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AN ANALYSIS OF GROUND WATER  
MONITORING DATA IN THE STEAMBOAT  
SPRINGS GEOTHERMAL AREA

Prepared for the  
Washoe County Department of  
Water Resources

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October 15, 2006

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## CHAPTER ONE - INTRODUCTION

### Background

During the past twenty years Washoe County has developed and continues to develop the ground water resources in the south Truckee Meadows. The ground water has become an important source of municipal water for the residential and commercial growth in the area. The continued use of this water source depends on protecting the water quality in the aquifers supplying the county wells. Of particular importance is the shallow water table aquifer in the Mt. Rose alluvial fan west of Steamboat Creek. Ground water studies in respect to geothermal energy development have been undertaken since 1981.

Starting in January of 1987 geothermal fluids from the Steamboat Springs geothermal system have been used for the generation of electricity. Ormat Energy Systems, Inc. (ORMAT) in 1987 and SBGeo in 1993 constructed what were then separate geothermal power projects, the former on what is known as the High Terrace and the latter on the Main Terrace. For this report the ORMAT operation is identified by its present name SBI/IA and the SBGeo project is identified as SBII/III. Caithness Power, Inc. began operation of a single flash steam driven power plant in February of 1988 (Figure 1). The generators employ either the two phase flash flow of steam and water from a geothermal well (Caithness) or the single phase pumping of the geothermal fluids (SBI/IA and SBII/III).

The SBI/IA and SBII/III spent geothermal fluids are injected into the subsurface. Caithness fluids also are injected but a portion (>15%) are evaporated. Under operating permits issued by the Nevada Department of Environmental Protection the spent fluids are to be injected into zones that are equal to or lesser than the water quality of the injected fluids. This invariably means that the spent fluids are injected into the geothermal system. Generally the injection zones are no deeper than the production zones for an individual project and may be shallower than the production zones. Geothermal energy production and injection has continued and expanded in the last 20 years.

### Purpose and Scope

With increasing demand for municipal water supplies the Washoe County Department of Water Resources has requested a review of the monitoring data to see if there have been changes in the cold, low total dissolved solids (TDS) water in the aquifer that is a source for the County's municipal wells and the target for future ground water development. This work focuses on ground water quality north of the geothermal production and injection areas. This is an area where there is natural subsurface geothermal discharge from faults in the bedrock into the shallow fresh water alluvial aquifer. With 20+ years of injection of spent geothermal fluids the question has arisen as to what effects, if any, has the injection had on the alluvial fresh water aquifer. This report has been prepared for the Washoe County Department of Water Resources for discussion with the Nevada Division of Environmental Protection and the geothermal operators.

The area of investigation in this report is north and northeast of the old U.S. Highway 395/Mt. Rose Highway intersection and on the east and west sides of U.S. Highway 395 (Figure 1). This area contains monitoring sites where there have been previous analyses of monitoring data. Comparison of these prior analyses with the subsequent monitoring data is helpful in drawing



conclusions regarding any possible changes in ground water quality. The current analysis has been restricted to the water chemistry data and measured water levels collected in the monitoring program. Data have been provided by the Washoe County Department of Water Resources. The most recent data are of June of 2006.

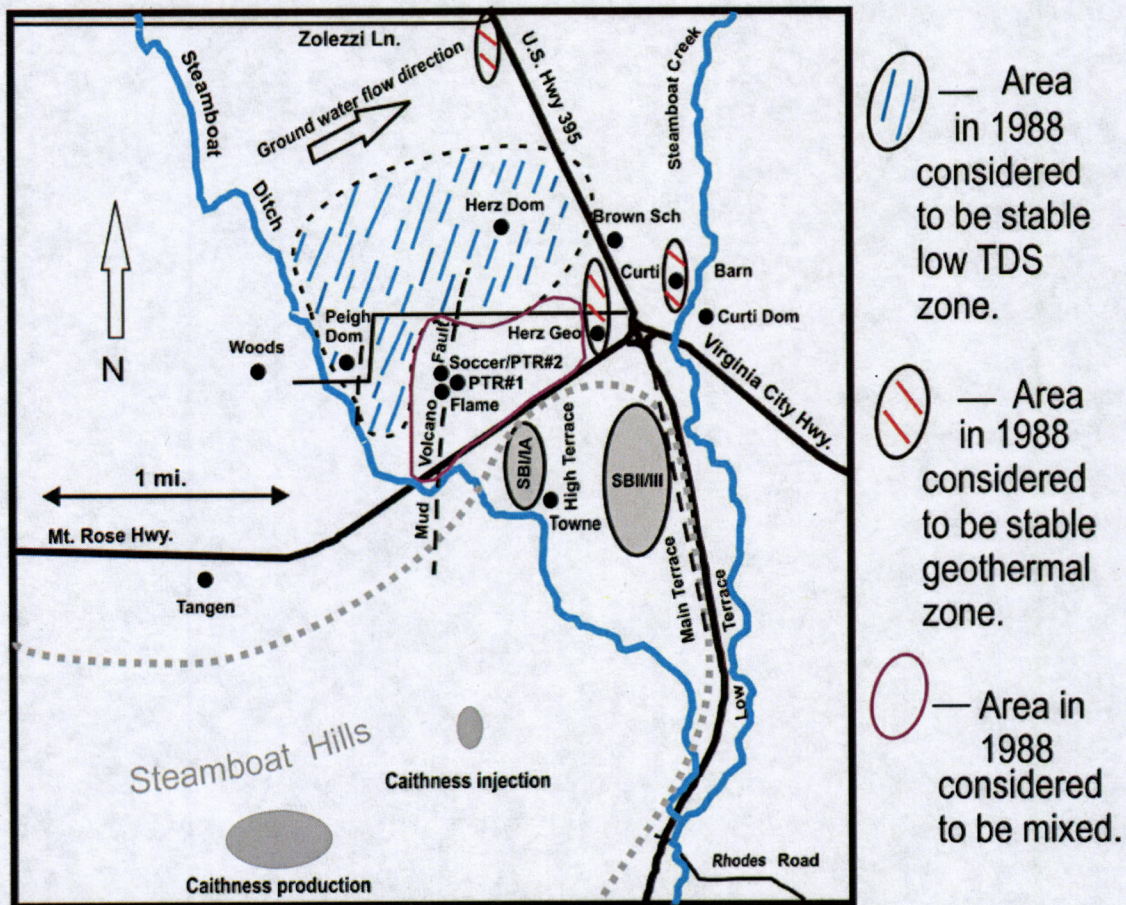


Figure 1. Location map.

## Previous Work

Prior to and after the large scale exploitation of the geothermal system numerous studies have been made, both of the geothermal system and the regional ground water system. One of the earlier geothermal studies and certainly the most extensive was that by the United States Geological Survey geologist Donald E. White and his co-workers G. A. Thompson and C. H. Sandberg. Working in the late 1940's and early 1950's their work resulted in the publication of three separate professional papers. One important conclusion from White's 1968 work was that the average natural discharge rate for the geothermal system was 1,100 gallons per minute based on an average chloride concentration of 820 mg/l. Only 6% of the discharge was visible as geothermal springs.

Other relevant works in the public domain include: Bateman and Scheibach (1975; Bonham and Rogers (1983); CH2M Hill (1982); Cohen (1962); Cohen and Loeltz (1964); GeothermEx (1989); Goranson and van de Kamp (1990); Goranson, van de Kamp, and DeLong (1991); Hunt-



ley, D., Collar, R.J., and Sorey, M.L., 1988; Katzer, Durbin, and Maurer (1984); Nehring (1980); Nork (1978a); Nork (1978b); Tabor and Ellen (1975); Thompson and White (1964); Trexler and McKinny (1980); van de Kamp and Goranson (1990); White (1968); White, Thompson, and Sandberg (1964).

### **Past Analyses by the Author**

In 1988 a study was made for the Nevada Division of Environmental Protection and ORMAT Systems, Inc. The work was focused on the hydrogeology and water chemistry in the vicinity of the Brown School well (Yeaman and Broadhead, 1988a). Data included not only that from the wells still used in the ongoing geothermal monitoring program but also data from the Nevada Division of Health for numerous domestic wells along Sage Hill Road just east of Brown School. The monitoring period included two years of background data (December, 1984 to December, 1986) and one year of operational data for the SBI/IA project (1987).

A 1988 statistical study (Yeaman and Broadhead, 1988b) included data for the same monitoring period as that for the Brown School report. Monitoring wells included the Herz Geothermal, Herz Domestic, Peigh Domestic, Pine Tree Ranch, Flame, and the Brown School wells. The Curti wells were not included in the analysis. The analysis was done to see if there were any statistical differences between the background and the operational data. Chloride was selected as the constituent for study.

### **Methodology and Approach**

After reviewing the 1988 statistical analysis it was decided to follow up on that work with the monitoring data that have been collected since 1987. The area of interest today is the same as that for the 1988 work, namely the shallow fresh water aquifer north and northeast of the geothermal area where there is natural subsurface discharge of geothermal water.

A brief examination of the current data shows a lack of continuity over the years. The in depth statistical analysis done for the 1988 work was not duplicated for this work. Significant changes can be recognized and discussed without detailed statistical analysis. Interpretation of graphical displays of data along with a discussion of the hydrogeological setting leads to an understanding of changes in water quality in the shallow fresh water aquifer.

## CHAPTER TWO - EXECUTIVE SUMMARY

Discontinuous monitoring data and the heterogeneous nature of the Steamboat geothermal system place some limits on reaching hard and fast conclusions. However the available data and what is known of the geothermal system in the area of the power plants and north and northeast of the Steamboat Hills can be combined to reach reasonable conclusions about changes over the last 20 years.

In the 1988 reports three hydrogeochemical zones were identified in the shallow water table aquifer in the alluvial fan north of the Steamboat Hills. The Herz Geothermal well represented a stable geothermal zone. The Peigh and Herz domestic wells were in a stable, low TDS fresh water zone. The Soccer and Flame wells were in a variable zone with fluctuating water quality.

Since the 1998 analyses there have been significant increases in the proportion of geothermal fluids found in several of the monitoring wells north and northeast of the geothermal operations. Specifically, wells that were formerly considered to be in stable zones of fresh water with low chloride concentrations now have concentrations greatly exceeding the earlier values (Figure 2). These wells include the Brown School and the Herz Domestic wells. To a lesser extent the Curti Domestic and the Tangen wells also have seen increases in their chloride concentrations. Where chloride concentrations previously were elevated but stable, the Curti Barn and the Herz Geothermal wells, increases have not occurred or are not as significant as those seen in the other monitoring wells.

- Chloride/boron ratios indicate that the source of the chloride is from geothermal fluids. Over time the ratios tended to merge to the average chloride/boron ratio value of 20 found in the geothermal fluids.
- There has been an overall long-term decline in the water table in the alluvial aquifer. As noted in previous works a decline in the static water level is matched by an increase in chloride concentrations. The decline in the water table could be caused by the loss of percolating irrigation water, climate, or by draw downs caused by the development of high yield wells to the north of the geothermal monitoring area.
- An unknown portion of the tremendous volume of spent geothermal fluids being injected by the SBI/IA and the SBII/III power projects may have migrated north to the monitored area along the natural subsurface discharge pathways. This would increase the rate of leakage to the shallow fresh water aquifer and cause the increase of geothermal fluids detected in the monitoring wells.
- The available data does not allow a determination of which influence is responsible for the increases in chlorides or has the greatest impact on the ground water quality.
- The most recent data from the Herz Domestic well, the most distant of the monitoring wells, show chloride and boron values continuing to increase. There is no data to indicate if water levels have stabilized or continue to decline.



- Most of the original monitoring wells have been destroyed with the advent of large scale commercial and residential development in the area. Without continued monitoring it will be difficult to determine when or if ground water quality has stabilized. This knowledge is necessary to insure the development of future municipal water supplies. A program should be maintained and/or developed to track ground water quality in the current monitoring area and where future water wells are planned.
- While there have been dramatic changes in the water chemistry of the alluvial aquifer north of the Steamboat Hills it may be possible to reduce or eliminate other monitoring sites where such changes have not been observed. Past work in Pleasant Valley suggest this may be an area suitable for a reduction in monitoring frequency.

