IWW Mini-grant Final Report: Groundwater-Surface Water Exchange Controls Nitrogen Export from Headwater Streams in Oregon

Project Type:	Research
Focus Categories:	Water Quality (WQL), Solute Transport (ST), Nutrients (NU), Nitrate Contamination (NC), Models (MOD), Methods (MET), Hydrogeochemistry (HYDGEO), Hydrology (HYDROL), Surface Water (SW), Groundwater (GW), Management and Planning (M&P)
Keywords:	nitrogen dynamics, groundwater-surface water exchange, hyporheic zone, Willamette basin, forested streams
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End Date:	March 15, 2008

Principal Investigator: **Jay P. Zarnetske**, PhD student, Geosciences Dept, Oregon State University, zarnetsj@geo.oregonstate.edu, (541) 758-2864

Executive Summary of Funded Research:

Groundwater – surface water (hyporheic) interactions are critical to understanding the transport and fate of nutrients in watersheds. However, uncertainties plague predictions of stream-groundwater interactions, and consequently, limit our ability to understand nutrient regulation in watersheds. The research supported in part by the IWW Mini-grant combines innovative shallow subsurface geophysical imaging and groundwater flow modeling techniques with existing empirical approaches to resolve two major sources of uncertainty in predicting hyporheic processes that influence on a model nutrient/pollutant, Nitrogen, through stream networks. These sub-surface uncertainty factors are the depth of saturated alluvium and spatial heterogeneity of that alluvium. To date, I have utilized continuous electrical resistivity imaging and subsurface tracer experiments to address and overcome these uncertainty factors and provide previously unrealized 3-D characterization maps of hyporheic dynamics. Additionally, I am processing samples and data from ^{15}N-Nitrate (NO_3^-) stream injection experiments at two Oregon headwater streams (1 forested and 1 agricultural) to determine the transport and transformation rates of NO_3^- in the subsurface (i.e., Nitrogen removal via hyporheic denitrification). These isotope experiments demonstrate denitrification is an active process in the hyporheic zone of these streams and that the different hydrodynamic and biogeochemical conditions of these streams dictate the levels of total observed denitrification. I am now coupling the geophysical imaging and groundwater flow modeling to assess the value gained from imaging the architecture of the groundwater flow conditions, such as alluvial package geometry and bedrock topography. Ultimately, this electrical resistivity image enhanced groundwater flow modeling will be linked to ^{15}N biochemical measurements in a hydrodynamic model to elucidate the factors controlling the distribution and concentrations of NO_3^- in different stream types.

To date the IWW Mini-grant has facilitated the dissemination of this research via 6 public/conference presentations, 2 published abstracts in conference proceedings, and development of 2 peer-reviewed manuscripts.

Critical Issues Addressed by Awarded Funds:

Nutrients such as Nitrogen (N) are essential to all aquatic biota. However, in excess, these nutrients adversely affect aquatic systems, contributing to algae blooms, hypoxia, and human/fish disease [NRC, 1992]. The sources of excess stream N have been extensively documented (e.g., point/non-point sources: sewage treatment discharge, storm/agricultural runoff, and atmospheric deposition via air pollution). Despite improved management practices, N pollution remains a substantial problem for surface and ground waters. Research has clearly established that stream-groundwater interactions have the potential to regulate excess nutrients [e.g., Holmes et al., 1996], but uncertainties limit the ability to develop management practices that would contribute to self-purification of stream water.

The interaction between subsurface fluxes of water, solutes, and biogeochemical processes is significant to stream nutrient regulation [Duff & Triska, 2000]. The region where these subsurface-surface water interactions occur is the hyporheic zone (Figure 1). The hyporheic zone can be a permanent sink of N, if nitrate (NO_3^-) is lost via denitrification. Substantial uncertainty regarding subsurface stream processes confounds quantification of hyporheic zone influence on N transport/loss in streams [Bencala, 2006]. The greatest uncertainty in observing and modeling hyporheic processes stems from the inability to accurately characterize the subsurface hydraulic conditions, especially the sediment heterogeneity and thickness of the saturated alluvial aquifer [e.g., Salehin et al., 2004]. These two factors are essential to interpreting empirical data and developing models of hyporheic processes. Previous studies have tried to address this impasse through extensive and costly field investigations [e.g., Wondzell, 2006], however, they still resorted to simplifying assumptions combined with sensitivity analyses to characterize the effects of uncertainty. Further, these difficulties constrain the applicability of the research to the specific study sites, preventing the findings from being generalized/scaled.

