Final report for: Loss of catchment retention: Interactions between catchment morphology, residence time, and geochemical processing amidst a changing hydrologic regime

Background
The purpose of this study is to assess landscape controls on hydrologic connectivity, nutrient processing, and nutrient flux in low gradient meadows of the Colorado Rockies within Rocky Mountain National Park. Hydrologic connectivity defines the movement of water across a landscape, and the mechanisms by which precipitation inputs link to stream networks. Connections through all aspects of the hydrologic cycle facilitate the transfer of nutrients, particulate matter, and organisms, and therefore facilitate ecological connections and geomorphological form. The means by which rainfall and snowmelt inputs interact with the hillslopes, riparian areas, and how, when, and where water ultimately reaches streams are quite important to understand for water quality concerns as well as riparian vegetation and wildlife studies. This study is in conjunction, and direct coordination with the Leaky Rivers project (PIs Wohl, Venarsky, Hall, Walters).

Additionally, we seek to assess the functional relationship between hydraulic residence time and geochemical transformation across distinct geomorphic units. Catchments can be conceptualized (in a simple sense) as collections of transport and retention zones. Retention zones at catchment scales include units such as lakes, wetlands, riparian areas, floodplains, and beaver dams. While evidence suggests that these geomorphic units have important influence on catchment hydrological, geomorphological, and ecological dynamics; they are rapidly being lost due to both climate and land-use / land-cover change, among other vectors of environmental change.

In this research we are investigating hydro-bio-geochemical interactions in landscapes within active (North Saint Vrain) and relict (Upper Beaver Meadows) beaver structures. We explicitly chose these sites to assess the influence the loss of catchment retention (or attenuation) zones and attendant residence times may have on catchment scale dynamics and geochemical processing. Our research has focused in in the North Saint Vrain (Wild Basin, wet valley bottom) and Upper Beaver Meadows (dry valley bottom). While these projects will occur in these specific catchments, the scientific knowledge created is more broadly applicable to catchments facing potential environmental changes that lead to changing hydrology, residence times, and geochemical function.

Initial results
Initial results (summer 2014) from this research are based on weekly stream water grab samples as well as continuous, in-situ water quantity (stage) and quality (dissolved oxygen, colored dissolved organic matter, turbidity, specific conductivity, and temperature) measurements at the inflow and outflow of the North Saint Vrain (Wild Basin) beaver meadow from July through November 2014. Discharge rating curves were developed to derive hydrographs from continuous stage (15 minute interval) at the meadow inflow and outflow. The hydrographs suggest variable sink/source dynamics of the meadow from snowmelt to baseflow (Figure 1). These results indicate that the meadow stores water during high flow events, and supplies water downstream during the hydrograph recession. Specifically, the meadow supplied approximately 2x10⁶ m³ of water to downstream locations as the hydrograph receded to baseflow from higher flows during
Snowmelt (Figure 1). This leads to substantial amendment of downstream flows particularly during low flow periods and has strong implications for drought amelioration and catchment resilience.

Fluxes in colored dissolved organic matter (cDOM) during the monitoring period were correlated with rain events (Figure 2). During the three biggest rain events of the monitoring period, the meadow stored approximately 3, 5, and 10 kg of cDOM (Figure 2). We are currently analyzing the weekly grab samples for a full suite of chemical constituents (nutrients, anions, cations) but initial results show reasonable agreement between in-situ measures of organic material (cDOM) and laboratory measures of dissolved organic carbon (DOC). We are currently working to develop a relationship between cDOM and DOC from which we can transform continuous cDOM time series into continuous time series of DOC flux. Carbon is the fundamental building block of ecosystem productivity, and monitoring DOC real-time at the upstream and downstream extents of the valley meadow provides us a metric to assess the way in which the system is processing carbon. Additionally, there has been considerable interest in quantifying the importance of fluvial carbon fluxes on carbon balances from watershed to global scales. Our work in collaboration with Ellen Wohl is also quantifying the way in which low gradient valley meadows can store organic carbon. Previous and ongoing work from the Wohl research group indicates that while these landscape features occupy relatively small portions of the larger watershed (~25%) they can account for a majority (~75%) of the carbon stored in fluvial sediments, highlighting their importance in moderating carbon flux (Wohl et al. 2012, Wohl 2013).

