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Using Temperature to Study Stream-Ground Water Exchanges

Temperature plays a key role in the health of streams, including the benthic habitat of streambed sediments. Stream temperatures are influenced by exchanges between streams and nearby ground water (fig. 1). Exchanges include solutes, in addition to water and heat. Protecting stream habitat and water supplies thus requires an adequate understanding of ground-water movement near streams. Heat provides a natural tracer of ground-water movement that is readily tracked by measuring temperature.

Surface water and ground water were once regarded as distinct resources that could be used and managed independently. The shortcomings of this practice became obvious where sustained depletions of one resource negatively impacted the other (Glennon, 2002). We now recognize that ground water and surface water are intimately coupled in many places, constituting a single system that must be understood and managed together (Winter and others, 1998; Alley and others, 2002).

Water that moves between a stream and adjacent sediments carries with it measureable amounts of heat. Therefore, solar-driven temperature flucuations at the land surface provide signals for tracing exchanges between surface water and ground water. The *conductive*-only propagation of daily and seasonal temperature fluctuations into the ground is modulated by heat carried upward or downward by flowing water (fig. 2). This additional, *advective*, transport of heat imparts distinctive thermal patterns to gaining versus losing streams (fig. 3).

Figure 1. Particular attention to spawning grounds is needed when ground water is pumped near streams. A fish counting wheel operates on the Russian River, Calif., near ground-water extraction facilities. Water temperature is especially important to the success of anadromous salmon and other cold water fish.

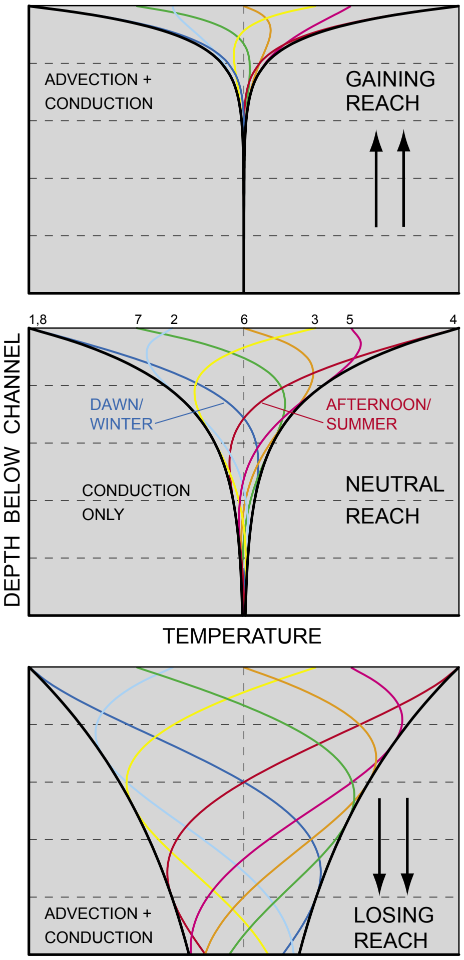

Figure 2. Heat is transported by water moving between streams and their underlying sediments, as well as by conduction. Moving water changes the propagation of daily and annual temperature fluctuations into the streambed. Colored lines (numbered 1 through 8 on the middle graph) show successive temperature profiles though one daily or annual temperature cycle (profile 8 = profile 1). Black lines show the temperature *envelope* formed by loci of minimum and maximum temperatures as functions of depth. This envelope contracts upward beneath a gaining reach (top) and stretches downward beneath a losing reach (bottom), compared to the conduction only case (middle).

