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Science FINDINGS

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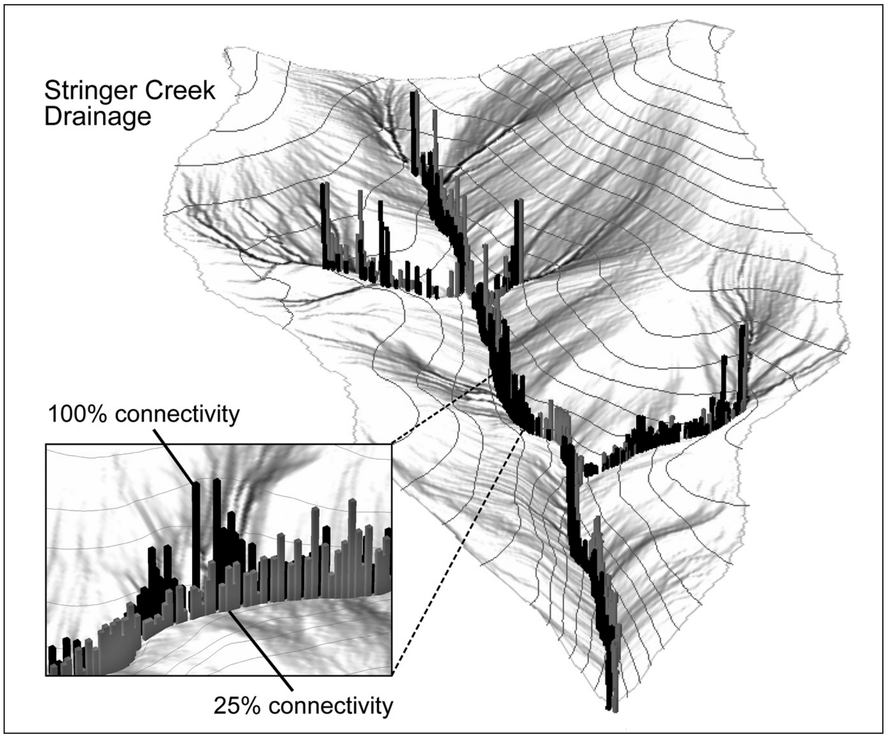
INSIDE

"Science affects the way we think together."
Lewis Thomas

EXPLORING CONNECTIONS BETWEEN LANDSCAPES AND STREAMS



The shape of a watershed determines the sources and timing of runoff that govern stream flow. Here, the bars represent the percentage of time that the uplands on either side of the stream remained hydrologically connected to Stringer Creek in Tenderfoot Creek Experimental Forest, Montana.

"When you put your hand in a flowing stream, you touch the last that has gone before and the first of what is still to come."
—Leonardo da Vinci

To the untrained eye, a stream may look like a simple water channel: turn on the rain and the water flows downhill, filling the channel to a greater or lesser degree. Across the landscape, small tributary streams are linked into a main water line—a river—forming a network of channels that drain watersheds. This all seems straightforward enough, but walk along a stream in late summer, when it hasn't rained for several months and hillslopes are bone-dry, and you may wonder, where does all the water come from? Likewise, if you observe a gurgling brook in the morning transformed to a dry streambed late in the day, you might ask, where did all the water go?

Hydrologists recognize that the answers to these deceptively simple questions lie

IN SUMMARY

New technology has given scientists the means to probe the hidden world of belowground hydrology. Steve Wondzell with the Pacific Northwest Research Station and his colleagues conducted several experiments in Montana's Tenderfoot Creek Experimental Forest and Oregon's H.J. Andrews Experimental Forest to determine which factors control the timing and location of water inputs from hillslopes to streams, the movement of water down the stream channel, and the consequences of these processes on watershed outputs. They found that the configuration of uplands draining into a watershed strongly affects the quantities of water delivered to a stream. In general, water from upper hillslopes reached the stream only during abundant precipitation and snow melting, except in places where the landscape was deeply incised and consistently hydrologically linked to the channel. These patterns of connectivity explain the seasonal patterns of runoff observed in individual watersheds.

