# Effects of upstream dams versus groundwater pumping on stream temperature under varying climate conditions

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Received 31 August 2009; accepted 26 January 2010; published 23 June 2010.

[1] The relative impact of a large upstream dam versus in-reach groundwater pumping on stream temperatures was analyzed for humid, semiarid, and arid conditions with long dry seasons to represent typical climate regions where large dams are present, such as the western United States or eastern Australia. Stream temperatures were simulated using the CE-QUAL-W2 water quality model over a 110 km model grid, with the presence or absence of a dam at the top of the reach and pumping in the lower 60 km of the reach. Measured meteorological data from three representative locations were used as model input to simulate the impact of varying climate conditions on streamflow and stream temperature. For each climate condition four hypothetical streamflow scenarios were modeled: (1) natural (no dam or pumping), (2) large upstream dam present, (3) dam with in-reach pumping, and (4) no dam with pumping, resulting in 12 cases. Dam removal, in the presence or absence of pumping, resulted in significant changes in stream temperature throughout the year for all three climate conditions. From March to August, the presence of a dam caused monthly mean stream temperatures to decrease on average by approximately 3.0°C, 2.5°C, and 2.0°C for the humid, semiarid, and arid conditions, respectively; however, stream temperatures generally increased from September to February. Pumping caused stream temperatures to warm in summer and cool in winter by generally less than 0.5°C because of a smaller pumping-induced alteration in streamflow relative to the dam. Though the presence or absence of a large dam led to greater changes in stream temperature than the presence or absence of pumping, ephemeral conditions were increased both temporally and spatially because of pumping.

**Citation:** Risley, J. C., J. Constantz, H. Essaid, and S. Rounds (2010), Effects of upstream dams versus groundwater pumping on stream temperature under varying climate conditions, *Water Resour. Res.*, *46*, W06517, doi:10.1029/2009WR008587.

## 1. Introduction

[2] Dams impact both temporal and spatial patterns of downstream water temperatures for several reasons, including alteration of annual streamflow patterns [*Webb and Walling*, 1993; *Collier et al.*, 1996; *Lowney*, 2000; *Sullivan and Rounds*, 2004, 2006; *Rounds and Wood*, 2001; *Risley*, 1997]. Groundwater pumping reduces streamflow by interception of groundwater discharge and/or direct withdrawal of stream water through streambed infiltration, both of which impact stream temperature (though empirical documentation is limited). Furthermore, stream temperature changes are inevitable with climate change, representing a third factor which interacts with the presence or absence of dams and pumping. Quantitative examination of the impacts of dams compared with pumping for a series of potentially warmer and drier climatic conditions affords an opportunity to analyze the relative impacts of a large upstream dam compared with in-reach groundwater pumping under varying climatic conditions. For this study a numerical model of a hypothetical watershed was used because available measured stream temperature data represent a limited number of climate and streamflow conditions. It is also difficult to use measured conditions from a specific location to systematically analyze the numerous factors affecting stream temperature response. Numerical modeling allows a comparison of a large array of environmental conditions while holding other factors constant. This approach provides a context for future investigators to assess the impact of dam removal and pumping for a specific location.

[3] The specific purpose of this work is to quantitatively examine the relative thermal effects of a large upstream storage dam versus in-reach pumping on stream temperatures through physically based simulation modeling of the effect of streamflow alteration on stream temperatures for midlatitude regions of the world having distinct wet winter and dry summer conditions. These regions include much of the western United States, some Mediterranean countries, eastern Australia, midlatitude regions of South America, and parts of Africa. Large upstream storage dams constructed in these regions typically have usable reservoir storage to mean annual flow volume ratios of 0.25 or greater, and this ratio typically increases with increasing aridity (Columbia Basin Water Management Division, U.S. Army Corps of Engineers, project data, available at http://www.nwd-wc.usace.army.mil/report/projdata.htm).

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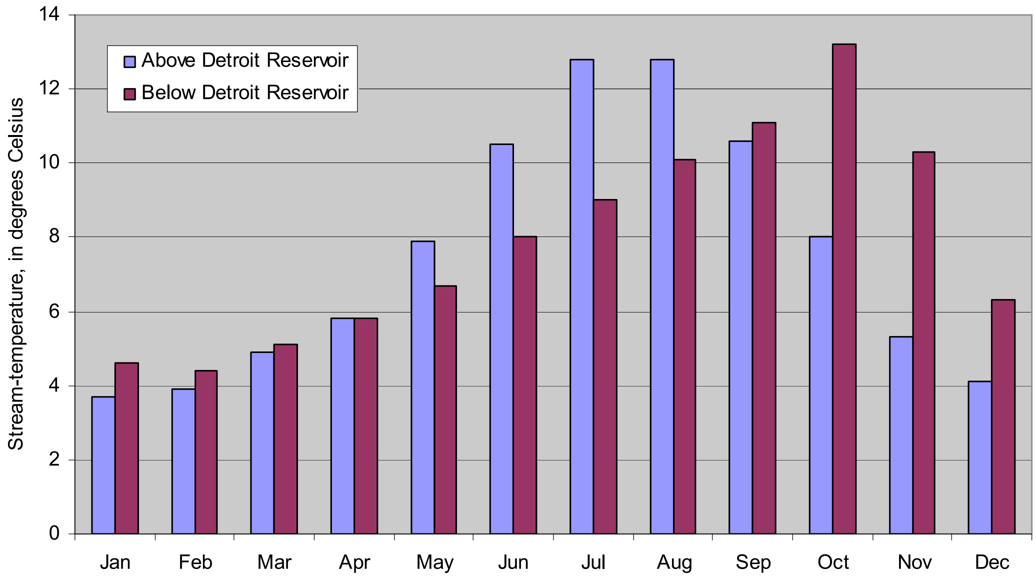


**Figure 1a.** Mean monthly observed stream temperatures for 1978–2007 above and below Detroit Reservoir on the North Santiam River, Oregon.

[4] Rather than developing a model calibrated to a specific river basin, we developed a representative hypothetical watershed framework, modifying climate, dam impoundment, and pumping conditions in order to contrast the effects of these physical changes on stream temperature. We couple streamflows generated using a groundwater model with streamflow routing to a stream temperature model, with defined headwater and groundwater inflow and water temperature boundaries, developing a series of scenarios for humid, semiarid, and arid conditions. Though the watershed configuration is hypothetical, measured meteorological data from humid, semiarid, and arid sites with distinct dry seasons in the western United States are employed as model input to simulate streamflow and stream temperature for the varying climate conditions.

[5] In general, stream temperature ranks second only to streamflow in terms of properties defining the quality and value of streams to all forms of life. Stream temperature has a direct relation to water quality parameters such as dissolved oxygen concentrations, biochemical oxygen demand rates, algae production, and contaminant toxicity, all of which influence suitability of a stream as a fish habitat or potential water resource. Stream temperatures also can directly influence the rate of exchange of stream water with underlying sediments due to the temperature sensitivity of the hydraulic conductivity of the streambed [*Constantz*, 1998]. Elevated stream temperatures are often caused by anthropogenic activities, such as the removal of riparian shade, stream channel alteration, effluent point discharges, and urbanization. During summer low-flow periods, stream temperatures typically increase when natural flow is decreased by surface water diversions and pumping. Stream temperature standards have been adopted by many States as part of their compliance with the Federal Clean Water Act. In Oregon, for example, elevated stream temperature is the single most common water quality violation. Hundreds of stream reaches exceed the maximum water temperature standard during summer low-flow conditions (Water Quality Division, Oregon Department of Environmental Quality, Oregon's 2004/2006 integrated report, 2006, available at http://www.deq.state.or.us/WQ/assessment/rpt0406.htm).

[6] In addition to water quality concerns, stream temperature is an essential component of fish habitat. Temperature has a major effect on the distribution, health, and survival of native salmonids (salmon, trout, and charr) and other aquatic species. Salmonid feeding, growth, resistance to disease, competitive ability, and predator avoidance are impaired when salmonids are exposed to unsuitable temperatures. High temperatures can cause direct mortality of salmonids. While lethal temperatures do occur naturally and can be locally problematic, temperatures in the range where sublethal effects occur are widespread and probably have the greatest effect on the overall well-being and patterns of occurrence of native fish populations [*Poole and Berman*, 2001]. Thus, quantitative measures of the effects of upstream dams and groundwater pumping on stream temperature processes under varying climate conditions are critical to future science-based management of streams and their encompassing watersheds.

## 2. Stream Temperature Processes

[7] Temperature in a stream is the product of heat energy exchange between the stream and its environment (i.e., riparian atmosphere and streambed). Processes contributing to that exchange include short-wave solar radiation, long-wave atmospheric radiation and stream emission, evaporation, convection, streambed conduction, and groundwater discharge or recharge. Of these processes, solar radiation is a critical source of energy that controls stream temperatures in most cases [*Brown*, 1969]. This is evident in the mean monthly temperatures of a naturally flowing stream reach of the North Santiam River in Oregon (Figures 1a and 1b). The watershed above USGS gage 14178000 is unregulated (upstream of Detroit Dam). Because this site is not thermally altered by flow regulations or diversions, it has a strong correlation between stream temperature and solar radiation that is qualitatively similar to reports by *Brown* [1969] for

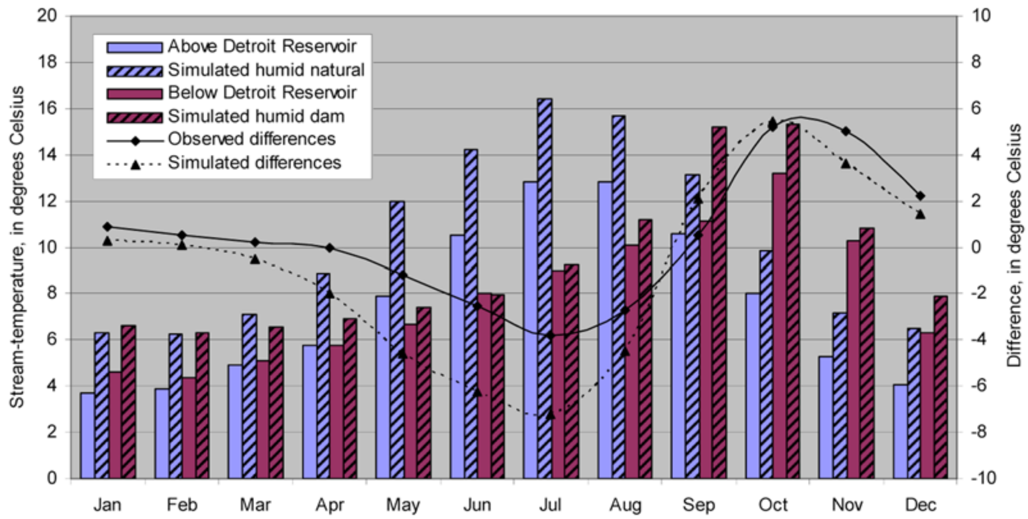


**Figure 1b.** Mean monthly observed stream temperatures above and below Detroit Reservoir compared with monthly mean simulated stream temperatures for natural and dam flow scenarios with humid climate conditions 101 km above the axis of the valley.

Oregon streams. On a daily basis, solar radiation typically has a 24 h cyclical effect on the temperature of the stream. Over the course of the year, the overall increase and decrease of temperatures in a naturally flowing Oregon stream often has a one to 2 month delayed correspondence with the increase and decrease in the number of hours of available daylight [*Moore*, 1967].

[8] Depending on its design and mode of operation, the effect of a large upstream reservoir on stream temperatures can be significant due to both the thermal characteristics of the reservoir and the altered downstream flows [*Sullivan and Rounds*, 2004, 2006]. Similar to lakes and other natural water bodies, a thermocline typically develops in a reservoir during the spring and summer as the upper layers are warmed by solar radiation and denser cooler waters remain underneath in the hypolimnion. In the fall, when the upper layer temperatures have cooled, thermal stratification is eventually eliminated and full vertical mixing ("turnover") occurs. The outflow structures of many reservoirs in the United States draw water from the hypolimnion level. Reservoir drawdown for flood control or irrigation supply typically occurs in late summer or fall bringing the warmer upper layer closer to the outlet. As a consequence, river reaches downstream of deep reservoirs often have unnaturally cool and warm temperatures during the summer and fall months, respectively (Figure 1a). In addition, annual streamflow patterns are altered as higher flows are stored and released resulting in dampened peak streamflows and augmented base flows [*Sullivan and Rounds*, 2004, 2006]. These stream temperature patterns would not necessarily occur with dams having a selective withdrawal or epilimnetic outflow structure. However, for this study the dam flow releases were assumed to come from the hypolimnion level because this type of withdrawal is so common.

[9] Groundwater pumping near a stream affects stream temperature by reducing groundwater discharge to the stream for gaining reaches, increasing stream loss in losing reaches, or converting gaining reaches to losing reaches. As the flow and stream depth in the channel decreases, the stream's thermal mass also decreases and its surface area to volume ratio might increase (depending on the channel shape). The stream temperature more rapidly approaches its equilibrium temperature through heat transfer processes at the water surface. These processes can cause stream temperatures to increase in the summer and decrease in the winter. Also, the groundwater temperature is generally cooler than the stream in the summer and generally warmer than the stream in the winter. Therefore the diminished thermal influence of groundwater also is a factor in increasing and decreasing summer and winter stream temperatures, respectively.

[10] Dynamic hydraulic flow and heat transfer models have been used effectively in recent years to predict stream temperature with fine temporal and spatial resolution. For many modeling studies errors between observed and simulated temperatures are typically within 1°C. *Risley* [1997] and *Rounds and Wood* [2001] used CE-QUAL-W2 to simulate stream temperatures in the Tualatin River, a tributary of the Willamette River located in northwestern Oregon, and produced root mean square errors ranging from 0.42°C to 1.10°C. *Carron* [2000] created unsteady flow and stream temperature models to simulate reservoir regulated flows on the Green and Stanislaus Rivers located in Colorado and California, respectively. *Sinokrot and Stefan* [1993] used a numerically based unsteady heat advection-dispersion equation model to simulate hourly stream temperatures with accuracies of 0.2°C to 1.0°C. *Sullivan and Rounds* [2004] also used CE-QUAL-W2 to simulate streamflow and water temperature in the North Santiam and Santiam Rivers, Oregon, producing root mean square errors ranging from 0.51°C to 0.76°C.

## 3. Previous Study

[11] *Constantz and Essaid* [2004, 2007] analyzed the effects of the presence or absence of an upstream dam and pumping (i.e., withdrawals) on streamflows for four hypothetical settings: (1) the natural case before either a dam or

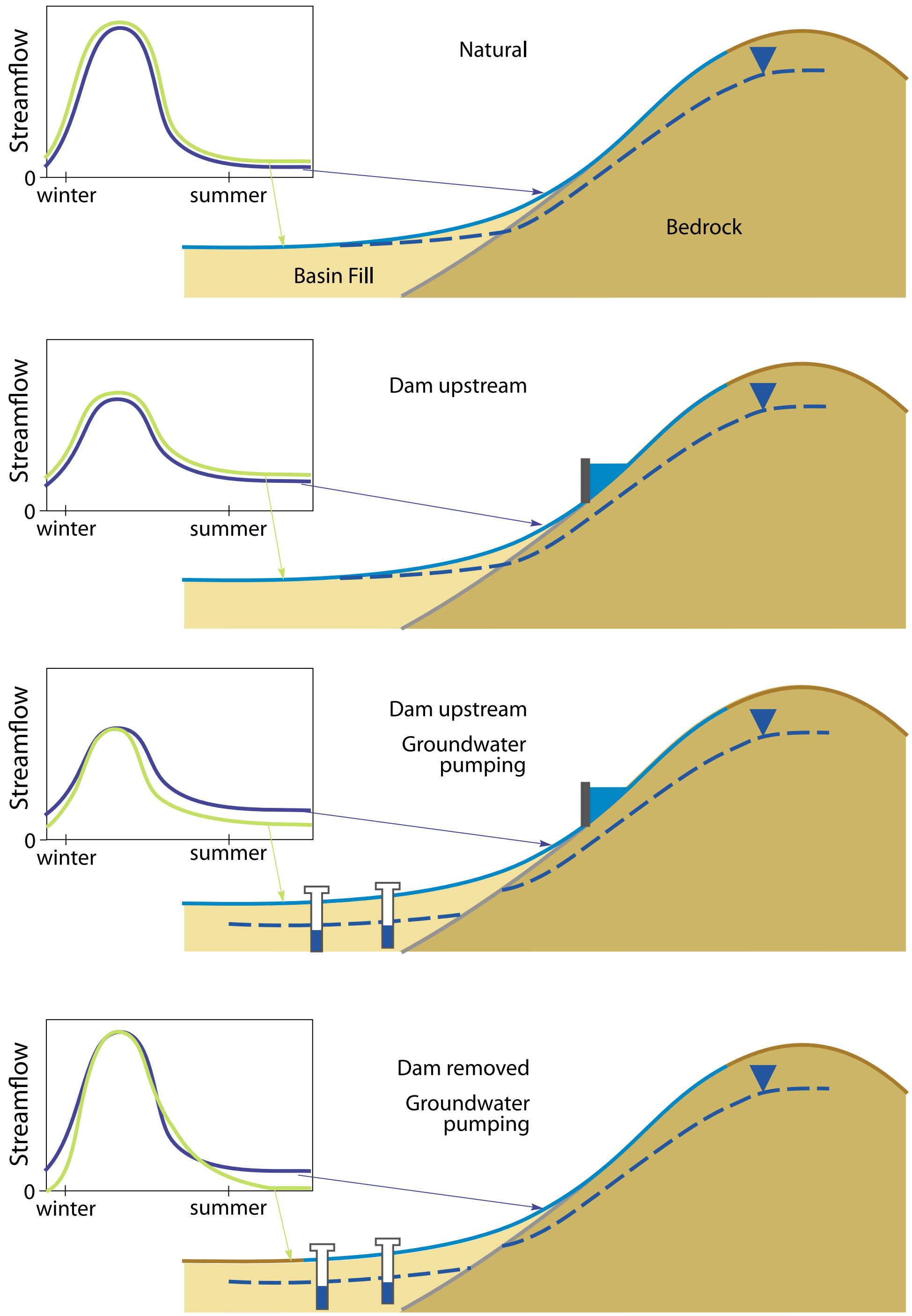


**Figure 2.** Four conceptual hydrogeologic cross sections and corresponding hydrographs showing a stream draining from mountainous terrain into a large alluvial basin for the cases of (1) a natural setting without large reservoirs or groundwater pumping (i.e., withdrawals), (2) a dam creating a large reservoir, (3) a dam and pumping in the alluvial basin, and (4) removal of the dam and continued pumping (modified from *Constantz* [2003]).