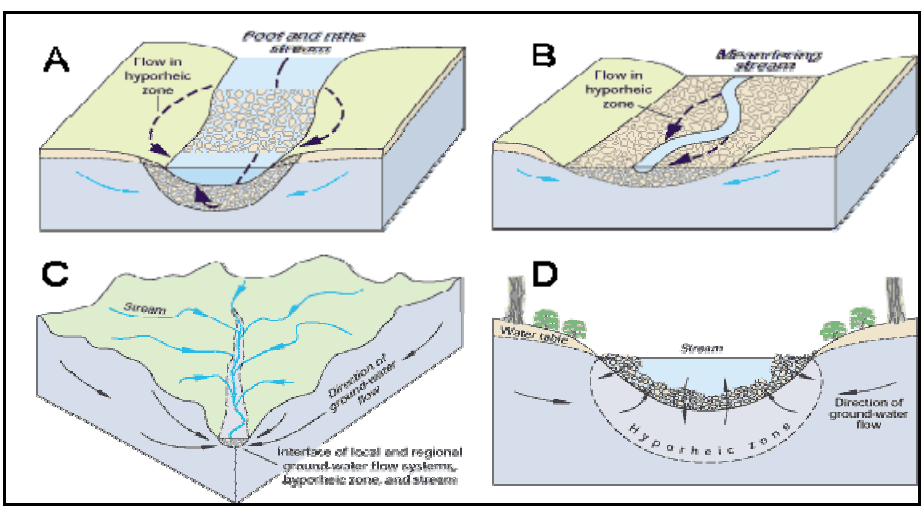

Figure 1. The hyporheic zone. Surface water exchange with groundwater in the hyporheic zone is associated with abrupt changes in streambed slope (A) and with stream meanders (B). Streambeds and banks (C and D) are unique environments because they are where groundwater, which drains much of the landscape subsurface interacts with surface water, which drains much of the surface of landscapes [modified from Winter et al., 1998].

The research initiated in part by IWW Mini-grant funding offers an innovative and cost-effective method for resolving these uncertainties, while identifying key hyporheic controls on N regulation in streams. Both outcomes are leading to a robust scientific account of previously immeasurable hyporheic-nitrogen interactions, which is crucial for managing excess stream N – a much sought after research goal of stream ecology and water quality [Ensign & Doyle, 2006].

Research Milestones and Progress Facilitated by Award Funds:

Hyporheic Electrical Resistivity Imaging and Transport Modeling

Improving our understanding of hydrological processes often requires that robust measurements be made in challenging environments where traditional techniques are inadequate. The IWW Mini-grant award partially supported a pilot study of using a novel measurement technique, electrical resistivity imaging (ERI), for advancing our understanding of the complex hyporheic sediment architecture of an Oregon mountain stream (Mack Creek study site, H.J. Andrews Experimental Forest, Figure 1A). This work represents collaborations between both Oregon State University and Stanford University NSF CUASHI Hydrologic Measurement Facility investigators, and has resulted in a manuscript (*Crook et al.*, in review).

The pilot study demonstrated that ERI, with the recent advancements in acquisition and inversion methods, coupled with simple ERI tool modifications provides a useful technique for characterizing the sediments underlying stream channels. By emplacing the electrodes directly in the sediments of the stream bed we obtained high resolution images of subsurface sediment architecture directly beneath the stream channel (Figure 1B). This technique provides a continuous image across the longitudinal alluvium-bedrock contact at Mack Creek. These ERI findings represent significantly greater understanding about the subsurface than is normally observable below stream channels and adjacent riparian zones.

