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EFFECTS OF GEOTHERMAL PRODUCTION AND INJECTION ON HOT SPRING AND GEYSER ACTIVITY, STEAMBOAT SPRINGS, NEVADA

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ABSTRACT

Hot spring and geyser activity at Steamboat Springs, Nevada has historically been second only in concentration to Yellowstone National Park in the continental United States. This activity began to decline in early 1987, shortly after a binary-type geothermal power plant began operating nearby, and coincident with well testing at a second, primary flash-type geothermal power plant. By early 1988, shortly after the primary flash-type power plant began operating, none of the numerous spring and geyser vents contained visible water. Data collected as part of a recent study suggest that geothermal production wells in the primary flash-type, and to a much lesser extent, binary-type, power plant well fields have significantly influenced spring and geyser activity. Observations of spring decline suggest that the mitigating effects of injection have been less than expected, probably as a result of heterogeneous and/or anisotropic conditions.

INTRODUCTION

The Steamboat Springs geothermal area is located approximately 9 miles south of Reno, in western Nevada. Steamboat Springs has been the site of historically continuous hot spring and geyser activity. The unique occurrence of the springs and geysers was second only in concentration to Yellowstone National Park in the continental United States. In 1983, to provide federal protection for these features, a tract of land containing some of the springs and geysers was designated an Area of Critical Environmental Concern (ACEC). The ACEC is administered by the U.S. Bureau of Land Management.

In January, 1987, electric power generation from a binary-type geothermal power plant began at a site near the springs and geysers (Fig. 1). This power plant is operated by Ormat Energy Systems, Inc. (OESI). In February, 1988, after several periods of well testing beginning in March, 1986, a second, primary flash-type, geothermal power plant began operating nearby (Fig 1). This power plant is operated by Caithness Power, Inc. (CPI). The two power plants utilize production and injection wells to supply and dispose of high temperature groundwater. Unlike the OESI facility, which injects 100% of the produced thermal water, operation of the CPI facility results in a net (mass) production (consumptive use) of about 11% thermal water. A therapeutic spa also operates one well, which is located about 3000 feet from the springs and geysers.

A study of the Steamboat Springs geothermal area, conducted jointly by the U.S. Geological Survey (USGS) and San Diego State University, was initiated at the request of the BLM as a result of the decline in, and cessation of, hot spring and geyser activity in the Steamboat Springs ACEC beginning in late 1986.

One objective of this study has been to determine the cause(s) for the decline of hot spring and geyser activity, while differentiating .between various natural influences known to affect the hot springs and potential impacts from geothermal development. Another objective of the study has been to describe the hydrogeology of the Steamboat Springs geothermal area and the relationship between production and injection of thermal water in the different well fields and hot spring and geyser activity. Possible methods to mitigate impacts to the springs and geysers caused by the production and injection wells have also been discussed.

STUDY APPROACH

In order to meet the study objectives, data collected by private persons, federal and state agencies, and geothermal developers have been reviewed and analyzed. Original data collection and analysis have been performed. During a detailed study from 1945-52, White (1968) ascribed changes in spring discharge and water levels (in nonflowing vents) to several factors, including (1) earthquakes, (2) random effects, (3) earth tides, (4) barometric pressure, (5) precipitation, and (6) discharging geothermal wells. Data have been collected in such a way as to attempt to assess the degree to which one, or more, of these factors affected the decline in spring and geyser activity.

Aerial photograph analysis, limited geologic mapping, structural data collection, and compilation of published geologic maps of the area have helped to understand groundwater flow in the fractured bedrock of the geothermal area. Barometric pressure data were obtained from a nearby weather station for selectedtime periods. Precipitation records dating back to 1937 were obtained and used to compare observations of hot spring activity and corresponding annual precipitation between 1945-52 with similar data from 1977 and 1986-89. Stream discharge and chloride concentration measurements along Steamboat Creek, a regional groundwater discharge point, have been used in mass flux calculations to make estimates of the total thermal groundwater discharge from the Steamboat Springs geothermal system. These estimates were compared to a similar estimate before geothermal development.

