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MONITORING THE HYDROLOGIC SYSTEM FOR POTENTIAL EFFECTS OF GEOTHERMAL AND GROUND-WATER DEVELOPMENT IN THE LONG VALLEY CALDERA, MONO COUNTY, CALIFORNIA, U.S.A.

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ABSTRACT

In the early 1980's, renewed interest in the geothermal potential of the Long Valley caldera, California, highlighted the need to balance the benefits of energy development with the established recreational activities of the area. The Long Valley Hydrologic Advisory Committee, formed in 1987, instituted a monitoring program to collect data during the early stages of resource utilization to evaluate potential effects on the hydrologic system. Early data show declines in streamflow, spring flow, and ground-water levels caused by 6 years of below-average precipitation. Springs in the Hot Creek State Fish Hatchery area discharge water that is a mixture of nonthermal and hydrothermal components. Possible sources of nonthermal water have been identified by comparing deuterium concentrations in streams and springs. The equivalent amount of undiluted thermal water discharged from the springs was calculated on the basis of boron and chloride concentrations. Quantifying the thermal and nonthermal fractions of the total flow may allow researchers to assess changes in flow volume or temperature of the springs caused by ground-water or geothermal development.

INTRODUCTION

In the early 1980's, renewed interest in the geothermal potential of Long Valley caldera, California (fig. 1), highlighted the need to balance the benefits of energy development with the established recreational activities of the area. In order to meet this need, the Long Valley Hydrologic Advisory Committee (LVHAC) was formed in 1987 with members from various government agencies and private geothermal developers. The U.S. Geological Survey is a nonvoting member of the advisory committee.

The purpose of the technical advisory committee was to implement a hydrologic monitoring program that focused on early detection of changes in such features as Hot Creek gorge, the Hot Creek State Fish Hatchery springs, Mammoth Creek, Hot Creek, and other thermal and nonthermal springs that potentially could be affected by development activities within the Long Valley caldera. In addition, the committee is to advise the permitting agencies of any significant changes in the hydrologic system and may suggest that certain conditions be imposed on specific development projects; however, considering the advisory nature of the committee, such suggestions do not create legal obligations of any kind. The Survey is responsible for collecting and compiling the baseline hydrologic-monitoring data and for providing these data to the committee on a quarterly basis.

This paper presents a discussion of the early data collected as a result of the hydrologic monitoring program. Data from the Fish Hatchery springs were analyzed to describe the hydrologic system prior to extensive geothermal development and to illustrate a technique for estimating the proportions of geothermal and nonthermal flow contributing to these springs.

Background

Exploration for a geothermal resource in the Long Valley caldera began in the early 1960's, when eight geothermal wells were drilled and tested at Casa Diablo by Magma Energy, Inc. Although these wells were not developed for commercial power production, they verified the existence of a moderate temperature (170 °C) hydrothermal resource at relatively shallow depths ranging from 500 to 800 feet below land surface. The only geothermal powerplant in Mono County, the Mammoth Pacific powerplant, began power production in February 1985 (fig. 1). This air-cooled, binary-cycle powerplant, owned by Pacific Energy, produces 7.0 MWe (megawatts electric) (net) of power, which is purchased and distributed by Southern California Edison.

In 1984, Mono County created the Energy Management Department to review and process use-permit applications for geothermal resource-development projects in the county. The first proposal to be considered by this department was the Mammoth/Chance Project. The proximity of this proposed 10 Mwe binary plant to the Hot Creek State Fish Hatchery and the Hot Creek gorge recreation area (fig. 1) prompted the department to require the Mammoth/Chance developer to install a series of shallow monitoring wells to collect baseline data. They were to do this prior to drilling production test holes in order to detect possible impacts on the thermally influenced springs at the fish hatchery and the recreational area from the exploratory drilling and testing.

Despite the extensive geological, geophysical, and hydrological studies that have been done in the Long Valley caldera (Goldstein, 1987), a lack of definitive information remains regarding the precise nature of the flow system (for example, the importance of lateral flow as compared with upwelling/fracture flow), the degree of hydrologic connection between hydrothermal reservoirs at various depths, and the connection between these reservoirs and the surface springs at Hot Creek gorge recreation area and the fish hatchery. Because of this lack of data, the Energy Management Department was reluctant to formulate threshold limits regarding the degree of change from the baseline conditions of pressure and temperature that would prompt the closing of a geothermal powerplant.

In 1986, the Mono County Board of Supervisors formally acknowledged and supported by resolution (Mono County Board of Supervisors, 1986), the concept of the Long Valley Hydrologic Advisory Committee. The resolution states that it is desirable to implement a monitoring program and to have a group of experts make nonbinding suggestions for monitoring programs and project conditions meant to protect those resources.

