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Quantitative Analyses of Warm Spring Waters at the Hot Creek Fish Hatchery, Mammoth Lakes, California

Michael L. Sorey[1] and Robert Sullivan[2]

[1]College of Marin, Kentfield, CA
[2]Mammoth Pacific, LP, Mammoth Lakes, CA

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Geothermal systems, modeling, spring flow, heat transfer

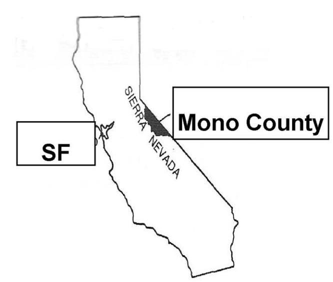
ABSTRACT

Springs at the Hot Creek Fish Hatchery, within the volcanically active Long Valley caldera in east-central California and contain mixtures of thermal and non-thermal groundwater. The average temperature in the westernmost AB spring group (17°C) is some 6°-7°C higher than temperatures in more dilute cold springs around the caldera margin. Hatchery spring temperature and chemistry data at AB suggest variable mixtures of about 5% thermal and 95% non-thermal groundwater. Periodic fluctuations in temperature and thermal-water mixing ratio have been observed over the monitoring period 1988-2003 described here. These fluctuations occur primarily in response to seasonal and annual variations in snow-melt generated recharge. Measured temperature variations are well-matched with power-law (exponential) relations of the form $\mathbf{T = AQ^{-B}}$, where **T** = spring temperature, **Q** = spring flow rate, and **A** and **B** are constants determined from regression analysis. In contrast, computations based on measured chemical flux values for boron and chloride show significant overestimates of spring temperature changes. In this paper, we show that consideration of a temperature-buffering process involving heat conduction between the mixed water aquifer and the surrounding rocks explains the over-estimation of temperature changes computed from chemical-flux data and yields estimates of spring temperatures as functions of flow rate that are in agreement with the results of power-law relations.

Introduction

The Hot Creek Fish Hatchery is located within the volcanically active Long Valley caldera where the geothermal system is currently being developed for electric power production at Casa Diablo (Figure 1). Springs at the Hatchery discharge mixtures of thermal and non-thermal groundwater from four geographically distinct groups of springs, denoted from west to east the AB, CD, H1, and H2,3 spring groups. Average temperatures of these spring groups decline from 17°C at AB to 11°C at H2,3 (Sorey, 2005). Temperatures of non-thermal springs around the caldera margin are near 10°-11°C. Higher-than-background spring temperatures and observed seasonal variability in temperature in the Hatchery springs are indicative of thermal-water components derived from the geothermal system that occurs at relatively shallow depths within the caldera's south moat. Geothermal development at Casa Diablo occurs in an extensively faulted region with natural springs and steam vents, located about 4 km west of the Hatchery.

The Hatchery springs discharge near the edge of a basalt flow, one of several flows filling the caldera's



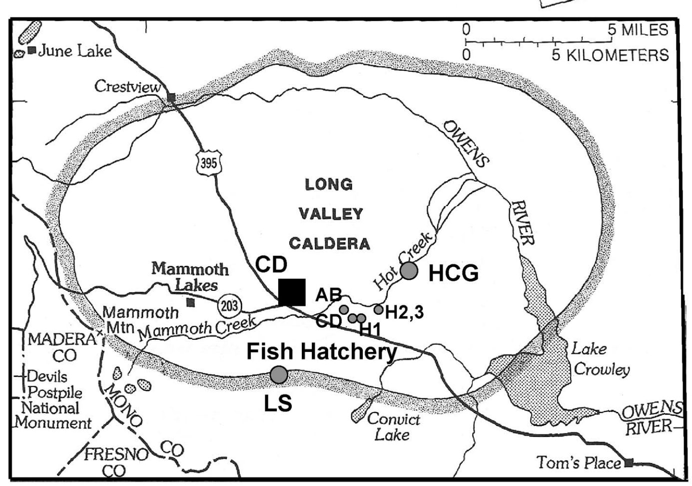


Figure 1. Locations of Long Valley caldera, spring groups AB, CD, H1, and H2,3 at the Hot Creek Fish Hatchery, HotCreek gorge springs (HCG), Laurel (cold) spring (LS), and the Casa Diablo area of geothermal development (CD).