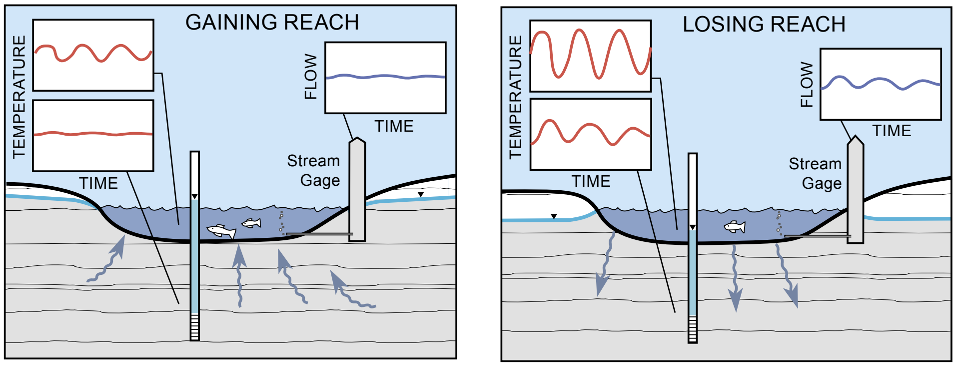

Figure 3. Stream flow and temperature histories for gaining and losing reaches of a stream coupled to the local ground-water system. Ground water is buffered from temperature fluctuations at the land surface. Temperature fluctuations in and beneath the gaining reach are therefore muted (left panel) compared to temperatures in and beneath the losing reach (right panel).

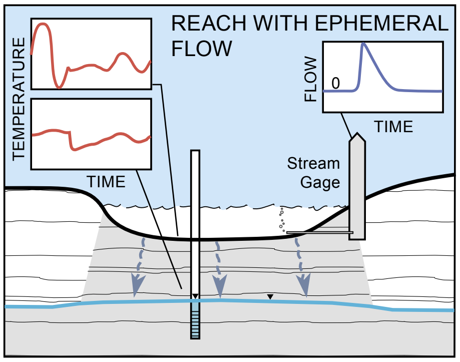

Figure 4. Ephemeral flow increases heat transport, as evidenced by thermographs.

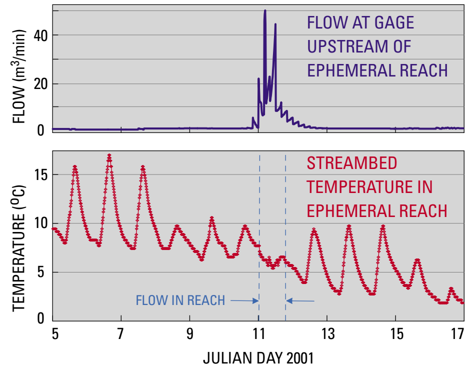

Figure 5. Streambed temperatures before, during, and after ephemeral flow event (example from the Amargosa River, Nev.; sensor is ~0.1 m deep).

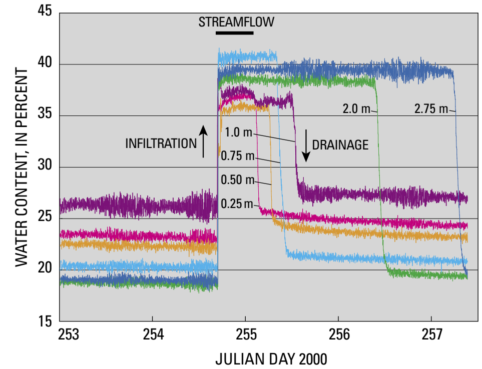

Figure 6. Ephemeral flow causes abrupt changes in streambed water contents and thermal regimes (fig. 5) (example from the Rillito River, Ariz.; sensors are 0.25 to 2.75 m deep).

Major reaches of streams in arid and semiarid regions, as well as headwater reaches of streams in humid regions, are ephemeral—that is, usually dry—and not directly coupled to an underlying ground-water system. Sediments beneath ephemeral reaches are unsaturated most of the time. Infiltration during flow events usually imparts distinctive thermal patterns that allow detection of flow in ungaged reaches (figs. 4 and 5). Temperature measurements thus provide an inexpensive means to monitor ephemeral flows in channels made of unconsolidated sediments (Constantz and others, 2001). These flows are difficult to gage with traditional methods.

Progress from Improved Measurements and Numerical Modeling

The idea of using heat as a tracer of subsurface water movement is not new. Analytical solutions to equations governing the coupled movement of water and heat (fig. 2) have been known more than 40 years (Suzuki, 1960; Stallman, 1965). Analytical solutions, however, have been derived for only a few idealized cases. Furthermore, until recently limitations in measurement capabilities precluded obtaining the data needed to apply analytical solutions.