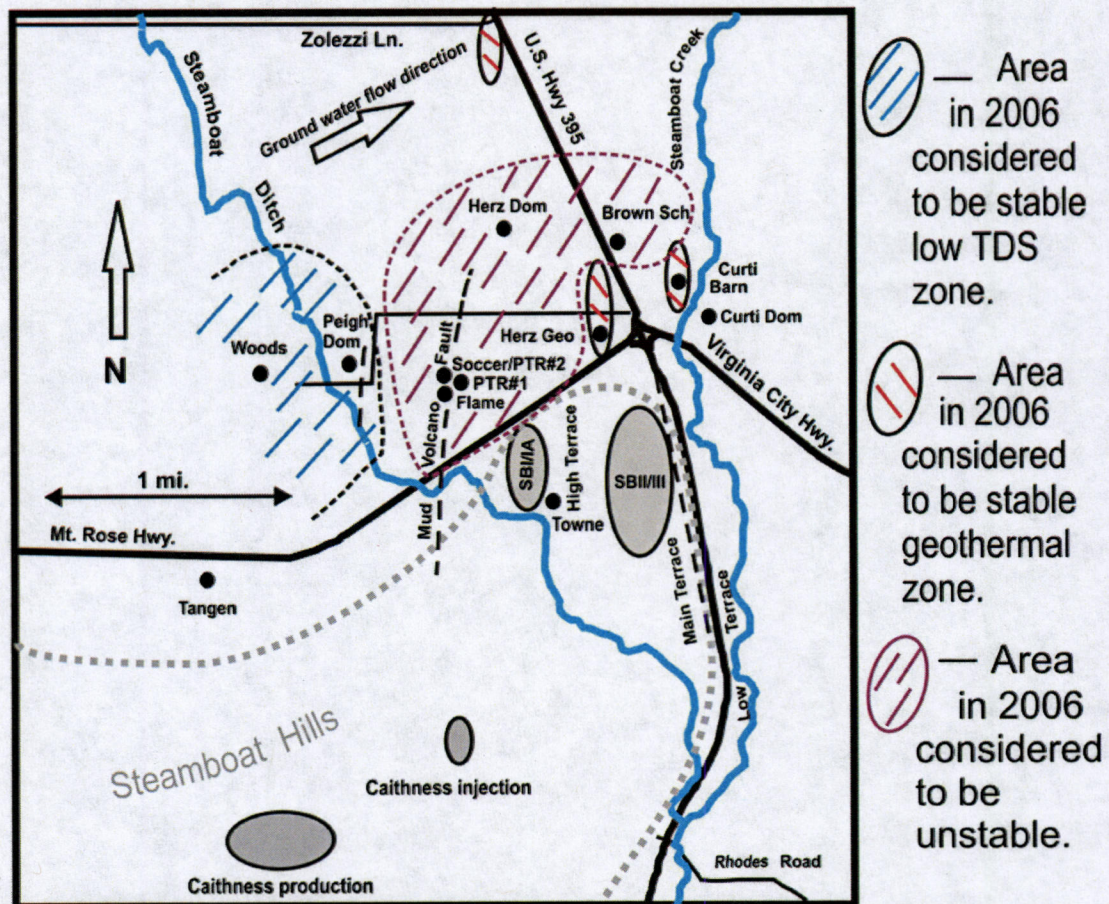


Figure 2. Ground water conditions – 2006.



## CHAPTER THREE – THE STEAMBOAT GEOTHERMAL SYSTEM

The following general description of the Steamboat Springs geothermal system has been taken from Thompson and White (1964), White, Thompson, and Sandberg (1964) and White (1968). Don White and his co-authors did their field work and research in the 1950's and 1960's. The three USGS professional papers that came out of this work are exemplary examples of classic geologic work. Anyone who desires to learn in detail of the Steamboat geothermal system is encouraged to read them.

### Geology

The Steamboat Hills is in many ways a replica of the major ranges in Nevada and Utah except that its long axis trends northeast, transverse to the north-trending structural pattern of the Basin and Range. The hills are composed of metamorphosed sedimentary rocks of probable Triassic age and younger Cretaceous age granodiorite. The hills have an anticlinal form produced by warping and by tilting of fault blocks. The structural relief has been produced by normal faults dipping away from the hills and tilting that more than compensates for antithetic faults dipping towards the hills.

The Steamboat thermal area lies on a line connecting several rhyolite domes that occur southwest and northeast of the thermal area. The rhyolite is named the Steamboat Hills Rhyolite. The emplacement of the large dome that lies southwest of Steamboat Springs was preceded by and accompanied by extensive pyroclastic eruptions that mantled much of the adjacent area with a layer of rhyolite pumice. White and others (1964) have proposed that another rhyolite intrusive may underlie the hot-spring area.

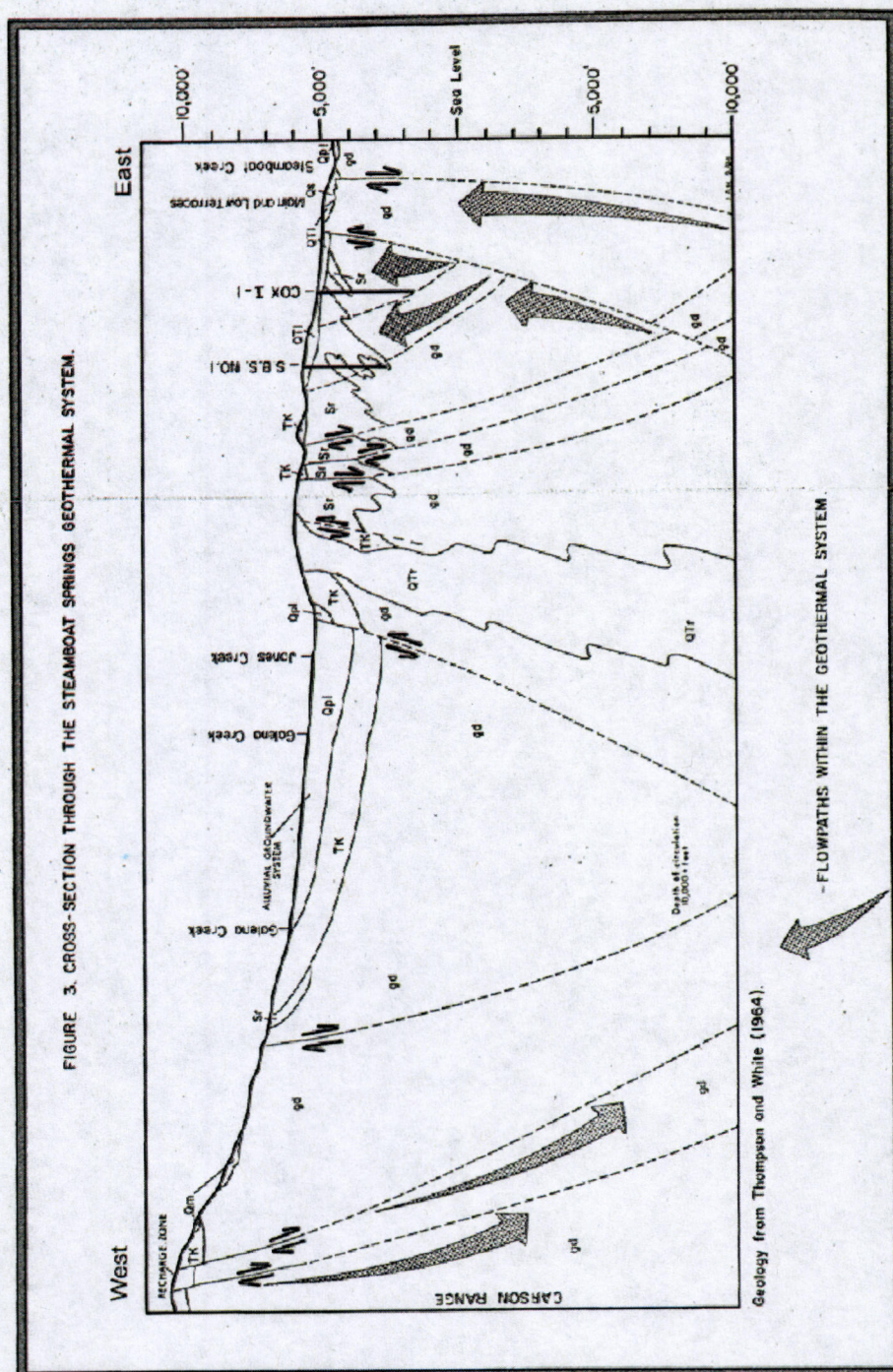
The hills lie in the midst of an area of Quaternary age faults that are well shown in the Mt. Rose alluvial fan west and north of the hills. Within the hills at least three systems of faults have been identified. One major set strikes northeast, parallel to the axis of the hills; many of these are antithetic. A second set of faults strikes northwest, nearly at right angles to the first. The third set strikes nearly north and many of these are antithetic in dipping toward the structural crest of the Steamboat Hills. The north-trending set of faults show evidence of being most active recently, displacing alluvium and sinter of middle-Pleistocene age. The Steamboat Springs fault zone is the largest of the north-striking system and provides the structural control for the Low and Main Terraces. As discussed below, certain of these faults are pathways for geothermal discharge into the shallow alluvial aquifer north of the hills. The location map for this report includes an outline of the Steamboat Hills to orient the reader (Figure 1).

### Hydrology

Recharge is thought to occur in the Carson Range to the west at an approximate elevation of 6,900 feet amsl (Nehring, 1980) (Figure 3). Flow through the system is driven by both the potential gradient created by the higher elevation recharge zone and a heat driven thermal density difference gradient.

As with almost every geothermal system it is only the discharge portion that is readily observable. The potential elevation of the Steamboat geothermal discharge zone is always greater than the surrounding surface and ground water systems; thus geothermal flow is always to the surface and ground water systems. Many thermal springs flowed from fissures and vents over an area of about one square mile near the northeastern end of the hills. Discharge occurs at several different elevations. Thermal chloride waters of the same chemical composition are found at elevations that range from 4,575 feet amsl at Steamboat Creek to 4,680 feet amsl in the Main and High Terraces. The chemical similarity is evidence that the structures are interconnected at depth. The differences in elevation of the discharge points are evidence that no single structure is permeable enough to discharge all of the geothermal water in the system. The discharge is distributed among many structures. Only about 6 percent of a calculated total discharge of 1,100 gpm appears at the surface as thermal springs or geysers. Most of the thermal water escapes northward below the surface and ultimately discharges into Steamboat Creek. Figure 4 is a generalized hydrogeological cross-section through the alluvial fan north of the Mt. Rose Highway showing the geothermal leakage into the shallow alluvial aquifer.





**Figure 3. Cross-section through the Steamboat Springs geothermal system.**



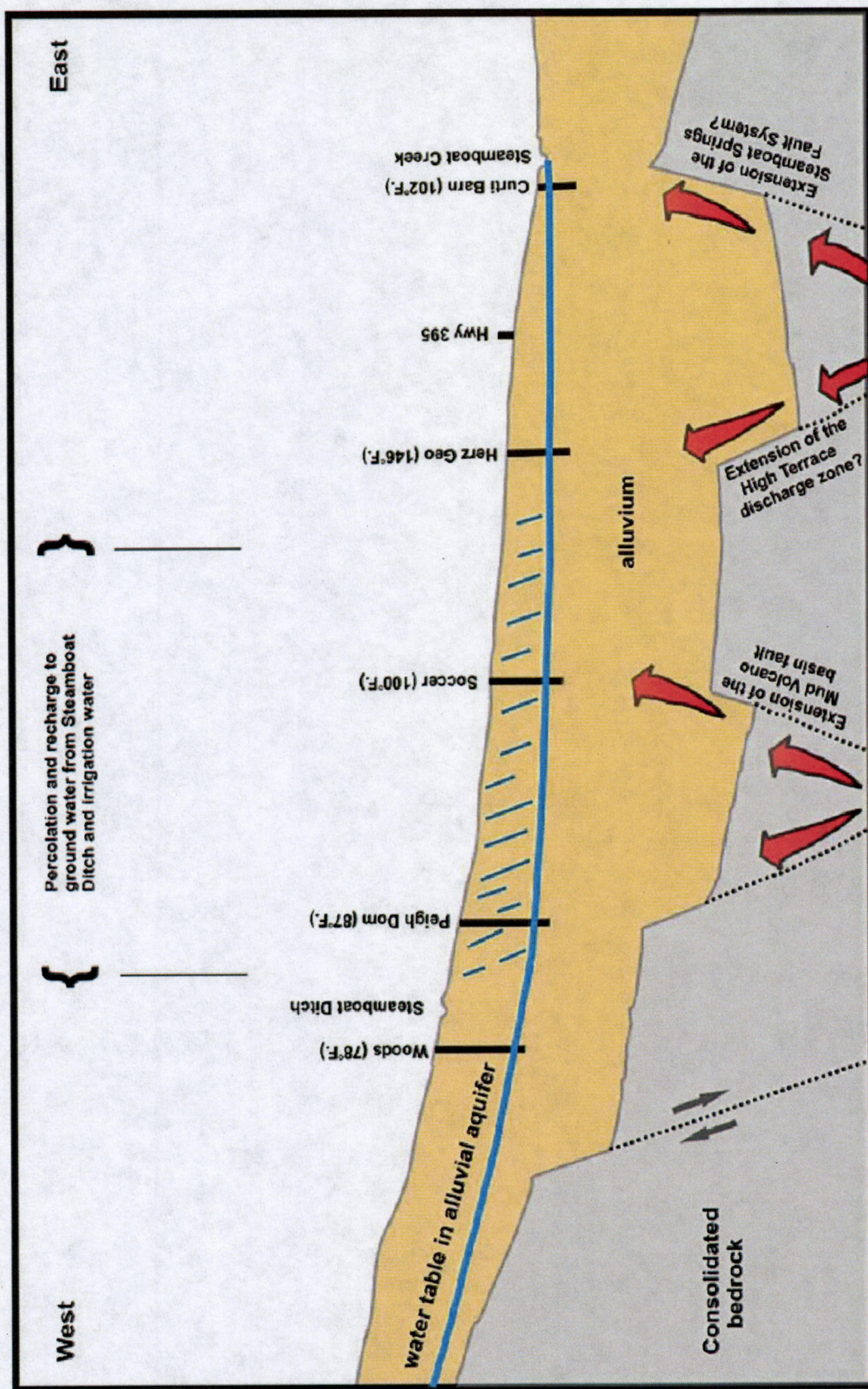


Figure 4. Hydrogeologic cross-section through the alluvial fan north of the Mt. Rose Highway.



