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IN THIS ISSUE

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Can Beaver Dams Mitigate Water Scarcity Caused by Climate Change and Population Growth?

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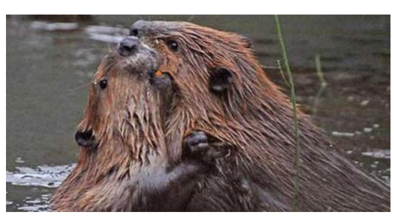
Precipitation and streamflow patterns have shifted in the western U.S. over the past few decades (Melillo et al. 2014) and, given projections of future climate change, there is strong potential for continued and accelerated hydrologic alterations and water scarcity in some areas (Stewart et al. 2004). In many sub-regions, snowpack is projected to decrease and peak streamflow is expected to come earlier in the year. Since much of the western U.S. depends on snowmelt-fed streams and reservoirs to meet urban and agricultural water needs, these alterations may affect the ability of current water resources infrastructure to meet future water demands. To make matters worse, rapid population growth in the western U.S. will likely increase future water demand and put additional stress on the current water resources infrastructure (Tidwell et al. 2014).

Projections of water scarcity have prompted investigations into methods to meet future water needs, with proposed projects often aimed at mitigating future water scarcity by developing additional, man-made water storage reservoirs. Such projects are very expensive and are often detrimental to wildlife populations and ecosystems due to their disruption of natural water and sediment flows. For example, two reservoir sites proposed by the Bear River Pipeline Project in northern Utah would flood part of the Bear River National Wildlife Refuge and Spawn Creek, which contains important spawning habitat for native Bonneville Cutthroat Trout and has been the focus of many restoration efforts (Figure 1). We hypothesize that the presence of beaver dam complexes and associated wet meadows may offer a viable and low-cost alternative to smaller-scale man-made reservoirs to help meet expected water demands and preserve important habitat and ecosystems.



StreamNotes is an aquatic and riparian systems publication with the objective of facilitating knowledge transfer from research & development and field-based success stories to on-the-ground application, through technical articles, case studies, and news articles. Stream related topics include hydrology, fluvial geomorphology, aquatic biology, riparian plant ecology, and climate change.

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Figure 1: A beaver dam complex on Spawn Creek in Logan Canyon, Utah on the Cache National Forest.

At the reach scale, beaver dams impound water above ground, increase groundwater elevations, and facilitate groundwater recharge. Water delivered during spring runoff and storm events is stored by beaver ponds, and as streamflow decreases in late summer beaver ponds can release water stored in the pond and the adjacent groundwater to supplement streamflow (Majerova et al. 2015, Nyssen et al. 2011). While the hydrologic effects of beaver dams at the reach scale have been well studied, the cumulative impacts of beaver dams at scales meaningful to water resource management (e.g. watersheds) are less clear. Furthermore, while beaver were ubiquitous throughout most of the contiguous U.S. before European settlement, they were heavily trapped and extirpated from many watersheds, leaving their current populations at a small fraction of historical abundance (Dolan 2010).

Our research focus is to extend reach-level findings of beaver dam effects to the watershed scale in order to quantify the potential hydrologic impacts of beaver dam complexes across riverscapes. Specifically, we are addressing such questions as: To what extent can increased beaver dam density improve water storage and availability at the watershed scale? Can promoting and encouraging the construction of beaver dams increase water storage to a level that such a strategy may be a low cost and ecologically sound alternative to smaller-scale reservoir construction projects?

The Beaver Restoration Assessment Tool

An important initial step to understanding how beaver dams influence water availability at the watershed scale is estimating how many beaver dams a watershed can support. The beaver dam capacity model within the Beaver Restoration Assessment Tool (BRAT) estimates the maximum number of beaver dams a stream reach can support (Macfarlane et al. 2015; Figure 2). This capacity estimate is derived by considering