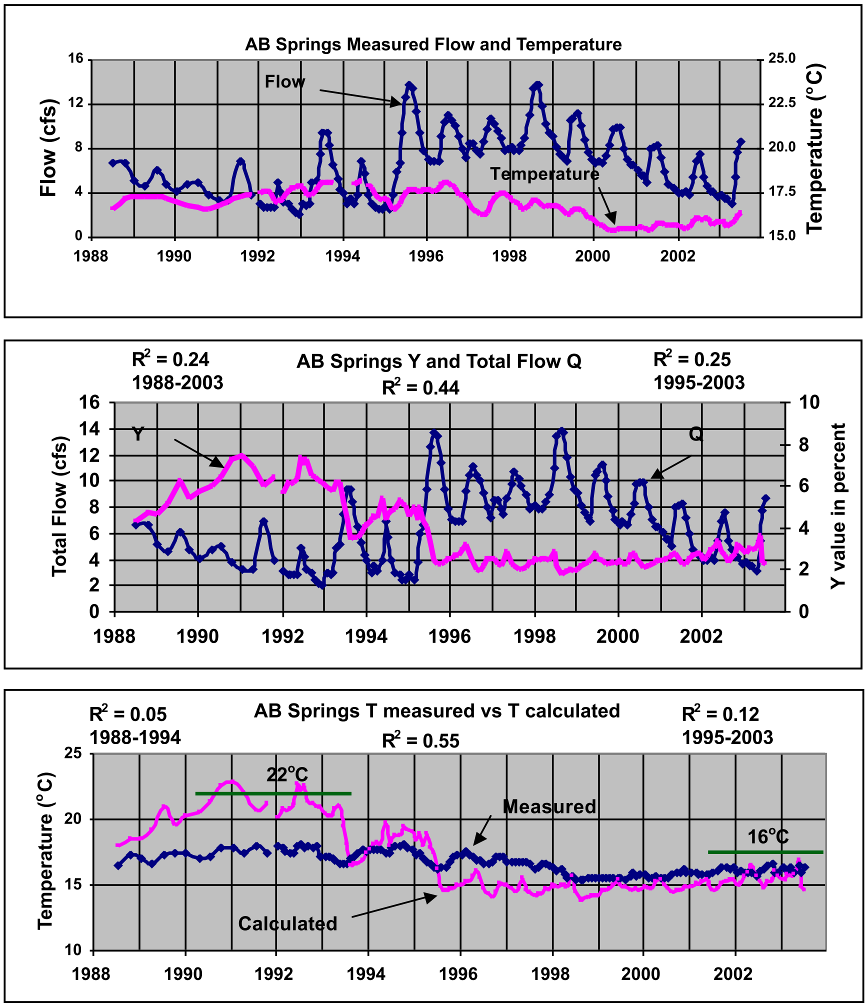


Figure 2. Measured flow and temperature (top), computed Y values based on chemical flux data (middle), and computed temperatures based on Y values (bottom) for AB springs at the Fish Hatchery.

south moat that originated from vents located west of the Hatchery. Spring temperatures at the Hatchery are near optimum for trout production. Although the dominate water source for these springs (over 90%) is shallow non-thermal groundwater, the thermal components and associated spring temperatures result in relatively high productivity for this particular Hatchery. Temperature, flow rate, and chemical composition data for these spring waters, determined at monthly intervals, are presented here for the period 1988-2003 (Figure 2). Measured spring flow rates and computed chemical flux values show considerable seasonal and annual variability in response to fluctuations in recharge to the groundwater system. In contrast, measured spring temperatures have shown little variability, suggestive of a moderating influence such as temperature buffering from conductive heating and cooling in the flow system and adjacent low-permeability rocks.

