Heat as a tracer to determine streambed water exchanges

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[1] This work reviews the use of heat as a tracer of shallow groundwater movement and describes current temperature-based approaches for estimating streambed water exchanges. Four common hydrologic conditions in stream channels are graphically depicted with the expected underlying streambed thermal responses, and techniques are discussed for installing and monitoring temperature and stage equipment for a range of hydrological environments. These techniques are divided into direct-measurement techniques in streams and streambeds, groundwater techniques relying on traditional observation wells, and remote sensing and other large-scale advanced temperature-acquisition techniques. A review of relevant literature suggests researchers often graphically visualize temperature data to enhance conceptual models of heat and water flow in the near-stream environment and to determine site-specific approaches of data analysis. Common visualizations of stream and streambed temperature patterns include thermographs, temperature envelopes, and one-, two-, and three-dimensional temperature contour plots. Heat and water transport governing equations are presented for the case of transport in streambeds, followed by methods of streambed data analysis, including simple heat-pulse arrival time and heat-loss procedures, analytical and time series solutions, and heat and water transport simulation models. A series of applications of these methods are presented for a variety of stream settings ranging from arid to continental climates. Progressive successes to quantify both streambed fluxes and the spatial extent of streambeds indicate heat-tracing tools help define the streambed as a spatially distinct field (analogous to soil science), rather than simply the lower boundary in stream research or an amorphous zone beneath the stream channel.

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1. Introduction

[2] *Vaux* [1968] published a seminal paper on stream water exchange within streambed materials for gravel bed streams that qualitatively predicted a diverse assortment of streambed flowpaths, and formed the foundation for current knowledge of streambed water exchanges. Comprehensive expansion of his work on flow in streambed over a broad class of stream environments has valuable for fields ranging from fishery biology to water law. Until recently, direct quantitative verification of his detailed description of processes, such as "intragravel" flowpaths and morphology-induced streambed exchanges, has been inhibited by lack of robust, automated streambed instrumentation to extensively examine spatial, and especially, temporal flow patterns. For those who have followed, advances in quantitative understanding of streambed processes often required labor-intensive stream and streambed sampling, as well as in-stream spatial surveying [*Bencala et al.*, 1984; *Harvey and Wagner*, 2000; *Gooseff et al.*, 2006], to advance knowledge in areas of transient storage, streambed flow paths, and other characteristics and processes related to conceptual understanding of streambed exchange and quantitative modeling [*Packman and Bencala*, 2000; *Lautz and Siegel*, 2006; *Lowry et al.*, 2007].

[3] Recently, improvements in automated temperature acquisition and simulation modeling afford the opportunity to use existing analysis techniques and long-established expressions for heat and groundwater flow [*Suzuki*, 1960; *Stallman*, 1965], to rapidly expand the use of heat as a tracer to examine streambed water exchanges. *Vaux* [1962, 1968] and numerous more recent researchers [*Constantz et al.*, 1994; *Constantz*, 1998; *Ronan et al.*, 1998; *Essaid et al.*, 2007; *Stewart et al.*, 2007; *Duff et al.*, 2008; *Fanelli and Lautz*, 2008] have in essence characterized streambeds as a distinct sediment type, by defining physical, chemical, or biologically properties unique to the streambed setting. Typically this setting results in large spatial and temporal variations in temperature and hence in exceptional opportunities to use heat as a tracer for tracking the flow of water through the streambed. As a result of these opportunities, researchers are affirming that streambeds represent a spatially quantifiable, distinct sediment type influenced by the overlying stream conditions, in the same sense that soils represent a unique sediment type influenced by their overlying surface conditions. The present work summarizes the theoretical development of heat as tracer in the streambed, describes techniques for measuring and analyzing stream-

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bed temperatures, and concludes with suggestions for future temperature-based research to advance streambed science.

2. Emergence of Heat as a Hydrologic Tracer

[4] Heat flows continuously between surface water, underlying sediments and adjacent groundwater, and for centuries, researchers have appreciated that heat not only travels through stationary water but that heat travels with moving water as well. On the basis of this appreciation, quantitative investigations of simultaneous heat and water flow in porous materials have occurred for at least a century [*Bouyoucos*, 1915], in hopes of using heat as a tracer of water flow. Over the last half century (as summarized in section 3), examination of temperature patterns has provided both qualitative and quantitative descriptions of an array of groundwater flow regimes, ranging from rice paddies to volcanoes. During this period quantitative analysis of heat and water flow was introduced via analytical and numerical solutions to the governing partial differential equations. These quantitative analyses often relied on field measurements for parameter identification and accurate predictions of flow rates and directions. However, field measurements of temperature had to be acquired manually, resulting in sparse data. Early numerical simulation of heat and mass groundwater transport required significant computational resources, which limited modeling to conceptual demonstrations. As a result of these challenges, the use of heat as a tracer of groundwater movement was confined to isolated research projects, which could only demonstrate the feasibility of the method rather than progressing toward routine application. Recently, measurement of temperature and the simulation of heat and water transport have benefited from significant advances in data acquisition and computer resources. The introduction of miniature, single-channel data acquisition devices, capable of insertion in piezometers and other invasive instruments was a key advancement that resulted in rapid proliferation of heat as a tracer in the near stream environment.

[5] Heat is particularly well suited for quantitative investigations of streambed water exchanges for several distinct reasons. Large, dynamic temperature patterns between the stream and underlying streambed are common, owing to large stream surface area to volume ratios relative to many other surface water bodies. Heat is a naturally occurring tracer, free from (real or perceived) institutional issues of contamination associated with the use of chemical tracers in stream environments. The use of heat as a tracer relies on the measurement of temperature, which is an extremely robust parameter to monitor, and now is immediately available as opposed to chemical tracers requiring laboratory analysis. Analysis of streambed temperature data permits augmentation of sophisticated, physically based models addressing streambed exchange [*Lautz and Siegel*, 2006], by enhancing process characterization and parameter identification [*Burow et al.*, 2005; *Niswonger and Fogg*, 2008]. Finally, heat is an intuitive tracer, leading to creative approaches of using heat as a tracer in novel investigations over an expansive range of hydrologic environments.

[6] Both foundation research and broader applications of heat as a tracer in streambeds are summarized below; however, please note several related review papers provide complementary information elsewhere. For a presentation of heat as a tracer of stream exchanges with shallow groundwater, including numerous case studies, see *Stonestrom and Constantz* [2003] and *Blasch et al.* [2007]. For work examining the use of heat as a tracer in wetland environments, with special reference to parameter estimates in groundwater models, see *Hunt et al.* [1996] and *Bravo et al.* [2002] For a comprehensive review of heat as a tracer of general groundwater transport, see *Anderson* [2005].

3. Heat Transfer During Streambed Water Exchanges

[7] The streambed pore space includes both gas and liquid; however, when water is present in the stream channel, heat and water transfer owing to vapor movement through streambed sediments is generally negligible relative to heat and water transfer owing to liquid water movement. This eliminates the need to address the complex processes of nonisothermal vapor dynamics in porous material when describing heat and water movement below streams. Within the streambed, heat is transferred into and through sediments as a result of four heat-transfer mechanisms, radiation, conduction, convection, and advection, which may act simultaneously to create dynamic spatial and temporal streambed-temperature patterns.

[8] Heat conduction occurs as diffusive molecular transfer of thermal energy between the streambed surface and the underlying sediments. Heat convection and advection are often used interchangeably in hydrology, as heat transfer resulting from the movement of water (or air). For the present work, heat convection is defined as heat transfer occurring while water (or air) flows above a streambed of dissimilar temperature. Heat advection is defined as heat transfer occurring while water (or air) flows through the streambed sediments. This distinction is useful for applications of heat as a tracer of streambed water exchange, because it aids in delineating between heat transfers owing to water movement in the streambed (advection) versus water movement above the streambed (convection). Radiative heat transfer occurs while solar radiation is adsorbed by the stream and/or streambed surface. This adsorption leads to rapid temperature changes in dry streambeds, but generally minor changes in streambed-surface temperature beneath flowing streams, owing to reflection at the stream surface and convection of heat adsorbed at the streambed surface. Thus, conduction, convection, advection, and radiations may all contribute to heat transfer across the stream/streambed boundary, but determination of heat advection is the focus for examining heat as a tracer of streambed water exchanges.

[9] Although all four heat transfer mechanisms may occur simultaneously within stream environments, often only one or two mechanisms dominate the resulting streambed temperature patterns. This is because each heat transfer mechanisms occurs in specific, overlapping regions in the stream and streambed, and the magnitude of water fluxes in each region strongly influence heat transfer mechanism occurring in each region. Figure 1 shows a longitudinal view of a stream and streambed with the four significant heat transfer mechanisms depicted passing over or through the streambed. Bidirectional heat-flow vectors for radiative, advective, and conductive heat transfer, indicate these mechanisms transfer heat either into or out of the streambed,

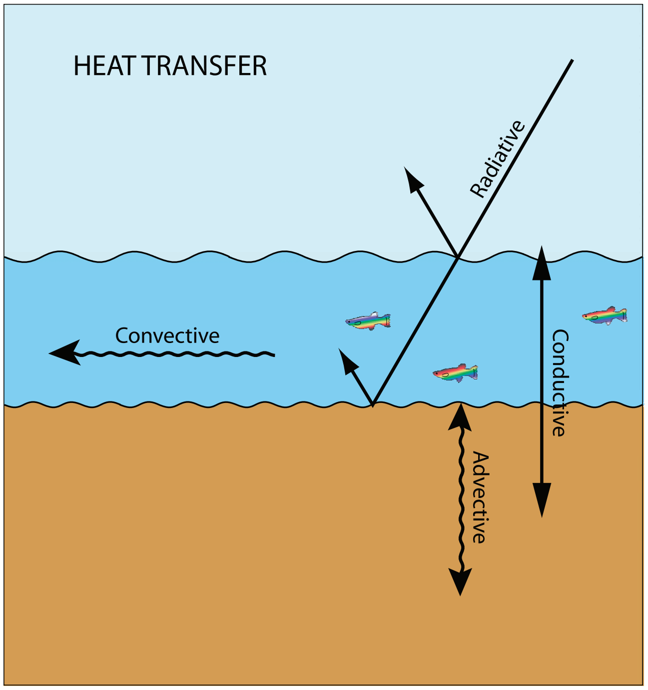


Figure 1. Longitudinal view of a stream and streambed with the four significant heat transfer mechanisms depicted passing over or through the streambed. Note that the bidirectional heat-flow vectors for radiative, advective, and conductive heat transfer indicate these mechanisms transfer heat either in or out of the streambed (graphic by P. McCrory, U.S. Geological Survey).

where as convective heat transfer occurs above the streambed in a downstream direction.

[10] In Figure 1, the cumulative radiative, conductive, and advective heating at the streambed surface is convectively transported downstream toward the left side of Figure 1. Heat conduction is ubiquitous from the stream surface down to any depth in the streambed where a temperature gradient exists, while heat advection is only present in the streambed where flowing pore water is present. Although radiative and convective heat transfers occur at the stream surface and streambed surface, their magnitude may vary widely depending upon stream setting and riparian conditions. For heavy shading over stagnant water, radiation and convection heat transfer are both negligible, while both are highly significant for locations in a flowing stream under full sun. For full sun, streambed-surface temperatures beneath the active channel are virtually identical to overlying stream water as heat is convectively transported downstream, while streambed-surface temperatures in a stagnant area may be significantly higher than temperatures in either the overlying stream or the nearby active channel streambed surface, as a result of the absence or presences of convective heat transfer.