pumping existed, (2) the case with an upstream dam impounding a large reservoir and without pumping in the downstream basin, (3) the case with an upstream dam and with pumping in the downstream basin, and (4) the case without an upstream dam and with pumping in the downstream basin. These four hydrologic scenarios are depicted in Figure 2, and represent the same four hydrologic scenarios examined in the present study. Each of these four flow scenarios was examined using humid, semiarid and arid climate conditions representative of regions with wet winters and dry summers (regions where large storage dams are common) resulting in a total of 12 hydrologic scenarios. *Constantz and Essaid* [2004, 2007] used the modular finite difference three-dimensional groundwater flow model MODFLOW-2000 [*Harbaugh et al.*, 2000] with the SFR1 [*Prudic et al.*, 2004] stream-aquifer interaction and streamflow routing package

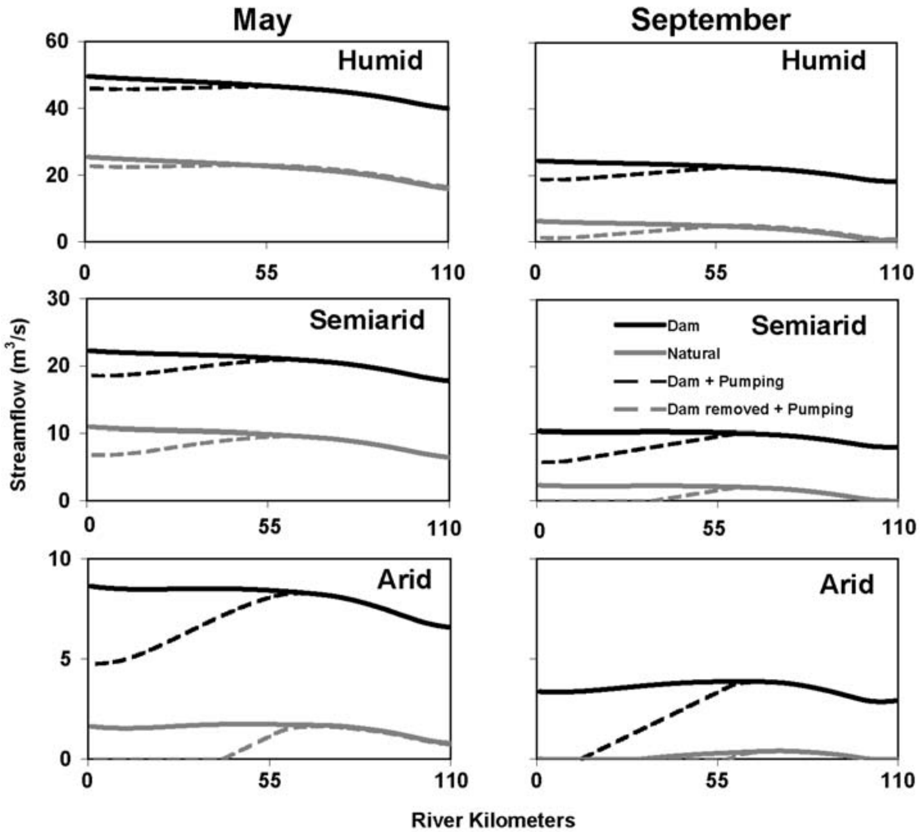


**Figure 3.** Model-predicted extent of streamflow from the dam at 110 km down to the axis of valley for natural, dam, dam with pumping, and dam removed with pumping scenarios under humid, semiarid, and arid conditions in May and September (modified from *Constantz and Essaid* [2007]).

and the grid block rewetting option. *Constantz and Essaid* [2004, 2007] used a model domain extending 180 km between downstream and upstream endpoints. Along the longitudinal axis of the stream, all cells were 1 km in length. MODFLOW and SFR1 were used to simulate monthly time series of groundwater discharge (or recharge) to each 1 km long model stream segment for all 12 scenarios. (Note there is a growing trend to use the phrase "hyporheic exchanges" to describe stream water exchanges with streambed and bank sediments; however, the spatial scale of hyporheic exchanges is universally described as mm to m in length, which was not a scale of detail modeled.)

[12] Model results from *Constantz and Essaid* [2004, 2007] showed that streamflow became ephemeral at certain stream reach locations during the late summer low-flow period for scenarios that included natural flow and pumping under semiarid and arid climate conditions. As reproduced from the work by *Constantz and Essaid* [2007], Figure 3 provides simulated streamflows plotted against location along the study stream reach for each case under humid, semiarid, and arid conditions. Summer and fall dam releases tended to prevent the stream from becoming ephemeral, while the pumping in some instances transitioned the stream from perennial to ephemeral. Under the humid climate conditions scenarios, the simulated streamflow was perennial for the entire stream and entire year for all four hypothetical flow management scenarios.

[13] Groundwater pumping rates were varied over the year to match seasonal variations in evapotranspiration demand, such that maximum pumping volumes occurred in summer months, with negligible pumping in some winter months. The total annual pumping volume was $1.5 \times 10^8$ $m^3$ for all three climate conditions, representing an equivalent volume of 13%, 29% and 78% of the total annual streamflow for the humid, semiarid, and arid conditions, respectively. Dependent on hydraulic conditions near the stream, these relative volumes produce greater potential stress on the stream regime during low-flow periods and for increasing aridity. This transition from perennial to ephemeral flow could have unanticipated impacts on spatial and temporal patterns of streamflows, habitats, and recreational opportunities. Decreased streamflow also has implications for stream temperatures as the stream becomes more susceptible to more rapid cooling or heating with decreased volume and depth.

## 4. Stream Temperature Model

[14] As described above, *Constantz and Essaid* [2007] created 12 monthly flow time series based on four scenarios (natural, dam, dam with pumping, and dam removed with pumping) for three climate conditions (humid, semiarid, and arid) on a hypothetical river system, which were used as time series streamflow boundary inputs to the stream temperature model in this study.

### 4.1. Model Description

[15] The stream temperature model used in this study was constructed using CE-QUAL-W2, version 3.5, a two-

dimensional, laterally averaged, hydrodynamic and water quality model [*Cole and Wells*, 2006]. The two dimensions simulated are longitudinal (along the length of the water body) and vertical. CE-QUAL-W2 is capable of simulating hydrodynamics, stream temperatures, and a number of water quality constituents. Numerical solution techniques are used to solve six main governing equations, which include (1) horizontal momentum, (2) constituent transport, (3) free-water-surface elevation, (4) hydrostatic pressure, (5) continuity, and (6) the relationships among pressure, temperature, and volume of water. The model uses a variable time step algorithm designed to ensure the mathematical stability of the numerical methods. For this study, the maximum time step was set to 10 s. By using a model capable of simulating small time steps it was possible to simulate the minimum and maximum daily stream temperatures.

[16] CE-QUAL-W2 was used to simulate stream temperatures using the term-by-term energy equation method. Components of the energy equation include incoming and reflected short-wave solar radiation, incoming and reflected long-wave atmospheric radiation, long-wave radiation emitted from the water surface to the atmosphere, evaporative heat loss, air or water heat conduction, sediment or water heat exchange, and groundwater discharge or recharge.

### 4.2. Model Framework

[17] A major portion of the 180 km long MODFLOW model domain created by *Constantz and Essaid* [2004, 2007] was used to create the CE-QUAL-W2 model for this study. Six of their twelve MODFLOW scenarios simulated flow releases from a dam located at river kilometer (RK) 110. Because a comparison of upstream dam versus pumping effects on stream temperature was of interest, only the portion of the MODFLOW model grid downstream of the dam was used in this study. The upstream and downstream ends of the CE-QUAL-W2 model grid were at RK 110 and RK 0, respectively. The CE-QUAL-W2 model grid was created with 110 segments. All segments were 1 km in length, which matched the MODFLOW model grid cell segments.

### 4.3. Bathymetry

[18] CE-QUAL-W2 represents the river cross section as a stack of layers. For this application each layer was 0.25 m in height. The lowest layer in the stack was 0.3 m wide. The widths of all other layers in the stack were 1.2 m wider than the layer just below it. This configuration created a near v shaped trapezoidal cross section having a side slope ratio of approximately 0.4 (rise or run). A cross section of this shape is reasonable for mountainous streams in Oregon and California [*Barnes*, 1967].

### 4.4. Meteorological Input Data

[19] The required meteorological input data to run CE-QUAL-W2 include air temperature, dew point temperature, wind speed, wind direction, cloud cover, and short-wave solar radiation. Long-wave atmospheric radiation is computed internally by the model as a function of air temperature and cloud cover. Hourly meteorological data collected at Eugene, Oregon; Sacramento, California; and Porterville, California were used to represent the humid, semiarid, and arid scenarios, respectively (see auxiliary material for plots showing air temperature and precipitation at these three locations and links to meteorological data).[1] Data from the period 1 January 2001 to 31 December 2002 was used in all CE-QUAL-W2 simulations.

[20] To account for riparian shading it was assumed that 50% of the short-wave solar radiation would be blocked by riparian vegetation and surrounding topography. For the medium-sized rivers and topography that were hypothesized by *Constantz and Essaid* [2007] this appeared to be a reasonable assumption.

### 4.5. Boundary Flows

[21] For each of the 12 scenarios, the upstream boundary inflows to CE-QUAL-W2 were the monthly streamflows simulated by *Constantz and Essaid* [2004, 2007], at river kilometer (RK) 110. MODFLOW's simulated monthly groundwater discharge (or recharge) to the stream at each of the 110 model cells between RK 0 and RK 110 was used as lateral boundary inflows (or outflows) to CE-QUAL-W2 at each stream segment. Although MODFLOW output was monthly, CE-QUAL-W2 interpolated the flows for every time step. Note that MODFLOW streamflow routing assumes continuity and no stream channel storage. Thus, the flow estimates reflect average conditions and daily, or instantaneous, streamflow fluctuations that could occur in all the flow scenarios (with or without a dam) were not represented in the modeling.

[22] For the MODFLOW simulation scenarios with pumping, a hypothetical well field was located in an alluvial section of the river between RK 10 and RK 60. The wells were positioned on both sides of the river in two parallel lines 2.1 km away from the river. A total annual pumpage volume of $1.5 \times 10^8$ $m^3$ was used for all three climate conditions. This volume also corresponded to a depth of water of 16.7 cm over the lower 60 km of the 15 km wide model grid area (not just the stream channel). The pumping occurred during the dry season (March through October) and was distributed over these months using monthly multiplication factors related to estimated evapotranspiration losses for those months [*Constantz and Essaid*, 2007].

### 4.6. Upstream Boundary Flow Temperatures

[23] The stream temperature of the upstream boundary inflows at RK 110 had to be specified in the model simulations for natural and dam conditions in each climate setting. It would have been preferable to use measured stream temperature data from rivers next to the three meteorological sites used in our study (Eugene, Oregon; Sacramento, California; and Porterville, California). However, adequate stream temperature data sets of both dam-regulated and natural flows were unavailable at these sites. As an alternative we based the inflow temperatures on observed and simulated daily mean stream temperature data from *Sullivan and Rounds* [2006] who compared observed temperatures of regulated flow below a small- to medium-sized dam on Scoggins Creek in northwestern Oregon with simulated temperatures representing unregulated predam flow for the same location. The

[1] Auxiliary materials are available in the HTML. doi:10.1029/2009WR008587.

dam on Scoggins Creek is approximately 46 m in height and operates with hypolimnetic flow releases. The reservoir behind the dam has a full capacity volume of approximately $68 \times 10^6$ $m^3$ and is used for flood control, irrigation and urban water supply, and recreation. For this study, we used their observed and simulated stream temperature as the basis for the CE-QUAL-W2 model input upstream boundary inflow temperature for the dam and natural flow scenarios, respectively. Prior to their use, the stream temperature data were adjusted for the climate conditions at the three meteorological sites used in this study by uniformly shifting their values up or down based on the difference between the 30 year (1971–2000) mean air temperature record of Forest Grove, Oregon (near the dam on Scoggins Creek) and those of Eugene, Oregon; Sacramento, California; and Porterville, California. For the humid scenarios (based on Eugene, Oregon conditions), the stream temperatures were decreased by 0.16°C. However, for the semiarid scenarios (Sacramento, California) and arid scenarios (Porterville, California) the stream temperatures were increased by 5.78 and 6.50°C, respectively.

[24] For the six stream temperature time series created for the dam scenarios, no additional adjustment was necessary prior to their use as model input. However, for the six natural flow (no dam) scenarios the preliminary CE-QUAL-W2 simulated stream temperatures in the upper 20 km of the model grid between RK 110 and RK 91 showed poor correspondence with the groundwater and meteorological temperature conditions. This was somewhat expected because the simulated Scoggins Creek stream temperature boundary data and the observed meteorological data were not of the same years or locations, and the influence of the upstream boundary temperatures propagated down the stream reach. To rectify the problem, "spin-up" simulations were made for the six natural flow scenarios by using locally adjusted simulated stream temperature data from *Sullivan and Rounds* [2006] as the upstream boundary input and using all other climate conditions and model inputs needed for each scenario. Spin-up simulations were run for the entire modeling period (2001–2002). Simulated spin-up stream temperatures from 20 km below the upstream boundary then were used as new upstream boundary model input at RK 110 for the final scenario simulations.

## 4.7. Groundwater Boundary Flow Temperatures

[25] *Constantz and Essaid* [2007] provided simulated monthly groundwater discharge and recharge at each of the 110 river kilometer segments. For each of these segments it was necessary to create stream temperature time series files for model input to CE-QUAL-W2. Although groundwater temperatures can vary in the vicinity of a stream due to local conditions, the modeled groundwater inflows represent large-scale average conditions. Thus, for simplicity of analysis, groundwater discharge temperatures at each of the 110 km segments were assumed to be constant at all segments and throughout the simulation period. *Conlon et al.* [2003] found groundwater temperatures in the Willamette Basin, Oregon, were nearly identical to mean annual air temperature. *Norris and Spieker* [1966] also determined that groundwater temperatures were generally the same as mean annual air temperature. Using this approach the period of record (POR) mean air temperatures for Eugene, Oregon (11.4°C, PORPOR: 1939–2007), Sacramento, California (16.3°C, PORPOR: 1890–2007), and Porterville, California (17.8°C, PORPOR: 1948–2007) were used as the constant groundwater inflow temperatures for the humid, semiarid, and arid scenarios, respectively.

## 4.8. Groundwater Heat Flux Analysis

[26] Water temperature in a stream reach is influenced by the temperature of the water flowing into the reach, the net heat flux across the air-water interface, and the groundwater heat flux. The temperature of groundwater seeping into a stream generally differs from the temperature of the water in the stream. The influence of groundwater inflow can be examined by calculating the thermal change caused by the temperature differential between the inflowing groundwater and stream:

$$H_{gw} = Q_{gw} C_w \left( T_{gw} - T_s \right) \quad (1)$$

where $H_{gw}$ is the groundwater inflow thermal effect (J/s); $Q_{gw}$ is the groundwater inflow ($m^3$/s, $Q_{gw} = 0$ in a losing stream); $C_w$ is the heat capacity of water and equals $4.2 \times 10^6$ (J/$m^3$°C) [*Stonestrom and Blasch*, 2003], $T_{gw}$ is the temperature of the groundwater (°C); and, $T_s$ is the stream temperature (°C). As a study objective we were interested in comparing the thermal effects of groundwater inflow with heat flux through the air-water interface. $Q_{gw}$ was set to zero during periods of groundwater recharge (stream water infiltration), which occurred in some of the semiarid and arid flow scenarios, because unlike groundwater input to the stream, thermal loss during stream water infiltration would not directly cause a change in stream temperature.

[27] Simulated hourly stream temperatures were used to calculate the groundwater inflow thermal effect for the stream segment at RK 2. Groundwater inflow to the segment ($Q_{gw}$) was obtained by subtracting the stream water inflow to RK 2 from the RK 2 outflow and using only positive values. As mentioned previously, the groundwater temperature was 11.4, 16.3, and 17.8°C for the humid, semiarid, and arid cases, respectively. Stream temperatures were taken from model results for RK 2. The calculated groundwater thermal effect (J/s) was then divided by the water surface area of the stream segment at RK 2 to obtain heat flux in W/$m^2$ for comparison to model calculated air-surface water net heat flux.

## 4.9. Model Evaluation

[28] Large dams lead to a shift in the date of maximum stream temperature from the summer to the autumn. This pattern is successfully produced in the stream temperature model results, as shown in Figure 1b in which mean monthly observed stream temperature data above and below Detroit Dam in the Cascade Range east of Salem, Oregon, are compared to simulated monthly mean simulated stream temperatures for the natural and dam flow scenarios for humid climate conditions at river kilometer 101 (i.e., immediately below the simulated dam). Both the natural and with-dam simulated stream temperatures follow similar trends in the observed stream temperature data. Under natural conditions stream temperatures in the northern hemisphere typically reach a maximum in July, while hypolimnetic level reservoir releases result in decreased summer and increased fall stream temperatures. In this comparison the simulated stream tem-

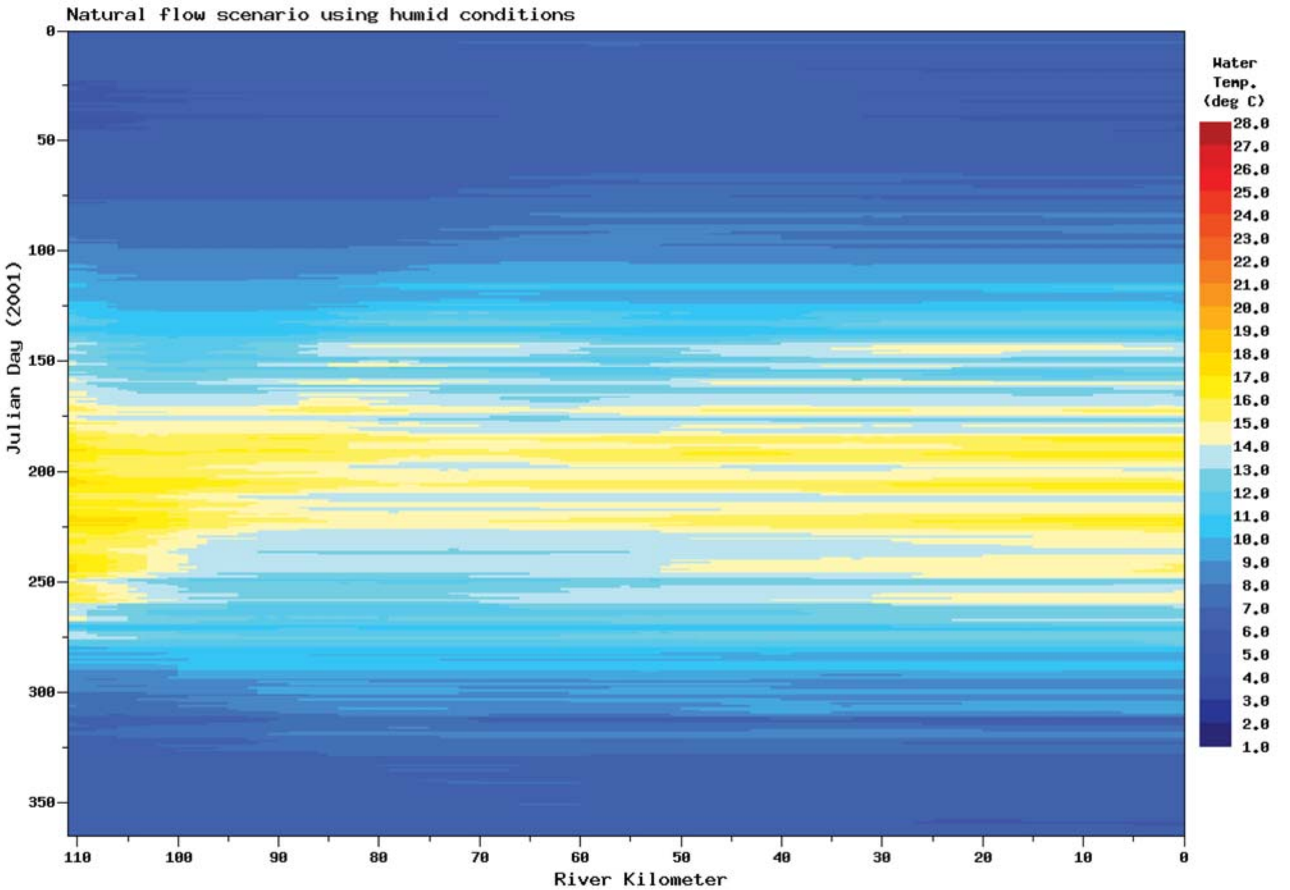


**Figure 4a.** Simulated daily stream temperatures from 110 km down to the axis of the valley for the natural flow scenario under humid conditions.

peratures are almost entirely higher than the observed stream temperatures in both natural and with-dam scenarios; however, this was expected because this section of the North Santiam River is largely snow driven and has a higher mean elevation than the humid case hypothetical watershed developed by *Constantz and Essaid* [2007]. The performance of the stream temperature model also can be examined by comparing the two difference lines plotted in Figure 1b. Reasonable simulation results are demonstrated by good agreement in Figure 1b between the lines for natural and dam streamflow cases.