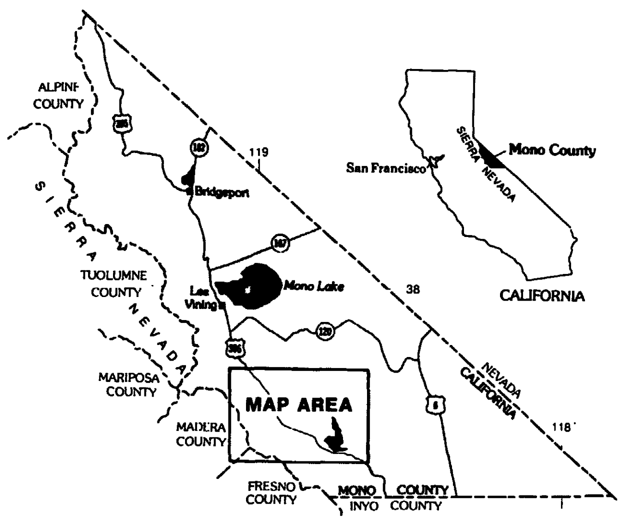
Description of Area

Long Valley is in eastern California (fig. 1) in the Mono-Long Valley Known Geothermal Resource Area (KGRA). The Long Valley caldera is a 175 mi^2 elliptical volcanic depression with a long history of volcanic activity, including eruptive activity less than 600 years ago. Hot springs, fumaroles, and elevated soil temperatures are surface manifestations of heat sources that exist at depth. There is much debate within the scientific community regarding the location, size, and depth of hot rock or magma underlying the Long Valley caldera. The volcanic history and regional geology were described by Bailey and others (1976) and by Bailey (1989).

General Hydrologic Conditions

Regional hydrology of the Long Valley caldera is characterized by a generally west-to-east ground-water flow from recharge areas in and near the base of the Sierra Nevada, around the west and south margins of the caldera, to points of discharge along Mammoth Creek, Hot Creek, and Lake Crowley (California Department of Water Resources, 1967, 1973; Sorey and others, 1978). Some of the recharge waters circulate along deep fault zones, and are heated to about 220 °C by hot rock less than 1 million years old. After rising toward the surface, hydrothermal fluids flow laterally eastward in one or more aquifers underlying the shallow nonthermal ground-water system (Sorey, 1985). Those hydrothermal fluids discharge at various places in the central and eastern parts of the caldera where northwest-trending normal faults provide paths for flow to the surface.

Mean annual precipitation at gage PGR (fig. 2) was 29.88 inches for 1982-89 (U.S. Forest Service, written commun., 1990). The monitoring period and the previous 4 years (1984-89) were characterized by below-average precipitation, low streamflow, and declining ground-water levels (fig. 3). Records of streamflow, ground-water levels, and spring discharge show seasonal trends along with the long-term trend of declining flows and water levels. Seasonal and long-term trends also are evident in the water-temperature records of some springs. In contrast, variations in water chemistry and in isotopic ratios of oxygen and hydrogen ($^{18}O/^{16}O$ and $^{2}H/^{1}H$, respectively) generally are small. Differences in isotopic ratios generally are <0.5 per mil for oxygen and <2 per mil for hydrogen. The largest variations in chemical composition (chloride ranges from 38 to 51 mg/L) are at site HCF on Hot Creek where thermal springs discharge to and mix with seasonally variable amounts of nonthermal stream water.



