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Natural dams and biogeochemistry at the river network scale: implications for water quality

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Basic Information

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Publications

There are no publications.

Problem Statement

In the absence of modern humans, river networks are patchy systems, where free-flowing reaches are interspersed with ponds and meadows generated by "natural" dams. In New England, most of these dams are beaver dams, which create ponds and meadows that can extend over more than half of the length of a headwater stream network. Additional natural dams that would have been common prior to the modern industrial age include bedrock knobs (which were blasted away for the sake of log drives), major log jams, and landslide dams. Despite this patchy nature of river systems, our conception of the pre-industrial river network is typically that of a system that is free-flowing and connected, and this assumption lies at the foundation of our infrastructure development and scientific models. As a result, when natural dams appear in a river network, both our infrastructure and scientific models tend to fail.

The impacts of natural dams on biogeochemical processing have dramatic implications for water quality. Intensive site studies show that the impoundments created by these dams tend to have higher temperatures, lower oxygen levels, higher concentrations of available nutrients, and larger pools of nutrients and organic matter. Although these characteristics are commonly viewed as undesirable for water quality, the opposite can often be the case. In particular, site studies show that, in enriched systems, these impoundments can remove significant amounts of nitrogen through denitrification. They also can provide sites of locally increased acid neutralizing capacity. However, nearly all of the knowledge of the impacts of natural dams is based on single site studies, with unknown implications for the river network scale. Given both the significant site-scale impact of single natural dams on biogeochemistry and the high frequency of natural dams in river networks without direct human intervention, we must understand the role of these dams on biogeochemical processes at the river network scale

Objectives

This research addresses the broad research question of: What is the difference in biogeochemical regime between free-flowing river reaches and river reaches associated with natural dams, and what is the extent of this difference at the river network scale? The three specific research questions addressed by this research are: (Q1) Can free-flowing river reaches and river reaches associated with natural dams be classified according to biogeochemical regime? (Q2) What is the nature of the transition in biogeochemical regime downstream of a natural dam? (Q3) Which landscape and demographic factors control their presence and frequency of natural dams? To address these questions, the research includes both of the following: measurement of site-scale biogeochemistry parameters along river networks that include free-flowing reaches and natural dams; and examination of the landscape-scale parameters that control the presence of natural dams.

Methods

The methods include field work and GIS, primarily in river networks in the Ashuelot and Contoocook basins of southwestern New Hampshire. The river networks in these basins range from entirely protected from modern human impact through highly managed urban streams.

Field research: Research questions 1 and 2 have been addressed with spatially and temporally extensive field data. The spatially extensive dataset was created using synoptic stream surveys along 138 river reaches in the summers of 2014 and 2015. The limits of the study reaches were defined by geomorphic features such as natural dams and the limits of the impoundments created by these dams. Field measurements in the study reaches include temperature, dissolved oxygen (DO), conductivity, pH, and oxidation-reduction potential (ORP) using an YSI Professional Plus multimeter. Channel cross-sectional shape and heights and widths of dams have also been surveyed with a laser distance meter and stadia rod.

Ten HOBO data logger arrays are collecting water level, temperature and conductivity at 15-minute (or shorter) intervals at three beaver ponds and one beaver meadow. The data logger arrays are upstream, downstream, and within each impoundment. An additional 27 temperature loggers are installed at an additional six ponds and meadows. These data are being used to both characterize biogeochemical state in the impoundments of natural dams versus free-flowing reaches and to assess the extent of downstream impact on biogeochemical state caused by these natural dam impoundments. Analysis of the hobo data has focused on temperatures as a proxy of ecosystem state.

GIS: Research question 3 has been examined for much of the Contoocook river network, in southwestern New Hampshire. For have been visually digitized and classified as one of the following patch types: (1) closed canopy; (2) beaver pond; (3) beaver meadow; (4) pond at a human-built dam; (5) meadow at a human-built dam; (6) human-managed floodplain (ditched); (7) unmanaged floodplain (many natural dams); and (8) renaturalizing human-created impoundment. The classifications were ground-truthed during the 2014 summer field season. These impoundments were overlaid onto a network for the study area extracted from the National Hydrography Dataset (NHD). A new river network of the study area was generated, where each segment of the extracted NHD network was assigned a patch type corresponding to the relevant digitized impoundment or, if there was no digitized impoundment that overlapped the network, the patch type was set as free-flowing.

We calculated a simple heterogeneity index (HI) for the new river network, where the HI at any given point is a simple count of the number of patch types along a reach that extends 500m upstream and 500m downstream of the each point. An alternative HI is the sum of the number of distinct patches, where a given patch type may be repeated. The HI was calculated every 25m along the digitized river network.