Other experiments charted significant gains and losses in water volume within and along the channel that were due to continual exchanges between the riparian zone, stream, and channel subsurface zone. A final facet of the research focused on the nuanced patterns of stream fluctuations caused by evapotranspiration from riparian trees. The researchers found that streamflow velocity governs the marked ebb and flow of evapotranspiration's influence on water output at the stream's mouth during summer. The findings provide clues to evaporative water loss from riparian vegetation and help elucidate how routing streamflow through stream networks affects whole-watershed responses.

largely below ground. The difficulties of investigating the subterranean realm have hampered progress in solving these puzzles. However, the development of powerful new technologies over recent years has given scientists the means for probing the hidden world of hydrology.

Steve Wondzell, a research ecologist with the Pacific Northwest Research Station's Olympia Forestry Sciences Laboratory, has taken up the challenge of teasing out the details of mechanisms governing streamflow. Over the last several years, Wondzell has collaborated with colleagues on a series of studies aimed at improving the scientific understanding of watershed dynamics. Describing this research agenda in plain terms, he says, "You can think of it like this: A drop of rainwater falls from the sky and moves downhill. Where does it go? How long does it take to get there? And, what are the mechanisms that take it there? Answers to these questions are critical to understanding streamflow generation—improving the ability to predict floods, and improving our understanding of land-use effects on streamflow, especially during low-flow periods.

KEY FINDINGS

- The landscape structure of watersheds is a primary control on the sources and timing of runoff that governs streamflow. Overall, hillslopes are hydrologically connected to streams only during major storms or snowmelt. However, where drainage is highly convergent, hillslopes can remain hydrologically connected to streams most of the year.
- Streams continuously gain and lose water along their length. The patterns of gains and losses are attributable partly to landscape structure, particularly the width and longitudinal gradient of the valley floor.
- Stream velocity controls the daily flow changes at the mouth of a watershed caused by evapotranspiration from streamside trees. Evapotranspiration creates wavelike signals that, at high flow velocity, accumulate "in phase" to produce strong daily fluctuations. At low stream velocity and minimal flows, evapotranspiration signals become increasingly out of phase, masking the daily fluctuations in streamflow.

HILLSLOPE-RIPARIAN-STREAM CONNECTIONS

Hydrologists have long suspected that watershed topography plays an important role in governing how streams respond to precipitation events such as heavy rainstorms and rapid snowmelt, and how streams continue to flow during dry seasons. In forested mountain terrain, hillslopes represent a major fraction of the landscape. However, except where soil is very saturated or packed down—as on trails or in deserts—water doesn't just flow over the surface; rather, it moves vertically through pores in the soil. Depending on soil permeability, slope steepness, the extent to which soil pores are connected via underground channels, and other lesser factors, water moves downhill in the subsurface, forging hydrological links between the hillslope, riparian, and stream zones. "These processes have been studied and measured by hydrologists at small spatial scales," Wondzell points out, "but without indepth landscape analysis and extensive monitoring, it's been impossible to extrapolate results across entire watersheds."

To investigate how the physical structure of a watershed influences hydrologic connectivity from hillslope to stream, Montana State University (MSU) graduate student Kelsey Jencso, under the direction of Brian McGlynn of MSU, along with other collaborators, including Wondzell, went to Tenderfoot Creek Experimental Forest (TCEF) in central Montana. Typical of Western mountain streams, the hillslopes of the Tenderfoot's watershed are steep, with shallow soils underlain by impermeable bedrock. The team's first step was to analyze the watershed's topography using GIS-based analyses of digital elevation models derived from airborne laser mapping. This approach allowed the researchers to calculate the amount of land draining laterally to the stream network.