## 5. Results and Discussion

[29] Using model output the impacts of upstream dams versus groundwater pumping on stream temperature are evaluated under various modalities. These include plots of daily mean stream temperatures displayed longitudinally over the 110 km model grid for all scenarios over an entire year (Figures 4a, 4b, 4c, 4d, 4e, 4f, 4g, 4h, 4i, 4j, 4k, and 4l). Also, with hourly stream temperature plots the diurnal temperature fluctuations for each scenario were assessed. Monthly mean stream temperature data were used to quantify the effect of an upstream dam and pumping in degrees. Finally, the influence of groundwater discharge on both dam impacts and pumping impacts on stream temperatures was evaluated by computing the groundwater thermal flux for each scenario.

### 5.1. Flow Scenario and Climate Condition Variations

[30] In the humid, semiarid and arid natural flow scenarios, annual simulated stream temperature trends tracked solar radiation trends with a delay of about 30 days (Figures 4a, 4e, and 4i). The maximum stream temperatures generally occurred in late July (around Julian day 200) throughout the length of the river reach. All three plots show a slight cooling during the summer between river kilometers 100 and 50, because cooler groundwater flows are added to the warmer upstream boundary flow water. However, further downstream the cooling effect of the groundwater diminishes because it is a smaller portion of the overall flow.

[31] With the upstream dam in place, maximum stream temperatures for all three climate conditions (Figures 4b, 4f, and 4j) occur in early October (around Julian day 275) in the upper reaches. For humid and semiarid conditions, the date of the maximum stream temperatures stays constant throughout the entire river reach. However, under the arid climate condition the maximum stream temperature occurs earlier in the year for much of the lower river. For all three climate conditions the thermal effect of the upstream dam release temperature decreases downstream. Solar radiation has an increased role in determining the overall stream temperatures in the lower reaches. For the arid climate condition, the influence of solar radiation is more pronounced than in the other climate conditions, because the flow volume is less,

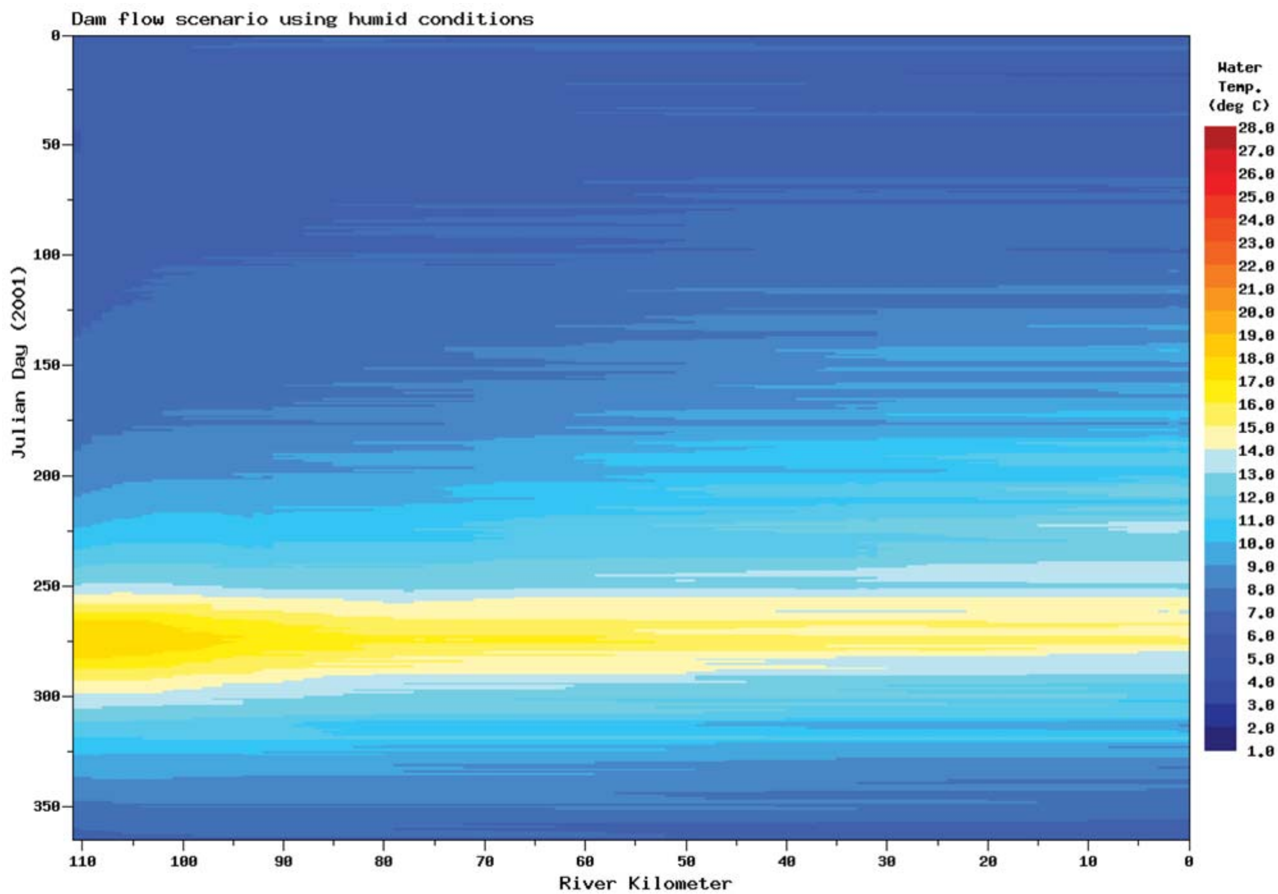


**Figure 4b.** Simulated daily stream temperatures from 110 km down to the axis of the valley for the dam flow scenario under humid conditions.

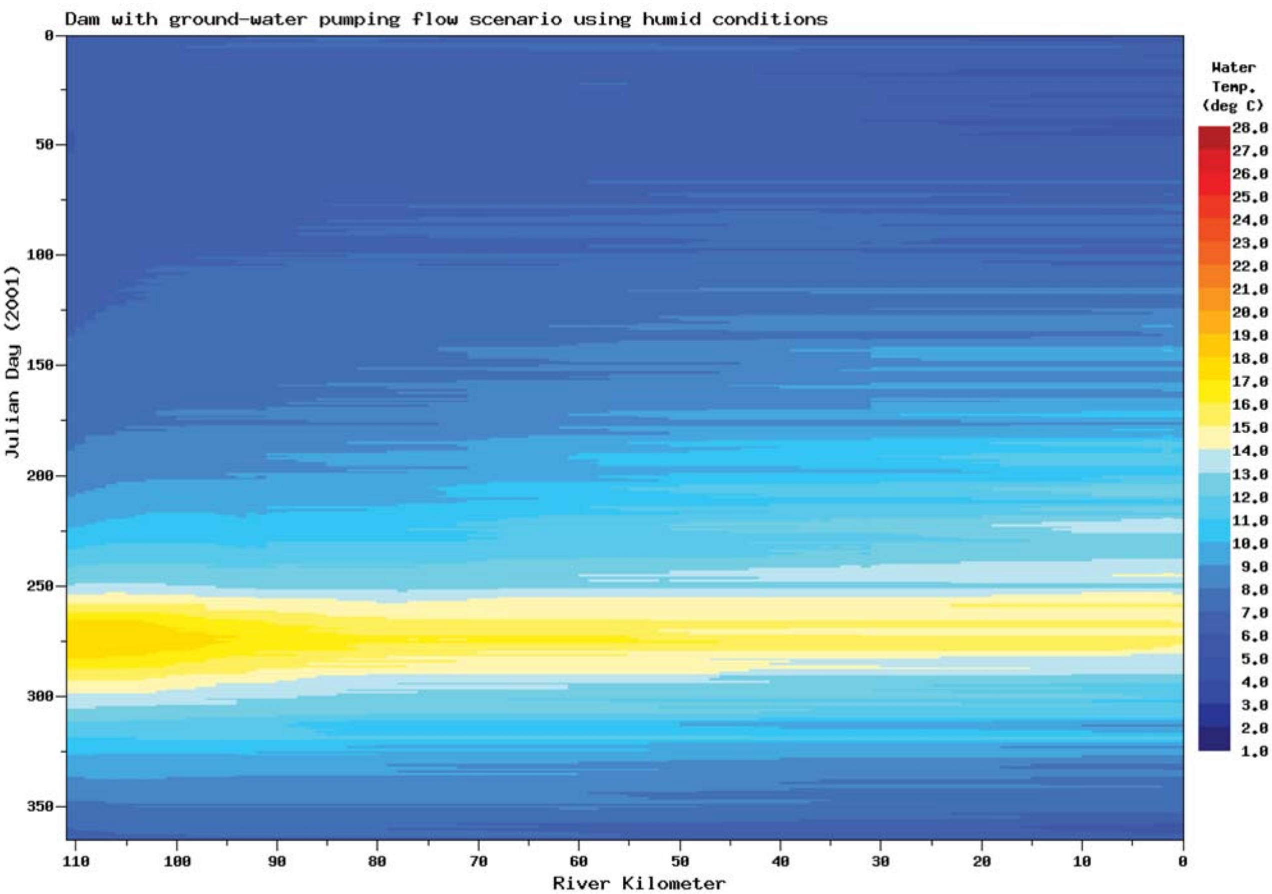


**Figure 4c.** Simulated daily stream temperatures from 110 km down to the axis of the valley for the dam with pumping flow scenario under humid conditions.

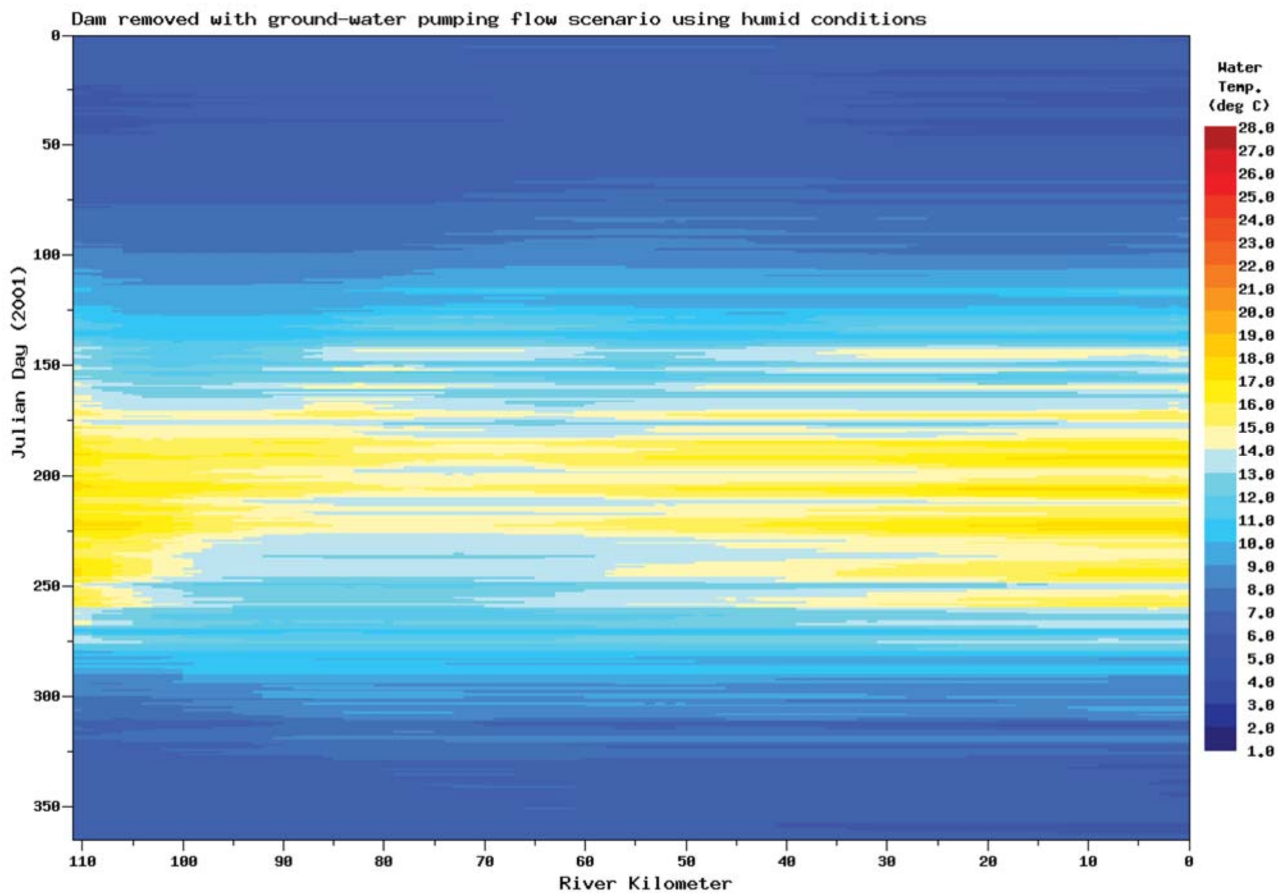


**Figure 4d.** Simulated daily stream temperatures from 110 km down to the axis of the valley for the dam removed with pumping flow scenario under humid conditions.

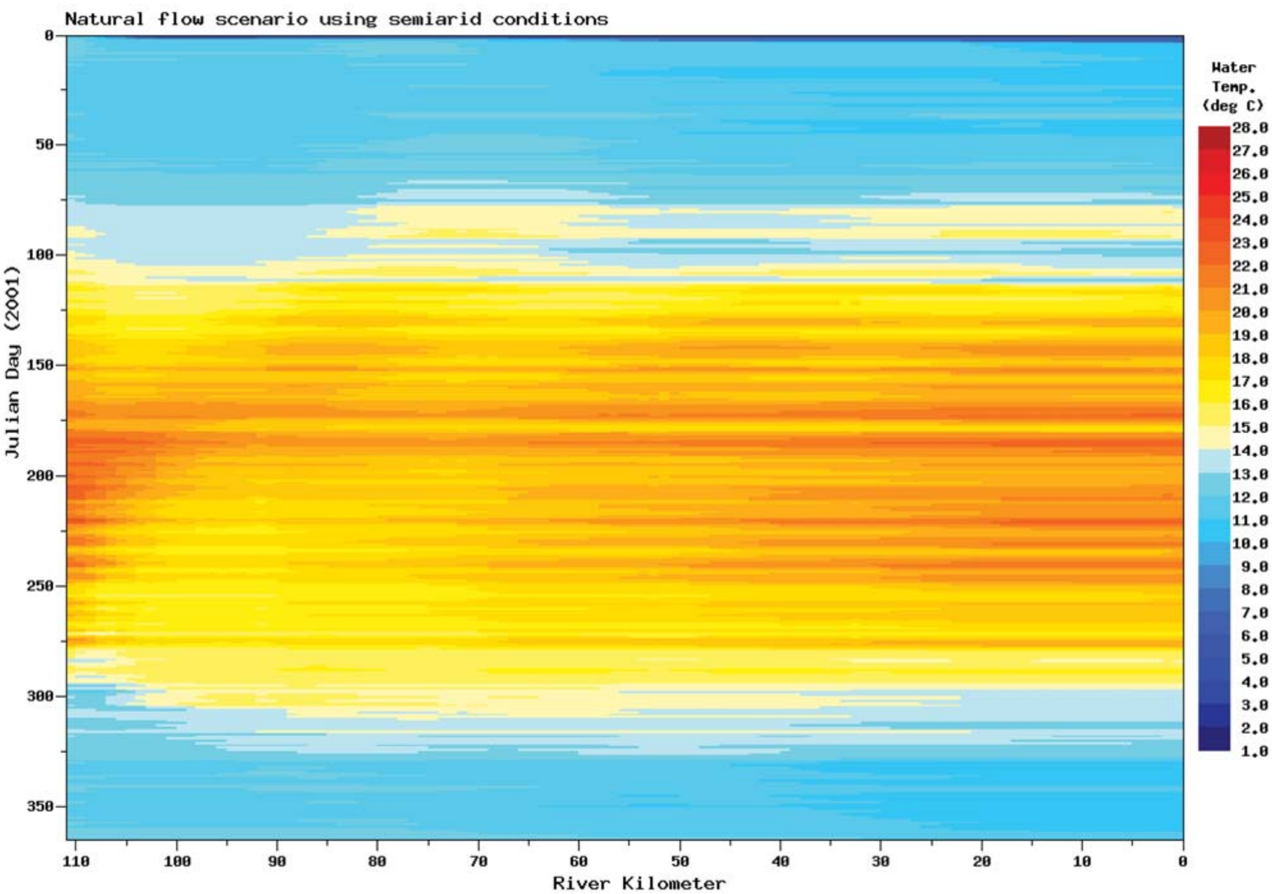


**Figure 4e.** Simulated daily stream temperatures from 110 km down to the axis of the valley for the natural flow scenario under semiarid conditions.