The landscape controls on patch type and HI are currently being assessed for the study network. The channel slope is calculated for each point on the digitized river network as the slope for the 250m reach extending upstream from the point. Elevations for slope calculations are extracted from the most recent DEM in the National Elevation Dataset. Relative stream power will be estimated as catchment area times channel gradient. The 2001 NH land cover assessment has been used to estimate percent forest, percent hardwood, and percent developed and agricultural land within a buffer for each reach. New Hampshire DOT GIS data have been used to estimate density of roads within a buffer along each reach, and the number of river crossings. When this dataset is complete, it will be used to determine the relationship between these physical parameters versus patch type and HI.

Findings

Field research – simple chemistry. The data from the synoptic sampling show a clear and distinct relationship between low oxygen and beaver meadows and ponds, with dissolved oxygen (DO) levels responding quickly as water flows into or out of a pond (Figure 1, next page). Examination of the high-temporal resolution data provides a more complex understanding (Figure 2, next page). Although these data generally support the simple message of lower oxygen levels in impoundments, they also show that the diurnal oxygen fluctuations are far greater within the impoundments, presumably due to increased photosynthesis and respiration generated by additional light. Further, the increased photosynthesis can even result in maximum oxygen levels in the impoundments that occasionally exceed the maximum in the free-flowing rivers. These fluctuations over space and time have obvious potential implications for biogeochemical cycling and water quality Continued research on a concurrent project involves lab analysis of collected water samples to assess the corresponding concentrations of common nitrogen species. Given the importance of oxygen in controlling biogeochemical reactions, particularly in the nitrogen cycle, these data strongly describe the importance of further understanding and assessing the network-scale role of beaver dams in water quality.

The pH data from the impoundments created by natural dams also show a similar trend of a clear, local impact, which is not necessarily transferred downstream (Figure 3, next page). These data show that the surveyed beaver ponds, as a population, have a lower pH than the free-flowing reaches; however, unlike the dissolved oxygen data, the longitudinal profiles show a more complex story at the local level (Figure 4, following page). There is a less clear trend in pH across the different patch types, with both increasing and decreasing trends found in meadows and free-flowing reaches. Log jams, on the other hand, show a much clearer trend of decreasing pH within the local impoundment (Figure 3). These log jam impoundments are usually less than 5m in length (in the direction of flow). When a given log jam impoundment is paired with its corresponding upstream and downstream reaches, the local pH is statistically lower, with an average decrease of 0.3. Unlike beaver dam impoundments, the changes in oxidative-reduction potential across the log jams are not statistically significant.

In combination, these data suggest that the small natural dams results in local changes in water chemistry—such as decreased pH, presumably due to increased organic acids—but not in larger changes in biogeochemical regime, which alterations of dissolved oxygen would generate. Further, these changes are only local in nature and the biogeochemical regime quickly returns downstream.

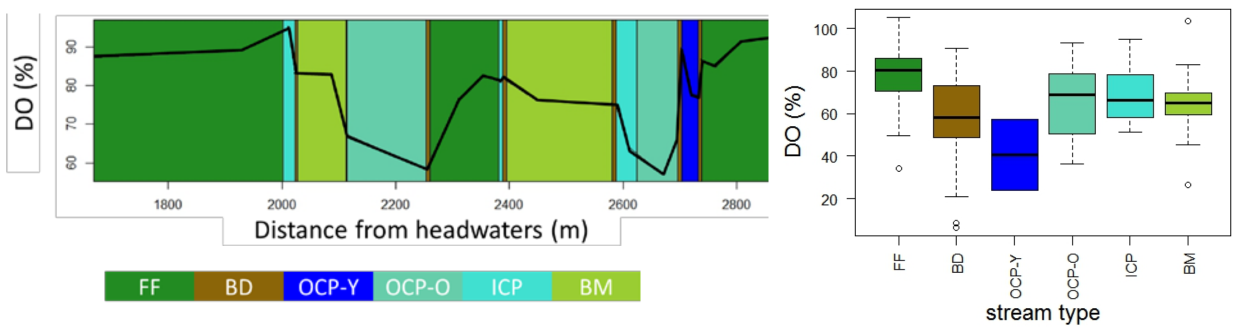

Figure 1. Left: example of dissolved oxygen profile along one study river (Hosley Brook, Hancock, NH). Right: comparison of DO across various feature types for all study reaches. Legend: FF—free-flowing; BD—beaver dam; OCP-Y—out of channel beaver pond, young; OCP-O—out of channel beaver pond, old; ICP—in-channel beaver pond; BM—beaver meadow.