[11] The daily and annual stream temperature oscillations are attenuated and delayed with depth in the streambed sediments, owing to heat absorption and travel time, respectively. The attenuation of temperature oscillations is determined by the bulk volumetric heat capacity of the sediments, as heat is rapidly exchanged at the pore scale. Delay in temperature oscillations is controlled by the net rate of heat transfer, which is dependent on the temperature gradient, thermal conductivity of the sediments and the pore water velocity through the sediments. A greater rate of heat transfer results in a greater depth of penetration of the oscillating thermal surface signal and a shorter delay (lag) in the damped temperature extremes. For losing stream reaches, the oscillating surface temperature signal results in both conductive and advective heat transfer, with higher infiltration rates resulting in greater advection, deeper penetration, and shorter lags in temperature extremes at a given depth [*Lapham*, 1989; *Silliman et al.*, 1995]. For a neutral stream reach (neither gaining nor losing), oscillating surface temperatures result in pure conductive heat transport as molecular diffusion transfers thermal energy. (Thus, if the Fourier equation for conductive heat transfer can explain the temperature patterns within a streambed, there is no stream/groundwater exchange.) For gaining stream reaches, the oscillating surface temperature signal is attenuated at shallow depths owing to upward advection [*Silliman and Booth*, 1993], such that the greater the discharge the greater the attenuation of temperature extremes and the greater the lag in temperature extremes in the sediments. For the special case of purely horizontal water flow through the streambed, vertical conductive heat transfer is often overwhelmed by horizontal advection, such that temperature oscillations are negligible within the streambed.

[12] Figure 2 provides a qualitative description of the thermal and hydraulic responses for four common hydrologic states of a streambed: a gaining stream, a losing stream, a hydraulically disconnected channel, and an ephemeral channel with streamflow [*Constantz and Stonestrom*, 2003]. Within each panel of Figure 2, a hydrograph is depicted on the right, while pairs of thermographs are depicted on the left, representing the diurnal pattern in the stream and streambed temperatures. For the case of a gaining stream as depicted in Figure 2a, the hydraulic gradient is upward as indicated by the positive water pressure in the observation well, relative to the stream stage. The stream is shown with a large diurnal variation in water temperature; however, the sediment temperature has only a slight diurnal variation in temperature. This is due to the inflow of groundwater to the stream, which is generally of constant temperature on a daily basis. Any variation in sediment temperature is a result of a diurnal variation in conductive heat transport and upward advective heat transport. Thus, for a high inflow of groundwater the sediment temperature will have no diurnal variations, while for a slight inflow of groundwater the sediment will have a small diurnal variation in temperature (decreasing with depth). Consequently, shallow installation of temperature equipment (in the observation well or directly in the streambed) is desired for a gaining stream reach, in order to detect significant temperature variations.

[13] Figure 2b depicts a losing stream, in which a downward hydraulic gradient transports heat from the stream into the sediments. The combined conductive and advective heat transport can result in large diurnal fluctuations in sediment temperature. Furthermore, groundwater is not flowing into the stream, so stream-temperature variations are generally larger than those for gaining streams [*Constantz*, 1998]. Consequently, deeper installation of

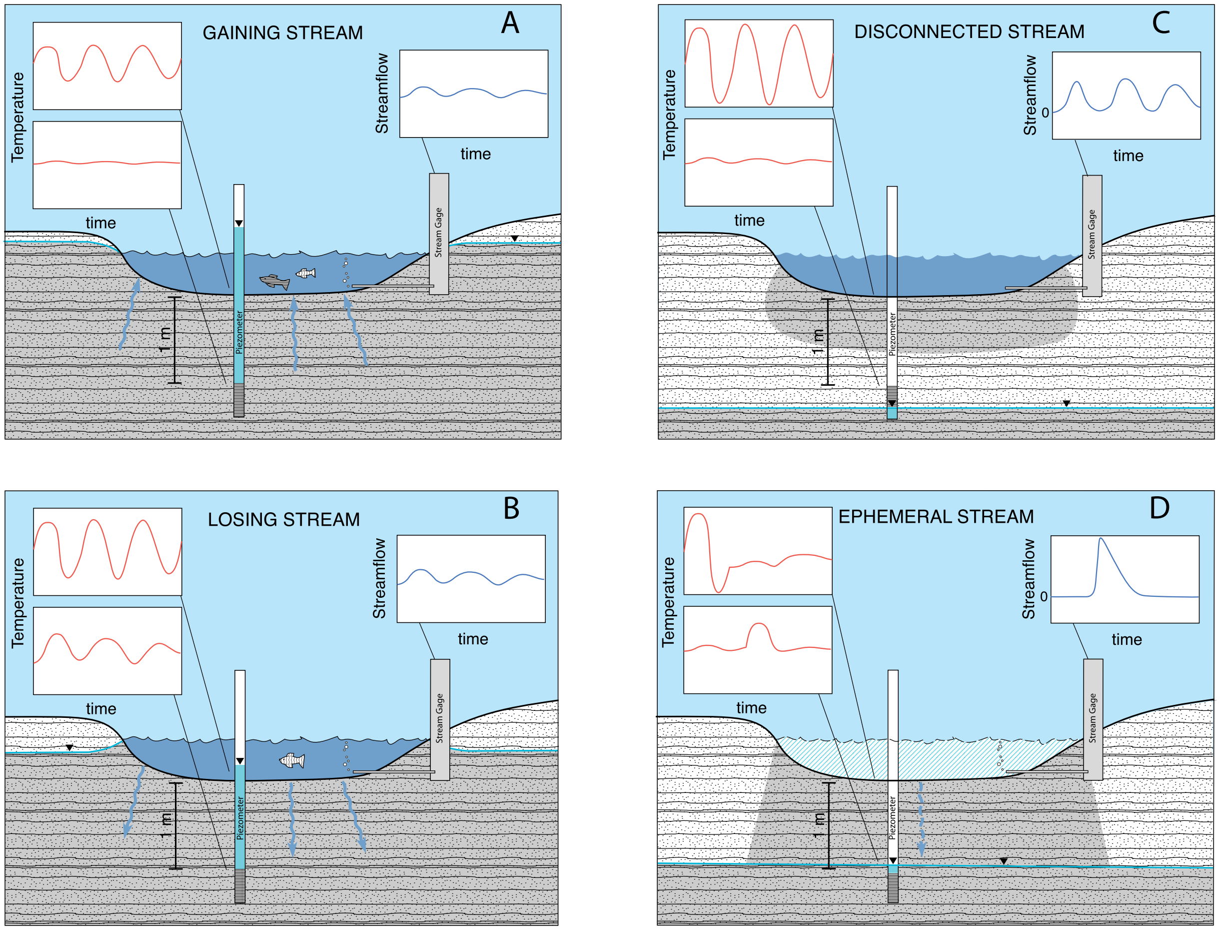


Figure 2. Thermal and hydraulic conditions in streambeds under the influence of streamflow for (a) gaining, (b) losing, (c) disconnected, and (d) ephemeral stream settings. Inset plots of thermographs and hydrographs are located in the upper left and right panels of the figure (modified from *Constantz* [2008]).

temperature equipment (in the observation well or directly in the streambed) may be advantageous for losing streams.

[14] Figure 2c depicts the case in which a lower hydraulic conductivity layer resides in the shallow streambed, resulting in an unsaturated region developing between the shallow saturated sediments and the underlying water table. In this case, the reduced flow of heat and water in the unsaturated zone results in damped thermal signals at depth. However, since loss from the stream channel is controlled by the shallow sediments, larger mean daily temperature amplitude in these sediments creates a larger diurnal variation in streamflow loss, owing to the temperature sensitivity of the hydraulic conductivity of sediments controlling the loss [*Constantz*, 1982; *Constantz and Murphy*, 1991; *Constantz et al.*, 1994].

[15] For ephemeral stream channels, as depicted in Figure 2d, a dynamic temperature pattern exists at the initiation/cessation of streamflow. As a result of air encapsulation (also known as air entrapment) in the streambed [*Constantz et al.*, 1988], the hydraulic conductivity and transmission loss are both reduced, such that hydraulic connection with the water table occurs only during prolonged streamflow events. The observation well remains empty owing to negative pore water pressures, until mounding of the water table results in water entry into the observation well. Radiative, convective, conductive, and advective heat transport all contribute to the rapid responses in streambed surface and underlying sediments, creating abrupt temperature deflections in both surface and streambed thermographs [*Constantz et al.*, 2001].

[16] In the case of a dry channel (not shown in Figure 2), radiative heat transfer is a dominant factor in creating a large thermal signal at the streambed surface, with convective heat transfer potentially moderating the thermal signal if significant surface winds are present in the channel. Heat conduction then controls heat transfer into the streambed and advective heat transfer is virtually absent (since the heat capacity and flow rates of air present in the streambed are exceedingly low). While dry streambed-surface temperature may have a larger diurnal magnitude, the deeper diurnal streambed temperatures are highly damped, as a result of lower thermal conductivities typical for dry material and the lack of significant advective heat transport into the streambed [*Constantz and Thomas*, 1996, 1997]. Also not shown in Figure 2, horizontal water flow through the streambed is often the results of a "flat" water table, lacking a vertical hydraulic gradient. Diurnal stream temperature are damped out in the streambed by horizontal advection of heat, such that streambed temperatures may vary with depth, but temperatures are constant at any depth over time [*Allander*, 2003]. In summary, a streambed may pass through all four thermal patterns depicted in Figure 2, as well as

those patterns described for no flow and horizontal flow, depending on the changing hydraulic conditions. Potentially temporal changes in streambed flow conditions are recognizable and classified from inspection of streambed thermographs without the aid of hydrographs. This may be envisioned by lining up the pairs of thermographs depicted in Figures 2a, 2b, 2c, and 2d horizontally, such that the four pairs form two continuous thermographs for the stream and streambed in a channel progressing from gaining, losing, disconnected, and ephemeral streamflow conditions.

4. Quantitative Analysis Using Heat as a Groundwater Tracer

[17] *Rorabaugh* [1954] examined correlations between stream temperature and seepage patterns and proposed the use of temperature measurement to quantify heat flow, and thus determine streambed seepage indirectly. He indicated that a groundwater model capable of quantifying heat and water fluxes appeared to be the appropriate tool. A physically based, quantitative analysis of heat and water transport through porous materials was introduced by *Philip and de Vries* [1956]. Their analysis resulted in a comprehensive mathematical description of the coupled process of liquid and vapor water transport simultaneous with the transfer of heat in the solid, liquid and vapor phases of unsaturated porous material. Application of their analysis has demonstrated that the transport of heat and water in the vapor phase is often significant in unsaturated soils, and generally dominates in dry environments [e.g., *Scanlon and Milly*, 1994]. As the degree of water saturation increases in sediments, heat transport in the vapor phase abruptly declines as the gas phase becomes discontinuous, and then vanishes as sediments approach saturation [e.g., *Stonestrom and Rubin*, 1989]. As a result, the comprehensive approach developed by Philip and de Vries is unnecessary for analysis of heat and water fluxes in material which is sufficiently saturated to inhibit macroscopic gas flow. Streambed sediments beneath wetted channels are sufficiently saturated to ignore macroscopic vapor transport.

[18] *Suzuki* [1960] and *Stallman* [1963, 1965] were able to use a single-phase approach to predict water fluxes through saturated sediments, on the basis of measured groundwater temperatures. Their work formed the basis for examination of flow in environments ranging from deep groundwater systems [*Bredehoeft and Papadopulos*, 1965] to humid hillslopes [*Cartwright*, 1974]. *Stallman* [1963] presented a general equation describing the simultaneous flow of heat and fluid in Earth. He indicated that groundwater temperatures could be used to determine the direction and rate of water movement. He also indicated that temperatures in combination with hydraulic gradients could be used to estimate sediment hydraulic conductivity. Stallman derived an equation for the simultaneous transport of heat and water through saturated sediments for the one-dimensional case of steady vertical flow, which forms the basis for quantitative analysis of the use of heat as a groundwater tracer. Stallman's equation for the one-dimensional case of vertical flow (z direction) is as follows:

$$\mathrm{K_T}\frac{\partial^2 T}{\partial z^2} - \mathrm{qC_w}\frac{\partial T}{\partial z} = \mathrm{C_s}\frac{\partial T}{\partial t}, \tag{1}$$

where $\mathrm{K_T}$ is the thermal conductivity of the bulk streambed sediments in W/m°C, T is temperature in °C, q is the steady liquid water flux through the sediments in m/s, $\mathrm{C_w}$ and $\mathrm{C_s}$ are the volumetric heat capacity of water and the bulk sediment in J/m^3 °C, respectively, z is depth in m, and t is time in s. The value of q is controlled by the Darcy equation as the product of the hydraulic conductivity, K, in m/s, and the total head gradient, H. When q is zero the equation reduces to the Fourier equation for the transfer of heat by conduction, and when q is large, advection dominates the transfer of heat, as well as the change of temperature throughout the streambed.