"The upslope accumulated area is often considered a surrogate for subsurface water flow," Jencso explains. "It's commonly assumed that the greater the hillslope area, the greater the expected subsurface water inputs to streamflow at a given point. However, this had never been explicitly tested," he says. So, the researchers selected 24 transects that spanned the hillslope-to-stream continuum, and monitored their groundwater dynamics by continuous recording of shallow groundwater wells. The sizes of the upslope accumulated area represented by each transect ranged from less than a quarter-acre to more than 11 acres. Some transects contained many small knolls or ridges, forcing water to diverge in different directions, whereas other transects encompassed big hollows that accumulated water, focusing water inputs to the stream. The well-monitoring data allowed the researchers

Steve Wondzell

Monitoring wells along a stream in Tenderfoot Creek Experimental Forest.

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To provide scientific information to people who make and influence decisions about managing land.

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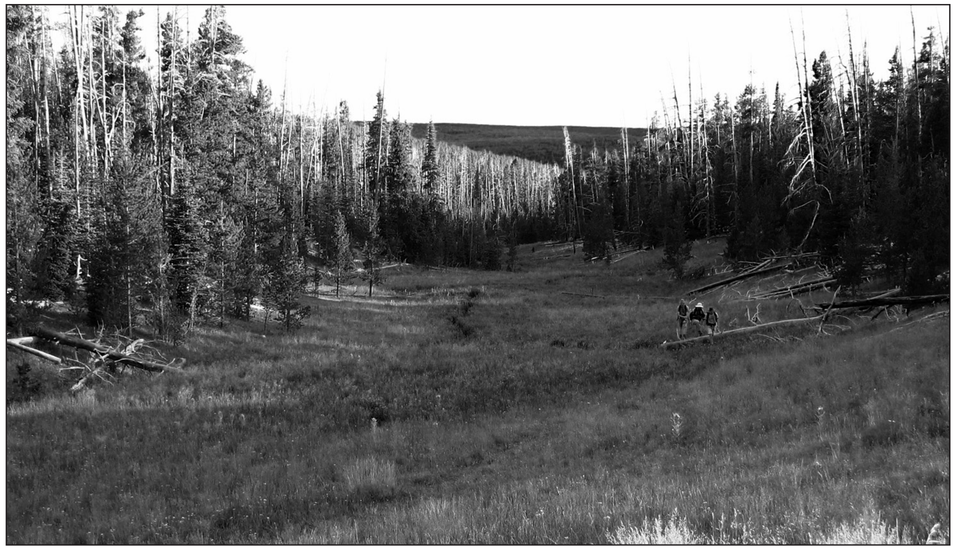
to track the number of days throughout the year that hillslope and stream were connected. "If wells in the hillslope and riparian zone on a given transect both registered ground water above bedrock, we considered the zones hydrologically connected," Jencso explains.

When all the data-crunching was complete, clear patterns emerged. The team found that hillslopes with small upslope accumulated areas were only occasionally hydrologically connected to the stream, if at all. Conversely, in the few locations where drainage converged within large hillslope hollows, hillslopes remain hydrologically connected to the stream over most of the year. "This indicated that the size of hillslope area is related to the amount of time water is conveyed to the stream zone," Jencso says.

This information allowed the researchers to calculate the amount of the stream network connected to its uplands over time. The more hillslopes were connected to streams, the greater the streamflow. As the watershed dries out over the summer, these connections are lost and streamflow decreases. The end results revealed that these relationships are controlled by the shape, or topography, of the watershed.



Steve Wondzell

Researchers used data from continuously recorded groundwater wells and topographical analyses derived from airborne laser mapping to calculate the amount of land draining laterally to the stream network.

But because no two watersheds have identical shapes, patterns of streamflows produced by different watersheds can be surprisingly different, even if they receive identical inputs of water through rainfall or snowmelt, Jencso explains.

"The take-home message is that the shape of a watershed acts as a major control on how rapidly water can move through a watershed into a stream. And it explains the seasonal patterns of runoff observed in individual watersheds," Wondzell adds.