Innovations in sensor and data-acquisition technology, along with substantial improvements in numerical modeling, present new opportunities for using heat as a tracer of stream-ground water exchanges (Stonestrom and Constantz, 2003). Inexpensive and accurate devices are now available for measuring temperature, water level, and water content (figs. 5 and 6). Temperature transducers

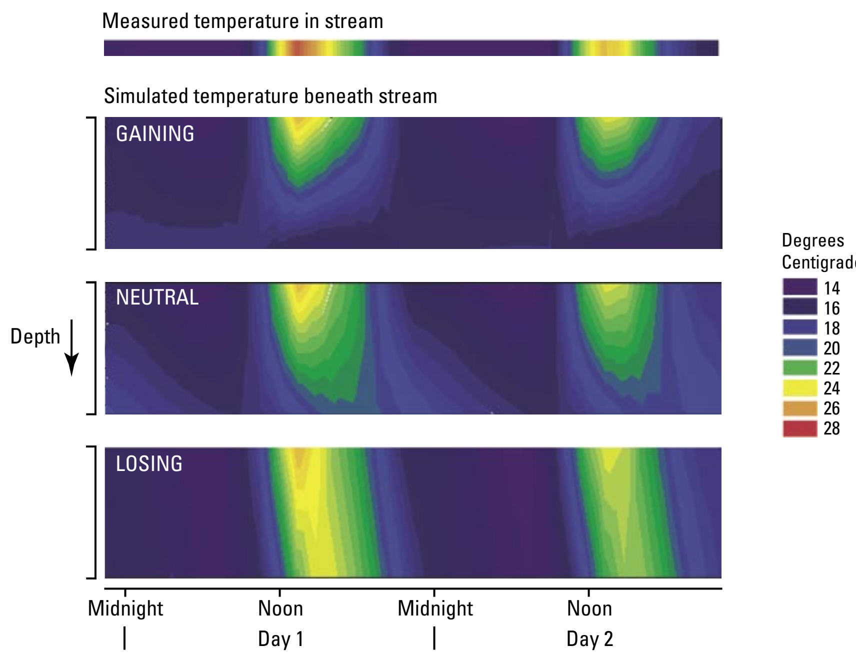

Figure 7. Computer simulations of streambed temperature contours for cases in which the stream is gaining water (top panel), neutral (neither gaining nor losing water, middle panel), or losing water (bottom panel) with respect to the underlying ground-water system. The water temperature history of the stream is shown in the stripe at top.

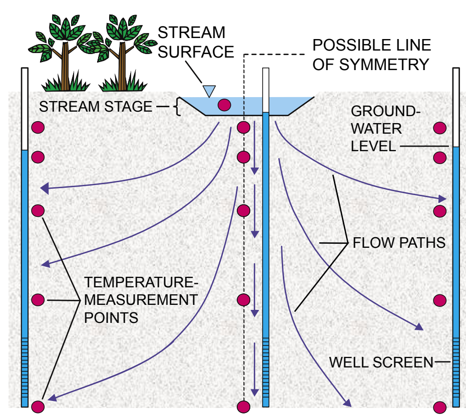

Figure 8. Cross section perpendicular to flow beneath a losing reach, with measurement locations for temperature and ground-water levels (stream stage is also being measured).

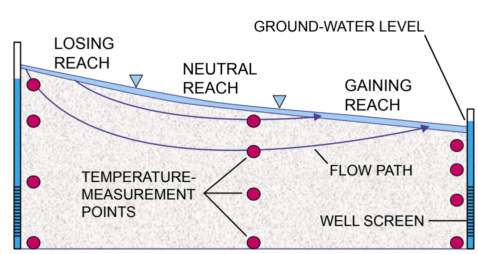

Figure 9. Cross section parallel to flow of a stream-ground water system with a losing reach, a neutral reach, and a gaining reach. Ground water near streams usually moves roughly parallel to the stream channel.

are relatively inexpensive, with thermal microloggers costing less than $100 each.