Estimates of the magnitude of the mixing ratio and flow rates of both thermal and non-thermal water in several of the Hatchery spring groups have been made from measurements of chemical flux (chloride and boron) and total spring flow, as described by Sorey and Farrar (1988). Such estimates involve assumptions regarding the temperature and chemical concentrations of thermal and non-thermal water sources that combine in a mixing region located somewhere upstream (west) of the Hatchery. Although these chemically based estimates of flow components have proven useful in understanding the Hatchery flow system, attempts to match spring temperature histories with chemical flux-based computations yield significant overestimates of actual temperature changes.

In this paper, power-law (exponential) relations between spring temperature and flow rate are shown to provide more reasonable fits to the measured temperature history at AB springs, the spring group with the largest thermal components and temperatures. Also described is a rectangular model of conductive and advective heat transfer within the Hatchery flow system and adjacent rocks. The rectangular model allows us to quantify aspects of thermal buffering of flow-system temperatures and yields estimates of spring temperature changes with flow rate that are in agreement with power-law computations.

Hydrologic Monitoring Data for the Hatchery Springs

Numerous individual springs produce a combined flow for each of four groups of springs at the Hatchery, as noted above. Spring monitoring data include total flow of each group, temperature of a representative source spring within each group, and integrated fluid samples of spring-group outflow. Chloride and boron concentrations in these samples allow estimates of chemical flux for each spring group. These chemical elements are chosen because of their relatively high concentration in thermal waters within the Long Valley geothermal system (Sorey and Farrar, 1988; Sorey et al., 1991; and Sorey, 2005). We focus here on data and interpretations for the westernmost AB spring group because this discharge is supplied entirely from recharge areas around the west rim of the caldera, whereas the other Hatchery spring groups contain additional inputs of non-thermal groundwater from sources to the south, complicating identification of flow channels and host rocks.

The AB springs are notable in that both the thermal and non-thermal components vary seasonally and annually, mainly in response to variations in snowmelt-induced groundwater recharge. Such variations can be inferred from measured flow rates, temperatures, and chemical-flux data for the 1988-2003 period (Figure 2). Over this period there are three basic subsets of data, including (1) low flow during 1988-1994, (2) high flow during 1995-2000; and (3) intermediate-to-low flow during 2001-2003. These subsets involve differing average spring-flow rates, temperatures, and thermal-water mixing ratios; together the data show that spring temperatures vary inversely with flow rate.

The mixing ratio **Y** (thermal-water flow/ total flow) varies with flow rate, as indicated by the fact that spring temperatures change as total flow varies. However, the rate of thermal-water upflow does not remain constant and instead tends to increase as total flow increases, reflecting an interaction between cold-water and thermal-water source reservoir pressures. Time histories of thermal and non-thermal flows are estimated from the chemical-flux data. These data, along with assumed properties of thermal and non-thermal source reservoirs that mix to form the Hatchery flow, yield computed **Y** values that range from 0.02 to 0.07 (i.e., 2-7 percent thermal-water fraction). There is a general inverse relation between flow rate **Q** and **Y** values, suggesting that although the rate of thermal-water discharge tends to increase as the cold-water flow increases, it does not keep pace. $\mathbf{R^2}$ values are less than 0.5, suggesting that actual conditions within the Hatchery springs flow system are more complex than assumed in this simplified treatment.

Such complexity also manifests itself in the lack of agreement between measured temperatures and temperatures ($\mathbf{T_Y}$) computed from **Y** values using the following relationships described by Sorey (2005):

$$\begin{aligned} \mathbf{T_Y} &= \mathbf{170°C\ (Y) + 10°C\ (1\text{-}Y)} \\ &= \mathbf{160°C\ (Y) + 10°C} \end{aligned} \qquad (1)$$

where thermal-water and non-thermal water source reservoirs are assumed to be at 170°C and 10°C, respectively. As seen in the plots in Figure 2, the use of **Y** values in **equation (1)** yields overestimates of spring temperature during periods of low flow and underestimates during periods of high spring flow. Thus, the overall range in flux-computed temperatures is 16-22°C or 6°C, compared with a range in measured temperatures of only ~2°C.