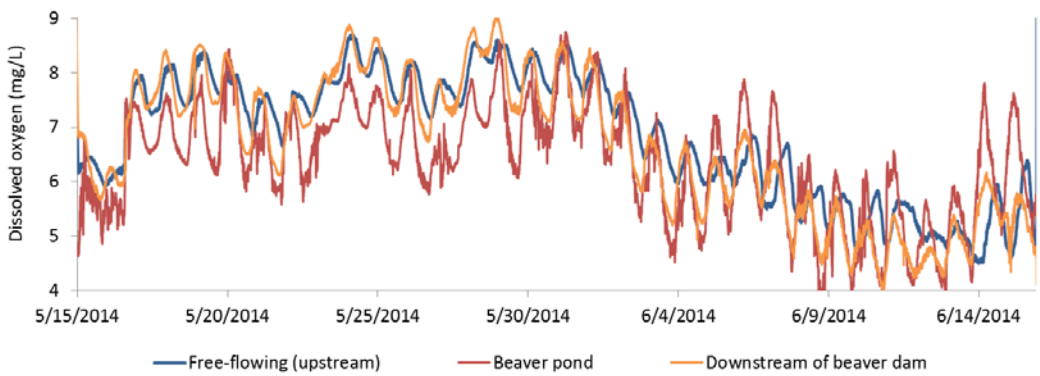

Figure 2. Dissolved oxygen concentrations over time (Hosley Brook, Hancock, NH).

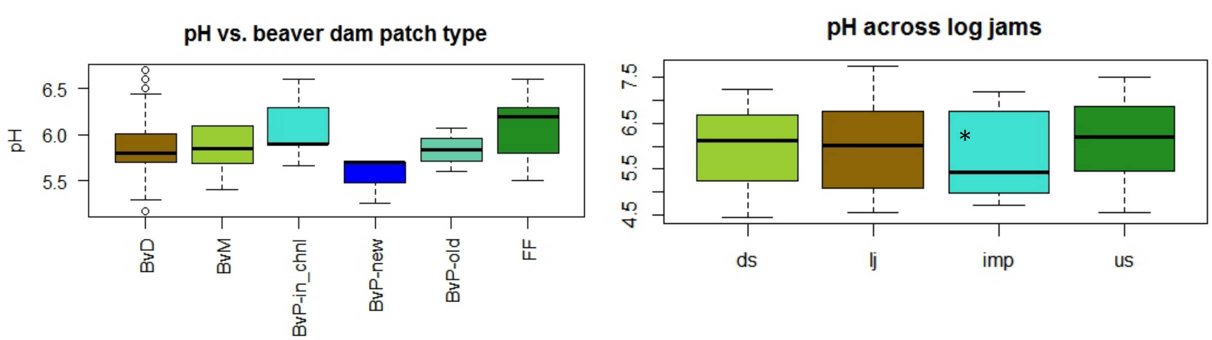

Figure 3. Left: Instream pH varies significantly across patch type associated with beaver dams (anova F=9.7, $p<0.001$).Legend: BvD—beaver dam; BvM—beaver meadow; BvP—beaver pond (can be young, old, or in-channel); FF—free-flowing. Right: Instream pH from downstream of log jams (ds), within log jams (lj), in the impounded water upstream of the log jam (imp), and in the free-flowing reach upstream of the log jam (us). pH was measured within each of these patches at each geomorphically significant log jam encountered.
* - significantly different from the upstream reach (paired t-test, $p<0.05$, mean difference = 0.36).

