Vermont Water Resources and Lake Studies Center
Annual Technical Report
FY 2010

Introduction

The Annual Report for the Vermont Water Resources and Lake Studies Center for FY2010 is attached. The grant awarded under the State Water Resources Research Institute Program is 06HQGR0123

Research Program Introduction

In the 2010-2011 project year the Vermont Water Resources and Lake Studies Center continued its collaboration with the Vermont Agency of Natural Resources (VTANR) within the Vermont Department of Environmental Conservation (VTDEC). Vermont Water Center RFP for 2010 was designed to specifically address several broad aspects of water resources management in Vermont that are of direct interest to the VTDEC as well as other collaborating stakeholder groups. These groups include the Lake Champlain Basin Program, the Lake Champlain Research Consortium, municipalities, and NGOs. Additional support for the Vermont Water Center was provided by the Lintilhac Foundation, which substantially supported the project on river bank stability that is reported by Morrissey and Rizzo below.

In the Vermont Water Center RFP process for 2010-2011 proposals on any topic relevant to the mission of the Water Center were considered. As in previous years the Vermont Water Center solicited proposals that would:

1. advance scientific understanding that helps quantify the contribution of sediment and nutrients derived from fluvial processes in Vermont's rivers;

2. establish the socio-economic justifications, costs, and benefits associated with or represented by river corridor protection in Vermont; and

3. contribute to Vermont's river corridor management, restoration, and protection infrastructure.

During the 2010-2011 project year a total of 3 proposals were funded. Two of these three projects are concluding and so the reports here are final reports that may be updated briefly next year. The research projects summarized in the following sections are:

Ross, D. and L. Morrissey. Estimating Soil Phosphorus Concentrations along Erodible Stream Corridors in Chittenden County, Vermont. (Continuing)

Morrissey, L. and D. Rizzo. Quantifying Sediment Loading due to Stream Bank Erosion in Impaired and Attainment Watersheds in Chittenden County, Vermont. (Final)

Eppstein, M. Advanced Computational Methods for Designing Stormwater Management Practices. (Continuing, but with separate funding)

These projects are described in detail in the sections that follow.

Quantifying Sediment Loading due to Stream Bank Erosion in Impaired and Attainment Watersheds in Chittenden County, VT Using Advanced GIS and Remote Sensing Technologies

Basic Information

Title:	Quantifying Sediment Loading due to Stream Bank Erosion in Impaired and Attainment Watersheds in Chittenden County, VT Using Advanced GIS and Remote Sensing Technologies
Project Number:	2009VT44B
Start Date:	3/1/2009
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	First
Research Category:	Water Quality
Focus Category:	Non Point Pollution, Sediments, Geomorphological Processes
Descriptors:	
Principal Investigators:	Leslie Morrissey, Donna M. Rizzo

Publications

1. Garvey, K.M., L. A. Morrissey, D. Rizzo, and M. Kline, 2010, Streambank Erosion in Chittenden County, VT: Application of Very High Resolution Remote Sensing and GIS Modeling, Lake Champlain 2010 Conference: Our Lake, Our Future, Lake Champlain Research Consortium, June 7-8, 2010, Burlington, VT.
2. Garvey, K.M., L. A. Morrissey, D. Rizzo, and M. Kline, 2010, Quantifying Sediment Loading due to Streambank Erosion in Impaired and Attainment Watersheds in Chittenden County, VT, Vermont Geological Society Winter Meeting, Feb. 6, 2010, Norwich, VT.
3. Ishee, E. and D. Ross, Contribution of streambank erosion as a non-point source of phosphorus to Lake Champlain from streams in Chittenden County, VT. American Society of Limnology and Oceanography Conference, Feb 13-18, 2011, San Juan, Puerto Rico.
4. Garvey, K.M. Streambank Erosion in Chittenden County, VT: Application of Very High Resolution Remote Sensing and GIS Modeling. MSc Thesis expected in August 2011.
5. Pelletier, Keith C., 2011, Use Of Very High Resolution Remote Sensing To Estimate Sediment Loading Due To Stream Channel Migration, The Rubenstein School of Environment and Natural Resources, The University of Vermont, Burlington, Vermont. 139 Pages.

Final Report

Title: Quantifying Sediment Loading due to Stream Bank Erosion in Impaired and Attainment Watersheds in Chittenden County, VT

Focus Categories: Nonpoint source pollution, sediments, fluvial processes
Research Category: Water Quality
Start Date: March 1, 2009
End Date: February 28, 2011
Principal Investigators: Leslie A. Morrissey (RSENR) and Donna M. Rizzo (CEMS)
Collaborators: Donald S. Ross (PSS) and Caroline Alves (NRCS)

<u>**Introduction**</u>: Streambank erosion is one of the most important yet least understood nonpoint sources of sediment and phosphorus threatening the impairment of surface waters within the Lake Champlain Basin. High spatial and temporal variability and the difficulties of measuring erosion rates at watershed scales limit our understanding and the ability to quantify the contribution of streambank erosion to water quality degradation. Previous research has not provided the quantitative basis to weight the importance of stream bank erosion relative to other sediment and P sources at watershed scales or the information needed to address within watershed variability in streambank erosion over time.

To address these issues, we combined remote sensing and field data to quantify sediment loading mobilized by streambank erosion in 15 Chittenden County watersheds. Three key subtasks were required to address our goal: 1) mapping of *erosion areas* due to channel migration over time using multidate imagery, 2) analysis of LiDAR-derived DEMs to quantify *streambank heights* that will be used to estimate soil volume loss, and 3) combined remote sensing and field observations to estimate sediment loading per eroded feature, reach, and stream. These analyses will allow us not only to efficiently quantify sediment loading mobilized by streambank erosion at watershed scales, but also to identify critical source areas that contribute a disproportionate amount of the total sediment load. Although most analyses were limited to single date LiDAR data, we also examined the value of multidate LiDAR data to partition sources of sediment (streambank erosion, channel erosion and deposition) and estimate total sediment loading within the Browns River watershed.

Study Area - Our research focused on 15 watersheds (Figure 1) in Chittenden County, VT, ten of which are on the state's 303d list of impaired waters [VT DEC, 2008] due to urban stormwater or agricultural runoff and six are identified attainment watersheds. The watersheds were selected because of long-standing federal, state and public focus on in-stream sediment, phosphorus, or fecal contamination and their contribution to water quality in Lake Champlain. These watersheds were also selected to leverage available aircraft and satellite imagery, LIDAR data, VT ANR RMP fluvial geomorphic assessments, USGS and UVM stream gage stations, and our previous channel migration mapping efforts in Allen Brook and Indian Brook watersheds. We also took advantage of LiDAR imagery from 2004 and 2007 along a portion of Brown's River.

Impaired watersheds
Allen Brook
Bartlett Brook
Centennial Brook
Englesby Brook
Indian Brook (south)
LaPlatte River (west)
Morehouse Brook
Munroe Brook
Potash Brook
Sunderland Brook

Attainment watersheds
Alder Brook
LaPlatte River (east)
Patrick Brook
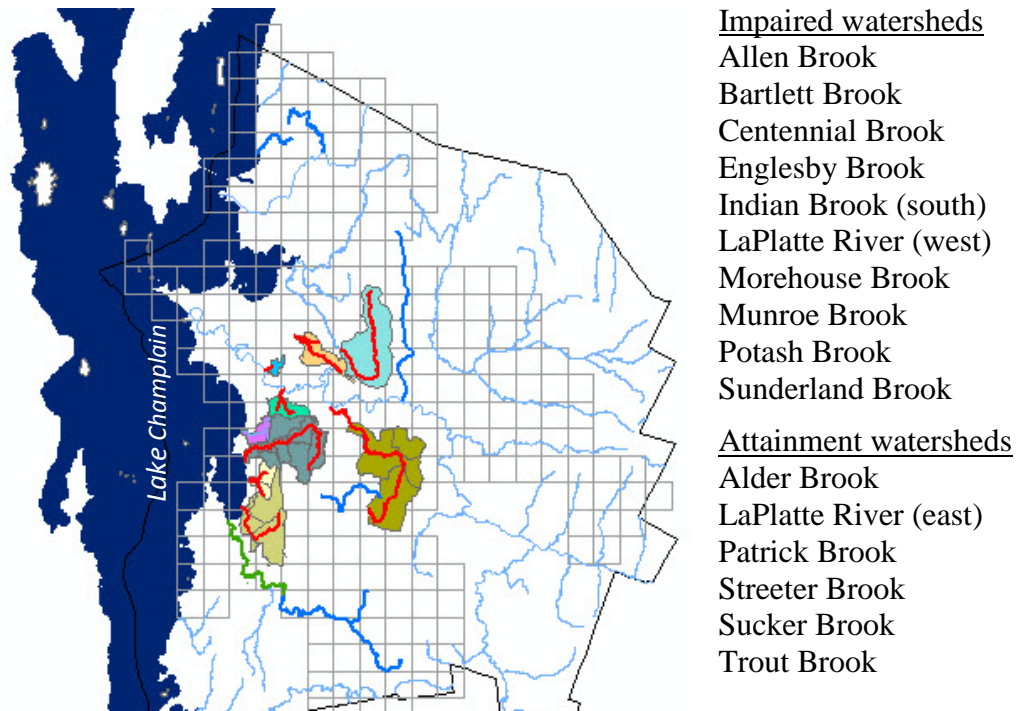Streeter Brook
Sucker Brook
Trout Brook

Figure 1. Chittenden County, VT study area showing 15 watersheds under study. Stormwater impaired streams are shown in red, the agriculturally-impaired LaPlatte River in green, and attainment streams in bold blue. The watershed areas associated with the stormwater impaired streams are also shown. The overlying grid indicates geographic coverage of CCMPO LiDAR data (acquired in 2004).

Methods: In support of efforts to map stream migration over time, USDA National Agriculture Imagery Program (NAIP) imagery and LiDAR data were acquired and compiled for the 15 identified streams in Chittenden County (Figure 1). Overhanging forest canopy cover unfortunately precluded mapping stream centerlines with the 2008 NAIP imagery (mid-summer coverage) for all but the LaPlatte River. Stream centerlines for the remaining streams were thus mapped using orthophotography collected during the spring leaf off period (CCMPO 1:1250 acquired in 2004) and compared to the 1999 (1:5000) VT Hydrography dataset. Channel migration was mapped as the lateral shift in stream centerlines between any two dates of observation (Figure 2) corrected for errors in image registration. The area of erosion associated with each shift in the stream centerline was then computed.
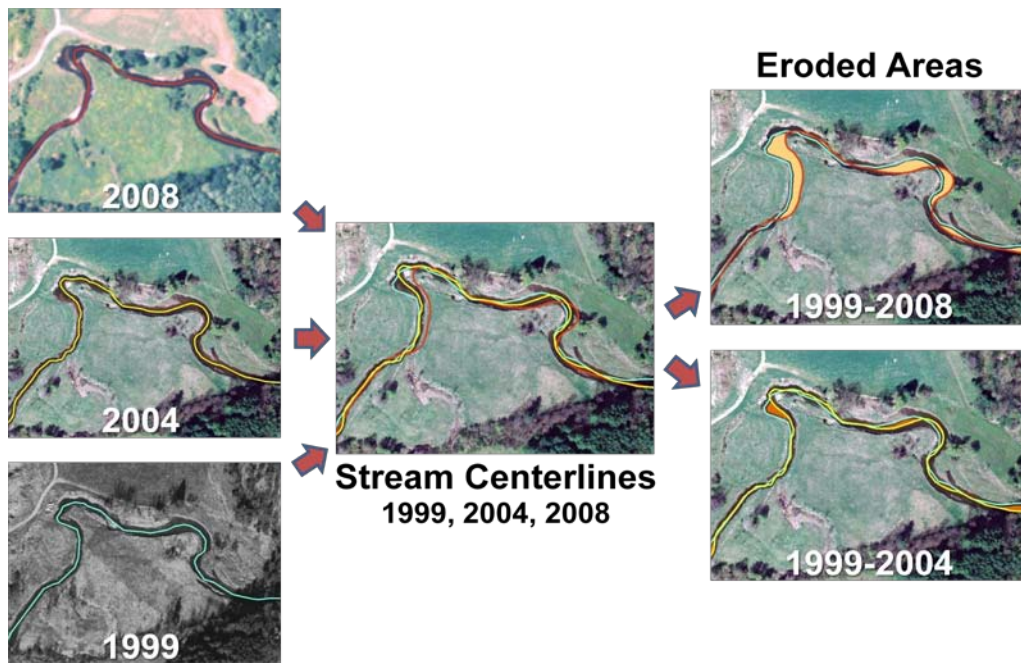
Figure 2. Stream centerlines were digitized for each image date and then overlaid to map stream migration over time (1999 – 2004; 1999 – 2008 for LaPlatte River).

