Integrating fine-scale field measurements with regional groundwater models to predict legacy nitrogen transport in Long Island Sound watersheds

Basic Information

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Principal Investigators:	Ashley M. Helton, Jeffrey Starn, Martin A. Briggs

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Introduction/Research Objective

Human activities have increased N loading to land surfaces by at least five times compared to pre-industrial conditions (Houlton et al. 2013). Over the past 50 years, this elevated N loading to land surfaces has dramatically increased N in receiving waters, resulting in eutrophication of coastal areas worldwide (Diaz and Rosenberg 2008). Surface runoff and river transport of N have been studied extensively at the watershed-scale (Van Breemen et al. 2002; Seitzinger et al. 2010; e.g. Moore et al. 2011). However, N applications to land surfaces have also substantially increased N in recharging groundwater, creating a source of N that is later discharged back to surface waters ("legacy N"). Typical groundwater transport times can be months, decades, or even centuries longer than surface water transport times (Hamilton 2012), creating substantial temporal and spatial lags between infiltration and discharge. Although approximately 70% of surface water in the U.S. is derived from groundwater that discharges during baseflow (Wolock 2003), the role of groundwater transport in reactive nitrogen (N) loading to receiving surface waters has not been quantified at broad scales and is typically not considered in management strategies for N load reductions. Indeed, N accumulating in aquifers and discharging to streams may be a reason many impaired coastal systems show little improvement despite efforts to reduce N loads (Sprague et al. 2011; Sanford and Pope 2013; Chen et al. 2014).

Recent research has begun addressing the effects of groundwater lags on the timing of N loading to sensitive downstream systems (Sanford and Pope 2013; Chen et al. 2014; Van Meter and Basu 2015). Ignoring these lags could lead to overly ambitious load reduction goals or incorrect conclusions about the effectiveness of N reduction strategies (Albiac 2009; Sanford and Pope 2013). Yet, we commonly apply surface runoff watershed models that disregard groundwater transport to predict surface water N dynamics. Therefore, there is a critical need for watershed-scale approaches that quantify legacy N loading from groundwaters to surface waters. In the absence of such approaches, our capacity to effectively evaluate management strategies that seek to improve coastal water quality will be inadequate.

For this project, our objectives were to 1) estimate the spatial distribution of groundwater discharge using a traditional groundwater modeling approach; 2) compare spatial patterns of modeled groundwater discharge to observed groundwater seeps over 10's of km of river length; and 3) identify initial locations where stream interface sediments are potentially important filters or conduits of legacy N.

Methods/Procedures/Progress

<u>Study site</u>: This project focused on the Farmington River watershed (1571 km^2) located in northwestern CT and southwestern MA (Figure 1). The Farmington discharges to the Connecticut River, which discharges to the LIS. Principal bedrock aquifers in the Farmington are the New England Crystalline-rock aquifer and the Mesozoic sandstone and basalt of the Newark Supergroup. The bedrock is overlain by glacial till across most of the watershed, with areas of

valley fill stratified drift aquifers (Olcott 1995). The watershed has experienced substantial changes in land cover over the last several decades. Between 1973 and 2011 there was a 38% reduction in agricultural and a 19% gain in urban land cover (based on GIRAS 1973 and NLCD 2011, D. Civco unpublished).

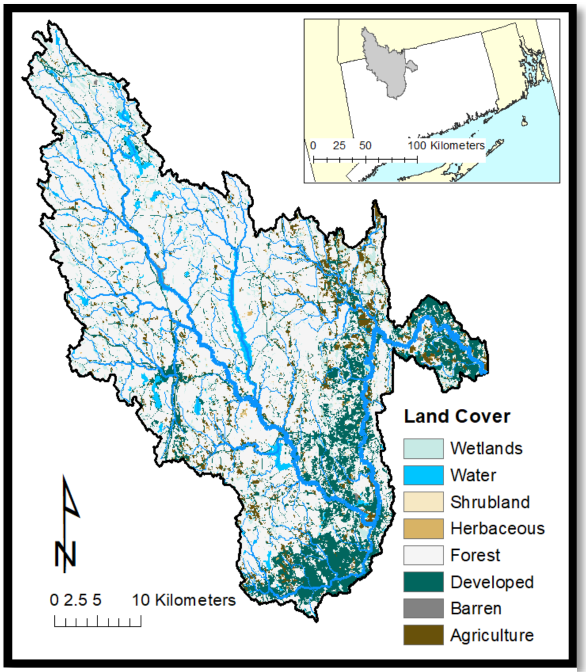


Figure 1. Farmington River watershed.