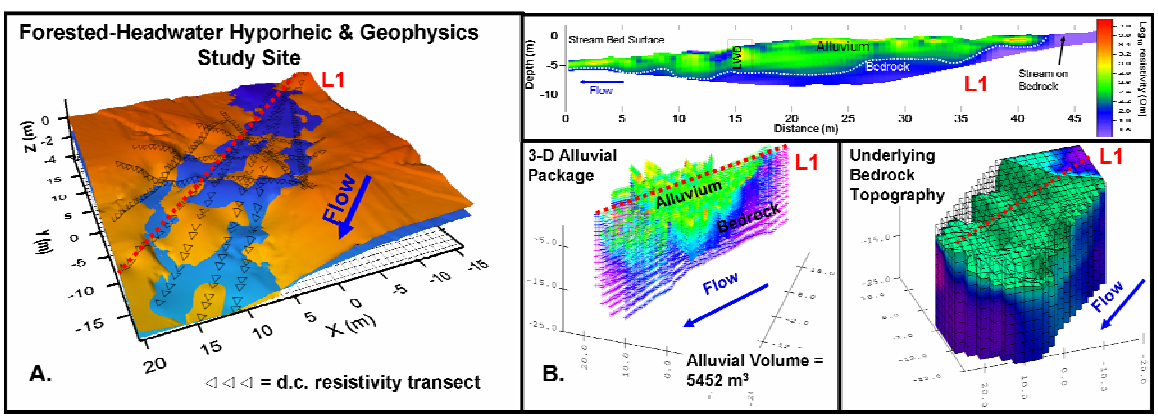

Figure 2. A. Aerial perspective of Mack Creek study site with georectified water elevation surface (blue) intersected with topographic landscape elevation surface (orange). Triangle symbols represent the location of the electrical resistivity survey transects. B. Electrical resistivity survey results, showing delineation and geometry of the alluvial aquifer and bedrock topography. These results will constrain hyporheic groundwater transport and spatially-explicit denitrification models. For spatial referencing, note the location of ERI survey line L1 (dotted red line) in figure plates.

Ground-truthing the ERI through comparison with alternative forms of subsurface information isolated the resistivity values for the shallow subsurface sediment and bedrock lithology (Figure 1B). These calibrations were then applied to all regions of the resistivity lines, allowing the interpretation of the architecture for the site to be determined beneath the stream channel.

This information will now be used to inform subsequent hydrological investigations and models of this stream. The first of these modeling investigations is underway, and represents the application of this ERI to inform and constrain the uncertainty associated with modeling the fluxes of water and solutes in the hyporheic zone of the Mack Creek site. In particular, this model will investigate how enhanced knowledge of subsurface boundary conditions and geometries translate to improved groundwater flow model accuracy and prediction. This Mack Creek groundwater flow modeling investigation is currently underway, and will ultimately result in a submitted manuscript (*Zarnetske et al.*, in prep).

