**Title:** Quantifying the impact of dam removals on nitrate retention using low cost nitrate sensors.

**Team**: Wilfred Wollheim, Kevin Gardner, Gopal Mulukutla, Julia Peterson. University of New Hampshire

**A. Nutrient Issue**

Anthropogenic nitrogen exports from watersheds to coastal zones are increasing and leading to eutrophication, deadzones, and loss of estuarine organisms (Howarth and Marino 2006, Diaz et al. 2008). In the Great Bay of New Hampshire/Maine, the focus area of this proposal, increased nitrogen inputs have been linked to loss of eel grass, as has occurred in estuaries worldwide (Orth et al. 2006). Eel grass is important "capstone" species in shallow estuaries, including Great Bay, that provides nursery fish habitat and maintains water clarity by protecting sediments from wave action (McGlathery et al. 2007). Both point and non-point sources contribute to increased nutrient fluxes, but over time non-point sources have begun to dominate as waste water treatment has improved (Carpenter et al. 1998). A similar dynamic has occurred in Great Bay watershed and currently non-point sources from the surrounding watersheds contribute the majority of N loads. Understanding the factors controlling watershed nitrogen delivery is critical, particularly as land use continues to change, and climate becomes more variable (Samal In Press).

A substantial proportion of anthropogenic nitrogen inputs that enter streams and rivers are retained or removed during downstream transport, thereby lowering fluxes to coastal areas (Wollheim et al. 2008a, b, Alexander et al. 2000). Reservoirs are thought to contribute to this retention, particularly reservoirs in relatively small watersheds (Gold et al. 2016). However, most of the estimates of reservoir retention are based on relatively course sampling in a small number of larger reservoirs (Gold et al. 2016, Seitzinger et al. 2002). Functions developed from large reservoirs are then used to parameterize models of reservoir N removal. Further, removal estimates are generally based on annual estimates, and do not consider the role of temporal variability in flow. A greater understanding of the strength and timing of N removal by reservoirs is needed.

Dams and their reservoirs are increasingly being removed from the landscape, often because they are aging and would need costly repairs, have no significant utility and/or to improve anadromous fish passage and connectivity with spawning areas (Doyle et al. 2008). There are over 100,000 dams in the nation (Poff and Hart 2002), with about 14,000 in New England alone (Martin and Apse 2011, Magilligan et al. 2014). Over 1000 of these New England dams are classified as high hazard dams that need to be either repaired or removed (ASCE 2012). Over 240 dams have been removed in New England since 1990 (American Rivers 2016). Because reservoirs created by dams are potentially effective at removing nitrogen (Gold et al. 2016), such dam removals come with tradeoffs, including reduced nitrate removal. Yet we have a poor understanding of the effectiveness of the reservoirs on smaller rivers that are common in much of New England and elsewhere, as well as how their effectiveness varies during different parts of the growing season and during storm events within season.

A new generation of high frequency, in situ nitrate sensors will greatly increase understanding of where and when reservoirs remove nitrogen. Such sensors have already been applied to understand watershed storm nitrogen dynamics (Carey et al. 2014, Pellerin et al. 2014), river network scale N retention (Miller et al. 2016, Wollheim et al. In Press), and aquatic ecosystem processes (Heffernan and Cohen 2010). The utility of these high frequency sensors is only beginning to be harnessed (Rode et al. 2016), and will accelerate as costs come down, which is one of the exciting aspects of the Nutrient Sensor Challenge. Sensors have not yet been used for quantifying nitrogen removal in individual water bodies using upstream-downstream deployments. We propose such a deployment to answer the overarching research question:

**How effective are smaller reservoirs in coastal New England at retaining or removing nitrogen, and how does this effectiveness vary across season and flow condition?**

We propose to deploy sensors upstream and downstream of several reservoirs in coastal New England to quantify nitrate removal across seasons and storm events. The wave of dam removals that is ongoing in New England, and throughout the country, also offers a unique opportunity, through before and after studies applying high frequency sensors, to quantify accurately the impact of reservoirs on N exports. We will therefore also take advantage of ongoing dam removals and management activities (such as reservoir drawdowns without dam removals) to quantify the N removal by reservoirs. We propose low cost sensor deployments in four reservoirs, distributed over a two-year period, involving two to four sensors per reservoir (depending on reservoir configuration within the river network). Findings will improve decision making by providing information regarding reservoir nitrate retention across flow conditions. This information can be used to prioritize dam removals in New England, while also developing an approach that could serve as a model for application elsewhere in the nation.