Streambank and stream channel heights derived from the LiDAR data were used to calculate soil volume loss for each eroded area. In this effort, we employed 3.2m posting bare earth (BE) and reflective surfaces (RS) LiDAR data collected in May 2004. Enhanced DEMs were derived using Natural Neighbor spatial interpolation and by combining BE systematic point grids with low lying RS elevation points. The resulting BERS data (BE plus low-lying RS points layer) increased the resolution of the Allen Brook DEM by 168% and reduced the mean point spacing of the BE layer from 3.2m to 1.0m. Developed as part of this research effort, this enhanced product provided significantly greater horizontal and vertical resolution than conventional DEMs. We then calculated an upper soil volume loss estimate as the product of the eroded area derived from the multidate imagery and the streambank height derived from the LiDAR elevation data. Within the Browns River watershed multidate LiDAR were used to more accurately estimate soil volume loss and identify areas of channel erosion and deposition. All processing was automated using ArcGIS ModelBuilder.

Volumetric measures of sediment loading within each watershed over the period of study were estimated from the remote sensing and GIS analyses in combination with *in situ* soil and bulk density measurements completed in the summers of 2009 and 2010 in concert with D. Ross (Plant and Soil Science, UVM) and Carolyn Alves (USDA NRCS). Field teams sampled 76 randomly located erosion areas (with replicates) along Allen Brook, Indian Brook, Alder Brook, and the LaPlatte River.

Results: Large spatial and temporal variability in stream migration was observed over the 1999-2008 study period within each watershed as exemplified by the LaPlatte River (Figure 3). Over the stream length, the number of erosion features within each reach ranged from 0-65 (averaging 23 ±18). The number of eroded features was higher (578) for the 1999-2004 time period compared to the 2004-2008 time period (463).
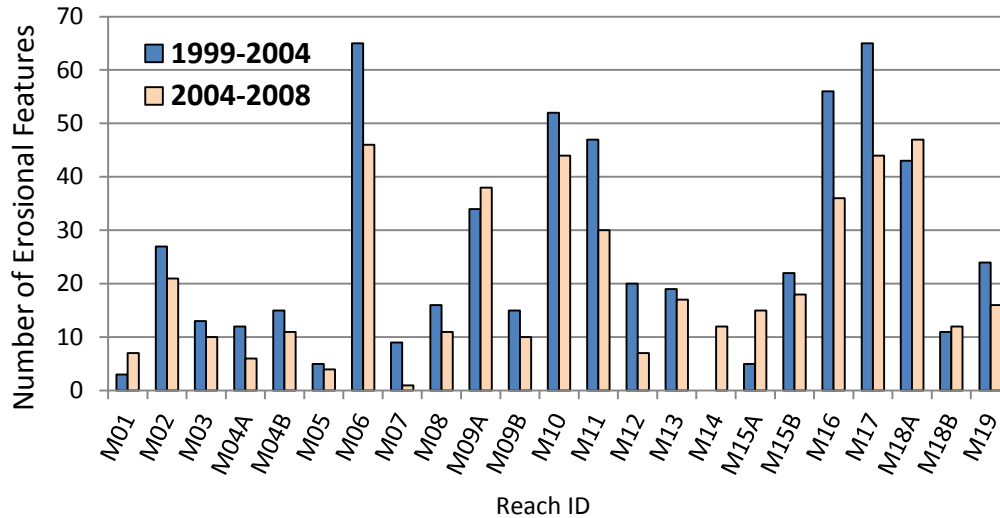

Figure 3. Number of eroded areas due to lateral stream migration summarized by reach for the LaPlatte River watershed (1999 – 2008).

Sediment load differed greatly by watershed ranging from 760 to 17,200 MT over the 5 year study period (1999 – 2004) and 0.12 to 4.6 MT m^{-1} when normalized by stream length (Figure 4). Reaches with large contributions of sediment were easily identified. As part of a collaborative project with D. Ross (PSS/UVM), these data also provided the basis for estimating phosphorus loading to Allen Brook. It was estimated that erosion due to lateral channel migration along Allen Brook (1999-2004) yielded 3 MT phosphorus or approximately 40% of the total P delivered to Lake Champlain from Allen Brook for that period. Our remote sensing-based estimates of soil loss due to streambank erosion represent a significant improvement over previous limited point sampling approaches and confirm that lateral channel migration represents a significant source of sediment and phosphorus loading in these streams.
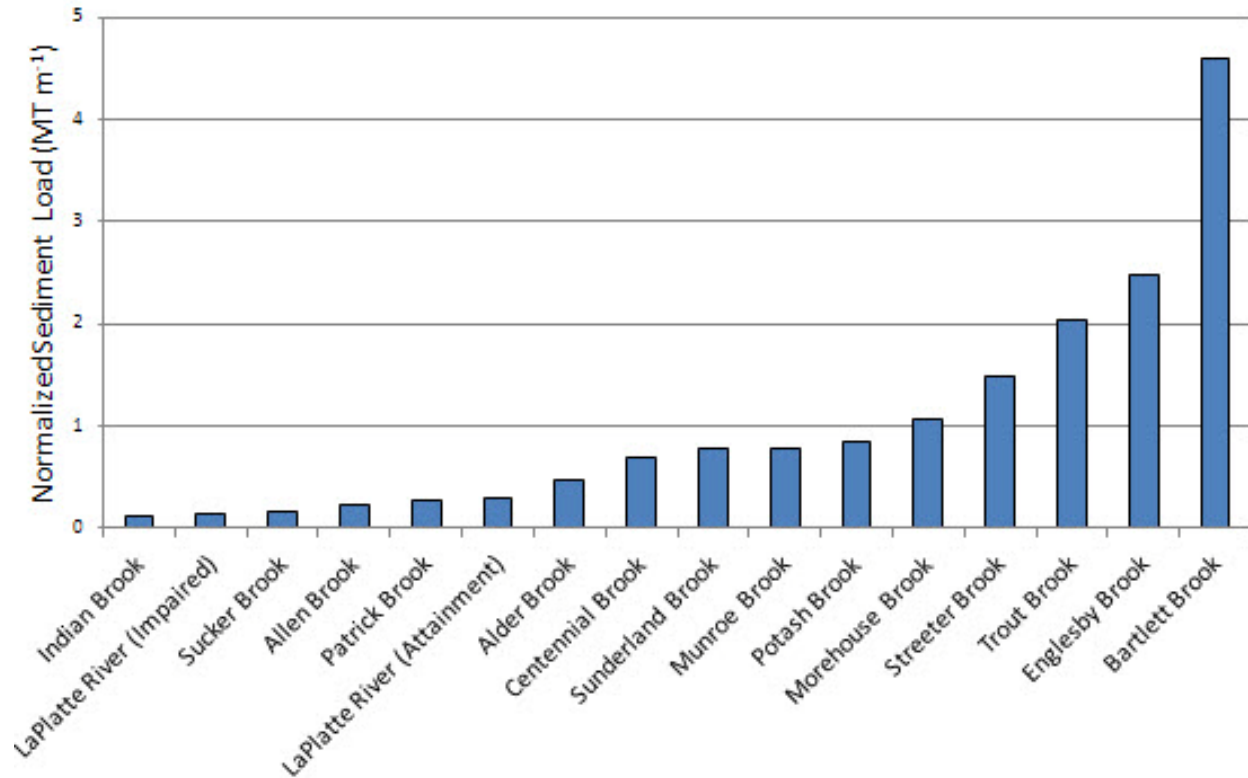
Figure 4. Sediment loading due to streambank erosion (1999-2004) normalized by stream length for 15 streams in Chittenden County, VT.

Within the Browns River watershed, DEMs were generated from LiDAR elevation data acquired in 2004 (3.2m posting) and 2007 (2.4m posting) that were then used to calculate channel erosion, deposition, and net sediment loading for 16 stream reaches. Results demonstrate that 9 reaches were dominated by erosion and 7 by deposition (Figure 5). Erosion and depositional processes within each reach were further analyzed based on VT ANR Phase 2 variables (e.g. grade and bedrock controls, bridges and culverts, stormwater inputs, and bank armoring and straightening) and geomorphic scores (aggradation, degradation, planform, and widening). Encroachment by development, stormwater inputs, straightening, and armoring of the banks lead to increased stream transport capacity and thus increased erosion while changes in the channel width, gradient, and confinement ratio support deposition. In addition to reach-level processes, erosion and deposition at locations within each reach have been identified. Our results also indicate that streambank erosion resulting from lateral channel migration represented from 0 to 26% of the total sediment loading contributed by channel processes on a reach-by-reach basis.

| Reach ID	M07	M08	M09	M10	M11	M12	M13A	M13B	M14	M15A	M15B	M15C	M15D	M16A	M16B	M16C
Stream Type	E	F	E	E	E	C	C	B	C	C	E	C	E	B	D	C
Width:Depth (ft)	9.8	16.3	7.0	11.1	9.9	13.7	15.5		17.5	26.5	8.9	9.7	41.3	17.8	37.9	20.9
Slope (%)	0.4	0.8	0.8	0.7	0.2	0.3	1.9	1.9	0.8	0.2	0.2	0.2	0.2	0.7	0.7	0.7
Confinement Ratio	9.7	23.1	95.3	32.1	26.8	16.7	2.0	2.0	23.4	19.7	19.7	19.7	19.7	24.8	24.8	24.8
Bank Armoring (%)	7	16	8	4	17	13	8	8	17	1	1	1	1	23	23	23
Straightening (%)	93	34	90	12	30	9	0	0	91	60	60	60	60	25	25	25
Bridges / Culverts (%)	8	8	20	20	30	10	1	1	10	7	7	7	7	0.4	0.4	0.4
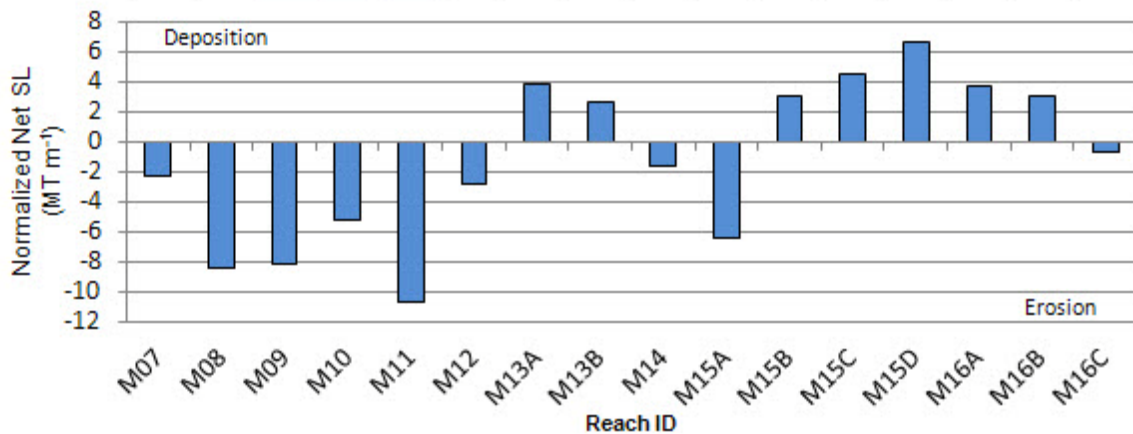
Figure 5. Net sediment loading (normalized by stream length) for Browns River reveals reach-level processes (erosion or deposition) that can be linked to VT ANR Phase 2 geomorphic variables (top pane). Extreme values are highlighted in the table.