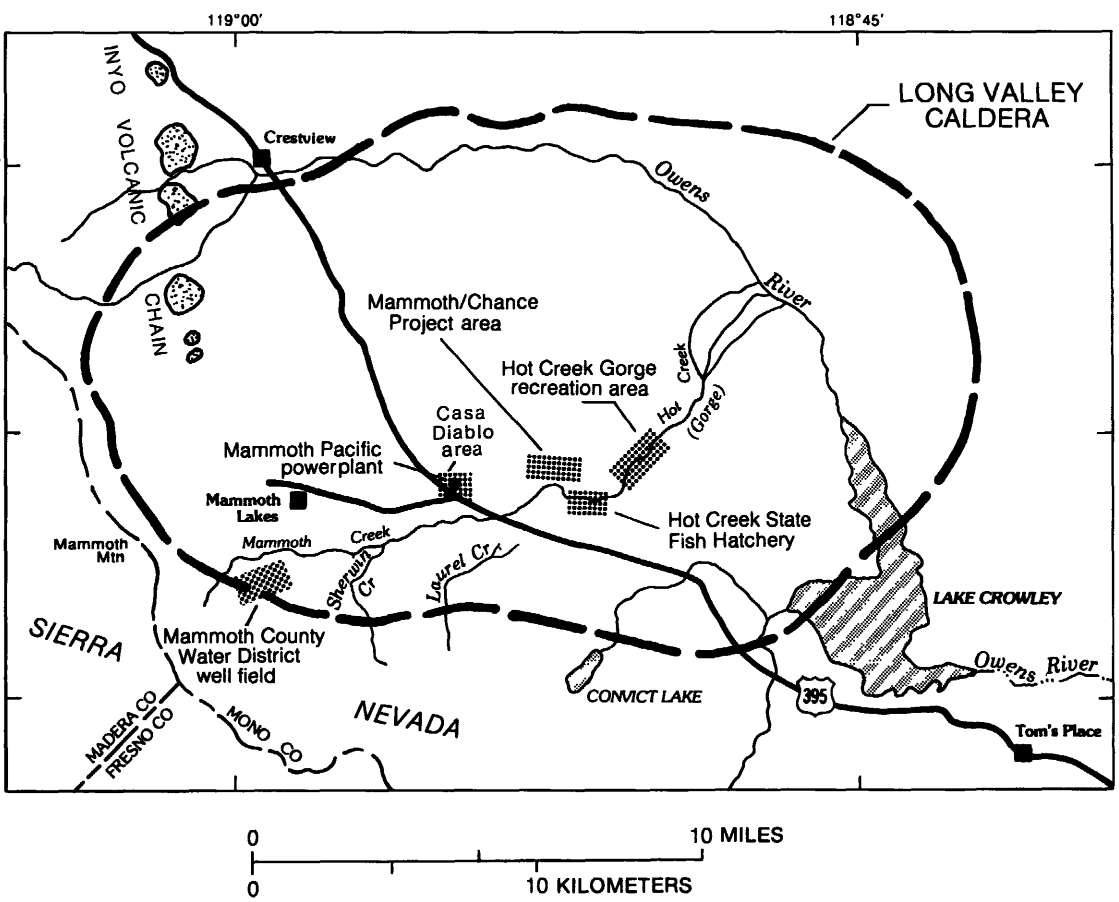


Figure 1. Location of Long Valley caldera and geographic features.

MONITORING NETWORK

The monitoring network consists of 25 sites (fig. 2), including wells, springs, streams, and one precipitation gage. Types of data collected include ground-water levels, well-temperature profiles, chemical concentrations and oxygen and hydrogen isotope ratios in ground and surface water, stream and spring discharge, water temperatures, precipitation quantities, and atmospheric pressure. In addition, ground-water pumpage, injection, and reservoir-pressure data are collected by the operator of the Mammoth Pacific powerplant. Pumpage and water-level data for each of the Mammoth County Water District wells also are recorded. The frequency of data collection varies from continuous to semiannual, depending on data type and site location.

Monitoring sites were selected to monitor hydrologic conditions of specific springs and streams or to monitor reservoir pressures in water supply or geothermal aquifers near well fields. Data from monitoring sites for specific springs or streams will provide a basis to detect changes in flows, temperatures, or water quality near existing features with established beneficial uses. Data from monitoring sites near well fields will provide a basis to assess the impact of resource utilization on reservoir pressures. If significant hydrologic changes are detected, statistical, analytical, or numerical methods may be used to establish cause-and-effect relations between resource utilization and impact to the features. At this point, data are being collected through the hydrologic monitoring network to establish baseline conditions. This step needs to be completed before any significant hydrologic changes can be detected and quantified and the possible causes of such changes determined.

Preliminary data from the monitoring network are available for the period June 1, 1988, to January 15, 1990 (hereafter referred to as "the monitoring period"). The period of record for some monitoring-network sites is much longer because additional data are available from previous studies (California Department of Water Resources, 1967 and 1973; Farrar and others, 1985, 1987, and 1989).

ANALYSIS OF MONITORING DATA FROM FISH HATCHERY SPRINGS

The fish hatchery data indicate the importance of both the nonthermal and thermal water components of the Long Valley hydrologic system and provide insights regarding the mixing of nonthermal and thermal water in the shallow subsurface of the southern part of the Long Valley caldera. In addition, the fish hatchery data are important because they will facilitate an understanding of the natural hydrologic conditions in both the thermal and nonthermal systems, with the expectation that effects of geothermal (and possibly ground-water) development can be recognized, identified, and evaluated. The fish hatchery data are discussed in detail for this reason and because of the importance the Long Valley Hydrologic Advisory Committee has attached to maintaining historical water temperatures, water quality, and flows of the hatchery springs.