We meet the three goals of the sensor challenge as follows. Details are provided below. *Challenge Goal 1. The effective use of low-cost continuous sensors.* The question we address requires at least two high frequency nitrate sensors, and possibly one or two additional sensors depending whether there are other tributaries entering the reservoir. The approach can therefore only be executed with two or more sensors, requiring them to be relatively low cost. Cost has been one of the reasons that the two-station method has not been used before. *Challenge Goal 2. Innovative partnerships to pilot the sensors and manage data.* We have an interdisciplinary team of an ecosystem ecologist, sensor engineer, and electrical engineer that has previous experience deploying sensors and managing large data sets. *Challenge Goal 3. Demonstrate how collected information can be used in state and local decision-making.* Because the issue of dam removals and their impacts is highly dynamic in New England and elsewhere, preliminary discussions about our project with various decision makers have garnered significant interest regarding how to prioritize dam removals (see Table 3).

**B. Team**

The team consists of an interdisciplinary partnership including an aquatic ecosystem ecologist (Dr. Wilfred Wollheim, Associate Professor, Department of Natural Resources and Environment, University of New Hampshire), environmental engineer (Dr. Kevin Gardner, Professor, Department of Civil and Environmental Engineering, UNH), sensor engineer (Dr. Gopal Mulukutla, Research Scientist, Earth Systems Research Center, UNH), data manager (Mulukutla), and extension personnel (Julia Peterson, New Hampshire Sea Grant Extension Partnership, UNH). Wollheim will be team lead and overall project coordinator (wil.wollheim@unh.edu). He specializes in the fate of nutrients in freshwater river networks, has used in situ high frequency sensors in his previous work to understand mobilization and fate of nutrients during storms (Carey et al. 2014, Wollheim et al. In Press), and uses river network models to understand conditions under which river networks are effective at removing nutrients (Wollheim et al. 2008a, b, Samal et al. In Press). Previous use of in situ sensors by the Wollheim lab relied on expensive SUNA's (> $20K, Satlantic Inc.), which is not sustainable for most research projects, and insufficient for the multiple sensor suites needed to understand the effect of individual dams (i.e. simultaneous input-output measurements integrated over time). Dr. Gardner is lead PI on the NSF "Future of Dams" Project, which is a regional effort to understand the function and tradeoffs of dams throughout New England. His work has focused on characterizing the trade-offs associated with dam removal, such as changes in flood risk, fish passage, sediment dynamics and hydropower generation. His research includes the development of methods to use aerial drones before and after dam removals to determine changes in geomorphology and flow conditions and contribute to understanding credit allocation in compensatory mitigation schemes that are commonly used to fund dam removals. He will be responsible for quantifying the changing hydraulics and sediment characteristics to help explain changes in N retention measured by the sensors. Dr. Mulukutla has previously developed a variety of sensors (Mulukutla et al. 2011, 2015), power systems, data transfer systems, database QA/QC (Wollheim et al. 2016), and conducted time series analysis of coupled watershed and estuarine water quality data (Mulukutla et al. In Review). He will be responsible for interfacing with Real Tech Inc. from whom we will be purchasing the sensors, and will lead the technical aspects of the sensor deployment (power management, infrastructure) and database management. Extension Specialist Peterson has extensive experience interacting with decision makers on coastal issues as part of her role in the New Hampshire Sea Grant Extension office. She will help us communicate our results to decision makers through meetings and facilitated discussions.

We will partner with the company Real Tech Inc. to deploy their low cost Real Nitrate Sensors (~$10K each). Mulukutla and Wollheim met with Kerim Kollu and Simon Savard of RealTech Inc. to discuss sensor specifications and whether the sensors would be appropriate for the sample setting, expected concentrations, and water matrix. We concluded that their nitrate sensors would be ideal for the proposed study.