## CHAPTER FOUR - REGIONAL GROUND WATER

The following general description of the regional ground water has been taken from Yeaman (1984). When written there was limited data from the initial network of monitoring wells. It also was written before the construction and operation of the present geothermal power plants and before the transformation of the area from semi-rural agricultural use to suburban residential and commercial uses. Although no attempt was made to update the material, the general description still should serve as a background for this work.

### Occurrence and Movement

Regionally, most of the economically recoverable ground water occurs under unconfined to semi-confined conditions in the unconsolidated sediments of the alluvial fans and valley fill deposits. The Mt. Rose alluvial fan complex extends from the base of the Carson Range eastward to Steamboat Creek. It is composed of pediment and fan deposits approximately 600 feet thick. Sediments of the alluvial fan are heterogeneous materials ranging from large pebble gravels with cobbles and boulders to sands and silts. The valley fill deposits, located in the center of the basin, consist of thin sheet-like aprons of fine- to medium-grained clayey sands and intercalated muddy, medium pebble gravels.

Ground water also occurs in the igneous and metamorphic basement rocks of the region, including those in the Steamboat Hills. Flow occurs along fractures, joints, and faults with no or little intrinsic permeability within the rocks themselves. There is ground water flow in the fractures and faults of the igneous and metamorphic rocks underlying the sediments of the Mt. Rose alluvial fan.

Ground water generally flows northeastward from recharge areas along the western margin of the basin to discharge in the valley floor either as evapotranspiration or inflow to Steamboat Creek. The hydraulic gradient is quite steep in the upper part of the alluvial fan, 880 ft. /mi., declining to approximately 40 ft. /mi. in the vicinity of Zolezzi Lane and U.S. Highway 395.

### Recharge and Discharge

Ground water recharge in the western part of the region is by deep percolation of precipitation and stream flow along the base of the Carson Range. Because of low precipitation there is negligible recharge from the Virginia Range on the east side of the Truckee Meadows. Beneath and down gradient from irrigation ditches recharge occurs from the unlined ditch bottoms and from deep percolation of applied irrigation water.

Steamboat Creek normally is not a source of recharge to the water table aquifer. It is only in those relatively rare flood events that the elevation of water in the creek is greater than that in the aquifer. At these times there is short-lived bank recharge which drains back to the creek as the creek level recedes.

Recharge from irrigation has created a large reservoir of high quality water in the aquifer down gradient from irrigation ditches, including Steamboat Ditch. Recharge can be significant. Cohen and Loeltz (1964) noted the water level rise in a well down gradient from the Last Chance Ditch north of the monitoring area was as much as 6 feet some years. A water level rise of 7 feet was recorded in the now destroyed PTR#2 well down gradient from the Steamboat Ditch (data held by the Phillips Petroleum Company). For a conservative estimated effective porosity of 10%

approximately 4,350 cubic feet of water move into or out of ground water storage for each foot change in the water level. Because percolation of spread irrigation water serves as a net gain to the ground water system there has been a net rise in the static water level over the long-term. This long-term rise is seen in the data of Cohen and Loeltz (1964) where the static water level rose an average of 0.5 feet per year in the interval 1950-1959.

Ground water discharge is by leakage into Steamboat Creek or by evapotranspiration by phreatophytes. Ground water discharge to the reach of Steamboat Creek between the USGS gage at Rhodes Road and the Huffaker Hills has been estimated from 5 cubic feet per second (cfs) (Hydro-Search, Inc., 1981) to 14 cfs (Cohen and Loeltz, 1964).

Discharge by evapotranspiration occurs in the meadowlands in the center of the south Truckee Meadows where the sediments were saturated to near the land surface. An estimated 8,200 acre-feet per year of ground water was discharged by evapotranspiration in an estimated 1,700 acres of irrigated and non-irrigated meadowlands just south of the Huffaker Hills (Hydro-Search, Inc., 1981). Much of this area is now covered by residential and commercial development, reducing the evapotranspiration potential.

## CHAPTER FIVE – WATER QUALITY

### Ground Water Quality

Regionally, non-thermal ground waters are of excellent to good quality. West of Steamboat Creek water in the alluvial fan is of the mixed cation-bicarbonate anion type with TDS values generally less than 250 mg/l. It can be classified as belonging to the uppermost vertical zone of the ground water system, characterized by a high rate of circulation through low mineralized rocks and sediments (Domenico, 1972). The Woods, Peigh Domestic and Brown School wells can be considered representative of this geochemical facies when they were sampled in the early 1980s (Table 1). Chloride, arsenic, boron and fluoride, constituents of health and agricultural concern, were either below detection limits or were found only in negligible amounts (Phillips Petroleum baseline monitoring data, 1981-1982). The Curti Domestic well showed a slight geothermal influence with elevated chloride and boron values.

**Table 1. Ground water and geothermal water chemistries<sup>1</sup>.**

Location	Constituent														
	T°F.	EC	TDS	Ca	Mg	Na	K	HCO <sub>3</sub>	Cl	SO <sub>4</sub>	SiO <sub>2</sub>	As	B	F	Li
Non Thermal Water in Alluvial Aquifer															
Woods <sup>2</sup>	80	256	176	31	8	8	4	108	2	15	59	-- <sup>8</sup>	0.1	0.08	0.02
Peigh Dom <sup>3</sup>	87	--	178	43	4	11	--	95	14	11	--	trace	--	0.07	--
Brown Sch. <sup>3</sup>	--	253	181	16	2.7	31	9	105	5	12	71	--	0.62	0.11	0.18
Slight Thermal Influence of Water in Alluvial Aquifer															
Curti Dom <sup>3</sup>	70	630	477	42	11	75	8	234	68	34	68	--	4.21	0.40	0.62
Strong Influence of Thermal Water in Alluvial Aquifer															
Curti Barn <sup>3</sup>	102	2880	1788	58	20	480	45	296	743	99	169	--	40.8	0.65	5.6
Geothermal Waters															
SB#1 <sup>4</sup>	442	--	2274	1.7	.007	567	94	216	757	92	492	3.02	44.3	2.97	7.6
Spring#8 <sup>5</sup>	--	--	2133	5.0	0.8	653	71	305	865	100	293	--	49	1.8	7.6
Towne <sup>6</sup>	--	--	2102	4.91	0.25	624	67	234	798	125	196	--	44.1	1.86	7.51

<sup>1</sup> Data from Yeamans (1984).

<sup>2</sup> Average from Phillips Petroleum Co. monitoring data; well up gradient from Steamboat Ditch.

<sup>3</sup> Average from Phillips Petroleum Co. monitoring data.

<sup>4</sup> July 1981 flow test; well renamed 21.5 – deep geothermal fluid.

<sup>5</sup> Main Terrace, (White, 1957) – shallow geothermal fluid.

<sup>6</sup> High Terrace – shallow geothermal fluid.

<sup>7</sup> Originally identified as PTR Cold in '84 rpt.

<sup>8</sup> -- Not analyzed for.

Chloride is used as the constituent of concern. Boron is used to a more limited extent. Chloride and boron are very conservative in low TDS ground water systems, precipitating out only under very unusual conditions.

Average values for chloride, boron and the Cl/B ratios for the monitoring wells have been calculated and are given in Table 2. The background and operational classifications in column one were used in earlier reports to identify monitoring data taken before and after the startup of the geothermal power plants. The background period was December of 1984 through December of 1986. In Table 2 this 25 month period is identified as 1985 through 1986. The SBI/IA power plant came online in January of 1987. The operational data for 1987 was the one year of data available for the 1988 analyses. The lower volume Caithness Power plant came online in February of 1988. In January of 1993 the much larger SBII/III project came online and all three have been operating since. The data often are not normally distributed so calculated average values can be misleading. A better understanding of changes over time will be seen in the following graphical displays of data and the discussions that go with them.

**Table 2. Average values for monitoring well chloride and boron concentrations and Cl/B ratios.**

Location	ave. Cl, mg/l	ave. B, mg/l	ave. Cl/B
<b><u>Brown School</u></b>			
Background (1985-1986)	9.2	0.194	55.4
Operational (1987)	6.9	0.23	36.7
SBI/IA (1/87-12/92)	314	9.2	60.7
SBI/IA+SBII/III (1/93-6/06)	593	33.3	17.7
<b><u>Curti Barn</u></b>			
Background (1985-1986)	NA <sup>1</sup>	NA	NA
Operational (1987)	NA	NA	NA
SBI/IA (1/87-12/92)	700	37.1	18.9
SBI/IA+SBII/III (1/93-6/06)	695	35.6	19.5
<b><u>Curti Dom</u></b>			
Background (1985-1986)	NA	NA	NA
Operational (1987)	NA	NA	NA
SBI/IA (1/87-12/92)	110	5.29	25.9
SBI/IA+SBII/III (1/93-6/06)	168	8.92	18.4
<b><u>Herz Geo</u></b>			
Background (1985-1986)	348	17.4	20.1
Operational (1987)	340	18.0	18.9
SBI/IA (1/87-12/92)	352	17.9	19.7
SBI/IA+SBII/III (1/93-6/06)	398	16.9	22.2
<b><u>Herz Dom</u></b>			
Background (1985-1986)	3.4	0.16	23.2
Operational (1987)	3.2	0.11	29.4
SBI/IA (1/87-12/92)	55.0	0.38	84.4
SBI/IA+SBII/III (1/93-6/06)	173	5.8	40.1
<b><u>PTR#1</u></b>			
Background (1985-1986)	11.2	0.57	30.1
Operational (1987)	37	2.8	14.5
SBI/IA (1/87-12/92)	53	3.3	15.7
SBI/IA+SBII/III (1/93-6/06)	NA	NA	NA
<b><u>Soccer/PTR#2</u></b>			
Background (1985-1986)	NA	NA	NA
Operational (1987)	NA	NA	NA
SBI/IA (1/87-12/92)	NA	NA	NA
SBI/IA+SBII/III (1/93-6/06)	445	25.5	17.1
<b><u>Flame</u></b>			
Background (1985-1986)	300	18.0	16.6
Operational (1987)	375	22.0	17.0
SBI/IA (1/87-12/92)	419	23.2	18.1
SBI/IA+SBII/III (1/93-6/06)	NA	NA	NA
<b><u>Peigh Dom</u></b>			
Background (1985-1986)	2.9	0.11	32.4
Operational (1987)	2.5	0.06	45.0
SBI/IA (1/87-12/92)	3.45	0.07	56.2
SBI/IA+SBII/III (1/93-6/06)	4.8	0.13	57.2

<sup>1</sup> Data not available.

## Geothermal Water Chemistry

The geothermal discharge zone is represented by samples from the High Terrace (Towne) and the Main Terrace (Spring #8) (Table 1). The slightly lower values for the High Terrace sample as compared to that from the Main Terrace suggest that geothermal fluids discharging through the High Terrace have undergone less boiling than those from the Main Terrace (White, 1968).

The geothermal system is thought to be the sole source of high chloride and boron waters with chloride concentrations between 757 and 865 mg/l. Boron concentrations are between 44 and 49 mg/l (Table 1). White (1968) used an average chloride value of 820 mg/l in calculating a total discharge of 1,100 gpm from the geothermal system. Chloride and boron concentrations for the injectate are given in Table 3.

**Table 3. Chloride and boron values for the injection wells.**

Well	total vol. Mgal.	monthly ave. Mgal.	gpm	ave. Cl, mg/l	ave. B, mg/l	ave. Cl/B,
SB I/IA	32,420	170	3,900	830	41.2	21.1
SB II/III	97,800	776	17,700	835	39.1	21.2
COX-1	14,300	109	2,500	920	46.2	19.9
62A-32	840	120	2,700	913	45.8	20.0
TOTAL	145,367	706	16,100	NA	NA	NA

Geothermal leakage is a source of natural degradation of the high quality ground water (see Figure 4). Geothermal leakage along shallow fracture zones results in marked changes in water chemistry in wells only a short distance apart or at different depths. The Curti Barn well has a chemistry that is almost pure geothermal discharge although the temperature is only 102°F. Directly across Steamboat Creek the Curti Domestic well had a very low TDS mixed cation-bicarbonate anion chemistry typical of ground water in the alluvial fan (see Table 1 and Figure 1). An adjacent deeper and hotter geothermal well at the Pine Tree Ranch house was used to heat an outdoor pool while the Peigh Domestic well supplied potable water to the house.

Geothermal leakage can be recognized by elevated chloride, boron and arsenic concentrations. Table 4 compares selected constituents of the ground water and the geothermal water.

**Table 4. Selected constituents for thermal and non thermal waters.**

Constituent, mg/l	Location					
	Non thermal		Mixed		Thermal	
	Woods <sup>1</sup>	Peigh Dom <sup>1</sup>	Soccer <sup>3</sup>	Flame <sup>3</sup>	IW3 <sup>3</sup>	Towne <sup>3</sup>
As	-- <sup>2</sup>	Trace	1.02	1.02	2.28	--
Cl	2	14	445	455	844	798
SO <sub>4</sub>	15	11	57.1	69	130	125
B	0.1	--	25.5	--	40.6	44
TDS	176	178	1320	1389	2163	1906

<sup>1</sup> Data from Yeamans (1984).

<sup>2</sup> Not analyzed for.

<sup>3</sup> Averaged from monitoring data.