Currently available numerical models provide general solutions of equations for the coupled transport of water and heat. These models allow for the treatment of complex geometries, heterogeneous sediment properties, and non-ideal boundary conditions. The U.S. Geological Survey's code for simulating water and solute movement through variably saturated sediments (VS2DT) has been adapted to simulate the simultaneous movement of water and heat (Healy and Ronan, 1996). The heat-transport version (VS2DH) can handle problems that have arbitrary initial and boundary conditions. A graphical-user interface (VS2DI) facilitates applying the model to specific problems (Hsieh and others, 2000). Figure 7 shows VS2DH-simulated temperatures beneath the center of a of hypothetical channel that is gaining water (top), losing water (bottom), and neutral (middle). These temperatures might correspond to the center column of data points in figure 8. Subsurface water movement near streams is often divergent or convergent (figs. 8 and 9). VS2DH simulates flow and transport in two spatial dimensions, readily handling divergent-convergent flow.

The normal procedure when using heat as a tracer is to adjust streambed hydraulic conductivities in a numerical model until seepage rates cause a match between observed and measured temperatures (fig. 10). The thermal properties of sediments vary within narrow ranges and can be obtained from literature values. In contrast, the hydraulic properties of sediments vary over orders of magnitude and are typically highly uncertain. Hydraulic properties are thus usually fit during construction of a model. Because seepage velocities and hydraulic properties are highly correlated, simultaneous fitting of temperatures at multiple points plus either (1) hydraulic heads, for streams directly coupled to the underlying ground-water system (fig. 3), or (2) unsaturated-zone water contents, for streams not directly coupled to the underlying ground-water system (fig. 4) is usually needed to characterize the system. Computer programs such as UCODE provide optimally fitted parameters together with estimates of sensitivity and uncertainty (Poeter and Hill, 1999). Sensitivity analyses can help discriminate among alternative conceptual models.

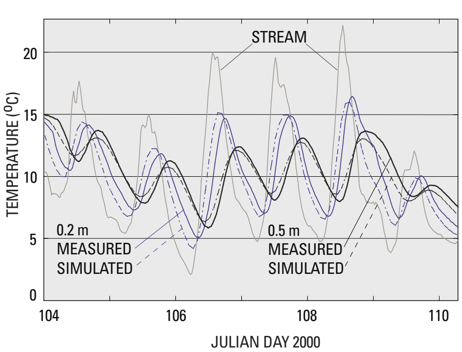

Figure 10. Simultaneously fitted streambed temperatures at two depths (example from Trout Creek, Nev.).