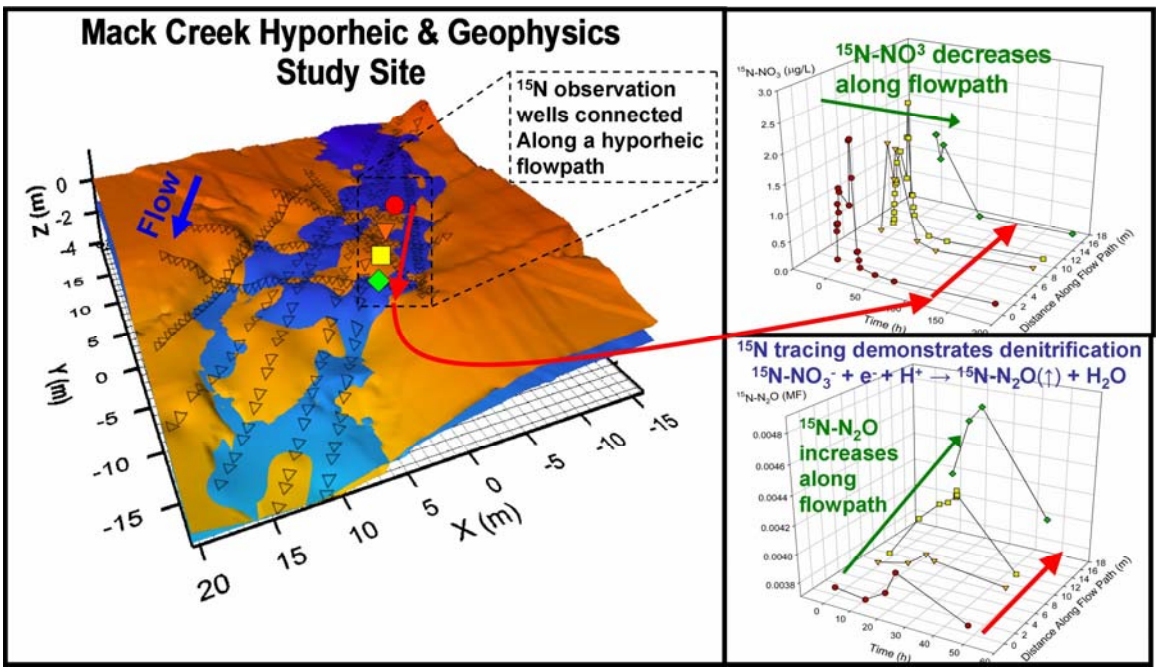

Figure 3. Illustration of observed denitrification in the forested-headwater hyporheic site. Red arrow shows flowpath direction across hyporheic water observations.

Synthesis of existing ^{15}N denitrification studies completed at Mack Creek site has demonstrated that denitrification does occur at this forested headwater stream. Ultimately, the goal is to link observed denitrification rates with the ERI enhanced groundwater flow model so that local hyporheic denitrification observations can be scaled up to larger spatial scales (i.e., reach and stream network). The results of the ^{15}N denitrification data indicates that while denitrification is an active process within the system (Figure 2), however, the total N removal from the system is likely limited by low background NO_3^- in the system as well as high levels of dissolved oxygen in the subsurface. Both of these biogeochemical conditions will limit observed denitrification rates. Hence, the hyporheic zone of this stream is not likely to play a large role in the total N budget at the reach scale. This is not likely the case for streams were NO_3^-

concentrations are higher and hyporheic exchange conditions are more conducive to low dissolved oxygen conditions. Consequently, an additional stream with high background NO_3^- levels and less potential subsurface dissolved oxygen was investigated via ^{15}N experiments to see if denitrification was present in the hyporheic zone and at rates higher than the forested stream. The preliminary results from this associated Oregon headwater stream site are presented in the following section.

Associated Hyporheic Denitrification Field Investigations

An extensive complementary investigation on the role of a hyporheic zone in removing nitrate from an agriculturally dominated Oregon headwater stream (Drift Creek, Silverton) was executed during the spring and summer of 2007. This stream was selected because it represents a system with high background nitrate levels and an active hyporheic system. Consequently, this stream is expected to yield higher rates of hyporheic denitrification than the pristine forested stream, Mack Creek.

The methods for the execution of this agricultural stream experiment are similar to the previously conducted Oregon and Pacific Northwest denitrification studies supported by outside research awards (e.g., NSF Lotic Intersite Nitrogen Experiments). This methodological similarity will allow our work to be added to the growing bank of stream denitrification studies, which ultimately can be utilized for broader synthesis investigations. Furthermore, the hyporheic models developed with the supported by this IWW Mini-grant are producing analysis methods that will be implemented to investigate denitrification across this new stream site as well as additional denitrification stream investigations and environments.

