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Contribution of fluvial wetlands to nitrogen retention in urbanizing coastal watersheds in New England across multiple scales

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Basic Information

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Project title: Contribution of fluvial wetlands to nitrogen retention in urbanizing coastal watersheds in New England across multiple scales

PIs: Anne Lightbody, Linda Kalnejais, & Wil Wollheim

Problem

Surface water quality in rapidly urbanizing coastal watersheds in New England is at risk due to excess anthropogenic nutrient inputs, which threaten downstream water uses and could lead to fluvial and estuarine eutrophication (Bricker et al. 1999, Caraco and Cole 2003). Fluvial wetlands, which are biologically reactive and have long residence times (Vidon and Hill 2001), can remove excess nitrate, thus providing an important ecosystem service (Wollheim et al. 2005, Rabalais et al. 2009). Flow-through wetlands consist of an advective main channel, plus slow-flowing off-channel areas collectively termed "transient storage." Wetlands with higher lateral connectivity between the main stream channel and transient storage are especially important because they may retain more nitrate than wetlands that receive little direct stream discharge (Racchetti et al. 2011). However, wetland connectivity and reactivity is still poorly understood, thus limiting our ability to predict the impact of future changes in land use and climate change on watershed retention of nitrogen inputs.

Project Objectives

1) Determine contribution of wetland-dominated stream reaches to surface transient storage as a function of inundation and season
2) Quantify nitrate uptake rate constants from model generalization among the different reaches.
3) Scale biogeochemical and hydrologic insights to wetland-dominated reaches throughout New England
4) Share results with local and regional policy makers

Methods

During the first year of study, 2014-2015, this project focused on eight wetland-dominated reaches (Figure 1) in four different watersheds in coastal New Hampshire and Massachusetts, with preference given to wetlands that have one channelized stream inlet and one channelized stream

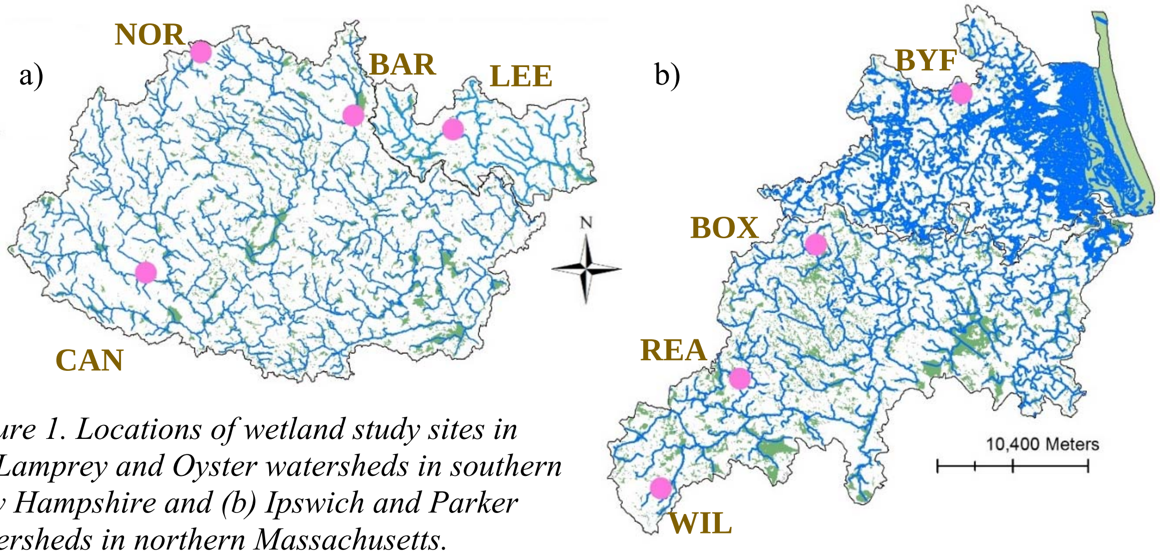

Figure 1. Locations of wetland study sites in (a) Lamprey and Oyster watersheds in southern New Hampshire and (b) Ipswich and Parker watersheds in northern Massachusetts.