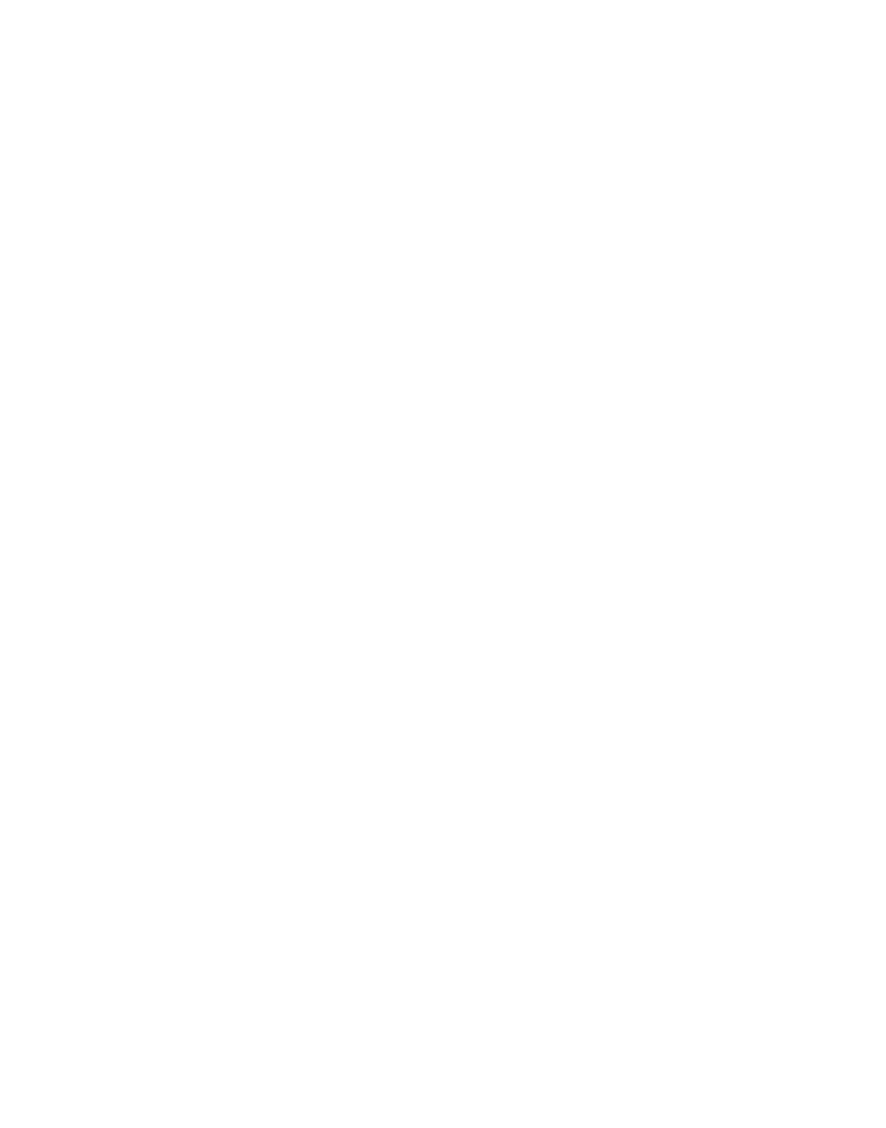
**C. Current Monitoring**

We will apply the approach to the existing monitoring efforts underway in the Great Bay region. Current monitoring consists of a network of sample sites located at the head of tide dams for the major rivers flowing into Great Bay https://www.greatbay.org/programs/monitoring.htm). This monitoring is funded by the Piscataqua Region Estuary Partnership (PREP) to track trends in nutrient loading to the Great Bay estuary and consists of relatively infrequent (monthly) grab sampling. A second monitoring effort is underway in the Oyster River watershed using high frequency nitrate measurements at several sites, including the head of tide dam as well as headwater sites of different anthropogenic land use (Wollheim et al. 2016, In Press). This network is being used to improve estimates of inputs of nitrate from different land uses during storms and whole river network nitrate retention across storm size. Results thus far suggest that the river network is able to retain a significant proportion of nitrate loads during small to intermediate storm events, but has not been able to identify where the retention occurs. We hypothesize that the reservoir behind the head of tide dam, the Mill Pond, is a major contributor. Monitoring results have to date been conveyed in final project reports (Wollheim et al. 2016) and peer review publications (Carey et al. 2014, Wollheim et al. In Press, Mulukutla et al. In Review). In this study, we will focus on three of the watersheds in Great Bay estuary that have dam removals underway, or in permitting/planning stages, including the Oyster R., Bellamy R. and Lamprey R. watersheds (Figure 1).