## CHAPTER SIX - GEOTHERMAL PRODUCTION AND INJECTION

### Production

Geothermal production is shown in Figure 5. Both production and injection data suffer from some inaccuracies as the projects have gone through several operators. Gage calibrations may have been missed, gages have been switched out and conversions from one scale to another, e.g., pounds per hour to gpm, affect the final data entries. The values used for this work are sufficient in light of the great volumes involved in the power projects as compared to the background estimated natural discharge of 1,100 gpm from the geothermal system (White, 1968). Also, data from the former Caithness project located at the crest of the Steamboat Hills is used sparingly in this report. Spent fluids from that project are injected at a greater distance from the monitoring wells and at a deeper depth than that for SBI/IA and SBII/III.

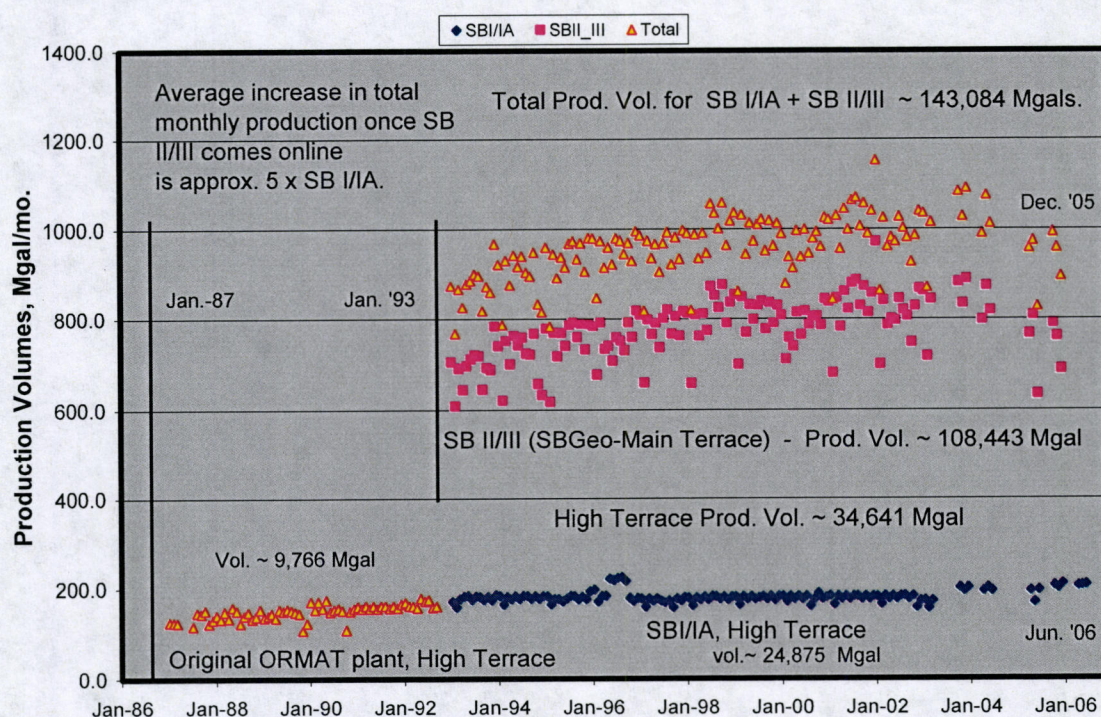


Figure 5. Geothermal production.

### Injection

Injection volumes and rates are given in Table 5 and shown in Figure 6. The "Total" volume is the total amount of fluids injected over the historic operating period of a particular project. The total amount of injected fluids, 145,367 million gallons (Mgal), is greater than the calculated produced fluids in Figure 3, 143,084 Mgal. As noted above, measurement errors and other factors probably contribute to the discrepancy. The point to note is that an injected volume in the neighborhood of 145,000 Mgal since January of 1987 greatly overwhelms a natural discharge volume of 11,300 Mgal for the same period based on a natural discharge rate of 1,100 gpm (White, 1968).

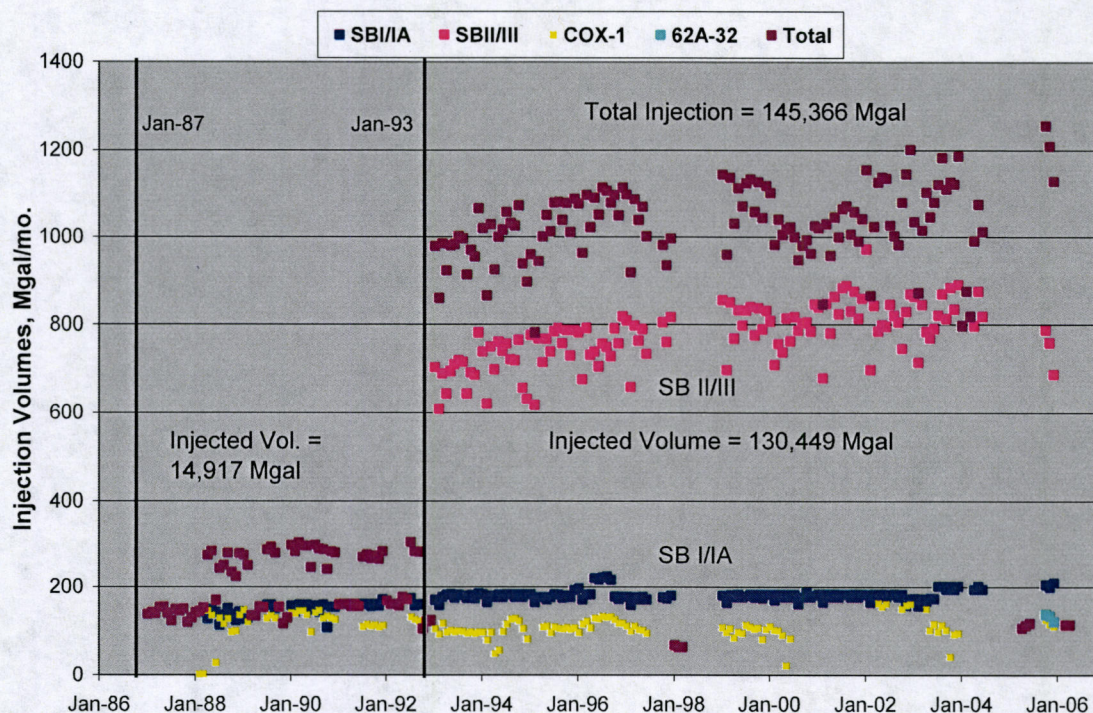


SBI/IA injected at a lower rate from January of 1987 until January of 1993 when SBII/III came online and began injecting at a much greater rate. There was an approximate five-fold increase in the production and injection of geothermal fluids when SBII/III came online. Spent fluids from the SBI/IA project are injected just south of the Mt. Rose Highway at the north end of the High Terrace. The SBII/III production and injection wells are located on the Main Terrace southwest of the old U.S. Highway 395 – Mt. Rose Highway intersection (Figure1).

Calculated averages include the initial 6 year period of much lower injection rates and volumes from SBI/IA (Figure 6). Therefore the total monthly average injection rate and the average injection rate expressed as gallons per minute (gpm) for the entire period ("Total Inj." column) are less than the values for the high volume SBII/III operation. Since January of 1993 production and injection rates have been increasing (Figures 5 and 6) with most of the increases from the SBII/III project. The year 2002 is the last with full data. The total volume and average injection rates for 2002 can be representative of recent operations.

**Table 5. Injection volumes and rates.**

SB I/IA	SB II/III	COX 1	62A-32	Total Inj.	2002 Totals
Total=32,420 Mgal	Total=97,800 Mgal	Total=14,300 Mgal	Total=840 Mgal	Total=145,367 Mgal	12,850 Mgal
170 Mgal/mo. ave.	776 Mgal/mo. ave.	109 Mgal/mo. ave.	120 Mgal/mo. ave.	706 Mgal/mo. ave.	1,070 Mgal/mo. ave.
3,900 gpm ave.	17,700 gpm ave.	2,500 gpm ave.	2,700 gpm ave.	16,100 gpm ave.	24,400 gpm
data from Jan.-87 to Dec.-05	data from Jan.-93 to Dec.-05	data from Feb.-88 to Dec.-03	data from Oct.-05 to Jun.-06	calc. for Jan.-87 to Jun.-06	



**Figure 6. Injection volumes.**



## CHAPTER SEVEN - ANALYSIS

### Prior Analyses

A brief review of previous work will help understand the analyses and conclusions for this report. The Brown School report (Yeamans and Broadhead, 1988a) used the two years of background monitoring data, 1985 -1986, and one year of operational data, 1987. The findings are noted below.

- The Brown School well was delicately balanced on a high quality, low total dissolved solids (TDS) water adjacent to subsurface high TDS geothermal leakage.
- As chlorides did not increase along with the arsenic it was concluded at that time there was not a direct relationship between geothermal fluids and the arsenic increase in the Brown School well.
- There had been a rising static water elevation in the Herz Geothermal well with no increase in the chloride and arsenic concentrations.
- If geothermal development was associated with the rise in the water level in the Herz Geothermal well the constant chemical and temperature measurements indicated that there was no significant impact on ground water quality in the vicinity of the Herz Geothermal well.

The 1988 statistical study (Yeamans and Broadhead, 1988b) included data for the same monitoring period as that for the Brown School report. Monitoring wells included the Herz Geothermal, Herz Domestic, Peigh Domestic, Pine Tree Ranch, Flame, and the Brown School wells. The Curti wells were not included in the analysis. The analysis was done to see if there were any statistical differences between the background and the operational data. Chloride was selected as the constituent for the analysis and the 95% confidence level was selected for the analyses.

- Two hydrogeochemical zones were identified in the shallow water table aquifer north of the Mt. Rose Highway:
  - 1). A stable fresh water zone existed in the vicinity of the Peigh and Herz Domestic wells;
  - 2). A stable geothermal zone existed in the vicinity of the Herz Geothermal well.

These two zones had remained statistically stable during the first year of geothermal operations when compared with the two years of background data.

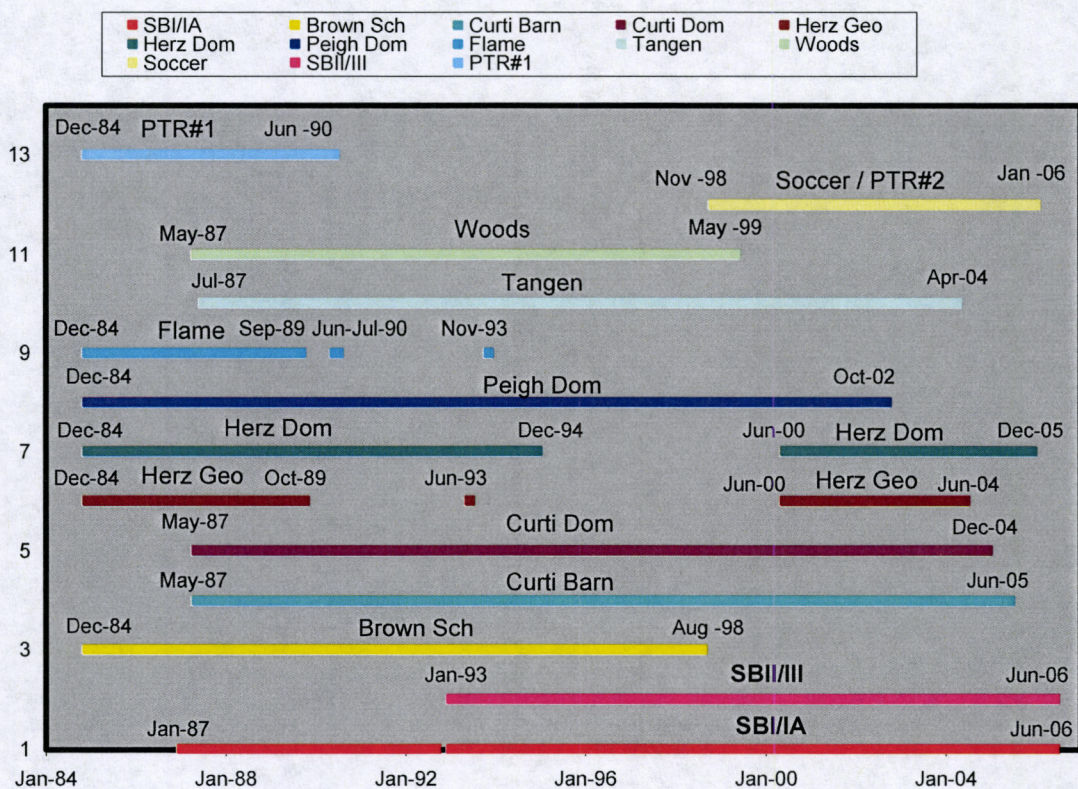
- A third zone of intermediate composition included the Pine Tree Ranch#1 (Soccer well today) and the Flame wells. There were significant increases in chlorides in the operational period over those for the background data. Two hypotheses were offered for the increase in chlorides:
  - 1.) There had been an increase in the amount of geothermal leakage into the shallow aquifer. This could be the result of injection of spent geothermal fluid during the first year of geothermal operations.
  - 2.) A decrease in the amount of seasonal irrigation lessened the dilutive effect of the percolating recharge water, increasing the proportion of geothermal water in these two wells. This hypothesis was accepted based on an identified reduction in the amount of irrigation water available for recharge and dilution of the natural geothermal leakage.



- Statistically the Brown School well data bordered on showing a statistical difference between background and operational data. At that time it was thought the well probably was balanced next to or between geothermal discharge zones.