outlet. The eight wetlands used in this study are of varying sizes and shapes. Wetland geometrical characteristics were calculated from delineation of aerial photography (Figure 2) for all eight study wetlands plus a randomly chosen subset of 50 wetlands in the neighboring Charles, Concord, Merrimack, and Piscataqua-Salmon watersheds. Watershed area was delineated from Light Detection and Ranging (LiDAR) digital elevation models. Due to the fine resolution of the LiDAR and the relatively flat terrain, watersheds were delineated at multiple points across the stream outlet and then total area for each was summed. Wetland area and main wetland channel length were delineated from aerial photography based on vegetation differences. National Wetland Inventory (NWI) datasets were used to obtain another measurement of wetland area. Specifically, all NWI polygons that shared a boundary with the target wetland were combined to create one large polygon. Wetland length was obtained by smoothing the main channel length. Average wetland width was then calculated from the wetland area divided by the length of the main channel. Width-to-length ratio was calculated as the wetland width divided by wetland length. Finally, sinuosity was measured as the length of the main channel divided by the smoothed length of the wetland. All geographical analyses were performed using ArcMap 10.1 Spatial Analyst Toolbox.

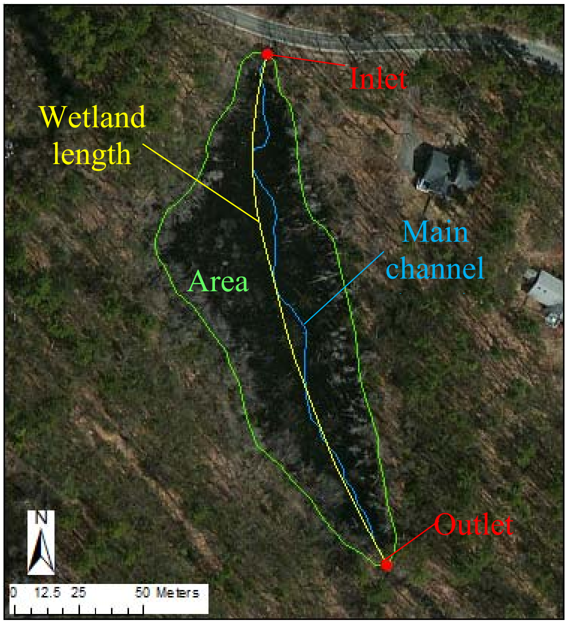

Figure 2. Aerial photograph of wetland site BOX in Boxford, MA, showing delineated geometrical parameters. Flow is from north to south; tracer was released at the wetland inlet and recorded exiting the wetland at the outlet.

Wetland connectivity was measured with the use of whole-reach slug releases of the nontoxic fluorescent tracer dye rhodamine WT (RWT). Tracer releases were performed between May and November 2014 during baseflow conditions. Three of the eight sites were studied twice to examine seasonal changes in baseflow connectivity, resulting in 11 studies in total. During each study, rhodamine was released into the stream feeding the wetland, then measured *in-situ* at the wetland outlet with a Turner C3 fluorometer set to record every 15, 30, or 60 seconds for at least 2 and typically 5 times the advective time scale of the wetland channel. Measured fluorescence at the wetland outlet was converted to excess rhodamine concentration using calibration curves and accounting for background fluorescence, instrument fouling, retardation, and photodegradation. Additionally, stage was measured at the inlet and outlet of each wetland at 12-15 minute intervals and converted to a continuous discharge record.

Tracer flux exiting the wetland was calculated by multiplying together tracer concentration and stream discharge (Figure 3). The mass of tracer recovered was calculated by integrating exit flux over time. The residence time distribution (RTD) of tracer in the wetland was calculated by dividing the exit flux by the mass recovered. The detention time (median travel time within the wetland) was calculated as the first moment of the RTD. Because studies occurred during steady base-flow conditions, it was assumed that the movement of the introduced fluorescent tracer was representative of other dissolved substances (in particular, dissolved inorganic nitrogen) also moving through the wetland at the same time.