Diel fluctuations in dissolved oxygen (DO) can be used to calculate whole stream metabolism. Stream metabolism is the combination of autotrophic and heterotrophic respiration. Autotrophic respiration produces oxygen while heterotrophic respiration consumes it. Accordingly, using these DO data we can calculate metrics such as gross primary productivity (GPP), ecosystem respiration (ER), and net ecosystem productivity (NEP). Diel fluctuations of DO were significantly larger at the meadow outflow than inflow, which suggests there was high metabolic activity in the meadow (Figure 3). Preliminary calculations of ecosystem metabolism (GPP, ER, NEP) were made for the meadow main channel from inflow and outflow DO data, channel geometry, stream discharge and velocity, and gas evasion rates (oxygen mixing between the...
The data suggest that the main channel is net heterotrophic and consumes an average of approximately 4 g O$_2$/m$^2$ a day (Figure 3). Stream heterotrophy indicates subsurface (hyporheic) biological activity as the main component of stream metabolism. This in turn suggests that the majority of biogeochemical processing and nutrient transformation is occurring in the hyporheic zone. This is not a surprising result as many studies have demonstrated that the majority of biogeochemical activity in mountain streams occurs in the hyporheic zone. However, in the valley meadow there are also many side channels and ponds. During summer (2015) we are investigating the metabolic activity of these surface water bodies in addition to the activity in the main channel. We seek to understand how biogeochemical processing varies between lotic (streams) and lentic (ponds) systems. We hypothesize that lentic components of the beaver meadow complex will have greater autotrophy – meaning a greater proportion of the biological processing is occurring above ground and being done by photosynthetic organisms. Additionally, we hypothesize that the level of autotrophy in the systems will vary as a function of flow state and connectivity via surface flow to the main channel. When these systems become disconnected from the main channel as flows decrease, we hypothesize that they will also become increasingly autotrophic. From these data and analyses we will investigate questions related to how aquatic systems function across the lentic to lotic continuum, which is a unique aspect of wet meadow systems.

Geochemical signatures of various source waters (e.g., snowmelt and groundwater) can be used to quantify the contributions to stream flow from various sources. This relatively simple approach requires that each source has a unique geochemical composition. If this requirement is met an end-member mixing model can be used to then quantitatively separate stream flow (or the amount of water in a pond) into its snowmelt and groundwater sources. Cation (Na$^+$, Mg$^{2+}$) concentrations from weekly grab samples indicate distinct geochemical signatures in surface runoff and groundwater, which will be used to evaluate spatiotemporal dynamics of sourcewater contributions to meadow water bodies. This will support our ongoing research that seeks to evaluate surface and subsurface connectivity of meadow water bodies from snowmelt to baseflow, and its relative contribution to meadow nutrient storage and flux dynamics.
**Current and on-going research**

**Combined influences of hydrologic connectivity and nutrient uptake on system-scale retention (led by Pam Wegener, MS student):**

We seek to relate shifts in surface and subsurface hydrologic connectivity in the beaver meadow to nutrient processing and ecosystem metabolism dynamics from snowmelt to baseflow. Currently, we are evaluating surface and subsurface connectivity of meadow water bodies across flow regimes using a combination of hydrometric and geochemical source water separation approaches. From March – May 2015, we installed TruTrack capacitance rods in 16 surface and 10 subsurface sites to monitor stage in real-time (15 minute intervals). Given that water flows substantially faster at the surface than subsurface, abrupt increases in stage-lags from the main-stem to side-channels and ponds will be used as a proxy for surface water disconnection as the hydrograph recedes. On a weekly to biweekly basis, we visit our monitoring sites to manually calibrate stage data, make a visual assessment of surface water connectivity, collect grab samples (to analyze for major nutrients, cations and anions), and monitor temperature and conductivity. Temperature and conductivity in the main channel and groundwater sites will be used to provide end members for geochemical source water separation analyses to address questions of surface and subsurface connectivity. In the 16 meadow surface water sites, we deployed STIC (Stream Temperature, Intermittency, and Conductivity) instruments to monitor temperature and conductivity in real-time (15 minute intervals). We will use these continuous data to evaluate spatiotemporal dynamics of source water inputs to meadow waterbodies from snowmelt to baseflow.

A major focus of this research is to evaluate the role of hydrologic connectivity on system nutrient (specifically, nitrate (NO$_3^-$)) uptake dynamics. To quantify NO$_3^-$ uptake dynamics in the beaver meadow and an upstream reference reach (a single threaded and constrained comparison reach), we use the tracer addition for spiraling curve characterization (TASCC) method from snowmelt to baseflow (Covino et al. 2010). TASCC is essentially a mass-balance approach that quantifies the relative decline of bioavailable (KNO$_3^-$) relative to conservative (NaCl) tracer across the tracer breakthrough curve (BTC). We have conducted the TASCC method three times since May 1st 2015 during relatively high flow states, and will conduct three more nutrient uptake tests as the hydrograph recedes. For the beaver meadow TASCC experiments, we co-inject KNO$_3$ and NaCl at the meadow inflow and collect samples across the BTCs at the meadow outflow and three meadow side-channels within the beaver meadow complex. We hypothesize greater NO$_3^-$ uptake rates in the beaver meadow relative to the reference reach, with increased...
autotrophy in meadow ponds (lentic systems) and extended interactions between microbes and nutrients that facilitate nutrient processing.