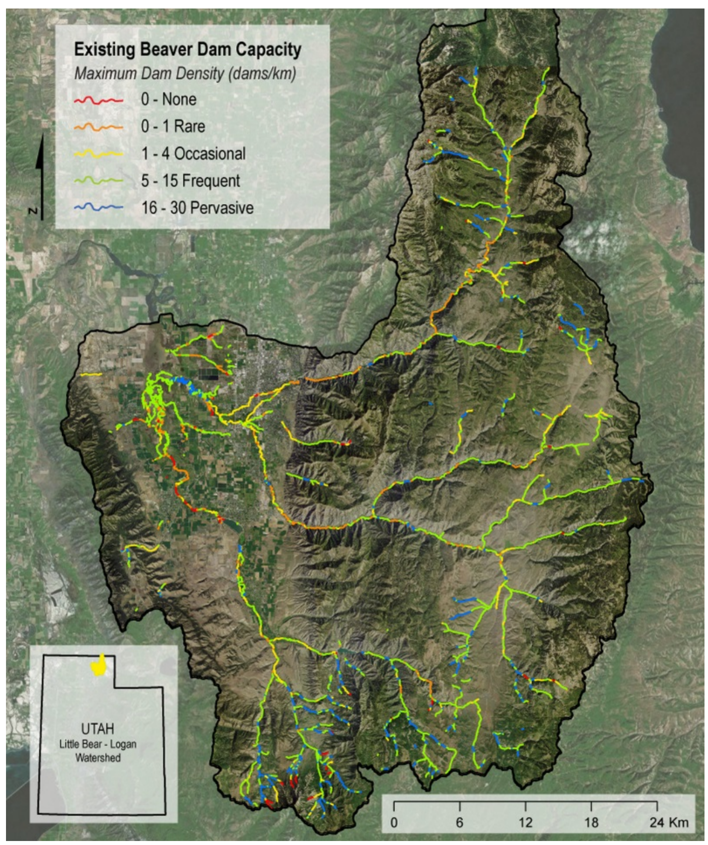

Figure 2: Modeled beaver dam capacity estimates from the Beaver Restoration Assessment Tool (BRAT) for the Little Bear-Logan River watershed in northern Utah.

seven variables required for beaver dam construction: (1) a reliable water source; (2) streambank vegetation conducive to foraging and dam building; (3) vegetation within 100 m of streams to support expansion of dam complexes and maintain large beaver colonies; (4) likelihood that dams could be built across the channel during low flows; (5) the likelihood that a beaver dam on a stream is likely to withstand typical floods, (6) a suitable gradient that is neither too low to limit dam density nor too high to preclude the building or persistence of dams and; (7) a suitable channel scale that is not too large to restrict the building or persistence of dams (Macfarlane et al. 2015).

When applied throughout the entire state of Utah, the dam capacity model indicates that watersheds throughout the state are roughly at only 10% of capacity (Macfarlane et al. 2015) – riverscapes throughout the state of Utah have the capacity to support substantially more beaver dams than currently exist. The beaver dam capacity model outputs can be used to identify where beaver conservation or relocation will have the most benefit or the highest potential for additional beaver dams.

Case Study: Little-Bear-Logan River watershed

An example from the Little Bear-Logan River watershed (HUC 8) helps illustrate how water storage in beaver ponds compares to traditional water management projects. The Little Bear-Logan River watershed is located in northern Utah and its water flows to the regionally important Bear River. Currently, a feasibility study is being conducted to identify locations for reservoirs that would store up to 220,000 acre-feet of water from the Bear River watershed. Two proposed reservoir sites are located in the Little Bear-Logan River watershed. The proposed reservoirs would store up to 40,000 acre feet of water but could damage important fish and wildlife habitat, and would cost an estimated $300 - $500 million.

The BRAT dam capacity model estimates that the Little Bear-Logan River watershed can support a maximum of 7400 beaver dams (Figure 2). Since it is very unlikely that every stream reach in the watershed would be at full dam capacity simultaneously, we could reasonably expect 3,700 dams (50% of estimated maximum capacity) to be actively maintained by beaver at a single point in time. These dams create water storage by directly ponding water and delaying this water from flowing downstream. Once a dam is built and water is ponded on the surface, additional water is forced into the soil adjacent to and downstream of the pond. This results in two primary water storage reservoirs created by beaver dams: water impounded (ponded) above ground, and groundwater (Figure 3). The average volume of above-ground water impounded by a beaver dam is estimated to be somewhere between 0.28 – 1.01 acre-feet. (Beedle 1991, Klimenko and Eponchintseva 2015). Groundwater storage is more variable and more difficult to monitor, thus reliable estimates of average groundwater storage per pond are not currently available. To get a sense for the total volume of water beaver dams can store in the Little Bear-Logan River watershed, we can multiply the expected dam