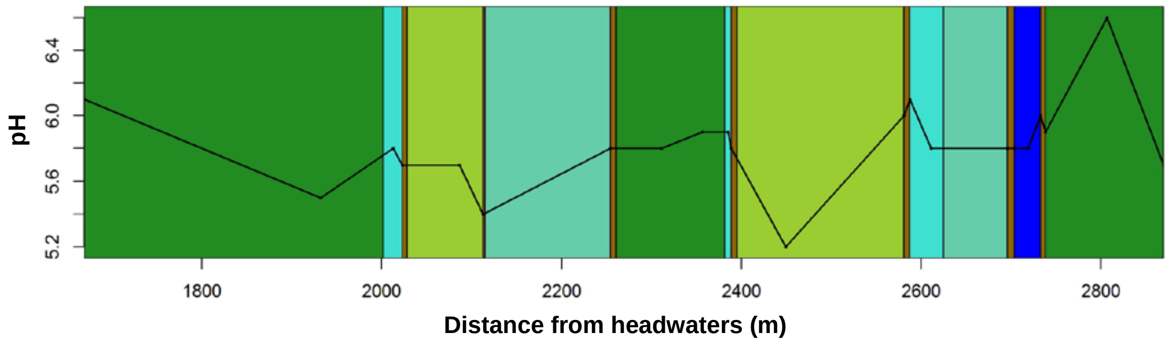

Figure 4. Example of a pH profile (Hosley Brook, Hancock, NH). FF—free-flowing; BD—beaver dam; OCP-Y—out of channel beaver pond, young; OCP-O—out of channel beaver pond, old; ICP—in-channel beaver pond; BM—beaver meadow.

In contrast to smaller log jams, the larger beaver dams create such significant changes—with accumulation of so much organic matter that decomposition drives the oxygen levels toward hypoxia or even anoxia—that the result is tremendous shifting in biogeochemical regimes, resulting in more complexity and less predictability with other measures such as pH. Further, although the impacts on dissolved oxygen are local and not transferred downstream, the resulting increased complexity of biogeochemistry is transferred downstream, as reflected in the fluctuations of pH.

Field research – temperature. The collected temperature data, which includes 15-minute data from 27 sensors, improve both the spatial and temporal extent of the data. Although temperature exerts less control on ecosystem state than a parameter such as oxygen, it is nonetheless a beneficial parameter because: heat is a useful tracer of water flow; incorporation of temperature allows for much greater spatial extent due to being much more affordable; it is a critical component of ecosystem state even if it is not the primary control.

The findings from the collected temperature data provide a more detailed description of the variability of ecosystem state in a river network that includes natural dams. This variability is most evident during the winter and summer, and less visible during the transitions of spring and fall (Figure 5, top, and Figure 6, top). In particular, during the winter, beaver ponds may be slightly warmer or colder than corresponding free-flowing reaches (Figure 5, top, and Figure 6, bottom left). In the summer, beaver ponds are generally warmer than free-flowing reaches; however, the beaver meadow group was somewhat cooler, and the one new beaver pond that was monitored was remarkably cooler (Figure 5, top, and Figure 6, bottom right). In addition to creating a wider range of variability across the river network, the beaver ponds and meadows also have a wider range of variability within each patch (Figure 5, bottom).

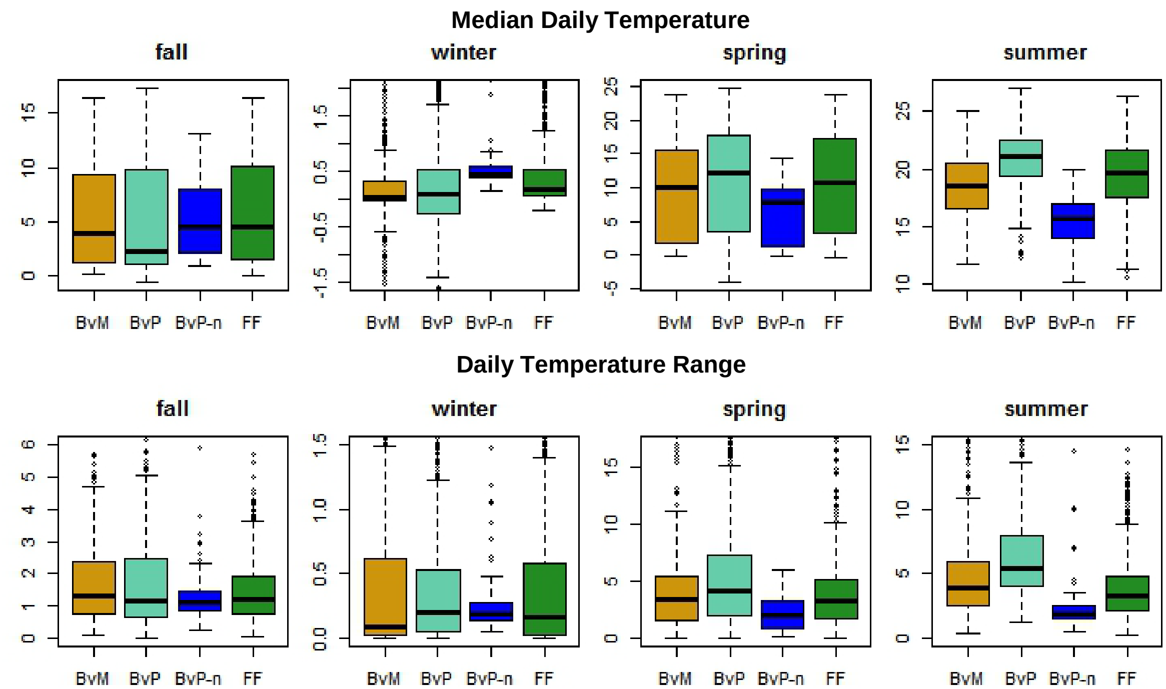

Figure 5. Maximum daily temperatures and daily temperature range (both in degrees C) across all patch types. See Figure 3 for abbreviations. Number of study sites (each with daily observations): BvM—6; BvP—8; BvP-n—1; FF—12.

