Statement of Critical Regional or State Water Problem

Many watersheds throughout New England are experiencing population growth resulting in increasing demands for water withdrawals and loading of anthropogenic by-products. The region is also expected to experience significant changes in the hydrologic cycle over the next century as a result of climate change (e.g. Hayhoe et al., 2007; Burakowski et al., 2008). Effective adaptation to both an increase in population and a changing climate will require a better understanding of the hydrology and biogeochemistry of the forested low-relief watersheds that are vital to sustaining our water resources and maintaining ecological habitats.

Streamflow during periods between precipitation or melt events is termed baseflow. Baseflow is often attributed solely to groundwater, though drainage from lakes, ponds, and unsaturated soils may also contribute to streamflow [Dingman, 2002]. In the most general terms, baseflow is considered whole catchment drainage [Stewart *et al.*, 2007]. In a changing climate, earlier snow melt [Hodgkins and Dudley, 2006], and the possibility for more pronounced seasonality of precipitation in the northeast [Hayhoe *et al.*, 2006] may result in increased reliance of summer baseflows to meet human and ecological water resource demands. The stores that generate baseflow have varied consequences on the water quality and quantity of water. For example, water draining from groundwater storage should generally maintain a lower temperature than water draining from surface reservoirs during summer months, which will benefit cold water fish species. Additionally, biogeochemical processing of solutes such as nutrients within surface and subsurface reservoirs would be expected to be different, and predicting the downstream influence of nutrient loading downstream requires an understanding of the relative contribution of reservoirs during baseflow.

Objectives

During the summer of 2010, streamflow from the Headwaters Lamprey River Watershed (New Hampshire) and one of its headwater catchments were investigated hydrologically and isotopically to assess which stores contributed to baseflow generation. Heavy isotopes of hydrogen and oxygen occur naturally in very small abundances within the water molecule and accumulate in surface reservoirs that undergo evaporation. These stable isotopes of water enable the differentiation between water stored as groundwater from water experiencing open-water evaporative enrichment. The primary objectives were to:

- Examine correlation between geographic metrics of wetland and waterbody coverage with observed isotopic enrichment and hydrologic response.
- Assess the quantity of direct groundwater and surface water discharge in observed streamflow throughout the dry summer.
- Assess the role of groundwater in the water balance of an upstream wetland reservoir.

Methods

The 740 ha Northwood Study Catchment (NWSC) was instrumented with four streamflow measurement sections, six riparian groundwater monitoring wells, and a stilling well set within the Lower Wet Meadow, an 11 ha beaver affected surface reservoir, and a meteorological station used to estimate evapotranspiration (Figure 1). Samples of groundwater, surface water, and precipitation were collected and analyzed for stable isotopic composition at the Northern Arizona

University Colorado Plateau Stable Isotope Laboratory, and dissolved silica and non-particulate organic carbon (NPOC) at the University of New Hampshire Water Quality Analysis Laboratory.

For both isotopes of the water molecule, abundances of stable isotopes of water are reported in the standard delta notation: the relative difference in the molar ratios of the heavy isotope to light isotope of a sample and Vienna standard mean ocean water (VSMOW) expressed in permil (‰). The contributions from evaporated surface water bodies (swb) and groundwater (gw), which are considered to be the only contributing sources to streamflow, are assessed using end-member mixing analysis of the proportional fraction of either end-member (f_{swb} or f_{gw}) evaluated from isotopic composition. The fractional contribution from surface water sources was derived from the Lower Wet Meadow. An isotopic mass balance of the Lower Wet Meadow was developed that used measurements of volumetric discharge and isotopic composition of inputs and accounted for evaporative fractionation under prevailing meteorological conditions to predict isotopic composition of the reservoir. The mass balance was calibrated to samples of the reservoir isotopic composition for different volumetric inputs of groundwater estimated as the residual. The findings from the mass balance were corroborated with sampling results from silica and NPOC.