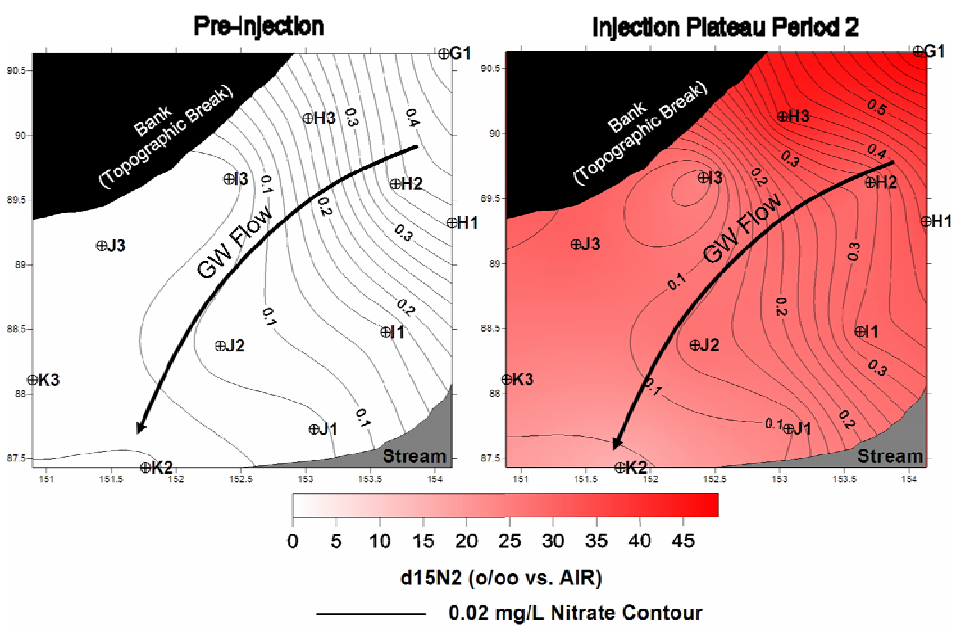

Figure 3. Plan view of the investigated Drift Creek gravel bar site pre-injection (ambient conditions) and during the ^{15}N denitrification experiment. Note the observation well network (circles with crosshairs), prevailing groundwater flow direction (arrow), NO_3^- concentration contours, and ^{15}N enrichment levels in the denitrification product, N_2 during the experiment.

Preliminary results from this agricultural stream experiment indicate a strong nitrate removal potential through the sediments of the study site. The stream nitrate levels at the beginning of the hyporheic flow paths are 0.45 mg/L (Figure 3), however, near the distal end of these same flow paths the nitrate concentrations have decreased to 0.04 mg/L. Observing the actual denitrification pathway as mediated by microbes ($^{15}N\text{-}NO_3^- + e^- + H^+ \rightarrow {}^{15}N\text{-}N_2O(\uparrow) + H_2O \rightarrow {}^{15}N\text{-}N_2\ (\uparrow) + H_2O$) will be possible via analysis of the $^{15}N\text{-}NO_3^-$ tracer experiments. The results of the ^{15}N experiments are incomplete at this time. However, preliminary results of the $^{15}N\text{-}NO_3^-$ denitrification product, $^{15}N_2$, indicate that the experiment was successfully executed because ^{15}N enriched N_2 levels before and during the experiment are very different, increasing from $\delta^{15}N_2$ 0.0-3.0 to 15.2-49.8 (‰ vs. air) during the experiment (Figure 3). Once the time series ^{15}N enrichment data from this compound as well as the other denitrification pathway compounds are available, denitrification rates will be quantified. These denitrification rates, in turn, will be used to quantify the role of the hyporheic zone on N removal in this stream system.

Presentations and Publications Facilitated by Award Funds:

To date the IWW Mini-grant has facilitated the dissemination of this research via 6 public/conference presentations, 2 peer-reviewed published abstracts in conference proceedings, and development of 2 peer-reviewed journal manuscripts.

Presentations

Zarnetske, JP, R Haggerty, N Crook , and DR Robinson. Hyporheic geophysics: D.C. resistivity imaging of valley-bottom alluvium in a 3rd-order mountain stream, HJ Andrews Experimental Forest, Oregon, USA.
-2006 American Geophysical Union, Annual Meeting, Peer-reviewed Proceedings Abstract
-2007 Oregon State University, WRGP Open House (awarded best presentation)
-2007 Oregon State University, Dept. of Geosciences External Advisor Board Symposium
-2007 Oregon State University, H.J. Andrews Experimental Forest, LTER Monthly Meeting

Zarnetske JP, MN Gooseff, WB Bowden, MJ Greenwald, TR Brosten, JH Bradford, and JP McNamara. Influence of morphology and permafrost dynamics on surface water - groundwater exchange in arctic headwater streams under present and enhanced thaw conditions.
-2007 American Geophysical Union, Annual Meeting, Peer-reviewed Proceedings Abstract
-2008 Oregon State University, WRGP Open House (awarded honorable mention)

Publications (summaries presented in research milestones section)

Crook N, A Binley, R Knight, DA Robinson, JP Zarnetske, and R Haggerty. (*In review*) Electrical Resistivity Imaging of the Architecture of Sub-Stream Sediments. *Water Resources Research*.