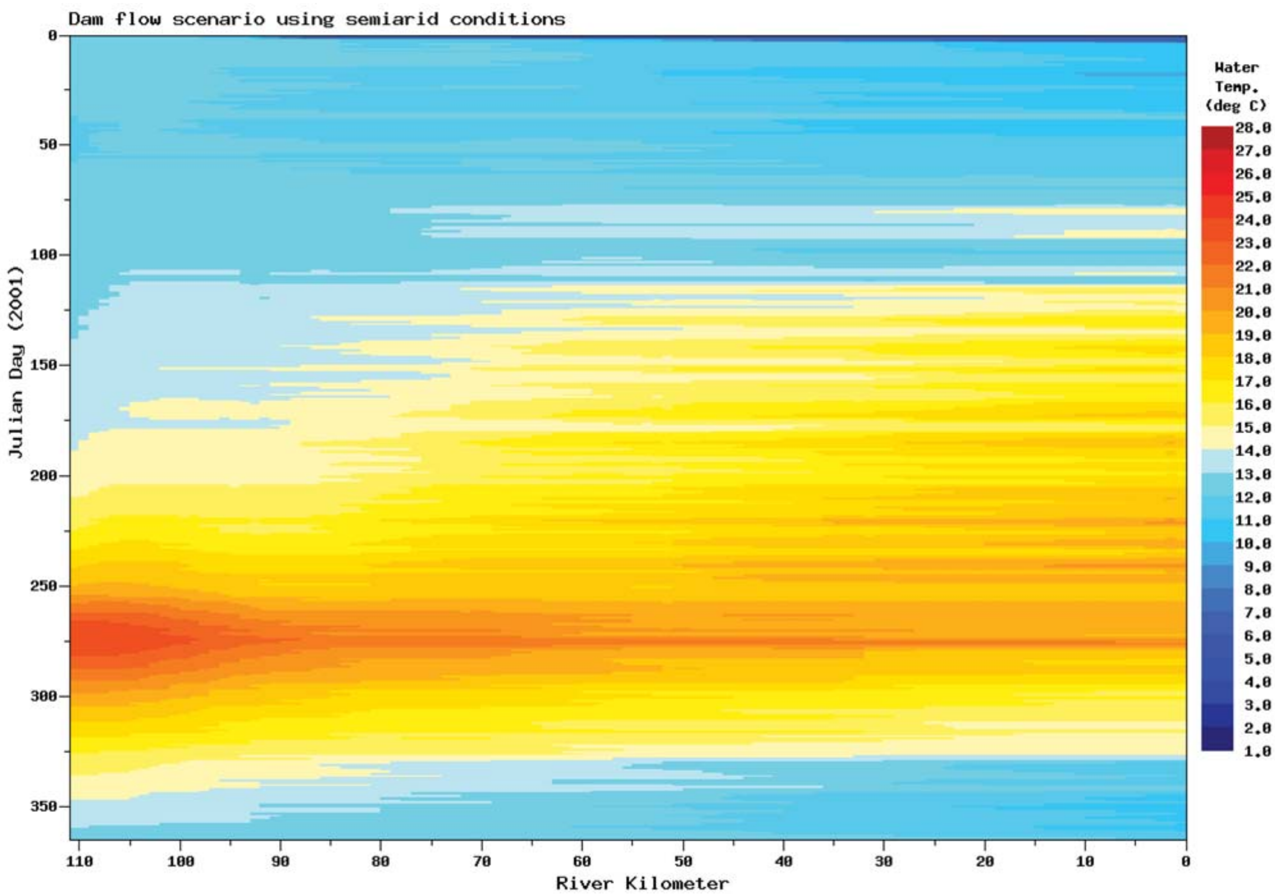


**Figure 4f.** Simulated daily stream temperatures from 110 km down to the axis of the valley for the dam flow scenario under semiarid conditions.

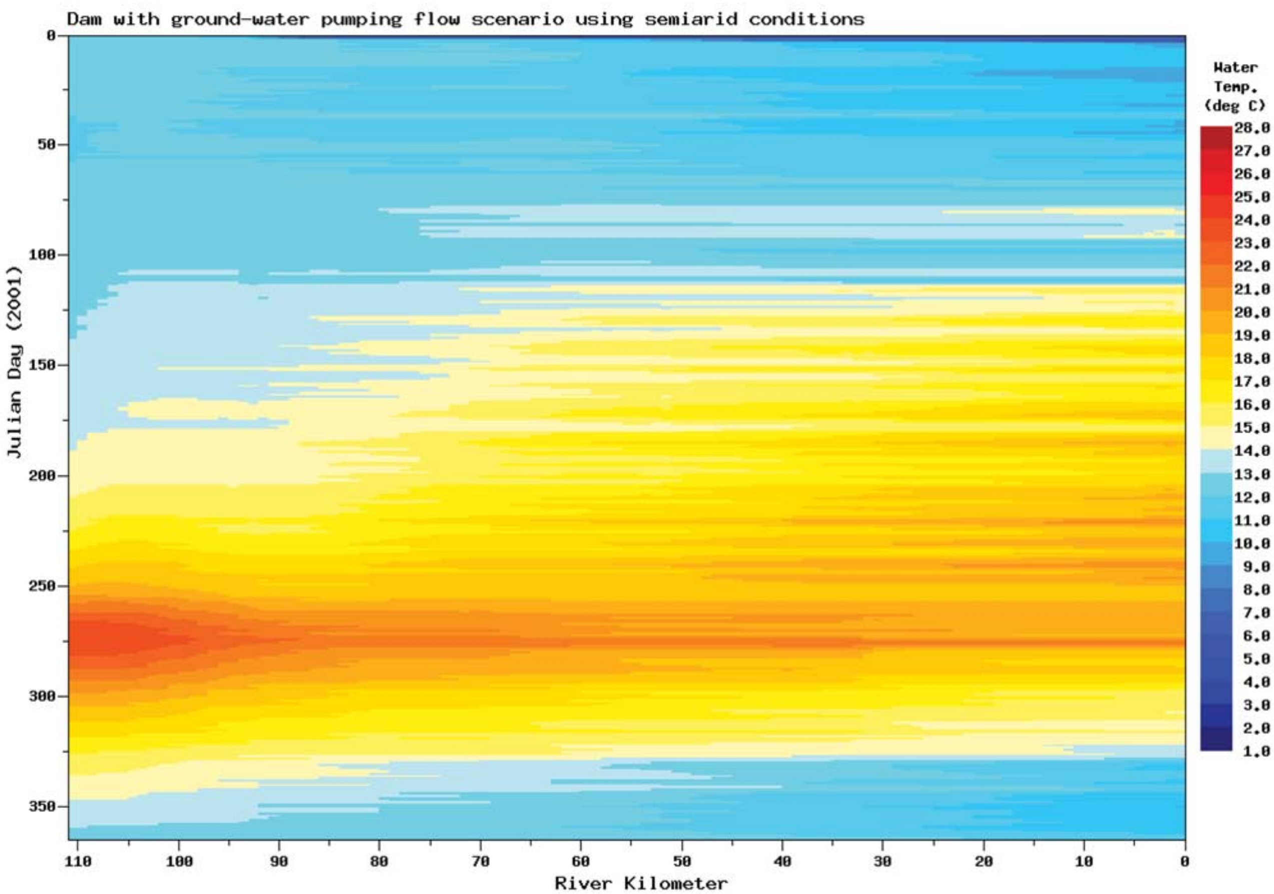


**Figure 4g.** Simulated daily stream temperatures from 110 km down to the axis of the valley for the dam with pumping flow scenario under semiarid conditions.

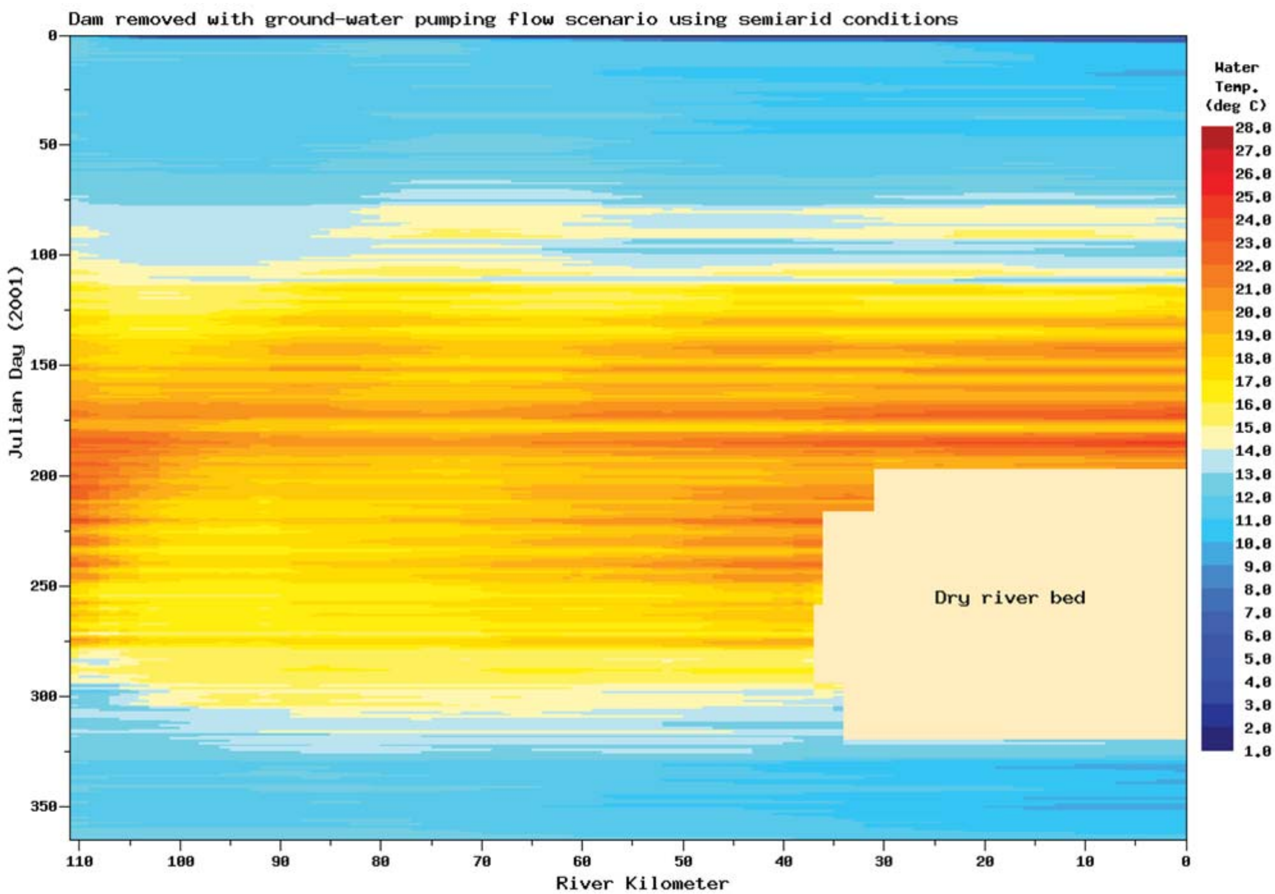


**Figure 4h.** Simulated daily stream temperatures from 110 km down to the axis of the valley for the dam removed with pumping flow scenario under semiarid conditions.

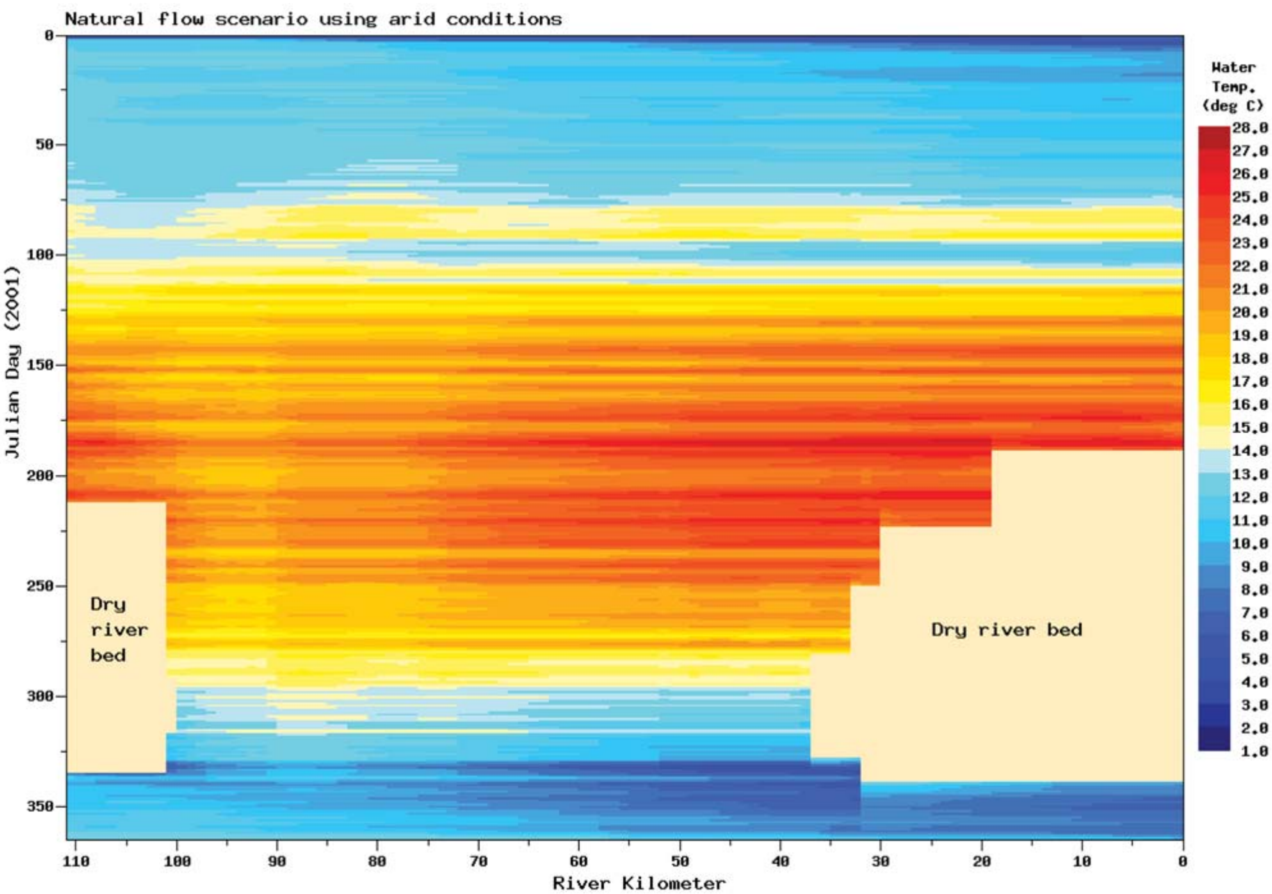


**Figure 4i.** Simulated daily stream temperatures from 110 km down to the axis of the valley for the natural flow scenario under arid conditions.

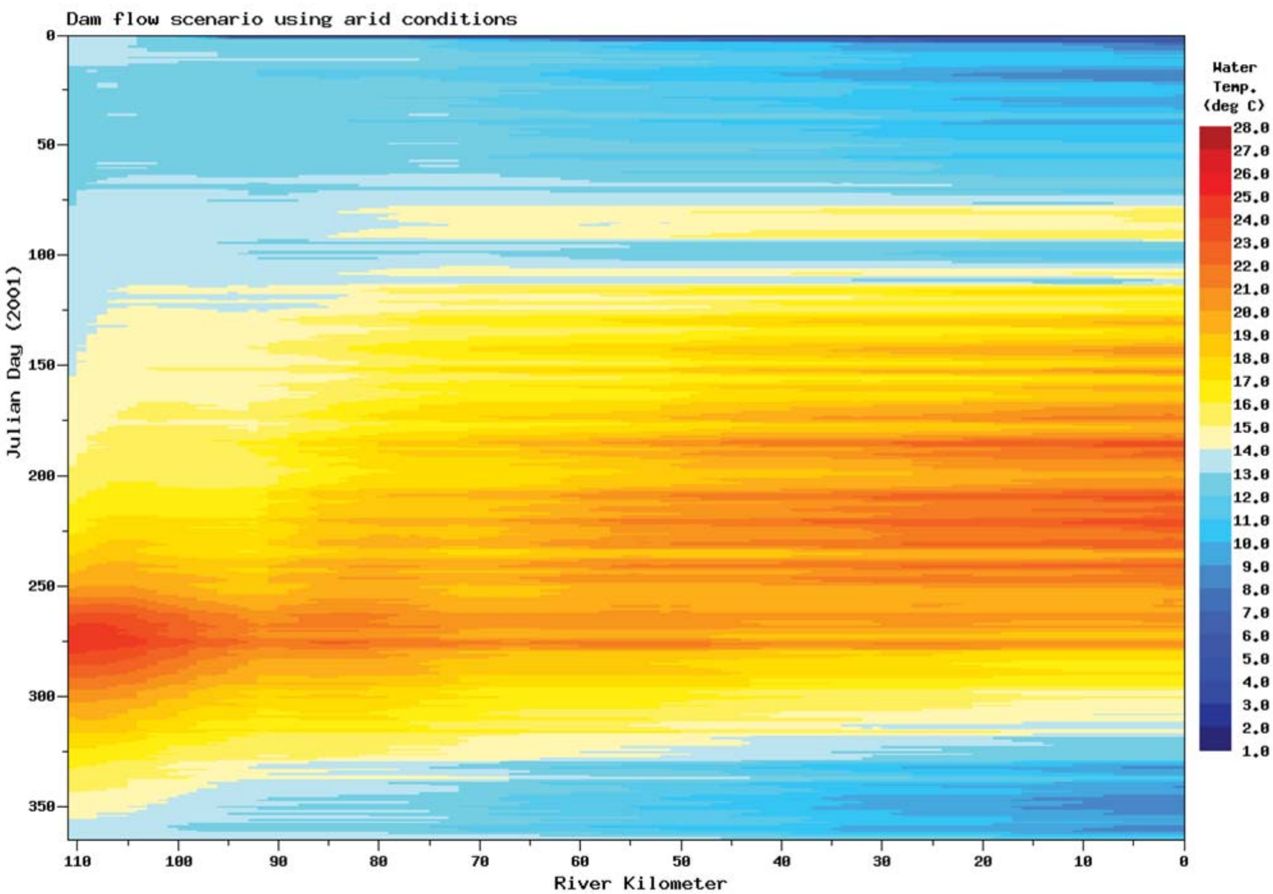


**Figure 4j.** Simulated daily stream temperatures from 110 km down to the axis of the valley for the dam flow scenario under arid conditions.

