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Science FINDINGS

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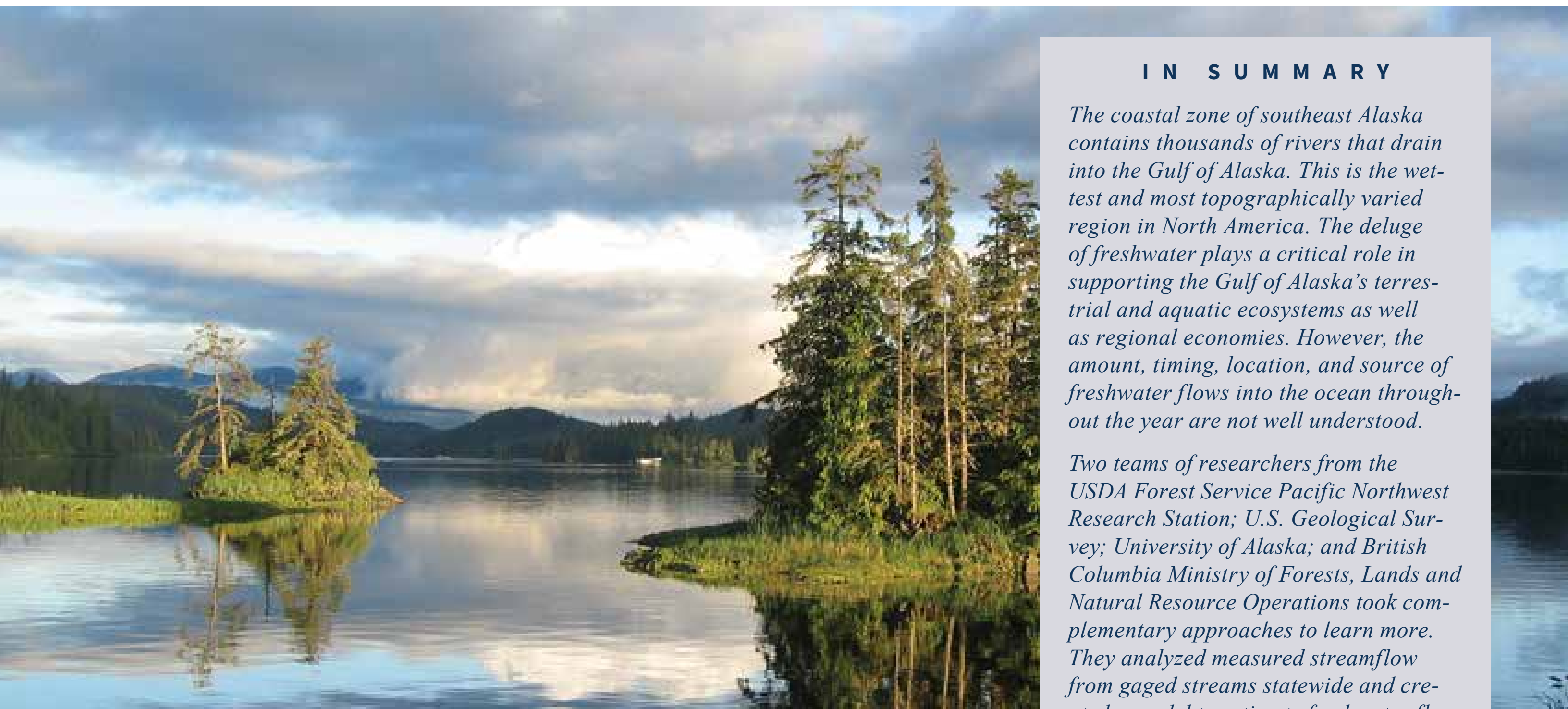
"Science affects the way we think together."
Lewis Thomas

The Dispersed Deluge: Freshwater Flow From Glaciers and Coastal Rainforests to the Gulf of Alaska



Thorne Bay, Alaska. On average, the amount of freshwater flowing from southeast Alaska into the Gulf of Alaska each year would cover the state of Texas in two feet of water. The timing and volume of this freshwater discharge is affected by drivers that may be vulnerable to climate change. USDA Forest Service photo.

IN SUMMARY

The coastal zone of southeast Alaska contains thousands of rivers that drain into the Gulf of Alaska. This is the wettest and most topographically varied region in North America. The deluge of freshwater plays a critical role in supporting the Gulf of Alaska's terrestrial and aquatic ecosystems as well as regional economies. However, the amount, timing, location, and source of freshwater flows into the ocean throughout the year are not well understood.