[19] Thermal parameters can be estimated given some knowledge of streambed materials. The heat capacity of variably saturated sediments can be estimated by the following:

$$\mathrm{C_s} = \mathrm{f_s}(\mathrm{c_s}\,\rho_\mathrm{s}) + \mathrm{f_w}(\mathrm{c_w}\,\rho_\mathrm{w}) + \mathrm{f_a}(\mathrm{c_a}\,\rho_\mathrm{a}), \tag{2}$$

where $\mathrm{f_s}$, $\mathrm{f_w}$, and $\mathrm{f_a}$ are the volumetric fractions of the sediment, water, and air, respectively, $\mathrm{c_s}$, $\mathrm{c_w}$, and $\mathrm{c_a}$ are specific heats in J/kg °C of the sediment water, and air, respectively, and ρ_s, ρ_w, and ρ_a are the densities in kg/m^3 of the sediment, water, and air, respectively [*de Vries*, 1963]. The product of the specific heat capacity and the density is the volumetric heat capacity, which is approximately 0.8×10^6, 4.2×10^6, and 0.001×10^6 J/m^3 °C for sediments, water and air, respectively [*de Vries*, 1963].

[20] An alternate approach to describe simultaneous heat and water transport through sediments has been to use a three-dimensional (3-D) energy transport equations on the basis of the convective-dispersion equation for simulating solute transport [*Kipp*, 1987]. These coupled heat and water-flow equations are included here as equation (3), (4), and (5).

$$\frac{\partial[\theta C_w + (1-\phi)C_s]T}{\partial t} = \nabla\cdot K_t(\theta)\nabla T + \nabla\cdot\theta C_w D_h \nabla T - \nabla\cdot\theta C_w T q + Q C_w T_s, \tag{3}$$

where θ is percent volumetric water content; φ is sediment porosity, dimensionless; $\mathrm{D_h}$ is the thermomechanical dispersion tensor (defined below), in m^2/s; q is the water flux, in m/s, and Q is the exchange rate of a fluid source with temperature $\mathrm{T_s}$. The left side of the equation represents the temperature change in the variably saturated volume over time. The first term on the right side represents the heat transport owing to heat conduction, the second term accounts for thermomechanical dispersion, the third term represents advective heat transport, and the final term represents heat sources or sinks to water movement into or out of the volume. As an extension of the work by *Buckingham* [1907], the flow of water through variably saturated sediments is described by *Richard* [1931] as follows:

$$C(h,x)\frac{\partial h(x,t)}{\partial t} = \nabla[K(h,x)\cdot\nabla H(x,t)] \tag{4}$$

where C is the specific moisture capacity in m^{-1}, h is the water pressure in m, K is the hydraulic conductivity in m s^{-1}, H is the total head in m, x is length in m, and t is time in s.

[21] The thermomechanical dispersion tensor is defined as [*Healy*, 1990]:

$$D_h = \alpha_T |v| \delta_{i,j} + \frac{(\alpha_l - \alpha_t) v_i v_j}{|v|}, \tag{5}$$

where α_l, α_t are longitudinal and transverse dispersivities, respectively, in m; $\delta_{I,j}$ is the Kronecker delta function; ν_i, ν_j are the ith and jth component of the velocity vector, respectively, in m/s.

[22] Sediment thermal conductivity, K_T, varies with texture and degree of saturation; however, for the typical case of saturated sediment in a general textural class, the range of K_T is quite small relative to K. For example, the streambed K_T for a sand channel typically varies between 1.0 and 2.0 W/(m °C), so that the value of K_T can be estimated as 1.5 W/(m °C) ± 0.5 W/(m °C) [*van Duin*, 1963], while the range in K may be several orders of magnitude for that same sand [*Freeze and Cherry*, 1979]. Furthermore, disparities in the magnitude in the range of K_T [*de Vries*, 1963] compared with K [*Moore*, 1939], generally increases with decreasing saturation for all textures. *Niswonger and Rupp* [2000] developed a Monte Carlo procedure to determine the effect of variability in sediment thermal properties and temperature measurement error on predictions of streambed exchange. Their work showed that temperature measurement errors affect the predicted streambed fluxes more than typical errors in sediment thermal properties. Fortunately, recent advances in automated methods to accurately measure water and sediment temperature operationally reduce temperature error.

[23] After the thermal parameters are assigned, flux is estimated via an appropriate heat and mass transport simulation model (discussed in detail below). For many studies the goal is estimates of q, so that streambed-temperature measurements applied to equation (1) or equation (2) have proved useful in determining the rate of water movement through a streambed region of interest. However, the hydraulic conductivity cannot be estimated using this procedure, unless the hydraulic gradient is also measured. This is because hydraulic conductivity values vary over several orders of magnitude for a given sediment texture. For example, even for saturated conditions sand-textured material can vary from hydraulic conductivity values of 10^{-2} down to 10^{-6} m/s [*Freeze and Cherry*, 1979, p. 29]. For a given sand-textured material, as saturation decreased, values of hydraulic conductivity were measured in the laboratory to vary from 10^{-5} m/s to 10^{-10} m/s [e.g., *Constantz*, 1982]. Thus, hydraulic conductivity values cannot be assigned in a similar fashion to thermal parameters, and as discussed below, saturated hydraulic gradients need to measured in addition to sediment temperatures to accurately estimated hydraulic conductivities in streambeds.

[24] Using measured or estimated boundary conditions and thermal and hydraulic parameters, a heat and water transport simulation code is run to predict temperature patterns in stream sediments. For the present application, predicted temperature patterns are matched to measured data using an inverse-modeling approach. Specifically, hydraulic information, such as stream stage is determined, and temperatures are monitored in the stream and streambed, then predicted temperatures are compared with measured temperatures, using trial and error, or a parameter-estimation code to determine simulated fluxes that result in minimum differences between simulated and measured streambed temperatures.

5. Measurement of Stream and Streambed Temperatures

[25] Measurement of temperature gradients in the sediments is required to estimate the rate of heat transfer through the streambed. Measurement of temperature over time at two or more depths within the stream/groundwater system is the minimum temperature data needed to estimate heat and water fluxes in the domain bounded by the temperature measurements. Measurements of hydraulic gradients are required in addition to temperature gradients, when it is desirable to obtain hydraulic-conductivity values as well as water-flux values. For disconnected streams (see Figure 2), a unit hydraulic gradient is generally assumed, which permits estimates of both the flux and hydraulic conductivity without a direct measurement of the hydraulic gradient. Note that accuracy in estimating thermal parameters is sometimes improved through laboratory analysis of sediment samples [*Stonestrom and Blasch*, 2003], especially for variables in equation (2) and equation (4); however, the spatial variability of textures in fluvial environments often diminishes the effectiveness of coring efforts [*Cardenas et al.*, 2004], such that an estimate based on the bulk textural class over the domain of interest may be a more sensible approach.

[26] Operationally, measurements of temperature in the stream environment involve logistical problems, which are generally not encountered in forest or agriculture [e.g., *Jaynes*, 1990]. In the stream environment, fluvial processes create installation challenges that often have to be overcome on a site by site basis. Some streams are wide and shallow with a mantle of boulders, while other streams are deep with steep banks. Furthermore, damage to or loss of temperature equipment, owing to high streamflows, is an issue unique to streams. Equipment and installation procedures are usually site specific, though two common requirements are equipment that is sufficiently durable to high flows and an installation procedure which avoids preferential flow of pore water along the length of the equipment embedded in the streambed. Often, the manner in which temperature is measured may differ for ephemeral channels as compared with perennial channels.

[27] Water and sediment temperatures can be measured directly by inserting a temperature probe (i.e., thermistor wire, thermocouple wire, or platinum resistance thermometer wire) into the medium of interest, or indirectly by inserting the probe to a depth of interest in an observation well. In either case, the selected temperature probe is connected to a data logger. Within observation wells, temperature can be monitored with temperature-logging equipment on a specific schedule such as, hourly, daily, monthly [see *Lapham*, 1989], or temperature can be continuously monitored at fixed locations within the observation well, using either a series of temperature probes at specific depths, or using a series of single-channel, submersible microdata loggers tethered at several locations in the observation well [see *Bartolino and Niswonger*, 1999]. There has been some concern about heat conduction down

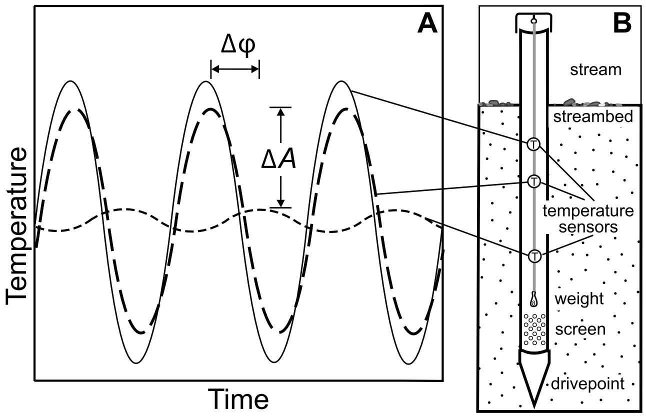


Figure 3. (a) Three hypothetical streambed thermographs graphed over three days, showing phase shift ($\Delta\varphi$) and difference in temperature amplitude (ΔA), and (b) a typical temperature acquisition assembly inside a piezometer (modified from *Hatch et al.* [2006]).

the steel casing of observation wells, and *Lapham* [1988] suggested that at least the first meter below the streambed may be influenced by this issue at upper boundary. However, more recent field observations indicate the depth of influence is shallower, and negligible with plastic well casing and when heat advection is significant [*Constantz et al.*, 2003a; *Constantz*, 2008]. *Alexander and MacQuarrie* [2005] examined the influence of well-casing material on sediment temperature using laboratory, field, and numerical simulation analysis, and concluded that typical piezometer and standpipe casing materials did not affect sediment temperatures. Another concern has been the development of a convection cell within observation wells, which would redistribute heat within the observation well. In geothermal investigations, *Sammel* [1968] calculated a convection cell 0.5 m in length could be established at the top of the water column during periods of large upward thermal gradients of 10°C m^{-1}. For the case of extreme thermal gradients, a series of baffles within in the well length or a well seal below the elevation of the water table inhibit the potential for circulation in the well. For large upward hydraulic gradients,, water in observation wells may stand exposed at a meter or more above the ground surface, creating a thermal gradient that results in periodic mixing or "turnover" of the water column in a similar fashion to that observed naturally in lakes on a larger scale. Capping the well at the ground surface prevents this problem.