**D. Sensors and Monitoring Plan**

Our overarching approach is to quantify nitrate retention by reservoirs across flow conditions using high frequency nitrate, conductivity, and water stage sensors deployed continuously at reservoir inputs and outputs. We will focus on reservoirs located in the seacoast region of New Hampshire that drain to the Great Bay estuary, which has been designated as nitrogen impaired by NH DES (NH DES 2017). We plan to deploy high frequency sensors in two reservoirs in year 1 and two reservoirs in year 2 (n=4 total reservoirs) to track net retention or release of nitrate. We will deploy two to four sensor sets in order to monitor the multiple inputs and outputs. At the reservoir that has three inputs with high nitrate loads (Mill Pond on the Oyster River), we will also rely on the SUNA that is currently deployed at the dam, while ensuring the different types of sensors are cross-calibrated. Each reservoir will be monitored for month-long deployment periods four times each year (e.g. April/May, June/July, August/Sept, October/November). We will use the resulting data to estimate nitrate retention in each reservoir during each deployment period, develop functions of retention vs. flow condition, sediment-water interface area, and season, and determine how the reservoir system responds to removal.

We will target the Sawyer Mill Dam on the Bellamy R. (scheduled for removal in summer of 2018), the Mill Pond Dam on the Oyster R. (dam removal being debated), the McCallen Dam on the Lamprey R. (dam removal being debated), and the Beards Pond Dam (which drains directly to the tidal Oyster River). All are head of tide dams. Each of these dams has different reservoir volume to watershed area relationships (Table 1), allowing us to assess nitrate retention functions of different types of reservoirs.



**Figure 1**. Watershed of the Great Bay Estuary, New Hampshire/Maine, with population of dams (blue points) and associated reservoirs. Four head of tide dams will be the focus of this study (Table 1).

**Table 1**. Characteristics of the proposed study sites.

|  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- |
| **Dam/**  **Reservoir** | **Watershed** | **Surface Area**  **(km2)** | **Watershed Area**  **(km2)** | **Dam Status** | **Number of Inflows** |
| Mill Pond Dam | Oyster River | 0.080 | 50.6 | Being Debated | 3 |
| Sawyer Mill Dam | Bellamy River | 0.008-0.08 | 86.8 | Removal July 2018 | 1 |
| McCallen Dam | Lamprey River | 0.46 | 549 | Being Debated | 2 |
| Beards Pond Dam | Oyster River | 0.043 | 8.3 | No removal discussions | 2 |

Real Nitrate Sensors (Real Tech Inc., Ontario Canada) will be deployed at the inflow(s) and the outflow of each reservoir. Some of the reservoirs have more than one significant inflow, requiring multiple sensors. In order to distinguish between hydrologic retention, and biological retention or permanent nitrate removal (e.g. via denitrification), we will also monitor conductivity using HOBO U24 conductivity loggers (Onset Inc., Falmouth MA), and develop chloride vs. conductivity relationships to track chloride as a conservative tracer. We will collect grab samples for lab analysis to develop chloride vs. conductivity relationships at each site. Chloride is a conservative tracer, so only experiences hydrologic storage (see Analysis section below for method of deriving continuous retention). In areas with elevated chloride due to road salt applications, chloride can be used as tracer of the hydrology (Wollheim et al. In Press). We will compare the ratio of nitrate flux to chloride flux at the inputs and outputs over time. To obtain fluxes, we will also estimate discharge at all inputs and outputs based on discharge vs. stage height relationships (Wollheim et al. 2016, In Press). Stage height at each measurement location will be measured continuously using HOBO U20 Water Level loggers (Onset Inc.).

The sensors will be deployed between early April and late November each year. This is the peak growing season in the estuary when nitrate inputs from the watershed have their greatest impact. Quantification of N retention by dams during this period is highly management relevant. For example, if reservoirs retain most of the nitrate from watersheds during summer, then algae in the estuary will remain N limited. The April to October period is also characterized by substantial changes in discharge and water temperature as the season progresses, so the impact of reservoirs across varying conditions can be determined. Storm events can occur at any point during the year, so we can also determine the influence of changing hydrology and reservoir retention time during different temperature conditions.