Principal Findings

The isotopic enrichment was observed to increase (less negative δ-values) at subcatchments of the NWSC that had greater measures of wetland or waterbody coverage; the strongest correlation, using Kendall's τ, was found comparing $\delta^{18}O$ with the length of catchment

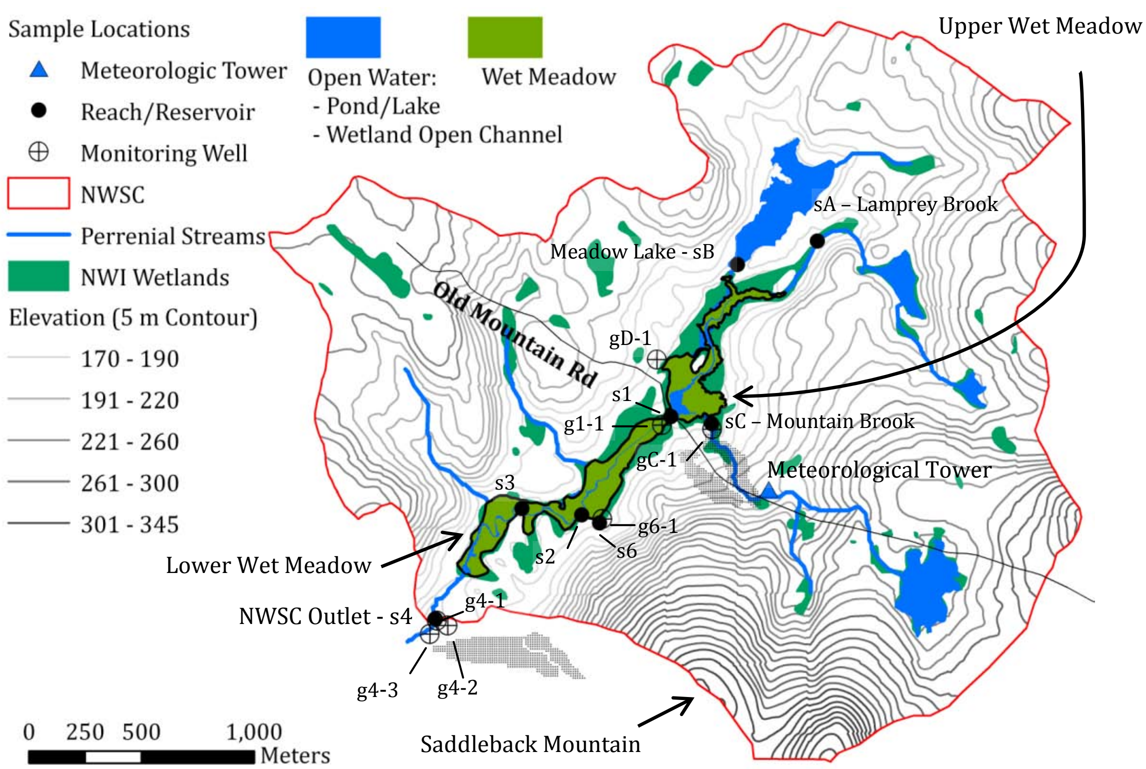

Figure 1: The Northwood Study Catchment in portions of the Northwood Meadows State Park and Forest Peters Wildlife Management area instrumented and investigated as part of the study. North is vertical.

stream course within wetlands (Figure 2). The relationship between stream length within wetlands and isotopic compositions suggests relative differences in groundwater contributions to baseflow, with watersheds having smaller streamlength in wetlands (e.g. SC) exhibiting more groundwater contributions (isotopically less enriched). Ranking subcatchments by the relative length of stream course within wetlands also provides insight into runoff mechanisms better than some more traditional metrics, such as wetland and waterbody areal coverage. For example, while Mountain Brook catchment (sC) has greater areal coverage of wetlands and waterbodies than the Lamprey Brook catchment (sA), it exhibits much lower runoff (Figure 3). In addition to the greater relative contribution of groundwater in sC (as indicated by isotopic characteristics), the lower runoff suggests that groundwater plays a subordinate role to stream-connected surface storage in the generation of runoff.

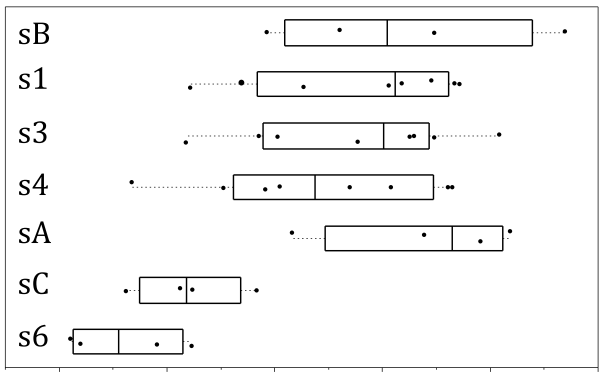

Figure 2: Correlation between stream length within wetlands and isotopic composition.