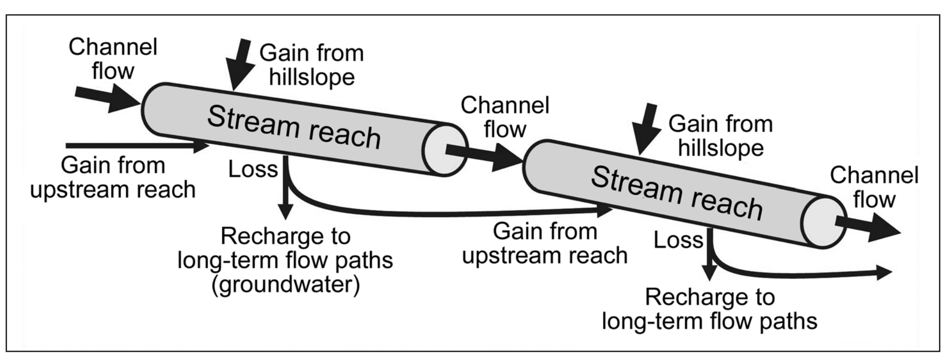
STREAMS ARE NOT CLOSED PIPES

Although it generally appears that water at a given location along the stream channel is the same water that flowed from upstream, studies have shown that streams actually gain and lose water concurrently along their course. This happens through the exchange of water between the stream and hyporheic zone—the subsurface region underlying the streambed. By releasing dyes, salts, and other soluble tracers into the stream channel and then measuring changing tracer concentrations from point to point, researchers have learned that streamflow can be partially replaced by "new" water even over short stream reaches. "The patterns of water gains and losses are related in part to the stream's volume and the landscape structure, particularly the width and downstream steepness of the valley floor," Wondzell says.

Traditionally, hydrologists have studied individual, short stream reaches to estimate net changes in streamflow and the temporary storage of water in the hyporheic zone. Wondzell contends that this approach doesn't reveal gross exchanges between the stream and subsurface over longer distances along the valley, nor does it reveal the influence of these exchanges over an entire watershed. He explains it like this: "In balancing a checkbook, you want to know the gross deposits and withdrawals that produce the net change resulting in the ending balance. So, too, with stream water balances. Together, the net change in streamflow and the amount of tracer lost over a given length of stream reflect the gross exchanges between the stream channel and groundwater."

Robert Payn (then at the Colorado School of Mines), under the direction of Michael Gooseff (Penn State University), along with Wondzell and other collaborators, explored channel water balance along Stringer Creek in the TCEF. Payn's team divided the entire 1.6-mile stream, which drains a basin of 2.1 square miles, into consecutive 650-foot reaches. First, they estimated the volume of streamflow at the bottom end of each reach. Then, they released tracers at the top end of each reach and used downstream tracer concentrations to estimate how much tracer was lost to the subsurface between the top and bottom ends of each reach.

"We found that at lower flows, tracer losses showed that many reaches lost more than 10 percent of their channel water to the subsurface," Payn explains. "But since the stream usually increased in flow over those reaches, they were actually both losing and gaining more water than suggested by the increase in streamflow alone." The experimental approach used by the group demonstrated that "we can find where streams are interacting with the surrounding subsurface over larger spatial extents," Payn says. He also notes that "this level of detail would be very helpful if, for example, you wanted to know the location and rate of contaminant inputs to the stream ecosystem."



Streams gain and lose water concurrently along their course.

A DAY IN THE LIFE OF A STREAM

Another rhythm in streamflow fluctuations investigated by Wondzell and his collaborators is the daily cycle of evapotranspiration by trees, long recognized as an important control on the magnitude of stream discharge in late summer, when streamflow is low. During the day, trees, like other plants, open tiny pores (stomata) in their leaves, or needles, to suck up carbon dioxide for photosynthesis. In the process, water evaporates from their internal stores, a process known as evapotranspiration. On a hot, dry day, a mature tree may transpire several hundred gallons of water, most of which enters the tree via its roots. Ground water diverted to evapotranspiration cannot contribute to streamflow.