Zarnetske JP, R Haggerty, N Crook, R Knight, and D Robinson. (*In preparation*) Application of Stream Bed Electrical Resistivity Imaging to Informed Stream – Groundwater Exchange Modeling. *Water Resources Research*.

Literature Cited:

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Ensign, S.H., and M.W. Doyle. 2006. Nutrient spiraling in streams and river networks. *Journal of Geophysical Research*. 111, doi:10.1029/2005JG000114.

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Salehin, M., A.I. Packman, and M. Paradis. 2004. Hyporheic exchange with heterogeneous streambeds: laboratory experiments ad modeling. *Water Resources Research*, 40, W11504, doi:10.1029/2003WR002567

Winter, T.C., J.W. Harvey, O.L. Franke, and W.M. Alley. 1998. Ground Water and Surface Water a Single Resource. *USGS Circular 1139*. Denver, CO. http://pubs.usgs.gov/circ/circ1139/

Wondzell, S.M. 2006. Effect of morphology and discharge on hyporheic exchange flows in two small streams in the Cascade Mountains of Oregon, USA. *Hydrological Processes*. 20(2), 267-287

Summary of Award Fund Disbursements:

- Stipend for recipient: payroll and OPE
- Annual American Geophysical Union Conference in San Francisco, California: attendance and associate costs
- Sample analytical costs from Marine Biological Stable Isotope Laboratory

Details of Award Fund Disbursements:

Expense Item	Date	Unit	# of	Spent	Spent Total	Remaining Total
						$10,107.00
Payroll (stipend)	1-Apr-07	$914.94	1.0	$914.94	$914.94	$9,192.06
Payroll (stipend)	1-May-07	$914.94	1.0	$914.94	$1,829.88	$8,277.12
Payroll (stipend)	1-Jun-07	$914.94	1.0	$914.94	$2,744.82	$7,362.18
OPE	1-Jun-07	na	na	$5.15	$2,749.97	$7,357.03
Payroll (stipend)	1-Sep-07	$915.12	0.5	$457.56	$3,207.53	$6,899.47
OPE	1-Sep-07	na	na	$37.82	$3,245.35	$6,861.65
Payroll (stipend)	1-Oct-07	$915.12	1.0	$915.12	$4,160.47	$5,946.53
OPE	1-Oct-07	na	na	$5.65	$4,166.12	$5,940.88
Payroll (stipend)	30-Nov-07	$915.12	1.0	$915.12	$5,081.24	$5,025.76
OPE	30-Nov-07	na	na	$5.65	$5,086.89	$5,020.11
Airfare - AGU Conf. in SF	3-Dec-07	na	na	$182.79	$5,269.68	$4,837.32
Airfare - AGU Conf. in SF	3-Dec-07	na	na	$32.50	$5,302.18	$4,804.82
Registration - AGU Conf. in SF	19-Dec-07	na	na	$247.00	$5,549.18	$4,557.82
Housing - AGU Conf. in SF	19-Dec-07	na	na	$661.64	$6,210.82	$3,896.18
Payroll (stipend)	31-Dec-07	$915.12	1.0	$915.12	$7,125.94	$2,981.06
OPE	31-Dec-07	na	na	$5.65	$7,131.59	$2,975.41
Payroll (stipend)	31-Jan-08	$915.12	1.0	$915.12	$8,046.71	$2,060.29
OPE	31-Jan-08	na	na	$5.65	$8,052.36	$2,054.64
Payroll (stipend)	28-Feb-08	$915.12	1.0	$915.12	$8,967.48	$1,139.52
OPE	28-Feb-08	na	na	$5.65	$8,973.13	$1,133.87
Analytical Costs - MBL	31-Mar-08	$10.50	67.0	$673.48	$9,646.61	$460.39
Payroll (stipend)*	31-Mar-08	$915.12	0.5	$457.56	$10,104.17	$2.83
OPE*	31-Mar-08	na	na	$2.83	$10,107.00	$0.00

*Outstanding Encumbrances $460.39