Conclusions: The results of this study demonstrate the potential value of remote sensing to augment stream geomorphic and water quality management efforts by providing consistent, accurate and relatively low cost information on stream geomorphic change and sediment loading over time at reach and watershed scales. These analyses also serve as a baseline against which future estimates of sediment loading can be evaluated and as a means to constrain subsequent P loading estimates due to streambank erosion. Our methodology represents a departure from previous studies that measured or modeled channel migration and streambank erosion at specific sites by assessing stream migration along the entire stream length. More importantly, this effort represents not only a significant step toward systematically quantifying sediment (and P) loading due to streambank erosion throughout the Lake Champlain basin and elsewhere, but also a watershed-scale approach that can greatly aid adaptive management efforts. By automating this process within a GIS and leveraging high spatial resolution remotely sensed data acquired over time, we provide a rapid, reliable and cost-effective method to quantify streambank erosion rates and sediment loading in streams across northern temperate regions.

Student Support: Graduate student, Ms. Kerrie Garvey, joined the project team in July 2009 under the direction of Leslie Morrissey and Donna Rizzo (anticipated graduation August 2011, M.S., Natural Resources Program, RSENR/UVM). Two peer reviewed journal articles derived from Ms. Garvey's thesis are planned for submission in the fall of 2011.

Conference Presentations:

Garvey, K.M., L. A. Morrissey, D. M. Rizzo, and M. Kline, Streambank Erosion in Chittenden County, VT: Application of Very High Resolution Remote Sensing and GIS Modeling, *Lake Champlain 2010 Conference: Our Lake, Our Future,* Lake Champlain Research Consortium, June 7-8, 2010, Burlington, VT.

Garvey, K.M., L. A. Morrissey, D. M. Rizzo, and M. Kline, Quantifying Sediment Loading due to Streambank Erosion in Impaired and Attainment Watersheds in Chittenden County, VT, *Vermont Geological Society Winter Meeting*, Feb. 6, 2010, Norwich, VT.

Ishee, E. and D. Ross, Contribution of streambank erosion as a non-point source of phosphorus to Lake Champlain from streams in Chittenden County, VT. *American Society of Limnology and Oceanography Conference*, Feb 13-18, 2011, San Juan, Puerto Rico.

Estimating Soil Phosphorus Concentrations along Erodible Stream Corridors in Chittenden County, Vermont

Basic Information

Title:	Estimating Soil Phosphorus Concentrations along Erodible Stream Corridors in Chittenden County, Vermont
Project Number:	2009VT45B
Start Date:	3/1/2010
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	First
Research Category:	Water Quality
Focus Category:	Nutrients, Non Point Pollution, Water Quality
Descriptors:	
Principal Investigators:	Donald Ross, Leslie Morrissey

Publications

1. Garcia, Angel, 2010, Understanding the Relationships between Beaver Dams and the Movement of Phosphorus through Allen Brook, Chittenden County, VT, Universidad Metropolitana 2nd Annual Vermont EPSCoR Streams Project Symposium, Apr 19, 2010 Burlington, VT.
2. Thomas, Maya, 2010, Riparian soil phosphorus and stream channel migration at Allen Brook in Chittenden County, VT, UVM Student Research Conference, April 22, 2010, Burlington, VT.
3. Alves, Caroline, 2010, Examining phosphorus contributions from alluvial soils - a comparison of three Vermont river corridors, (USDA-Natural Resources Conservation Service). Lake Champlain 2010 Conference: Our Lake, Our Future, Lake Champlain Research Consortium, June 7-8, 2010, Burlington, VT.
4. Young, Eric, Don Ross, Caroline Alves, and Thomas Villars, 2010, Spatial variability of riparian soil phosphorus at a site along the Rock River, Vermont, Lake Champlain 2010 Conference: Our Lake, Our Future, Lake Champlain Research Consortium, June 7-8, 2010, Burlington, VT.
5. Valentin, Dorielys 2010. Examining Effects of a Capped Landfill on Groundwater and Alluvial Soils near Indian Brook in Essex, VT. (Universidad Metropolitana). Ana G. Méndez University System 2010 Research Symposium, Sep 10-11, 2010, San Juan, Puerto Rico.
6. Ishee, Eulaila and Don Ross. 2011. Contribution of streambank erosion as a non-point source of phosphorus to Lake Champlain from streams in Chittenden County, VT. American Society of Limnology and Oceanography, Feb 13-18, 2011, San Juan, Puerto Rico.
7. Valentin, Dorielys. 2010. Examining effects of a capped landfill on ground water and alluvial soils along Indian Brook in Essex, VT. (Universidad Metropolitana). Third Annual Vermont EPSCoR Streams Project Symposium, Apr 26, 2011, Burlington, VT.
8. Valentin, Dorielys M., 2010, Examining Effects of a Capped Landfill on Groundwater and Alluvial Soils Near Indian Brook in Essex, VT, ANA G. MÉNDEZ UNIVERSITY SYSTEM (AGMUS) 2010 Research Symposium, San Juan, Puerto Rico, Page 38.
9. Young, Eric, Don Ross, Caroline Alves, and Thomas Villars, 2011, Influence of soil series on phosphorus forms and availability at two riparian sites in the Lake Champlain Basin (Vermont). J. Soil Water Conserv.: In Press.

Progress Report

Estimating Soil Phosphorus Concentrations along Erodible Stream Corridors in Chittenden County, Vermont

Principal Investigators: Donald S. Ross, Research Associate Professor, Department of Plant and Soil Science, University of Vermont (dross@uvm.edu) and Leslie A. Morrissey, Associate Professor, Rubenstein School of Environment and Natural Resources, University of Vermont

Cooperators:
Caroline Alves, GIS Specialist/Soil Scientist, USDA-NRCS, Williston
Steven H. Gourley, State Soil Scientist, USDA-NRCS, Colchester
Donna M. Rizzo, Associate Professor, School of Engineering and Mathematical Sciences, UVM
Thomas Villars, Soil Scientist, USDA-NRCS, White River Junction

Abstract

Phosphorus (P) loss from stream bank erosion is thought to be a major and underestimated contributor of P loading to Lake Champlain. Soil variability strongly influences the chemical and physical properties of riparian areas. To assess potential P contribution, we sampled riparian soils along four streams in Chittenden County, Vermont. At 76 erosion sites, we collected over 900 soil samples in depth increments for particle size determination and P analysis. Total P (TP) and soil test P (Modified Morgan's) were relatively consistent across the four stream corridors with means of 625 and 2.2 mg kg^{-1} respectively. The concentration of both P measurements usually decreased with depth. Bulk density increased with depth but was also relatively consistent across the sites. Texture varied among the stream corridors from high sand to high silt content and was, by itself, only weakly correlated with TP. When coupled to historical measurements of streambank erosion, results from this project provide improved estimates of P mobilized by fluvial systems and contribute to a greater understanding of P dynamics in the Lake Champlain Basin. Eroded features along Allen Brook from 1999-2004 contained 3 MT P, approximately 40% of the TP delivered to Lake Champlain from Allen Brook for that period.

Introduction

Phosphorus loading from stream bank erosion is a major concern in Vermont watersheds, and geomorphic assessment indicates that approximately 75% of the assessed stream and river reaches (757 miles) in Vermont are eroding due to floodplain loss (VT DEC, 2007). Studies have indicated that streambank erosion and associated P can be a large nonpoint pollutant source (Kalma and Ulmer, 2003; DeWolfe et al., 2004). Riparian soil variability influences the form and amount of P in soils and legacy sediments. Variation in the chemical and physical properties of riparian soils also influences the potential for stream bank erosion, and thus affects the susceptibility of this P to erosive fluvial forces. In addition, soil drainage variation in riparian zones can strongly influence soil genesis, total soil P levels, organic carbon, redox patterns, and P mobility through different hydrologic pathways over time (Young and Ross, 2001; Young and Briggs, 2008; Young et al., 2011). Finer-textured sediments can have greater total P contents, but also a greater sorption capacity for orthophosphate (McDowell et al., 2002). The particle size distribution (texture) of both stream bank soils and fluvial sediments appear to be an important constraint on total P content. There is a clear need to quantify the P fractions (total

and bioavailable) in these riparian soils and to develop predictive tools to estimate how much P is coming from stream bank erosion.

Our study had two main objectives: i) sample soils to determine P content within and among soil types along impaired and attainment streams in Chittenden Co., Vermont and ii) estimate historic sediment and P loading due to stream bank erosion on selected streams in Chittenden County over the period 1999-2008 in collaboration with stream bank erosion mapping efforts by Morrissey et al. (2009). Our currently funded project (through Feb, 2012) is using statistically selected samples from this set to quantify the slow-cycling P contribution (Pox) from eroding stream bank sediments into Lake Champlain. We will report the results from these analyses next year.