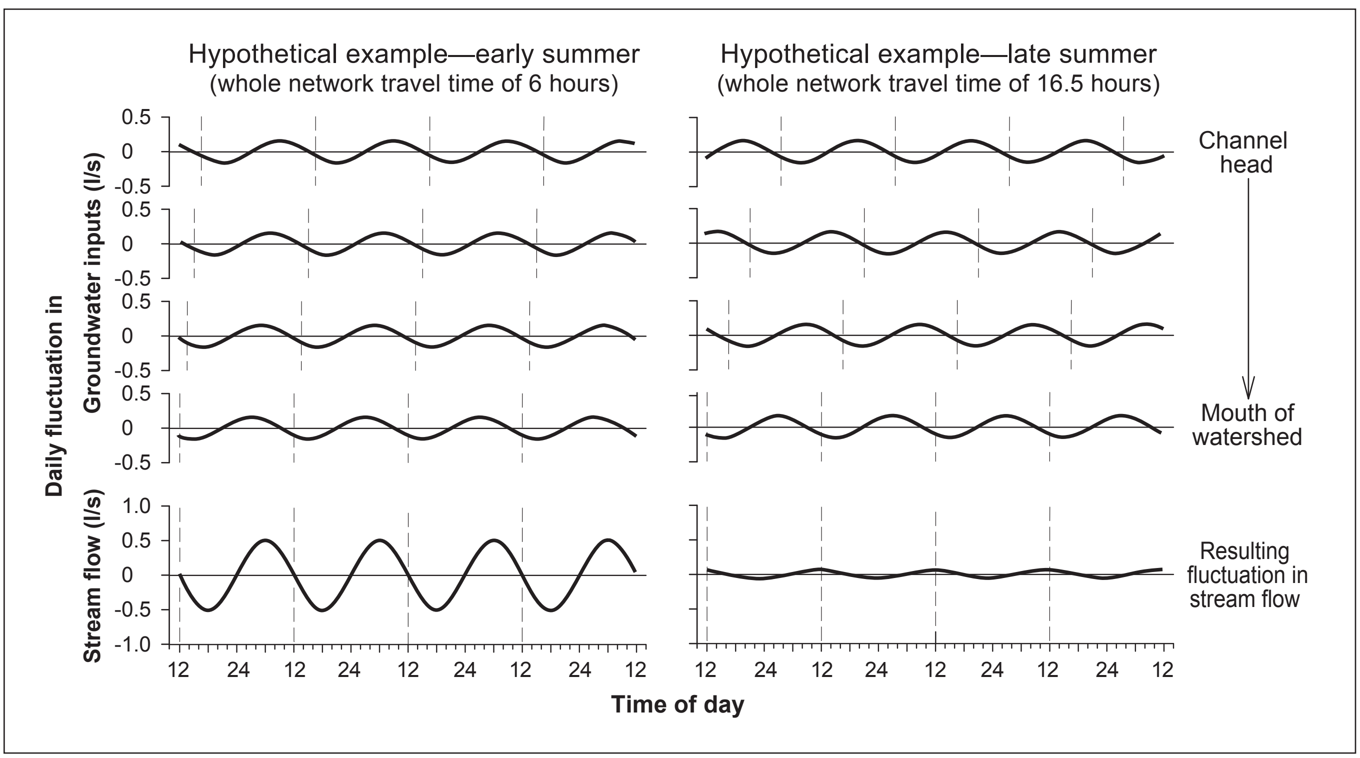
Data from stream gauges show that flow rises at night, hours after daytime evapotranspiration has shut down. "Evapotranspiration peaks during the afternoon, but the associated water losses aren't immediately reflected in water discharges at the stream outlet. This is because the pulse of water freed up from each tree arrives at different times at the stream gauge," Wondzell explains. However, as the TCEF studies demonstrated, most of a watershed's trees are not hydrologically connected to a stream most of the time. Thus, "It's the trees in riparian areas, and at the bases of big hollows where water accumulates, that count," he says.

But the daily pattern of rising and falling streams is far from simple. They change over the course of the summer as watersheds dry out. As streamflow decreases, there's a longer and longer lag between peak evapotranspiration and the time at which the stream gauge records the lowest daily flows—which occurs in late afternoon during early summer, but in the middle of the night in late summer. In tandem with this, the magnitude of the changes in streamflow between day and night become smaller and smaller.