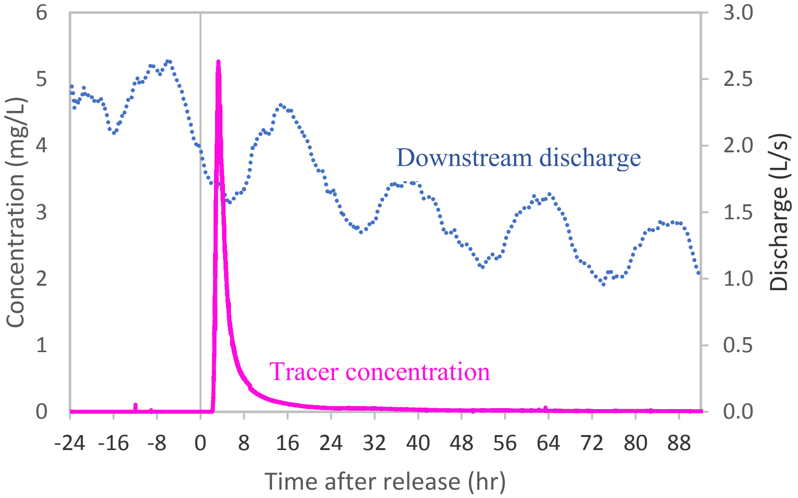

Figure 3. Continuous breakthrough curve of rhodamine WT (RWT) tracer concentration measured at the outlet of wetland study site BAR from June 18-23, 2014. The peak tracer concentration reached the outlet 3.5 hours after the release. Half of the dye exited by 9.7 hours. Discharge generally declined during the steady period.

Transient storage characteristics at the reach scale were determined from inverse modeling of each reach-scale tracer RTDs using the transient storage model STAMMT-L (Haggerty 2009). This approach conceptually divides the wetland into a main advective channel that exchanges water with stationary transient storage zones. The number of transient storage zones is specified in advance, and their size and connectivity are estimated by trying different parameter values until obtaining the best fit between the observed tracer RTD and a semi-analytical solution to the underlying partial differential transport equations. Three different transient storage models (Figure 4) were compared:

1. single-zone model, which allows for one transient storage zone adjoining the advective main channel. There is only one connectivity parameter (α) which represents the first-order exchange coefficient between the main channel and the storage zone.
2. multiple-zone single-size model, which divides the storage area into many zones of equal size but different connectivity ($\alpha_1, \alpha_2 \dots \alpha_N$) which are distributed according to a power-law function.
3. multiple-zone different-size model, which maintains a power-law distribution of transient storage zone connectivities but also assumes that zone size is inversely proportional to zone connectivity. That is, as the zone size increases, the connectivity decreases.

The multiple-zone models reflect the field observation that some regions of transient storage (e.g., channel margins) are more connected than others (e.g., pools far from the main channel). For the multiple-zone models, 30 different zones were used (cf. Haggerty 2009); preliminary testing showed no difference in model parameter estimates for 30, 40, 50, or 60 zones.

Nitrate samples were collected at the inlet and the outlet of each wetland once during each tracer study. Samples were filtered in the field, placed on ice, then analyzed at the UNH Water Quality Analysis Laboratory using standard methods. Nitrate flux at the wetland inlet and outlet was calculated by multiplying concentration measurements by stream discharge.

Nitrate uptake rate constants was estimated by combining the optimized transport parameters determined from the slug releases of rhodamine with the observed inlet and outlet fluxes of nitrate. Specifically, the models were re-implemented assuming steady discharge conditions and the measured inlet flux of nitrate. The nitrate uptake rate constant was increased until the steady modeled outlet concentration matched the measured outlet concentration. Two scenarios were considered to apportion uptake between the main channel and the storage zones. First, whole-wetland uptake rate constants were calculated assuming the same rate constant for

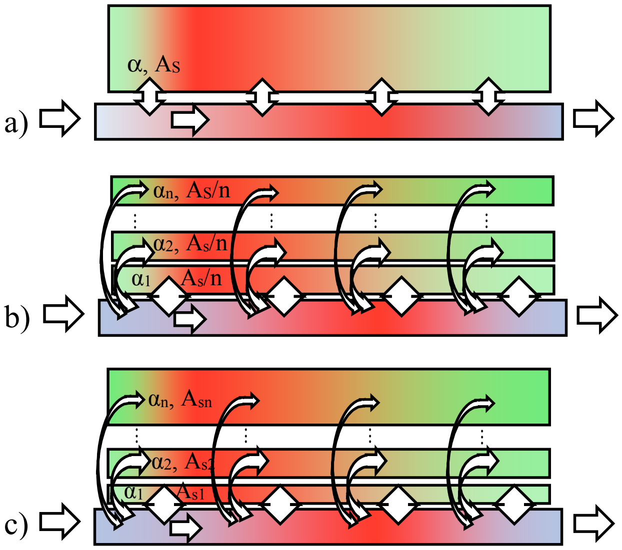

Figure 4. Conceptual model of the different model geometries used to parameterize transient storage connectivity α and size A_s*: (a) single-zone model, (b) multiple-zone single-size model, and (c) multiple-zone different-size model. Red color represents the conservative tracer added to the main channel, which advects and disperses in the main channel and is also transferred to and back from the transient storage zones.*

both the channel and the storage. Second, maximum storage uptake rate constants were determined by assuming no uptake in the channel, which forced all the uptake to occur in the storage zones.