Methods

Field work. Seventy-six sites along 4 streams in Chittenden County were sampled in 2009 and 2010 (Fig. 1). Allen Brook and Indian Brook were both identified as impaired while Alder and LaPlatte were sampled along attainment reaches. Areas of active erosion were identified via remote sensing by co-investigator Morrissey. Twenty-five locations were randomly selected for sampling along Allen and Indian Brooks, while 13 locations were sampled on Alder and LaPlatte. All remotely identified features were first verified by a site visit. We then sampled at the center of the erosion feature, 1.5 m from the bank edge (Fig. 2). At each site, three soil cores were taken 1 m apart, at four depths: 0-15 cm, 15-30 cm, 30-60 cm and 60-90 cm. These depths were selected to provide P concentrations for the upper soil layers that may reflect historical land use and also for lower soil layers that are representative of soil parent material. This approach resulted in 12 samples per feature unless sampling was impeded by coarse fragments or bedrock.
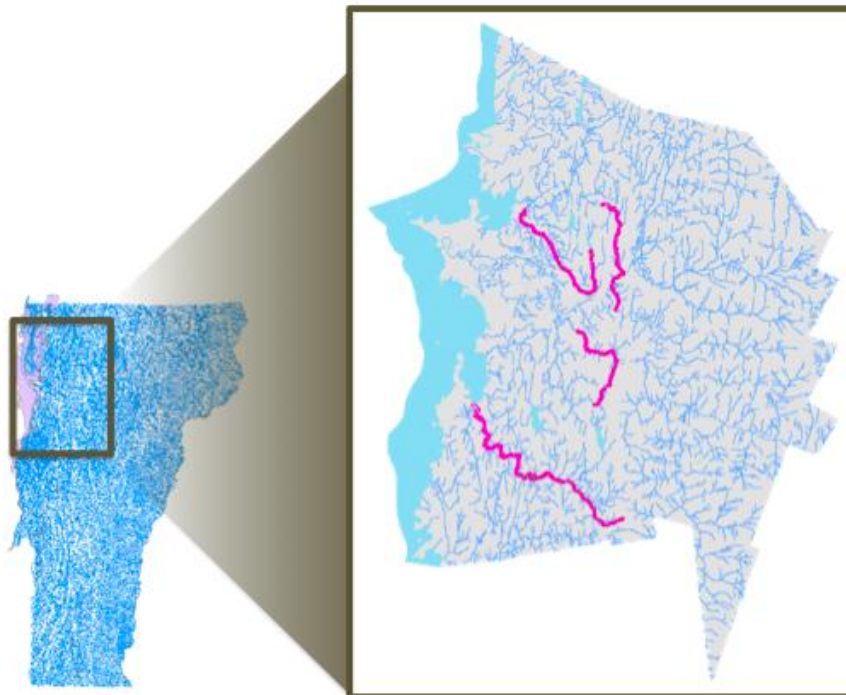

Figure 1. Study location: 4 streams in Chittenden County (clockwise from upper left: Indian Brook, Alder Brook, Allen Brook, LaPlatte River).
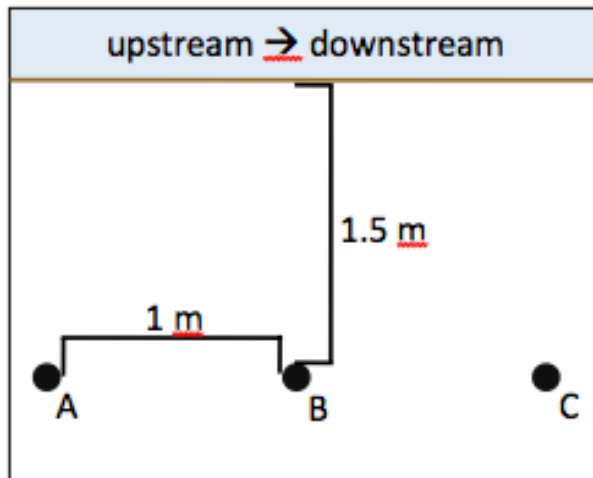
Figure 2. Sampling diagram.

Additional samples were irregularly collected along the slope of the erosion feature when exposure allowed sample collection at depths greater than 1 m. These samples will be used to determine if soil changes take place at these greater depths. Bulk density cores were also taken with a Uhlander device at two depths (approximately 0-15 and 10-30 cm) adjacent to each coring location. All soil sampling locations were georeferenced to ensure a match with the remote sensing data. Approximately 912 soil samples were collected for chemical tests and 456 samples for bulk density and coarse fragment measurements. In addition to this sampling, we dug 18 classification soil pits along the four streams in collaboration with cooperator Caroline Alves of the USDA NRCS. Samples from these pits have been sent to the National Soil Survey Lab for complete physical and chemical analysis, and the data will be used to definitively classify the sampled soils. In these pits, we also obtained bulk density samples from the lower depth increments that are being analyzed at UVM.

Sample Preparation. Augered samples were air-dried for 3-4 days and sieved through a 2 mm sieve to remove coarse fragments. Most samples were gently ground by hand in a mortar and pestle, however firmer samples with higher clay content were ground using a Humboldt soil grinder (H-4199). Subsamples were taken from each bulk sample after thorough mixing and completely ground and sieved through a 0.25 mm sieve for total P and oxalate-extractable P analysis.

Bulk Density. Bulk density samples were oven dried at 105°C overnight and weighed following removal from oven. Bulk density samples were sieved through a 2 mm sieve to remove coarse fragments (CF). Coarse fragment weight and volume (assumed density of 2.65 Mg/m^3) were subtracted from total weight and core volume to calculate weight and volume of soil.

Total Phosphorus. Total phosphorus concentrations were characterized using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) following nitric acid microwave digestion (USEPA Method 3501). The ICP was calibrated with NIST-traceable standards and quality control samples included reference soils and NIST-traceable P solutions purchased from a different vendor than the standards.

Soil Test Phosphorus. The Modified-Morgan soil test P (MM-P) method (Wolf and Beegle, 2009) was used to determine soil test P. Phosphorus concentrations in the extractions were determined colorimetrically on a flow injection autoanalyzer (Lachat QuikChem AE) using the Murphy-Riley procedure.

Particle Size Analysis. Percent sand, silt, and clay was determined using the hydrometer method. A representative 50 g subsample was taken from each sample (100 g for sandy soils) and placed in a 500 mL polyethylene bottle. Soil aggregates by overnight shaking (minimum 16 hours) with

3

100 mL of 5% calgon solution (sodium hexametaphosphate) and ~200 mL reverse osmosis (RO) water.

Results and Discussion

Soil texture. Particle size distribution in the soils differed somewhat among the four stream corridors (Fig. 3). Allen and Indian had relatively high sand and low clay content whereas Alder and Laplatte had higher silt and clay. The parent materials for these soils were sediments derived primarily from alluvium, with some input from glaciolacustrine materials. The dominance of sand across all samples sites (Fig. 4) reflects the alluvial source. These soils may have developed on 'legacy' sediments from large erosion events related to land clearing in the late 18th and early 19th centuries or from any series of events dating back to the retreat of the last glacier circa 12,000 years ago. Phosphorus content is likely derived from the parent material and our previous work has shown a relationship between texture and total soil P.
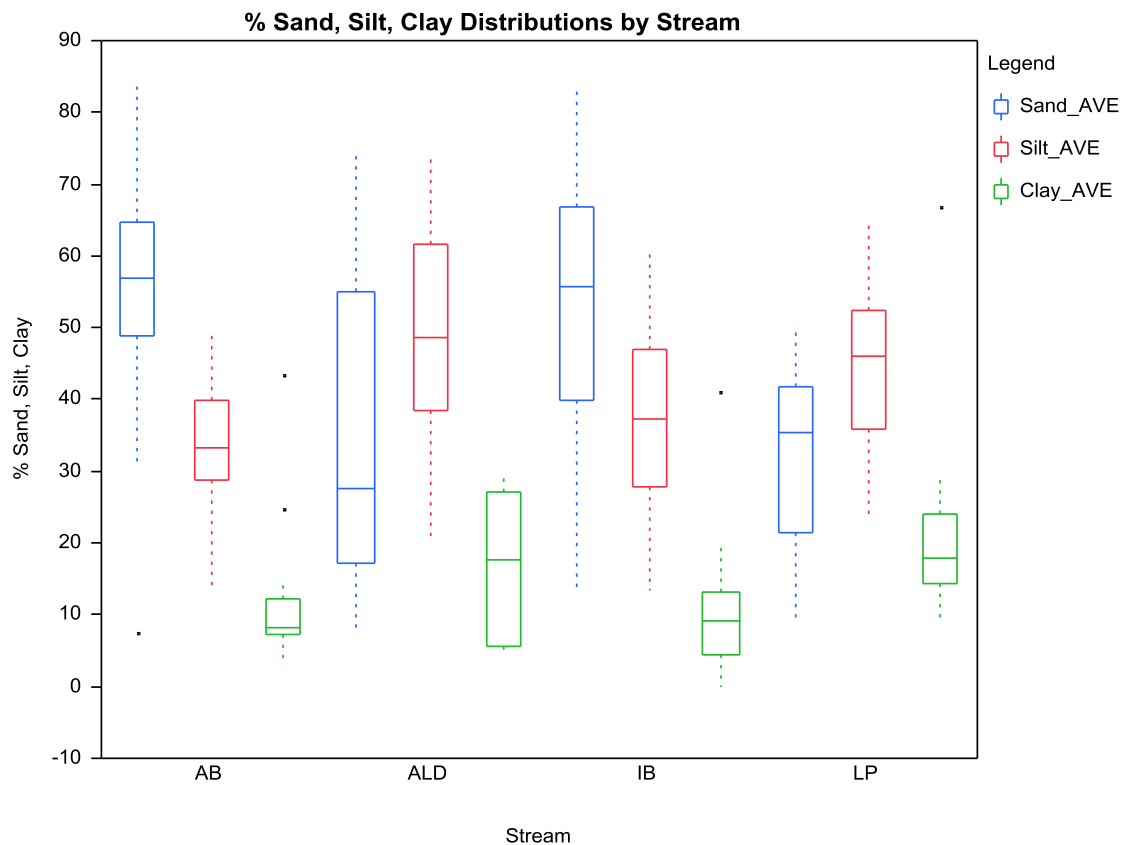

Figure 3. Box plots of the sand, silt and clay distribution along the four stream corridors. AB = Allen Brook, ALD = Alder Brook, IB = Indian Brook, LP = LaPlatte River
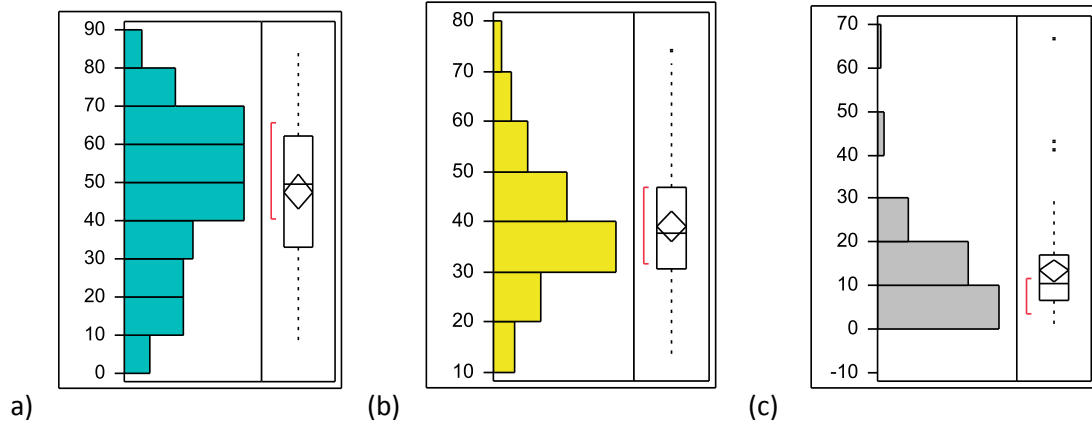
Figure 4. Histogram and boxplots of particle size for all streams: (a) % sand, (b) % silt, and (c) % clay.
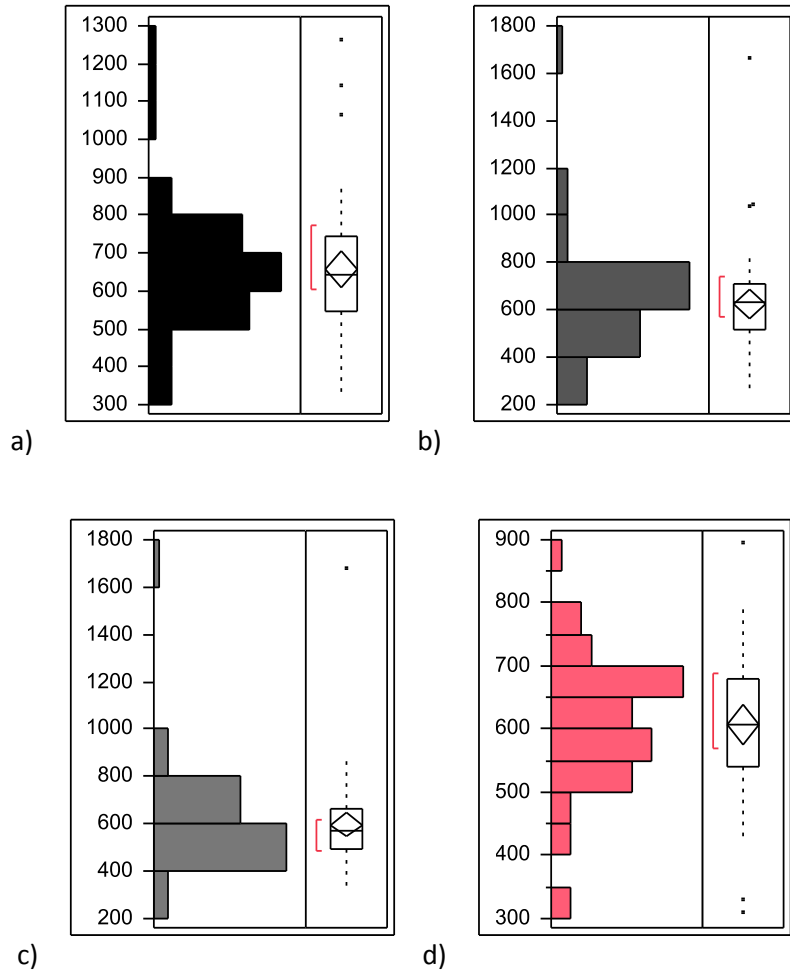