Two teams of researchers from the USDA Forest Service Pacific Northwest Research Station; U.S. Geological Survey; University of Alaska; and British Columbia Ministry of Forests, Lands and Natural Resource Operations took complementary approaches to learn more. They analyzed measured streamflow from gaged streams statewide and created a model to estimate freshwater flow across the drainage basin. The analysis of statewide streamflows revealed that rainfall, snowmelt, and high-elevation snow and ice storage create streamflow patterns that affect the timing and volume of freshwater flowing through a watershed. At the regional scale, the southeast Alaska drainage basin has a mean annual freshwater discharge of 430 km^3, and watershed discharge is affected by its size and streamflow drivers.

Collectively, this information can help managers identify watersheds where streamflow drivers may be vulnerable to climate change and anticipate changes to stream discharge that might affect aquatic resources or infrastructure such as bridges and culverts.

"All the water that will ever be is right now."

—National Geographic, October 1993

The 188,800-km^2 southeast Alaska drainage basin, an area slightly larger than Washington state, delivers freshwater from thousands of streams to the coastal waters and estuaries of the Alexander Archipelago and the Gulf of Alaska. Although southeast Alaska represents only 46 percent of the drainage—the other 54 percent is in Canada—its thousands of individual watersheds produce about 70 percent of the region's freshwater that flows to the ocean.

"Freshwater is visible almost everywhere," says Rick Edwards, an emeritus research aquatic ecologist with the USDA Forest Service Pacific Northwest (PNW) Research Station. "When you fly around at low altitudes and look out the window, you see the reflection of water across the surface of the landscape, from valley bottoms up to the tops of ridges and along the sides of mountains."

This freshwater supports two critical ecosystems. The terrestrial ecosystem is an 87,000-km^2

rainforest complex that provides timber for commercial harvesting and cultural uses; habitat for recreational and subsistence fishing, hunting, and foraging; dense stores of carbon; exceptional outdoor recreation opportunities; and a world-renowned tourist destination. The vast aquatic ecosystem sustains the commercial fisheries industry, the largest private sector industry in the region, valued at $653 million per year. The abundant water resources are also the primary source of electricity for the region; more than 95 percent of southeast Alaska's electricity is derived from hydropower.

Despite freshwater's importance, researchers don't completely understand how much freshwater flows through the streams in the southeast Alaska drainage basin or the timing of discharge to the ocean throughout the year. Much of southeast Alaska does not have streamgages to measure steamflow because the area is remote and rugged, and streamgages are expensive to install and maintain.

"We don't have a very big stream-gaging network for southeast Alaska, or Alaska in general," says Katherine Prussian, a hydrologist and the watershed program manager for the Tongass National Forest. "It's really hard to design culverts when you don't have small streams gaged." These unknowns also make it challenging to manage infrastructure, such as culverts or bridges.

Streamflow measurements are not just critical to planning and maintaining infrastructure. "Freshwater has a huge impact on ocean chemistry and ocean pH," explains David D'Amore, a research soil scientist with the PNW Research Station. "Freshwater flowing into the ocean interacts with biological cycles in ocean water, controlling ocean acidity, which influences overall marine productivity."