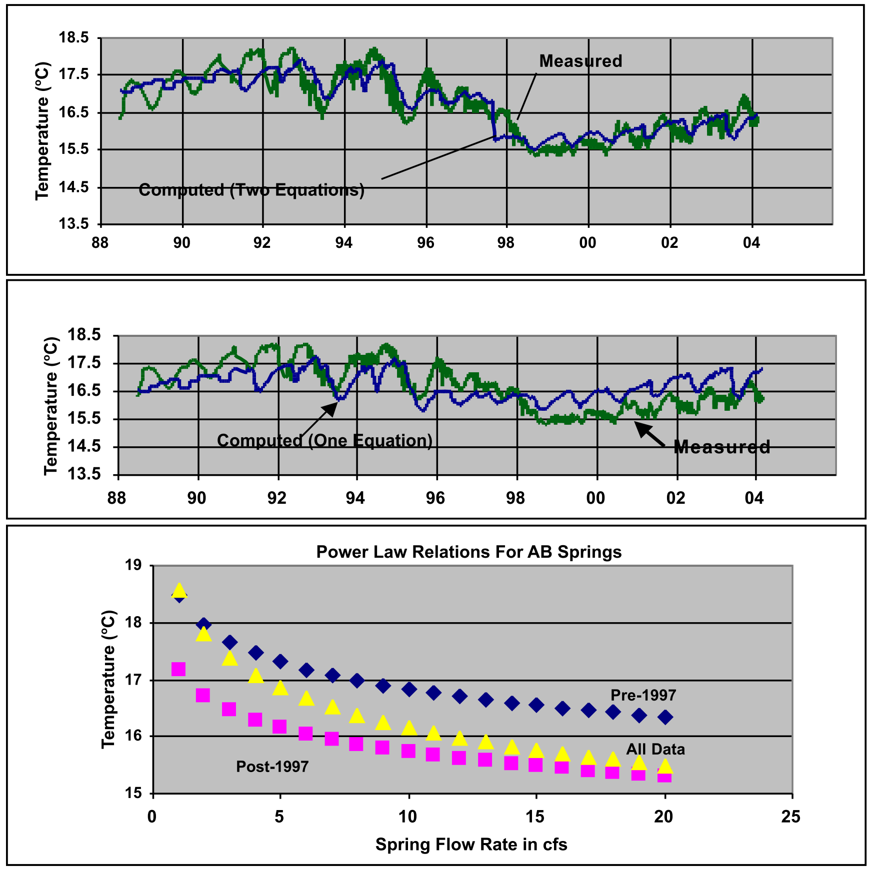


Figure 3. Two exponential equation match to measured temperature history (top), one exponential equation match (middle), and corresponding computed values of temperature and spring flow.

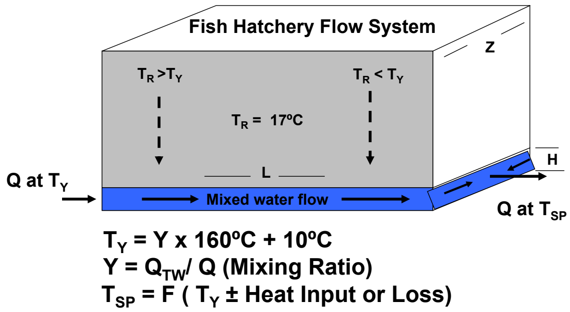
Power-Law Relations Between Flow and Temperature