Figure 5. Total P concentration histograms and boxplots for all streams by depth: (a) 0-15 cm, (b) 15-30 cm, (c) 30-90 cm and (d) weighted average representative of all depths. Units are mg kg^{-1}.

Total soil phosphorus. Total P had a wide range across all samples (Fig. 5) but most values fell between 550-750 mg kg^{-1} soil. This is consistent with previous findings from similar stream corridors in Vermont (Young et al., 2011). Total P is a measure of the maximum amount of P that could be released from sediments after transport. The common procedure used to determine total P, microwave-assisted nitric acid digestion, does not completely dissolve all soil minerals (O'Halloran and Cade-Menun, 2007) yet still represents more P than is likely to ever be released and become bioavailable. Other measurements of P, including soil test P, have been used to predict the readily bioavailable pool and this is always much lower than the total (see below). Our ongoing work is examining the usefulness of a moderately strong extractant, pH 3 ammonium oxalate. This procedure has been found to dissolve the less crystalline iron and aluminum oxides that are known to be associated with sorbed and precipitated P. Redox cycling in the lake can reduce the iron oxides and release associated P. Finding an appropriate test for this potentially bioavailable soil and sediment P remains a challenge. However it is clear that we need to move beyond the use of Total P as a surrogate for potentially bioavailable P.

Soil test phosphorus. The Modified Morgan's (MM) soil test extractant (pH 4.8 ammonium acetate, 1.25 *M* with respect to the acetate) is used by a number of New England states for soil fertility recommendations. Unlike other common soil test solutions, e.g. Mehlich-III and Bray's, it does not contain fluoride (F), which is an efficient replacer of tightly bound P. This results in MM-P usually being about 10x less than the F-containing extractants. Magdoff et al. (1999) showed that MM-P was a better predictor of immediately bioavailable P than Mehlich-III and can be used to estimate the quantity of sediment P that would easily move into the water column. The concentration of MM-P in the stream corridor soils that we studied was low relative to what is considered optimum for cropped land (7 mg kg^{-1} is the critical or optimum value). There was little variation among the four stream corridors (Table 1) and concentrations usually decreased with depth. This trend towards lower concentration with depth mirrors that found with Total P and likely reflects both inputs from past land-use and natural soil horizonation in which organic C and associated nutrients accumulate near the surface. Some of the higher concentrations found at lower depth in some samples may have been from buried A horizons, resulting from past erosion and deposition.

Table 1. Mean soil test total P (MM-P) concentrations of sample sites along streams individually and combined.

Stream	Depth Interval cm	n	Mean MM-P mg/kg	SEM*
Allen	0-15	25	3.4a**	0.5
Allen	15-30	25	1.8b	0.2
Allen	30-90***	25	1.7b	0.2
Indian	0-15	25	2.8a	0.3
Indian	15-30	25	1.8b	0.2
Indian	30-90	25	1.8b	0.2
Alder	0-15	13	2.9a	0.3
Alder	15-30	13	2.4a	0.4
Alder	30-90	13	3.1a	0.5
LaPlatte	0-15	13	2.9a	0.5
LaPlatte	15-30	13	1.9a	0.4
LaPlatte	30-90	13	1.7a	0.2
All Sites	0-15	76	3.1a	0.2
All Sites	15-30	76	1.9b	0.1
All Sites	30-90	76	2.0b	0.1

* Standard error of the mean
** Means within a depth with different letters are significantly different at $P \leq 0.05$
*** 30-60 and 60-90 depth categories were combined to represent the lowest depth category

Table 2. Mean bulk density and coarse fragment mass of sample sites along streams individually and combined.

Stream	Depth Interval	n	Mean BD Mg/m3	SEM*	%CF	SEM
Allen	upper**	25	1.0	0.04	5.66	0.02
Allen	lower**	24	1.2	0.04	4.65	0.02
Indian	upper	25	1.0	0.04	1.04	0.00
Indian	lower	25	1.1	0.03	1.16	0.00
Alder	upper	13	0.9	0.11	0.82	0.00
Alder	lower	13	1.2	0.14	0.67	0.00
LaPlatte	upper	13	1.0	0.04	0.40	0.00
LaPlatte	lower	13	1.2	0.04	0.39	0.00
All Sites	upper	76	1.0	0.02	2.44	0.01
All Sites	lower	76	1.2	0.02	2.08	0.01

* Standard error of the mean
** Upper and lower depth classes correspond to 0-15 cm and 10-25 cm respectively.

Soil bulk density. Bulk density (BD) was similar among the stream corridors. Higher BD values at the 15-30 cm depth were expected because of less organic carbon lower in the profile (Table 2). Bulk density measurements were taken at multiple depths in pit samples (data not shown) and we used those values for an average BD for depth increments below 30 cm. Coarse fragments (CF) were primarily gravel and stones > 2.0 mm in diameter. These values differed among the stream corridors ranging from a low of 0.4% at Alder to 5.7% at Allen. Because the large fragments are considered inert, a higher %CF translates to a lower total P per volume of sediment. This needs to be factored in when scaling up these results to calculate the P content of eroded stream banks.

Relationships among measured variables. In our previous study of three stream corridors in Addison and Franklin Counties (VT), we found significant relationships between particle size and total P (Young et al., 2011). While the trends are the same in our recently collected data, the relationships we've examined to date are much weaker. The data is currently in the final stages of quality assurance procedures and we will reanalyze when we have a complete and robust dataset. In addition to the data presented above, we will have additional elemental analysis from both the Total P digestion and the soil test extraction. We will examine the interaction between total Ca and P relative to soil texture. Soil test available aluminum (Al) has been correlated with P availability (Bartlett, 1982) and we will include those data to determine possible interactions with particle size. These data, combined with newly analyzed oxalate extractions should provide a variety of approaches to develop predictive tools for stream corridor soil P.

Hotspot analysis. Total P concentrations were interpolated across all erosion features on Allen Brook by applying a regression of percent silt (NRCS representative values) versus TP for Allen Brook samples alone (y=5.07x + 398.11; R^2= 0.32*). Total mass P contribution was calculated by multiplying TP concentrations and mass of erosion feature yielding a total of 3191 kg TP for erosion between the years 1999-2004. This value may change with better predictive tools for TP. The majority of TP in eroding streambanks was isolated to a few particular regions. A Getis-Ord hotspot analysis of total mass P per erosion feature yields 3-4 hotspots and two coldspots representing areas where total masses of P are consistently high and consistently low respectively (Fig. 6). Extruding the erosion features by total mass P (Fig. 7) shows how a few erosion features contain the majority of total mass P. By isolating the components of total mass P (TP concentration and mass of erosion feature), it is clear the mass of the erosion feature drives the total mass P more than the concentration of TP. This can also be explained by the range of data: the mass of erosion features ranges from <1 MT to >1,000 MT while the calculated TP concentrations only range from 400 to 500 mg/kg. Proportioning the total P load of Allen Brook from 1999-2004 by watershed size, 3191 kg TP represents 40% of the total P delivered to Lake Champlain via Allen Brook from 1999-2004. Thus, bank erosion could be a substantial portion of the total P loading to Lake Champlain, at least from Allen Brook.

Ongoing schedule

A subset of the above 900+ soil samples will be selected to represent a range of geographic locations, soil textures, and TP and MM-P concentrations within the larger dataset. These samples will be analyzed for acid ammonium oxalate extractable P (P_{ox}) to assess the long-term potential bio-availability of riparian soils in Chittenden County.

Allen Brook Hot Spots: RV_AB

Legend

Hotspot Analysis RV_AB

GiZScore
- ● -3.07 - -2.58
- ● -2.57 - -1.96
- -1.95 - 1.96
- ● 1.97 - 2.58
- ● 2.59 - 5.94
- —— Merged stream centerlines
- ▢ Allen Brook Subwatersheds
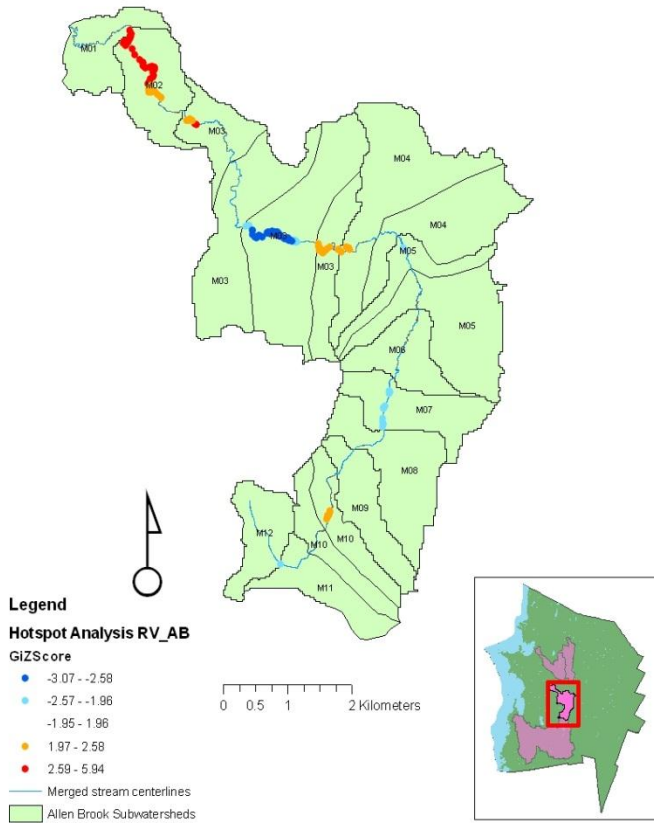
0 0.5 1   2 Kilometers

Figure 6. Getis-Ord hotspot analysis of total mass of TP per erosion feature estimated by TP concentration regression applied to NRCS silt values*mass of erosion feature.
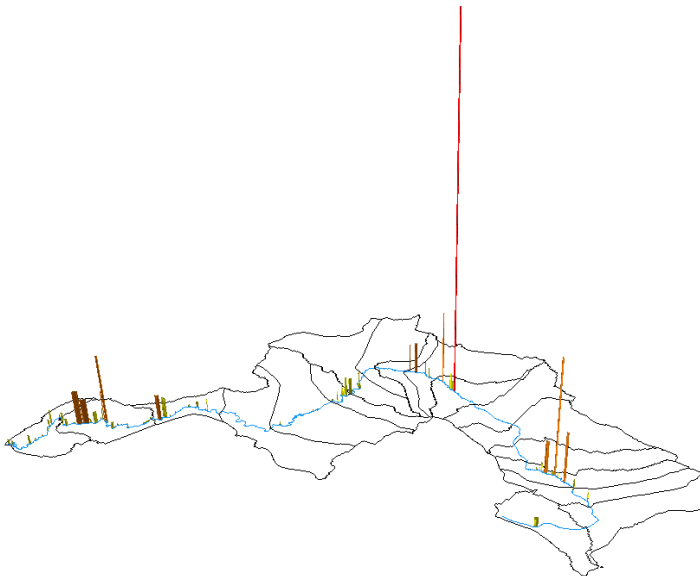
Figure 7. Erosion features extruded by estimated total mass of P along Allen Brook.

