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INSIDE

Science FINDINGS

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

Fluid temperatures: Modeling the thermal regime of a river network

Aimee Fullerton

A scientist downloads water temperature data in the Snoqualmie River watershed, Washington. New techniques for modeling temperature variability along a river network are the foundation for tools that may help pinpoint where restoration efforts to lower water temperature would be most beneficial to species of concern.

IN SUMMARY

Water temperature drives the complex food web of a river network. Aquatic organisms hatch, feed, and reproduce in thermal niches within the tributaries and mainstem that comprise the river network. Changes in water temperature can synchronize or asynchronize the timing of their life stages throughout the year. The water temperature fluctuates over time and place, creating variability in the network's thermal regime. Because of this variability, many important details in the thermal regime of a river network cannot be simply represented by an average temperature.

New research by Ashley Steel, a quantitative ecologist and statistician with the Pacific Northwest Research Station, and her colleagues documented the variability of water temperature over time and place on the Snoqualmie River network in Washington. They found clear spatial patterns in temperature metrics, and these patterns shifted over time. They demonstrated that it is possible to model key facets of the thermal landscape that are tied to the places and times in which coho and steelhead salmon are at critical life stages.

Their findings provide a basis for more precisely focused habitat restoration efforts. This fundamental information can be used to develop tools that help identify where to take action to mitigate the effects of warmer air temperatures and of changes in winter precipitation on salmon and other species of concern.

"Any river is really the summation of the whole valley. To think of it as nothing but water is to ignore the greater part."
—Hal Borland

Aquatic life thrives in specific thermal niches—pockets of warmer and colder water that vary from night to day, summer to winter. Water temperature is a moving mark, shifting over place and time. Temperature, and temperature change, drive the timing of river life. Temperature triggers enzymatic reactions that control changes in the life stages of all aquatic organisms—from the bloom of algae eaten by caddis fly larvae to the emergence of fish that eat the caddis flies.

Temperature is only one component of habitat, however. Aquatic communities also thrive in very specific places that are driven, in part, by network processes beyond the water's edge. The gravel where salmon spawn, for example, may have been delivered via a landslide. Streamside vegetation overhanging a pool hosts insects that fall into the slower moving water and are eaten by juvenile salmon.

Salmon and trout native to the Pacific Northwest are coldwater fish. Warmer than optimal water can change their growth rate, lower the amount of available oxygen, and make them more susceptible to disease. If a temperature threshold is crossed, the stream can become uninhabitable to these cold-water species. Many restoration efforts are designed to lower summer water temperatures. Common restoration efforts include streamside plantings to shade the water during the summer, and placing logs in the stream to create pools of cooler, deeper water. But, as Ashley Steel points out, critical life stages happen year-round in Northwest streams and rivers. Changes in water temperature in January or March can have ramifications to specific species and the greater food web. Water temperatures throughout the year can affect the ability of a river community to thrive.

"We've been worried about lethal temperatures in August," says Steel, a quantitative ecologist and statistician with the U.S. Forest Service Pacific Northwest Research Station. "We manage and think first about means and maximums." A pervading notion, she explains, is that "if we understand what's happening in the summer, we can just cool that down and understand what's happening in the winter. Our study on the Snoqualmie River system shows that stream temperature is not shifting consistently with elevation or with season. Each spot along the network varies in time. Each time is variable over space. Those two things together create a complex landscape that all these species are adapted to."

KEY FINDINGS

- Average water temperature does not sufficiently characterize the complexity of a river network's thermal regime and its relationship to aquatic communities.
- Complex thermal regimes in a river network can be understood as the arrangement of temperature facets, each of which can be modeled independently on the network and for time windows of interest to particular species.
- The thermal regime in the Snoqualmie River, Washington, for example, is not simply warmer at low elevations or warmer in summer. Water temperature patterns at particular locations differ from one another with respect to magnitude (averages, minimums, and maximums) and also with respect to variability.
- Along the Snoqualmie River network, there are clear spatial patterns in all temperature metrics, and for most metrics, these patterns shift over time.