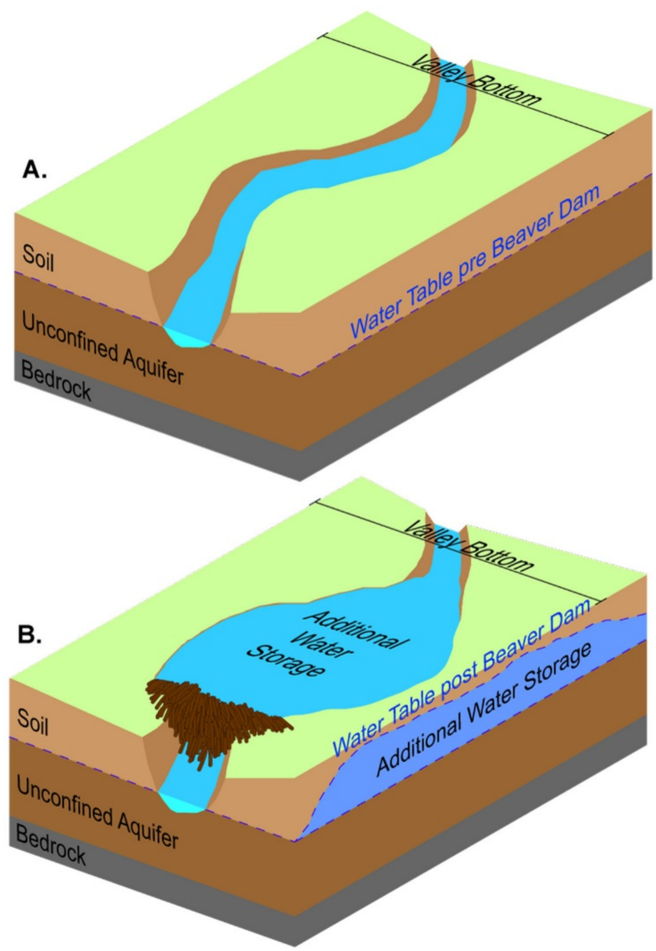

Figure 3: Conceptual illustration of water storage additions pre-beaver dam (A) and post-beaver dam (B) construction to above and below ground water storage.

capacity (3,700 dams) by estimated pond storage. This yields an estimate of 1,000 – 3,700 acre-feet of water that could be stored in the Little Bear-Logan River watershed. Including groundwater storage could increase these volumes by more than 5 fold, with a conservative estimate doubling these values and resulting in an estimated storage volume between approximately 2,000 and 7,500 acre-feet.

Though the estimated water storage resulting from additional beaver dams in the Little Bear-Logan River watershed is well below the capacity of proposed reservoirs, it is not insubstantial, is low cost, and also provides ecological and hydrological benefits. For example, the timing of water delivery is often more important than the quantity of water delivered. Beaver dams may store water from spring runoff then release the stored water in drier summer months, providing an increase in water supply when demand is highest. While preliminary analyses (such as the one described above) suggest beaver dams may indeed significantly affect hydrology favorably for water resource management, more detailed analyses are necessary to determine just how many dams are needed to produce meaningful results and determine the maximum beneficial effects. Since our understanding concerning beavers' impact on hydrology prior to the fur trade is extremely limited, perhaps the best way to gain an understanding of these effects is through the use of water storage models.

At the core of our research is development of a model to estimate the potential surface water and groundwater storage created by beaver dam construction. This model will allow simulation of multiple beaver dams along a stream, or in a watershed, to identify potential changes to storage.

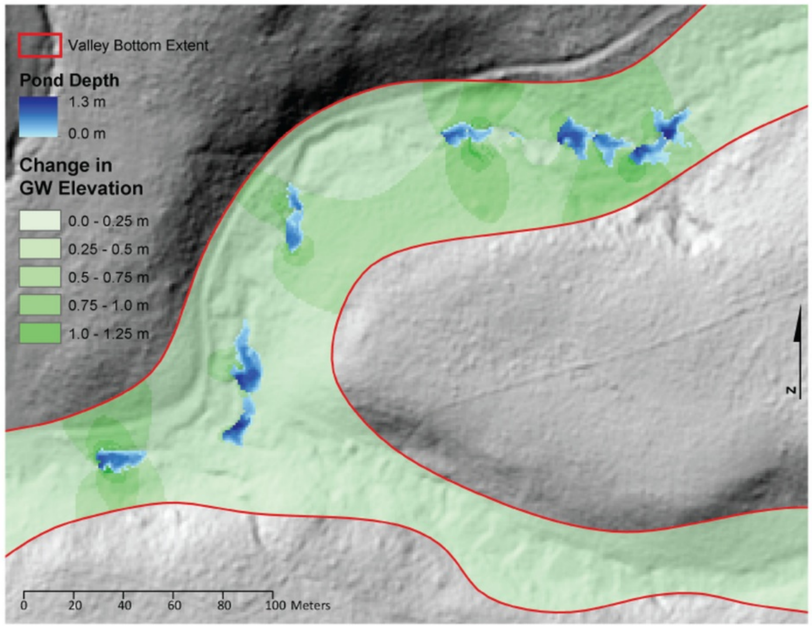

Figure 4: Modeled beaver pond depths and potential changes to groundwater table elevations resulting from beaver dam construction for Spawn Creek. This stream is in the Little Bear-Logan River watershed in northern Utah, on the Cache National Forest.