Probably the most valuable data collected and analyzed included water level measurements (using a graduated rule or electronic water level probe) in hot spring vents, as well as water level and pressure measurements in observation wells in the vicinity of the springs and the geothermal well fields. A fairly detailed history (e.g. hydrographs) of the decline in hot spring activity and geyser water levels was prepared from the spring measurements, This history was compared to

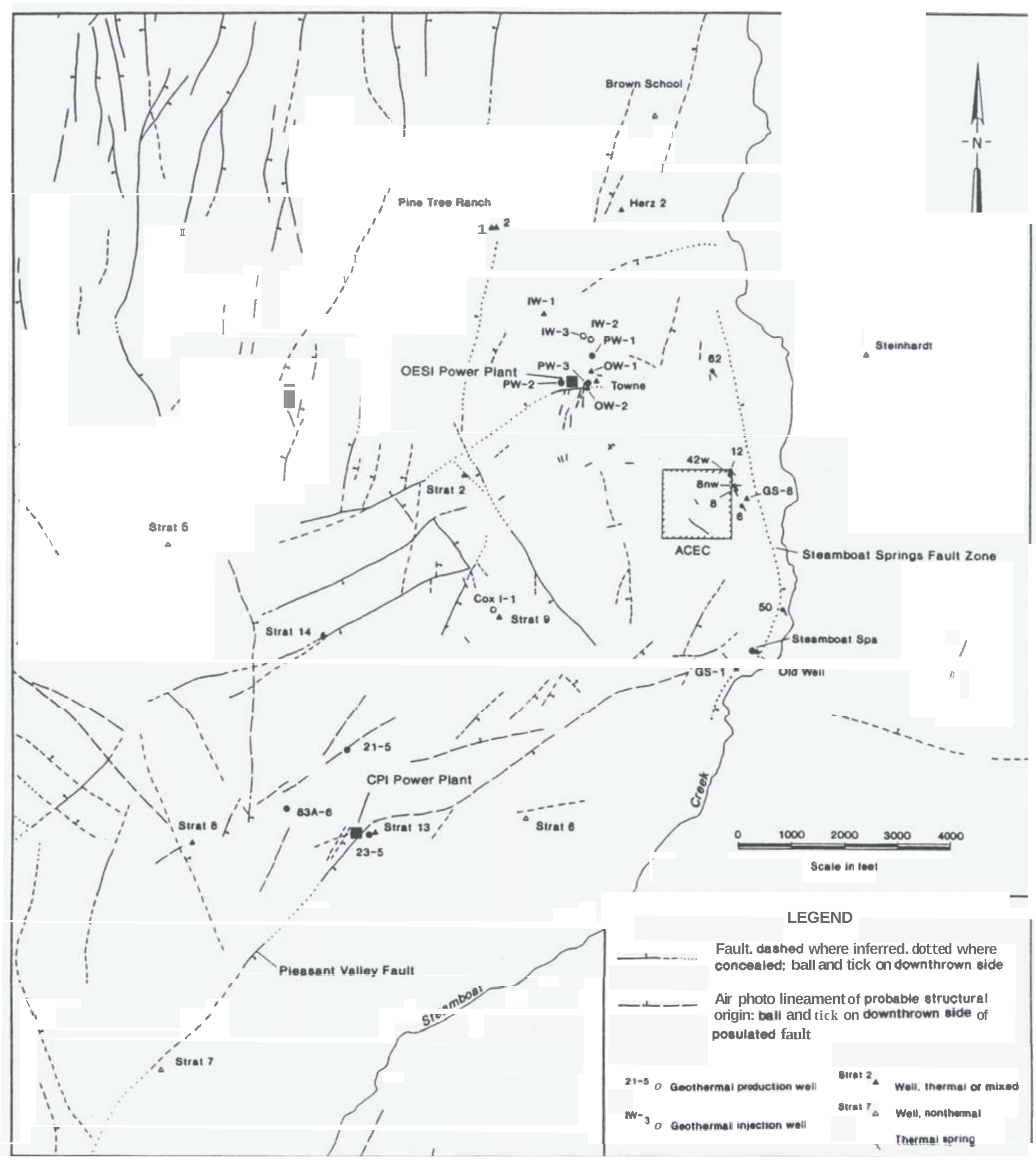

Figure 1. Fault and air photo lineament map of the Steamboat Springs geothermal area, including the location of selected wells. 21-5, 83A-6 and 23-5 = CPI production wells; Cox I-1 = CPI injection well: PW-1, PW-2 and PW-1 = OESI production wells: IW-2 and IW-3 = OESI injection wells (Collar, 1990).