<u>Thermal infrared (TIR) surveys & regional groundwater modeling</u>: Heat can be an ideal tracer of groundwater flow in late summer as groundwater temperature is predictable, colder than surface water, and easily visualized with thermal infrared (TIR) cameras (Hare et al., 2015; Rosenberry et al., 2016). We surveyed 36.6 km of stream length, including 31 km of the 5th order main stem of the Farmington River by watercraft and 5.6 km of 1st to 3rd order tributaries in the Farmington River watershed by wading with handheld TIR cameras in summer and fall 2017 (Figure 2). Typically, focused groundwater discharge characterizations made with physical seepage meters and piezometers are done over reach lengths that do not exceed 100's of meters (Rosenberry et al. 2013). Thermal infrared surveys allowed us to efficiently map a comprehensive spatial distribution of groundwater seeps across 10's of kilometers.

We implemented and calibrated a steady-state groundwater flow model (MODFLOW-NWT; Niswonger et al. 2011) for the Farmington River watershed. The model has a daily time-step, a uniform horizontal grid of 300 m, four vertical layers of increasing thickness with depth, and five zones of surficial materials (Soller et al. 2012). Spatially varying recharge (Wolock 2003) drives subsurface flow. The model was calibrated with PEST++ (Welter et al. 2015) using 287 well head (USGS 2017) and 217 stream elevation measurements (US EPA & USGS 2012). We used MODPATH (Pollock 2012) with recharge scaled particle inputs to calculate median subsurface travel times.

We compared the occurrence of modeled groundwater discharge to discharge observed in the field during TIR surveys. Our field survey included 168 (out of 3743) model river cells. We will also evaluate predictions from a series of additional MODFLOW models. We expect hydraulic conductivity (K) of surficial materials, riverbed conductance, and the resolution of topography to drive disparities between spatial patterns of observed and modeled discharge. Thus, our initial model refinement will focus on these, with four specific models: 1) Base model (described above, 300 m grid) - K in unconsolidated sediments will vary smoothly across the study area using a single zone with uniform riverbed conductivity; 2) Heterogeneous surficial materials (300 m grid) - Five zones will correspond to surficial material (coarse, fine, till, wetlands, and open water) with uniform riverbed conductivity; 3) Variable riverbed conductivity (300 m grid): Five zones and riverbed conductivity will correspond to surficial material; 4) Higher resolution: (50 m grid) - We anticipate better model predictions in larger streams, where topographic drivers of discharge are more consistent with model resolution. To address the computational challenge of calibrating a finer resolution model, we will use pilot points from the best coarse model to create the K layer, rather than recalibrating. We acknowledge that further refinement may be needed in later models - such as observations of where organic-rich river fines “cap” sand and gravel deposits that intersect the river corridor or where flow patterns are dominated by bedrock fracture connectivity. Locations where model refinement does not improve model fit are particularly important for understanding where and why current model and field techniques cannot be reconciled. *Progress: The base model scenario and field surveys are complete and other model scenarios are in progress for a manuscript in preparation (Barclay et al. In Prep. A).*

Groundwater sampling and analysis: At locations of apparent groundwater discharge identified during the field surveys we collected sediment water samples (n=50, depth = 23.5 cm unless local conditions require shallower) using a pore water sampler (Henry) perpendicular to groundwater flow. At each site we also collected surface water samples for comparison. We analyzed all water samples for N species (NO_3^-, N_2O, NH_4^+ and Total Dissolved N (TDN)), anions (Cl^-, SO_4^{2-}, Br-, and PO_4^{3-}), dissolved gases (CO_2 and CH_4), dissolved organic carbon (DOC), and specific conductance. In addition, we analyzed sediment water samples for O_2, N_2, and Ar. We measured specific conductance in the field using a hand-held YSI 556 probe. Dissolved N_2O, CH_4, and CO_2 were measured using headspace equilibration techniques (Helton et al., 2014; Hudson, 2004), and analyzed on a PerkinElmer Clarus 580 gas chromatograph. NO_{3-} (and a suite of anion concentrations including Cl_-, SO_4^{2-}, Br^-, and PO_4^{3-}) were measured on a Thermo Fisher Ion Chromatography System (ICS-1100) and TDN (by persulfate digestion) and NH_4^+ was measured on a SmartChem 200 discrete analyzer. DOC was measured by combustion on a 1020A OI Analytical TOC Analyzer. Ambient N_2, O_2, and Ar were analyzed by Membrane Inlet Mass Spectrometry (MIMS). All laboratory analysis was completed at the University of Connecticut. *Progress: The laboratory analysis is complete and data analysis is in progress for a manuscript in preparation (Barclay et al. In Prep. B).*