Preliminary results (Figure 4) are achieved using estimates of beaver dam height, a digital elevation model (DEM), and a groundwater model (MODFLOW; Harbaugh 2005). With an estimate of beaver dam height, simple numerical models are applied to the DEM to determine the size and volume of the resulting pond. Pond size and volume information are then used as inputs to the groundwater model which estimates how changes to surface water resulting from dam construction will affect groundwater. In contrast to the water storage estimates presented above, these methods account for changes to groundwater storage and account for variation in dam location. Taking this one step further, spatial estimates of the effects of beaver dams on water storage may be used to parameterize hydrologic models to assess how these dams may affect the timing of water delivery. These hydrologic models may then be used by water managers to identify where beaver restoration may potentially supplement water supplies and reduce the need for additional man-made reservoir storage.

Management Implications

- Beaver dams increase water storage on the landscape to a degree that may compete with man-made reservoirs in some situations.
- With information from the BRAT dam capacity model, spatially explicit estimates of increased water storage from beaver dam construction can be modeled.
- Hydrologic modelling may aid water managers in identifying situations where beaver restoration may mitigate water scarcity and reduce the need for man-made infrastructure.

Acknowledgements

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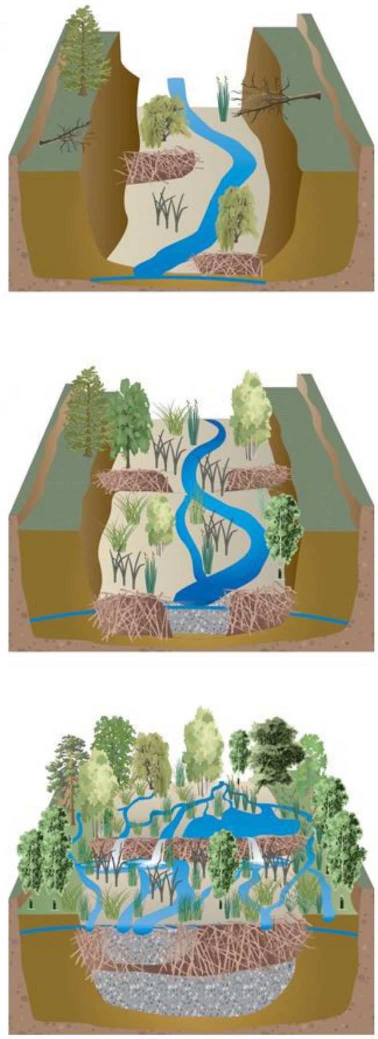


Beaver-induced recovery of incised streams. Graphic extracted from Pollock et al. 2015

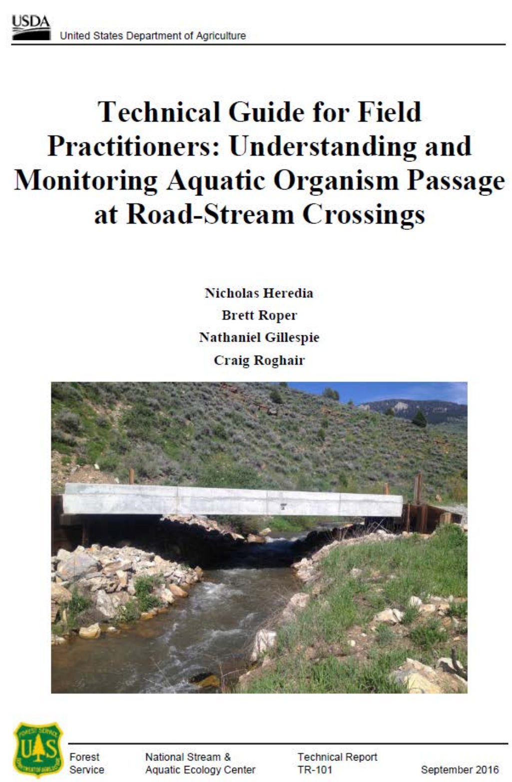
Notices and Technical Tips

- **Direct technical assistance from applied scientists at the National Stream and Aquatic Ecology Center** is available to help Forest Service field practitioners with managing and restoring streams and riparian corridors. The technical expertise of the Center includes hydrology, fluvial geomorphology, riparian plant ecology, aquatic ecology, climatology, and engineering. If you would like to discuss a specific stream-related resource problem and arrange a field visit, please contact a scientist at the Center or David Levinson, the NSAEC program manager.