On weeks in which we are not collecting samples for nutrient uptake kinetics, we inject only the conservative tracer (NaCl) at the meadow inflow and collect BTCs at the meadow outflow and in three meadow side-channels. BTCs provide information on how water moves through the system, such as transit times, hydrologic exchange, and gross gains and losses to and from valley groundwater. In the meadow side channels where we monitor BTCs, the data will be used to independently support our evaluation of hydrologic connectivity dynamics. In two of the side-channels where we collect BTCs and in a pond with an active beaver lodge, we deployed miniDOT sensors which monitor dissolved oxygen (DO) on 15 minute intervals. From these data, we will calculate ecosystem metabolism metrics (GPP, ER, NEP) to understand how biogeochemical processing varies between lotic and lentic systems, and test whether or not decreased hydrologic connectivity leads to more autotrophic meadow water bodies.

**Investigating the influence of valley wetness state on soil respiration (led by Melissa Miller, undergraduate honors student):**

We are investigating the influence valley wetness state has on soil structure, soil carbon (C) and nitrogen (N) content, and soil respiration rates. Watershed Science undergraduate honors student Melissa Miller is taking a leadership role in the data collection and analysis for this aspect of our project and this will be the focus of her Honors Thesis. Our measurements occur on a grid network of 20 sampling points in both Wild Basin (wet) and Upper Beaver Meadows (dry). Every ten days we measure soil moisture, soil temperature, and CO$_2$ flux from the soil to the atmosphere at each of the 40 total sampling sites. We are also collecting soil samples from each location for analysis of bulk density, texture, and C and N content. From these data we will develop time series for each location of soil moisture, soil temperature, and CO$_2$ flux as well as spatial snapshots of these dynamics for particular points in time. These spatial snapshot maps will provide information on the spatio-temporal evolution of soil moisture, soil temperature, and CO$_2$ flux dynamics in wet vs. dry valley systems of the Colorado Rockies. Additionally, these analyses will be tied stream C fluxes to assess the way in which terrestrial and aquatic systems are linked or disconnected through time and across landscapes. Because the river-floodplain system in the dry Upper Beaver Meadows system is hydrologically disconnected due to river incision we hypothesize that the terrestrial-aquatic system will less tightly linked than the wet Wild Basin system, particularly as the watershed dries down in the late summer / early fall baseflow season.

**Hydrologic and nutrient resource constraints on hyporheic community dynamics and organic carbon processing (led by Laurel Larson, PhD candidate):**

Previous research has shown microbial communities adapt to environmental variability, however, the effects of ecosystem resource variability on hyporheic microbes remain poorly understood. We hypothesize localized specialist microbial communities develop within stream networks in response to varying hydrologic and nutrient inputs. To validate whether adapted communities process DOM differently, native microbes will be incubated in bioreactors. The bioreactor cultures will be fed carbon collected locally and from different sites within the stream network to examine differences in biolability and preferential compound metabolism. Water samples will be collected from the main channel of an active beaver meadow (M), as well as a
side channel (S), and a semi-connected beaver pond (BP). Carbon will be concentrated using resin extraction columns, and stable microbial cultures will be incubated with all six possible combinations of microbial community and carbon chemistry in bioreactors at controlled inflow and outflow rates. Following 14 days of incubation we will assess microbial community structure using metagenomic sequencing, and changes in metabolite chemistry with GC-MS. Changes in outflow chemistry from the bioreactor represent a proxy of microbial activity; our novel technique will help identify ecological functionality of microbes and better characterize specific organic compound bioavailabilities.

**Determining gross hydrologic exchange across wet and dry valley bottoms (led by Joe DiMaria, undergraduate honors student):**
The purpose of this research project is to develop a new understanding of the role of watershed retention zones (e.g., valley wetlands) in shaping surface water/ground water and nutrient fluxes. For this project, we are investigating how solute transport, surface water/ground water fluxes, and storage of water and nutrients is influenced by valley wetness states in active and inactive beaver meadows located in the Rocky Mountains of Northern Colorado. In the dry valley (Upper Beaver Meadow) previous land management has led to considerable channel incision and disconnection of the river-floodplain system. This disconnect should result in decreased exchange between the stream and groundwater system relative to dynamics in the strongly connected Wild Basin valley bottom (wet valley system). In this research we are using serial injection techniques (Payn et al. 2009, Covino et al. 2011) to assess channel water balances across the wet (Wild Basin) and dry (Upper Beaver Meadows) valley bottoms across flow states (e.g., from high to low flow conditions). These experiments will provide quantitative analyses of gross hydrologic exchanges and runoff source contributions across these systems. These hydrologic dynamics are strongly organized by geomorphic form and the two in turn have strong influence on biogeochemical processing and flux.