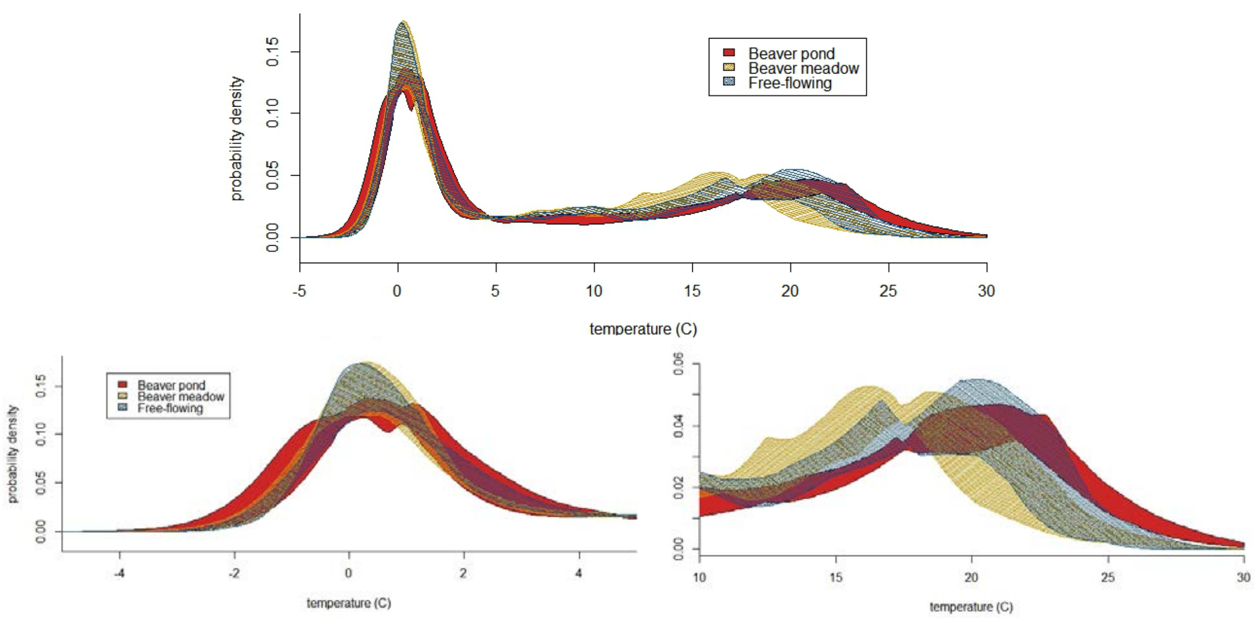

Figure 6. Top—probability distribution function (pdf) of temperature for each patch type. These were generated by first determining the pdf for the water year for each station. These were combined for each patch by determining the 25% and 75% exceedance of the probability density across the range of temperatures. Bottom—close-up views of the pdfs at low and high temperatures.

GIS: The GIS component of the research documented the extent of beaver ponds and meadows within the study landscape. A surprising finding as part of the GIS research is the occurrence of "naturalizing" river reaches that were once impounded by humans, where the impoundment has filled in with sediment and beavers have moved in to create small ponds within the human-created wet meadow. The GIS research has produced a complete data layer (see Figure 7) that has been created as a linearly referenced network.

The data layer shown in Figure 7 was used to calculate the relative representation of each patch type in the river network, as shown in Table 1. As Table 1 shows, up to 25% of the length of the river network is comprised of patches created by natural dams, which is particularly important in the headwaters. Human-created dams claim up to, and even more than half, of the river network length, and are particularly prevalent in the higher order watercourses. This analysis does not show the high frequency and extent of beaver ponds and meadows at the higher orders, because these features are embedded within the floodplains, which were mapped as larger "natural" features.

Table 1. Percentage of the study river network length comprised of patch types associated with natural dams and human-created dams.