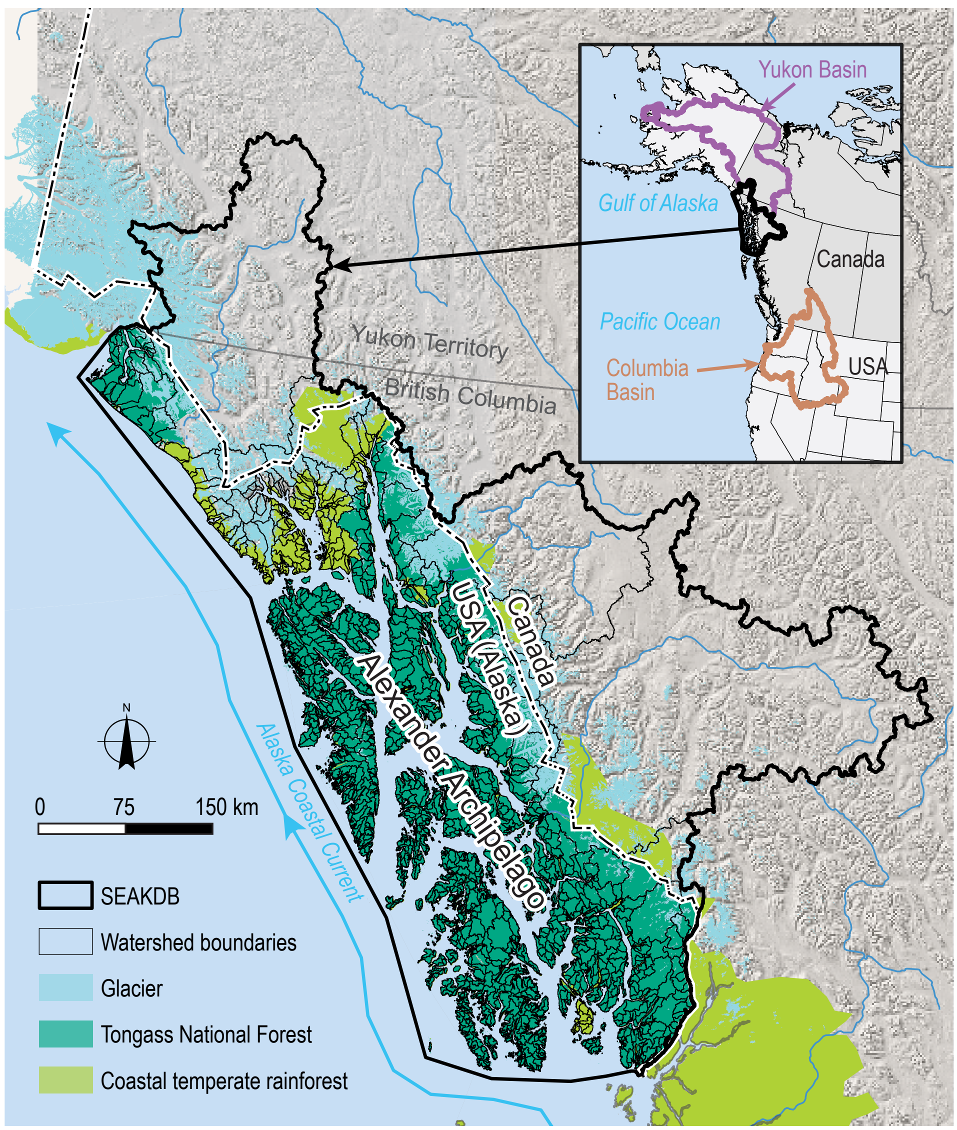
To learn more about of the flow of freshwater throughout the region, two teams of researchers took complementary approaches: one analyzed measured streamflow from gaged streams statewide and the other created a model to estimate freshwater flow from both gaged and ungaged areas across the southeast Alaska drainage basin.

Following the Freshwater

Janet Curran, a hydrologist with the U.S. Geological Survey (USGS) Alaska Science Center, focuses on quantifying streamflow volume and timing. She authored the most recent statewide flood frequency equations, which use streamflow and basin characteristics of gaged streams to enable users to estimate flow in ungaged streams. The Alaska Department of Transportation and Public Works relies on those equations, along with other hydrology research produced by the USGS Alaska Science Center, when designing and maintaining infrastructure, such as bridges, roadways, and culverts, throughout the state.

"For the flood frequency report, I found myself struggling to point to some kind of documentation that outlined the different streamflow patterns we have," Curran explains. "To further our understanding of, not only the present streamflow patterns, but also how these patterns might change in response to climate change, we need to first understand the existing drivers of streamflow."

The seasonal pattern of a stream's discharge is called its "seasonal flow regime," which is visualized by creating a graph of streamflow, known as a hydrograph. Flow regimes characterize the average magnitude, timing, and variability of a stream's discharge and are



The southeast Alaska drainage basin (SEAKDB), Alexander Archipelago, and Gulf of Alaska.

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determined by the seasons and the stream's freshwater source. Rainfall, snowmelt, and icemelt are the primary drivers of daily streamflow and annual peak streamflows in Alaska. Factors related to stream location and watershed characteristics, such as local and regional climate and storm patterns, elevation, position of mountain ranges, and distance from the coast, influence these streamflow drivers and seasonal responses. Identifying how streamflow responds to these physical factors across the landscape is fundamental to understanding present patterns and planning for possible future changes.

A meeting in Juneau found Curran serendipitously learning that Frances Biles, a geographer with the PNW Research Station, was also researching how to classify streams by their streamflow patterns. "It just made so much sense to collaborate," says Curran. "We both brought different skillsets to the table, and it was a productive collaboration."