End-member mixing analysis showed that groundwater provided 18-30% (<50% at 95% confidence) of the direct volumetric discharge from the catchment at s4 (Figure 4). The mixing fraction analysis results varied little if the groundwater component of streamflow was assumed to have an isotopic composition of bedrock groundwater, which was measured by Frades and others [In Prep] near the NWSC and found to maintain a consistent isotopic composition annually. A similar magnitude of streamflow generation from wetland drainage in a small catchment in central Maine (40-80%) has been reported recently [Morley *et al.*, 2011].

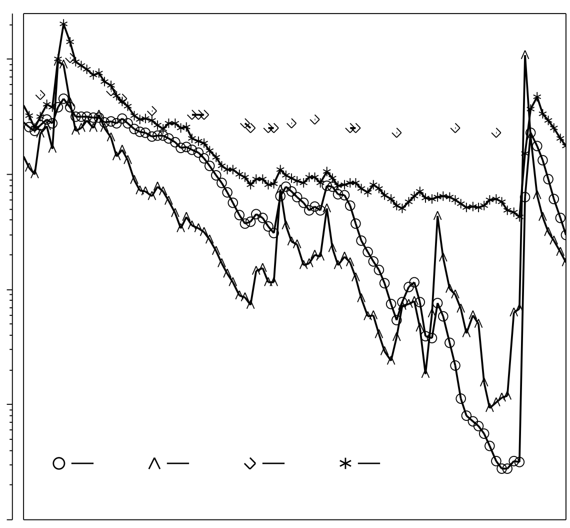

Figure 3: Area-average runoff for four subcatchments of the NWSC (locations on Figure 1).

The remainder of streamflow leaving the catchment was derived from the Lower Wet Meadow; by mid-summer upstream streamflow into the meadow was essentially cut-off due to drying upstream. The isotopic mass balance model for the Lower Wet Meadow confirmed that groundwater inflows were <35% of total surface discharge and that most streamflow leaving the meadow was likely the result of a loss from surface storage. The groundwater influx is controlled by the specific yield of the Lower Wet Meadow – larger values for the specific yield require a greater inflow of groundwater to maintain volumetric and mass balance of the meadow. The isotopic mass balance appears to optimally predict observed isotopic composition (Nash-Sutcliffe efficiencies for both $\delta^{18}O$ and $\delta^{2}H$ >0.95) for a value of the shallow specific yield of 0.8. Groundwater inflow likely increased late in the summer (Figure 5), possibly due to drying of the meadow outpacing groundwater drainage. Increased groundwater inflows were corroborated by dissolved silica and NPOC analytical results, which showed concentrations in the Lower Wet Meadow and streamflow at the catchment outlet more similar to groundwater later in the summer.

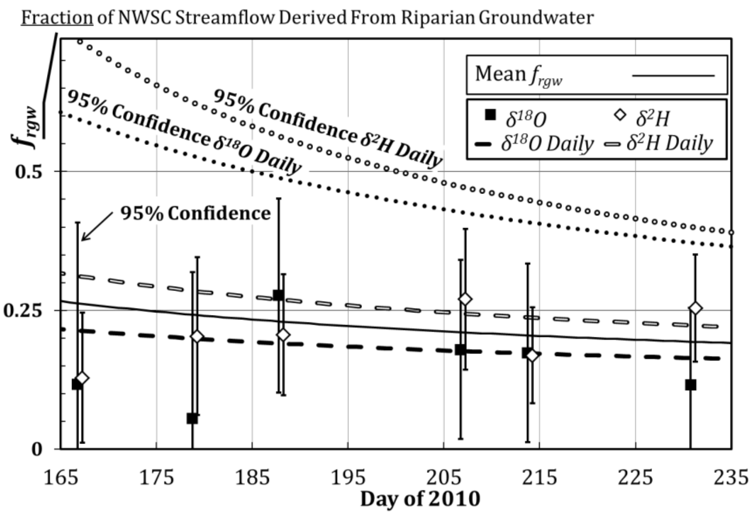

Figure 4: Fraction of groundwater in surface discharge from the NWSC. f_{rgw} assumes only riparian groundwater. Mixing fraction is presented from both $\delta^{18}O$ and $\delta^{2}H$ sampling results. Markers with error bars and dashed lines with dotted error intervals indicate the estimate of mixing fraction and associated uncertainty on sampling dates and from daily trend regression estimates, respectively.