- **What is the scientific method, and why do so many people get it wrong?** From Peter Ellerton (University of Queensland) and ScienceAlert, this article reviews the scientific method within the context of the controversy (in some quarters) regarding climate change and other hot-button scientific topics. These issues are, in part, symptomatic of general ignorance of how the scientific process works. "When our theories are successful at predicting outcomes, and form a web of higher level theories that are themselves successful, we have a strong case for grounding our actions in them."

- **Blueheads & Bonnevilles: A partnership effort to benefit two native fish species** "The Western Native Trout Initiative and the Desert Fish Habitat Partnership are proud to present *Blueheads and Bonnevilles*, a short film about the work we are doing with our partners in the Weber River, Utah, to benefit the native bluehead sucker and Bonneville cutthroat trout. We produced the film to celebrate the fish and their habitat, the strong partnership that has developed for the Weber River, and the 10th anniversary of the National Fish Habitat Partnership."

- **Technical Guide for Field Practitioners: Understanding and Monitoring Aquatic Organism Passage (AOP) at Road-Stream Crossings**, has been released from the National Stream and Aquatic Ecology Center. "Past USFS road-stream crossing remediation efforts have produced varying degrees of success, as measured by newly available habitat per dollar spent. The need to ensure that AOP projects are implemented correctly coupled with the challenge to prioritize AOP among many potential aquatic barrier road-stream crossings creates the need for a comprehensive and concise protocol for road-stream crossing AOP assessments. Because identifying potential barriers to AOP can be difficult and costly, we suggest the following steps for focusing barrier remediation efforts: 1) Identify locations of road-stream crossings; 2) Determine passability of barriers; and 3) Identify where remediation efforts will be most effective to achieve goals and objectives."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Technical Guide for Field Practitioners: Understanding and Monitoring Aquatic Organism Passage at Road-Stream Crossings

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Mediating Water Temperature Increases Due to Livestock and Global Change in High-Elevation Meadow Streams

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Salmonids have very restricted water temperature tolerances; warming water from climate change could create stressful and possibly lethal stream habitat for native trout. To help understand the interactive effects of climate warming with ongoing stressors such as livestock grazing on water temperature, researchers from the Pacific Southwest Research Station and University of California, Berkeley, conducted a six-year study documenting high elevation water temperatures in areas of the Golden Trout Wilderness. The wilderness area is located within the Sequoia and Inyo National Forests in California and was designated Wilderness primarily to protect the native California golden trout (*Oncorhynchus mykiss aguabonita*), the state's official fish.

In this study (PlosOne article), we investigated the effect of livestock on stream water temperature in high elevation meadows of the Golden Trout Wilderness. Vegetation removal and the degradation of the riparian zone (Figure 5) from livestock activities are particularly deleterious for cold-water salmonids because the streamside vegetation is an important factor in keeping the stream cool. Golden trout are additionally at risk due to degraded habitat, genetic introgression, limited distribution, competition with exotic trout, and warming water temperatures. The California golden trout could be particularly sensitive to warming because of their naturally restricted distribution in headwater meadow streams prevent refuge to higher, cooler elevations.

To understand the impact of land use on water temperature, we measured streamside vegetation and monitored water temperature in three meadow streams. We compared livestock impacts on the meadow systems under different grazing management, including two meadows where cattle have been excluded since 2001 and a third meadow where an experimental cattle-exclusion area was constructed in 1991. In the partially-grazed meadow, we examined the direct effect of cattle on the vegetative cover and stream shading inside and outside the cattle exclosure and we measured temperature along the stream in both areas. Additionally, we compared water temperatures among meadows using temperature data collected over six years. Together, these analyses allowed us to assess the influence of cattle on stream temperatures in these meadow streams. Finally, we modeled expected future temperatures under different climate change scenarios to understand how these human impacts interact to influence the water temperature.

Figure 5: Mulkey Meadows stream condition in the Golden Trout Wilderness.

Our key findings included:

- Water temperatures approached the upper limit of tolerance for the golden trout in some habitat areas (Figure 6).
- Water temperatures were cooler in ungrazed meadow areas with willows.
- Riverbank vegetation was both larger and denser where livestock were not present.
- Future water temperatures will be highest in grazed areas.