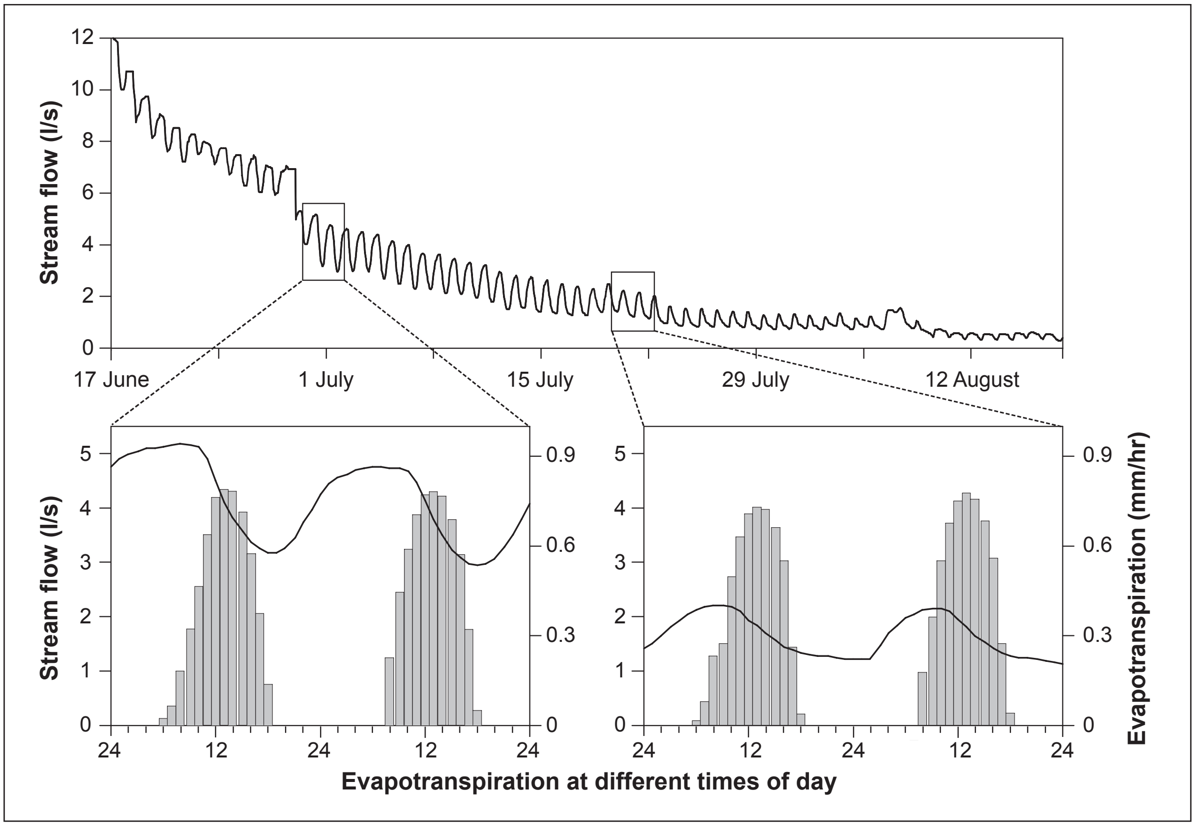
To determine what causes this pattern, Wondzell's team used a computer model to mimic streamflow at various discharges for a 0.85-mile mountain stream in the H.J. Andrews Experimental Forest, located in the western Oregon Cascades. The results showed that at higher discharges, increased stream velocity resulted in greater extremes in stream discharge between day and night. The findings suggest that, to varying degrees, water pulses from trees at upstream locations either reinforce or cancel out pulses from trees further downstream, depending on how fast the stream water is moving.