The observed relation between spring flow **Q** and temperature **T** at AB springs is best described by equations of the form $\mathbf{T = AQ^{-B}}$, where A and B are coefficients that provide best-fits in associated regression analyses. This power-law (exponential) form describes the non-linear relation between spring temperature and flow rate (as shown in the bottom graph in Figure 3). Results for matches between measured and power-law computed temperature histories at AB springs are shown here for cases with both one (best-fit) power-law equation for the 1988-2003 period and separate (best-fit) equations for the 1988 to fall-1997 period and the fall-1997 to 2003 period. Correlations for each case are reflected in $\mathbf{R^2}$ values of 0.57 (one equation) and 0.89 (two equations), suggesting that physical changes in the flow system may have occurred in the fall of 1997 during a period of significant crustal unrest (enhanced rates of ground deformation and seismicity) in the southern part of the caldera (Sorey et al., 2003). A comparison of the one- and two-equation fits suggests that such a change may have involved a decrease in permeability of the conduit for upflow of thermal water beneath the mixing region. The effect of such a chancge would likely be lower temperatures and mixing fractions as functions of flow rate (Figures 2 and 3).

The exponential equations used to compute values of $\mathbf{T_{PL}}$ for comparison with measured temperatures are listed below and shown graphically in Figure 3.

One Equation – $\mathbf{T_{PL} = 18.56\ Q^{-.06}}$
Two Equations – $\mathbf{T_{PL} = 18.48\ Q^{-.041}}$ **(>1997)**
$\mathbf{T_{PL} = 17.17\ Q^{-.038}}$ **(<1997)**

Such equations adequately account for the complexities described above for the Hatchery flow system, including variations in rates of thermal-water and non-thermal water flow rates and mixing ratios **Y**. Adding more equations for specific periods and seasons can provide higher degrees of correlation, but the comparison between the simplest cases of one- and two-equation matches for AB temperature history is sufficient to show that (1) the flow system is sensitive to crustal unrest (elevated rock strain and seismicity) and (2) there may be a physical process that affects spring temperatures but not chemical flux values such that temperatures computed from chemical-flux data tend yield overestimates of actual spring temperature changes with time.



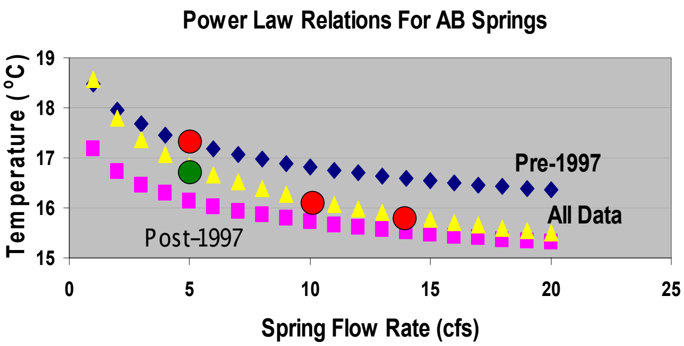


Figure 4. Rectangular model of Hatchery springs aquifer used in this study (top) and power-law results for one and two (power-law) equation fits to measured spring data (bottom). Also plotted in the bottom graph are values of spring temperature computed from the model for flow rates of 5, 10, and 14 cfs (large dots) and for assumed geometric parameters of L = 4 km, Z = 75 m, and φH = 1 m. Results for Q and Y values taken from the pre-2000 period are shown as red dots; a result for the post-2000 period is shown as a green dot.

Thermal Buffering Process

Changes in mixing ratio **Y** in the region where hot and cold waters combine and subsequently begin to flow laterally toward the Hatchery springs result in corresponding changes in chemical flux reaching the springs. In the mixing region, changes in chemical flux should be accompanied by proportionate changes in fluid temperature. As the mixed water flows laterally downstream. fluid temperatures are likely to be modified, or buffered, by heat conduction into or from rocks adjacent to the aquifer, depending on the differences in temperature between fluid and adjacent (impermeable) rock .

The thermal buffering process is analyzed here using a rectangular block model to quantify rates of conductive and advective heat transfer in the region between the mixing zone and the Hatchery springs (Figure 4, overleaf). The basic idea is that conductive heat transfer will occur if flow-zone temperatures differ from adjacent rock temperatures, assumed to be equal to the long-term average temperature of the AB springs (~17°C). With this type of model, the rate and total amount of conductive heat transfer are functions of time and of heating/cooling area (aquifer length times width, or **L x Z** in Figure 4). Similarly, the time over which fluid heating or cooling takes place is a function of aquifer length **L** and fluid velocity, the latter being proportional to aquifer volume divided by flow rate, or **LYZ/Q.** Expressed in this form, **t** becomes a measure of the average residence time between mixing and spring discharge regions.