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Training

This project is training a M.S. candidate (Eulaila Ishee) in all aspects of the proposed research. In additional, the project is providing valuable training for a number of undergraduate students majoring in Environmental Sciences and student interns in UVM STREAMS program. During the first field season we had the help of two students (Edward Garcia and Angel Garcia) from Universidad Metropolitana of Puerto Rico as part of the UVM STREAMS internship program. We also had the assistance of a UVM McNair scholar from the Rubenstein School, Maya Thomas. These three students have given presentations on the research they performed in 2009. Angel Garcia presented at the annual STREAMS conference and Maya Thomas at the UVM Student Research Conference (citations below). In addition, Angel was admitted to UVM's graduate program in the Geology Dept. and commenced studies in the fall of 2010. For the second field season (2010), we again had the assistance of two students from Universidad Metropolitana (Dorielys Valetin and Karoline Rios) and one UVM Environmental Sciences undergraduate (Alison Nord). Dorielys Valetin presented at the Universidad Metropolitana and at the annual STREAMS conference (citations below). All three students were able to attend the Lake Champlain 2010 Conference. During this past school year, undergraduate student Charlotte Ford (UVM Environmental Sciences) was trained and assisted with field and lab work.

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Advanced Computational Methods for Designing Stormwater Management Practices

Basic Information

Title:	Advanced Computational Methods for Designing Stormwater Management Practices
Project Number:	2010VT50B
Start Date:	3/1/2010
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	First
Research Category:	Water Quality
Focus Category:	Water Quality, Sediments, Hydrology
Descriptors:	None
Principal Investigators:	Margaret J Eppstein

Publication

1. Four publications are anticipated from this project and are in various states of preparation and review. We will report more fully on the fate of these publications in the 2011 Annual Report.

Advanced Computational Methods for Designing
Stormwater Management Practices

Principal Investigator: Margaret J. Eppstein, Associate Professor, Computer Science, College of Engineering and Mathematical Sciences, University of Vermont, Burlington, Vermont.

Collaborators: Karim Chichakly, Ph.D. Student, Computer Science, College of Engineering and Mathematical Sciences, University of Vermont, Burlington, Vermont and William B. Bowden, Professor, and Joel Nipper, Ph.D. student, Rubenstein School of Environment and Natural Resources, University of Vermont, Burlington, Vermont.

Abstract

High-levels of phosphorus loading to Lake Champlain have been linked to algal blooms and to eutrophication of sections of the lake. Previous research suggests that runoff from impervious surfaces in developed areas around the lake have accelerated runoff and increased sediment and phosphorus loading, leaving many watersheds impaired and the Lake threatened. There is, therefore, considerable interest in designing cost-effective strategies for reducing sediment and phosphorus loading. In addition, it will be important to design strategies that are robust to anticipated changes in precipitation patterns resulting from global climate change. To this end, we have integrated a process-based hydrologic model into a multi-scale, multi-objective evolutionary algorithm in order to evolve populations of potential watershed management practices and applied the method to the impaired Bartlett Brook watershed in Chittenden County, VT. The solutions along the resulting Pareto front will enable watershed managers to assess the trade-offs between cost, effectiveness, and uncertainty when selecting best management practices (BMPs) for watershed management. We are also conducting a nonlinear analysis of characteristics of solutions along and orthogonal to the Pareto front in order to try to identify patterns from which we could extract fundamental design principles that would allow for direct design of effective solutions. Lastly, we are testing a set of hydrologic indicators for their ability to discriminate among Vermont's stormwater impaired and attainment watersheds, using data collected in by the UVM Flow Monitoring Project. We expect that results from this research will contribute to the understanding of watersheds as complex systems and will provide useful information to managers and policy makers who must decide how to allocate scarce resources for stormwater management most effectively.

Introduction

The State of Vermont has 111 impaired streams (State of Vermont, 2004) it must bring into compliance with the Environmental Protection Agency (EPA)-enforced Total Maximum Daily Load (TMDL) targets, as a result of the Clean Water Act. Many of these streams are impaired by urban stormwater runoff and directly affect Lake Champlain. The Best Management Practices (BMPs) that might be useful to address these problems are reasonably well known. However, the lowest cost and most effective plan to deploy these BMPs is a complex problem whose solution is not obvious. Identifying placement and sizing of BMPs (such as detention ponds and rain gardens) is a time-consuming process that is still typically done manually, and

although there have been advances in the development of computational tools to aid in this process are limited.

Objectives

This one-year project had 4 specific objectives that complemented a larger project goal, as follows:

1. Develop an effective multi-scale, multi-objective evolutionary algorithm that evolves a population of optimal solutions,

2. Use this evolutionary algorithm on the Bartlett Brook watershed as a specific case study in designing an optimal watershed management plan, and

3. Apply advanced non-linear pattern analysis to potential solutions in the search space in order to extract general design principles relating BMP design to the effectiveness, robustness, and cost-effectiveness of solutions.

4. Determine if simple hydrologic indicators can discriminate among watersheds that are impaired by stormwater runoff and those that are not

Each of these objectives has an ongoing component. However, for the portion of the project funded by the Vermont Water Resources and Lake Studies Center, there were particular objectives. Below, we describe progress attained and results from each of these objectives.

Objective 1: Develop an effective multi-scale, multi-objective evolutionary algorithm that evolves a population of optimal solutions.

We developed a multi-objective evolutionary algorithm based on differential evolution (Storn and Price 1997) that places BMPs in a watershed at the subwatershed level while optimizing the performance at the watershed level. The multi-objective survivor selection mechanism used is based on NSGA-II (Deb, et al. 2001) with some important modifications to improve spread across the Pareto front. This algorithm evolves a population of potential solutions, each of which represents a specific combination of amount of hydrologic control within each of the subwatersheds (the BMP configuration).

The method finds the set of optimal solutions that minimize both cost and sediment loading, while simultaneously minimizing the uncertainty in precipitation patterns due to climate change. The watershed was first divided into subwatersheds. To determine the cost of a given BMP configuration, we pre-calculated a cost curve for each subwatershed. The cost curve relates fraction of subwatershed area treated to the minimum cost BMP configuration required to treat that fraction. Possible BMP configurations and maximum treatable area for each subwatershed were derived from a combination of GIS data, such as slope and land use, and planning information, such as expected uptake of rain gardens on single family lots and preference for rain gardens. One of the cost curves is shown in Figure 1, illustrating that these subwatershed-specific curves can be nonlinear and even monotonic. For each fractional area of the

subwatershed treated, there exists one minimal cost BMP configuration that treats that area; pre-computation of these curves greatly simplifies the evolutionary search process for watershed-level optimization by reducing the search space to vectors of feasible continuous values representing the treated area for each subwatershed.
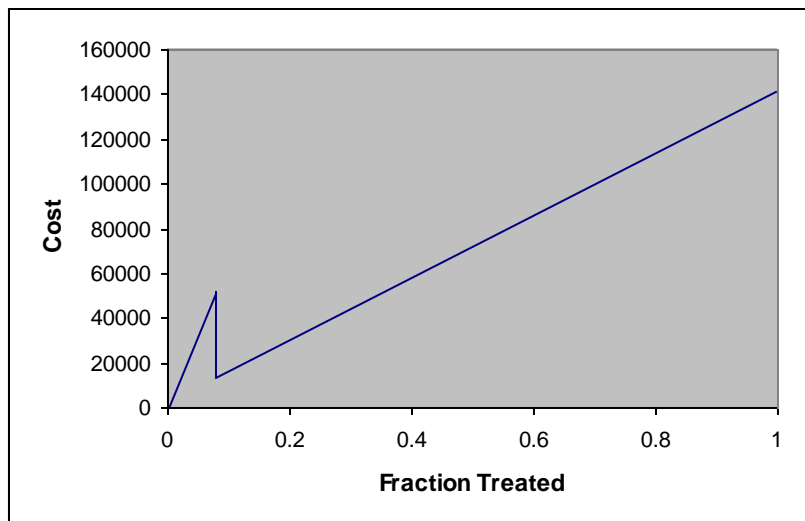

Figure 1. *Cost curve for one subwatershed in Bartlett Brook. The associated cost for each fraction treated is the minimum cost BMP configuration. Each cost thus implies an underlying precalculated BMP configuration.*

We developed a model for the Bartlett Brook watershed (see Objective 2) using HSPF (Hydrological Simulation Program – FORTRAN) (Bicknell, et al. 2001). Sediment loading for each BMP configuration was determined by modifying the base HSPF model to include the indicated BMPs and then simulating the derived model. Due to the higher computational cost of modeling sediment, we used the standard deviation of discharge as a surrogate for sediment loading. In preliminary work we had identified this surrogate to have a very high coefficient of determination (≥ 0.85) with sediment loading in real watersheds (we are currently preparing this work for submission to *Hydrologic Processes*). After Pareto optimal solutions were evolved, they were re-evaluated using sediment to make minor adjustments to the Pareto front that ensure that sediment load is being minimized.

Finally, we pruned solutions in order to reduce uncertainty of response due to anticipated climate change. In the Northeast, storms are expected to become more intense and more frequent (NECIA 2006; Hayhoe, et al. 2006), so we created a precipitation pattern with these characteristics and compared the results of the Pareto optimal solutions on the predicted and current precipitation patterns. This enabled us to further refine the Pareto front to contain only those solutions that were performed most consistently under the different precipitation scenarios.

Objective 2: Use this evolutionary algorithm on the Bartlett Brook watershed as a specific case study in designing an optimal watershed management plan.