We will also collect bi-weekly grab samples at each measurement location throughout the deployment periods for chemical analysis in the UNH Water Quality Analysis Lab. Analysis will include a suite of solutes including NH4+, NO3-, total dissolved nitrogen (TDN), particulate organic nitrogen (PON), and Cl-. Dissolved organic nitrogen will be determined as TDN - NH4+ - NO3-. NO3- data will be used to compare against the Real Nitrate Sensor estimates to validate and if necessary correct the NO3- measurement. Nitrate sensor estimates can have site-specific offsets due to the water matrix (e.g. dissolved organic carbon can also absorb in part of the light spectrum that nitrate absorbs). Chloride will be used to develop site specific Cl- vs. specific conductance relationships. The remaining nutrients (NH4+, DON, PON) will provide an assessment of the net retention of other N forms for which we don't have high frequency measurements, including possible transformation of nitrate and export as dissolved or particulate organic nitrogen. Although these measurements will not be high frequency, these will provide important context for the high frequency nitrate measurements.

The Real Nitrate Sensor requires deployment on the bank (i.e. they are not submersible), and pumps water from the stream or river to the measurement unit. The units will be placed on the bank with water intake set in the flowing, well-mixed part of the water body, based on observation of flow conditions. Water will be pumped and the sensor turned on every 15 or 30 minutes depending on the response time of flow in response to storms in the stream or river. Most larger rivers and reservoirs are not very flashy, so less frequent sensing is possible to conserve power. Each sample time will consist of one minute measurement bursts to estimate an average reading for the time period. A path length for the instrument will be selected to ensure detectability across the concentration levels expected at each site (ranging from 0.01 mg NO3--N L-1 to 2 mg NO3--N L-1). The Real Nitrate Sensor has adjustable path lengths. Real Nitrate Sensors will be deployed with a course particle screen (~200mm pore size) to prevent large particles, which may be an issue during algal blooms or high sediment storm events. Sensors will be visited once a week for cleaning of any biofouling. The sensor will be modified to run on direct power, from deep cycle marine batteries, regenerated with solar panels, which we already have in house. Each nitrate sensor will contain internal data-logging. Due to the complexity of nitrate measurements, the final configuration of this sensing systems will vary based on site-specific considerations such as power availability (line power or solar power) and water depth,. Each system will be assembled with a wireless telemetry solution after accounting for power, cost and other deployment considerations (vegetation, topography etc.). Telemetry solutions include range-independent cell phone modems (high cost), or low range (low-cost) Internet-of-Things (IoT) based Long Range (LoRa) radio communication technology (0-10 km range). UNH’s Data Discovery Center our data storage, and archival system will host streamed in data for real-time visualization, and further processing (see section E. Data, for more information on the solution architecture). Conductivity and stage loggers, which will provide essential information to estimate nitrate retention, will be deployed in situ, are stand alone, have internal data logging capacity, and will monitor at identical frequencies.