water level changes in the various observation wells and to periods of production and/or injection at the geothermal well fields.

RESULTS

The springs investigated during this study (elev. approx. 4650 ft) occur in the discharge area of a regional-scale groundwater flow system (Fig. 1) referred to as the Steamboat Springs geothermal system. Under natural conditions, groundwater flows from the recharge area in the southwest (elev. 7000 ft), parallel to the dominant fracture trend in the Steamboat Springs geothermal area, and discharges as thermal water to the springs and Steamboat Creek (Fig. 1; Collar, 1990). A number of production, injection, and observation wells have been completed in the fractured bedrock in the Steamboat Springs area. Production wells in the OESI well field (elev. 4700 ft), located northwest of the springs, are completed in

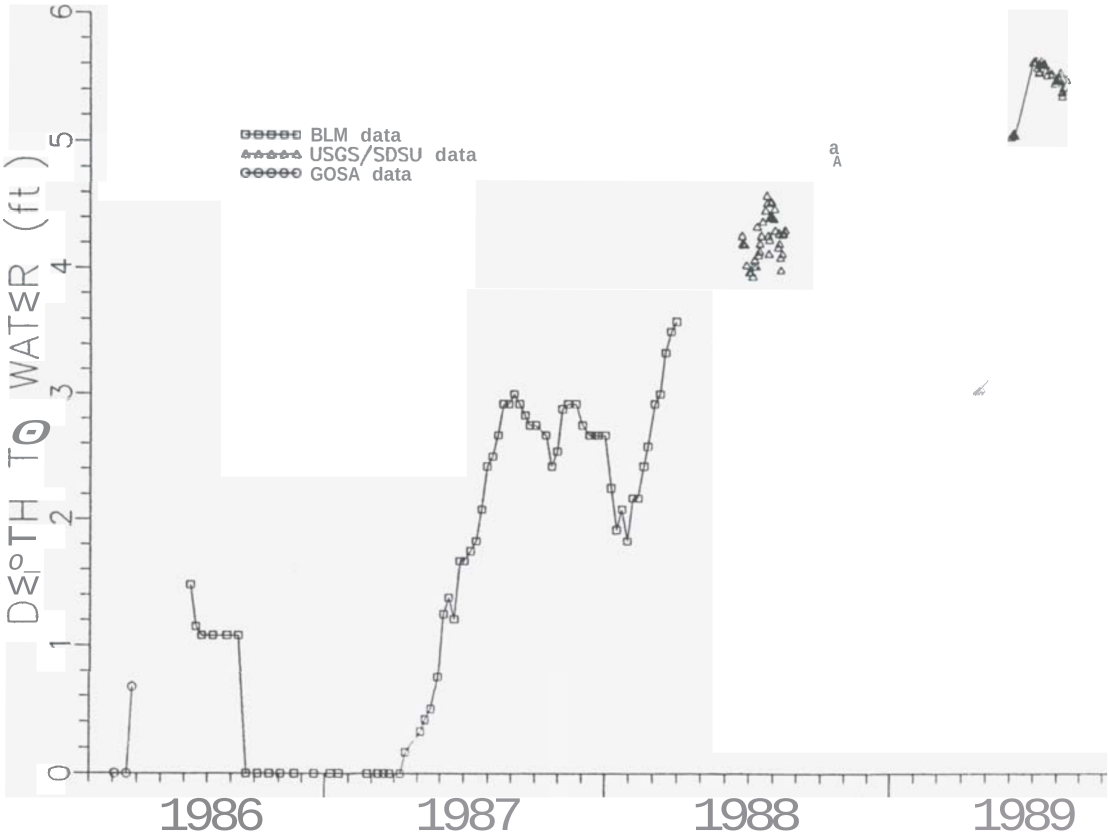

Figure 2. Hydrograph of spring 6, March, 1986 to September, 1989 (see Fig. 1 for location). Zero water depth corresponds to period of spring discharge.