Why is this important? "Variations in stream discharge that happen over 24-hour periods can be seen as signals showing how a stream is responding to inputs from rainfall or snowmelt, or losses of water to evapotranspiration," Wondzell explains. "Understanding these patterns provides a barometer for what's happening inside a watershed." He offers a practical application: monitoring acid mine drainage in a stream. During the day, various biological processes lower the water's acidity, keeping heavy metals in an inactive state, so daytime measurements of contaminants may appear low. But at night, when those biological controls turn off, the stream turns more acidic, and metals are liberated to move downstream. "Without nighttime sampling, it's possible that spikes in metal concentrations could exceed pollution standards and be missed. So, understanding how stream channels work and how transport influences what we measure at the mouth of a watershed actually is quite important for water quality," he concludes.

As Wondzell notes, streamflow generation has long posed fundamental questions for hydrologists: "The answers to these questions have important impacts on many social needs, from flood forecasting to understanding how land-use practices influence streamflow."



Fluctuation in groundwater inputs to streams is tied to the evapotranspiration of surrounding vegetation, creating daily pulses. In early summer, when stream flow is high and moving quickly, these groundwater pulses reach the stream gauge at the same time (the dashed lines represent 12 noon), amplifying each other and producing distinct daily fluctuations in stream flows. In late summer, when stream flow is low and moving more slowly, groundwater pulses tend to arrive at different times, cancelling each other out and resulting in little daily stream flow fluctuation.



Evapotranspiration—water loss by trees and plants during photosynthesis—peaks near noon. Trees replenish their water stores by drawing up groundwater, diverting it from the stream. The corresponding dip in stream flow lags the daily maximum evapotranspiration.

Whereas most research on the subject has focused on storms and peak flow responses of streams, Wondzell and his colleagues have examined the processes occurring over a wide range of stream discharges, investigating the connections between hillslopes and streams that generate streamflow and tracing the flow of water through stream networks. The research can be applied by land managers working to increase water yields by altering land-use methods and improve stream management practices, among other water resource objectives.

"The River itself has no beginning or end. In its beginning, it is not yet the River; in its end, it is no longer the River. What we call the headwaters is only a selection from among the innumerable sources which flow together to compose it...."

—T.S. Eliot

WRITER'S PROFILE

Noreen Parks has been writing about science and the environment for nearly 20 years, frequently covering topics related to forests and their ecology. She lives in Port Townsend, Washington.

LAND MANAGEMENT IMPLICATIONS

- Riparian forests play a critical role in regulating summer streamflow. Thus, although managing upland vegetation in watersheds may increase total annual water yield, to optimally enhance low-flow discharge in summer, management efforts should focus on riparian vegetation.

- Stream water quality is often compromised during summer by low flows, elevated air temperatures, less dissolved oxygen, and increased levels of pollutants. Paying attention to naturally occurring flow "signals" could advance our understanding of whole-watershed processes during these critical bottleneck periods and help inform management designed to protect or improve water quality.

FOR FURTHER READING

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STEVE WONDZELL is a research riparian ecologist located in Olympia, Washington, and working in the PNW Research Station's Land and Watershed Management Program. His research combines hydrology and geomorphology with ecology to better understand how physical processes within landscapes influence ecosystems. Wondzell's current research spans the wet and dry sides of the Pacific Northwest, examining stream and riparian issues in the H.J. Andrews Experimental Forest and in western Washington, as well as projects in the Blue Mountains of eastern Oregon and Washington.

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KELSEY JENCSO is a Ph.D. student in Ecology and Environmental Sciences in the Watershed Hydrology Laboratory at Montana State University. His research focuses on the spatial and temporal scaling of hydrological and biogeochemical processes within watersheds. Jencso looks forward to a career in the hydrologic sciences where he hopes to build upon knowledge gained from his research at the Tenderfoot Creek Experimental Forest.

ROB PAYN is a postdoctoral researcher in the Department of Land Resources and Environmental Science at Montana State University. He made stream hydrology and ecology his second career after spending 7 years as a computer network engineer. Payn's current research applies mechanistic approaches of hydrology to better understand the physical template of stream ecosystems and to explore how stream ecosystems respond to climate and hydrologic variability over time and space.

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H.J. Andrews Experimental Forest in Oregon and the Tenderfoot Creek Experimental Forest in Montana