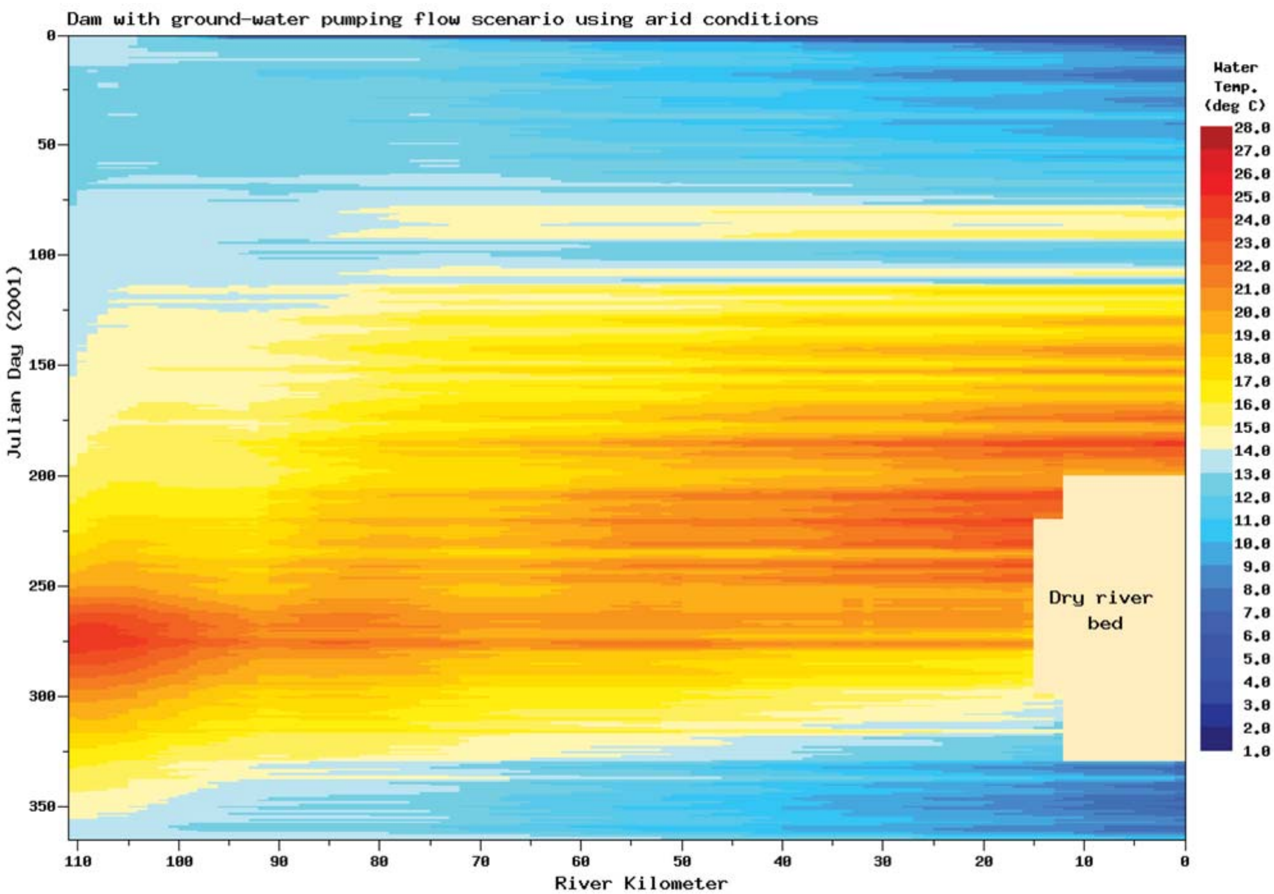


**Figure 4k.** Simulated daily stream temperatures from 110 km down to the axis of the valley for the dam with pumping flow scenario under arid conditions.

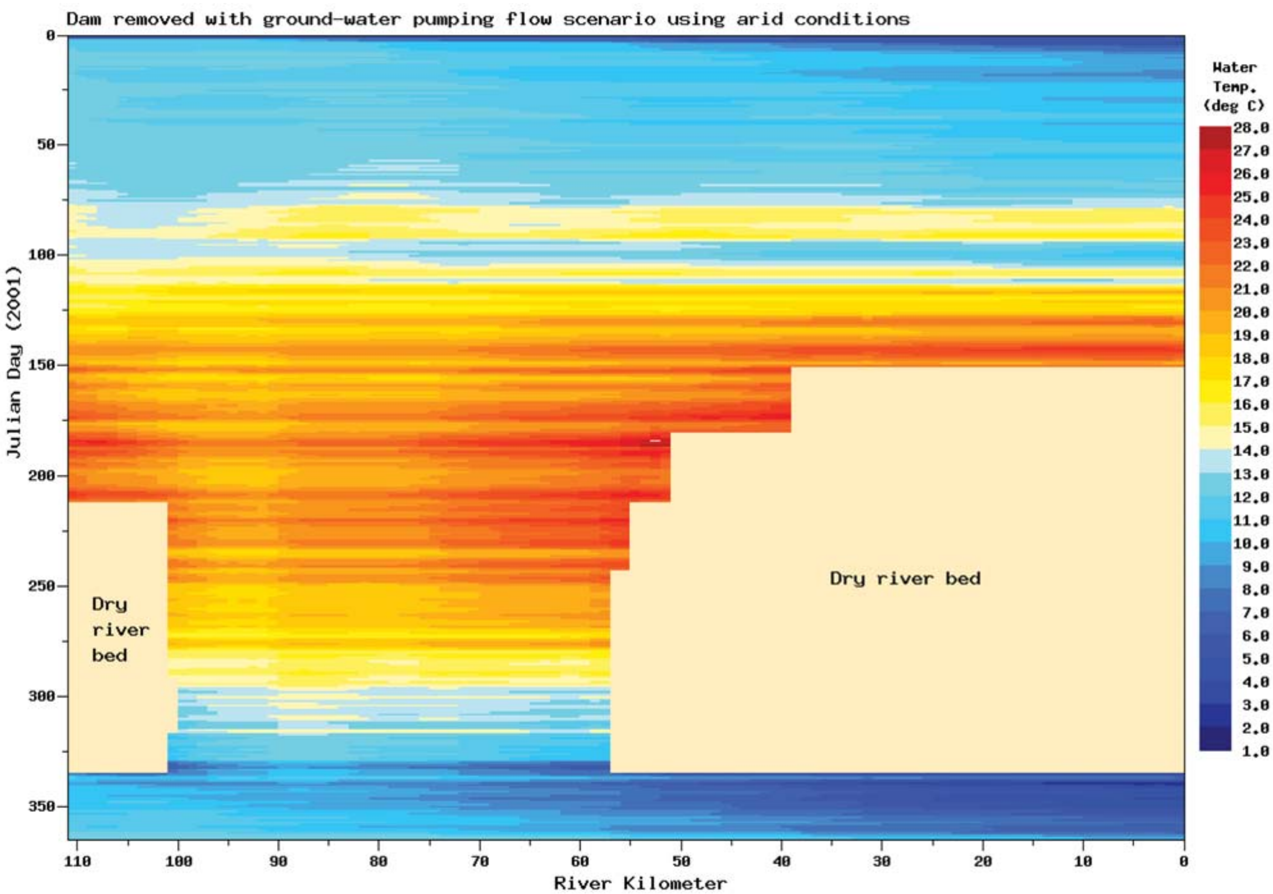


**Figure 4l.** Simulated daily stream temperatures from 110 km down to the axis of the valley for the dam removed with pumping flow scenario under arid conditions.

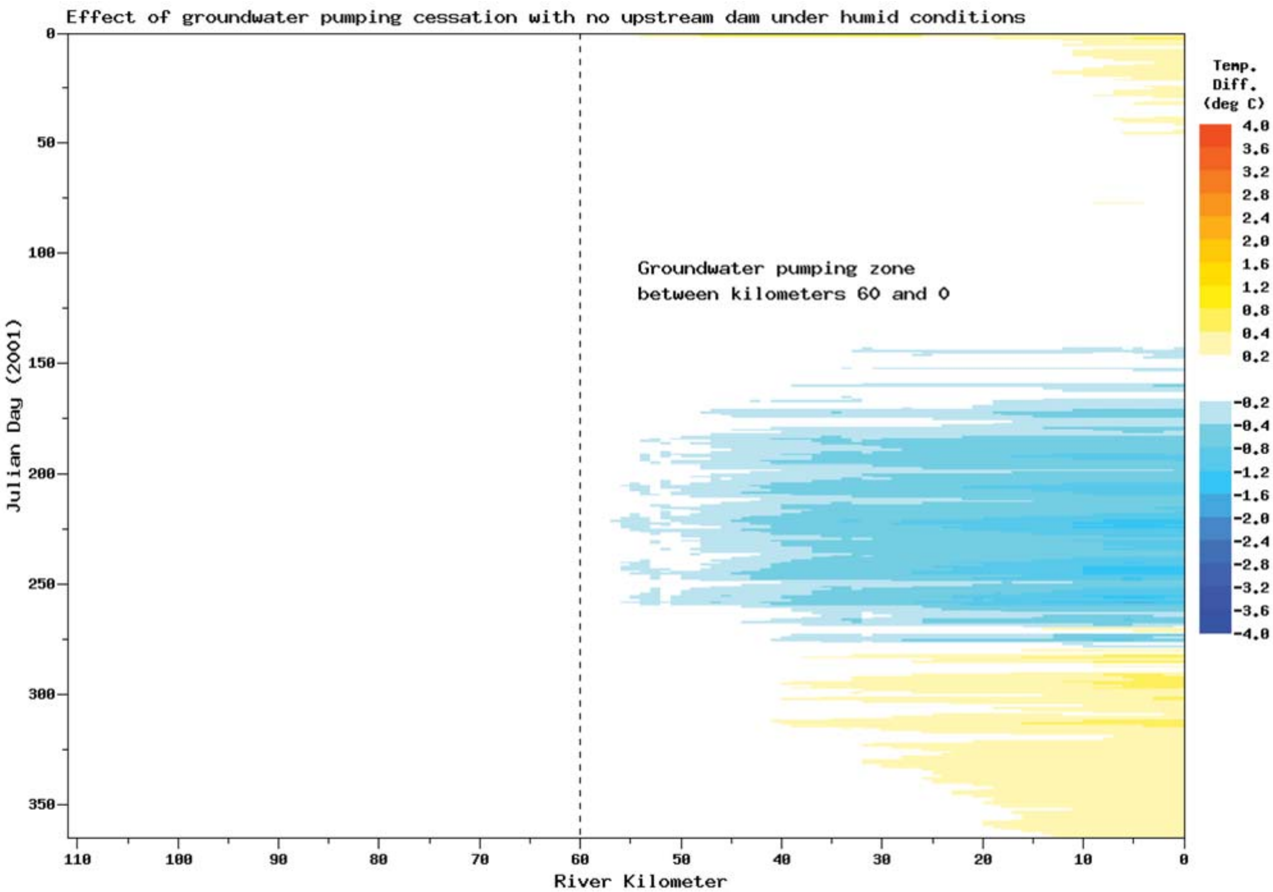


**Figure 5a.** Changes in simulated daily stream temperatures from 110 km down to the axis of the valley resulting from pumping cessation with no upstream dam under humid conditions.

which enhances the effect of near-surface thermal forcings (solar and air temperature).

[32] The stream temperature impact of pumping (comparing Figures 4a, 4e, and 4i with Figures 4d, 4h, and 4l, respectively) is more subtle than the impact of an upstream dam (comparing Figures 4a, 4e, and 4i with Figures 4b, 4f, and 4j, respectively). These stream temperature changes resulting from pumping are also plotted as differences before and after pumping with or without an upstream dam for the three climate conditions (Figures 5a–5f). The effect of pump stoppage with no upstream dam (Figures 5a, 5c, and 5e) had greater variability than pump stoppage with an upstream dam (Figures 5b, 5d, and 5f) for all three climate conditions. Also, pump stoppage cooled stream temperatures from approximately May to September without the dam, and from approximately June to October with the dam. Although the effects of pump stoppage on stream temperature could not be evaluated during no-flow periods for some of the semiarid and arid conditions, lack of water in stream channels generally increases temperature extremes in the channel [*Constantz et al.*, 2001].

[33] Flow volume and length of day are factors that are strongly manifested in the simulated water temperatures from all tested scenarios. Simulated hourly stream temperatures in the lower reach (RK 2) for the natural flow scenario for the three climate conditions generally follow the increase and decrease of available hours of daylight with a delay of approximately a month (Figures 6a–6c). The impact of an upstream dam at RK 110 is also evident as cool water released from the dam during the summer months keep stream temperatures below their natural levels even in the lower reach (RK 2). In the fall, stream temperatures are higher than their natural levels when warmer water is released from the dam. The effect of the dam on stream temperatures is most and least pronounced with humid and arid conditions, respectively (Figures 6a and 6c). With lower flows in the arid condition there is a greater influence of climatic forcing and a reduced propagating influence of the upstream boundary condition. These results would not necessarily apply to all situations since the stream temperature boundary conditions used in this study were derived from a specific precipitation flow regime and type of reservoir. Flow in the Scoggins Creek, Oregon, drainage is mostly rain driven. If the flow were mostly driven by snowmelt the overall stream temperatures probably would have been cooler and the date of the annual maximum stream temperature probably would have occurred later in the summer. The reservoir on Scoggins Creek is medium sized ($68 \times 10^6$ m$^3$ at full capacity) and fairly wide. If the reservoir were deeper and narrower the overall stream temperatures probably would have been cooler.

[34] During the summer, pumping can increase stream temperature extremes by causing a smaller flux of cool groundwater to discharge into the stream. This is evident in Figure 6a where the "dam removed with pumping" scenario

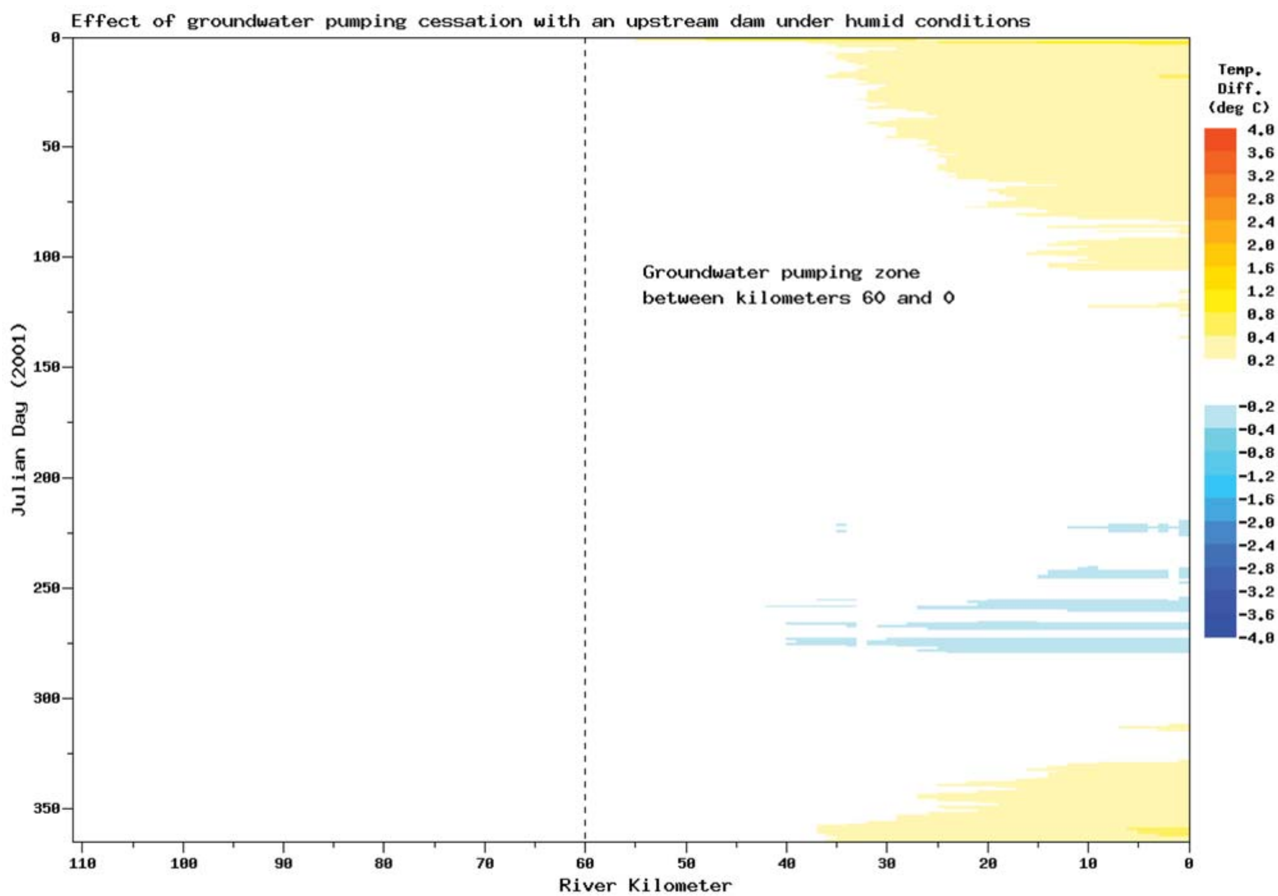


**Figure 5b.** Changes in simulated daily stream temperatures from 110 km down to the axis of the valley resulting from pumping cessation with an upstream dam under humid conditions.

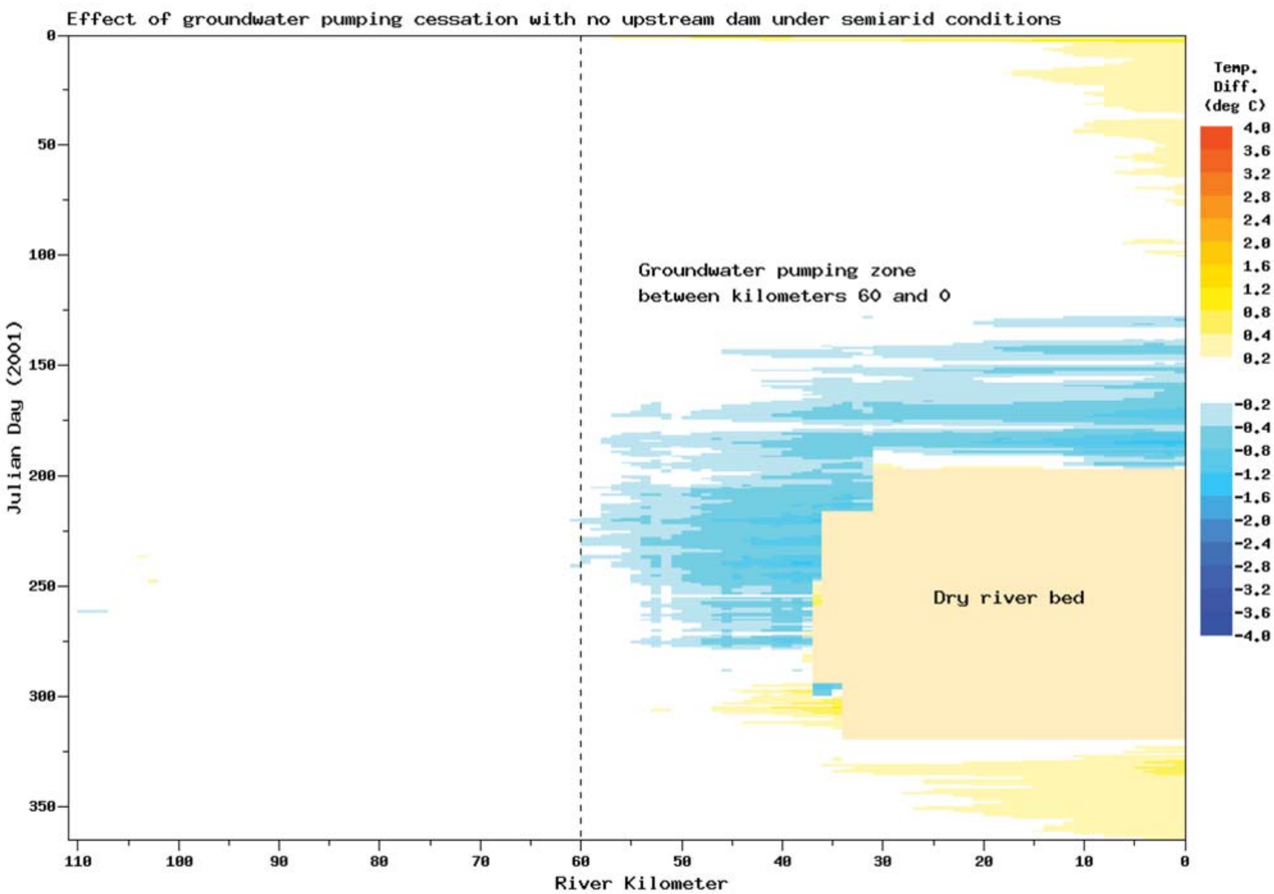


**Figure 5c.** Changes in simulated daily stream temperatures from 110 km down to the axis of the valley resulting from pumping cessation with no upstream dam under semiarid conditions.