## Monitoring Data

Figure 7 shows the operating and monitoring coverage over time. There was not necessarily consistency in sampling from a particular well. Sometimes water levels were measured but no samples collected for chemical analyses, e.g., the Soccer well. The monitoring wells are/were wells of opportunity in the alluvial aquifer. The PTR#2 well was later renamed the Soccer well while PTR#1 well was an adjacent well where sampling ceased in June of 1990. Locations are shown in Figure 1. The injection wells for SBI/IA and SBII/III are located closest to the fresh water aquifer and they inject, by far, the greatest amount of spent geothermal fluids. (Figure 1).



**Figure 7. Operating and monitoring intervals.**

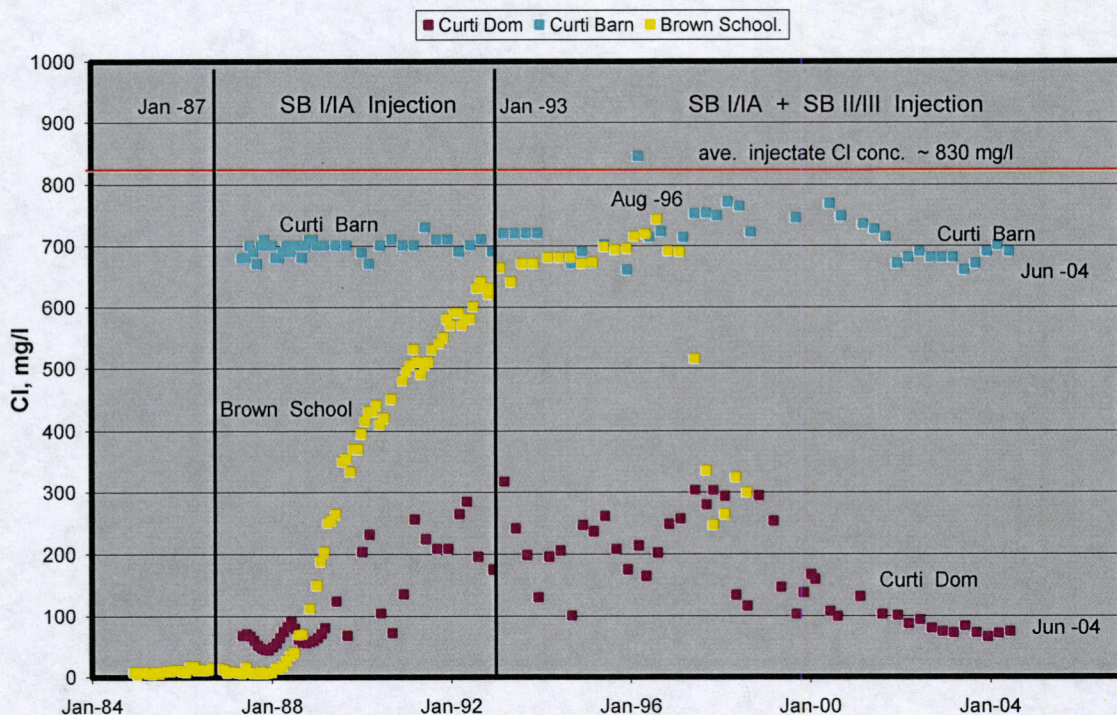
The following examination of the data divides the monitoring wells into three groups from east to west: 1) the Brown School well and the Curti wells; 2) the Herz Geothermal and Domestic wells, the PTR#1, Soccer and Flame wells; and 3) the Peigh Domestic well and the Tangen and Woods wells.



## The Brown School Well and the Curti Wells

Chlorides in the Brown School well took a dramatic climb starting in February of 1988; a little more than a year after SBI/IA began injecting its spent geothermal fluids (Figure 8). Delayed slightly in time, this same trend is seen, although not as sharply, in the Curti Domestic well. The Curti Barn well, already with high chloride values, had a slight increase in August of 1996 with values returning to normal by September of 2002.

What is not clear is the steep decline in chlorides in the Brown School well after August of 1996. As will be seen in the data for the Herz Domestic and Soccer wells, there was a later increase in chlorides in these two wells.



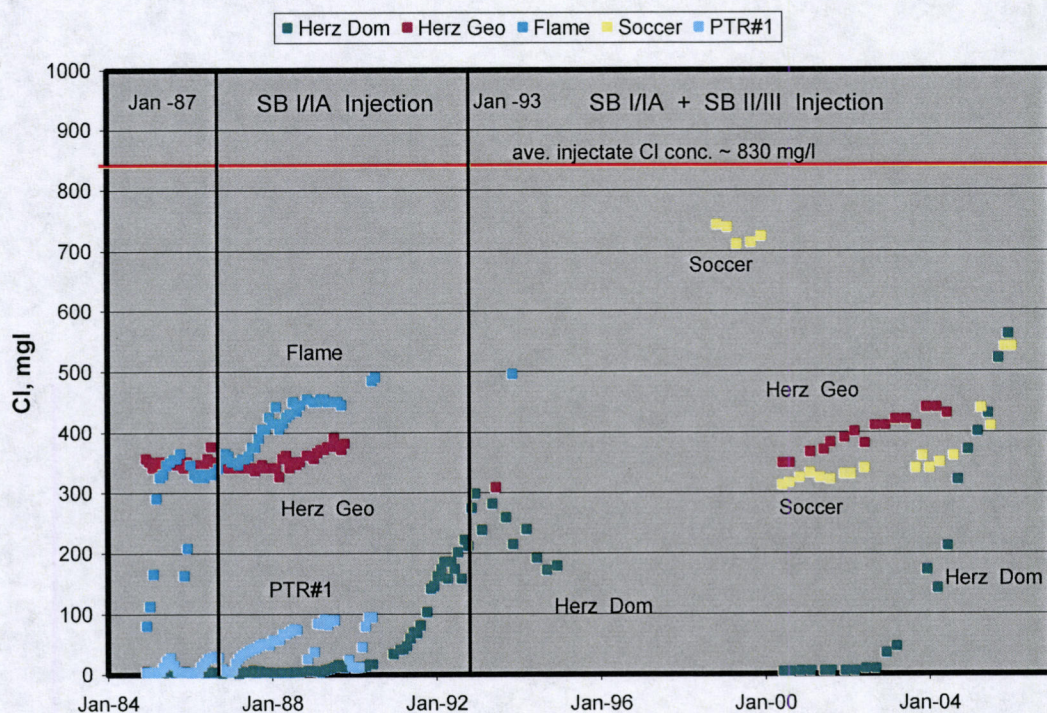
**Figure 8. Chloride concentrations – Curti Barn and Domestic wells, Brown School well.**

## The Herz Geothermal and Domestic Wells, the Soccer and Flame Wells

The Soccer and the Herz Domestic wells show trends similar to that observed in the Brown School well (Figure 9). Both have increases in chlorides beginning after startup of the SBI/IA geothermal plant. The short record for the Flame well approximates the chloride increase for the adjacent PTR#1 well in 1987 and 1988. In Yeamans and Broadhead (1988b) it was noted that the Flame restaurant had been closed for at least a year and only recently had reopened when the monitoring program began in December of 1984. It was speculated that reactivation of the well may have drawn a greater portion of geothermal fluids to the well and could explain the increase in chlorides prior to January of 1987.



The Herz Domestic well had a sharp decline in chlorides after January of 1993, approximately three and a half years before the decline of chlorides in the Brown School well. As with the Brown School well there is no readily available explanation for the subsequent decrease in chlorides. The extended monitoring data for the Herz Domestic and the Soccer wells show a subsequent increase in chlorides after September of 2002. Comparing Figures 8 and 9 one wonders what the data for the Brown School well would have shown had it been possible to continue sampling the well.



**Figure 9. Chloride concentrations – Herz Domestic and Geothermal wells, Soccer and Flame wells.**

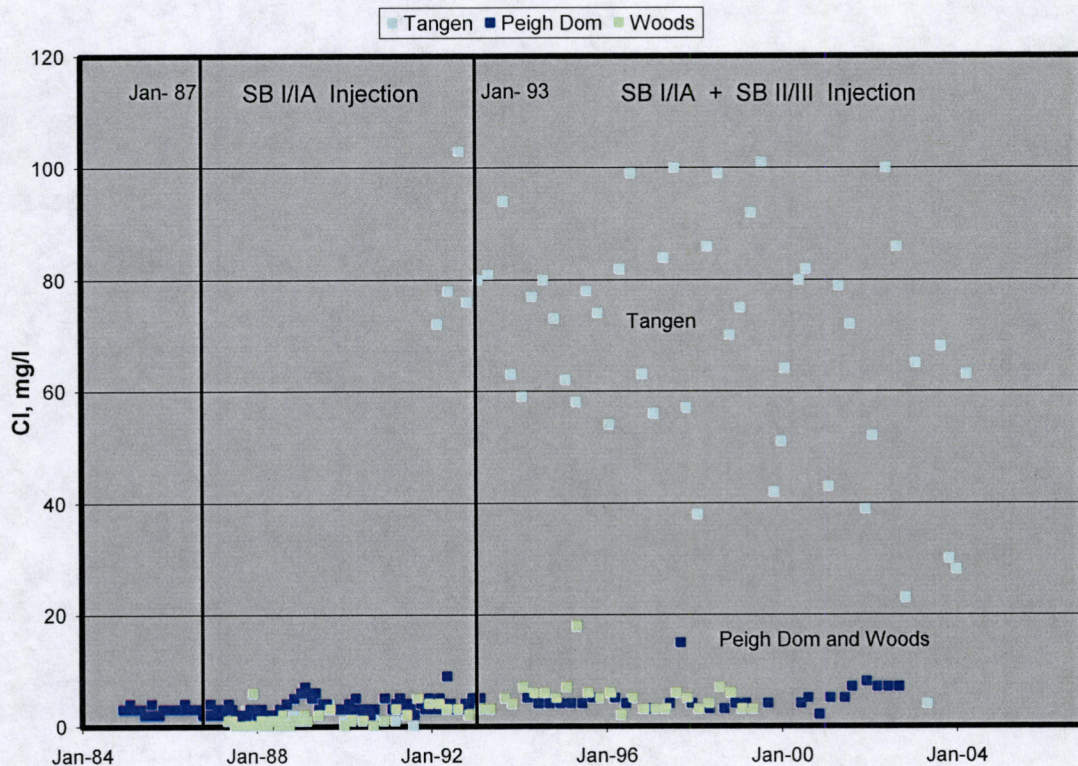
### **The Peigh Domestic Well and the Tangen and Woods Wells**

In the 1988 statistical analysis the Peigh Domestic well was considered to be within a stable low TDS zone. This zone has continued to exist through the latest monitoring period (Figure 10). The well is just down gradient from the Steamboat Ditch but there is/was very limited irrigation above the well that would affect water quality in the well. There is a north-trending fault which is directly in front of the Peigh home (Figure 1). The veranda on the east side of the house is on the up thrown block of the fault. This fault is thought to discharge geothermal fluids into the shallow alluvial aquifer as a geothermal well on the property was used to heat water for the outdoor pool. The Peigh Domestic well is up gradient from this fault and apparently has not been affected by any possible increase in geothermal discharge through this fault.

The Woods well is west of the Peigh Domestic well and up gradient from the Steamboat Ditch. It generally has been considered to be up gradient from any geothermal leakage into the alluvial aquifer. The chloride values have remained consistently low over the life of the monitoring period with no indication of the presence of geothermal fluids.



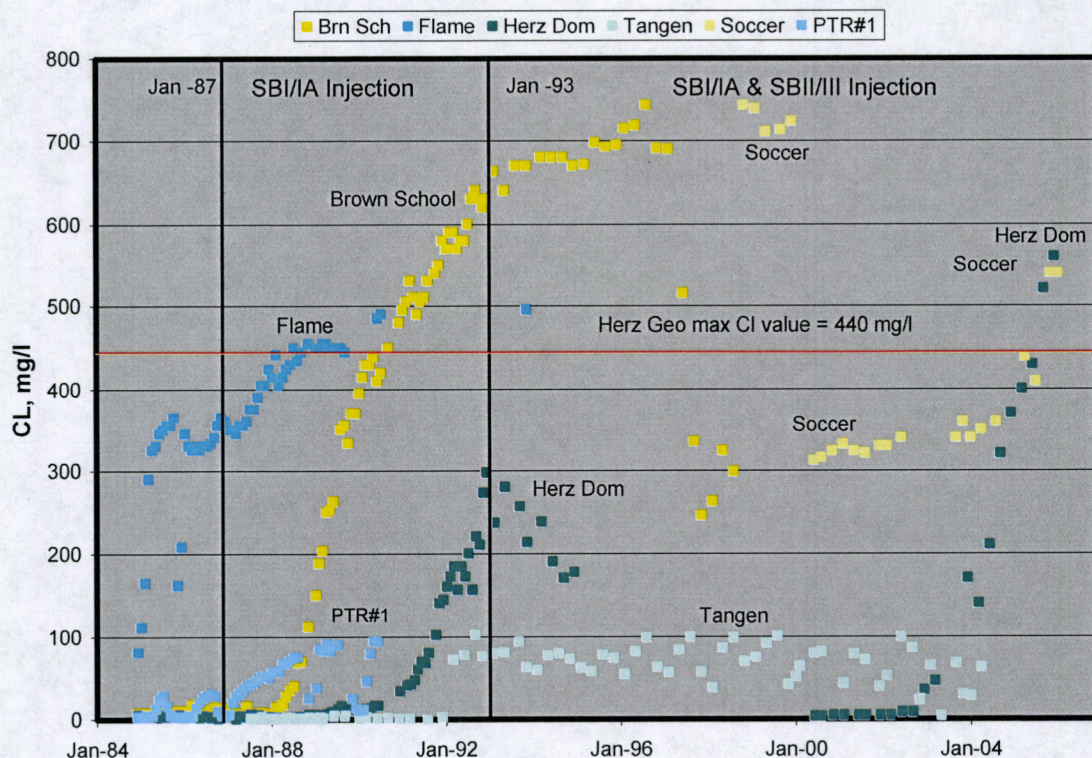
The Tangen well is on the south side of the Mt. Rose Highway in the vicinity of the Galena High School. Chlorides increased dramatically prior to the startup of the SBII/III project. The data suggest there is a decline in values towards the later part of the monitoring period. An airborne resistivity map prepared by the Washoe County Department of Water Resources shows a low resistivity zone east of the Tangen well. This may be a subsurface discharge zone for geothermal fluids.