Principal findings and significance

The watershed area of the study wetlands ranged from 0.5 to 210 km^2. Wetland area ranged from 2,400 to 40,00 m^2, NWI area ranged from 1,200 to 52,000 m^2, wetland length ranged from 120 to 650 m, average width ranged from 18 to 50 m, width-to-length ratio ranged from 0.07 to 0.24, and wetland channel sinuosity ranged from 1.0 to 1.4. Only width was statistically different from (specifically, smaller than) a broad selection of other New England wetlands.

Following each tracer release, the time to tracer peak concentration (a measure of transport in the main wetland channel) ranged from 0.7 hours to 55 hours. Preliminary analysis indicates that the amount of RWT recovered ranged from 63 % to 137% of the amount released. If the tracer were truly conservative then 100% should have been recovered, but error resulted from uncertainty in both tracer concentration and discharge. Detention times ranged from 1.8 to 70 hours and were 1.3–3.7 times longer than the times to peak concentration, indicating long tails reflecting the influence of transient storage.

Transient storage models were successfully fit to all measured tracer breakthrough curves. For nearly all studies, the multiple-zone models better matched experimental data, especially in matching tracer concentration in the tail of the breakthrough (Figure 5). The tail of the tracer breakthrough curve at the wetland outlet exhibits the most sensitive response to different transport pathways including exchange with transient storage zones (Wang and Jawitz 2006, Gooseff et al. 2011); the better fit of the multiple-zone models confirmed that different types of transient storage were present in the study wetlands. The fraction of median travel time due to transient storage (Runkel 2002) ranged from 42–95%, indicating that most solutes moving through these reaches spent half or more of their time traveling through transient storage areas that may have exhibited high biogeochemical reactivity.

Single-zone transient storage zone size and connectivity values were consistent with previous observations in small fluvial wetlands in Wisconsin (Powers et al. 2012; Figure 6). The ratio of the transient storage area to the area of the main channel, A_s/A, was statistically correlated to the width-to-length ratio (p=0.04) for the multiple-zone single-size model. Few other significant relationships were found between optimized transport parameters and wetland geometry measured

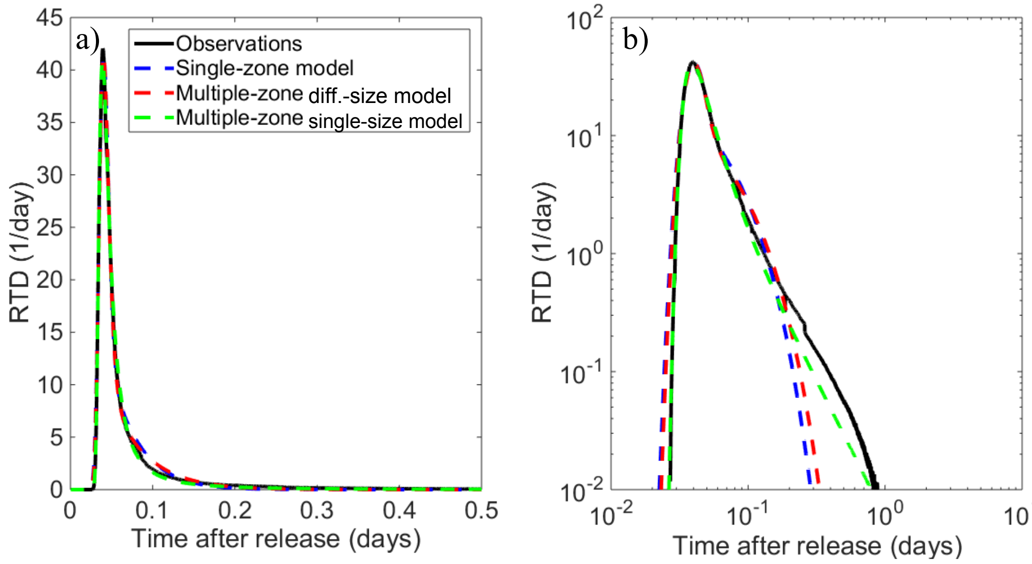

Figure 5. Measured and modeled residence time distribution (RTD) on (a) linear and (b) logarithmic axes for study REA2.

from aerial photographs. Instead, during summertime low-flow conditions, off- channel areas of study wetlands became disconnected from the main channel, and nitrate processing was limited to channel margins, the near-bed region of the channel, and the hyporheic zone. Increases in discharge can reconnect additional transient storage areas: for the multiple-zone different-size model, the minimum connectivity α_{min} and maximum connectivity α_{max} were correlated with discharge (p=0.02).