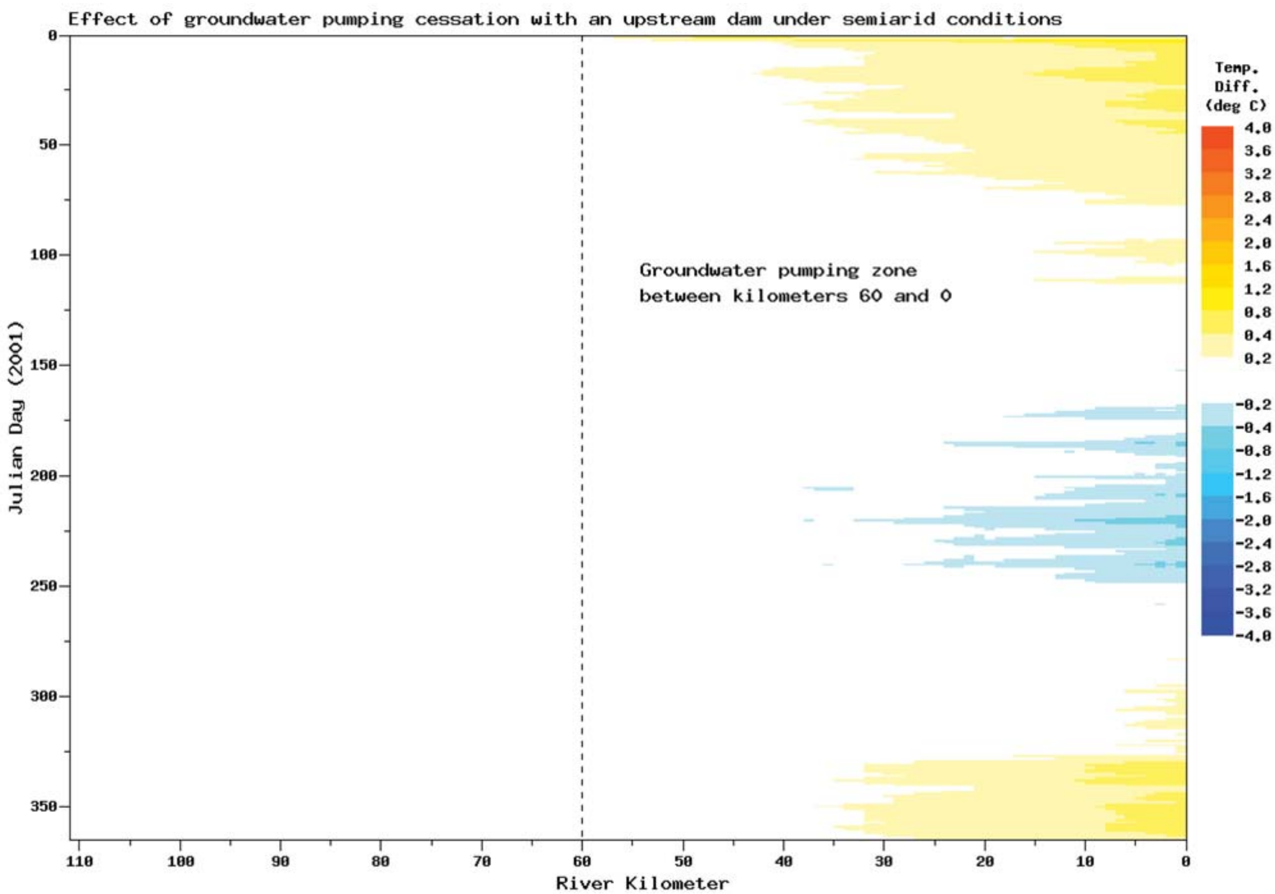


**Figure 5d.** Changes in simulated daily stream temperatures from 110 km down to the axis of the valley resulting from pumping cessation with an upstream dam under semiarid conditions.

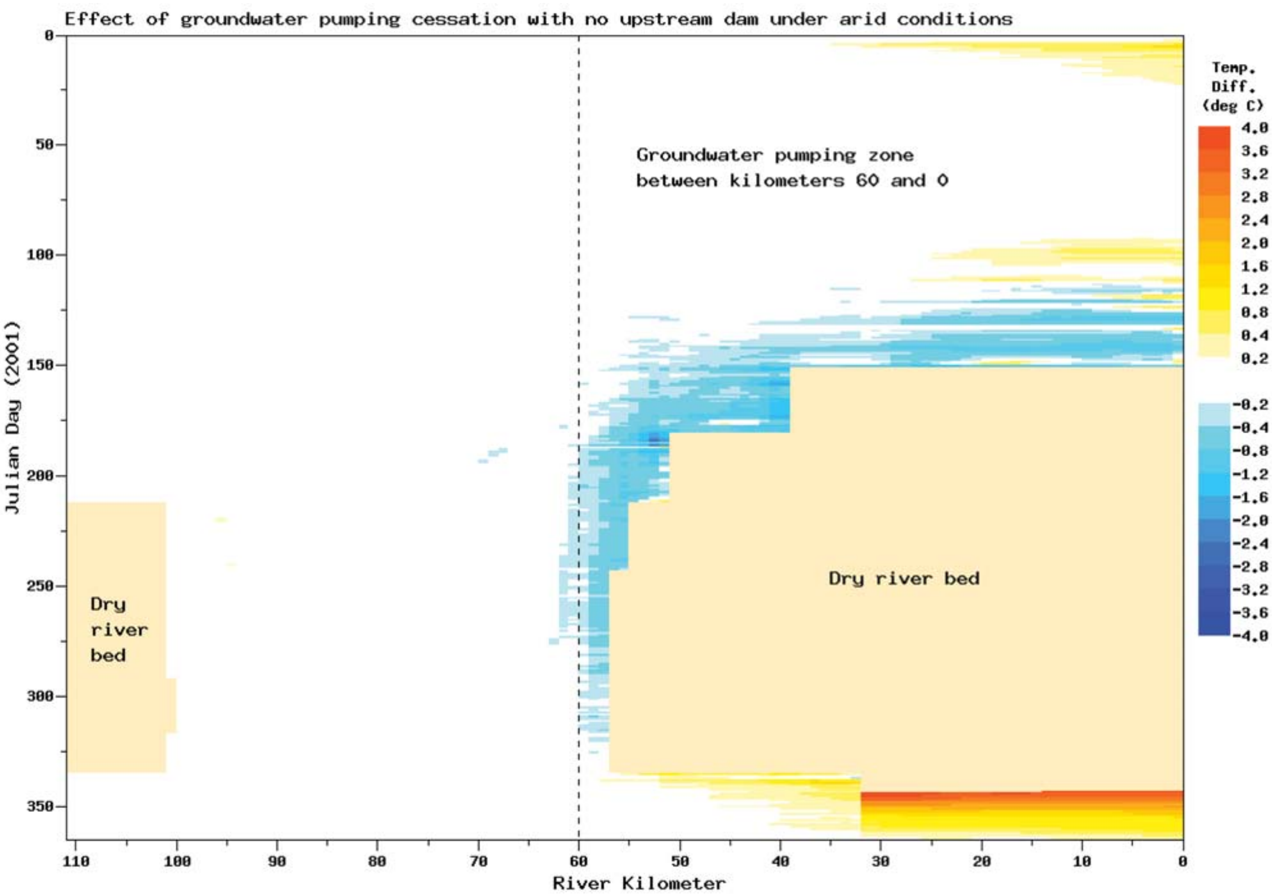


**Figure 5e.** Changes in simulated daily stream temperatures from 110 km down to the axis of the valley resulting from pumping cessation with no upstream dam under arid conditions.

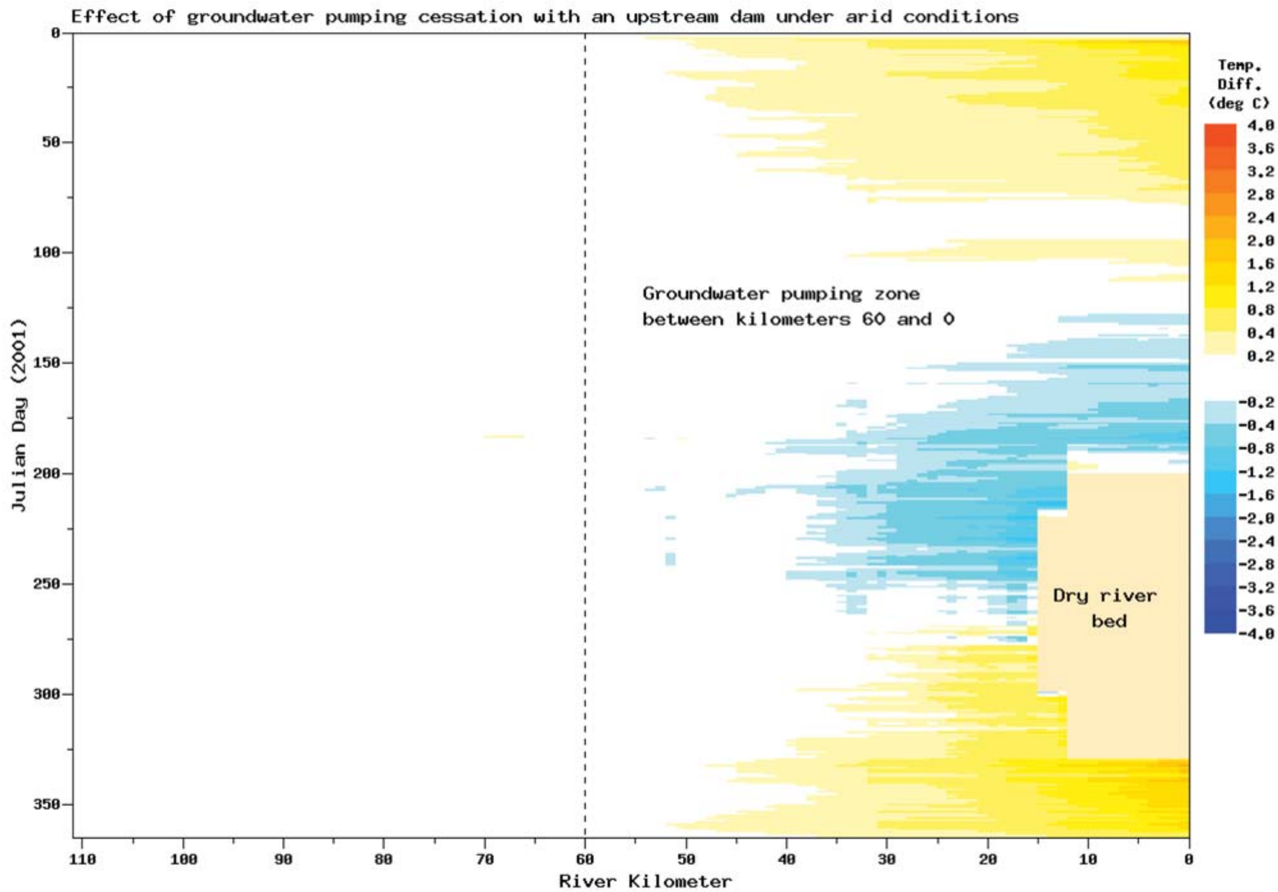


**Figure 5f.** Changes in simulated daily stream temperatures from 110 km down to the axis of the valley resulting from pumping cessation with an upstream dam under arid conditions.

has higher stream temperatures than the natural scenario. Also, as the volume and depth of flow in the stream is decreased, the stream temperature can more rapidly change through heat transfer processes at the water surface. In the winter pumping can have the opposite effect and can decrease stream temperatures if the groundwater temperature is warmer than the streamflow temperature. For one of the semiarid flow scenarios (dam removed with pumping) and three of the arid

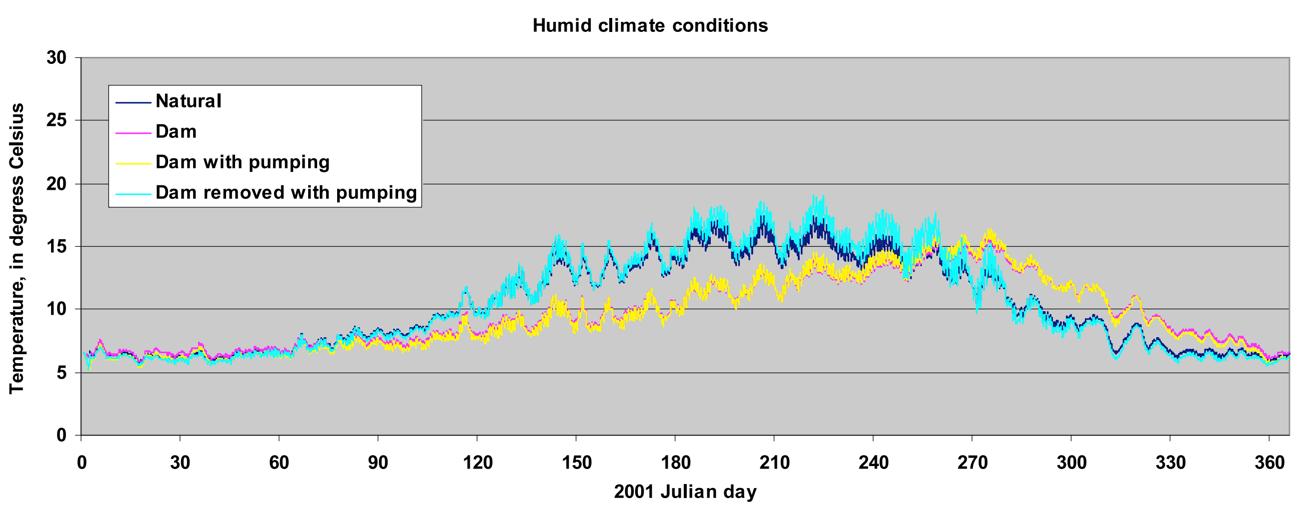


**Figure 6a.** Simulated hourly stream temperatures for the natural, dam, dam with pumping, and dam removed with pumping flow scenarios 2 km above the axis of the valley under humid conditions.

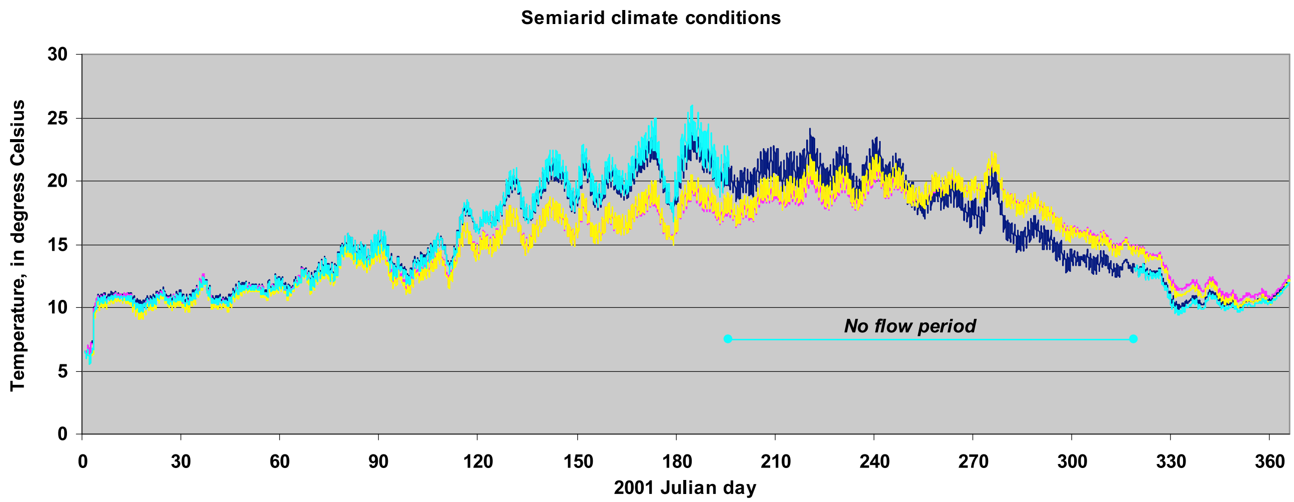


**Figure 6b.** Simulated hourly stream temperatures for the natural, dam, dam with pumping, and dam removed with pumping flow scenarios 2 km above the axis of the valley under semiarid conditions. Horizontal line represents a period when the streambed is dry for dam removed with pumping scenario.

flow scenarios (natural, dam with pumping, and dam removed with pumping) the stream becomes dry for a period during the year. These periods are indicated in Figures 6b and 6c by horizontal lines.

### 5.2. Upstream Dam and Pumping Impacts

[35] The effects of pumping on stream temperatures can be assessed in these scenarios by comparing temperatures in the reach between RK 60 and RK 0 (the simulated pumping well field was located between RK 60 and RK 10). The effects of pump stoppage on stream temperature are relatively small, and reflect seasonal patterns in pumping (Figures 7a–7c, red lines). Temperature differences in Figures 7a–7c (red lines) were computed by subtracting the monthly mean simulated stream temperatures of the "no dam with pumping scenario" from the natural (no dam, no pumping) scenario. After pump stoppage temperatures are cooler during the low-flow summer months because more surface water flow is added to the stream from groundwater discharge. The temperature of the groundwater discharge is cooler than the midsummer stream temperatures. The magnitude of the summer cooling ranged from 0.08°C to 1.05°C during May to September for the humid climate condition at RK 2. A slight warming effect, generally less than 0.5°C, occurs during the high-flow winter months, which is a consequence of groundwater temperatures being warmer than the stream at the time.