granodiorite, while injection wells are completed in volcanic rocks and/or granodiorite. Production wells in the CPI well field (elev. 5350-5660 ft), located southwest of the springs, are completed in granodiorite and metamorphic bedrock, while the single injection well (elev. 5050 ft) is completed in granodiorite.

Between March, 1986, and August, 1989, many springs experienced several periods of parallel water level decline and recovery, superimposed on a general decline in hot spring water levels. Following a period of "normal" spring discharge and geysering in the fall and winter of 1986, numerous springs and geysers experienced declining water levels over a 7 month period. These temporal variations are best illustrated by spring 6 (Fig. 2). At the end of this period, in July, 1987, all but two of the springs and geysers were reported as dry. Water level declines, interrupted by brief periods of recovery, have generally continued through 1989. The water level decline from 1987 to 1989 in spring 12 (Fig. 1) has been as much as 17 feet.

Analysis of previous studies of the springs and use of simple barometric pressure corrections (Collar, 1990) suggest that water level fluctuations caused by earth tidal stresses, changing barometric pressure, or other factors (e.g. earthquakes) are small, short lived, or random in comparison to those caused by discharging geothermal wells. Therefore, it is unlikely that these influences have contributed to the long term decline in spring water levels.

Analysis of historical spring discharge data suggests that there is only a weak, if any, relation between spring discharge and seasonal variations in precipitation. Further, analysis of annual precipitation data shows that the observed decline in spring activity and discharge rates are not consistent with any relationships between spring discharge and annual precipitation suggested by White (1968). The 3 to 4 gallons per minute (gpm) spring discharge measured in 1988 is significantly lower than the 34 to 40 gpm predicted from spring discharge-annual precipitation relationships derived from White's data.

The general spring and geyser decline began before the start of the current drought in western Nevada and long term precipitation data and observations indicate that the springs and geysers have remained active during previous prolonged droughts (White, 1968 and Collar, 1990). However, it is unclear whether consecutive below normal precipitation years have contributed to the spring and geyser decline.

Current estimates (Collar, 1990) of the natural rate of thermal water discharge (as inflow to Steamboat Creek) are about 80% of that estimated by White (1968) in 1955, with most of the decrease occurring in the vicinity of the geothermal area. Only when the net production rate from the CPI wellfield is added to recent estimates of the natural discharge rate is the total estimated discharge rate from the Steamboat Springs geothermal system (as wells and inflow to Steamboat Creek) similar to the 1120 gpm (as wells, springs and inflow to Steamboat Creek) estimated by White. These observations suggest that thermal water which formerly discharged to the springs and Steamboat Creek in the geothermal area has been diverted by the CPI wells. One additional factor that could influence the spring and geyser activity, and that was not specifically considered by White (1968) or Collar (1990), is changes in hydraulic head in some nonthermal