**E. Data**

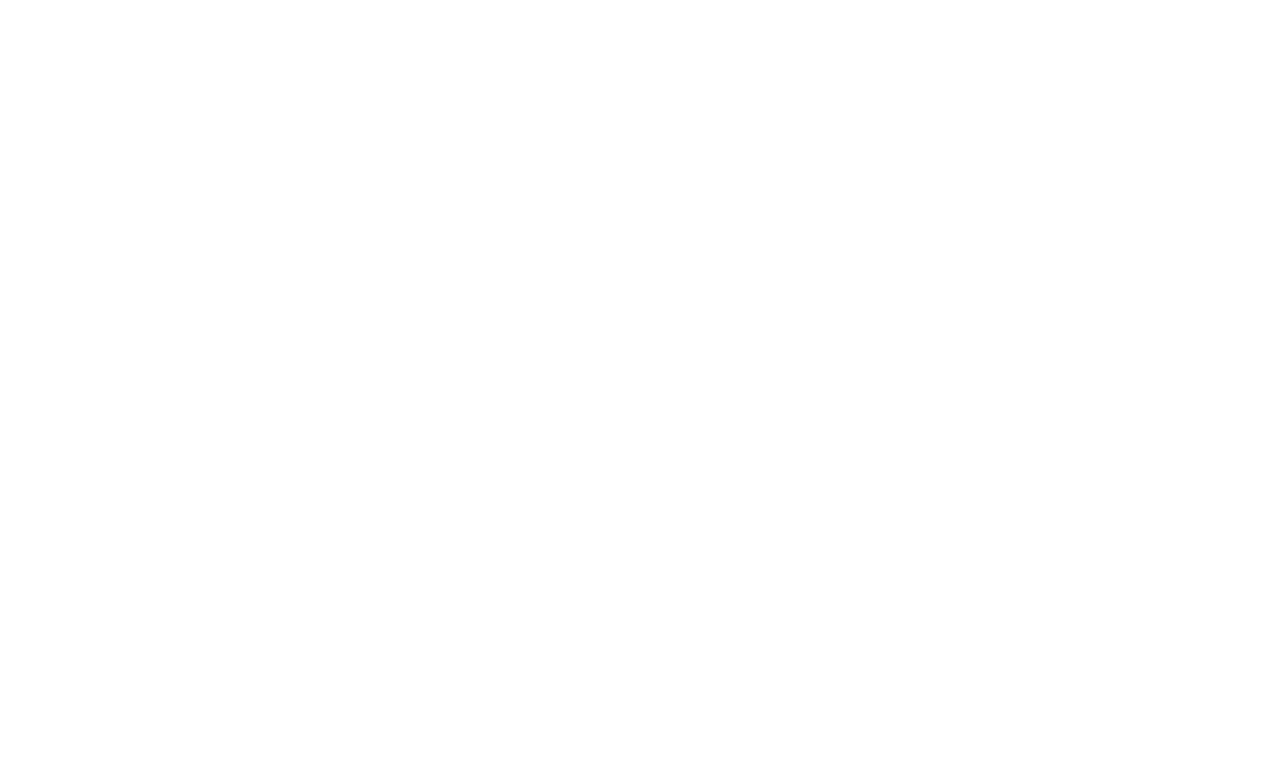
**Solution Architecture.** We will be following a solution architecture previously used on other projects run by our group (see ddc.unh.edu).Data streams from the sensors and periodic grab samples will be housed on a server, part of a network of servers located within UNH’s Research Computing Center (RCC) (Figure 2). All servers are part of an internal gigabit network that allows easy transfer of data for QA/QC, data and archiving in real-time. Data is protected by secure password access with restrictions on file-read and write access implemented by Linux based file and group permission control. The Linux-based operating systems allow hierarchical directory structures on RAID disks with built in redundancy, for fast, efficient, and safe data storage. Data security is implemented with daily onsite and periodic offsite backups.

Sensor data is collected via manual download or an implemented telemetry solution with data streamed directly to staging area located on the server (Figure 2). This will include multiple data streams consisting of time stamps, raw and calibrated sensor (e.g. nitrate concentration, and corresponding raw absorbance spectrum), sensing system function, and operational characteristics that help better understand the quality of data captured. This data will include independent variables that will be related to dependent data such as stage height, discharge, specific conductance, and temperature. Nutrient data from grab samples will be recorded and entered into the work-flow immediately after the data is available. Example sensor variables include: Time stamp (format: yyyy-mm-dd hh:mm), Nitrate-N (milligram/liter), specific conductance (microSiemens /centimeter), stage height (meters). Derived data include: corrected Nitrate-N (milligram/liter), chloride (milligram/liter), and discharge (cubic meters per second). All data will be formatted in comma separated ASCII format easily convertible to other formats.

**QA/QC.** We will employ a widely-used approach of versioning data (Levels 0, 1A, 1B, Table 2, Figure 2), to develop well-curated aggregated datasets so as to be distributable to the wider community. Level 0 datasets contain data collected as is, with no pre-processing or qualifying flags. Level 1A data will be corrected for outliers identified by an automated procedure based on site-specific QC criteria for individual water quality parameters. Level 1B data will be generated first by applying a manual process of identifying and flagging additional outliers, and grab sample data will be aggregated into the dataset. This version of data will also contain variables generated by correcting for sensor vs. grab deviation (e.g. nitrate) or surrogates (e.g. chloride from specific conductance).