**Figure 10. Chloride concentrations – Peigh Domestic, Woods and Tangen wells.**

The chloride increases first started in the PTR#1 and Flame wells in the spring of 1987 (Figure 11). These wells lie along the Mud Volcano Basin fault north-northwest of the SBI/IA project. (See Figure 1). The fault is a natural discharge pathway for geothermal fluids. Next was the Brown School well in the spring of 1988. Increases in the Herz Domestic well began in the summer of 1989. There is a rough correlation between distance from the geothermal area and the first increase in chlorides; the closer the well, the earlier and the greater the increase.





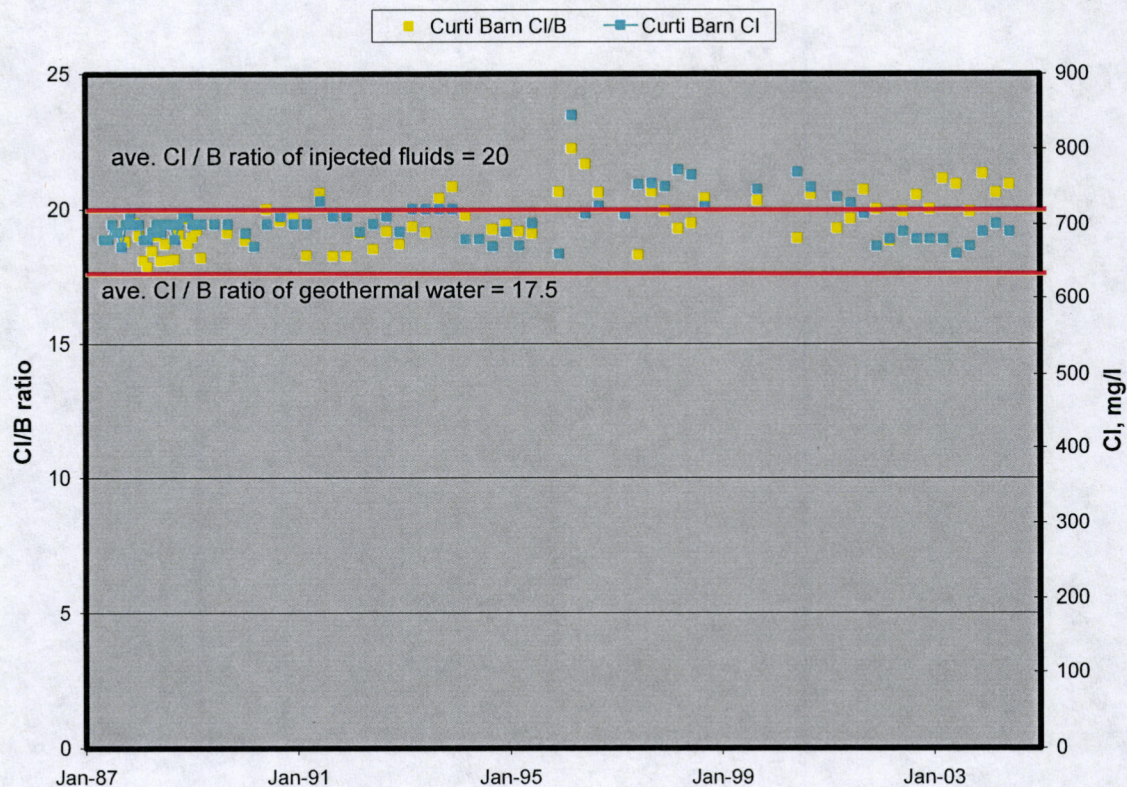
**Figure 11. Chloride concentrations – Brown School, Flame, Herz Domestic, Tangen, and Soccer wells.**

An examination of the above graphs shows that the Brown School well, the Herz Domestic well, the Soccer well, the Flame, and the Tangen well all have undergone significant increases in their chloride concentrations. Note that the latest chloride data for the Herz Domestic and the Soccer wells show continuing increases (Figure 11). Note also that the most recent values for these two wells now exceed the historic values for the Herz Geothermal well. The next question is whether the chlorides represent increases of geothermal fluids within the fresh water aquifer?

### Chloride/Boron Ratios

Chloride/boron ratios can be used to identify waters with a geothermal component. The geothermal fluids are the only known source of high boron water in the south Truckee Meadows. The average chloride/boron ratio for the geothermal water is 17.5 (Table 1) while that for the geothermal injectate is 20 (Table 3). As an example the Curti Barn well has both a high chloride concentration and a chloride/boron ratio between the two geothermal ratios (Figure 12).

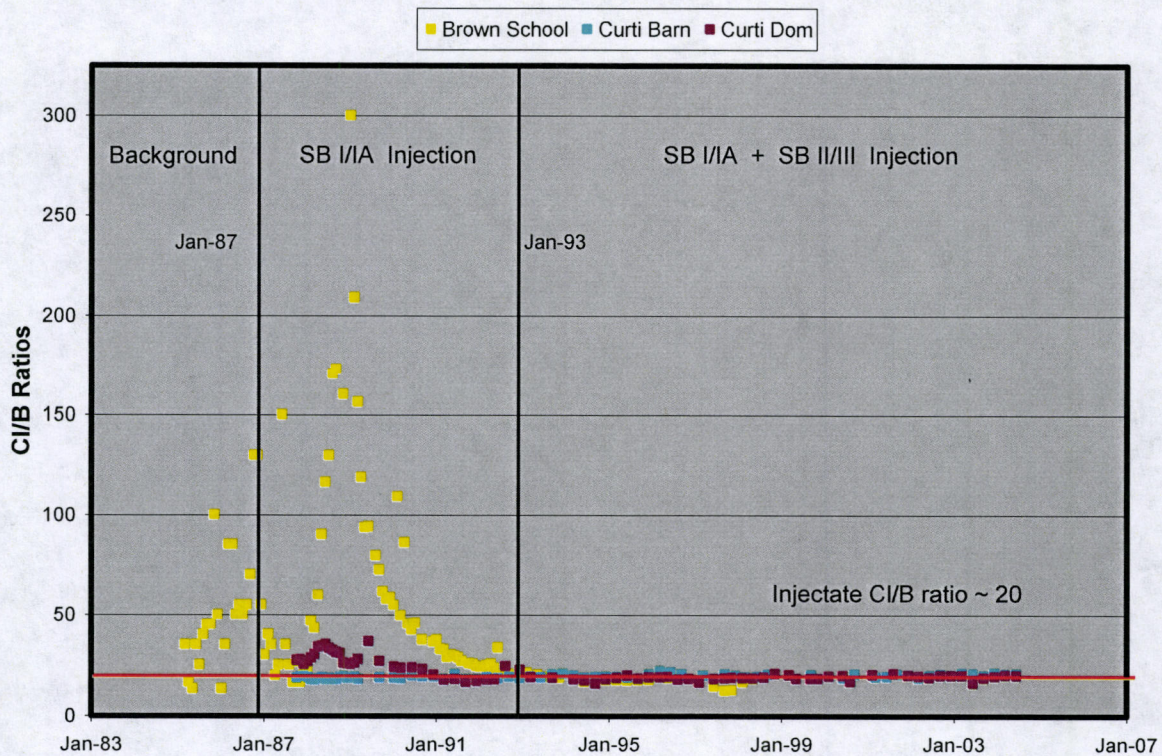




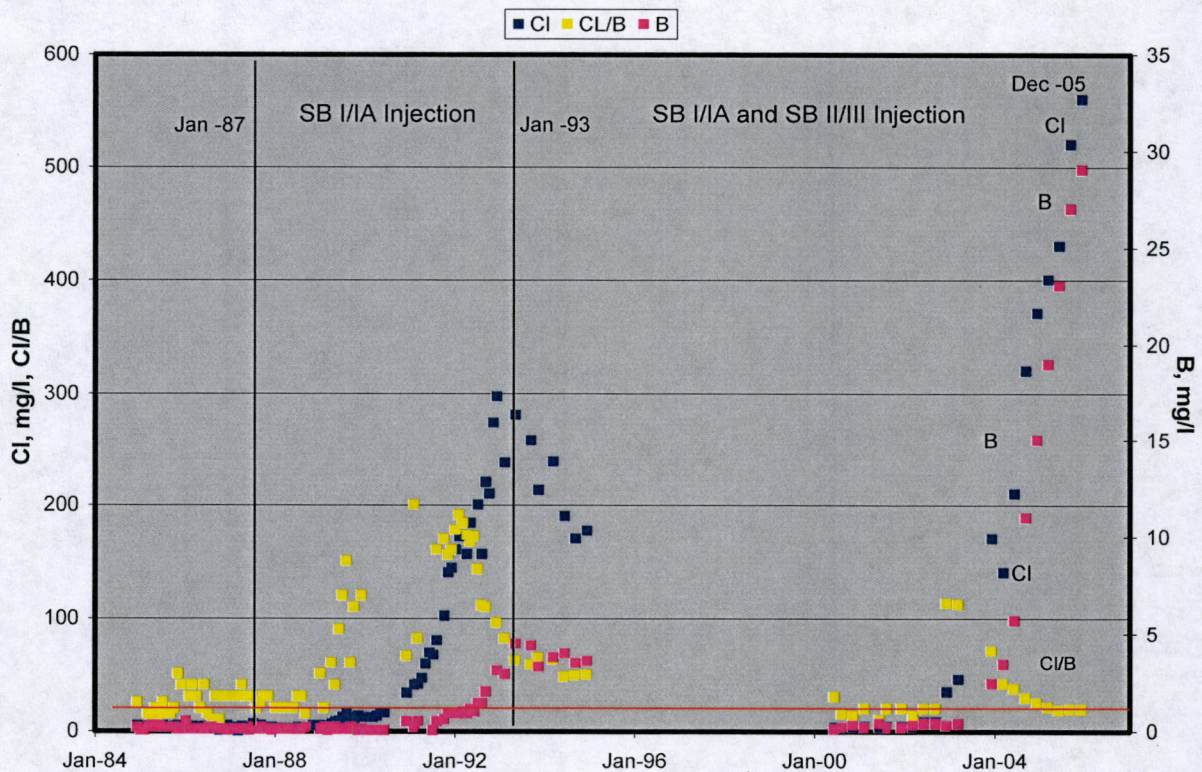
**Figure 12. Chloride and chloride/boron ratios for the Curti Barn well.**

Cl/B ratios for those wells that have had significant increases in their chloride concentrations, the Brown School, Curti Domestic, Herz Domestic, Soccer and the Tange wells, are graphed in Figures 13 through 16. Often plotted for comparison is an adjacent well that historically has had a high chloride concentration and a chloride/boron that closely matches that of the geothermal fluids. The Cl/B ratio for the Herz Domestic well approaches the average of the injectate as the chloride and boron values undergo rapid increases (Figure 14). Note that by March of 2005 the Cl/B ratios trend to the average ratio of the injected fluids, indicating an increase in the percentage of geothermal fluids in the aquifer.