The appropriate equation for heat flow between rock and fluid (**q**) is

$$\mathbf{q = 2\,(T_R - T_Y)\,[\,K\,C_R\,/\,\pi\,t\,]^{1/2}} \tag{2}$$

where **K** and $\mathbf{C_R}$ represent the thermal conductivity and heat capacity of the rock layer(s) and **t** is time since mixing occurs at the upstream end of the model (Carslaw and Jaeger, 1959). Here we have used $\mathbf{T_Y}$ (**equation 1**) to approximate the aquifer temperature after mixing but before conductive heating or cooling take place. Heat flow declines with **[t]** $^{1/2}$**,** which means for example that **q** would decline by a factor of 5 for times between 1 day and 30 days. To express **equation 2** in terms of geometric parameters and flow rate only, we substitute **t = φLYZ / Q**, which represents the aquifer pore volume (porosity x total volume) divided by fluid flow rate. Heat flux between mixing region and spring discharge is then given by **qLZ** which can be evaluated from:

$$\mathbf{qLZ = 2\,LZ\,(T_R - T_Y)\,[K\,C_R\,Q\,/\,\pi\,(\varphi LHZ\,)]^{1/2}} \tag{3}$$

We can also write an energy balance for advective heat transfer into and out of the model as

$$\mathbf{Q\,C_F\,T_{SP} = Q\,C_F T_Y + qLZ} \tag{4}$$

where $\mathbf{C_F}$ = fluid heat capacity and $\mathbf{T_{SP}}$ = spring temperature. Combining (**3**) and (**4**) and solving in terms of the quantity $\mathbf{\Delta T_{SP} = (T_{SP} - T_Y)}$, or the increase or decrease in fluid temperature resulting from heat conduction downstream of the mixing zone, we obtain

$$\mathbf{\Delta T_{SP} = [K\,C_R\,/\,(C_F)^2]^{1/2}(T_R - T_Y)\,[LZ/Q\varphi H]^{1/2}} \tag{5}$$

Then for reasonable values of rock and fluid thermal properties, **(5)** becomes

$$\mathbf{\Delta T_{SP} = 0.056\,(T_R - T_Y)\,[LZ/\varphi H\,Q]^{1/2}} \tag{6}$$

There are admittedly too many unknowns and too few constraints in this analysis to provide unique results for aquifer geometric parameters affecting thermal buffering such that modeled spring temperatures match measured values as a function of spring flow. Instead, we use this model mainly to demonstrate the feasibility of the thermal-buffering process as an influence on spring temperatures. Toward this end, we use the simplifying approximation that **φH ~** 1m and then evaluate relationship (**6**) for several combinations of **Q, Y, L,** and **Z**. The monitoring data for the period 1988-2000 (Figure 2) yield three basic combinations of **Q** and **Y:**

Q = 5 cfs, Y = 0.06
Q = 10 cfs, Y = 0.03
Q = 14 cfs, Y = 0.025.

For these combinations, we seek aquifer geometric parameters that allow for sufficient conductive heat loss or gain to yield $\mathbf{\Delta T_{SP}}$ values of **±** 1-2°C, so as to bring the flux-based temperature changes more in line with those actually observed.

By first assuming a value for **L** of 4 km, based on the distance between Casa Diablo and the Hatchery, we are able to satisfy the conductive heat flow criteria noted above with **Z** values of 50–100 m. For much lower **Z** values (e.g. 1-10 m), conductive heat flow rates are too low to alter aquifer temperatures sufficiently, given that **L** cannot reasonably be > 4 km. Conversely, for **L** values less than 4 km, the required values of aquifer width would need to be correspondingly greater than 50-100 m. Model computations for **L** = 4 km and **Z** = 75 m (and the **Q,Y** pairs noted above) yield values of $\mathbf{T_{SP}}$ that match those from power-law computations reasonably well, as plotted in Figure 4. Furthermore, for a range of **Q** from 5-14 cfs, these geometric parameters (along with the φ**Y** ~ 1m assumption) yield values for groundwater velocity of 0.14 to 0.48 km/day. Corresponding travel time estimates for a flow path of 4 km would be 29-8 days, values which are equal to or less than intervals over which temperature and chemical concentrations change at the Hatchery springs.