[28] Observation wells are generally air filled in ephemeral stream channels, leading to concerns regarding potential lags between diurnal sediment temperature changes and measurements in the air-filled observation well owing to the extremely low thermal conductivity of the air cavity. As a result of this concern, several approaches have been examined. For flowing ephemeral channels, temperature sensors were inserted down a hollow-stem-auger drill hole, and as the drilling stem was raised, streambed sediment collapsed into the hole, thus inhibiting preferential flow [*Thomas et al.*, 2000]. For dry stream channels, temperature sensors were installed in a similar fashion, though backfilling with either native materials or with diatomaceous Earth was required to inhibit preferential flow next to sensors [*Bailey et al.*, 2000]. However, for deeper installations of 10 m or more, where sediment temperature changes are more gradual, *Izbicki and Michel* [2002] found temperature sensors suspended in air-filled boreholes provided accurate measurements of surrounding sediment temperatures, yielding a least squares regression line with a slope and R^2 of 1.0 and 0.99, respectively. Relatively shallow instrumentation may also be installed horizontally from a trench excavated along the stream bank, which eliminates concerns related to instrument-induced thermal boundary effects near the ground surface [*Ronan et al.*, 1998]. A detailed description of numerous options for deployment and monitoring of sediment temperature is given in the work of *Stonestrom and Constantz* [2003]. Extensive information is available concerning optimal depth for temperature measurements, on the basis of criteria including streamflow characteristics, and thermal and hydraulic properties of fluids and sediments of interest in a specific stream channel [*Blasch et al.*, 2004]. Note there has been a similar efforts to use heat as a tracer of exchanges in lakebeds [*Lee*, 1985]; however, prominent thermal differences exist between sediments typically found in lakebeds compared with streambeds, including significantly lower bulk densities and specific heat capacities in lakebed sediments owing to stagnant water and higher organic matter, respectively, yielding significantly lower volumetric heat capacities in lakebeds.

6. Visualization of Streambed Temperature Patterns

[29] Visualization of physical, chemical, or biological parameters leads to intuitive or semiquantitative interpretations, by examining plots constructed from observed or simulated data. Traditionally in hydrology, hydraulic-gradient and water table maps have been valuable visualization tools to aid in understanding the flow of groundwater. With the advent of automated temperature acquisition, researchers throughout the scientific community have graphically visualized temperature data at increasing frequency. Colorful plots mapping specific colors to temperatures or temperature ranges are now ubiquitous in science, and especially common in the biological and Earth sciences. In studies using heat as a tracer of streambed water exchanges, streambed-temperature patterns are most commonly visualized as thermographs (continuous temporal changes), temperature envelopes (periodic temporal and spatial changes), or temperature contour plots (mapped temporal and spatial changes), for the purposes of developing conceptual models, determining model boundary and initial conditions, detecting preferential flow paths, and optimal positioning of proposed instrumentation.

[30] Figure 3a gives an example of hypothetical streambed thermographs for three depths graphed over three days, showing the phase shift ($\Delta\varphi$) and amplitude difference (ΔA) between specific depths shown in Figure 3b. Thermographs are the most common visualization of temperature patterns, representing a direct output of the time and temperature values logged, and providing a temperature history for one location. Comparison of multiple thermographs with defined spatial relation within a physically characterized space forms the basis of heat tracing.

[31] Figure 4 shows hypothetical temperature envelopes composed of streambed-temperature profiles for both a

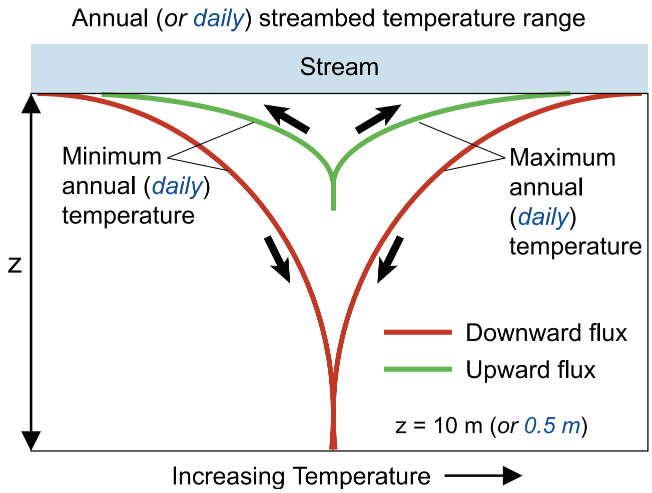


Figure 4. Hypothetical temperature envelopes depicting the extreme high and low annual (or daily) temperature profiles propagating downward into homogeneous sediments from the streambed surface in the absence of nonvertical flow components (modified from *Constantz and Stonestrom* [2003]).

gaining stream (upward water flux) and a losing stream (downward water flux) over either annual or daily cycles, depending on the depth of interest. The temperature profiles for the annual (or daily) extremes forms the temperature envelope within which all temperature profiles for other times reside. When groundwater is discharging to the stream, the annual envelope visually collapses upward toward the streambed surface, and when the stream is rapidly losing water to the sediments, the envelope visually expands and extends to greater depths. A similar pattern exists in the shallow streambed on a daily timescale, with the dawn and afternoon temperature profiles forming the daily envelope, in which all other hourly temperature profiles reside. A range of temperature envelopes for various spatial and temporal scales is discussed in the work of *Constantz et al.* [2003b]. Additionally, nonvertical flow and/or stratigraphy in the streambed result in depth-specific secondary features in temperature envelopes [*Bartolino and Niswonger*, 1999].

[32] Advanced methods for visualizing heat in the streambed broaden or blend spatial and temporal temperature information. Figure 5 portrays a suite of temperature contour (TC) plots with extensive supporting information. On the basis of the spatial extent of temperature data, TC plots can be one-, two-, or three-dimensional plots. Figure 5 contains several 2-D TC plots depicting isothermal regions in a streambed over two clear days for a study site on the Santa Clara River (CA). At the top of Figure 5, the measured stream temperature is depicted in a single 1-D TC plot, above a set of three 2-D TC plots depicting simulated streambed temperature patterns for gaining, neutral, and losing hydraulic gradients. These simulation temperatures were generated using data shown in the 1-D TC plot and measured hydraulic data input into a heat and groundwater transport model VS2DH [*Healy and Ronan*, 1996]. A shaded relief map located in the center of Figure 5 shows the Santa Clara River study reach, with an insert of the location of the five temperature-monitoring sites. Below this a bar graph provides synoptic streamflow patterns at specific locations at and between the five sites, on the basis of differential discharge measurements. At the bottom of Figure 5, measured stream and streambed temperatures are depicted in a pair of 1-D and 2-D TC plots, respectively, for sites 5 and 3. Note the measured TC plot for the discharge (gaining) case at site 3 documents warmer streambed temperatures than predicted in the simulated TC plot for gaining conditions at the top of Figure 5, indicating the simulated lower-temperature boundary conditions were set below the actual groundwater temperatures. Also note that comparison of the 1-D TC plots for sites 5 and 3, indicates the diurnal range in measured stream temperature for site 3 is moderated by gaining conditions, as predicted in Figures 2a and 2b.

[33] Recently, 2-D TC plots were constructed from another perspective, in which time is plotted on the vertical axis and distance longitudinally down the stream channel is plot on the horizontal axis [*Selker et al.*, 2006a, 2006b]. This type of TC plot creates longitudinal temperature visualization over time from an entire stream reach, such that, thermal impacts of focused discharge, tributary inflows, and riparian cover are clearly depicted over time. Unlike thermographs and temperature envelopes, which are constructed to facilitate best fits of simulated temperatures, TC plots are typically constructed to identify temporal and spatial patterns of stream exchanges with shallow groundwater, and to clarify streambed processes of site-specific importance. This type of visualization is often enhanced by postprocessing a series of TC plots into a motion picture of migrating TC plots over time, colorfully depicting the impact of stream exchanges with shallow groundwater on temperature patterns throughout the streambed. As discussed later, full 3-D TC plots are leading to improved understanding of complex streambed flow paths created by sediment heterogeneity [*Niswonger and Fogg*, 2008].

7. Application of Heat as a Tracer in Streambeds

[34] A comment on appropriate environments for using heat as a tracer prefaces individual listing and summarizing of five specific applications. A general misperception persists that warmer environments are required for application of heat as a tracer for estimating streambed exchanges. This notion may be related to the volume of work reported from studies in the southwestern United States, starting with *Constantz and Thomas* [1996] and most recently *Stonestrom et al.* [2007] However, as expressed in equation (1), (3), and (4), spatial and temporal contrasts in

Figure 5. Simulated and measured streambed temperature contour (TC) plots for two daily cycles beneath a site on the study reach of the Santa Clara River, California. Measured stream temperature and simulated 2-D streambed TC plots for gaining (upward), neutral, and losing (downward) conditions are shown in the upper plots. The site map and spatial distribution of measured streamflows during October 1999 are shown in the center. Measured TC plots for sites 5 and 3 are shown in the lower plots (modified from *Constantz et al.* [2003c] and *Stonestrom and Constantz* [2004]).

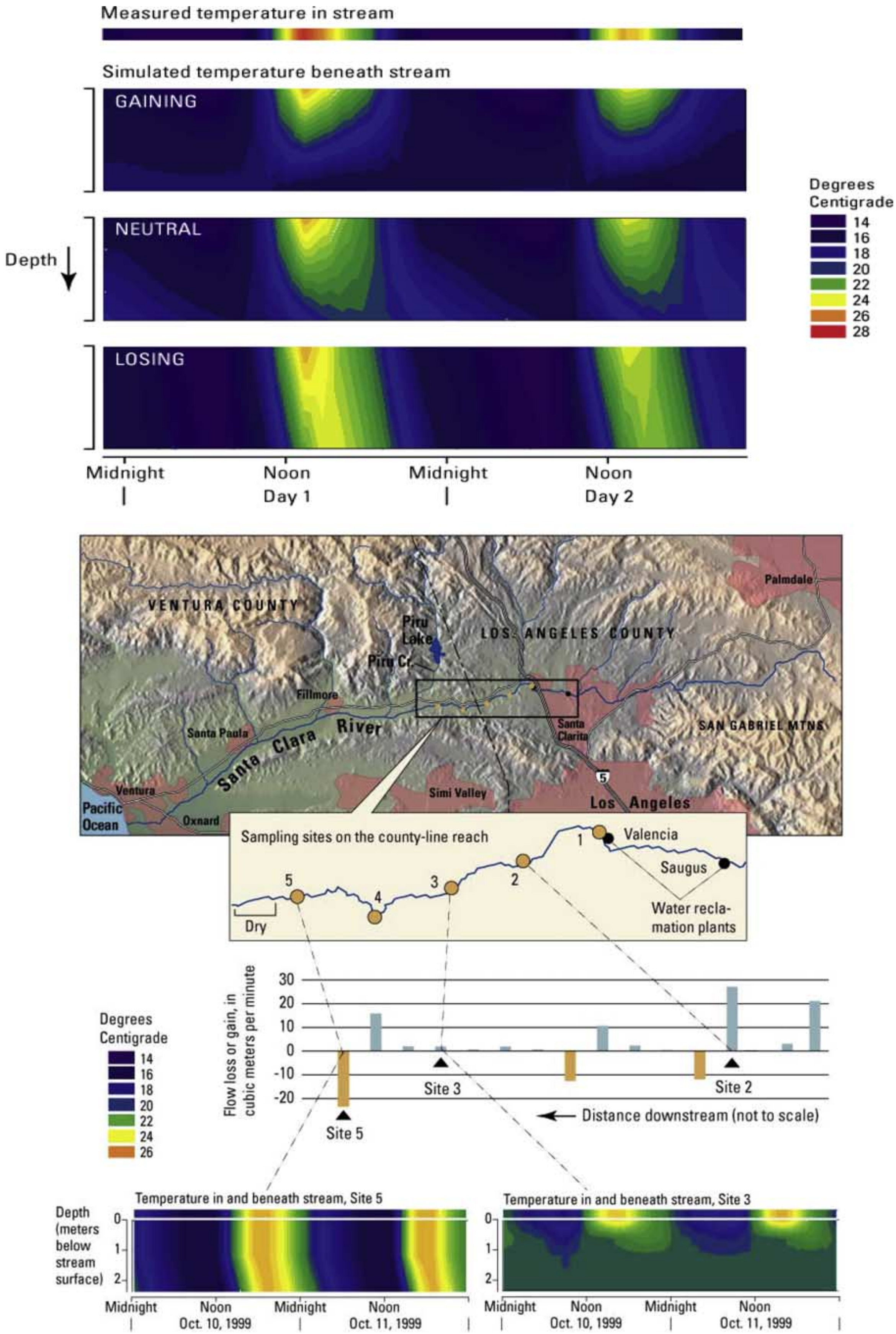

Measured temperature in stream
Simulated temperature beneath stream
GAINING
NEUTRAL
LOSING
Depth
Degrees Centigrade
14
16
18
20
22
24
26
28
Midnight
Noon
Day 1
Midnight
Noon
Day 2
VENTURA COUNTY
LOS ANGELES COUNTY
Piru Lake
Piru Cr.
Palmdale
Fillmore
Santa Paula
Santa Clara River
Santa Clarita
SAN GABRIEL MTNS
Ventura
Pacific Ocean
Oxnard
Simi Valley
5
Los Angeles
Sampling sites on the county-line reach
1
Valencia
Saugus
2
3
4
5
Dry
Water reclamation plants
Degrees Centigrade
14
16
18
20
22
24
26
Flow loss or gain, in cubic meters per minute
30
20
10
0
-10
-20
Site 5
Site 3
Site 2
Distance downstream (not to scale)
Temperature in and beneath stream, Site 5
Temperature in and beneath stream, Site 3
Depth (meters below stream surface)
0
1
2
Midnight
Noon
Oct. 10, 1999
Midnight
Noon
Oct. 11, 1999