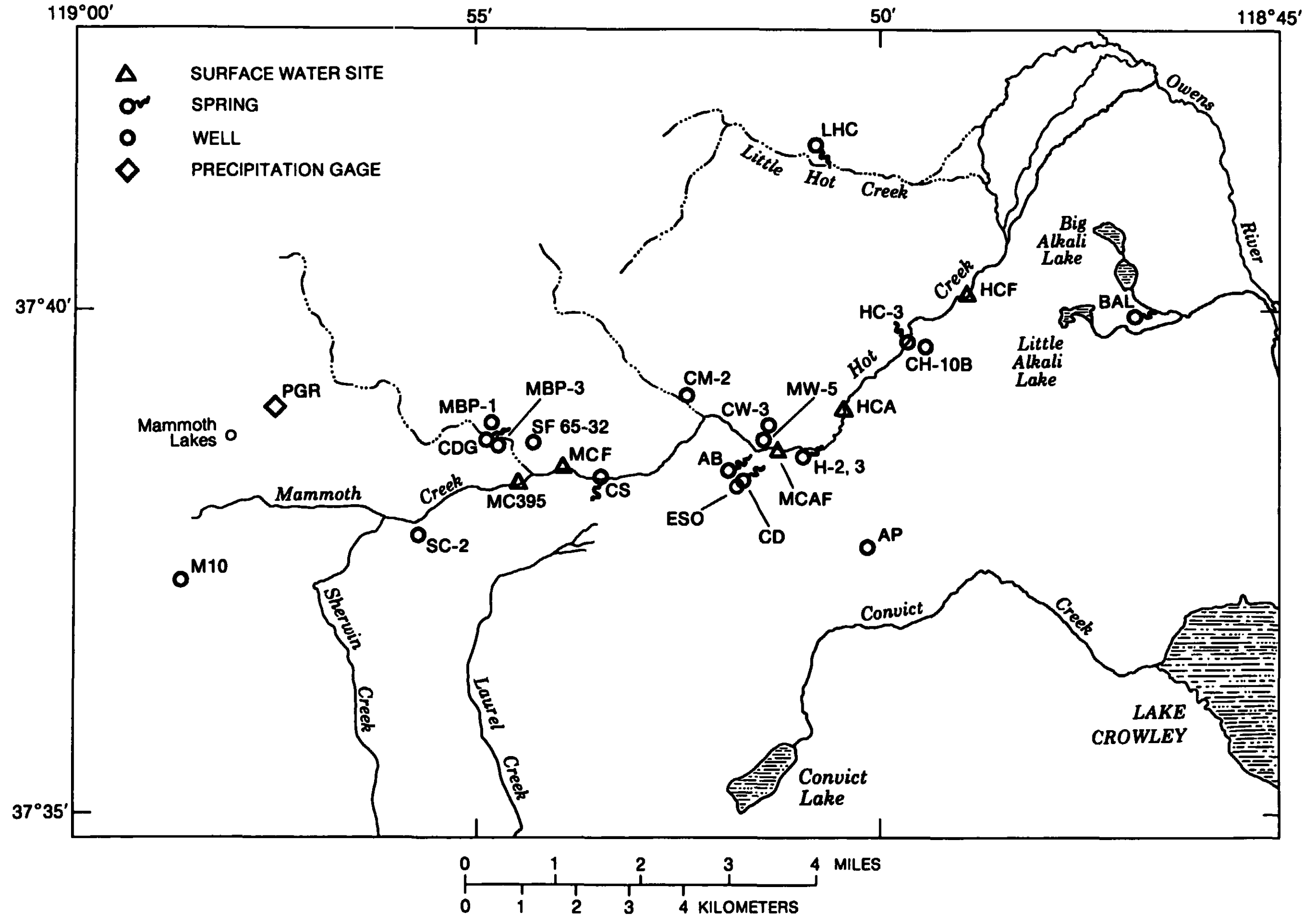


Figure 2. Location of monitoring sites.

Four groups of springs discharge water from fractured basalt flows that have been eroded to form a low cliff along the southern side of the fish hatchery. Water temperatures of the springs range from 10.8 to 17.6 °C (local nonthermal ground-water temperatures range from 6 to 12 °C). Three of the four spring groups (AB, CD, and H-2,3) are sites in the monitoring network (fig. 2). The alphanumeric identifiers for the springs are those used by hatchery personnel. Each spring group includes several vents that contribute water to pools or channels within the hatchery.

The chemical composition of water in various spring groups shows a relation consistent with the pattern of water temperatures. Spring group AB has the highest concentration of dissolved constituents [≥220 mg/L residue on evaporation (ROE)] and the highest temperature (17.6 °C); spring group H-2,3 has the lowest concentration of dissolved constituents (≤140 mg/L ROE) and the lowest temperature (10.8 °C). Distribution of water temperatures and chemical compositions indicates that the percentage contribution of thermal water varies among spring groups, with the greatest percentage of thermal water in the westernmost spring group (AB) and the least in the easternmost spring group (H-2,3).