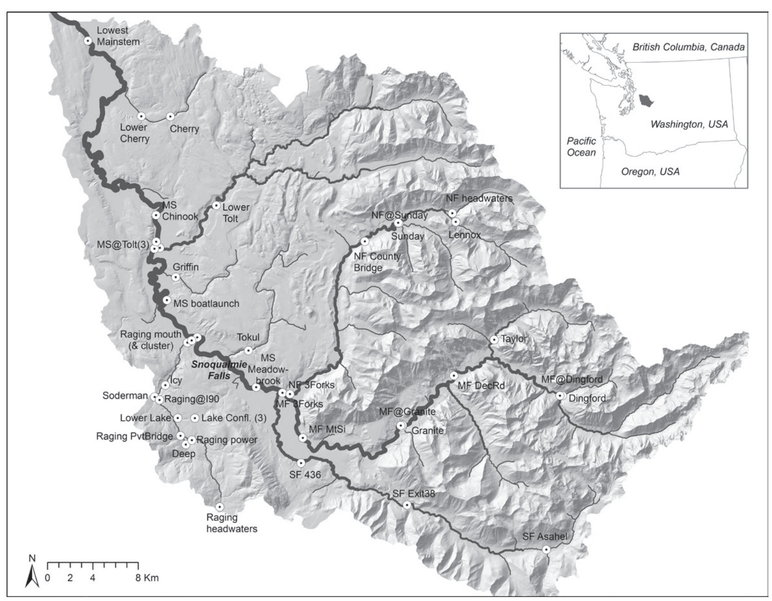
That complexity exists is not a new idea; what is new is the ability to model it. Steel's work is giving language and method for quantifying variations that have not previously been systematically accounted for. By using a spatial stream network model, Steel and her colleagues were able to integrate variability—as a statistical concept—with biological information, and then model various facets of the thermal riverscape.

"We know that stream temperature in one part of the network is related to stream temperature in another part of the network," says Steel. "That relationship is very different than it would be over a two-dimensional space because it has a directionality to it. It flows from upstream to downstream and has the branching structure of a network. New spatial stream network models can incorporate these unique features of streams and make better predictions of unmeasured places." The models also help illuminate how factors outside the stream, such as elevation, riparian cover, or urbanization, affect temperature, and thus life, in the stream.

Time Windows and Temperature Triggers

To better understand these nuances in the thermal regime of a river network, Steel and her colleague Aimee Fullerton from the National Oceanic and Atmospheric Administration's Northwest Fisheries Science Center established a temperature monitoring network along the Snoqualmie River network in 2011. The year-round data, collected every 30 minutes by gauges at more than 40 locations, combined with the new statistical tools, allowed the researchers to glean valuable insights into the variability of stream temperature.

The Snoqualmie River flows down the west side of the Cascade Range in Washington. It is home to Chinook, chum, coho, pink, and winter steelhead salmon, as well as many other aquatic organisms that form the greater



The Snoqualmie River in western Washington. In 2011, researchers installed more than 40 water temperature gauges that collect data every 30 minutes along the network.

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Rhonda Mazza, editor; rmazza@fs.fed.us

Cheryl Jennings, layout; cjennings@fs.fed.us

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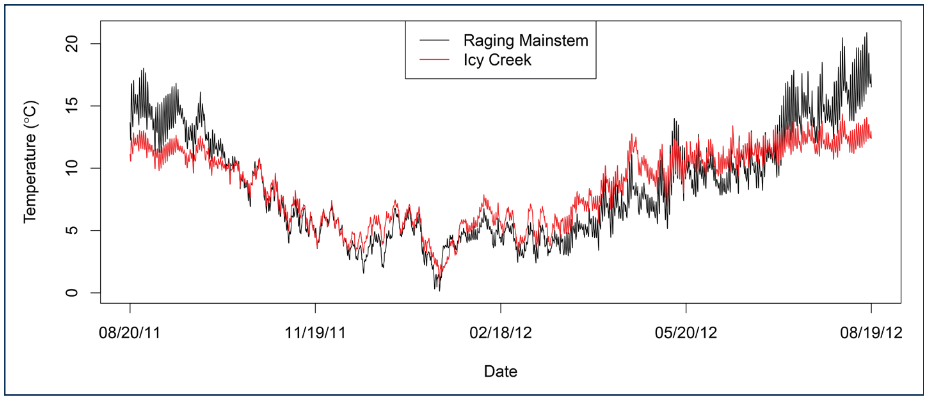
food web of the river system. At the upper elevations, the river network runs through mostly forested public land managed by the Washington Department of Natural Resources and the U.S. Forest Service. Downstream, the surrounding land transitions to more developed uses.