Management Implications

- Cattle grazing can interact with climate change to intensify warming in high elevation meadow streams; protecting and restoring streamside vegetation can help keep streams cool for the California golden trout. Management practices that increase and improve streamside vegetation must be employed to protect native trout.
- Ensuring resilience of streams to future climate warming requires a realistic assessment of whether cattle grazing is compatible with trout survival.

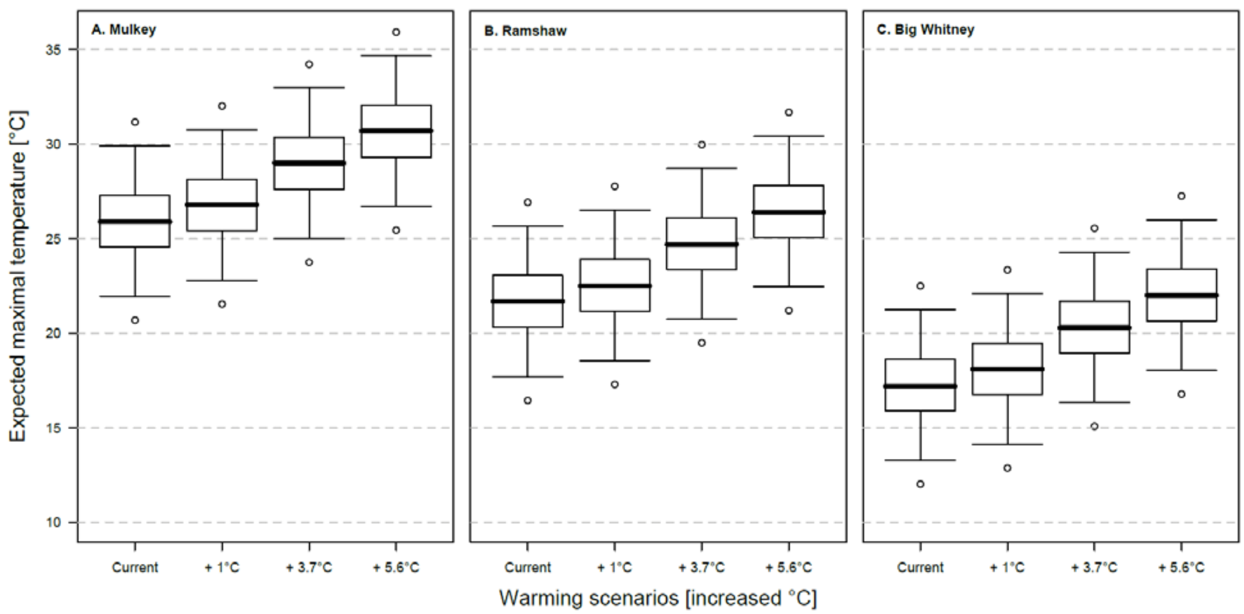

Figure 6: Current water temperatures and predicted future temperatures under 3 different climate warming scenarios (PlosOne article) in Mulkey, Ramshaw, and Big Whitney meadows, Golden Trout Wilderness, California.

Coarse Particulate Organic Matter Transport in Mountain Channels

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Coarse particulate organic matter (CPOM) consists of leaves, needles, coniferous cones, twigs, sticks, branches, bark pieces, and wood fragments that range in size between approximately 1-100 mm (Figure 7). Forested headwater stream store and transport an abundance of CPOM, which is important ecologically for macroinvertebrates and benthic organisms as this material provides food for shredders and grazers. Shredders such as stoneflies feed on CPOM and break it into smaller particles through their feeding and digestive processes. Grazers such as snails and beetles feed on algae and other plant material living on CPOM and rocks. CPOM also provides habitat for macroinvertebrates that bore into wood or incorporate organic material into their casing. Changes in the amount and composition of CPOM to streams from events such as clear cutting, wildfires, or severe flooding can have ecological implications by altering nutrient cycling and food web dynamics.

CPOM is supplied to streams directly from vegetation sources along channel banks as well as transported from overland flow and soil erosion. The input and retention of CPOM in streams is a function of channel morphology, flow hydraulics, and vegetation structure. Because CPOM has low density and is easily entrained by flowing water, instantaneous rates of waterlogged CPOM transport is influenced by the interactions between local flow hydraulics and the dynamics of CPOM stored and released from within the streambed and along the banks.