Groundwater flux measurements: In 26 locations of apparent groundwater discharge, indicated by anomalously cold temperature, we installed discrete temperature loggers (e.g., iButtons®) in short vertical profilers designed to capture the unique shallow surface heat propagation of discharge zones (Briggs et al., 2014). We used the USGS GUI for VS2DH 1DTempPro (Koch et al., 2015) to analyze the temperature data and calculate variable groundwater discharge rates over time using proven methods. Recently, Rosenberry et al. (2016) showed that when thermal parameters are measured in-situ using passive diurnal signals, 1D temperature-based models return comparable data to seepage meter measurements over a large range of natural groundwater discharge (0-3 md-1). However, unlike most seepage meters, the thermal models can be applied at sub-daily timestep over many months to elucidate spatiotemporal groundwater discharge patterns. *Progress: We are currently analyzing this dataset.*

Results/Significance of Research

Initial Results

<u>Thermal infrared surveys</u>: We observed extensive focused groundwater discharges (stars and crosses, Figure 2b) along the main stem of the Farmington that included both expansive stream bank seepage facie (Figure 2c) that spanned up to 10s of meters along stream banks and individual or clusters of individual seeps (Figure 2d).

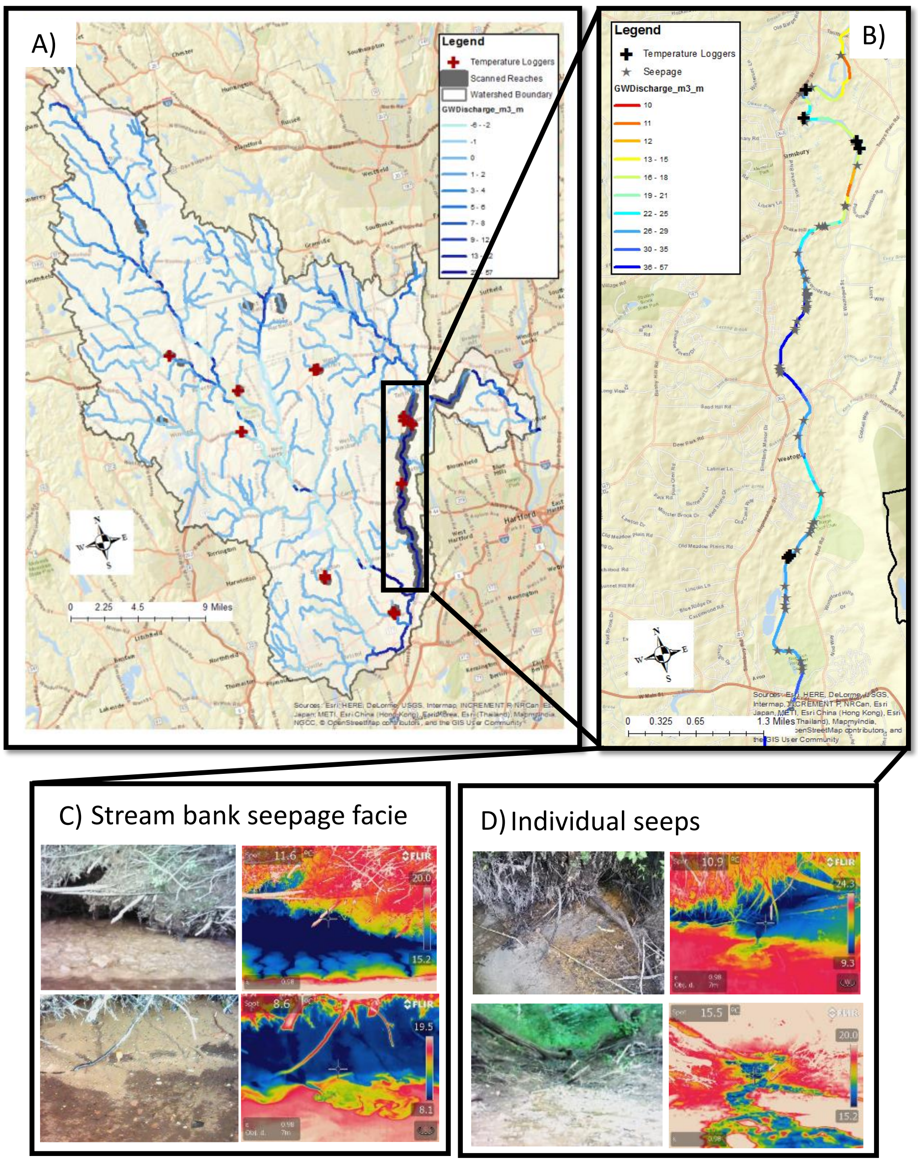


Figure 2. We implemented a groundwater model and surveyed >35 km stream length for focused groundwater discharges using thermal infrared (TIR) imagery surveys in the Farmington River watershed. A) Farmington River watershed. Grey shading indicates TIR survey extent and blue shading indicates simulated groundwater discharge rate (higher rates are darker blue). B) Survey length of the 5th order main stem