The stable isotope ratios, $^{18}O/^{16}O$ and $^{2}H/^{1}H$, of water from the springs also vary from west to east and provide evidence of differences in ground-water source areas. The heaviest $^{2}H/^{1}H$ ratios are in the west (AB) with δD=-115 and the lightest are in the east (H-2,3) with δD=-120. Ratios for the other two spring groups are between -115 and -120. The isotope ratios are primarily dependent on the location of recharge areas for the nonthermal components of flow. Fractionation of

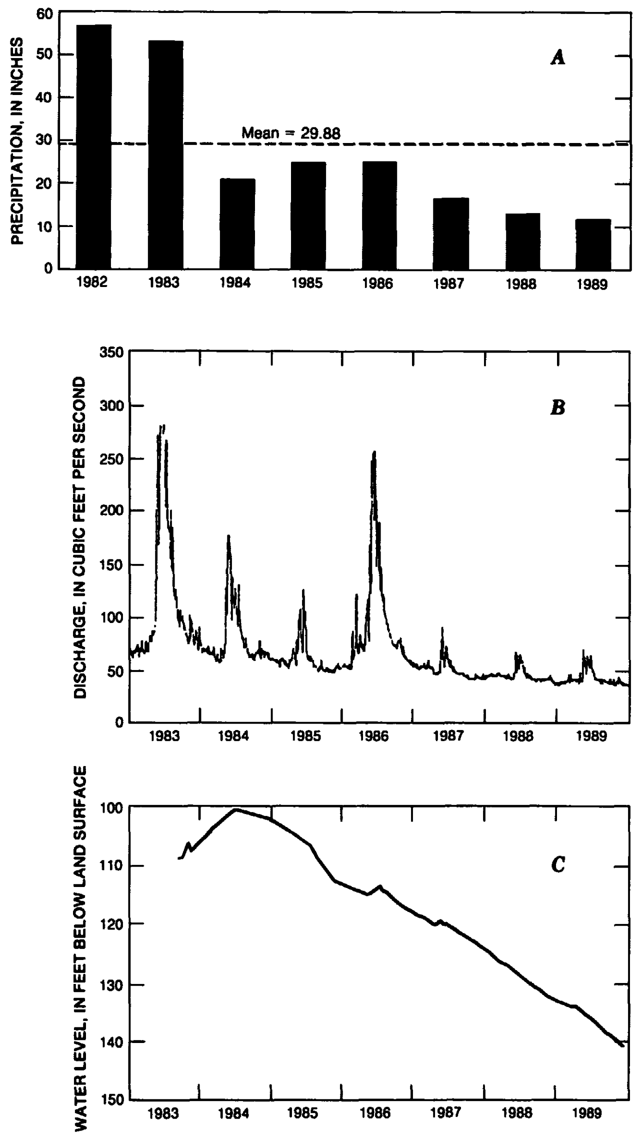


Figure 3. Precipitation, discharge, and ground-water levels for representative sites. *A*, Gage PGR. *B*, Surface-water site HCF. *C*, Well SC-2.