There is ample information on annual carbon exports in the form of fine organic material (particles < 1 mm) that is contained in suspended sediment samples and in the form of large woody debris. However, there is little information about the role of CPOM in carbon export budgets. Fluvial transport of CPOM may be the dominant form in which particulate carbon is exported from a watershed (Turowski et al., 2016). Accordingly, there is a need to better quantify and understand CPOM transport rates when establishing nutrient and carbon budgets in a watershed.

Figure 7: Coarse particulate organic matter (CPOM).

Measuring CPOM conveyance has been a challenge to advancing insights into its transport dynamics in streams. Excavating and analyzing the annually accumulated material in debris basins can quantify CPOM export, however, that method reveals little insight into seasonal CPOM transport dynamics. The collection of mobile CPOM in a screened sampling box under a drop structure and emptying the box episodically is an effective method, but is limited to small streams draining small catchments of a few hectares and having discharges of just a few liters/second. CPOM has also been collected by installing drift nets in the water column, but this method is limited to low-gradient streams with tranquil flows.

A recent study by Bunte et al. (2015, 2016) quantified CPOM transport in two Rocky Mountain streams using bedload traps (Figure 8) and provided insights on factors controlling CPOM transport rates and dynamics. This article provides an overview of the results of this work. For information regarding methods and analysis, refer to Bunte et al. (2015, 2016).

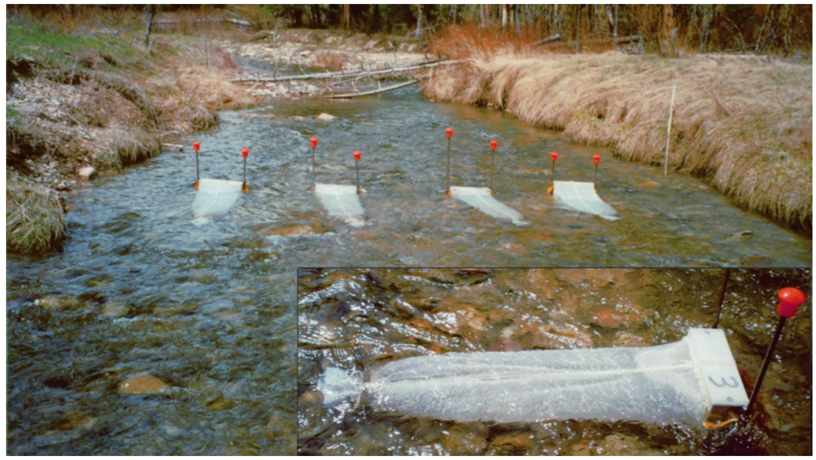

Figure 8: Bedload traps in Little Granite Creek, with bedload trap detail.

Results

At the study sites on East St. Louis Creek and Little Granite Creek (Figure 8), two streams in subalpine watersheds of the Rocky Mountains, CPOM transport was driven by availability and supply. CPOM transport was much higher for a given discharge during the first rising limb of the hydrograph than on the first falling limb as well as subsequent rising and falling limbs. The data describe a clockwise hysteresis loop for a storm event or a sequence of clockwise hysteresis loops for days with consecutively increasing flows in a snowmelt flow regime (Figure 10). Consecutively, sampled data typically follow a similar hysteresis loop pattern, but each hysteresis loops tends to get flatter with time. This hysteresis loop pattern can be used to interpolate CPOM rates when only a few samples are collected.

Annual CPOM loads were 3.2 metric tonnes/year for East St. Louis Creek and 3.6 metric tonnes/year for Little Granite Creek. These CPOM loads were collected during a low flow years in which bankfull discharge occurred only briefly. A long-term average CPOM load would be larger because high flow years would be included. For example, long-term annual CPOM load data from deciduous forests demonstrated that annual loads vary within a factor of about 10 between low flow years and high flow years. Accordingly, the long-term average load for the study streams was estimated as the geometric mean of the low flow load and its 10-folds value, yielding 10.2 and 11.3 tonnes/year for East St. Louis Creek and Little Granite Creek, respectively.

Because there are very few measured CPOM transport relations in forested mountain watersheds, it may likely be necessary to estimate a transport relation for un-sampled streams. A plot of CPOM transport rates against unit discharge (discharge divided by bankfull stream width) from the two Rocky

