower left corner of the graph, but also shows a trend of increasing chloride during the historical drought of 1988-1994. Beginning in 2003, concentrations are following the mixing line and trending toward "pure" thermal water. Pure thermal water is defined as the chemistry of the "flashed" Steamboat Hills production fluid, approximately 750 ppm chloride and 40 ppm boron. This graph would indicate that the Herz Domestic water chemistry is tending towards pure thermal water.

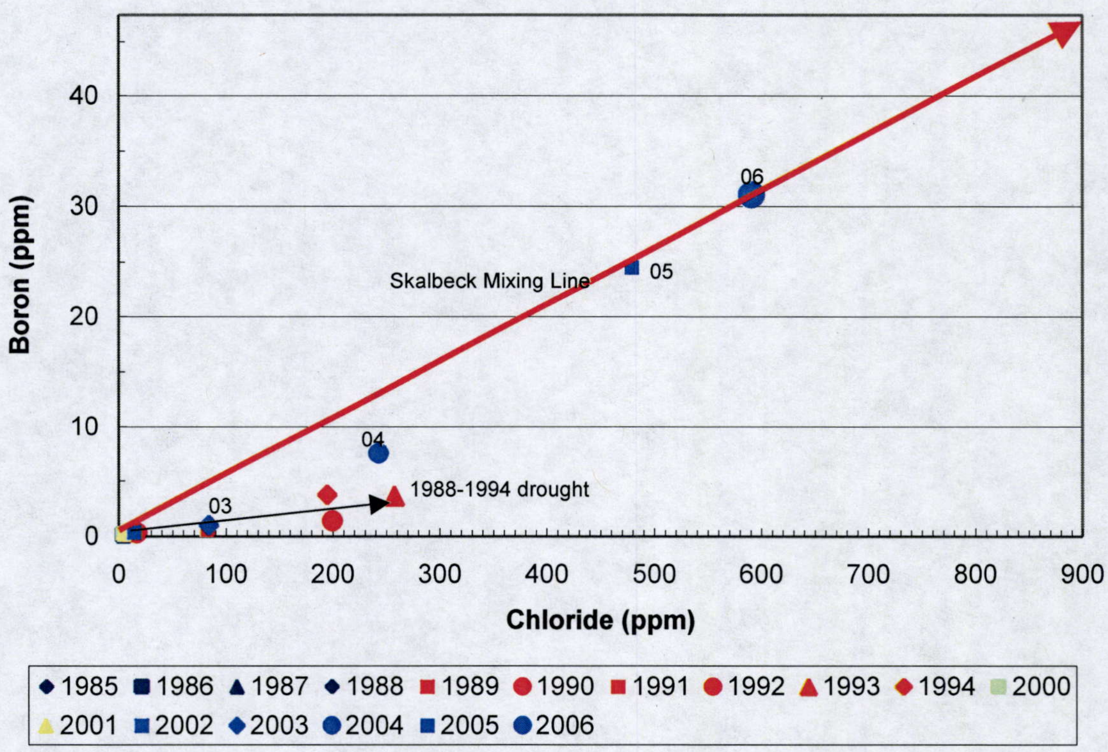

Figure 28. Herz Domestic chloride and boron concentrations related to Skalbeck's Mixing Line

CONCLUSIONS

1. Water levels in the geothermal monitor wells are greatly affected by the annual amount of ground water recharge that occurs, primarily as snowmelt in the Carson Range. Figures 12, 13, and 14 all support this conclusion. The reduction in irrigation within the Pine Tree Ranch area has also played a major role in water level decline at least during the late 1980s.

2. To a lesser degree, municipal production of ground water affects water levels measured in the geothermal area during the late 1980s and early 1990s. This initial effect appears to no longer have an effect as shown in Figures 15 and 16, primarily due to the constant or declining annual rate of production.

3. Geothermal production does not have a clear correlation with water level declines noted in the geothermal monitor wells, shown in Figures 18 and 19. Geothermal injection patterns do not support a rise or decline in water levels in adjacent monitor wells.

4. The geothermal monitor wells are located within a historical geothermal discharge area. The timing of the measured water quality changes coincide with the startup of the geothermal operations. There is little doubt that the increases in chloride and other water quality constituents are caused by the geothermal operations. Additionally, the lowering of the water table within this region has most probably allowed an increase in geothermal discharge as well.

5. It is difficult to determine the exact cause of the fluctuating concentrations of water chemistry in the geothermal monitor wells. It is certain that fluctuating water levels and geothermal injection patterns both play a role in the water quality changes noted. A lag in time periods of geothermal discharge and perhaps pressure responses appear to be responsible for this uncertainty.

6. The lack of geothermal monitoring data exacerbates this analysis' conclusions. Injection patterns probably affect water quality changes noted in the geothermal monitor wells. Lack of supporting data, such as individual injection well pressures and injection volumes, would greatly help in determining cause and effect of water quality changes.

7. Understanding the fracture and fault patterns would most likely give a better insight to water quality changes measured in the geothermal monitor wells.

8. Currently, the Herz Domestic well water quality is trending towards a pure geothermal concentration.

QUESTIONS LEFT UNANSWERED

1. How the potentiometric depression measured over the SBI/IA plant affects geothermal discharge outside of the reservoir area is unknown. The rise in this surface, apparently centered over ST5 is also poorly understood.

2. The effect of the reduction in irrigation recharge would be helpful, but may be academic at this point. With sufficient data from the Steamboat Ditch Company, this could be worked out.

3. Neither the sudden drop in the chloride concentration measured at the Herz Domestic well during 1993-1994 nor the sudden rise in concentration in 2003 is explained.

4. The sudden drop in chloride concentration at the Brown School well during 1997 is not fully explained.

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