**Metadata.** Individual sensor and grab sample datasets will be accompanied by metadata produced in the Ecological Metadata Language (EML) format. EML is implemented as a series of XML document types that can be used in a modular and extensible manner to document ecological data (Michener et al. 1997). Primary metadata for grab samples will contain information such as sampling station location, implemented method of sample collection and laboratory analysis and point of contact information using the naming convention provided by national water quality monitoring council (NQMC). Metadata for sensor data streams will contain sampling location and sensor QA/QC criteria used to flag data. In addition, complex data related to the calibration of sensors, development of flow rating curves and workflow will be documented separately as secondary metadata documents (.doc or .PDF) and distributed with accompanying datasets.

**Data Sharing.** Compiled data and metadata will be distributed through UNH’s Data Discovery Center’s portal (DDC.unh.edu), a digital library of earth science data, compatible with Open Geospatial Consortium data standards for communicating and sharing continuous monitoring data. This portal enables the real-time viewing as well as querying and download of data.

**Figure 2**. Configuration of proposed data solution.

**Table 2.** Versioning of field measurement data

|  |  |  |  |
| --- | --- | --- | --- |
| Data Type | Data Level | Description | Format |
| Sensor Measurements | Level 0 | Preserved raw sensor streams captured with no QC, no data qualifying flags. Data logger conversion of units or format may be acceptable | comma separated values (CSV), ASCII or binary files |
| Sensor Measurements | Level 1A and 1B | Automated QC criteria applied, data qualifying flags, calibration, sensor vs. grab corrections applied, manual QC applied. | CSV |
| Grab sample data | Level 1B | basic QC criteria – identify outliers. | CSV |

**F. Analytics and Interpretation**

The core analysis is to quantify a time series of net NO3- retention for each deployment period. The sensors and measurements will provide continuous discharge, nitrate flux, and chloride flux for each site. We will estimate the net proportion of nitrate retained by the reservoir (R, unitless) as:

R = 1 - NO3:Clflux\_out / NO3:Clflux\_in.

Where, NO3:Clflux\_out is the ratio of nitrate to chloride flux exported from the reservoir, and NO3:Clflux\_in is the ratio of nitrate to chloride flux entering the reservoir. In reservoirs with more than one inflow (Table 1), NO3:Clflux\_in will be estimated by summing the fluxes from all input contributing areas. The ratio of NO3 to Cl will be used to account for hydrologic retention (Wollheim et al. In Press). R will be calculated at different time scales, including 1) high frequency, 2) daily, 3) monthly, and 4) storm event scale. Under stable, base flow conditions, we can assume hydrologic inputs and outputs are approaching equilibrium (which is accounted for using the chloride mass balance), and so can quantify base flow retention. During storm events, we will integrate over the storm pulse both nitrate and chloride, and use the storm event scale to determine input and output N:Cl ratios. Storm events will be identified using hydrograph separation techniques using the R package , EcoHydRology, BaseFlowSeparation function (R Studio Team 2015). For each reservoir and time period, we will estimate NO3 retention curves as a function of discharge, residence time (determined from estimates or discharge and reservoir volume), water temperature, or light conditions using regression analysis in R. We will also use time series analysis techniques to gain a better understanding of patterns captured in data at inflow and outflow locations. Application of techniques such as *frequency dependent coherence* (Mulukutla In Review) can provide a window into the coupled or uncoupled behavior of nitrate across partitioned timescales (hourly through seasonal). This may indicate the degree of influence and role of watershed vs. reservoir processes in driving variability on concentrations (or fluxes) across seasons and storms.

**G. Communication and Use**

The products of this study will yield an improved understanding of the impacts of reservoirs on nitrate fluxes. The individuals and agencies who have thus far expressed the need for this knowledge to improve decision making include: Kalle Matso (Piscataqua Region Estuaries Project), Kevin Lucey (New Hampshire Department of Environmental Services), Ruth Ladd (United States Army Corps of Engineers), Melinda Bubier (NH DES), and April Talon (Town of Durham) (Table 3). Co-investigator Julia Peterson, extension specialist with NH Sea Grant, will help the research team convey results effectively to these decision makers through meetings, management summaries, and fact sheets. We will hold a workshop that will emphasize how to access the data sets through the UNH Data Discover Center (DDC, see above). The DDC allows graphical representation, in addition to access to the QA/QC'd data.