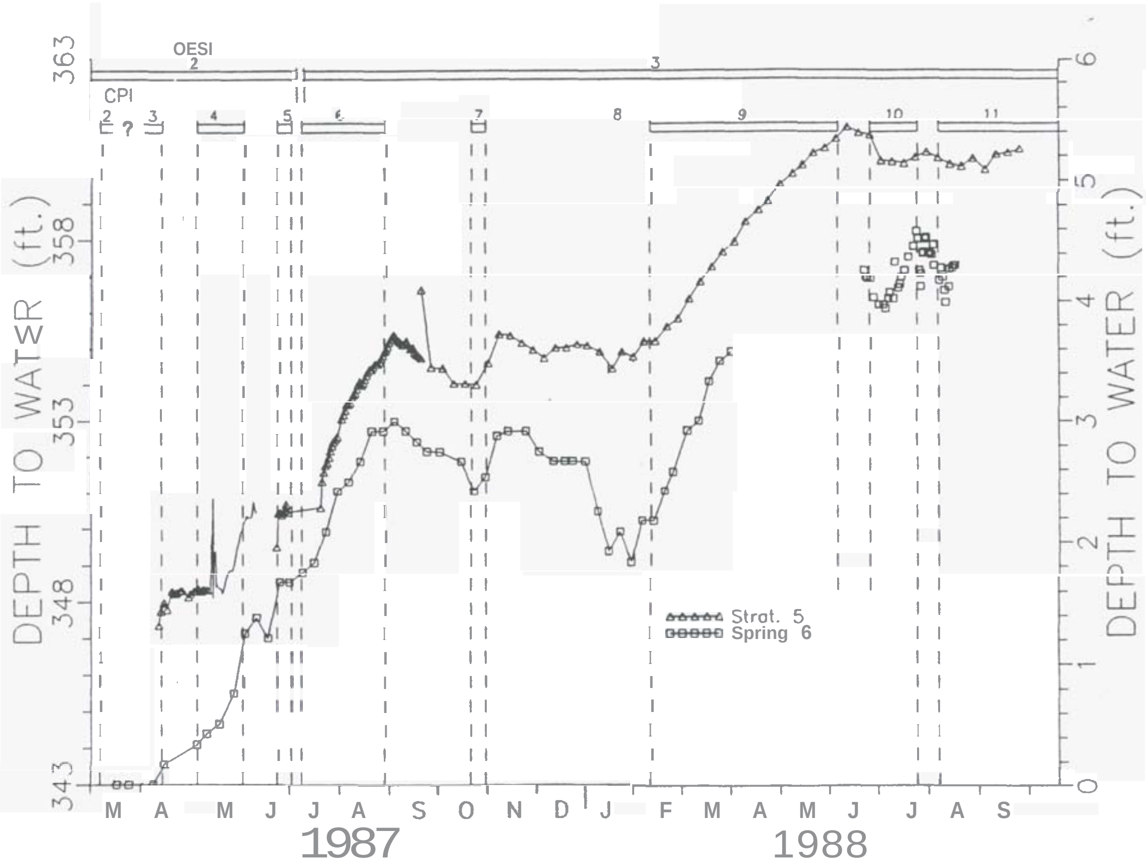

Figure 3. Hydrograph of spring 6 and strat well 5, March, 1987 to September, 1988. Horizontal bars represent periods of geothermal well discharge. OESI: 2 and 3 with injection: CPI: 6 and 7 without injection, and 4, 5, 8 (duration not shown), 9, 10 and 11 with injection.

alluvial aquifers surrounding the geothermal area. These changes could potentially affect the proportion of thermal water discharging to the springs, Steamboat Creek, and the alluvial aquifers (Sorey et al., 1990). These effects have not been satisfactorily delineated at this time, partly as a result of the ambiguity in hydraulic head changes in different portions of the alluvial aquifers.

There is no evidence to suggest that the therapeutic spa well (Fig. 1) has influenced spring and geyser activity near the ACEC (White, 1968 and Collar, 1990). However, periods of water level decline in the springs do generally correlate with periods of production (and often concurrent injection) from geothermal wells operated by both power facilities (Fig. 3; Collar, 1990). Periods of rising water levels in many springs correlate with periods of no production in the CPI well field (Figs. 3 and 4). Water level fluctuations in spring 6 mimic those from strat well 5 (Fig. 3) and thermal bedrock wells whose hydraulic connection to CPI production wells has been established (Chevron Resources, 1987). In contrast to the random nature of spring discharge and water level fluctuations noted by White between 1945 and 1952, recent water level fluctuations in a number of spring vents have been uncharacteristically parallel, apparently in response to discharging geothermal wells (Fig. 4). Further, data from some springs show increased rates of water level decline in some springs upon interruption of injection during geothermal production (Yeamans, 1987; spring 12, Fig. 4). Log-log hydrographs of some springs match closely the Theis solution for production from a well in an ideal aquifer (a line sink). Short term spring responses are consistent with those predicted by well hydraulics theory (Fig. 5). The values of transmissivity (kh) and storage coefficient calculated from this analysis are also similar to those determined from reservoir tests involving wells (Faulder, 1987).