During 8 out of 11 studies, the outlet concentration of nitrate was less than the inlet concentration. In addition, in 7 out of 11 studies, nitrate fluxes (concentration × discharge) entering the wetlands were smaller than fluxes out of the wetlands. Thus, nitrate was retained within most of the study reaches during the period of observation.

Reach-scale nitrate uptake rate constants (Figure 7) calculated for study sites exhibiting retention were within the range of previous results from flow-through wetlands in Massachusetts (Wollheim et al. 2014) and Wisconsin (Powers et al. 2012) and, with the exception of study LEE, are higher than uptake rate constants for streams (Wollheim et al. 2014), confirming that small wetlands do play a large role in providing the important ecosystem service of nitrate retention. In general, nitrate uptake rate constants were similar between sites. There was no significant relationship between nitrate uptake rate constants and wetland geometry.

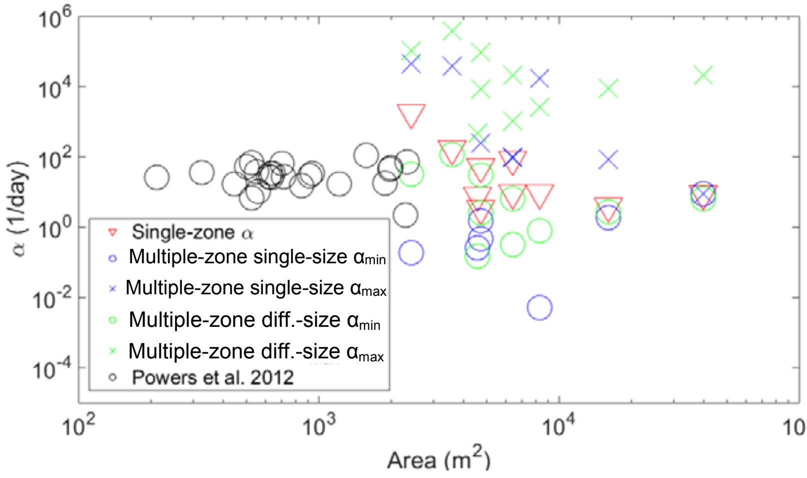

Figure 6. Comparison of connectivity parameters as a function of wetland area for study wetlands in NH and MA as well as Powers et al. (2012) data from small wetlands in Wisconsin.

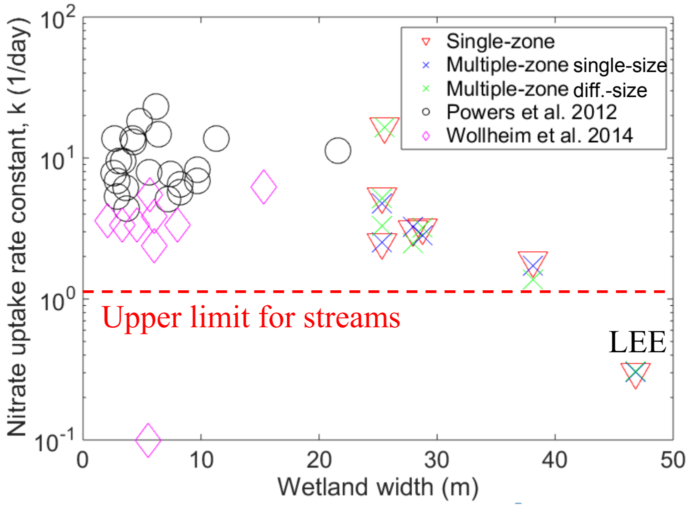

Figure 7. Reach-scale nitrate uptake rate constants for study wetlands, calculated assuming constant removal rates throughout the wetland. Results are compared to previous observations in fluvial wetlands (Wollheim 2014, Powers 2012) and streams.

When retention was assumed constant in the wetland channel and storage zones, different storage zone models resulted in similar reach-scale nitrate uptake rate constants (Figure 7). When all the nutrient uptake was forced to occur in the storage zones, however, the different models (which assumed different storage zone contributions) resulted in different effective storage zone uptake rate constants: a small or poorly connected storage zone would need to provide rapid uptake to result in the same observed reach-scale retention. The role of different aquatic patches in contributing to reach-scale uptake is still poorly understood.