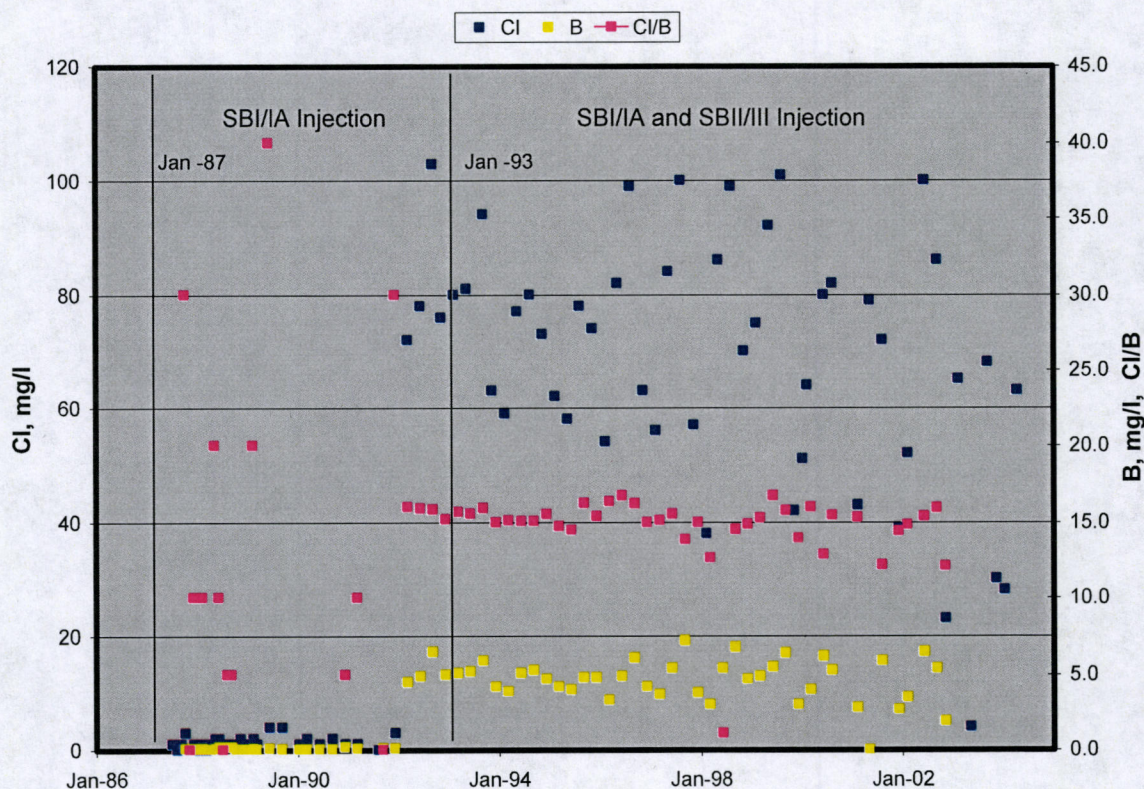
**Figure 13. Chloride/boron ratios – Brown School and Curti Barn and Domestic wells.**



**Figure 14. Chloride, boron and C/B ratios – Herz Domestic well.**



In the Tangen well chloride and boron simultaneously increased in March of 1992 (Figure 15). The new values are less than increases observed in the other monitoring wells (see Figure 11 above). Following the increases there is significantly more scatter in the chloride and boron values but the CL/B ratio steadies out at an approximate of 15. Although the well has an anomalously deep water level it does appear that geothermal fluids influence the later chemistry of the well.



**Figure 15. Chloride, boron and Cl/B ratios – Tangen well.**

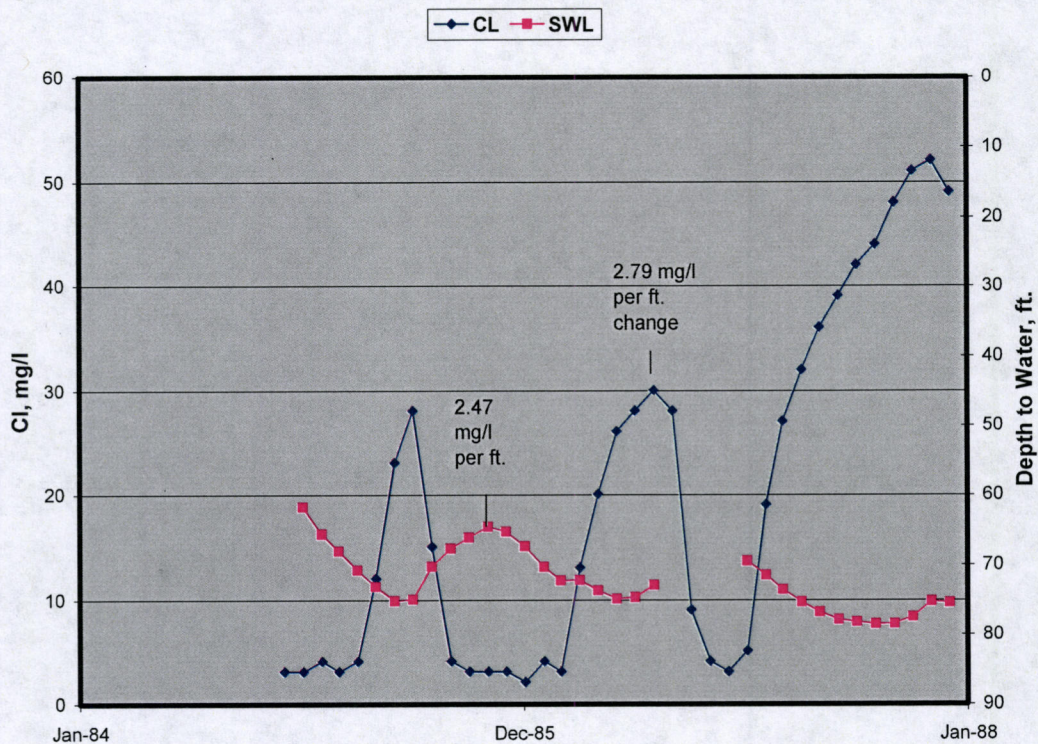
The Cl/B ratios indicate a geothermal source for the increases in the chloride and boron measured in the monitoring wells.

### Water Levels

It long has been recognized that water chemistry in the fresh water aquifer near the subsurface geothermal discharge zones is affected by changes in water levels in the aquifer (Yeaman, 1984, Yeaman and Broadhead, 1988a). For almost a hundred years water has been diverted from the Truckee River and conveyed by the Steamboat Ditch for spread irrigation on the agricultural lands of the south Truckee Meadows. The pasture lands were entitled to 4 acre-feet of irrigation water per acre with an assumed consumptive use of 2.5 acre-ft./acre. This left a potential 1.5 acre-ft/acre for recharge (Yeaman and Broadhead, 1988a). This was an annual recharge event with significant increases in the static water level. The recharge was followed by a seasonal decline of water levels in the aquifer. Decades of flood irrigation had built up a reservoir of low TDS ground water below the irrigation ditches. (See Cohen and Loeltz, 1964). The past tense has been used to describe the above because the previously irrigated pastures have undergone extensive residential and commercial real estate development in the last 20 years.



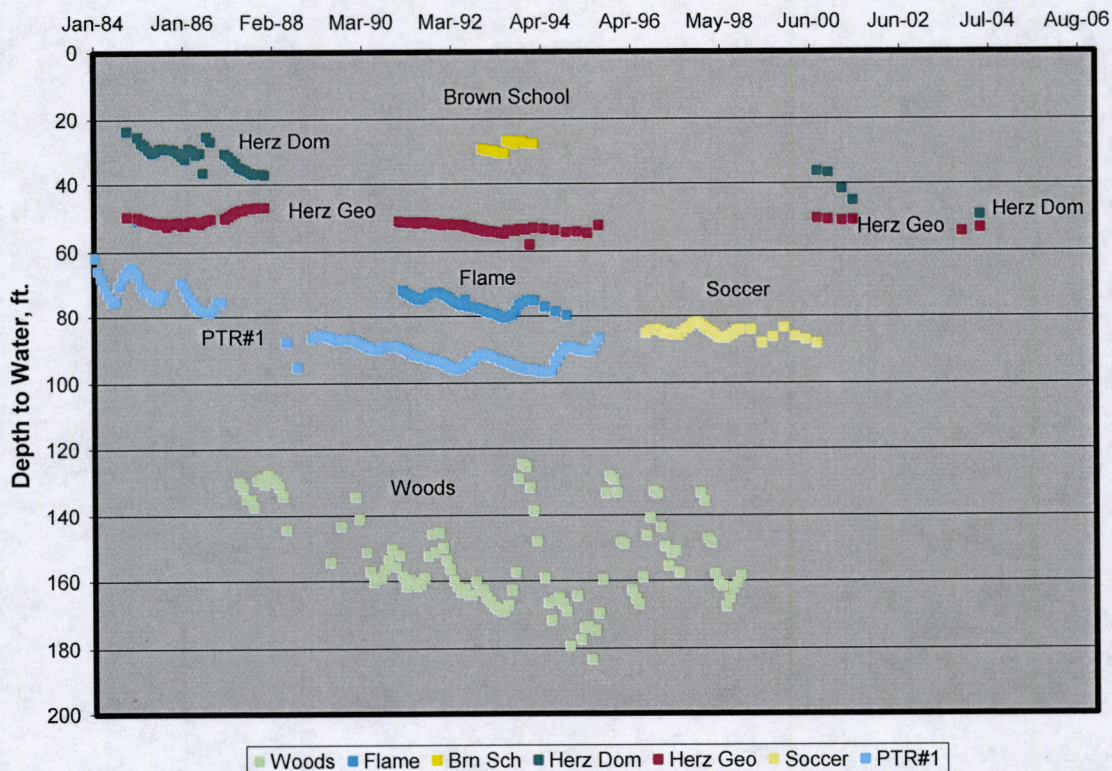
In the mid 80's declines in the static water level in the PTR#1 well were matched by increases in the chloride concentration (Figure 16). The seasonal changes in chlorides and static water levels were attributed to the percolation of irrigation water in the pastures north of the Mt. Rose Highway, below Steamboat Ditch and west of Steamboat Creek. From the Peigh Domestic well eastward to Steamboat Creek the majority of the monitoring wells in this report are down gradient from the Steamboat Ditch and are either within irrigated pasture lands or adjacent to the irrigated lands (Figure 1). The Woods and Tangen wells are up gradient from the ditch. The following is an analysis of water level changes and the impact on the water quality in the shallow fresh water aquifer.



**Figure 16. Chloride and water levels – PTR#1 well.**



Figure 17 is a graph of water levels in several of the monitoring wells.



**Figure 17. Water level changes.**

Water level declines are accompanied by increases in the chloride concentrations for the Herz Domestic well (Figures 18) and the PTR#1 and Flame wells (Figure 19). In the Herz Domestic well water levels have declined over 25 feet during the monitoring period and appear to continue to decline. Chloride concentrations continue to increase.

There was a steady recovery of the static water level in the Soccer well starting in the spring of 1995 (Figure 20). Through November of 1997 the water level had a net rise of over 15 feet. The water level data from the Soccer well are the only data for the interval October of 1996 to November of 1998. This period roughly coincides with the steep decrease in chlorides in the Brown School well where there are no water level data for this interval. Was there a corresponding rise in the water level in the Brown School well that was responsible for the decline in the chloride values? What was the cause of the water level rise in the Soccer well?



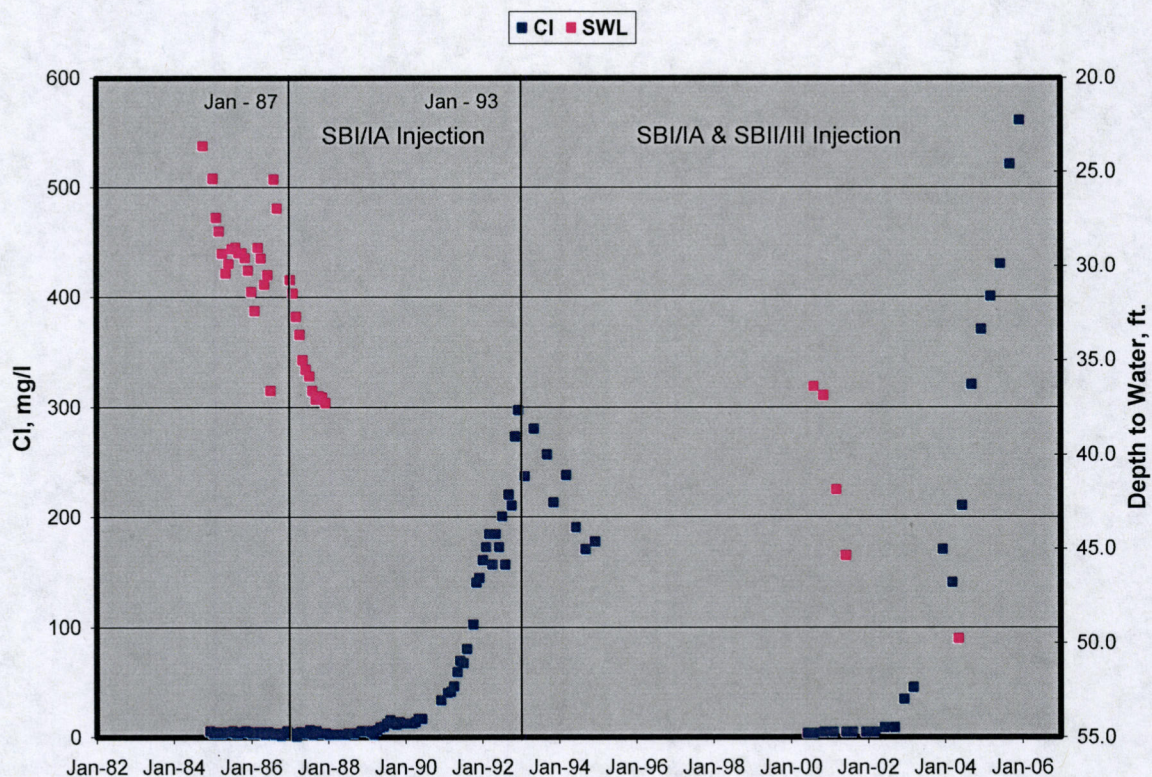


Figure 18. Chlorides and water levels – Herz Domestic well.