The above work was tested using the Bartlett Brook watershed as a case study. The Bartlett Brook watershed, a small, mixed-use, impaired watershed, is just south of Burlington, Vermont,

and discharges directly into Lake Champlain. The optimal solutions discovered by our algorithm are shown in Figure 2, before (blue dots) and after (red plusses) reducing uncertainty due to climate change. The results of Objectives 1 and 2 are in preparation for submission to IEEE Transactions on Evolutionary Computation.
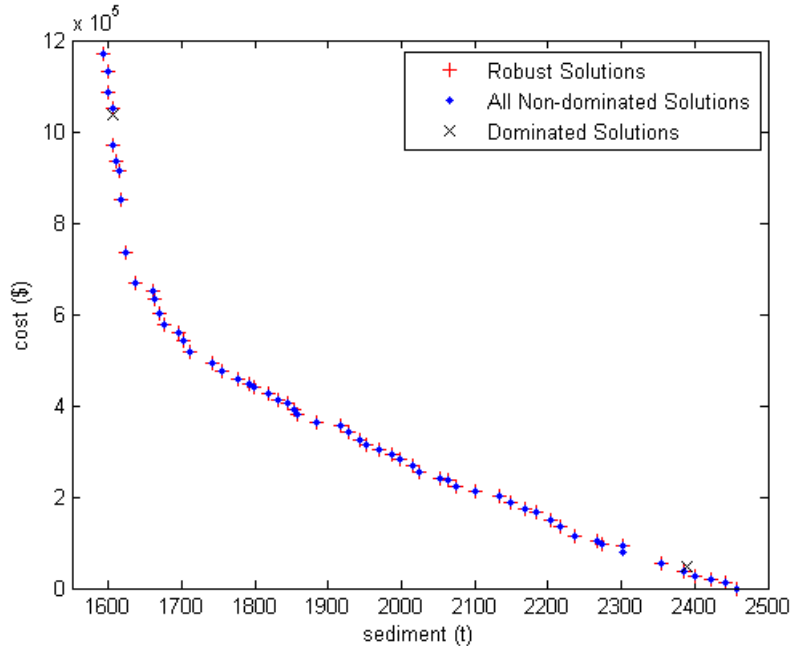

Figure 2. *Robust sediment solutions (plusses) plotted with all non-dominated normal-precipitation sediment solutions found (dots). Two solutions were dominated when re-evaluated with sediment (Xs).*

Objective 3: Apply advanced non-linear pattern analysis to potential solutions in the search space in order to extract general design principles relating BMP design to the effectiveness, robustness, and cost-effectiveness of solutions.

The enormous amount of data gathered through the optimization process lends itself to analysis after the fact, both along the Pareto front and orthogonal to it, as a means to identify patterns in underlying parameters and how they relate to the objectives; i.e. to minimize cost and maximize treatment. The goal of this analysis is to determine general design principles that can be used either (i) to create good solutions without running the optimization again, and/or (ii) to better inform the optimization process. This process has been dubbed 'innovization' (Deb and Srinivasan 2006). For example, what attributes of a solution make it more robust to changing rainfall patterns? For a given cost, how do various attributes change based on distance to the Pareto front?

We analyzed each decision variable along the Pareto front to try to find patterns in the optimal placement of BMPs in the watershed. An example of this is shown in Figure 3. We also intend to examine aggregate surrogate variables along the Pareto front, e.g., the watershed-wide area

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treated by BMPs and the weighted average elevation of the BMPs (weighted by fraction of total area treated in that subwatershed).

We created heat maps showing all of the Pareto optimal solutions across the watershed (see Figure 4; high-cost low sediment solutions at the top, low-cost high sediment solutions at the bottom). The heat maps were sorted (left to right in Figure 4) first by mean elevation of the subwatershed and second by increasing maximum treatable area of the subwatershed. We found that Pareto optimal solutions tend to require that the higher elevation subwatersheds have a large amount of control (as illustrated by the prevalence of white in the rightmost columns of Figure 4).
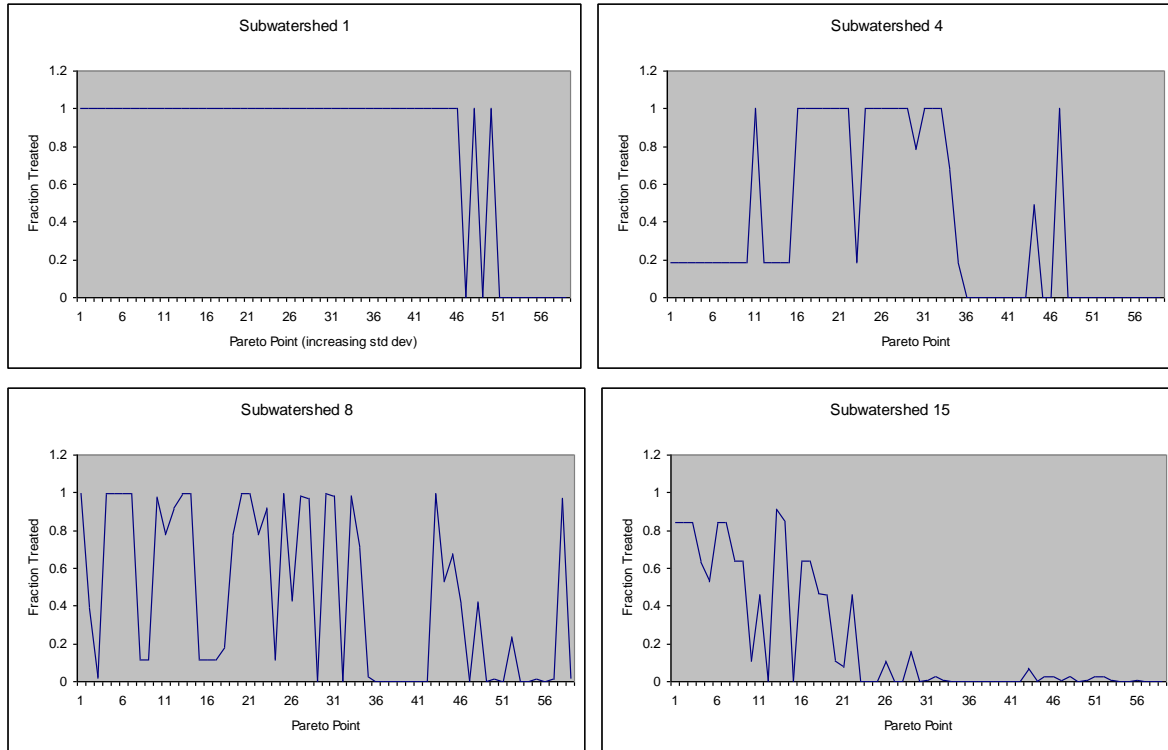

Figure 3. Decision variable values on Pareto front for representative subwatersheds
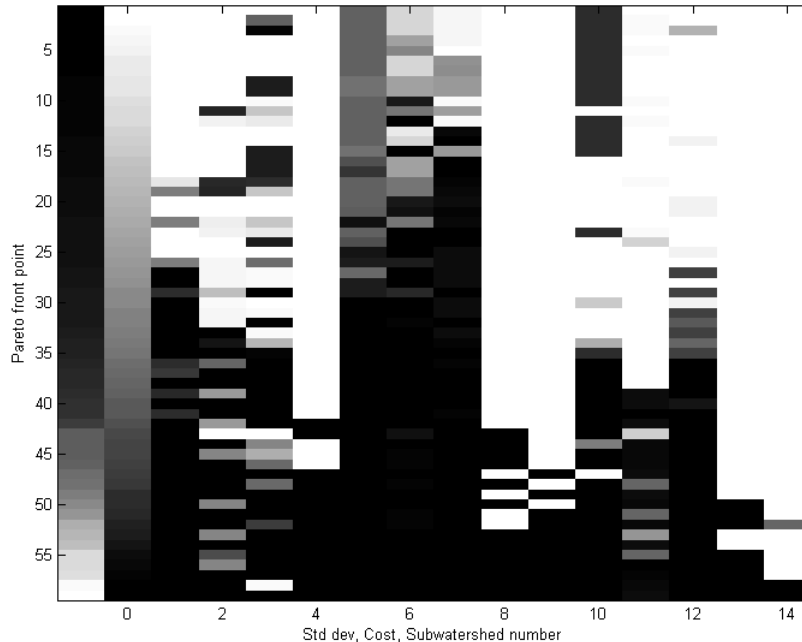
Figure 4. *The leftmost (shown at x = -1) bar shows the range of the standard deviation of discharge (black represents less pollution). The second leftmost bar (shown at x = 0) shows the range of the cost (black represents the lowest cost). Heat map of solutions plotted by increasing mean elevation (from x = 1 to x = 14); black represents no treatment while white represents full treatment (100%).*

We have started to apply Kohonen Self-Organizing maps (SOMs), a form of unsupervised artificial neural network (Kohonen 2001), in an attempt to identify patterns in the search space, due to multivariate interactions. Prior related innovization research with SOMs has been completed by Obayashi and Sasaki (2003) for aircraft wing design, a problem with many design variables and objectives. One important way in which our attempt differs from other automation attempts (e.g., Bandaru and Deb 2010) and manual innovization work is that existing methods focus solely on the final optimizer-generated non-dominated Pareto solutions, whereas we are also examining solutions orthogonal to the front, using different-sized sliding windows to select which points to examine in each direction. We expect to submit our results from Objective 3 in the late summer or early fall of 2011.

Objective 4) Determine if simple hydrologic indicators can discriminate among watersheds that are impaired by stormwater runoff and those that are not.

The determination of watershed status for the purposes of EPA 303.d reporting relies on bio-monitoring data. A critical assumption in the Vermont approach to stormwater management is that "impairment" – defined on the basis of biotic and geomorphic criteria – is directly correlated with altered hydrologic regimes. Altered hydrologic regime (e.g., changes in frequency and amplitude of runoff) can be measured fairly easily. Thus, if there is a strong correlation between specific metrics of hydrologic regime and the fundamental indicators of impairment, then these hydrologic metrics might serve not only as useful surrogates for the degree of impairment but as a means to track recovery from impairment. This would be particularly advantageous given that the hydrologic effects of stormwater mitigation practices (i.e., installation of BMPs) are nearly

immediate, while shifts in stream biology and geomorphology driven by stormwater mitigation may take years to become evident. To this end we investigated the ability of the hydrologic metrics developed in Objective 1 to discriminate between the hydrologic regimes of watersheds that have been listed by the state (i.e., 303.d) as impaired versus selected watersheds that are not listed. The hydrologic data for this analysis came from the UVM Flow Monitoring Project (FMP) funded separately VTANR.

We used the full set of indicators investigated in Objective 1 to investigate their performance over the 25 watersheds monitored in the FMP. Over the period of this award, datasets from 2006-2008 have been used. However, other datasets from 2009-2011 are being processed now by the FMP and will be incorporated in this analysis as they become available (though fewer sites were instrumented in 2010-11). Fourteen of the FMP watersheds are listed as being impaired by stormwater discharges, while the remaining 11 have moderate levels of development, impervious cover, and stormwater discharges, but are not biologically impaired nor 303.d listed (hereafter referred to as attainment watersheds).