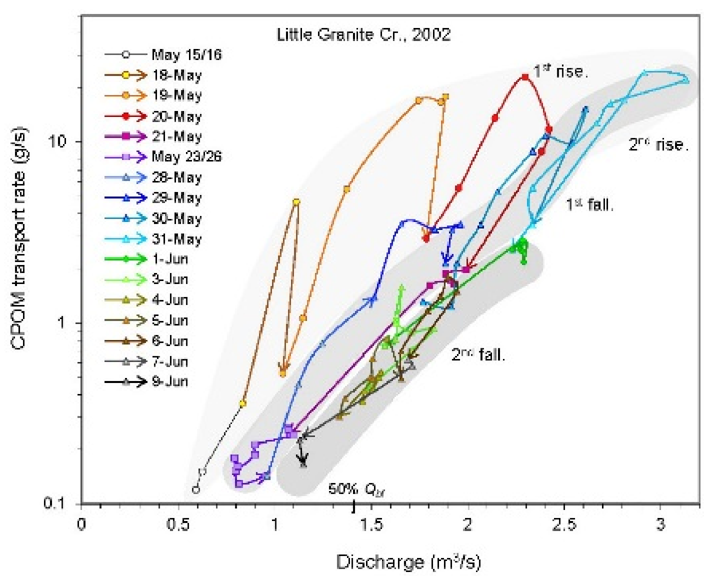

Figure 9: CPOM transport rates versus discharge, with hysteresis loops.

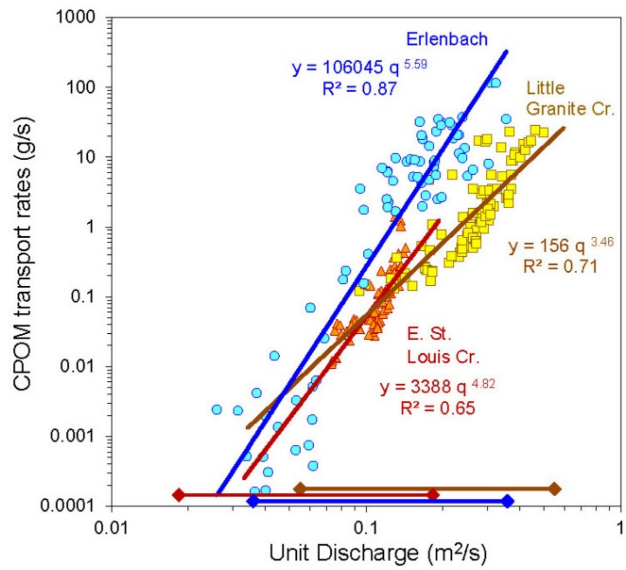

Figure 10: CPOM transport versus unit discharge, E. St. Louis, Little Granite, and Erlenbach Creeks.

Mountain sites plot along similar lines (Figure 11). The slightly higher CPOM transport relation for East St. Louis Creek for a specified unit discharge is attributed to slightly greater CPOM production and slightly higher drainage density in the wetter, north facing East St. Louis Creek watershed compared to the colder, southeast facing Little Granite Creek watershed.

A CPOM transport relation developed from a different study of an alpine stream in the Swiss Alpine foothills (Turowski et al. 2013) is included to compare the factors that influence CPOM transport rates and for predicting CPOM transport rates at un-sampled sites. Erlenbach is a small, steep channel in a coniferous-forested watershed with a drainage area of 0.7 km^2. Compared to the two sites in the Rocky Mountains, CPOM transport rates were considerably higher at Erlenbach (Figure 11). At high unit discharges, CPOM transport rates are 2-3 orders of magnitude higher at Erlenbach than at the two Rocky Mountain sites. The higher CPOM transport rates at the Erlenbach are attributed to a substantially larger input of CPOM to the stream because of unstable slopes, more efficient hillslope-channel connections, higher wood decay rates due to a wetter and temperate climate, higher drainage density, higher bedload transport that breaks down large wood during high-energy flows, and multifaceted flow regime consisting of snowmelt runoff, summer rainfall, and intense storm events.

We consider the Erlenbach site to be a high-end member of CPOM transport, whereas the two streams in the much drier Rocky Mountain climate are likely low-end members of CPOM transport. Therefore, CPOM transport relations from other mountain streams in mainly coniferous forests are likely to fall somewhere in between these measured relations.

Key Findings and Management Implications

- CPOM transport relationships are known for very few mountain streams.
- Bedload traps are suitable samplers for both CPOM and gravel bedload in wadeable streams, which invites collaboration between CPOM and gravel bedload studies.
- Intensive field sampling is required due to strong hysteresis relations between CPOM transport rates and discharge.
- Difference in CPOM transport relations between streams is attributed to CPOM supply (e.g., primary production, wood decay rate) and effectiveness of CPOM transfer to the channel (e.g., drainage density, hillslope connectivity).
- Based on assessments of supply and transfer effectiveness, CPOM transport relations may be estimated for mountain streams in coniferous-forested watersheds.

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