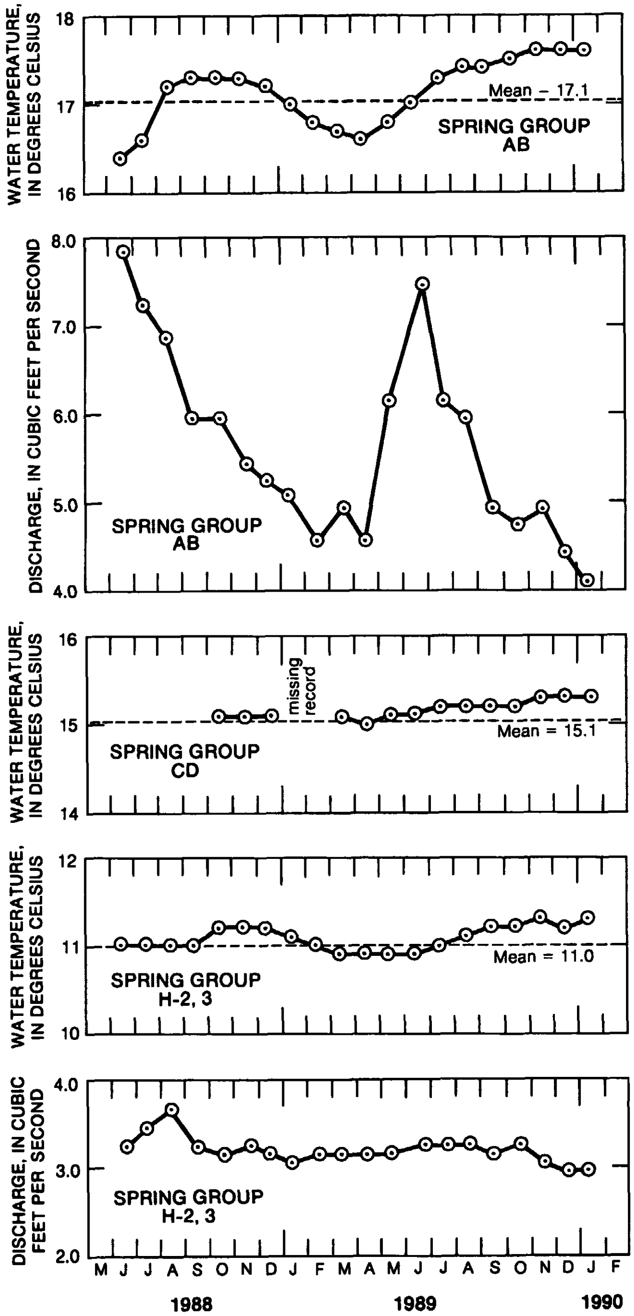


Figure 4. Discharge and water temperature for spring groups AB, CD, and H-2,3.

oxygen and hydrogen isotopes in precipitation due to rainout and topographic effects in the Long Valley area results in significant variations (>20 per mil δD) in isotopic ratios (Sorey and others, 1984). The isotopically heaviest precipitation falls in the western part of the area. The waters in nonthermal springs and streams in the western part also are isotopically heavier than nonthermal springs in the eastern and southern parts.

Hydrographs showing discharge from two of the three monitored spring groups (AB and H-2,3) are given in figure 4; discharge data for spring group CD are too imprecise to include in this analysis. Both hydrographs show seasonal variations in discharge but the general trend is for diminution of flow. The reduction in flow is even more pronounced when recent data are compared with instantaneous measurements made during July 1984, when the discharge from spring group AB was 12.9 ft^3/s (cubic feet per second) and from spring group H-2,3 was 4.9 ft^3/s. Thermographs of water temperatures recorded from the three monitored spring groups are also shown in figure 4. Considering seasonal variations and trends during the monitoring period, each spring group shows unique trends in discharge and water temperature.

Variation of discharge is greater for spring group AB than for spring group H-2,3. The discharge of spring group AB also exceeds that of spring group H-2,3 and peaks about 1 month earlier.

Temperatures also vary from west to east. Spring group AB has the highest mean temperature (17.1 °C), the greatest annual range (1 °C), a strong seasonal variation, and a general trend toward higher temperatures for the monitoring period. Spring group CD has a lower mean temperature (15.2 °C), little or no seasonal variation, and a slight trend toward higher temperatures for the monitoring period. Spring group H-2,3 has the lowest mean temperature (11.0 °C), a pronounced seasonal variation, and possibly a trend toward higher temperatures for the monitoring period.

Variations in discharge, water temperature, water chemistry, and isotopic composition among the hatchery spring groups demonstrate that the hatchery vicinity is the discharge area for a complex hydrologic system wherein thermal water mixes in variable proportions with nonthermal water from more than one source area. To account for differences in the timing of peak discharge between spring groups AB and H-2,3, either traveltime of flow from recharge areas to the springs is greater for the H-2,3 nonthermal source area than for AB, or the timing of snowmelt is later for the H-2,3 nonthermal source area than for the AB nonthermal source. Additional studies with stable-isotope data can be used to identify possible source areas for the nonthermal components. The isotopically light water (δD=-120±1 per mil) discharged by H-2,3 may originate from stream losses in Laurel Creek (δD=-121.5 per mil for one sample) with headwaters in the Sierra Nevada south of the caldera (fig. 1). The isotopically heavier waters discharged from AB (δD=-115.5±1.5 per mil) and from CD (δD=-116.5±1.5 per mil) may originate west of the Laurel Creek drainage where δD values range from -113.5 per mil in Mammoth County Water District wells tapping basalt aquifers to -117.5 per mil in Sherwin Creek (fig. 1).

Identification of source areas for water discharged from the hatchery springs is pertinent to this monitoring program because of the potential impact to the hatchery springs caused by the removal of ground water from basalt aquifers in the Mammoth Creek basin. If the springs have