of the Farmington River. Stars and crosses indicate groundwater discharge zones observed during TIR surveys. Blue shading indicates high rates of simulated groundwater discharge. Examples of focused groundwater discharge zones observed with handheld TIR cameras: C) Stream bank seepage facie and D) Individual groundwater seeps. Blue indicates colder water from regional groundwater flow paths.

Groundwater model: For the base model scenario, modeled well head and stream elevation measurements fit observed datasets well (Figure 3). We are currently analyzing model output and refining model scenarios.

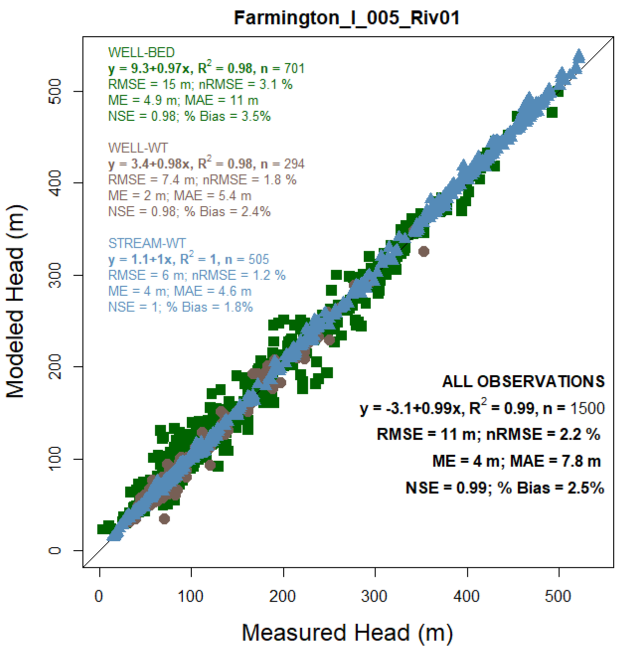
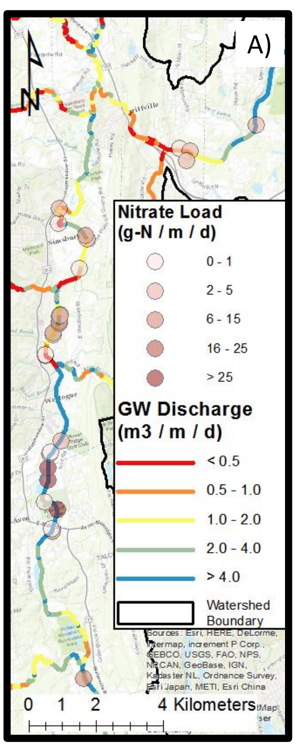


Figure 3. Modeled versus measured well head and stream elevation for MODFLOW base scenario.

Model comparison: We observed groundwater discharge with TIR imagery in the majority of model cells surveyed (>60% in the 5th order Farmington, i.e., paddling reaches, and >80% in small tributaries, i.e., wading reaches). We are currently evaluating model predictions against the observed spatial distribution of seeps.

Nitrogen dynamics: Legacy N loads, based on measured concentrations and modeled discharge rates, vary considerably from near detection to higher than 25 g N $m^{-1}d^{-1}$ (Figure 4a). Even in areas with high rates of groundwater discharge, a wide range of nitrate concentrations drives huge variability in N loads to the stream. Areas with high nitrate concentrations (darker red circles, Figure 4b), high groundwater discharge, and long travel times are of particular interest from a legacy N perspective because they may contribute disproportionately large N loads for many years into the future. We are currently building statistical models to predict spatial patterns of legacy N loads and denitrification.