In their study, Steel and her colleagues Colin Sowder and Erin Peterson looked at time windows that are biologically important to coho and steelhead salmon—specifically when they spawn and when the eggs incubate in the gravel—and examined the relationship between these biological events and particular facets of the thermal regime. They defined a facet as any part of the thermal landscape that has potential ecological consequences. They wanted to know if it was possible to model the temperature regime in relation to these biologically important time windows and at places where particular life stages occur in the river network.

In the Snoqualmie River network, coho salmon spawn November through January and the eggs incubate December to July. Steelhead, on the other hand, spawn March to June and their eggs incubate mid-April through mid-August. "The temperature during those times and at those places is not just a middle range between the coolest and the warmest temperature," explains Steel. "Each time window has its own distribution of thermal regimes based on solar radiation and patterns of snowmelt. At times, parts of the basin are more driven by earlier snowmelt, whereas others are driven by rain. It makes sense that each part of the basin would respond uniquely within seasons or time windows that matter to fish or other parts of the food web."

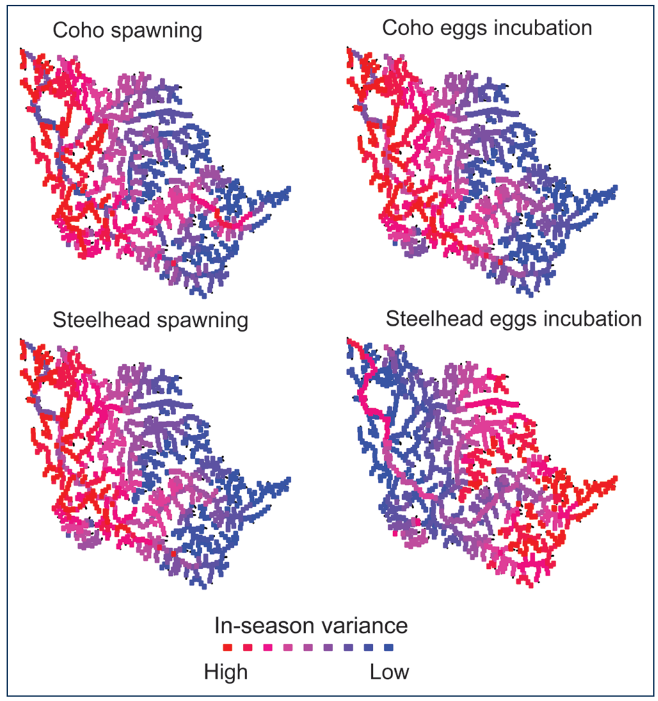
The researchers found that the thermal regime in the Snoqualmie River network is not simply warmer at low elevations or in the summer. For example, Icy Creek and the Raging River are two waterways in the network that have nearly the same annual average temperature. A year's worth of data revealed, however, that they have very different thermal profiles. In summer, the Raging River is several degrees warmer than Icy Creek, but in the winter and spring, it is somewhat cooler than the creek. Not only is the seasonal change in river temperature more dramatic than in the creek, the daily temperature fluctuations in summer are much larger.

This was a surprise. The researchers expected the thermal regime over the whole river network to vary with time and space because water temperatures are warmer overall in summer than in winter and, in general, water warms as it descends in elevation. This study revealed that water temperature patterns are more complex than these rules of thumb suggest. Seasonal temperature patterns vary over space, and spatial temperature patterns vary by season. And, importantly—this study revealed that it's possible to model this complexity. Each facet can be modeled independently on the network and for key periods in the annual life cycle of a species of interest. This idea lays the foundation for developing tools that could help pinpoint where human efforts to lower water temperatures likely would be of most benefit to species of concern.