Figure 5

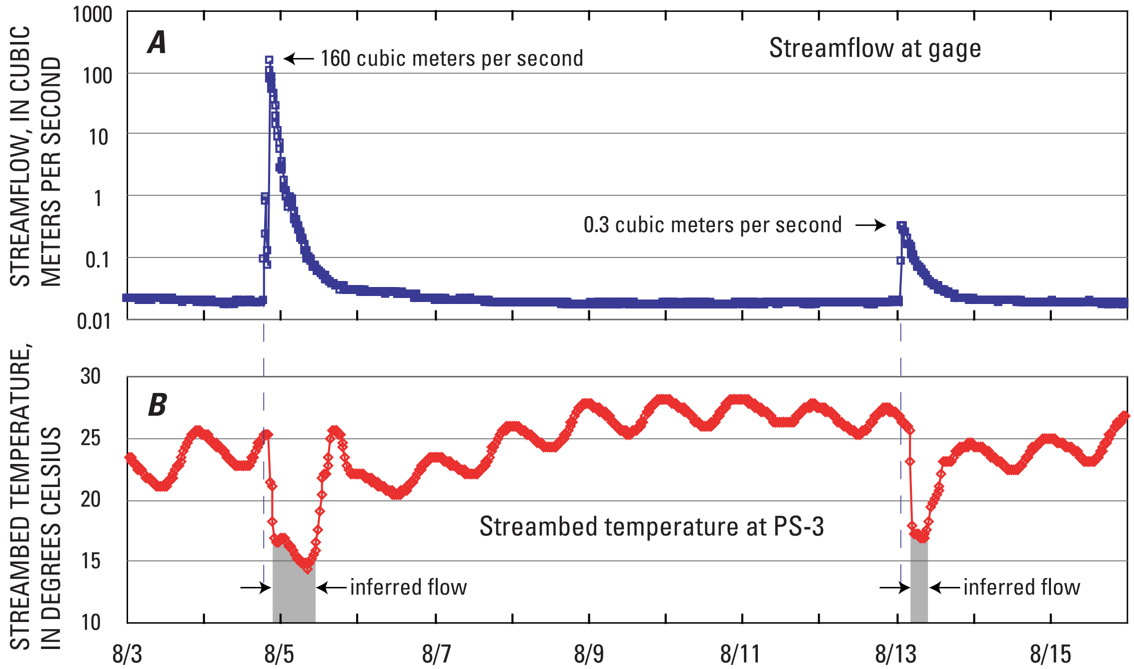


Figure 6. (a) Streamflow hydrograph at Abo Arroyo (USGS gage 08331660) and (b) streambed thermograph at a probe site 2.6 km downstream, 3–16 August 1998. Shaded areas on the thermograph indicate periods of inferred streamflow reaching the probe site [from *Stewart et al.*, 2007].

temperatures are the critical criteria rather than mean temperature, such that heat as a tracer is more clearly applicable in mid to northern latitudes than near the equator, where pseudoisothermal conditions often create subtle and difficult to resolve streambed-temperature contrasts.

7.1. Analysis of Stream Data to Evaluate Streambed Exchanges

[35] In the absence of temperature and hydraulic information in the streambed, comparisons of stream thermographs and streamflow hydrographs often aid in evaluating streambed exchanges. *Constantz* [1998] examined stream temperature and streamflow patterns on the Truckee River (CA), and its tributaries to demonstrate the use of stream-temperature analysis to determine spatial and temporal patterns of exchange in selected reaches. Following a three-week July dam release, residual "damping" in downstream thermographs suggested significant transient storage discharged from the streambed in an instrumented reach of the Truckee River during flow recession, compared with an instrumented reach of an upstream tributary immediately below the dam, see *Constantz* [1998, Figure 10]. Site inspection confirmed the streambed of the Truckee River was composed of alluvial sediments, while the streambed of the tributary was composed of a thin layer of sediment overlying bedrock and other consolidated bed material. Also, impacts of evapotranspiration losses compared with temperature-induced streambed losses were estimated by factoring in the temperature-sensitivity of the streambed hydraulic conductivity [e.g., see *Constantz and Murphy*, 1991; *Constantz et al.*, 1994]. Furthermore, simultaneous analyses of stream temperature and streamflow patterns were shown to be useful in analyzing a range of streambed hydraulic issues, such as an estimate of the depth of the controlling layer within the streambed.

[36] In a similar mountain setting, remotely sensed, surface-temperature-based estimates of stream exchanges with groundwater were reported by *Loheide and Gorelick* [2006, 2007]on the basis of a forward looking infrared (FLIR) technique. Using FLIR results, surface temperature patterns clearly demarked the impact of groundwater discharge and transient stream exchanges with the streambed. As another technique with great potential, fiber optic distributed temperature systems (DTS) technique represent surface-based, spatially distributed, automated temperature acquisition techniques, which were recently extended to water resources applications from other Earth science disciplines [*Selker et al.*, 2006a, 2006b]. Together these surface-based techniques indicate that in the absences of direct streambed measurements, analysis of stream thermographs provides quantitative insight into relative streambed exchanges between multiple stream reaches.

[37] In a more economical approach, researchers deployed arrays of individual temperature probes along nonperennial stream channels to analyzed spatial and temporal patterns in streamflow [*Constantz et al.*, 2001]. The streambed-surface-temperature (SST) approach relies on amplitude differences in stream-channel thermographs for dry versus flowing channels. Analysis of these differences permits determination when and where specific seasonal, intermittent, or ephemeral reaches of the channel contain streamflow, on the basis of temperature data retrieved at discrete sites along the channel. Figure 6 compares a streamflow hydrograph (Figure 6a) for channel site located in the upland area of Abo Arroyo (NM), and a SST thermograph (Figure 6b) for a channel site located 2.6 km downstream in an ephemeral reach of the channel. Two brief streamflow events are shown in the hydrograph with the thermograph depicting the corresponding thermal response

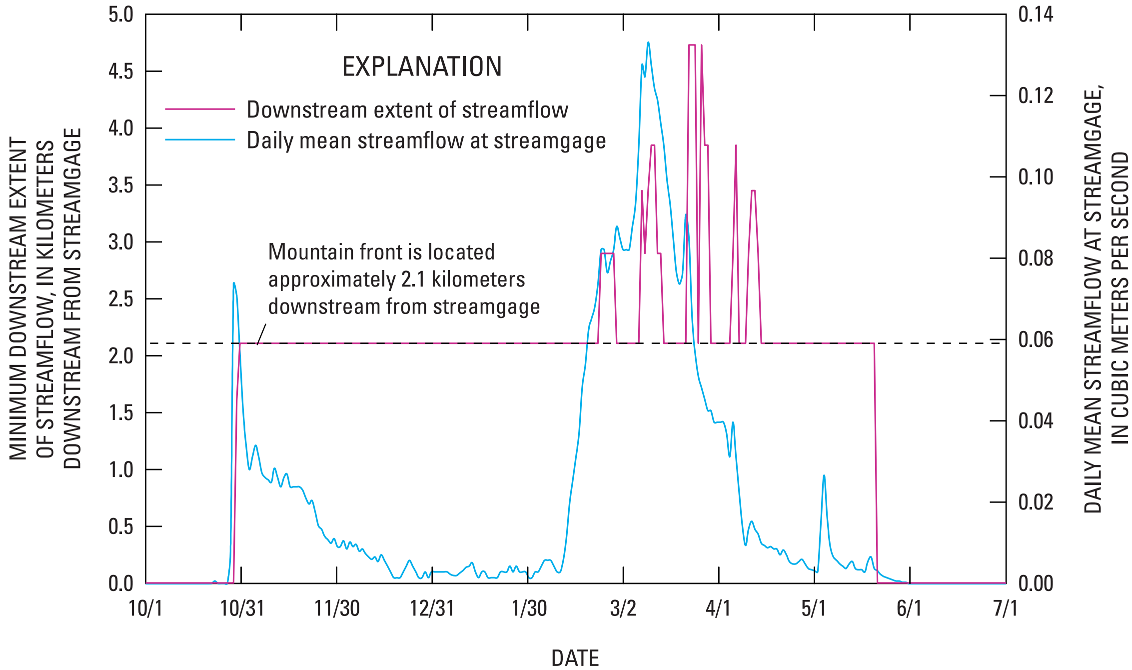


Figure 7. Minimum downstream extent of seasonal streamflow in Arroyo Hondo, New Mexico, compared with the daily mean streamflow at the upstream streamflow station (USGS gage 08317050) over the 2000–2001 seasonal streamflow season [from *Moore*, 2007].

in the shallow sediments near the channel thalweg. A multiyear series of SST thermographs were developed along the channel between eight SST sites from the uplands site and the confluence with the Rio Grande, to determine the spatial and temporal pattern of streamflow along the entire ephemeral extent of Abo Arroyo [*Stewart et al.*, 2007].

[38] In a similar fashion, a series of SST thermographs were analyzed to provide a quantitative measure of the extent of seasonal streamflow downstream from the Sangre de Cristo Mountain Range along Arroyo Hondo, NM [*Moore*, 2007]. Figure 7 provides a plot of SST-based estimates of the minimum streamflow distance downstream of the mountain front compared with streamflow measured at the mountain front over a flow season. In this specific case, the resolution in the temporal streamflow pattern is limited by the sparse number of temperature monitoring locations down channel from the mountain front, i.e., 0.0, 2.2, 3.4, 3.4, and 4.7 km down channel. This technique was broadly applied along a series of mountain-front channels draining in the western Mojave Desert, CA, to estimate the spatial and temperature pattern of intermittent streamflow [*Izbicki*, 2007]. Analysis of SST patterns indicate mountain-front channels are spatially isolated from lower-elevation hydrologic features, such as springs, playa lakes, and the Mojave River, except for brief periods of significant mountain precipitation and/or snowmelt. In an application designed to aid in evaluating the potential for inducing favorable stream habitat conditions for the Santa Ana Sucker (catostomus santanae), *Mendez* [2005] applied the SST approach using temperature data generated in the channel below Lower Big Tijunga Dam in the San Gabriel Mountain Range, CA, to determine the downstream extent of a prescribed dam releases along the seasonally dry channel. On the basis of SST analysis, a dam release of about 0.3 m^3/s required two days to reach the targeted habitat location 10 km downstream of the dam. Overall for this study, SST-based estimates of travel time and transmission loss for specific reaches below the dam complemented other criteria for development of a dam release schedule designed to provide suitable fishery habitat downstream of the dam. Most recently SST analysis provided spatial and temporal streamflow patterns for testing a surface water model designed to investigate heterogeneity in streambed seepage rates in intermittent and ephemeral reaches of the Amargosa River, NV [*Niswonger et al.*, 2008]. On the basis of these successful applications, SST analysis should be available at a significantly higher spatial resolution using either FLIR or fiber optic DTS data acquisition approaches.