DISCUSSION

Considering the results above, discharging geothermal wells utilized by the power plants appear to have significantly influenced the springs and geysers within and outside the ACEC. Most of the data, though qualitative, suggest that CPI wells have influenced the springs more than OESI wells (Collar, 1990).

Several conditions exist which could have been conducive to declines in spring and geyser water levels due to geothermal well including, (1) net production of thermal groundwater from the CPI well field, (2) bedrock fracture and fault patterns which may provide hydraulic connection between the geothermal production wells and the springs, (3) production from, and injection into, different fractures or bedrock intervals, or (4) the heterogeneous nature of permeability in the fractured bedrock between production and injection wells and the springs.

One of the most interesting of these observation6 is the decline in spring water levels during production from the CPI wellfield, despite concurrent injection into the Cox I-1 well (Fig. 1). Because the Cox I-1 injection well is located closer to the hot springs than the CPI production wells, the observed decline in spring water levels is

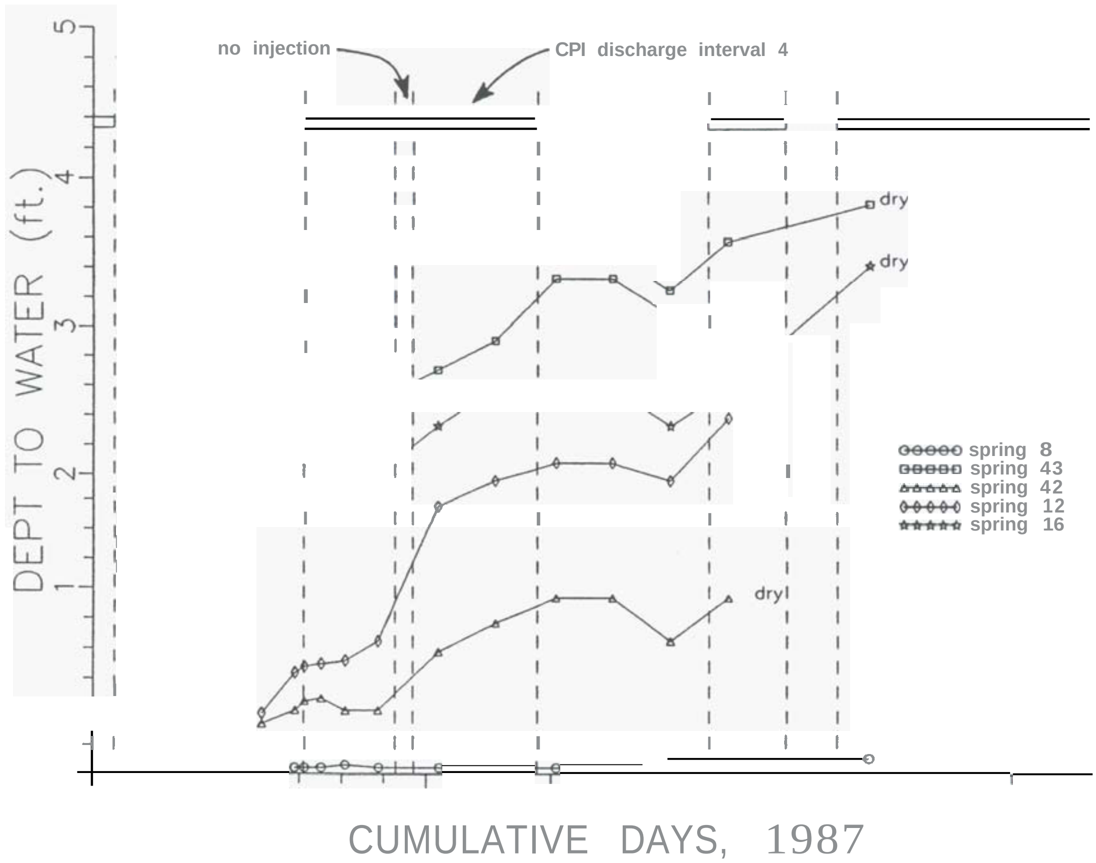

Figure 4. Hydrograph of springs 8, 12, 16, 42 and 43, May to July, 1987. Springs are located near the ACEC (Fig. 1). Horizontal bars represent periods of CPI geothermal well discharge (see Fig. 3). Dry = no measurable water in spring vent.