Our results are relevant for several specific management issues. One of the reservoir sites we expect to monitor is located at the mouth of the Oyster R. watershed in Durham NH. It has accumulated sediments over the years and is turning into a wetland, which is potentially ideal for nitrate retention. Durham is in the midst of conducting a study of the Mill Pond, including a nitrogen source study. This study is expected to fulfill requirements for the Federal NH Small MS4 Permit, which will become effective on July 1, 2018 (Durham updates 2017-09-08). The town is planning to test how lowering water levels in the reservoir will alter water quality. Our plan for sensor deployment would be able to quantify changes in nitrate removal by the reservoir under different flow conditions, which is not part of the study being planned by Durham. This information is needed to weigh the tradeoffs necessary for deciding whether the dam and its associated reservoir should be permanently removed.

A second study involves the Sawyer Mill dam and its reservoir located at the mouth of the Bellamy River watershed in Dover NH. This dam is undersized for current estimates of the 100 yr flood (Kevin Lucey, NH DES, personal communication), and could damage associated apartments. This dam is scheduled for removal in July 2018, and will include contaminated sediment removal, replacement and restoration. The reservoir is already being maintained at a low water level because of the risks should a flood event occur. Deployment of the sensor network will allow quantification of nitrate removal under current conditions, after dam removal, and following riparian restoration.

A series of other dam removals are being considered. Kevin Lucey is the primary coordinator of the Sawyer Mill removal, but also sits on the technical advisory committees of the McCallen Dam (Lamprey R. watershed in Newmarket, NH) and the Oyster River dam at Mill Pond. Ruth Ladd (USACE) manages the compensatory mitigation credit granting mechanism often used for project funding, and Melinda Bubier (NH DES) manages the In-Lieu Fee program that provides funding for local communities engaged in dam removals, and selects projects based on costs and benefits of each removal. Knowledge of the N removal capacity of different dams at different times of year and flow conditions will inform these cost benefit analyses, which are particularly important in sensitive coastal estuaries.

The final use of the findings of this study relate to future projections of risks to the Great Bay Estuary associate with increased nitrogen loading with continued land use change, ongoing dam removals, and increased climate variability. Kalle Matso of PREP is currently preparing the triennial State of the Estuaries Report for Great Bay, which includes an assessment of the health of the Great Bay estuary. The eelgrass in Great Bay is declining (Short 2013), and one of the proposed mechanisms for this loss is the increase in nitrogen exports from the watershed due to population growth leading to increased algal growth that shade eelgrass plants. Knowledge of how N fluxes may change is therefore of considerable interest. If dam removals continue watershed N retention capacity may decline, resulting in an acceleration of N inputs. Decisions could focus on not removing dams with critical N retention functions, or targeting nitrogen mitigation activities in watersheds where dams are removed, such as targeted fertilizer reductions.

**Table 3**. Decision makers who will use study results.

|  |  |  |  |
| --- | --- | --- | --- |
| **Decision maker** | **Title** | **Agency** | **Interest** |
| Kalle Matso | Coastal Science Program Manager | Piscataqua Region Estuaries Partnership | Dam removal impacts on trends in non-point nitrogen fluxes from watersheds and impacts on Great Bay |
| Kevin Lucey | Coastal Habitat Restoration Specialist | New Hampshire Department of Environmental Services (DES) | Primary coordinator of Sawyer Mill Dam removal project; Advisory committee for other removals; Impacts on coastal habitat |
| Melinda Bubier | Program Specialist, Freshwater Restoration | New Hampshire DES | Net benefit of dam removal for ecological stream restoration and in-lieu fee program funding |
| Ruth Ladd | Chief, Policy Analysis and Technical Support | U.S. Army Corps of Engineers | Prioritizing dam removal projects accounting for costs and benefits. Mitigation credit determination. |
| April Talon | Town Engineer | Town of Durham, NH | Optimal management of Mill Pond reservoir on the Oyster R. |

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