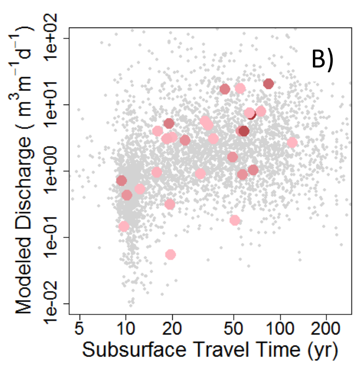


Figure 4. A) Nitrate loads in groundwater discharge estimated along the Farmington main stem. B) Modeled groundwater discharge versus travel time. Grey dots represent all stream reaches. Larger dots are sites with measured nitrate. Darker colors indicate higher nitrate concentrations.

Significance of Research

We expect our proposed project to contribute widely to the field of hydrologic sciences, to have a significant positive impact on N management strategies, and to have immediate implications for the management of N and the evaluation of N reduction strategies for the Long Island Sound watershed. Upon completion of the proposed research, we expect to have established groundwater model downscaling techniques that integrate fine-scale empirical measurements of groundwater-surface water exchange with regional groundwater models to accurately predict spatiotemporal patterning of groundwater discharge. These patterns are not typically the focus of groundwater model calibration; however, it is essential that we represent the spatial and temporal patterns of groundwater discharge as accurately as possible because we are interested in the discharge of legacy N from groundwaters to surface waters.

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Names and degree level of any students working on project.

- Janet Barclay, PhD Candidate, NRE, University of Connecticut
- Ann Hunt, Undergraduate (USGS Office of Groundwater, Branch of Geophysics summer internship program)

Presentations

- Helton, AM, JR Barclay, MA Briggs, JJ Starn, A Hunt. 2018. River network-scale patterns of groundwater discharge and denitrification of legacy nitrogen at the streambed interface. Society for Freshwater Science Annual Meeting. Detroit, MI.
- Barclay JR, AM Helton, MA Briggs, JJ Starn. 2018. What's old is new: Managing nitrogen legacies. Connecticut Conference on Natural Resources. Storrs, CT.
- Barclay JR, AM Helton, MA Briggs, JJ Starn, A Hunt. 2018. Groundwater Discharge of Legacy Nitrogen to River Networks: Patterns of Subsurface Travel Time, Nitrogen Loading, and Denitrification. Geological Society of America, Northeastern Section Meeting. Burlington, VT.
- Barclay JR, AM Helton, MA Briggs, JJ Starn, A Hunt. 2017. Poster: Groundwater Discharge of Legacy Nitrogen to River Networks: Linking Regional Groundwater Models to Streambed Groundwater-Surface Water Exchange and Nitrogen Processing. American Geophysical Union Fall Meeting. New Orleans, LA.
- Barclay, JR, AM Helton, JJ Starn, MA Briggs. 2017. Quantifying legacy nitrogen transport in Connecticut watersheds. Connecticut Conference of Natural Resources. Storrs, CT.

Publications - In Preparation

A. Barclay, JR; Helton, AM; Briggs, MA; Starn, JJ; Hunt, A. Groundwater Discharge of Legacy Nitrogen to River Networks: Linking Regional Groundwater Models to Streambed Groundwater-Surface Water Exchange.
B. Barclay, JR; Helton, AM; Briggs, MA; Starn, JJ; Hunt, A. Groundwater Discharge of Legacy Nitrogen to River Networks: Patterns of Nitrogen Loading and Denitrification.
C. Barclay, JR; Helton, AM; Briggs, MA; Starn, JJ. Groundwater Discharge of Legacy Nitrogen to River Networks: Spatial patterns of vulnerability and management implications.

Additional Items

We have two grants pending (recommended for funding but not yet funded):

- The role of stream interface sediments in legacy nitrogen removal at groundwater discharge zones. PI: AM Helton, co-PIs: MA Briggs, JJ Starn. USDA-Hatch. $59,996
- Groundwater discharge of legacy nitrogen at the scale of river networks: Where are stream interface sediments conduits or filters? PI: AM Helton, co-PIs: MA Briggs, JJ Starn. NSF-Hydrologic Sciences. $696,729