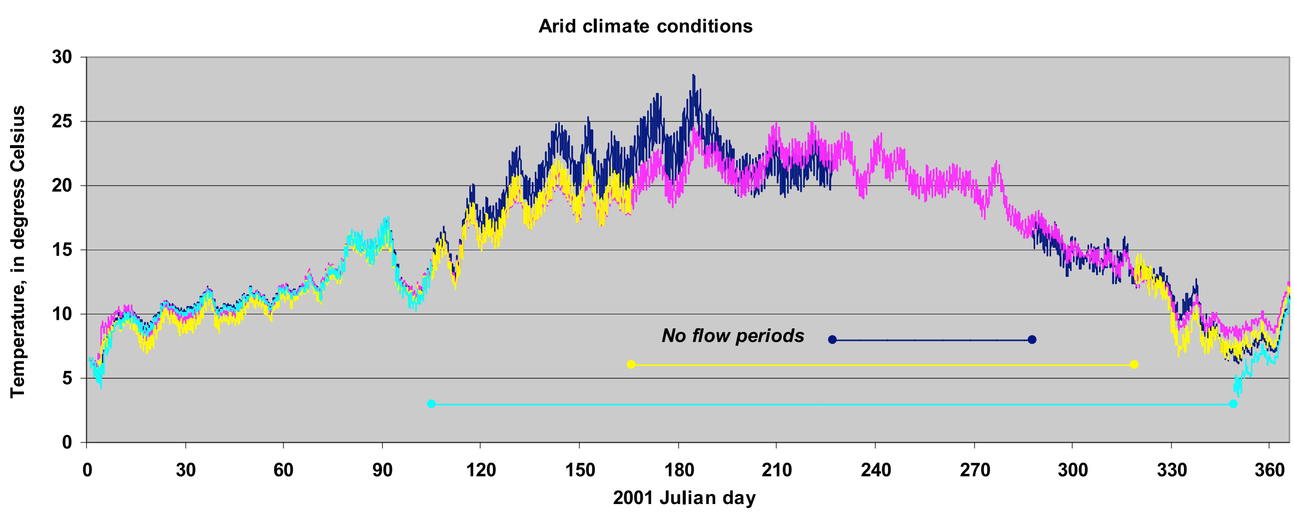


**Figure 6c.** Simulated hourly stream temperatures for the natural, dam, dam with pumping, and dam removed with pumping flow scenarios 2 km above the axis of the valley under arid conditions. Horizontal lines represent a period when the streambed is dry for the natural, dam with pumping, and dam removed with pumping scenarios.

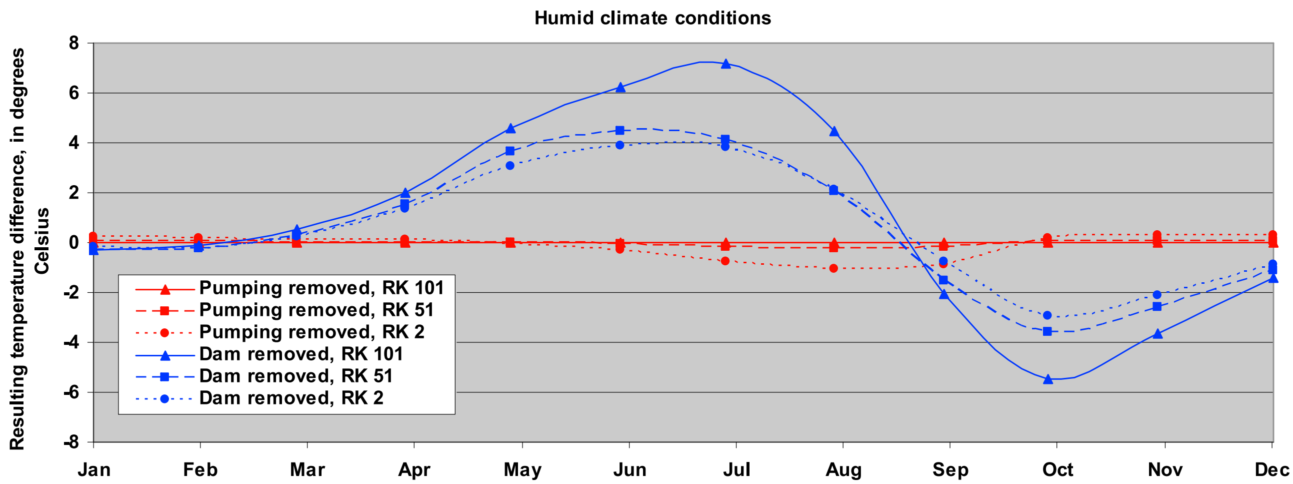


**Figure 7a.** Changes in simulated monthly stream temperatures resulting from groundwater pumping cessation and upstream dam removal under humid conditions.

[36] The effect of dam removal with no pumping results in a characteristic seasonal pattern (Figures 7a–7c, blue lines). These results were obtained by subtracting the monthly mean simulated stream temperatures of the "upstream dam with no pumping" scenario from the natural (no dam, no pumping) scenario. Changes in monthly mean temperatures are substantive throughout the year. From March to August, monthly mean stream temperatures increased at all three river locations on average over this 6 month period by approximately 3.0°C, 2.5°C, and 2.0°C for humid, semiarid, and arid conditions, respectively. The greatest increase (7.18°C) occurred at the upstream reach (RK 101) in July under humid conditions. The temperature increase is a consequence of the loss, after dam removal, of unnaturally cool water released from the hypolimnion of a deep reservoir during the spring and summer. For the other 6 months of the year, September to February, dam removal decreased stream temperatures on average by about 1.5°C to 2.0°C for the three climate conditions. The decrease is expected because dam flow releases during the fall and winter are warmer than they would be under naturally flowing conditions. The greatest decrease (6.52°C) occurred at the upstream reach (RK 101) in October under arid conditions. Moving downstream away from the dam (RK 110) the magnitude of the temperature increase (or decrease) diminishes because meteorological conditions and groundwater temperatures have an increasing influence on stream temperature in relation to the upstream dam release temperature.

[37] For all three climate conditions the magnitude of temperature changes associated with dam removal was greater than that associated with no pumping (Figures 7a–7c). For humid climate conditions, the maximum temperature increase for dam removal (7.18°C for July at RK 101) was almost seven times greater than the maximum temperature decrease for no pumping (1.05°C for August at RK 2). The magnitude of the changes, for either dams or pumping, was

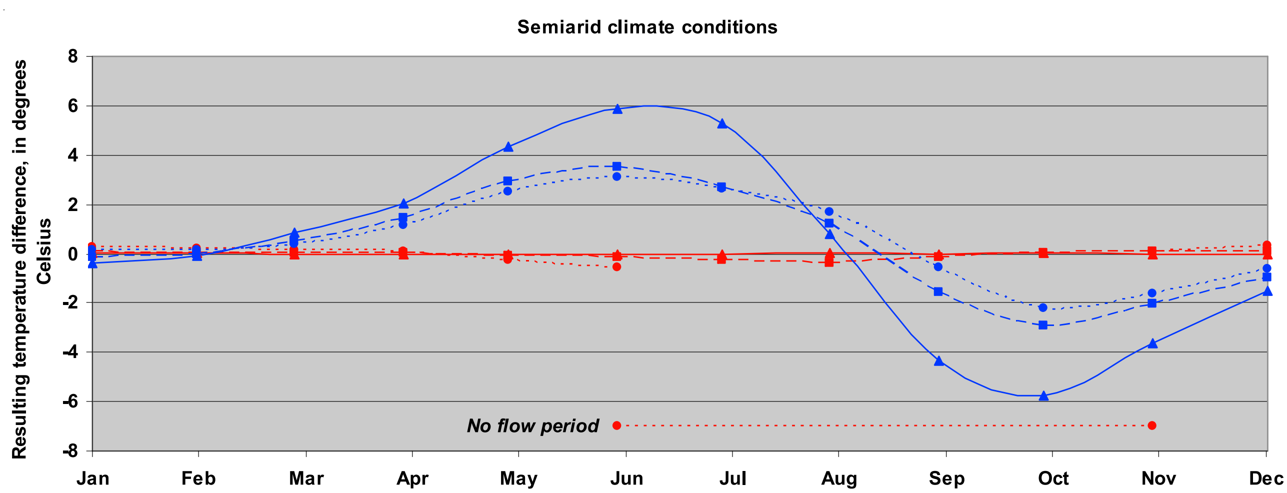


**Figure 7b.** Changes in simulated monthly stream temperatures resulting from groundwater pumping cessation and upstream dam removal under semiarid conditions. Horizontal line represents a period when the streambed is dry for dam removed with pumping scenario.

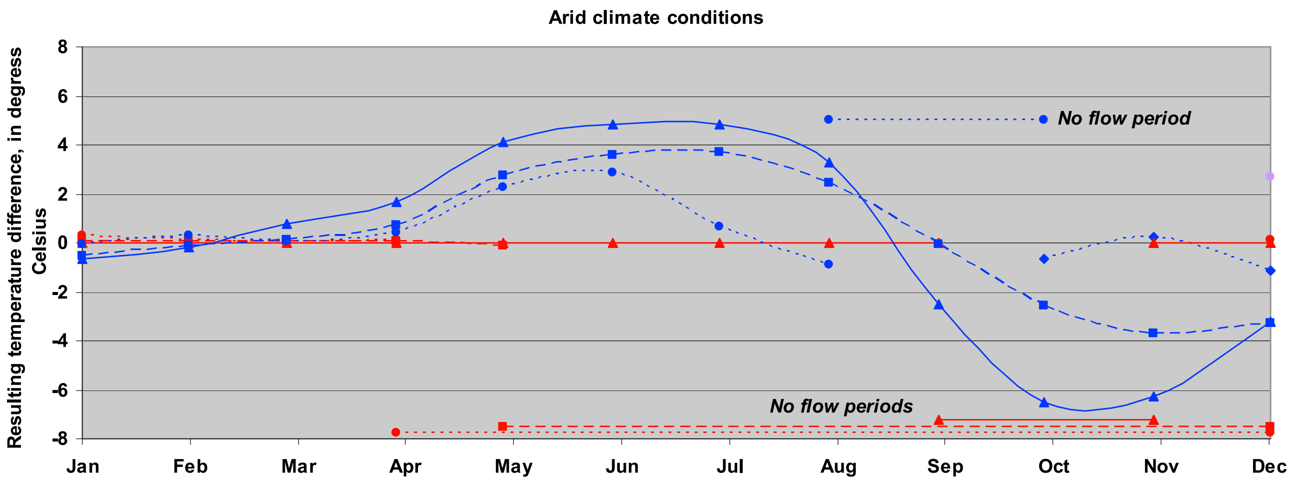


**Figure 7c.** Changes in simulated monthly stream temperatures resulting from groundwater pumping cessation and upstream dam removal under arid conditions. Horizontal lines represent a period when the streambed is dry for the natural, dam with pumping, and dam removed with pumping scenarios.

greatest at locations closest to the dam or well field. The impacts of the dam consistently decrease going from upstream to downstream and the impacts of pumping on stream temperatures increase between RK 51 and RK 2.

### 5.3. Dam Removal With Continued Pumping

[38] Historically, pumping has developed downstream after dam construction, to supplement surface water resources. *Constantz and Essaid* [2007] presented simulated flow results showing the likelihood of the downstream stream reaches as ephemeral after dam removal and with continued pumping. Stream temperature changes that occur as a consequence of dam removal with continued pumping were computed by subtracting the monthly mean simulated stream temperatures of the upstream dam scenario from the "dam removed with pumping" scenario (Table 1). From March to August stream temperatures increased at all three river locations on average by 3.25°C and 2.5°C for humid and semiarid conditions, respectively. The effect of pumping slightly increased the magnitude of the temperature increase because the river had less flow in the downstream reaches. At RK 2 the average of March to August stream temperatures for the humid climate condition increased by 2.81°C (Table 1). At all three river locations for the period from September to February, stream temperatures, as a consequence of dam removal with pumping, generally decreased on average by about 1.5°C. For downstream stream reaches during the summer period under the arid climate condition, pumping lead to ephemeral flow and thus no stream temperatures for comparison.

[39] The combined effect of dam removal and pumping stoppage on stream temperatures can be computed by subtracting the monthly mean simulated stream temperatures of the upstream dam with pumping flow from the natural flow scenario. However, the timing, pattern of change, and magnitude of increased and decreased stream temperatures is generally very similar to the "dam removed with continued pumping" scenario in Table 1, as a result of the large impact on streamflow of a large upstream dam.

### 5.4. Minimum and Maximum Stream Temperature Range

[40] The magnitude of the temperature range between minimum and maximum hourly stream temperature over a

**Table 1.** Changes in Simulated Stream Temperature Resulting From Dam Removal With Groundwater Pumping[a]

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Humid simulations | | | | | | | | | | | | |
| River kilometer 101 | **−0.28** | **−0.11** | 0.52 | 1.98 | 4.58 | 6.23 | 7.18 | 4.49 | **−2.07** | **−5.47** | **−3.65** | **−1.41** |
| River kilometer 51 | **−0.28** | **−0.23** | 0.29 | 1.56 | 3.66 | 4.54 | 4.30 | 2.28 | **−1.44** | **−3.71** | **−2.63** | **−1.12** |
| River kilometer 2 | **−0.03** | **−0.09** | 0.30 | 1.43 | 3.28 | 4.26 | 4.53 | 3.06 | **−0.11** | **−3.17** | **−2.29** | **−0.84** |
| Semiarid simulations | | | | | | | | | | | | |
| River kilometer 101 | **−0.38** | **−0.09** | 0.84 | 2.04 | 4.36 | 5.87 | 5.26 | 0.77 | **−4.36** | **−5.79** | **−3.64** | **−1.52** |
| River kilometer 51 | **−0.07** | 0.01 | 0.51 | 1.45 | 2.99 | 3.65 | 2.94 | 1.48 | **−1.50** | **−3.04** | **−2.11** | **−0.97** |
| River kilometer 2 | 0.34 | 0.29 | 0.46 | 1.22 | 2.80 | 3.60 | NF | NF | NF | NF | **−1.42** | **−0.51** |
| Arid simulations | | | | | | | | | | | | |
| River kilometer 101 | **−0.64** | **−0.16** | 0.75 | 1.68 | 4.15 | 4.83 | 4.84 | 3.30 | **−2.50** | NF | **−6.27** | **−3.19** |
| River kilometer 51 | **−0.39** | **−0.05** | 0.18 | 0.75 | 2.84 | NF | NF | NF | NF | NF | NF | **−3.25** |
| River kilometer 2 | 0.43 | 0.69 | 0.23 | 0.46 | NF | NF | NF | NF | NF | NF | NF | **−2.62** |

[a]Values are given in degrees Celsius. Positive and negative (bold) values reflect a warming and cooling effect, respectively; NF indicates that temperatures could not be compared because one or both scenarios had no flow during the month. River kilometer is the distance from the downstream end of the model grid. The upstream end of the model grid and the dam are at river kilometer 110.