The pair focused on categorizing the different seasonal streamflow regimes found statewide. Streamgages provided the needed information, but finding a robust dataset to capture all regimes in the state proved challenging. Years of continuous streamflow measurements are needed to establish a good picture of the timing and amount of freshwater discharge. And in addition to a sparse gage network, many gage records are too short to reliably identify a pattern, and gage sites are often biased toward larger streams or sites being explored for hydropower or other resources. "We were able to use measured streamflow from sites with as little as 5 years of record, as long as all other data quality requirements were met," Biles says. In total, they compiled data from 253 streamgages located throughout the state: from the southernmost tip of Alaska to a gage on the Alaska Peninsula and on the north slope of the Brooks Range.

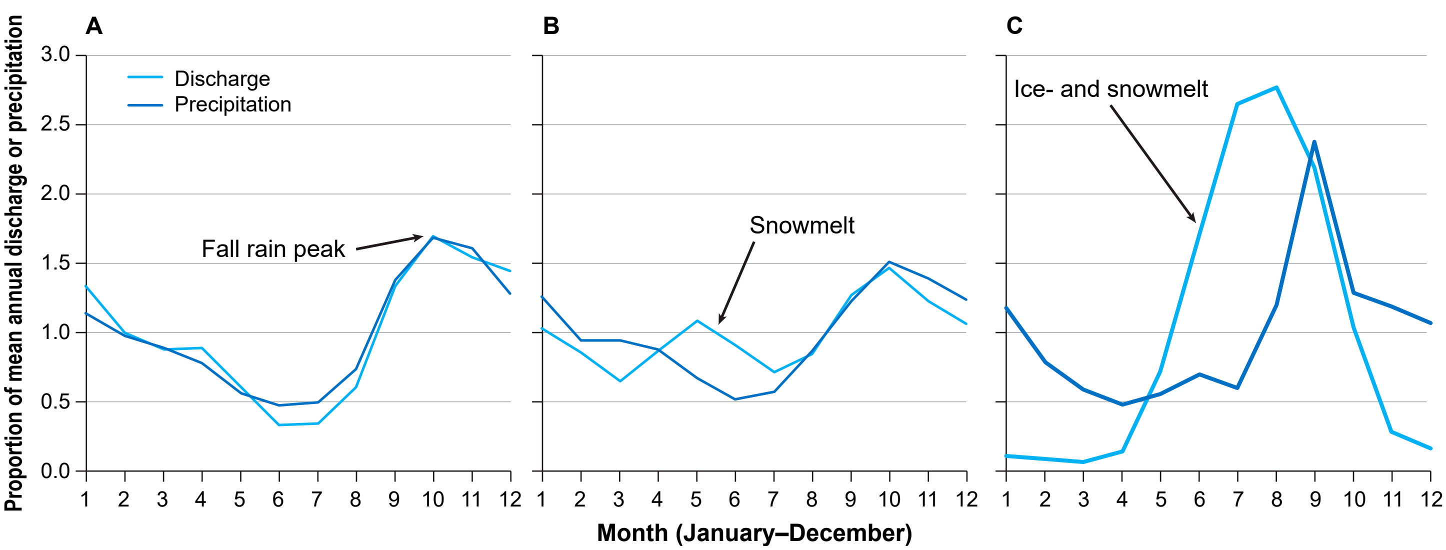
Streams were classified by their similarities in seasonal flow pattern. Using weather data and watershed characteristics, such as mean basin elevation, percentage of glacier cover, drainage area, and latitude, they inferred the primary drivers of streamflow for each regime class. The team identified nine seasonal flow regime classes statewide that fell into three major groups: rainfall dominant, snowmelt dominant, and high-elevation snowmelt or icemelt dominant. Each seasonal flow regime has a different timing and magnitude of seasonal and peak streamflows, and most regimes contain a mix of more than one seasonal driver.

"It is useful to understand the relationships between a watershed's climatic and physical characteristics, the streamflow drivers present in the watershed, and the resulting flow regime produced," explains Biles. For example, in southeast Alaska, low-elevation, low-relief watersheds typically do not store much winter snowpack or have glaciers. Incoming precipitation comes mostly as rain, and snowfall melts quickly. The seasonal flow regime associated with streams in these watersheds closely matches the precipitation pattern and has little to no extra pulse in streamflow due to spring snowmelt visible in the hydrograph. Higher elevation watersheds store more snow over winter, and a snowmelt pulse is clearly visible in the spring.