Adapted from Steel et al. 2016

The thermal regimes of the Raging River and Icy Creek, two nearby sites in the Snoqualmie River network, have similar full-year means (8.4 °C and 8.5 °C) but different patterns over the year. The river is warmer than the creek in the summer but cooler in the winter and spring.



Adapted from Steel et al. 2016

Projections of variability in water temperature during spawning and egg incubation for coho and steelhead salmon in the Snoqualmie River network.

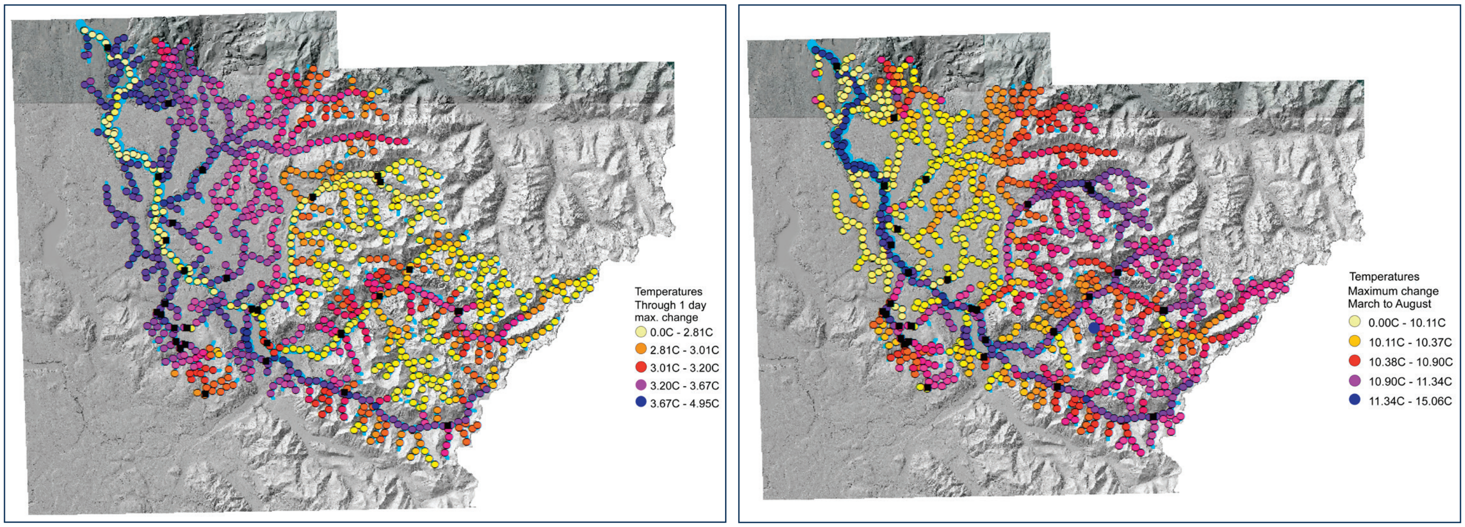
This is exactly what Elizabeth Ablow, a strategic advisor with Seattle City Light, the public electric utility serving the Seattle area, is hoping for. Seattle City Light hydroelectric projects provide about 90 percent of the electricity used by its customers, so the utility has a vested interest in being an environmental steward of those river networks, as well as a legal responsibility to do so.

Ablow recalls the drought of 2015 with its warm winter and very little snow: "During 2015, everyone had heightened concern about water temperature," she says. "By late June, early July, we were seeing water temperatures everywhere higher than we'd seen before for this time of year. We didn't know how long the dryness and the heat would persist. Everyone—we, King County, others—was throwing [temperature] loggers in the rivers."

"We are always concerned about water temperature for fish during the summer, and the Washington Department of Ecology has definitive requirements for the temperature thresholds that we should not exceed. But regionally that was not the case. Temperatures were higher."

Ablow, a fish biologist, is also the co-chair of the Tolt Fish Habitat Restoration Group, a stakeholder group for the Tolt-Snoqualmie River systems. She became familiar with Steel's work on the Snoqualmie River during the drought when another member of the restoration group was collecting water temperature data and ran into Steel collecting temperature data at the same place.