7.2. Thermal-Pulse Arrival Time

[39] Measurements of stream and streambed surface temperatures document the impact of streambed fluxes on surface temperatures and spatial patterns of streamflow and provide inferences concerning the direction and magnitude of streambed fluxes, where as temperature measurements at multiple depths within the streambed lead to direct estimates of streambed fluxes. In early analysis of streambed temperature patterns at multiple depths, several researchers developed simplifying assumptions for the general case in which streambed infiltration is rapid. A simplistic, first-approximation approach was suggested for the case where pore water velocities are sufficiently high (e.g., 10^{-3} m/s), such that heat transport by conduction is negligible compared with heat transport by advection [*Constantz and Thomas*, 1997]. This case is typical during flow events in many ephemeral streambeds (see Figure 2d), and common in perennial streams with permeable streambeds. For those cases where conduction is small compared to

advection, the left term in equation (1) can be ignored, such that water flux is approximated by:

$$\mathbf{q} = \mathbf{V_T}\,\frac{Cs}{Cw}, \tag{6}$$

where V_T is the propagation velocity of the temperature peak (also known as "wave" or "front") down into the streambed sediments. This simplification was tested in laboratory columns [*Taniguchi and Sharma*, 1990] and an artificial recharge basin [*Cartwright*, 1974]. *Constantz and Thomas* [1996, 1997] applied this simplification at Tijeras Arroyo, New Mexico, by monitoring temperatures between the surface and a depth of about 3 m during ephemeral streamflow events [*Thomas et al.*, 2000]. *Stewart* [2003] examined the error in using results from equation (6) compared with equation (1) by generating sediment temperature patterns from VS2DH simulations, and applying equation (6) to the simulated temperature patterns. Good agreement resulted for higher streambed fluxes, but results from equation (6) overestimate simulated fluxes by 30% at fluxes lower than 10^{-5} m/s (as heat conduction progressively contributes proportionally more to total heat transported).

[40] A comparison of V_T with the propagation velocity of a conservative chemical tracer, V_C, is possible by expanding equation (6) as follows [*Blasch et al.*, 2007]:

$$V_c/V_T = 1/\theta\left(\frac{Cs}{Cw}\right). \tag{7}$$

The propagation velocity of a conservative chemical tracer will thus exceed that of the temperature signal by a factor of about two, depending on the magnitude of the volumetric water content, θ. This has implications in tandem tracer analysis, as discussed below in section 8.

7.3. Temperature Time Series Analysis

[41] *Silliman and Booth* [1993] and *Silliman et al.* [1995] used time series analysis of stream and sediment temperature patterns in Indiana to identify losing reaches. In a similar fashion to *Suzuki* [1960] working in rice fields, these researchers used a one-dimensional solution to equation (1), with an assumed sinusoidal temperature pattern for upper boundary condition. *Silliman and Booth* [1995] examined the range of the Peclet number (a measure of advective to conductive transport) for which a solution should be applicable. (See *Silliman and Booth* [1993, p. 106], for the specific values for Peclet parameters selected for a streambed environment.) They concluded that for Peclet numbers of less than 2×10^{-4}, which represents a flux of 8×10^{-8} m/s, that the advective component of the solution is negligible. Thus, this approach may not be useful for very low water fluxes found in streambed environments with extensive clay textured streambeds and/or very low hydraulic gradients. *Hatch et al.* [2006] developed a time series analysis for determining streambed seepage rates using changes in phase and amplitude of streambed temperatures, as depicted in Figure 3. A unique attribute of the method is its insensitivity to scour and depositional induced changes in streambed elevation, making the method especially attractive for application to data generated from stream reaches with sandy and other unarmored channels. In subsequent work, *Keery et al.* [2007] developed a dynamic harmonic regression technique to process streambed temperature diurnal patterns at multiple depths to develop time series estimates of vertical seepage. These time series methods have particular appeal for cases where good temporal information is available for temperature gradients, but a lack of temporal information is available for hydraulic gradients.

7.4. Analysis of Temperature Envelopes

[42] *Anderson* [2007] provides a concise discussion on insight provided by temperature envelopes to general groundwater physics. Traditional groundwater temperature logging approaches, such as *Boyle and Saleem* [1979], have been extended to the analysis of fluxes beneath streams. Notably temperature envelope analyses have been performed by *Lapham* [1989] and *Bartolino and Niswonger* [1999] to estimate diurnal and annual patterns of stream exchanges with depth in streambed sediments, in which streambed temperatures were periodically logged in observation wells to deep as 50 m below the streambed surface. Temperature logs were processed to construct temperature envelopes by complying streambed temperature profiles for each measurement period, as generalized in Figure 4. The salient differences between annual and daily temperature envelopes is the temperature range and vertical extent, which can be several times greater in magnitude for annual envelopes. See *Lapham* [1988, 1989] for a series of annual and daily example temperature envelopes beneath streams in the eastern United States, and *Bartolino and Niswonger* [1999] for annual envelopes beneath the Rio Grande, NM. Figure 8 provides temperature envelopes for one of the Rio Grande stream sites, showing a more complex pattern than the generalized pattern depicted in Figure 4. Arrival of the minimum and maximum streambed temperatures are delayed from the minimum and maximum periods of daylight owing to the thermal mass embodied in a stream the size of the Rio Grande, which results in a temporal offset in the temperature envelope. Also, the thermal pulse is clearly seen with depth in individual temperature profiles, and stratigraphy is inferred by secondary patterns in individual temperature profiles. Visual inspection allows temperature envelopes to provide qualitative heat tracing inferences; however, analytic or numerical models are employed to yield quantitative fluxes from temperature (as discussed in both the above citations).

[43] Using a method developed for the poorly defined upper hydraulic boundary conditions common for nonperennial channels, temperature envelopes were successfully analyzed to determine both streamflow pattern and channel infiltration estimates for intermittent stream channels along the western edge of the Mojave Desert, CA [*Izbicki and Michel*, 2002]. In this case, annual streambed infiltration was estimated from temperature envelope data using the following relations:

$$q = \sum_{i=0}^{n} \Delta T\,Cs\,L/(Cw\,\Delta Ts), \tag{8}$$

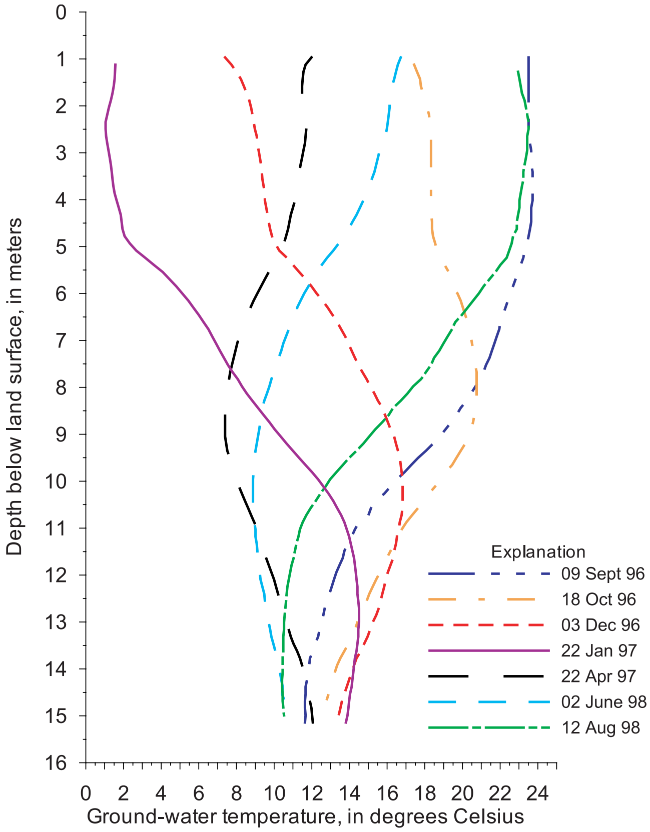


Figure 8. Temperature envelopes for the streambed of the Rio Grande, New Mexico, collected beneath the right (west) bank from September 1996 through August 1998 to a depth of 15 m below the elevation of the streambed surface (modified from *Bartolino and Niswonger* [1999]).

where ΔT is the incremental temperature differences between sediment temperature in/out of the channel with depth, determined from temperature envelopes of length, *L*, and ΔTs is the difference in temperature of infiltrating water and the dry surface adjacent to the channel, with other symbols defined in equation (3). Temperature-based annual channel infiltration estimates decreased with distance from the mountain front and with decreasing water temperature. For the overall study, channel infiltration estimates ranging from 0.85 m/a up channel to 0.13 m/a down channel for water temperatures ranging between 4° and 10°C.

7.5. Physical Simulation Models

[44] Physically based finite difference and finite element simulation models are the most comprehensive and quantitative tool for examining stream exchanges with groundwater, through simple forward modeling with comparison of simulation and observed streambed temperature, or advanced forward modeling with optimization and/or parameter estimation [*Niswonger and Prudic*, 2003]. Several simulation models are routinely cited in the literature as successfully applied using heat as a tracer of stream exchanges with streambed or shallow groundwater, as discussed below. Regardless of which physically based model is applied, the relative uncertainty of hydraulic conductivity relative to thermal conductivity is managed in a similar fashion. For sediments, variations in hydraulic conductivities range over several orders of magnitude, while variations in thermal conductivities are sufficiently small to assign a fixed estimate in the model [*Stonestrom and Constantz*, 2003]. Thus, within simulation models, the thermal conductivity is assigned a value from the literature (decreasing from this value in model-defined manner as a function of sediment saturation), while the hydraulic conductivity is adjusted (manually or through an optimization package) to establish a water flux which minimizes the difference between observed and simulated sediment temperature [*Niswonger and Prudic*, 2003].

[45] Specially designed for near-stream variably saturated environments, VS2DH [*Healy and Ronan*, 1996] is a finite difference, two-dimensional heat and groundwater flow simulation model, which was initially developed for improved understanding of ephemeral stream channel environments, as reported in the work of *Thomas* [1995], *Thomas et al.* [2000], and *Constantz and Thomas* [1996, 1997]. The simulation model was originally designed to examine heat and water fluxes below a stream, such that vapor flow in the streambed was assumed negligible relative to liquid flow in the streambed. VS2DH was first successfully applied using heat as a water tracer for estimates of mountain-front recharge beneath a seasonal stream flowing out of Vicee Canyon in the Carson Range, NV [*Ronan et al.*, 1998]. On the basis of multiple 2-D streambed-temperature cross sections, logged during the initial seasonal streamflow over a three-day period in May 1994, VS2DH simulations successfully estimated streambed infiltration rates compared with measured streamflow-loss measurements. In additions, temperature-based simulated streambed moisture distributions provide insight into patterns of shallow groundwater flow in mountain-front environments. Figure 9 displays broad volumetric-water-content contours in the streambed, for a cross section in which the stream meandered across the mountain-front fan within Vicee Canyon. Though these early graphic results are low resolution, downslope moisture migration is clearly evident, as is an artifact as migrating moisture encountered the right side of the simulation grid on the afternoon of 25 May. Temperature-based simulated moisture patterns provide evidence that as the stream flowed in a northerly direction across the mountain-front fan, shallow groundwater flowed in a more easterly direction toward the axis of Carson Valley.