Previous research has suggested seasonal cycles in nutrient uptake and release in coastal New England (Claessens et al. 2009). In this study, all three of the instances when nitrate was produced occurred in fall, when uptake rates tended to be low as well (Figure 8).

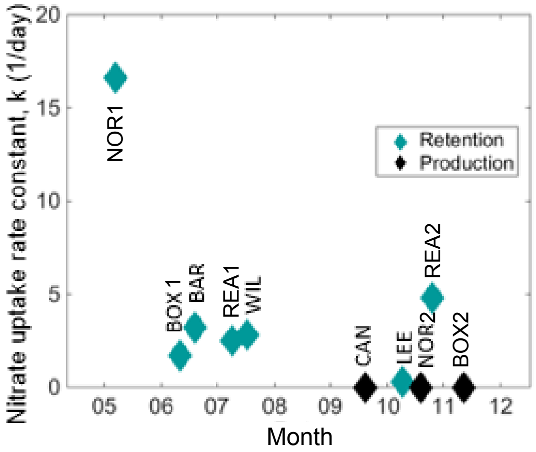

Figure 8. Uptake rate constants for studies that had measured nitrate retention, and the timing of studies with nitrate production.

Study Plans

During our second and final year of this study, 2015-2016, we are building on the above results to better characterize seasonal and spatial patterns of nitrate retention. Specifically, at 2 of these 8 wetlands, we will use *in-situ* chamber and core experiments to measure nitrate uptake in different wetland zones during the growth season (June) and the senescing season (October), which will help determine the variability of rate constants over the year. These rate constants will then be combined with estimates of the fraction of flow that accesses each wetland zone, along with the residence time distribution of flow in that zone. We will validate the ability of this approach to provide a reach-average bulk uptake rate constant by comparison with upstream and downstream grab samples from the same time period. We will also share results with local and regional policy makers to assist in on-going efforts to manage and mitigate nitrate loading in coastal New England rivers.

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Presentations

Dougherty, Michael P. Analysis of the photodegradation and sorption of Rhodamine WT in New Hampshire wetlands. UNH Undergraduate Research Conference. April 22, 2015.

May, Christian J. Using diurnal variations of stream discharge in small wetlands to determine water lost to evapotranspiration in New Hampshire and Massachusetts. UNH Undergraduate Research Conference. April 22, 2015.

Lightbody, A., Wilderotter, S., Wollheim, W. M., Kalnejais, L. Contribution of surface transient storage to nitrogen retention within wetland-dominated stream reaches in New England. Northeast Section Meeting of the Geological Society of America. March 23, 2015.

Wilderotter, S., Lightbody, A., Zuidema, S., Kalnejais, L. H., Wollheim, W. M. Predicting nitrate retention in wetland-dominated stream reaches using a conservative tracer. Conference on Partnerships for Environmental Progress, New England Association of Environmental Biologists. March 18, 2015.

Lightbody, A., Wilderotter, S., Rosengarten, D., Lawrence, K. Contribution of fluvial wetlands to nitrogen retention in urbanizing coastal watersheds. Lamprey River Research Symposium, NH Water Resources Research Center. January 9, 2015.

Wilderotter, S., Lightbody, A. F., Kalnejais, L. H., Wollheim, W. M., Zuidema, S. Transient Storage Parameterization of Wetland-dominated Stream Reaches. Lamprey River Research Symposium, NH Water Resources Research Center. January 9, 2015.

Wilderotter, S., Lightbody, A. F., Kalnejais, L. H., Wollheim, W. M., Zuidema, S. Transient Storage Parameterization of Wetland-dominated Stream Reaches. American Geophysical Union Fall Meeting. December 15, 2014.

Outreach

Presentation of watershed hydrology and water quality to 40 elementary school students as part of the UNH Leitzel Center, Kids Eager for Engineering Program with Elementary Research-based Science (KEEPERS) program, July 2014. Unit featured on KEEPERS promotional materials: http://www.leitzelcenter.unh.edu/pdf/carmelina_cestrone.pdf

Hydrology and water quality presentations to over 300 elementary and middle students and the public through UNH Ocean Discovery Day, Oyster River Girls' STEM Club, Hampstead Middle School, Moharimet Elementary School Science Friday, etc.

Participation in the Lamprey River Advisory Committee, and discussion with volunteers/staff from the Ipswich River Watershed Association and Oyster River Watershed Association

Initiation of collaboration with Peter Steckler at the Nature Conservancy, who is currently updating the Land Use Plan for New Hampshire’s Coastal Watersheds to account for differences in wetland ability to retain nitrogen

Students supported

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