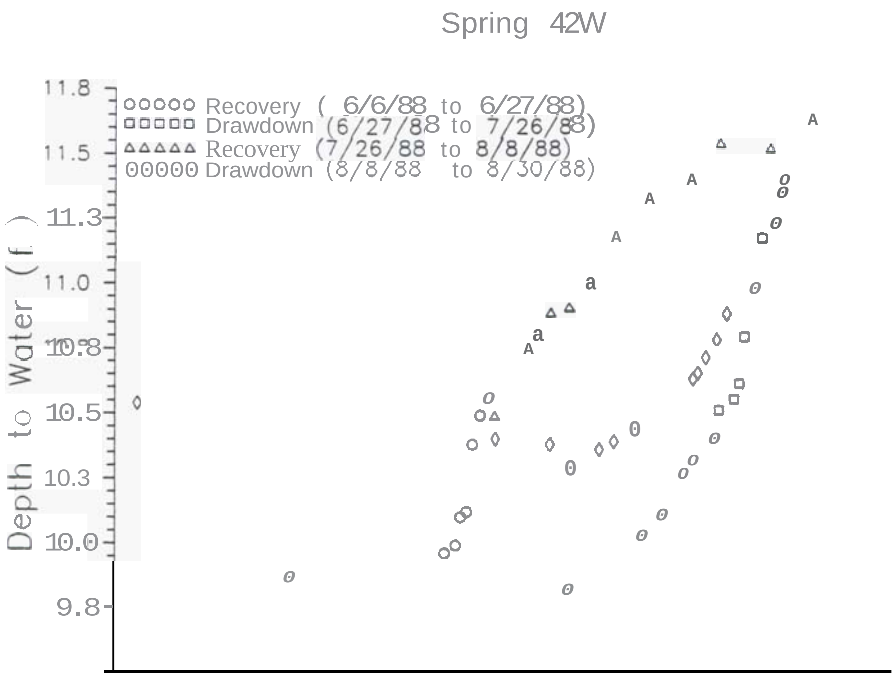

Figure 5. Semi-log plot of spring 42w water levels from June to August, 1988, using the method of Birsoy and Summers (1980) during CPI intervals 10 and 11 (and preceeding nonproduction intervals-Fig. 3). calculated transmissivity (kh) = 3000 ft^2/day and storage coefficient = 2.6×10^{-3}.

contrary to the effect predicted for a homogeneous, isotropic reservoir. The decline of hot springs during periods of production and the subsequent recovery during periods of non-production (Figs. 3 and 4) suggest that the hot springs are responding to the net production from the reservoir, as if the production and injection wells were located at similar hydraulic distances. This implies, of course, that the effects of geothermal production and/or injection on the springs may not be predicted in impact assessment using models that assume homogeneous, isotropic reservoirs. As would be expected for the fractured bedrock reservoir at Steamboat Springs, heterogeneous and/or anisotropic conditions exist. Under such conditions, use of simple map-view distances between wells and springs may not represent the effective hydraulic distance along fractures. Several lines of evidence suggest the presence of heterogeneous conditions (Collar, 1990), including the results of reservoir tests (Faulder, 1987).

The declines in spring and geyser water levels caused by geothermal production and injection might be reversed by utilizing injection wells that are located hydraulically closer to the springs and geysers. This might be accomplished, for example, by perforating the CPI injection well (Cox I-1, Fig. 1) casing in areas of suspected favorable permeability (Collar, 1990). However, constructing additional injection wells that intersect fractures with a more direct connection to the springs and geysers may be necessary.

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