[46] This work was followed by an application of VS2DH to determination of streamflow losses from the perennial La Bajada reach of the Santa Fe River, NM, in which stream and streambed temperatures were used to estimate percolation rates and compared to losses estimated from a series of streamgaging stations along the reach [*Thomas et al.*, 2000]. After these two introductory studies, the use of VS2DH steadily increased to examine a range of stream environments in which streambed temperature data were available. VS2DH contains a robust solver for highly nonlinear unsaturated hydraulic conductivity changes with pore water content, including a function for the temperature sensitivity of K [see, e.g., *Constantz*, 1982]; however, there is no adjustment for other pore water properties less sensitive to temperature, including water retention [see, e.g., *Constantz*, 1982] or the density of water. In addition, more subtle

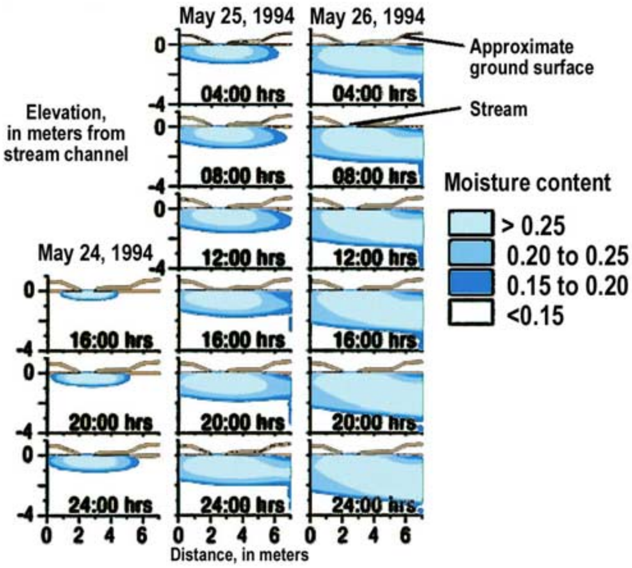


Figure 9. Simulated streambed moisture content (volumetric water content) beneath the stream channel in Vicee Canyon, Nevada, following initiation of seasonal streamflow on 24 May 1994. Simulated moisture contents are based on measured streambed temperatures and VS2DH simulations (graphic by D. Prudic and P. McCrory, USGS).

factors related to water retention, such as rate-dependent retention [*Constantz*, 1993] or isobaric-dependence retention [*Constantz*, 1991] are not included in VS2DH. The considerably larger effect of air encapsulation during initial stages of streambed infiltration and the resulting influence on infiltration rates (as discussed in the work of *Constantz et al.* [1988]) is successfully model with VS2DH. The graphical user interface, VS2DI [*Hsieh et al.*, 2000], was developed to accommodate the demanding boundary and layering conditions common in stream environments, such that large data files for boundary conditions are easily read, and stratigraphic layering and subsequent impact on water retention [see, e.g., *Constantz*, 1995] are easily approximated using VS2DI. The VS2DI interface reads in input values for each recharge or stress period from a file rather than as manual input, creating an efficient automation feature for large temperature files.

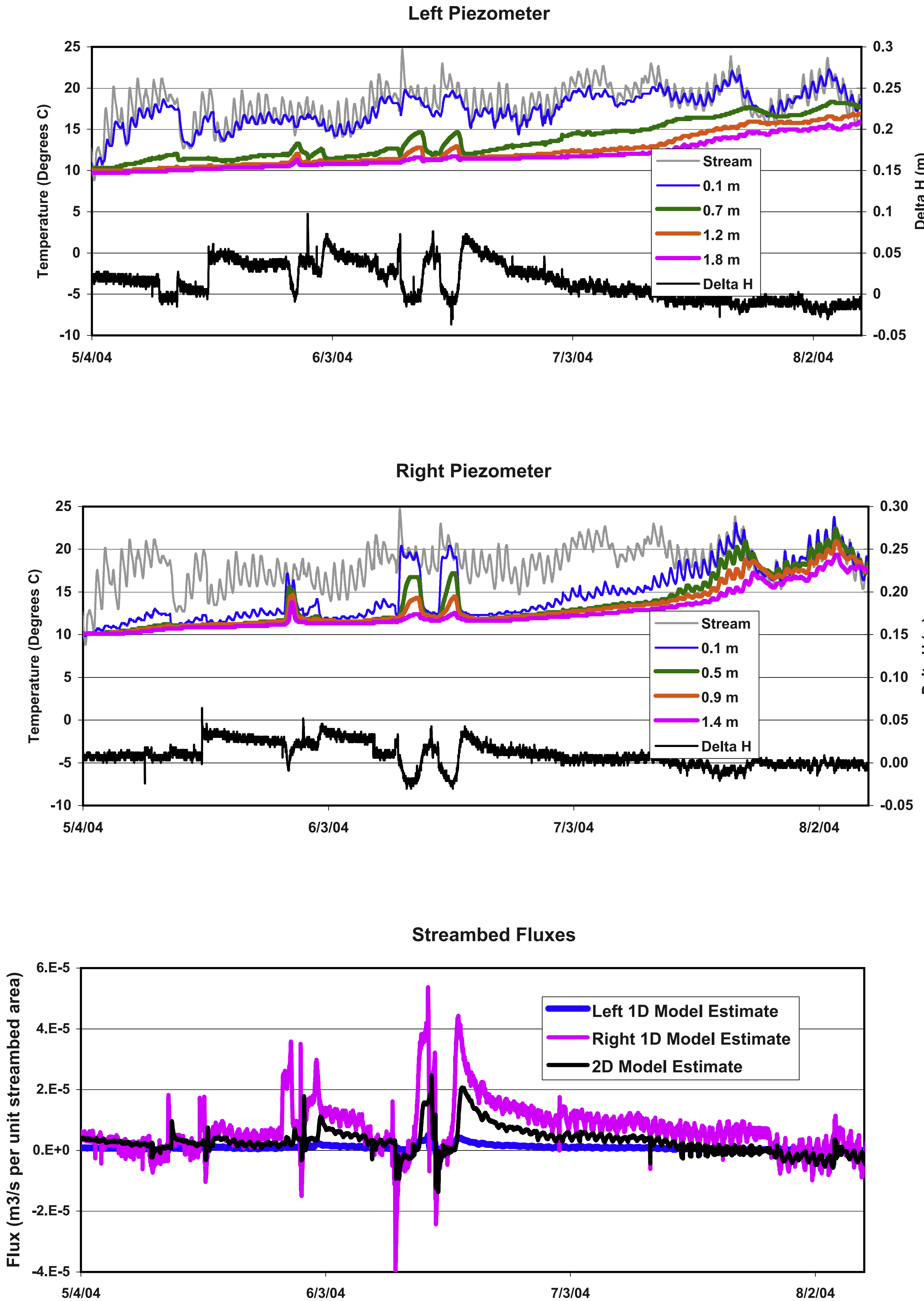
[47] SUTRA [*Voss*, 1990] is a multiphase, finite element, three-dimensional heat and groundwater transport model, primarily developed for saturated conditions, but effectively simulates unsaturated conditions for the case where the hydraulic conductivity decreases gradually with decreasing water content. The complex hydrologic flow system beneath islands in California's Delta was quantitatively examined using SUTRA [*Burow et al.*, 2005]. The model incorporated the unique thermal and density properties of peat-dominated sediments, to examine fluxes through the shallow sediment to the regional groundwater system the Delta. TOUGH2 [*Pruess et al.*, 1999] is an integrated finite difference, three-dimensional nonisothermal multiphase heat and groundwater flow model, initially developed to simulate fluxes in geothermal regions and high-level nuclear wasted buried in the deep unsaturated zone. Streambed flow processes were analyzed using TOUGH2 to examine the pattern of pumping-induced desaturation beneath the streambed along the Russian River, California [*Su et al.*, 2007]. The model calibration relied on 1-D and 2-D heat-based estimates of hydraulic conductivities for shallower sediments on the basis of VS2DH simulations [*Su et al.*, 2004], to constrain seepage and hydraulic parameters within the 3-D TOUGH2 model. Most recently TOUGH2 has been successfully used for analyzing streambed fluxes beneath the Consumnes River, CA [*Niswonger and Fogg*, 2008], where the complex streambed heterogeneity and nonperennial streamflow patterns were modeled using streambed temperature data and the versatility embodied in TOUGH2. Other simulation models show encouraging results as well. For example, FEFLOW [*Diersch*, 1998] was successfully utilized to estimate seepage losses below the Truckee Canal east of Reno, NV, on the basis of thermocouple wires installed on an angle from the side to monitor temperatures beneath the aging cement lining of the canal [*Mihevc et al.*, 2002].

8. Innovative Streambed Heat-Tracing Techniques

[48] Currently there is a surge in the use of heat as tracer to examine streambed properties and processes. Areas of emphasis include streambed mapping, identification of spatial and temporal pattern of streamflow, heat-based parameter estimation for surface water/groundwater linked models, indicators of streambed heterogeneity, and influence of bed forms on streambed flow patterns. In an exceptional instrumentation approach, *Conant* [2004] logged 500 streambed temperatures on a tightly spaced 2-D grid and deployed 34 minipiezometers in a short (<100 m) reach of the Pine River, Ontario, Canada, to successfully map the complex streambed flux pattern on the meter scale, with an empirical technique to relate streambed temperatures and fluxes in small piezometers. In expansion of this work, *Schmidt et al.* [2007] applied the 1-D steady state heat flow equation in an analytical approach to the same data set, obtaining values similar to those obtained from the empirical method.

[49] In a study advancing understanding of recharge estimates for the Basin and Range, NV, researchers applied temperature-based estimates of streambed hydraulic conductivity as input into a surface water model, to examine unsteady seasonal streamflow distributions, along the channel of a mountain-front stream at Battle Mountain, NV [*Niswonger et al.*, 2005]. These researchers successfully predicted seasonal streamflow distributions along the channel, using streambed hydraulic conductivities estimated from streambed-temperature patterns from the previous year. In an ephemeral channel in southern Arizona, heat as a tracer was utilized to analyze the relative contribution of multiple, short-duration transient flow events compared with longer, quasi-steady state flow events in reference to cumulative streambed infiltration, demonstrating the importance of streambed stratigraphy in determining cumulative infiltration on the basis of thermal tracking of the wetting front [*Blasch et al.*, 2006].

[50] In a comprehensive exploration of 2-D flow paths, *Essaid et al.* [2006, 2008] examined streambed exchanges in a heavily agriculture-impacted tributary of Sugar Creek,



Left Piezometer
Temperature (Degrees C)
Delta H (m)
Stream
0.1 m
0.7 m
1.2 m
1.8 m
Delta H
5/4/04
6/3/04
7/3/04
8/2/04
Right Piezometer
Stream
0.1 m
0.5 m
0.9 m
1.4 m
Delta H
Streambed Fluxes
Flux (m3/s per unit streambed area)
Left 1D Model Estimate
Right 1D Model Estimate
2D Model Estimate

Figure 10

IN, using multiple nested piezometer to acquire streambed temperature and water level transects across the channel and adjacent stream bank. Streambed temperature patterns at each cross section inferred site-specific stratigraphic layering and resulting details of streambed fluxes along the study reach. For example, at one site the presence of a subsurface clay layer beneath the left piezometer and its absence below the right piezometer were vividly characterized in the temperature data. For this site, Figure 10 shows streambed thermographs and hydraulic gradients down to 1.4 m below the streambed for the left and right piezometer, as plotted in the upper and middle plots, respectively. Detailed inspection of thermographs and hydraulic gradients for the left piezometer revealed larger gradients in both temperatures and water levels than the right piezometer, inferring more resistance to flow of heat and pore water. When vertical 1-D simulated sediment temperature were fit to observed temperatures, the resulting fluxes were significantly greater near the right piezometer. A 2-D model provided estimates of the spatial averaged fluxes across the streambed. Figure 10 also provides (in the lower plot) both 1-D and the 2-D estimates of streambed flux from May to August 2004, with the dynamic impact of the lack of a clay layer clearly visible through the record. *Essaid et al.* [2006] utilized VS2DI output to construct flux vectors and automate TC plots to create animations of changing streambed temperatures in response to directional flux arrows over the entire flow season during 2004.