These dominantly rain-fed and snowmelt regime types also have a clear second pulse in the hydrograph that is coincident with the fall heavy rain period and a low-flow period during the summer when snowmelt is depleted and precipitation is at its lowest. In contrast, the highest elevation watersheds store large amounts of snow and tend to have glaciers. Streams in these watersheds maintain high summer flows because of a continuous supply of meltwater and have lowest flows in the

KEY FINDINGS

- The southeast Alaska drainage basin, which contains the rivers in southeast Alaska, parts of northwest British Columbia, and southwest Yukon Territory, discharges about 430 km^3 of freshwater into the Gulf of Alaska each year. This discharge is larger than either the Yukon or Columbia Rivers and greatly influences the hydrology of the Gulf of Alaska and its estuaries.
- Rainfall, snowmelt, and high-elevation snow and ice storage create a range of streamflow patterns that vary in the timing and magnitude of seasonal and peak streamflows.
- Maps of average monthly runoff illustrate the spatial variation in runoff timing by watershed and provide a template for future investigations into how nutrients are moved and cycled along coastal environments from enclosed estuaries to the open ocean.



Hydrographs showing the pattern of stream discharge from three southeast Alaska watersheds with different seasonal streamflow regimes. Precipitation timing is also plotted to illustrate the streamflow drivers. (A) Discharge closely mimics precipitation year-round, indicating that rainfall is the primary source of streamflow. (B) Snowmelt-driven streamflow can be identified where discharge exceeds precipitation in the spring. (C) Discharge far exceeds precipitation in spring through summer in watersheds where glaciers and high-elevation snowpack provide a steady supply of meltwater.

winter when precipitation remains frozen until the following spring.

The associations between flow regimes and basin characteristics are useful for understanding how streamflow patterns might respond to climate change. For example, "As climate warms, we can visualize what a progression from a spring snowmelt-dominated regime to a fall-winter rainfall-dominated regime might look like," explains Curran. This progression would change the timing and amount of freshwater delivery to marine systems and produce changes in stream temperature and water chemistry. In addition to potential effects on aquatic systems, changes to streamflow patterns and peak flows may impact infrastructure, like culverts, bridges, and hydroelectric plants.

Managers and planners can use this information to identify watersheds and associated aquatic systems that may be most vulnerable to climate change-induced disruptions to established streamflow patterns.

Managing the Flow

"Managing water on the Tongass," is how Prussian describes her work in the Tongass National Forest. When planning the placement of culverts or roads, "We have to think about how streamflow looks today, what streamflow looks like year-round, and what streamflow might look like in the future," she explains. "How is a management activity that we're proposing going to interact with flow, and what might the effects of this management in flow be, both from a water quality and water quantity perspective? Frances' [Biles] and Janet's [Curran's] research helps frame that."

LAND MANAGEMENT IMPLICATIONS

- Changes in temperature, precipitation, and snow and glacier cover affect the timing and volume of water flowing through a watershed. Identifying watersheds by their current streamflow drivers enables managers to focus on vulnerable watersheds and anticipate changes to stream discharge that can affect aquatic resources.
- Integrating seasonal streamflow regimes, elevation, and climate data is key to better understanding how projected future changes in snowfall, rainfall, and temperature will affect streamflows.

Knowing a stream's flow regime and its likely response to climate change can inform other management activities, such as doing instream work when placing or replacing culverts or monitoring stream health. Scheduling instream work is based on timing windows of salmon migration, whether outgoing or incoming. If the seasonal flow regime shifts, this could affect the timing of fish migration. "We actually may shift our work a bit to accommodate different timing of migration," says Emil Tucker, also a hydrologist with the Tongass National Forest.

Tongass staff also monitor stream water temperature because it's a significant driver for fish productivity. "One of the ways we look at our water temperature network is by stratifying streams into these different seasonal flow regimes," Tucker explains. "We look at the rain-fed streams because those are the warmest and have the lowest summer flows and are therefore the most vulnerable under a warming climate to habitat conditions that are harmful to fish, especially if warmer temperatures are combined with less precipitation. If a low-flow summer water period is really low, this historically has led to fish kills."

Into the Ocean

While Curran and Biles used observed data from the streamgage network to look at seasonal discharge patterns and associated drivers of streamflow, the second research team took a modeling approach to estimate the quantity of freshwater discharge flowing from all watersheds in the southeast Alaska drainage basin to the ocean. Biles, D'Amore, and Edwards worked with their Canadian colleagues Joel Trubilowicz and Bill Floyd to create a distributed climate water balance model that estimates average monthly freshwater runoff for the entire Gulf of Alaska drainage basin. Landcover, temperature, precipitation, and measured streamflow from streamgages were input to the model to produce a 400-m grid of average monthly runoff.