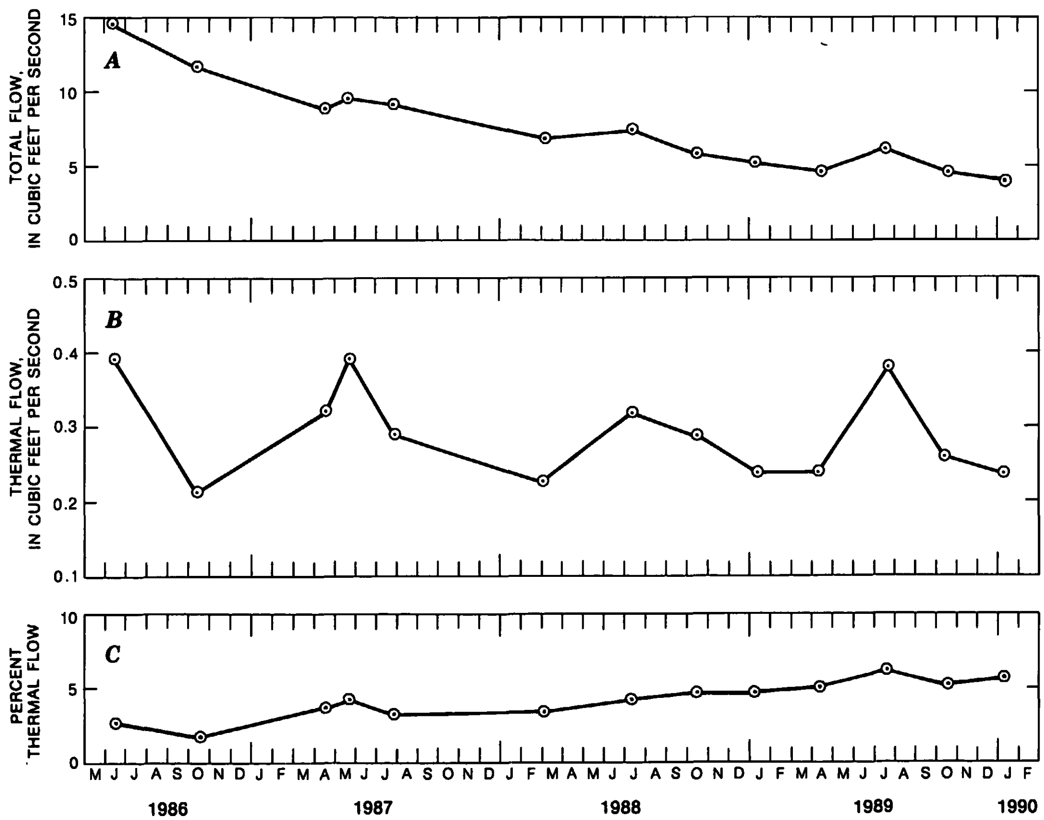


Figure 5. Discharge of Hot Creek State Fish Hatchery spring group AB: *A*, Total flow. *B*, Thermal flow. *C*, Percent thermal flow.

different source areas, then pumping in Mammoth Creek basin may affect spring groups AB and CD but not H-2,3. If spring groups AB and CD receive a mixture of water from recharge in both Mammoth Creek basin and the Laurel Creek drainage, the effect of pumping may be limited to the fraction derived from Mammoth Creek basin. Quantification of the thermal component of water in hatchery spring discharge is also pertinent to this monitoring program because of potential impacts caused by production of geothermal fluids from wells west of the hatchery.

The water temperature of springs does not provide a quantitative measure of the ratio of thermal to nonthermal water because the complexities of potential conductive-heat loss cannot adequately be measured. An estimate of the thermal to nonthermal ratio can be made using the concentrations of chemical constituents that tend to be low in nonthermal waters but high in the thermal waters. The conservative ions, boron and chloride, are good choices for this purpose. Concentrations of boron and chloride in nonthermal recharge waters probably are similar to concentrations in Mammoth Creek before any thermal water enters (boron ≤0.01 mg/L, chloride ≤1 mg/L). Concentrations of boron and chloride in the thermal component probably are similar to those in thermal water discharged from the boiling-temperature springs in Hot Creek gorge (boron, 10 mg/L, chloride, 220 mg/L).

Estimates of thermal contributions to spring group AB were made assuming the nonthermal component has concentrations of 0.01 mg/L boron and 0.3 mg/L chloride; thermal waters contain 10 mg/L boron and 220 mg/L chloride. The means of the estimates (fig. 5) indicate that the percentage of thermal contribution is, in general, inversely related to total discharge for spring group AB and ranged between 2 and 6 percent for the period shown.

When percentages are converted to flow volume, another relation becomes apparent: the amount of thermal water discharge varies seasonally. The quantity of thermal water is lowest following periods of high thermal discharge; the quantity of thermal water discharged is highest during times of peak total discharge (May to July). If it is assumed that the hydrothermal system is relatively deep and that flow paths from recharge areas to points of discharge are long, the quantity of thermal water flow should not vary in response to recent (1-5 years) precipitation patterns. This suggests that pressurization of the thermal aquifer due to hydrostatic load from recharge to the overlying nonthermal aquifer causes increase in discharge rather than overall increase in thermal water flow. This relation is supported by the data (fig. 5), which show that periods of excess discharge are followed by periods of relatively low discharge.