Stream order	Beaver	Human	Other "natural"
1	11%	12%	77%
2	18%	17%	65%
3	26%	20%	54%
4	11%	44%	45%
5	12%	29%	60%
6	2%	49%	49%
7	0%	55%	45%

Note: "Beaver" = representation of beaver ponds and meadows along the river network; "Human" = representation of human-created ponds, meadows that have developed in human-created impoundments, and ditched floodplains; "Other natural" = free-flowing rivers, ponds with other natural genesis, and natural floodplains. Note that most natural floodplains also include extensive beaver activity and many small beaver ponds and meadows that were not captured by this study.

Analysis of the heterogeneity index versus the patch types shows a clear trend of increased heterogeneity at the beaver pond and meadow patch types versus the free-flowing reaches (Figure 8). There are two different heterogeneity indices: both describe the spatial heterogeneity around a given point. One index calculates the number of different distinct patches located 500ft upstream and downstream of an analysis point (Figure 8, left), and the second index calculates the number of patch types in the same distance (Figure 8, right). In both cases, the free-flowing patches in the river network are located in areas of less spatial heterogeneity, as are the impoundments associated with human-created dams. As the impoundments created by humans become more naturalized (see Figure 8 for the transitions from HmP to HmM to NHmP), they are also more likely to be set within increased spatial heterogeneity.

<ins>*Summary:*</ins> Natural dams are ubiquitous and their impoundments can occupy a significant percentage of the length of the study network. Without direct human intervention, these dams create a spatially heterogeneous network, with fluctuating patch types that exhibit distinct biogeochemical characteristics. Without human intervention, the river will shift from one state to the next as water moves downstream. In the case of the larger natural dams, the impact of the altered biogeochemical regime can extend downstream. Further, natural dams also increase the temporal heterogeneity within a given site. All of these alterations leads to a continued need to assess the impacts of these different states on water quality.