**Table 2.** Range Between Maximum and Minimum Simulated Stream Temperatures During Each Month[a]

| | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| *Humid Simulations* | | | | | | | | | | | | |
| River kilometer 101 | | | | | | | | | | | | |
| Natural | 1.3 | 1.1 | 2.2 | 4.7 | 7.6 | 5.5 | 4.1 | 4.8 | 5.5 | 6.3 | 2.5 | 0.7 |
| Dam | 1.0 | 0.6 | 0.8 | 1.2 | 1.9 | 2.6 | 3.6 | 4.8 | 6.4 | 5.6 | 4.0 | 2.4 |
| Dam with pumping | 1.0 | 0.6 | 0.8 | 1.2 | 1.9 | 2.6 | 3.6 | 4.8 | 6.4 | 5.6 | 4.0 | 2.4 |
| No dam with pumping | 1.3 | 1.1 | 2.2 | 4.7 | 7.6 | 5.5 | 4.1 | 4.8 | 5.5 | 6.3 | 2.5 | 0.7 |
| River kilometer 51 | | | | | | | | | | | | |
| Natural | 1.4 | 0.8 | 2.0 | 4.7 | 7.2 | 4.9 | 4.7 | 4.8 | 5.0 | 5.5 | 3.1 | 1.0 |
| Dam | 1.6 | 1.2 | 1.3 | 2.4 | 3.3 | 3.3 | 4.6 | 4.2 | 5.1 | 5.4 | 4.1 | 2.3 |
| Dam with pumping | 1.6 | 1.2 | 1.4 | 2.4 | 3.4 | 3.4 | 4.7 | 4.3 | 5.2 | 5.5 | 4.2 | 2.3 |
| No dam with pumping | 1.4 | 0.9 | 2.1 | 4.8 | 7.4 | 5.1 | 5.0 | 5.1 | 5.4 | 6.0 | 3.2 | 1.0 |
| River kilometer 2 | | | | | | | | | | | | |
| Natural | 1.4 | 1.2 | 2.3 | 3.9 | 6.3 | 4.5 | 4.3 | 4.2 | 5.3 | 5.5 | 3.4 | 1.1 |
| Dam | 1.7 | 1.3 | 1.7 | 2.9 | 3.6 | 3.4 | 3.8 | 3.2 | 3.6 | 5.4 | 4.1 | 2.3 |
| Dam with pumping | 2.1 | 1.4 | 1.9 | 3.0 | 3.9 | 3.5 | 4.0 | 3.4 | 3.8 | 5.7 | 4.4 | 2.5 |
| No dam with pumping | 1.8 | 1.3 | 2.4 | 4.2 | 6.8 | 5.2 | 5.1 | 5.5 | 8.0 | 7.5 | 3.6 | 1.1 |
| *Semiarid Simulations* | | | | | | | | | | | | |
| River kilometer 101 | | | | | | | | | | | | |
| Natural | 6.1 | 2.0 | 4.7 | 5.9 | 6.9 | 4.6 | 7.3 | 6.0 | 5.3 | 6.1 | 2.9 | 1.4 |
| Dam | 6.4 | 1.2 | 2.3 | 2.7 | 3.8 | 3.7 | 4.0 | 5.4 | 6.7 | 6.3 | 4.3 | 2.2 |
| Dam with pumping | 6.4 | 1.2 | 2.3 | 2.7 | 3.8 | 3.6 | 4.0 | 5.4 | 6.7 | 6.3 | 4.3 | 2.2 |
| No dam with pumping | 6.1 | 2.0 | 4.7 | 5.9 | 6.9 | 4.6 | 7.3 | 6.0 | 5.3 | 6.1 | 2.9 | 1.4 |
| River kilometer 51 | | | | | | | | | | | | |
| Natural | 5.8 | 2.3 | 5.2 | 6.2 | 6.1 | 6.1 | 5.7 | 5.5 | 5.8 | 7.0 | 4.2 | 1.8 |
| Dam | 5.9 | 2.2 | 3.8 | 4.9 | 5.5 | 4.8 | 4.5 | 4.4 | 4.2 | 6.3 | 4.4 | 2.1 |
| Dam with pumping | 6.2 | 2.3 | 3.9 | 5.0 | 5.6 | 4.9 | 4.6 | 4.6 | 4.3 | 6.4 | 4.5 | 2.2 |
| No dam with pumping | 6.1 | 2.3 | 5.3 | 6.3 | 6.3 | 6.5 | 6.1 | 6.2 | 6.3 | 7.6 | 4.2 | 1.9 |
| River kilometer 2 | | | | | | | | | | | | |
| Natural | 5.3 | 2.3 | 5.0 | 6.4 | 5.8 | 6.5 | 5.4 | 5.8 | 6.4 | 8.3 | 4.6 | 2.2 |
| Dam | 5.0 | 2.6 | 4.3 | 5.4 | 4.7 | 4.7 | 3.8 | 3.8 | 2.9 | 6.5 | 4.8 | 2.0 |
| Dam with pumping | 5.4 | 2.7 | 4.6 | 5.7 | 4.9 | 5.1 | 4.1 | 4.4 | 3.6 | 7.1 | 5.2 | 2.2 |
| No dam with pumping | 5.9 | 2.4 | 5.2 | 6.7 | 6.6 | 8.2 | NF | NF | NF | NF | 5.8 | 2.3 |
| *Arid Simulations* | | | | | | | | | | | | |
| River kilometer 101 | | | | | | | | | | | | |
| Natural | 6.7 | 2.0 | 4.2 | 5.4 | 7.4 | 6.8 | 7.3 | 7.9 | 8.6 | 10.1 | 9.2 | 6.2 |
| Dam | 7.1 | 1.6 | 2.6 | 3.4 | 4.4 | 4.5 | 4.9 | 5.7 | 6.8 | 6.7 | 4.9 | 2.7 |
| Dam with pumping | 7.1 | 1.6 | 2.6 | 3.4 | 4.4 | 4.5 | 4.9 | 5.7 | 6.8 | 6.7 | 4.9 | 2.7 |
| No dam with pumping | 6.7 | 2.0 | 4.2 | 5.4 | 7.5 | 6.8 | 7.3 | 7.9 | 8.6 | NF | 9.2 | 6.2 |
| River kilometer 51 | | | | | | | | | | | | |
| Natural | 6.3 | 2.2 | 5.3 | 8.4 | 8.3 | 8.0 | 8.8 | 8.9 | 9.5 | 11.3 | 10.5 | 6.9 |
| Dam | 6.4 | 2.5 | 4.7 | 6.0 | 6.0 | 5.6 | 5.3 | 5.7 | 4.1 | 7.1 | 5.6 | 3.1 |
| Dam with pumping | 6.4 | 2.6 | 4.9 | 6.2 | 6.1 | 5.7 | 5.6 | 5.9 | 4.3 | 7.3 | 5.8 | 3.1 |
| No dam with pumping | 6.3 | 2.2 | 5.4 | 8.6 | 8.9 | NF | NF | NF | NF | NF | NF | 7.6 |
| River kilometer 2 | | | | | | | | | | | | |
| Natural | 6.0 | 2.3 | 6.1 | 9.3 | 8.4 | 8.3 | 9.6 | 6.3 | NF | 8.4 | 6.9 | 6.6 |
| Dam | 5.6 | 3.0 | 5.5 | 7.4 | 6.2 | 6.0 | 5.7 | 6.1 | 5.6 | 7.9 | 6.5 | 4.6 |
| Dam with pumping | 5.5 | 3.5 | 6.1 | 8.1 | 6.8 | 7.1 | NF | NF | NF | NF | 11.0 | 5.7 |
| No dam with pumping | 6.7 | 2.3 | 6.4 | 10.9 | NF | NF | NF | NF | NF | NF | NF | 10.0 |

[a]Values are given in degrees Celsius. NF, no flow conditions. River kilometer is the distance from the downstream end of the model grid. The upstream end of model grid and the dam are at river kilometer 110.

day (or a month) can be a function of the flow volume and stage in the stream and available solar radiation. For all the flow scenarios the daily minimum and maximum temperature range increases during low-flow periods (Figures 6a–6c). Having less flow, the stream is less able to act as a thermal storage buffer to dampen the effect of increased solar radiation. Compared to the arid and semiarid scenarios, temperature ranges for the humid scenarios are generally narrow for most months, because magnitude of flow in all of the humid scenarios was greater than those in the arid and semiarid scenarios (Table 2). Total annual solar radiation for Eugene, Oregon, is also less than solar radiation for Sacramento and Porterville, California.

[41] An upstream dam decreases both the daily and monthly minimum and maximum temperature range during the midsummer (Figures 6a–6c and Table 2). Dam flow releases during the summer provide greater flow volumes and stream depths than those that would have occurred under natural conditions, thus reducing diurnal warming and cooling of stream water. Groundwater pumping, with or without an upstream dam for all three climate conditions, has the effect of increasing the temperature range in the summer months, which is also a consequence of decreased streamflows (Table 2).

### 5.5. Groundwater Contribution to Stream Heat Budget

[42] The simulated hourly groundwater inflow thermal effect for the four scenarios (natural, dam, dam with pumping, and dam removed with pumping) and monthly average air-

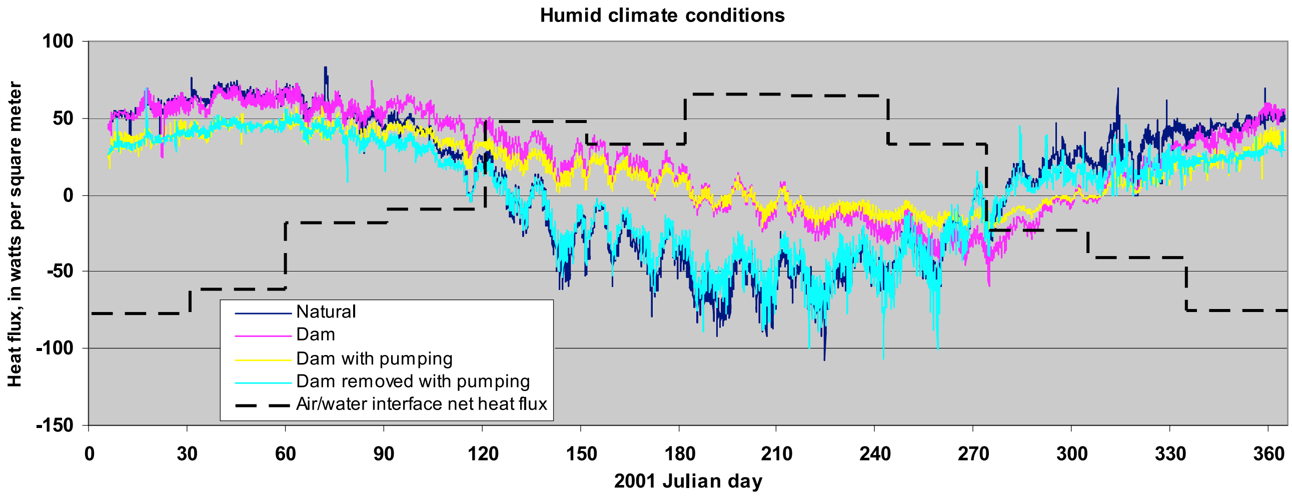


**Figure 8a.** Simulated hourly groundwater thermal effect with monthly average air-water interface net heat flux 2 km above the axis of the valley under humid conditions.

water interface net heat flux (natural flow scenario only) reveals the importance of groundwater to the stream's heat budget (Figures 8a, 8b, and 8c). The air-water interface net heat flux is the sum of simulated short-wave, long-wave, back radiation, evaporative and conductive heat fluxes through the stream air-water interface (indicated by the heavy black dashed line). Negative net heat flux values represent a net loss of heat across the air-water interface during colder months, and positive values represent a heat gain across the air-water interface during warmer months. For one of the semiarid flow scenarios (dam removed with pumping) and three of the arid flow scenarios (natural, dam with pumping, and dam removed with pumping) flows become ephemeral for a period during the year. These periods are indicated in Figures 8b and 8c with horizontal lines.

[43] For all simulated scenarios (Figures 8a–8c), the thermal groundwater effect had a negative relation with the stream's air-water interface net heat flux. During winter months groundwater has a warming effect on the stream (positive values) because the groundwater temperature is greater than the stream temperature. Conversely, in the summer there is a cooling effect (negative values) because the groundwater temperature is less than the stream temperature. Thus, groundwater inflow has a moderating effect on climate induced temperature changes in the stream. A decrease in groundwater inflow to the stream will result in cooler winter stream temperatures and warmer summer stream temperatures. Examination of Figures 8a–8c shows that pumping decreases the groundwater thermal effect resulting in a decrease in winter stream temperatures and an increase in summer stream temperatures for all climate conditions (Figures 6a–6c). These temperature changes are superimposed on larger-scale temperature shifts caused by the presence or absence of the upstream dam and reservoir.

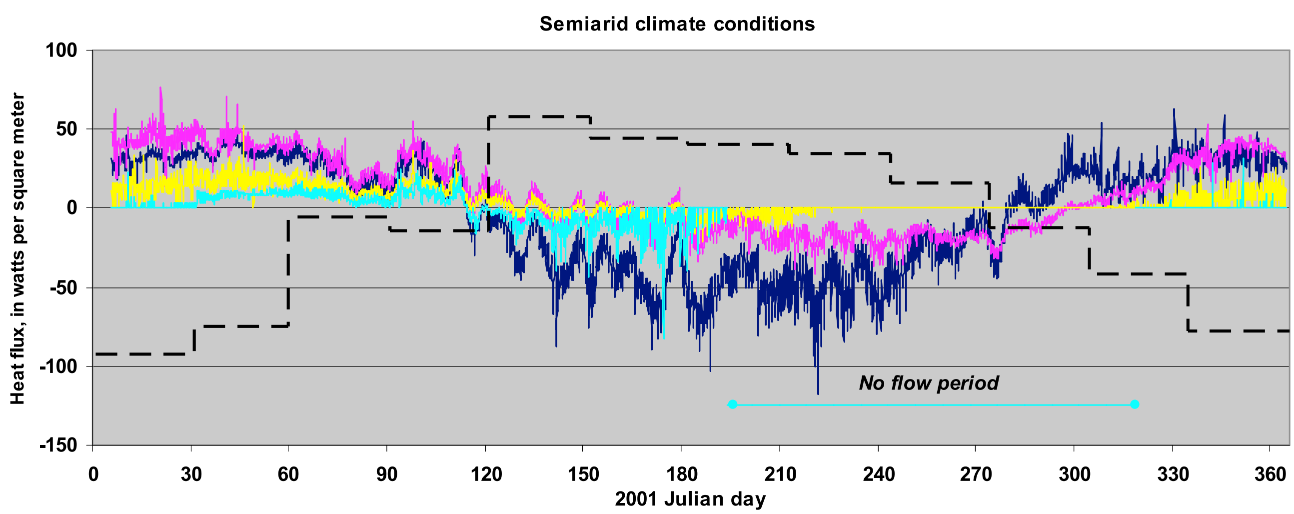


**Figure 8b.** Simulated hourly groundwater thermal effect with monthly average air-water interface net heat flux 2 km above the axis of the valley under semiarid conditions. Horizontal line represents a period when the streambed is dry for dam removed with pumping scenario.

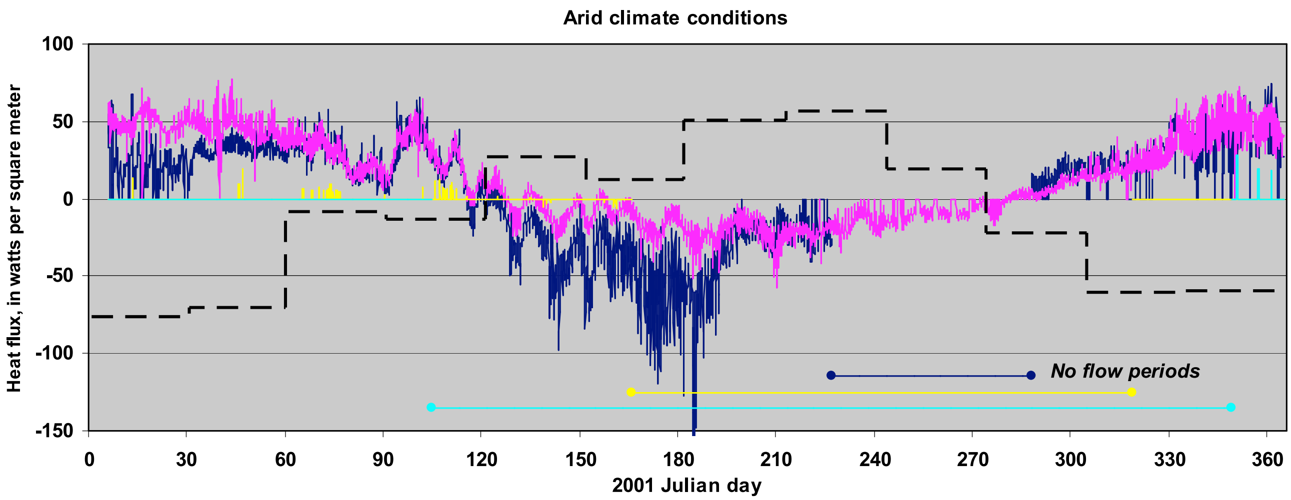


**Figure 8c.** Simulated hourly groundwater thermal effect with monthly average air-water interface net heat flux 2 km above the axis of the valley under arid conditions. Horizontal lines represent a period when the streambed is dry for the natural, dam with pumping, and dam removed with pumping scenarios.

With an upstream dam summer streamflows are unnaturally higher, which in turn reduces the groundwater thermal effectiveness. In the extreme case the groundwater thermal effect becomes zero when pumping causes the stream to become a losing stream and/or become ephemeral (semiarid and arid scenarios with pumping). In a scenario of dam removal with continued pumping, natural stream temperatures will not be restored, not only because of increased heating and cooling caused by the meteorological forcings on a decreased streamflow, but also because of the decreased groundwater thermal effect.

[44] The groundwater thermal effect for all flow scenarios is similar in magnitude to monthly average air-water interface net heat flux, though it would not be similar in magnitude to hourly air-water interface net heat flux since the variability of hourly air-water interface net heat flux values is much greater. This would indicate that the influence of groundwater inflows can be just as, or more, crucial in determining stream temperatures as the net heat flux through the air-water interface interface. The similarity in magnitude may be unique to this study and is a result of the net effect of the modeling assumptions (boundary forcings, bathymetry, shade, etc.) that were used for these simulations. However, the general results demonstrating the importance of groundwater discharge to moderation of stream temperatures remains valid for all cases examined in this study.

## 6. Summary and Conclusions

[45] Though presence or absence of a large upstream dam led to greater changes in stream temperature than the presence or absence of in-reach pumping, ephemeral conditions were increased both temporally and spatially due to pumping. Specifically, model results indicate both groundwater pumping and a large upstream dam produced substantive changes in stream temperature for most months of the year and for most downstream locations in the model grid for the humid, semiarid, and arid watersheds. Stream temperature was impacted to a significantly larger degree by the presence or absence of a large dam versus groundwater pumping, mainly due to the significantly greater alteration of streamflows created by the dam compared with pumping. From March to August, monthly mean stream temperatures increased on average by approximately 3.0°C, 2.5°C, and 2.0°C for humid, semiarid, and arid conditions, respectively with dam removal. The temperature increase is a consequence of the absence of unnaturally cool waters from a hypolimnetic reservoir release point. However, stream temperatures after dam removal generally decreased from September to December by approximately 1.5°C to 2.0°C on average for all three climate conditions, because flows released from reservoirs during the fall months are typically warmer than temperatures found in a naturally flowing stream.

[46] Pump stoppage impacted stream temperatures by increasing discharge to the stream; however, the stream temperature changes were significantly less than changes from dam removal. During the summer, stoppage cooled stream temperatures (generally less than 0.5°C) as additional cool groundwater entered the stream. Alternatively, during the winter, pump stoppage warmed (generally less than 0.5°C) the stream as additional groundwater warmed the surface water.

[47] Details of dam characteristics are paramount in evaluating the importance of a large upland dam with downstream groundwater pumping. Both the absolute and relative impoundment volume of a dam (or dams) is critical to the analysis. Large dams may impound a significant volume of the annual streamflow, while pumping generally represents a smaller volume compared with annual streamflow (though this volume has increasing significance with increasing aridity). Furthermore, different impoundment strategies, such as a series of low-control structures (e.g., check dams), tend to dampen the impacts relative to a large upland dam [*Bartholow et al.*, 2004]. Different reservoir flow release points (hypolimnetic, selective withdrawal, or epilimnetic) might lead to different results with respect to the relative

impact of dams versus pumping on stream temperature, and thus warrants future investigation.

[48] Variations of groundwater thermal effect in response to the presence or absence of an upstream dam versus pumping were analyzed. The simulated hourly groundwater thermal effect for the four flow scenarios (natural, dam, dam with pumping, and dam removed with pumping) to the monthly average net heat flux across the air-water interface (natural flow scenario only) reveals the importance of groundwater to the stream's heat budget. For all scenarios, the thermal groundwater effect had a negative relation to the stream's net surface heat flux. During winter months, groundwater has a warming effect on the stream (positive values) because the groundwater temperature is greater than the stream temperature. Conversely, a cooling effect occurs in the summer (negative values) because the groundwater temperature is less than the stream temperature, such that summer pumping reduced the volume of groundwater discharge to the stream leading to increased stream temperature. However, an upstream dam also reduces the groundwater thermal effect during the summer because of increased streamflow.

[49] Finally, some insights are provided regarding the impact of potential climate change on stream temperatures. As a qualitative example, if humid regions, with similar climatic conditions as Eugene, Oregon, were to become warmer or drier, stream temperature conditions might approach semiarid conditions similar to those currently predicted for Sacramento, California. Likewise, if semiarid regions like Sacramento were to become warmer or drier, stream temperature conditions might approach conditions similar to those currently predicted for Porterville, California. In a more quantitative approach, simulated climate change results from general circulation models could be incorporated into the stream temperature modeling approach used in this study to predict impacts of climate change on future streamflows, developing more defensible predictions than simply comparing two figures already generated in the present study. In future research this modeling approach affords opportunities to determine both impacts of varying anticipated climate changes in humid, semiarid or arid watersheds on future stream temperatures, and the impacts of more site-specific modification to both groundwater pumping and altered operation of large upstream dams on future stream temperatures under varying climate conditions.

[50] **Acknowledgments.** The authors would like to acknowledge and thank Annett Sullivan, U.S. Geological Survey, Portland, Oregon, and Donald O. Rosenberry, U.S. Geological Survey, Denver, Colorado, for their insightful feedback which improved the analysis and the manuscript.

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