"Other freshwater discharge models have been developed that include the southeast Alaska drainage basin, but these were either too coarse to use for calculating discharge from smaller watersheds, or they only provided annual estimates," explains Biles. "We envisioned that our model, with a more refined picture of the distribution and timing

A newly constructed footbridge in the Tongass National Forest. Information about streamflow is critical when designing infrastructure projects that could be damaged during floods. USDA Forest Service photo.

A newly installed culvert in the Tongass National Forest sized for 100-year flows and for facilitating fish passage upstream. Information about the stream's flow regime was critical for determining the needed size and scheduling the instream work. USDA Forest Service photo by Heidi Lombard.

of flow into the ocean, could be used to better quantify and illustrate nutrient delivery to coastal habitats. We also thought the model could help oceanographers detect relationships between freshwater discharge patterns and ocean chemistry and currents."

The team calculated a mean annual freshwater discharge of 430 km^3. "Southeast Alaska discharges nearly as much freshwater as the Yukon and Columbia Rivers combined," D'Amore says. "These are rivers that people have studied extensively, but the southeast Alaska drainage basin has considerably more freshwater flowing into the ocean than either river; it's just not apparent because discharge from the southeast Alaska drainage basin is distributed across thousands of small and large streams instead of flowing from a single large river." Much of this freshwater flows into the enclosed coastal waters of the Alexander Archipelago before emptying into the open ocean.

An aerial view of streams flowing into Boussole Bay. The southeast Alaska drainage basin annually discharges nearly as much freshwater as the Yukon and Columbia Rivers combined. Photo courtesy of Mandy Lindeberg, National Oceanic and Atmospheric Administration Fisheries, Alaska ShoreZone Program.

What's Next for Freshwater?

These teams have addressed their immediate questions regarding freshwater, but the answers prompted other lines of inquiry. Using the distributed climate water balance model, one team is calculating the volume of various stream nutrients, such as dissolved organic carbon and dissolved nitrogen, that are delivered to the ocean as a source of energy for the food web.

"We really need to better understand the spatial distribution and quantity of stream nutrients being delivered to the marine environment as this affects the health and productivity of the coastal margin," D'Amore says.

As for the streamflows carrying these dissolved nutrients, a next step is assessing how climate change is altering the volume and timing of freshwater discharge. D'Amore and Prussian have both observed changes in the timing, type, and severity of storms.

"Water is being delivered in very strange and extreme ways, either too little or too much at a time," D'Amore explains. Since 2019, southeast Alaska has experienced record drought, record rainfall, and disastrous landslides.

"Landslides used to happen at a certain time of year, and our big flows used to happen in September through November," adds Prussian. "Now we're seeing big storms in August, and regionwide, we are seeing more episodic events, like atmospheric rivers."

Biles wonders about the existence of other streamflow regimes, such as those from watersheds with extensive wetlands or significant groundwater flow. These systems were absent or not well-represented in their study because they are not typically gaged and lack measurements. "We don't have a good idea of where these systems are or what they look like," she says. "They may not be big players in the overall Alaska freshwater discharge picture, but we don't know yet how they might be uniquely contributing to Alaska's coastal ecosystems."

These observations tie in with the need to consider how changes in streamflow drivers can affect not just the seasonality, but also the amount, of streamflow. According to Curran, this is a natural follow-on question that builds on the foundation of her and Biles' research identifying existing seasonal streamflow patterns and drivers. To which Biles adds, "If infrastructure is designed for certain types of peak flows or possible flooding events, and those triggers are changing or becoming more extreme, then this information could help to inform future plans."

"Over all, rocks, wood, and water, brooded the spirit of repose, and the silent energy of nature stirred the soul to its inmost depths."

—Thomas Cole, English-American painter

For Further Reading

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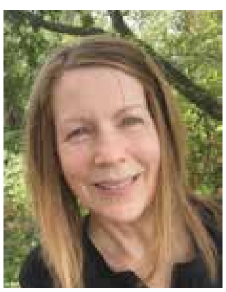

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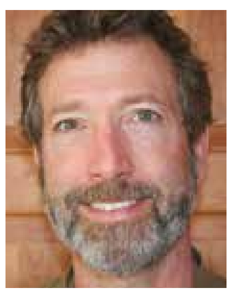

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