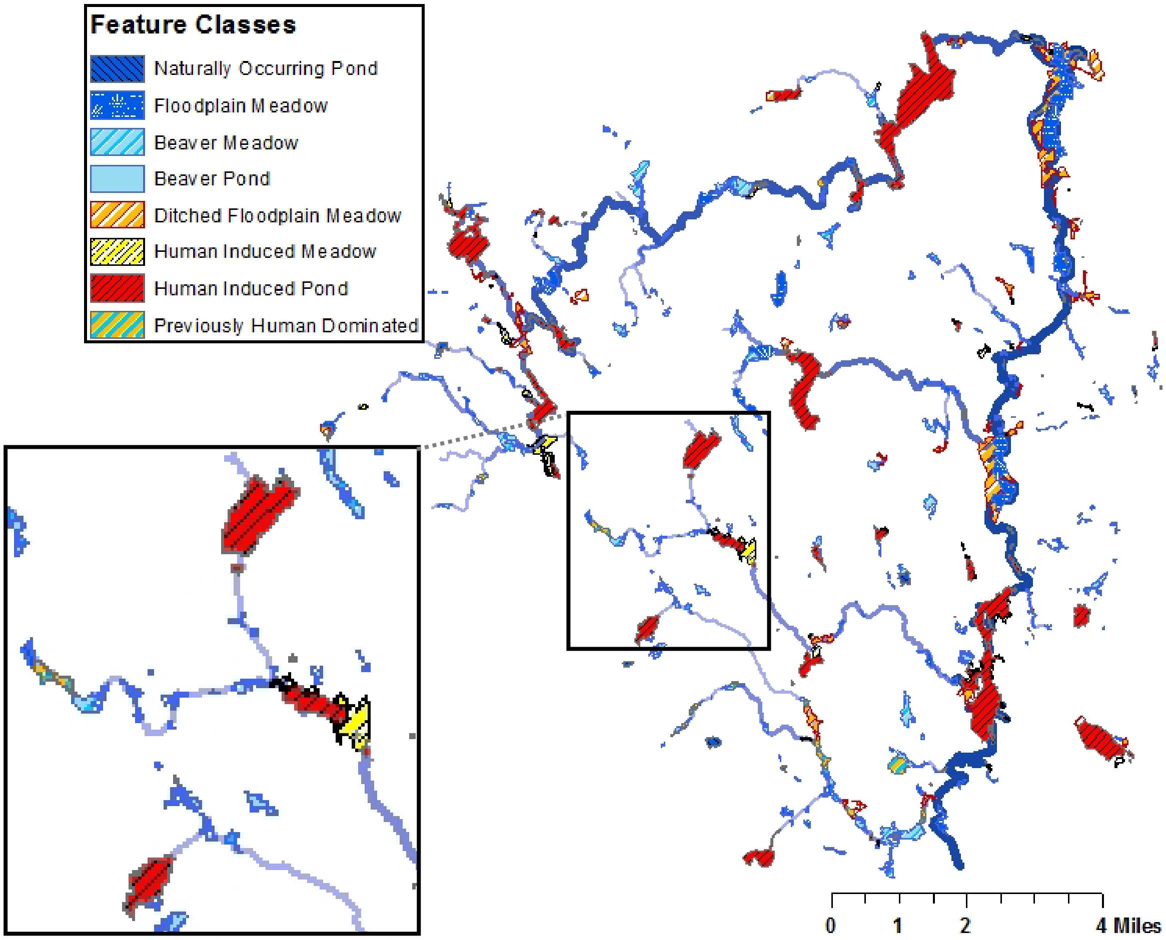

Figure 7. Impoundments along the river network for the Contoocook River, southwestern New Hampshire, digitized in Year 1 of this study. Inset shows typical detail. These digitized data will be used as the foundation for calculations of river network heterogeneity, of correlation between heterogeneity and land use, and for a predictive model of natural dam location.

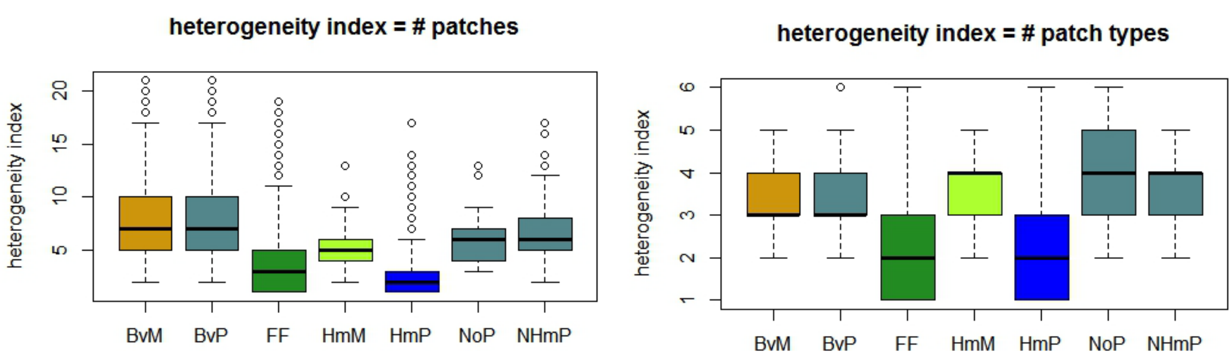

Figure 8. Spatial heterogeneity versus patch type. Left: heterogeneity is defined as the number of distinct patches within 1000' of a given point. Right: heterogeneity is the number of patch types within 1000'. Legend: BvM—beaver meadow; BvP—beaver pond; FF—free-flowing; HmM—meadow forming in human-created impoundment; HmP—human-created pond; NoP—naturally-occurring pond; NHmP—naturalizing area, previously HmP

Publications and presentations

Presentations at professional society meetings

Burchsted D. March 24, 2016. Stream temperature demonstrates that rivers are patchy systems. New England Association of Environmental Biologists. Rockport, ME.

Brehme, Christopher; Stoll, Charles*; Burchsted, Denise, 2014, *Using photo interpretation and linear referencing to quantify stream heterogeneity*, NESTVAL 2014: Water in a Changing World, New England-St. Lawrence Valley Geographical Society, Durham, NH.

Brehme, Christopher; Stoll, Charles*, 2014, *A classification and analysis of river channel conditions using aerial photos and network analysis*, American Association of Geographers Annual Meeting, Paper session 3567—Remote Sensing Applications for Characterizing Wetlands, Chicago, IL.

** - undergraduate student*

Presentations at local scientific meetings

Burchsted D. 2015. Heterogeneity of instream temperature. Hubbard Brook annual cooperator's meeting. Woodstock, NH.

Burchsted, Denise, 2015, *Natural dams and river network heterogeneity*. NH EPSCoR Ecosystems & Society All Hands Meeting, Durham, NH.

Burchsted, Denise. 2014. *Natural dams: Fluvial geomorphology and biogeochemistry,* Hubbard Brook Experimental Forest Cooperator's Meeting, Woodstock, NH.

Burchsted, Denise. 2014. *Patchy rivers: Implications for ecosystem function and services,* NH EPSCoR Ecosystems & Society All Hands Meeting, Concord, NH.