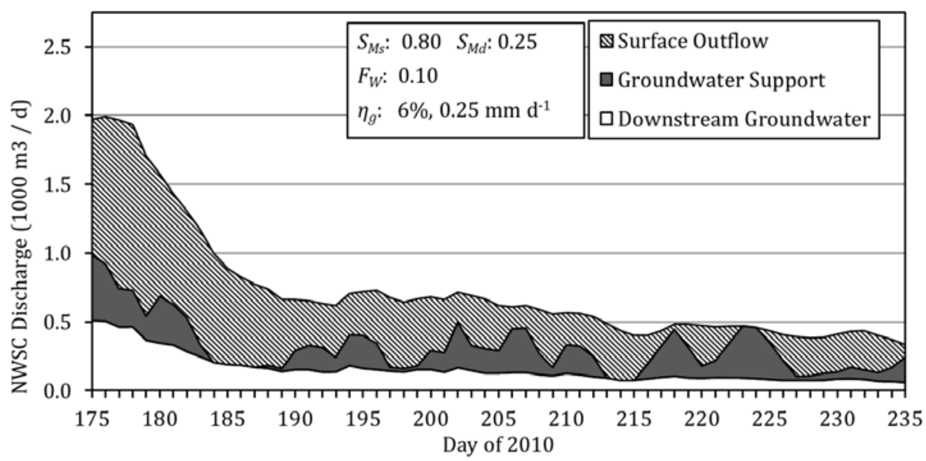

Figure 5: Discharge hydrograph of component outflow from the NWSC. Groundwater support is calculated from the water balance as the ratio of the net groundwater flux (residual) to surface outflow from the meadow, and is presented as the 3-day moving average assuming an optimized value of S_{Ms} = 0.80. Groundwater inflows appear greater later in the summer.

<u>Statement of Significance or Benefits</u>

The investigation resulted in the establishment and characterization of the dominant hydrological processes of the Northwood Study Catchment, a mesoscale study catchment in the headwaters of the Lamprey River. The study found evidence for surface drainage from wetland surface reservoirs as a possible baseflow generating mechanism in the headwaters of the Lamprey River, an often overlooked mechanism. Wetland resources may therefore be critical to meeting water resource demands in a climate of greater seasonality. An extensive inventory of stable isotopic samples was collected throughout the Northwood Study Catchment and the Headwaters Lamprey River Watershed between June and August 2010, a period that experienced about 60% of normal precipitation for the season [Zuidema, 2011]. The inventory of samples will be utilized to inform the broader effect of wetlands on baseflow generation at the catchment scale as Mr. Zuidema pursues his Ph.D. in Earth Systems Science at the University of New Hampshire. The results of this investigation advances our understanding of how temperate near-coast catchments may respond to prolonged dry conditions and how drainage from wetlands and other small surface stores relates to whole catchment drainage.

Publications and Presentations

Zuidema, S., 2011, Identifying groundwater contributions to baseflow in a temperate headwater catchment, Thesis, M.S., University of New Hampshire, Durham, NH.

Zuidema, S., 2011, The role of wetlands on sustaining base flow in the headwaters of the Lamprey with implications for water supply and biogeochemistry, Lamprey River Symposium, Session I, January 7, 2011, University of New Hampshire, Durham, NH.

Students Supported

The project has partially supported one master's student in the University of New Hampshire, Department of Earth Sciences Hydrology program, Shantar Zuidema, who has successfully defended his master thesis. Additional project participants include Charles Grant, who graduated from the University of New Hampshire with a B.S. in Environmental Science, and Cathleen Turner, who is currently enrolled in the Environmental Science program focusing in hydrology. The project and the Northwood Study Catchment have been used for introducing hydrological measurement techniques to additional undergraduate (Molly Jankolovits) and graduate (Scott Arndt) students.

References

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Hodgkins, G.A., Dudley, R.W., 2006. Changes in the timing of winter–spring streamflows in eastern North America, 1913–2002. Geophysical Research Letters, 33, L06402.

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Stewart, M.K., Mehlhorn, J., Elliott, S., 2007. Hydrometric and natural tracer (oxygen-18, silica, tritium and sulphur hexafluoride) evidence for a dominant groundwater contribution to Pukemanga Stream, New Zealand. Hydrological Processes, 21, 3340-3356.