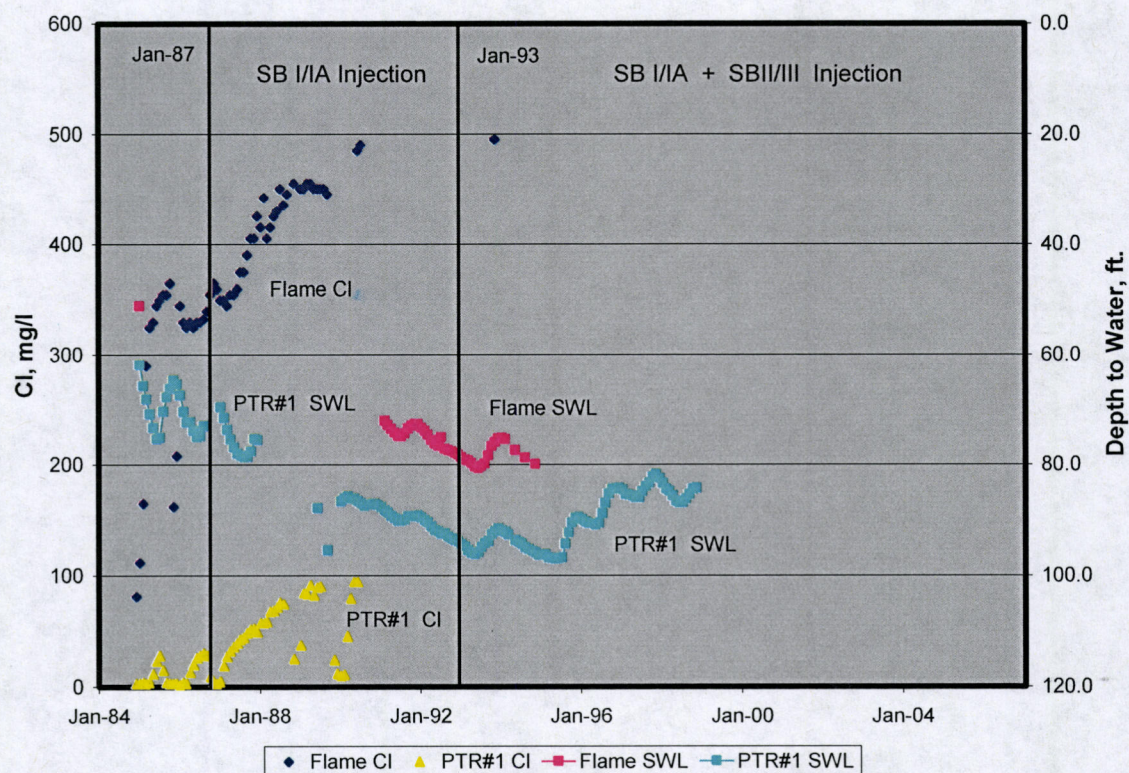
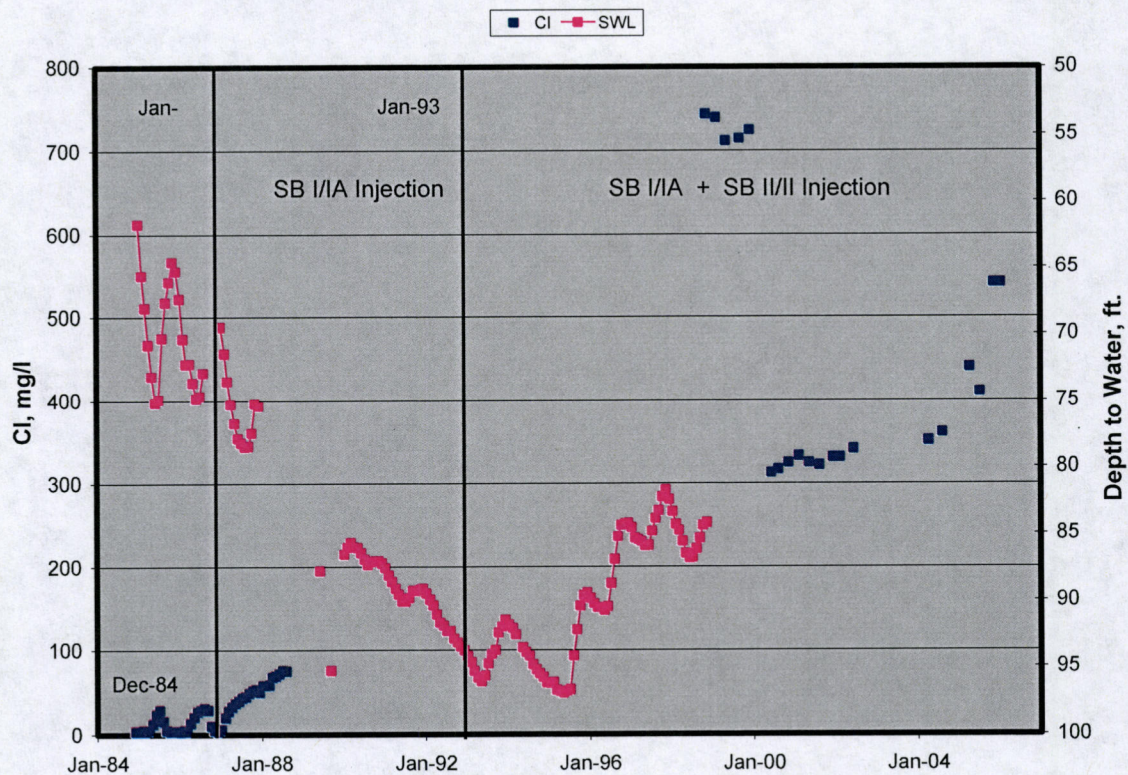


Figure 19. Chlorides and water levels – PTR#1 and Flame wells.





**Figure 20. – Chlorides and water levels – Soccer well.**

Geothermal observation wells also show water level declines (Figure 21). The observation wells are located at the north end of the SBI/IA project and just south of the Mt. Rose Highway (see Figure 1). Observation wells OW1 and OW2 are 657 feet and 570 feet, respectively, in depth. OW3 should roughly be of the same depth. The decline in water levels may be the result of shifting injection eastward to the SBII/III injection zone.



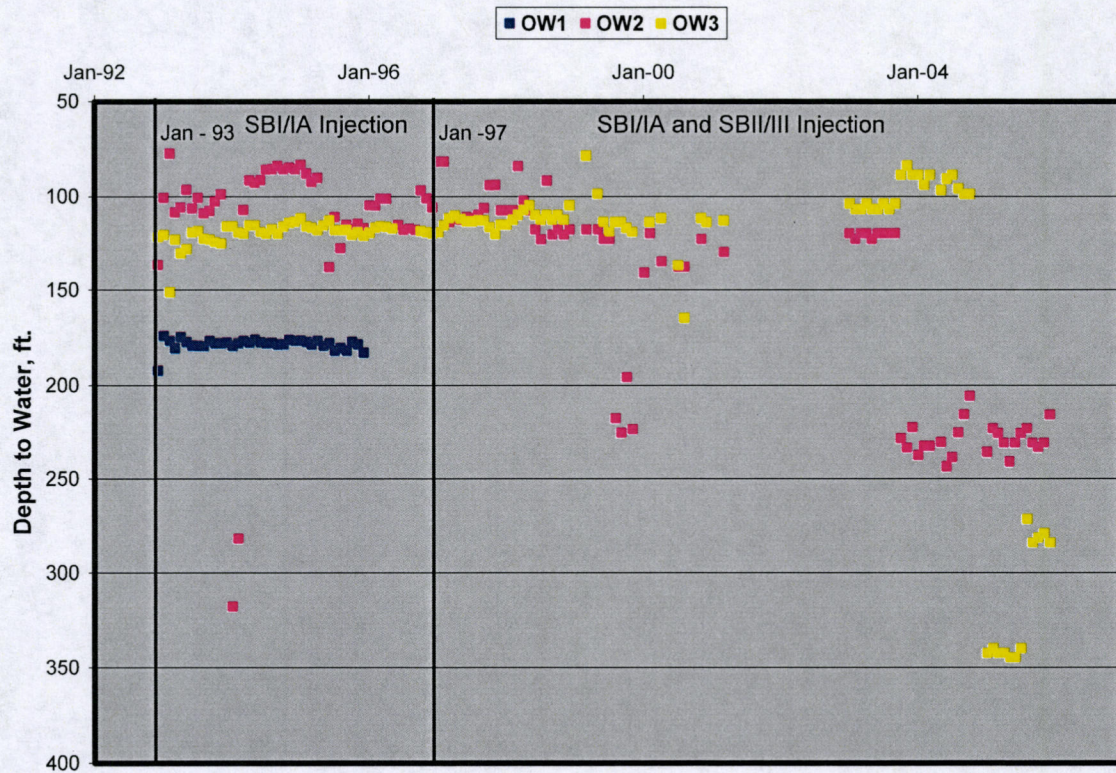
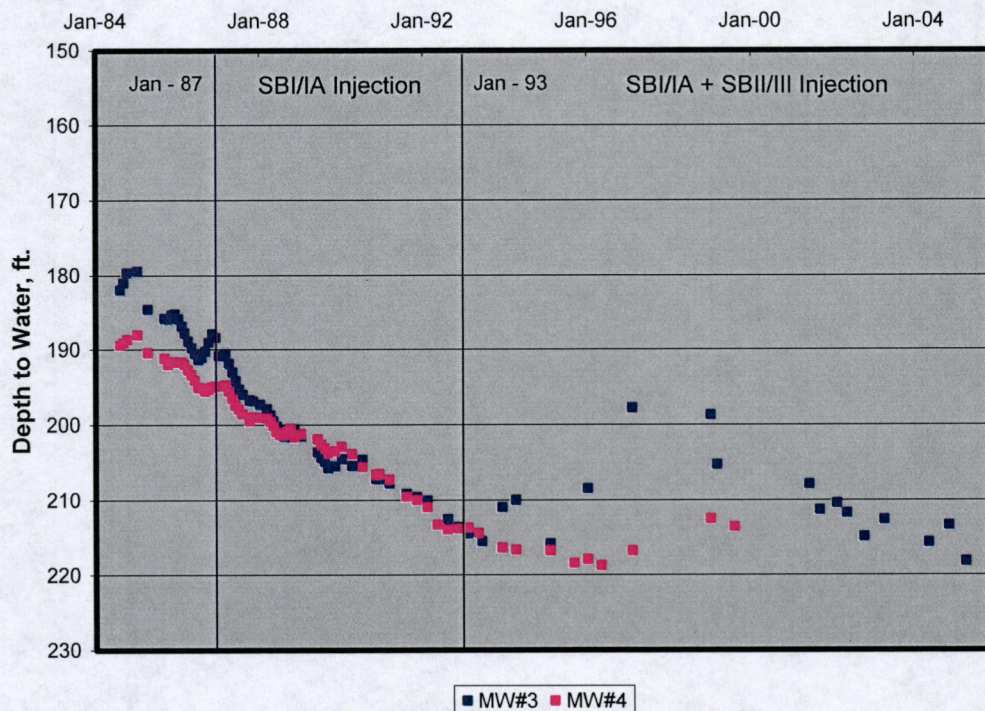


Figure 21. Water levels – SBI/IA observation wells.



Water level declines have been measured in monitoring wells operated by Washoe County (Figure 22). MW#3 is located approximately 4,500 feet west of the Herz Domestic well. MW#4, now destroyed, was adjacent to MW#3.



**Figure 22. Water levels – Washoe County monitoring wells MW#3 and MW#4.**



## CHAPTER EIGHT - DISCUSSION

In the broadest sense what were equilibrium conditions prior to 1987 have been upset. Prior to 1987 recharge from irrigation seasonally diluted the natural leakage of geothermal fluids into the alluvial aquifer. In the spring of 1987 seasonal responses disappeared as chloride concentrations began a steep increase in the Flame and Soccer wells. Similar increases were later noted in other monitoring wells.

No single factor can be identified as being responsible for the observed changes. As described above, an inverse relationship often is found between chloride concentrations and water levels in a monitoring well. The water table is a variable head or variable pressure boundary on the geothermal system in the zones of leakage. Lowering the water table decreases the fresh water pressure boundary on the geothermal system, allowing greater geothermal leakage. A higher water table increases the pressure boundary, restricting the leakage.

The loss of the annual recharge from percolating irrigation water would allow a draining of the former "reservoir" of fresh water built up over a century of irrigation. This would result in a decline in the elevation of the water table. The potential for a significant detrimental impact on the fresh water aquifer if irrigation recharge were to be curtailed and the reservoir "drained" long has been recognized (Yeamans and Broadhead, 1988a). Conversion of the former irrigated pastures to residential and commercial use has resulted in a loss of this source of recharge.

The current geothermal injection rates overwhelm the natural discharge rates. It would be not be unexpected to discover that there have been major increases in the amount of geothermal fluids discharging into the shallow aquifer. Pressure changes resulting from the injection of spent geothermal fluids are not expressed by changes in the water table of the alluvial aquifer. Injection pressure increases, however, can force more geothermal fluids into the aquifer. Higher injection pressures would increase the geothermal gradients to the aquifer, forcing greater geothermal discharge into the aquifer. Increases in chlorides in the Flame, Soccer and Brown School wells closely follow the start up of the SBI/IA project. These wells are located close to known subsurface discharge zones for geothermal fluids.

Third, ground water development up gradient from the monitored area would both create zones of drawdown that lower the water table and intercept the natural flow of high quality water from the west. Either result would allow for the increase in the proportion of geothermal fluids in the monitored area.

One thing seems certain; new equilibrium conditions have not been reached. Water levels down gradient from the Steamboat Ditch continue to decline. Chloride concentrations continue to increase. The highest priority should be given to maintaining and/or establishing monitoring sites in this area. Major development of the fresh water aquifer in this area should not be undertaken until there is confidence that geothermal fluids will not subsequently invade that part of the aquifer slated for development.

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