Stoll, Charles*; Brehme, Christopher; Burchsted, Denise, 2014, *Classifying riverine heterogeneity using photo interpretation*, NH EPSCoR Ecosystems & Society All Hands Meeting, Concord, NH.

Dallesander, Joshua*; Thorndike, Olivia*; St. Pierre, Lindsay; Burchsted, Denise. 2014. *Characterizing biogeochemical regime in river networks.* Council of Public Liberal Arts Colleges, Northeast Regional Undergraduate Research Conference.

** - undergraduate student*

Outreach or Information Transferred

Training sessions: Seminars

Burchsted, Denise, July 12, 2014, *Beaver dams as "natural dams" and the river dis-continuum*, Lake Nubanusit Watershed Association, Hancock, NH.

Burchsted, Denise, October 16, 2014, *Beavers: Nuisance species or ecosystem engineers?* Harris Center for Conservation Education Speaker Series, Hancock, NH.

Students

Joshua Dallesander, BS 2015, Environmental Studies, Keene State College

Michael McGuinness, BA 2015, Biology, Keene State College

Lindsay St. Pierre, PhD in progress, Environmental Science, Antioch University New England

Charles Stoll, BA 2015, Geography, Keene State College (first-generation student)

Olivia Thorndike, BS in progress, Environmental Studies, Keene State College

Faculty

Christopher Brehme, Associate Professor, Keene State College

Denise Burchsted, Assistant Professor, Keene State College

Special Story

Charles Stoll, one of the students supported through this research, is a first-generation student who worked for the first ten years of his adult life as a plumber. He is largely responsible for the GIS conducted as part of this research, and has presented his work at three meetings: locally (NH EPSCoR), regionally (NESTVAL), and nationally (AAG). Charles received his BA in May 2015 and is continuing to work on this research project this summer. We anticipate that, by the end of the summer of 2016, Charles will submit an undergraduate first-author manuscript for review for publication in *Northeastern Geographer*.

The attached Keene State news story provides some highlights regarding Charles' decision to restart his career as a student. The research mentioned in the news article is complementary summer research funded under a different grant. His work on the WRRC research was conducted primarily in the academic year.

Keene
STATE COLLEGE

From Plumber to Geography Major, Charles Stoll Finds Himself. Here.

October 1, 2014

After spending 10 grueling years as a plumber and suffering three fairly significant injuries, **Charles Stoll** decided he needed a change of direction—something a little more rewarding and less physically taxing. So he enrolled at Keene State, thinking he'd pursue a career in engineering or business management.

Charles Stoll gathers data logger downloads for Prof. Burchsted's EPSCoR research project. (Photo by Mark Reynolds)

But, even for a non-traditional student with his feet well planted beneath him, the opportunities and avenues for exploration that KSC laid before him let Stoll discover an even more engaging path. "After taking a few ISP courses throughout my first two semesters, I decided that I was more lent to the sciences and figured that was the direction I needed to follow," he explained. He found himself especially drawn to his Does the Earth Have a Fever? Integrative Quantitative Literacy (IQL) course, an entry-level earth systems science course, and Introduction to Geography.

It was in that geography course that Stoll found his predilection. "I was motivated to pursue a bachelors in geography because I feel as though I can relate to that spatial mindset," he recalled. "Geography is a spatial science, and given my previous occupation, I tend to think about things more analytically I think—processes and patterns, relationships and positioning. I also really enjoy history, and the cultural and/or sociopolitical aspects of geography help to satisfy those curiosities. It helps that I am also an anthropology minor, because learning about and developing an understanding of the human relationship with the environment is a story I have become more and more fascinated with."

Along with his geography major, Stoll is pursuing GIS certification. GIS (geographic information system) is a computer system designed to capture, store, manipulate, analyze, manage, and present spatial or geographical data. In the spring semester of 2014, he got an opportunity to put his science aptitude and geography skills to work when he began working with Assistant Professor of Environmental Studies **Denise Burchsted** on her EPSCoR research project on natural dams. "She enlisted me to analyze aerial photography of southwestern New Hampshire and to begin classifying watersheds for land cover, specifically for ponds and meadows caused by natural dams like those created by beavers, and for similar, though less natural, ponds and meadow systems created by humans," Stoll said.

That work led to a summer internship that saw Stoll in the field collecting data for the project. "I have to say it has been a truly awesome experience, and I feel very fortunate to have been involved with it. I have been learning about how river systems function, and what some of the influences on river characteristics are," he said.

Though Stoll hasn't decided exactly where he wants to go with his new career path, he's confident with the many options his education has opened for him. "I do feel as though the education that I have been receiving through KSC has more than fully prepared me for anywhere I choose," he said.