"As co-chair," says Ablow, "I want to ensure collaboration among the stakeholders



Water temperature can vary by hour, day, and month. These different types of variability have unique spatial patterns. The figure on the left illustrates areas of highest daily fluctuation, whereas the figure on the right illustrates areas of highest seasonal fluctuation. Temperature change triggers biological changes in aquatic life; changes in temperature patterns will likely alter the synchronization of the aquatic food web.

working on these rivers. It's a lot of effort to drive out there and get data. We don't need to have two people collecting the same data if we can share and collect our information. So I contacted Ashley. She came to a Tolt Fish Habitat Restoration Group meeting and shared her work."

"When we learned that Ashley wasn't just monitoring, but that she was taking these data and incorporating them into a model so there'd be more predicative functions in her work, that was very intriguing," Ablow continues. "With a tool like that we could hopefully see where our vulnerabilities are and where our resilience is in a given watershed."

Steel's analysis showed that, in 2015, parts of the Snoqualmie basin warmed proportionally more than others. The areas most affected were along the historical snowline where little snow fell that year. The precipitation that did fall generally fell as rain. This, of course, affects the timing of high and low water flow, which can be a determining factor in the survival of fish in a particular life stage.

For example, winter flooding can scour coho salmon eggs from their redds (spawning nests), or smother them with sediments. When coho fry emerge, will they find turbid or calm waters? These young coho salmon feed almost entirely on insects and need to begin feeding right away. Increased turbidity and high flows at the wrong time can decrease their chances of survival.

"If you want to understand the whole food web, you need to understand how each species is distributed and that's one of the things that I think this kind of work can help with." Steel says. "We know the climate is going to be different in the future. We think of each species shifting up or of shifting their timing, but river food webs are complex; each species may react quite differently.

"Understanding this complexity, and thinking about how the different parts of the thermal landscape may be important for particular species, should help us make more informed predictions about how things may or may not break apart in the future," says Steel.

The Power in Variability

Prior research by Steel found that early Chinook salmon life stages can be altered by variations in stream temperature, even when the daily mean temperature remains relatively unchanged and fluctuations are within established thresholds. "The effects of temperature on fish growth and phenology are nonlinear," she explains. "Even small fluctuations in water temperature can have large unexpected effects."

This biological phenomenon in which species respond to variable thermal regimes differently than they do to the same mean temperature but delivered as a constant can be explained through a statistical concept known as Jensen's inequality. For example, a 5-day average if all days are 31° may not be the same, biologically speaking, as 5 days at 25, 32, 38, 34, and 26 degrees, even though the average temperature for the second set is also 31°. Steel was fascinated when she realized this connection and how it can be applied. "We understand that climate is not stationary, that seasonal patterns and solar radiation are changing over time. Jensen's inequality shows we can't just think about the mean temperature. That's a good starting place, but it's going to be a lot more complicated, and that complication has biological consequences."

"Aquatic life evolved to a certain timing of temperature and flow," Steel continues. "The variability of the thermal landscape can shift that timing quite substantially. Even a day off here or there can make a big difference so that things are no longer happening at the same time or even in the same sequence that we originally learned about them."

Monitoring Water and Air Temperatures

In 2017, Steel and her colleagues installed paired air temperature loggers for the entire Snoqualmie River monitoring array. The paired air and water loggers can help differentiate places where solar radiation versus groundwater control water temperature. They also began collecting water samples that, after analysis, will help them model water sources in the basin, which will help identify where low flows are most susceptible to climate change.

"After talking with Ashley and others, we also added more air temperature monitoring to sites where we are collecting water temperature," Ablow says. "We want to understand where air temperature is the driver of water temperature, and understand the lag of warming time. It will allow us to be more focused on those areas and understand them better."

"If groundwater is contributing to moderating the temperature," Ablow says, "those areas might not be the best candidates for planting trees. Instead we can ask, 'are those areas protected? Are they vulnerable?' Land acquisition might be a more appropriate strategy there." On the other hand, areas where water temperature is tightly coupled with air temperature might be areas where shade from riparian plantings will most effectively cool the water. "Understanding that will be a great thing to all people working in these systems and trying to have a climate adaptation perspective as we do our restoration projects," she says.