Of the many simplifications and assumptions made in this analysis, three are perhaps most significant. These are (1) the approximation that porosity x aquifer thickness ~ 1m, (2) the (unstated) assumption that heat flow depends only on $\mathbf{t}^{1/2}$ and the difference in temperature $(\mathbf{T_R} - \mathbf{T_Y})$, and (3) the possibility that the flow system is constrained to a cylindrical geometry with conductive heat flow occurring in the radial dimension. In the first case, we note that various reasonable combinations of porosity and aquifer thickness would fit the φ**Y** ~ 1m relation, including say φ = 0.1 and **H**= 10 m. If the Hatchery aquifer actually occurs within a brecciated zone between two separate basalt flows, H values of 1-10 m would be reasonable. But if φ = 0.1 and **H**= 1 m, φ**Y** = 0.1, so that obtaining results similar to those shown in Figure 4 would require corresponding reductions in values chosen for **L** and **Z.**

In the second case, we would expect that as fluid temperatures change downstream of the mixing region as a result of thermal buffering, the gradient for heat conduction into or out of the aquifer will decrease from its initial value of $(\mathbf{T_R} - \mathbf{T_Y})$. By ignoring this effect, our model results would tend to overestimate conductive heating and thermal buffering—the significance depending on fluid flow rates and fluid heat capacity. On the other hand, by selecting a **t** = average residence time between mixing region and spring discharge, our solution tends to underestimate conductive heat flow and related thermal-buffering effects.

Regarding the third conditions, a transient mathematical solution for radial heat flow into a cylinder of radius r is not available. However, the rectangular model results indicate that as heating/cooling areas decline, the heat flux and amount of thermal buffering of aquifer temperature also decline. Simple substitution in of heat transfer area = πr^2 and aquifer volume = $2\pi rL$ into the previous equations shows that unless the aquifer radius is on the order of 10 m or more, conductive heat transfer and related thermal buffering effects in a radial flow model would be too small to fit with observed spring temperature data.

Finally, we point out that the observed **T** and **Q** data over the post-2000 period show temperatures and mixing fractions for flow rates near 5 cfs that are lower than values observed and computed for the earlier monitoring periods. As noted earlier, this may reflect a strain-induced reduction in vertical permeability. However, even for this later data set, the rectangular model results can still provide a match with observed temperatures and temperature changes. For example, the appropriate **Q,Y** pair for the post-2000 period is **Q** = 5 cfs, **Y** = 0.03. **Equation (6)** then yields $\mathbf{\Delta T_{SP}}$ = 1.8°C, which for $\mathbf{T_Y}$ = 14.8°C, yields $\mathbf{T_{SP}}$ = 16.6°C (Figure 4). Thus, our model of the thermal buffering process is robust enough to handle apparent shifts in magnitude of mixing fraction as a function of spring flow rate.

Conclusions

Warm springs at the Hot Creek Fish Hatchery east of Mammoth Lakes, CA, discharge variable mixtures of thermal and non-thermal groundwater and provide fluid sources at optimum temperatures for Hatchery operations. Although flow rates of thermal and non-thermal spring components vary significantly over seasonal and annual cycles, spring temperatures are buffered by heat conduction within the flow system and show only moderate changes on the order of 2°C over the 1988-2003 period. The relation between flow rate and spring temperature at the AB spring group can be well-matched by power-law equations of the form $\mathbf{T = AQ^{-B}}$. Using separate power-law equations for the pre- and post-1997 periods results in a significantly increased correlation with measured temperature values, suggesting that enhanced crustal strain rates measured in 1997 may have initiated changes in the physical properties of the Hatchery flow system.

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