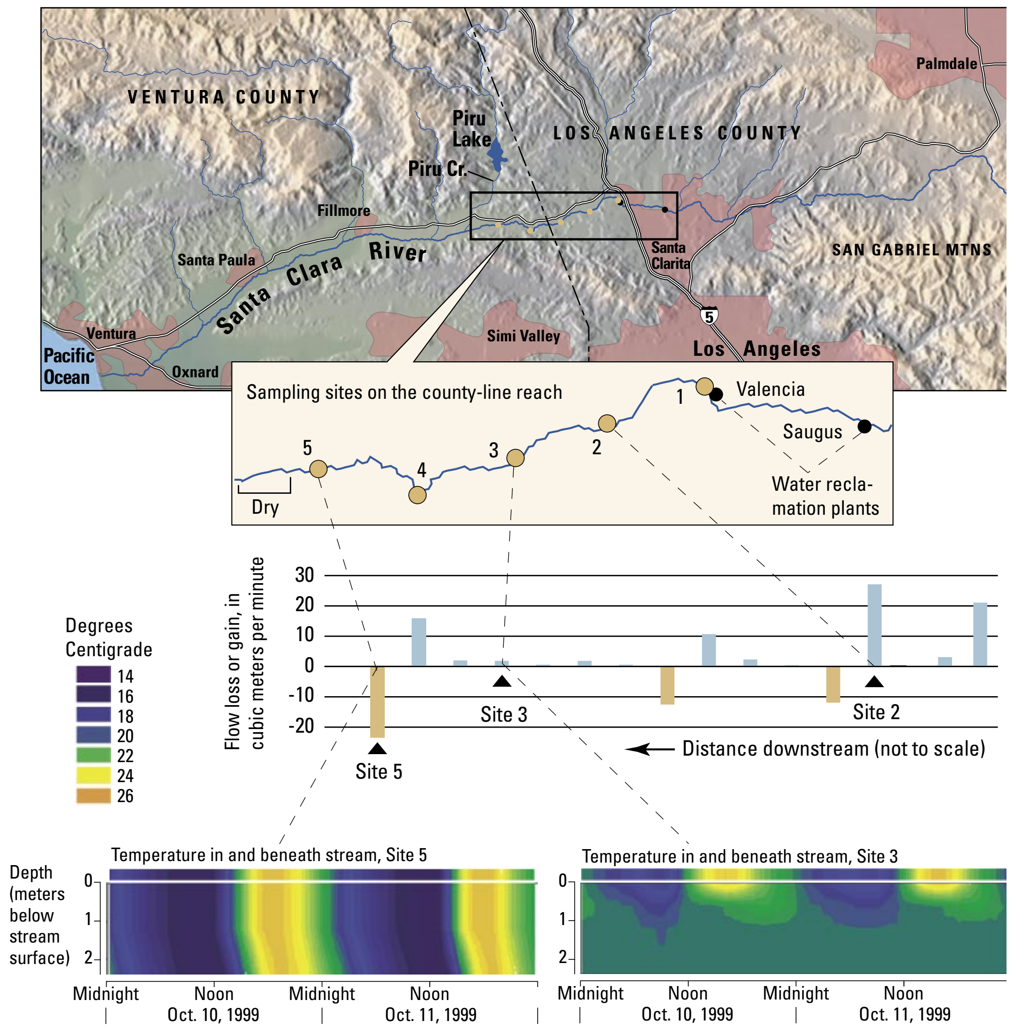

Figure 11. Heat was used to study exchanges of water between the Santa Clara River (Calif.) and ground water. Bar chart shows point-to point changes in streamflow measured by in-stream gaging. Blue bars indicate gaining reaches, brown bars losing reaches. Bottom panels show measured temperature profiles through time for a losing reach (left) and a gaining reach (right).

Temperature Measurements Lead to Improved Models

Conceptual model testing is an important reason for using temperatures to augment hydraulic methods when studying exchanges between streams and ground water. Interpretation of temperature measurements offers an expedient means not only of identifying gaining and losing reaches, but also of mapping subchannel flow paths. Techniques that utilize heat take advantage of readily obtained information to constrain conceptual models at reach to watershed scales. These ideas are illustrated in the following case study.

Water quality downstream of reclamation plants on the Santa Clara River (fig. 11) is influenced by exchanges of water between the stream and the unconsolidated sediments through which it runs (fig. 12). Residence times and exchange rates depend on hydraulic properties of stream sediments that are difficult to characterize. Modeling subchannel temperature responses to diurnal forcings proved highly effective in building well-constrained numerical models of the

Figure 12. Santa Clara River, Calif., looking south (site 5 in fig. 11). The riparian ecosystem is sensitive to exchanges of water between the channel and the unconsolidated sediments through which it runs. Tracing heat helped quantify lateral and vertical flows of water between the stream channel and local ground water.

stream-ground water system (Constantz and others, 2002). These models clearly showed the importance of lateral as well as vertical components of subchannel flow.

Knowledge gained from thermal studies is useful for evaluating the sustainability of biological and water resources. It is also useful for evaluating system responses to changes in surface-water utilization, ground-water utilization, and climate. Because nature provides abundant thermal forcing at the land surface, heat is useful for developing a better understanding of stream-ground water interactions.

—D.A. Stonestrom and J. Constantz

Credits

Figure 1 – photograph by Christine E. Hatch. Figure 12 – photograph by Jim Constantz. Other figures (adapted from USGS Circular 1260): Figures 3 and 4 – Patricia A. McCrory; Figure 6 – John P. Hoffman; Figure 7 and 11 – Lisa Sarma; Figures 8, 9 and 10 – Richard G. Niswonger.

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http://water.usgs.gov/software/ground_water.html

http://pubs.water.usgs.gov/circ1260

http://water.usgs.gov/nrp/proj.bib/constantz.html