We are actively continuing these analyses and field campaigns during the summer-fall 2015 season. While these results are preliminary we believe that they suggest exciting opportunities to learn how wet and dry meadows process and store nutrients and water. These unique settings provide an ideal situation in which to address fundamental questions in environmental science that have meaningful importance to society and represent a frontier in interdisciplinary science at the intersection of hydrology, geomorphology, and ecology.

**Project outcomes**
- Two seasons of field data (summer – fall 2014, 2015)
- Data used in support of NSF Hydrologic Sciences proposal (December, 2014; unfunded) and resubmission to NSF Hydrologic Sciences (December, 2015)
- Two AGU sessions convened (December, 2014 & 2015)
  - “Feedbacks among geomorphology, hydrology, and biology across terrestrial and aquatic ecosystems” (AGU Fall Meeting 2014 Session ID: 3737)
  - “Interacting Physical and Biological Processes across Terrestrial and Aquatic Systems” (AGU Fall Meeting 2015 Session ID: 8612)
- Two AGU presentations (December, 2014 & 2015)

- Began establishing research program at Pingree Park (summer – fall 2014, 2015)
- Established first collaboration between PIs Covino, Hall, and Wohl
- Provided support for a MS student (Pam Wegener) and a junior faculty member (Tim Covino)
- Engaged two Watershed Science undergraduate Honors Students (Melissa Miller and Joe DiMaria) and an ESS SUPER student (Rachel Funke – begins on project fall 2015)
- Water Center funding used to leverage startup funding to Covino, Colorado Water Institute funding ($5000) awarded to Covino and Wegener, McIntire-Stennis funding awarded to Wohl and Covino ($20,000) and Covino, Wohl, and Rhoades ($16,000)
- Helped establish CSU Hydro-bio-geo working group (website under construction: http://ibis.colostate.edu/cwis438/websites/hbg/Index.php?WebSiteID=6)
- Helped develop field and lab infrastructure including:
  - Three gauging stations in the North Saint Vrain (NSV) Watershed
  - Monitoring at NSV gauging stations includes continuous (15 minute) stage, electrical conductivity, temperature, turbidity, dissolved oxygen, and colored dissolved organic material (cDOM) and weekly water quality samples and discharge measurements for rating curve development
  - Two gauging stations in the South Fork Poudre, CSU Mountain Campus.
  - Bio-reactor columns for laboratory column experiments to quantify nutrient processing rates in sediment columns
  - Outfitting of Watershed Hydrology and Biogeochemistry lab (NR326) that is a collaborative lab utilized by Watershed Science and Geomorphology faculty and students

Submitted proposals
- Understanding the influence of valley bottom geomorphology and wetness state on the quantity, quality, and timing of water exported from two watersheds of the Colorado Front Range (McIntire-Stennis, funded, $16,682)
- Quantifying Response Curves of Beaver Meadows (McIntire-Stennis, funded, $20,000)
- Saving the dammed: Beavers, catchment morphology, hydrologic retention, and geochemical processing amidst widespread environmental change (NSF Hydrologic Sciences, not funded, $633,044, in preparation for resubmission 12/2015)
- Combined influences of hydrologic connectivity and nutrient uptake on system scale retention (Colorado Water Institute, funded, $5,000)
- Combined influences of hydrologic connectivity and nutrient uptake on system scale retention (NSF GRFP, honorable mention, $125,000)
- Combined influences of geomorphic form, hydrologic connectivity, and nutrient uptake on system-scale retention (NASA fellowship program, not funded, $60,000)
- Combined influences of hydrologic connectivity and nitrogen uptake on system-scale retention (EPA STAR, in review, $88,000)
Publications and presentations

- Covino, T. (2015) Physical and Biological Controls on Water and Solute Retention from Reach to Catchment Scales, Colorado School of Mines Van Tuyl Lecture [INVITED]
- Covino, T., E. Wohl, E. Hall. (2014) Saving the dammed: Beavers, catchment morphology, hydrologic retention, and geochemical processing amidst widespread environmental change, NREL symposium, Fort Collins, Colorado
- Wegener, P., T. Covino, E. Wohl, and E. Hall. (2014) Evaluating the interactions between landform and fluvial flux in minimally disturbed catchments of the Front Range of Colorado, NREL symposium, Fort Collins, Colorado

References