[51] Researchers are now exploring the use of heat as a tracer to investigate a range of particularly challenging hydrologic environments. A 3-D TOUGH2 analysis was developed for study reach 100 m in length along the Consumnes River, CA [*Niswonger*, 2005], to examine the details of stream exchanges with a highly heterogeneous streambed. During 2004 streambed temperatures were continuously measured at 20 m spacing in the longitudinal direction, 3 m spacing across the channel, and approximately 20 cm spacing to a depth of 8 m into the streambed, to create a sample grid of approximately 400 locations within the streambed. Streambed temperatures were interpolated to an even grid of 1 m by 1 m by 20 cm (vertical) for model comparisons. Figure 11 provides a pair of 3-D TC plots for the entire stream reach, with the Consumnes River flowing above the plot from the upper right toward the left, during the two distinct periods of February and July 2004. For February cooler stream visibly water infiltrates into the warmer subsurface, while for July warmer stream water visibly infiltrates into the relatively cooler streambed. A consistent trend in higher seepage flow paths is suggested in the downstream section of the study reach, as inferred by 3-D CT patterns in both plots. On the basis of interpolated streambed temperature values, Tough2 best fit simulations predicted seepage rates ranging from 1×10^{-8} m/s to 7×10^{-5} m/s progressing from upstream to downstream regions of the streambed, respectively.

[52] In an elegant study examining multidimensional streambed flow paths, a precisely crafted and explicitly visual analysis of the coupling of heat and water fluxes was developed by *Cardenas and Wilson* [2007], to delineate the pronounced effects of channel bed forms on streambed fluxes paths and the resulting streambed thermal patterns even in a homogeneous sand channel. In achieving the highest spatial resolution to date, *Fanelli and Lautz* [2008] analyzed streambed temperatures to infer a mosaic of flowpaths, created by small log dams in Red Canyon Creek, WY. Streambed flowpaths varied spatially from minimal penetration to long-distance flowpaths approaching the same spatial scale as the log dams, which lead to a range of residence times and created heterogeneous streambed biogeochemical transformations in response to the log dams.

[53] As a result of the increasing volume of reports confirming the robust nature and versatility of heat as a tracer of streambed fluxes, a general trend has emerged to co-locate stream and streambed temperature monitoring along with traditional streamflow and water levels monitoring equipment, to leverage thermal and hydraulic data on a regular basis. As summarized by *Constantz et al.* [2007], long-term simultaneous temperature and streamflow monitoring was performed to examine recharge beneath stream channels in the southwestern region of the United States. The region-wide spatial and temporal diversity in seasonal and interannual streamflow-loss patterns was successfully captured through targeted temperature and streamflow monitoring in desert rivers, seasonal mountain-front stream, and ephemeral arroyos throughout the region, to aid in quantifying the influences of climate, geology, and changing land use on trends in groundwater recharge. During and after strong El Nino climatic conditions, time series analysis quantified cumulative channel loss, and documented a region-wide pronounced decrease in winter stream-channel recharge, but the persistence of summer (monsoon) stream-channel recharge in the southern most areas of the region.

[54] Tandem tracer comparisons between heat and other groundwater tracers may provide coupled insight into flow paths and textural stratigraphy, beyond that possible from a single tracer. Although variations in chemical tracers are less ubiquitous and more difficult to analysis than temperature variations, conservative tracers travel faster and further than heat, as indicated in equation (8). These characteristics potentially broaden the spatial field of investigations nears streams. Also, differential absorption of nonconservative chemical tracers compared with heat may vary as a function of sediment texture, thus permitting insight into the presence or continuous nature of stratigraphic layers. In an initial examination of tandem tracers on the Santa Clara River (CA), heat and bromide streambed exchange suggested both textural nonuniformity and associated nonvertical flow, which was not indicated by individual examination with either tracer [*Constantz et al.*, 2003a]. As a consequence, parameters traditionally collected for

Figure 10. Stream and streambed temperatures and hydraulic gradients (shown lower in each plot) from the left and right piezometers in Leary Weber Ditch, Indiana, are plotted in the upper and middle plots, respectively (modified from *Essaid et al.* [2008]). Also shown are modeled 1-D streambed flux estimates from temporal temperature and hydraulic gradients in each piezometer, and model 2-D streambed flux estimates from gradients in both piezometers, with positive and negative fluxes indicating upward and downward fluxes, respectively (modified from *Essaid et al.* [2006]).

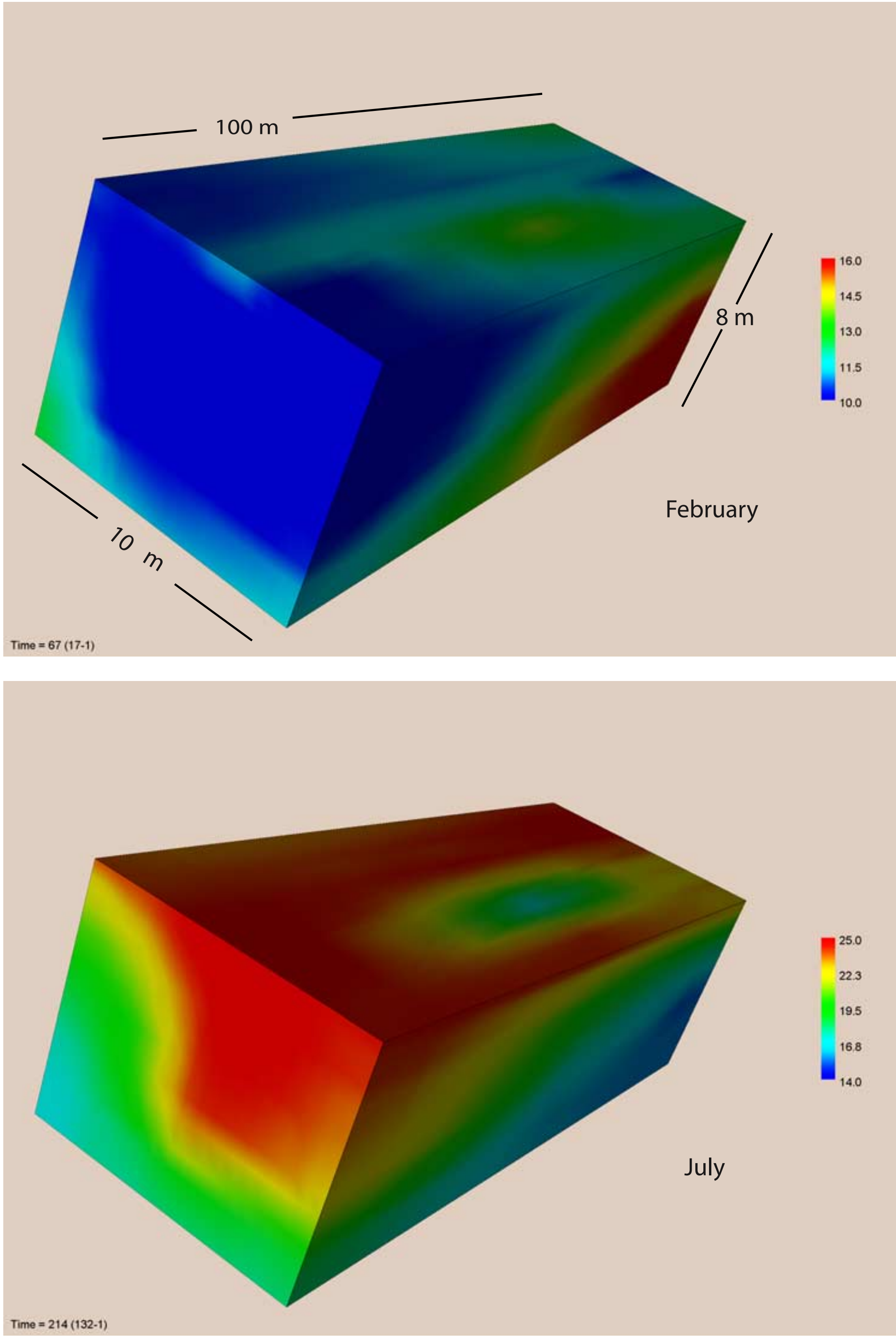


Figure 11. A pair of instantaneous 3-D streambed TC plots for early February and early July 2004 beneath a flowing reach of the Consumnes River, California, based on interpolation of a series of thermocouple cross-sections. The upper surface of TC plots denotes the streambed surface, with the stream residing above this surface, flowing from the upper right corner toward the left along the 100-m axis (modified from *Niswonger* [2005]).

water-quality purposes, including temperature, chloride and electrical conductivity, are being investigating for their potential as tandem tracers. In an initial study, *Cox et al.* [2007] analyzed a suite of regulator-mandated water-quality data (including temperature) collected on the Russian River (CA), and discussed several specific sites where tandem-tracer analysis significantly augmented heat tracing alone. For example, best fit VS2DH simulation results indicated sediment hydraulic conductivities were high at a specific stream site but simulated fluxes were anomalously low; however, chloride and EC results confirmed a long residence time at this specific site. *Stewart et al.* [2007] examined heat, chloride, and bromide patterns in streambeds and adjacent soils to estimate spatial and temporal patterns of groundwater recharge over a 20+ km reach during a four-year period, in a study comparing temperature logging with concentration profiles in arroyo (wadi) and interarroyo areas of the Middle Rio Grande Basin, MN. Comparison of heat and chemical tracers' vertical profiles at distinct locations down the arroyo channel revealed spatial patterns of cumulative transmission loss, while comparisons of tracers' vertical profiles at discreet transects perpendicular to the channel confirmed a lack of recharge in interarroyo areas for current hydrologic conditions.

9. Summary and Future Directions

[55] Working simultaneously and possibly unaware of each other's work, *Vaux* [1962, 1968] created a framework describing the nature of flow in streambeds, while independently *Suzuki* [1960] and *Stallman* [1965] provided analytical tools for using heat as a tracer to quantify water flow in porous materials. Coupling their seminal works required appreciate of the value of merging their research approaches, as well as advancements in environmental instrumentation and simulation modeling. Successful coupling their conceptual approaches with these technical advancements has resulted in temperature-based estimates of stream exchanges, streambed infiltration, percolation, groundwater recharge and discharge, and most recently the complex, multidimensional flow paths through streambeds. In addition, spatial and temporal patterns of streamflow in seasonal and ephemeral channels are now available using resourceful temperature monitoring at the channel surface. The advent of advanced remote sensing of surface temperatures and spatially extensive fiber optic thermal applications point toward the potential for heat-based estimates of streambed exchanges on the watershed scale.

[56] The range and robust nature of the types of temperature measurement devices, especially in terms of resolution and spatial coverage, and a choice of heat and water transport models, create opportunities to broaden heat tracing investigations beyond gross accounting of stream/streambed water exchanges for comparison with nearby seepage meters [*Su et al.*, 2004] or reach-scale differential streamflow measurements [*Thomas et al.*, 2000]. Creative deployment of temperature equipment holds great practical promise for the use of heat as a tracer to catalog and potentially predict the diverse spatial and temporal patterns of streambed water flow critical to fields ranging from stream ecology to water-treatment plant operations. Emerging areas of research using heat as a tracer include spatially comprehensive studies of flow geometry using physically based 3-D modeling, coupled with tandem-tracer analysis of the differential absorption within the 3-D stratigraphy. In a broad sense, the use of heat to quantitatively characterize the extent and properties of the streambed, may raise the stature of the streambed to the level of a distinct hydrologic body rather than simply the lower boundary in stream research, or an amorphous zone beneath the stream. Thus, use of heat as a tracer in streambeds holds the potential to aid in creating a distinct field of "streambed science" comparable to soil science in both interest and appreciation to the hydrologic cycle.

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