Just as human activities can increase or decrease mean stream temperatures, they can also either exaggerate or minimize temperature variability in space or time on the river network. Riparian restoration that increases the amount of shade along a stretch of water, for example, likely decreases the spatial variation in mean and extreme temperatures and reduces daily temperature range in the area. Removing levees increases the spatial diversity and availability of thermal refuges. An improved ability to model variability can help predict how restoration might be used to create thermal landscapes that help river communities thrive.

Data from the Snoqualmie River network were used for statistical research to identify principles of efficient monitoring arrays for river networks. This work emphasized the need for clustering temperature loggers along the network so the model can understand the similarity of nearby sites. Steel and colleagues also found that models built from data collected at as few as 20 sites performed adequately in most cases, although more sites are better. Surprisingly, the location of new sites did not matter much. "I see these as encouraging results for anyone needing to initiate new monitoring arrays, even if the distribution of available sites seems imperfect," Steel says.

Building on these findings, in summer 2017, Steel's colleagues at the PNW Research Station, Rick Edwards, a research ecologist, and Ryan Bellmore, a research fish biologist, began installing a water and air temperature monitoring array in the Héen Latinee Experimental Forest in southeast Alaska. The Cowee Creek watershed where they are working is fed in part by glaciers that are receding rapidly. When the glaciers vanish entirely, as is predicted, the thermal controls within the watershed will rapidly change.

Comparing and contrasting the data from Snoqualmie and the Héen Latinee monitoring programs will reveal where the relationships between air and water temperatures are strongest and how those patterns differ across basins. "Comparison of existing data with new data from a basin with receding glaciers adds an exciting dimension to the research and to our ability to explore and imagine future thermal landscapes" Steel says.

LAND MANAGEMENT IMPLICATIONS

- Particular human actions within a watershed, changing patterns of air temperature, solar radiation, and precipitation may affect one facet of an aquatic thermal regime but not others.
- Management of any species requires spatial predictions of suitable habitat by life stage. For aquatic life, these spatial predictions can be built on the particular facets of the thermal regime that limit the species of concern, as well as its competitors.
- Using this kind of information, managers can more precisely focus restoration and mitigation efforts on a species and even on a particular life stage of that species, or on the natural thermal complexity of river systems.

The findings from these two watersheds will help describe how future climates may affect species at particular life-history stages or in particular parts of a river network. They will also identify potential future fish habitat distributions for native and non-native species across climate scenarios in the two watersheds. Eventually, the researchers would like to compare spatial patterns in water temperature and in correlations between air and water temperature across the Snoqualmie River and a range of other watersheds to develop more general guidelines for conserving fish habitat.

"When informing and collaborating with others on how best to manage, preserve, or restore a watershed, having a tool like the one Ashley is developing that puts brackets around things is really helpful," says Ablow. "Modeling might not be precise, but it puts brackets on what you're trying to understand."

Rick Edwards

A researcher installs a water temperature gauge in Canyon Creek in the Héen Latinee Experimental Forest, Alaska. Findings from this and the Snoqualmie watershed will provide insight into how future climates may affect species at particular life-history stages or in particular parts of a river network.

"Statistics is the grammar of science."

—Karl Pearson

For Further Reading

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Writer's Profile

Rhonda Mazza is a science writer for the Pacific Northwest Research Station based in Portland, Oregon.

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Scientist's Profile

ASHLEY STEEL is a quantitative ecologist and statistician with the Pacific Northwest Research Station. She received her Ph.D. in quantitative ecology from the University of Washington. Her research has focused on harnessing landscape-scale data to predict in-river conditions, quantifying and modeling complex water temperature regimes, and performing sensitivity analyses to support the best use of modeled data. She enjoys collaborating with other scientists to link ideas and tools from aquatic ecology to research on trees, wildlife, fire, and people.

Steel can be reached at:

USDA Forest Service
Pacific Northwest Research Station
400 N 34th St.
Seattle, WA 98103

Phone: (206) 732-7823
E-mail: asteel@fs.fed.us

Collaborators

Aimee Fullerton, National Oceanic and Atmospheric Administration, Northwest Fisheries Science Center, Seattle, WA

Amy Marsha, University of Washington, Seattle, WA

Erin Peterson, Queensland University of Technology, Brisbane, Australia