SUMMARY AND CONCLUSIONS

The formation of the Long Valley Hydrologic Advisory Committee facilitated approval of two geothermal projects, now in the preliminary stages of construction, by providing a forum for discussion of key issues and concerns relative to potential adverse impacts to hydrologic features that might result from pumping and injecting geothermal fluids. Important functions of the committee are to assure that reasonable compromises can be made by recognizing the divergent concerns of various groups, to institute measures to monitor and assess potential adverse impacts, and to choose remedial measures to mitigate negative impacts.

Baseline conditions cannot be determined because resource utilization of nonthermal ground water and hydrothermal fluids began prior to establishment of the monitoring network. However, additional developments using both nonthermal and thermal resources are planned, and the effects from these future developments could be estimated by comparing post-development trends with other data from this monitoring program.

Baseline data collection for this monitoring program began during a period of below-average precipitation. Consequently, the data represent only the low-flow, low-recharge component of the dynamic range of natural hydrologic conditions existing prior to significant ground-water withdrawal. Limited historical data provide some measure of conditions in a wetter environment.

A method to determine the proportions of thermal and nonthermal flows to the various spring groups is needed to establish the level of variability under predevelopment or early development conditions to determine whether flows of either component have been reduced by resource utilization. Quantification of the proportions of nonthermal water from different source areas could establish the extent to which withdrawal of ground water from different areas of Long Valley will affect the temperature, chemical quality, and flow volume of the hatchery springs.

The trend of diminishing flow, along with relatively constant, but cyclical, contributions of thermal water to the hatchery springs suggests that the geothermal production at Casa Diablo has not caused any measurable reduction in thermal discharge during the monitoring period. The diminishing flows relate primarily to reduction in the nonthermal contribution to the springs. The extent to which this reduction may be due, in part, to extraction of ground water from Mammoth Creek basin, as opposed to being entirely due to successive years of below-average precipitation, cannot be assessed at this time.

Continued collection of hydrologic data, evenly spaced in time, through periods of average and above-average precipitation could lead to a more complete conceptual understanding of the flow systems that contribute water to the hatchery springs. Additional data that could help identify source areas for the mixing components include seasonal analyses of hatchery waters for tritium content, and quarterly determinations of stable isotopes in water from a network of streams, springs, and wells in the western and southern parts of the Long Valley caldera.

REFERENCES CITED

Bailey, R.A., 1989, Geologic map of Long Valley caldera, Mono-Inyo craters volcanic chain and vicinity, eastern California: U.S. Geological Survey Miscellaneous Investigations Map I-1933, scale 1:62,500, 2 sheets.

Bailey, R.A., Dalrymple, G.B., and Lanphere, M.A., 1976, Volcanism, structure, and geochronology of Long Valley caldera, Mono County, California: Journal of Geophysical Research, v. 81, no. 5, p. 725-744.

California Department of Water Resources, 1967, Investigation of geothermal waters in the Long Valley area, Mono County: California Department of Water Resources, 141 p.

_____1973, Mammoth basin water resources environmental study (final report): California Department of Water Resources, 70 p.

Farrar, C.D., Sorey, M.L., Rojstaczer, S.A., Janik, C.J., Mariner, R.H., Winett, T.L., and Clark, M.D., 1985, Hydrologic and geochemical monitoring in Long Valley caldera, Mono County, California, 1982-84: U.S. Geological Survey Water-Resources Investigations Report 85-4183, 127 p.

Farrar, C.D., Sorey, M.L., Rojstaczer, S.A., Janik, C.J., Winett, T.L., and Clark, M.D.,1987, Hydrologic and geochemical monitoring in Long Valley caldera, Mono County, California, 1985: U.S. Geological Survey Water-Resources Investigations Report 87-4090, 71 p.

Farrar, C.D., Sorey, M.L., Rojstaczer, S.A., Steinemann, A.C., and Clark, M.D., 1989, Hydrologic and geochemical monitoring in Long Valley caldera, Mono County, California, 1986: U.S. Geological Survey Water-Resources Investigations Report 89-4033, 69 p.

Goldstein, N.E., ed., 1987, Proceedings of the symposium on the Long Valley caldera: A pre-drilling data review: Lawrence Berkeley National Laboratory Report, LBL 23940, 195 p.

Mono County Board of Supervisors, 1986, Support of Long Valley technical advisory committee: Resolution no. 86-110, 1 p.

Sorey, M.L., 1985, Evolution and present state of the hydrothermal system in Long Valley caldera: Journal of Geophysical Research, v. 90, no. 13, p. 11219-11228.

Sorey, M.L., Farrar, C.D., and Wollenberg, H.A., eds., 1984, Proceedings of the workshop of hydrologic and geochemical monitoring in the Long Valley caldera: Lawrence Berkeley National Laboratory Report, LBL 20020, 82 p.

Sorey, M.L., Lewis, R.E., and Olmsted, F.H., 1978, The hydrothermal system of Long Valley caldera, California: U.S. Geological Survey Professional Paper 1044-A, 60 p.