Twenty two hydrologic indicators have been applied to the database thus far, with the six best able to discriminate among impaired and attainment watersheds presented below (Figure 5). Each hydrologic indicator was calculated using the data from each watershed, with the resulting values from the impaired (n=14) and attainment (n=14) watersheds tested for differences using the Wilcoxon rank sum test. The six indicators found to differ most significantly between the impaired and attainment watershed groups are the maximum 5 min flow rate (Max Q), the maximum daily average flow (1D Max), the maximum daily average flow minus the minimum daily average flow (1D Rng), the standard deviation of flows greater than the median flow (StDev >Q50%), the standard deviation of all flows (StDev), and the flow rate that is exceeded for 0.3% of the data record (Q 0.3%).
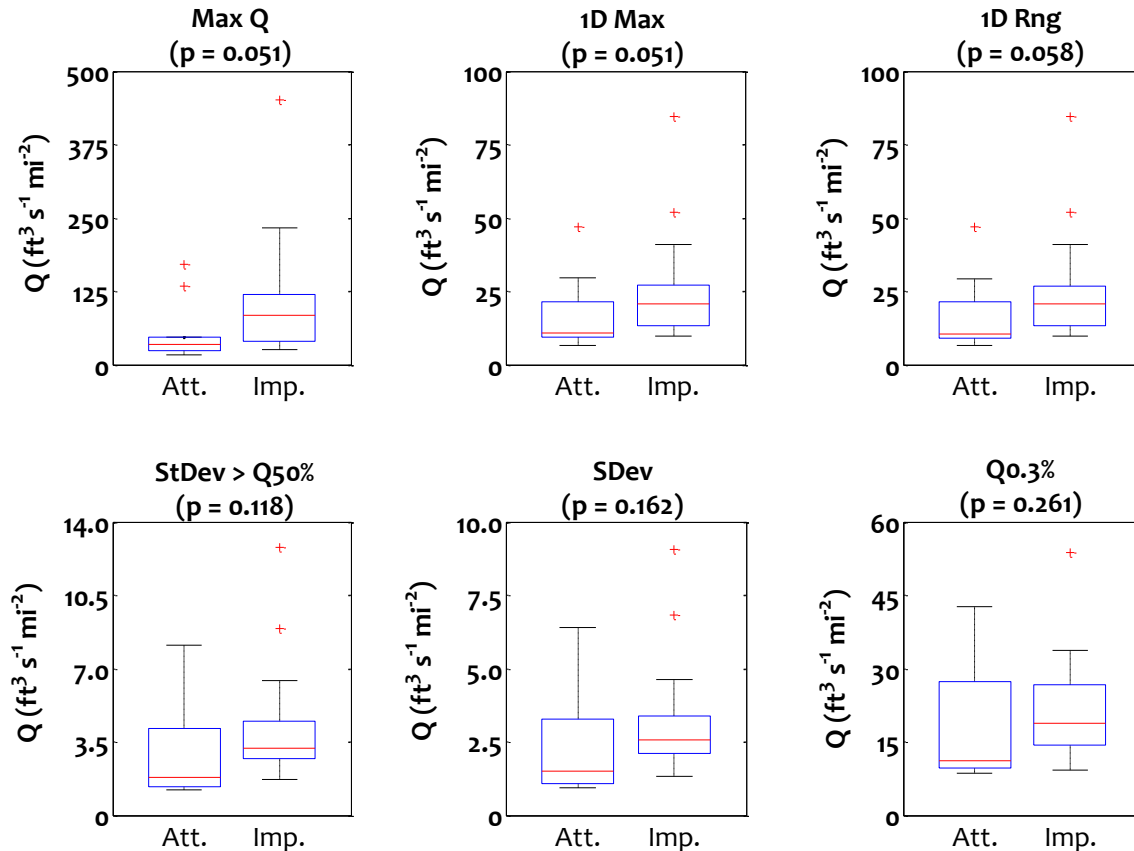
Figure 5. *Box plots of six indicators, grouped by watershed status (attainment vs impaired), with p values for rank sum tests of attainment vs impaired groupings. Box plots show the median (center line), interquartile range (box), 1.5 times the interquartile range (whiskers), and outliers (pluses).*

This analysis shows that the best three indicators tested thus far (Max Q, 1D Max, and 1D Range) are based on 5 minute peak flow rates or daily peak flow rates. This is not surprising given that the landscape factors contributing to stormwater runoff can increase peak flow rates. However, for the purposes of discriminating among impaired and attainment watersheds these indicators are not ideal, for two reasons. First, the peak flow rates are not very robust, potentially changing with the inclusion of a single additional storm event. Second, given the open channel profiling methods used to measure the flow rates in the study watersheds, the highest flow rates are inherently the least certain measurements. As a result, our ongoing work is focused in part on identifying additional indicators not subject to these limitations.

Also shown are StDev > Q50% and StDev, which less convincingly discriminate between impaired and attainment watersheds than the indicators based on peak flow rates. In Objective 1 we found that these two indicators were the best predictors of suspended sediment loading. Lastly, the Q 0.3%, which is the flow metric used in Vermont's stormwater impaired watersheds Total Maximum Daily Loads (TMDLs), is presented for the impaired and attainment groupings. The Q 0.3% does not discriminate well between impaired and attainment watersheds based on the 2006-2008 datasets. However, this lack of significance may be due to structural stormwater

improvements (installation of BMPs) that has been ongoing in the impaired watersheds through the period of record.

Work on the objective 4 analysis is currently ongoing. We are investigating both additional hydrologic indicators that may be useful for predicting watershed status, and are planning on incorporating additional years of FMP streamflow data as it becomes available. We anticipate having all streamflow data collected through the 2011 field season incorporated into the analysis by December 2011. The results of objective 4 will be submitted to the Journal of Hydrology for publication.

Overall Summary

An automated method has been developed for optimizing multiple BMP placement and sizing in order to meet TMDL targets. Strengths of the method include:

- BMP placement and sizing are simultaneously optimized at the subwatershed and watershed scales;
- Potential management plans are optimized for multiple objectives, including minimizing cost, minimizing TMDL, and minimizing uncertainty of TMDL in response to anticipated changes in precipitation patterns due to climate change;
- The method utilizes an established process-based model to assess hydrologic impacts of BMPs, and leverages our preliminary work in identifying an appropriate hydrologic metric to act as a surrogate for sediment transport;
- Rather than returning a single solution, the method returns multiple potential solutions that will enable decision makers to understand trade-offs between cost and performance so they can select the design that best meets their short and long term needs;
- The method facilitates the discovery of fundamental design principles that relate cost-effective BMP management designs to performance and robustness.

Specific benefits resulting from this project include:

- A family of Pareto optimal watershed management plans for Bartlett Brook, an impaired watershed discharging into Lake Champlain near Burlington, VT;
- A software and method that can be applied to arbitrary watersheds elsewhere in Vermont and the U.S;
- General design principles for designing optimal stormwater management plans for arbitrary watersheds, independent from running the software;
- Identification of hydrologic indicators capable of distinguishing between stormwater impaired and non-stormwater impaired watersheds based on streamflow and precipitation records.

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Information Transfer Program Introduction

The following section describes the Information Transfer activities of the Vermont Water Resources and Lake Studies Center in FY2010.

Information Transfer Activities

Basic Information

Title:	Information Transfer Activities
Project Number:	2008VT39B
Start Date:	3/1/2010
End Date:	2/28/2011
Funding Source:	104B
Congressional District:	First
Research Category:	Water Quality
Focus Category:	Education, Management and Planning, Methods
Descriptors:	
Principal Investigators:	William Breck Bowden

Publication

1. There are no publications specific to this project. However, papers presented at the conference supported by the Vermont Water Center in 2010 will be published in a special issue of the Journal of Great Lakes Research, expected in late 2011.

The Vermont Water Resources and Lake Studies Center facilitates information transfer in a variety of ways. The Center maintains a web site that highlights emerging research funded by the Center or relevant to water resources management in Vermont.

The Director of the Water Center is also the Chair of Lake Champlain Basin Program's (LCBP's) Technical Advisory Committee (TAC). In this capacity he also is a member of the Executive and Steering Committees for the LCBP and regularly brings information from Center-funded projects to the attention of the TAC and other LCBP committees.

The Center regularly supports seminars, workshops, and conferences relevant to water resources management issues in Vermont. Examples include specialty workshops designed to showcase emerging results from Center-funded projects. At other times the Center supports meetings that address topics that are directly relevant to the Center's mission. In 2010 the Water Center co-sponsored the biennial conference on science relevant to the management of Lake Champlain and its basin. This conference – entitled *Lake Champlain: Our Lake, Our Future 2010* – was held June 7-8, 2010 in Burlington, Vermont. The conference was managed by the Lake Champlain Research Consortium with addition co-sponsorship by the Lake Champlain Basin Program, the USGS, and the Vermont Agency of Natural Resources.

USGS Summer Intern Program

None.

Student Support					
Category	Section 104 Base Grant	Section 104 NCGP Award	NIWR-USGS Internship	Supplemental Awards	Total
Undergraduate	4	0	0	0	4
Masters	2	0	0	0	2
Ph.D.	2	0	0	0	2
Post-Doc.	0	0	0	0	0
Total	8	0	0	0	8

Notable Awards and Achievements

Waters Corp. Award in Environmental Sciences: Valentin, Dorielys M., 2010, Examining Effects of a Capped Landfill on Groundwater and Alluvial Soils Near Indian Brook in Essex, VT, ANA G. MÉNDEZ UNIVERSITY SYSTEM (AGMUS) 2010 Research Symposium, San Juan, Puerto Rico.

Publications from Prior Years

1. 2002VT5B ("Detection of cyanobacterial blooms using remote sensing") - Articles in Refereed Scientific Journals - Wheeler, S., L. Morrissey, S. Levine, G. Livingston, and W. Vincent, 2002, Mapping Cyanobacteria Blooms in Lake Champlain's Missisquoi Bay Using QuickBird and MERIS Satellite Data, Journal of Great Lakes Research, In Press.

2. 2005VT22B ("Trophic status of Lake Champlain over 400 years of changing land use: A paleolomnological study") - Articles in Refereed Scientific Journals - Levine, S.N., A. Lini, M. L. Ostrofsky, L. Bunting, H. Burgess, P. R. Leavitt, D. Rueter, A. Lami, and P. Guilizzoni. 2011. The eutrophication of Lake Champlain's Northeast Arm: Insights from paleolimnological analyses. J. Great Lakes Res. (in press).

3. 2005VT22B ("Trophic status of Lake Champlain over 400 years of changing land use: A paleolomnological study") - Other Publications - Levine, S. N., A. Lini, M.L. Ostrofsky, L. Bunting, H.D. Burgess, P. Leavitt, D. Dahlen, A. Lami, and P. Guilizzoni. 2010. Paleoreconstruction of the trophic history of Lake Champlain: The Northeast Arm. 2010 ASLO/NABS meeting, Aquatic Sciences: Global Changes from the Center to the Edge, Santa Fe, NM.

4. 2005VT22B ("Trophic status of Lake Champlain over 400 years of changing land use: A paleolomnological study") - Other Publications - Lini, A., S. Levine, H. Burgess, M. Ostrofsky, P. Guilizzoni, A. Lami, D. Dahlen, P. Leavitt, and N. Kamman. 2010, The Eutrophication of the Main Basin and Southern Arm of Lake Champlain: A Paleolimnological Assessment. Lake Champlain Basin Research Conference - June 7 & June 8, 2010. Burlignton, VT.

5. 2008VT36B ("Improvement of Phosphorus Load Estimates through the use of Enzyme-Hydrolysis Measures of Phosphorus Bioavailability") - Dissertations - Johnson, Nicholas, 2011, Soil Organic Phosphorus Classification using high-throughput enzymatic hydrolysis, M.S. Thesis, Civil and Environmental Engineering, The University of Vermont, Burlington, Vermont.

6. 2008VT36B ("Improvement of Phosphorus Load Estimates through the use of Enzyme-Hydrolysis Measures of Phosphorus Bioavailability") - Articles in Refereed Scientific Journals - Johnson, N.R. and Hill, J.E. 2010 Phosphorus composition of a poultry manure-amended soil via enzymatic hydrolysis: demonstration of a high-throughput method and hints on enzyme-labile P Soil Science Society of America Journal 74 (5): September-October issue.

7. 2008VT36B ("Improvement of Phosphorus Load Estimates through the use of Enzyme-Hydrolysis Measures of Phosphorus Bioavailability") - Articles in Refereed Scientific Journals - 2. Johnson N.R. and Hill J.E. High-throughput method for the characterization of organic P in environmental samples (accepted; Journal of Visualized Experiments).

8. 2008VT36B ("Improvement of Phosphorus Load Estimates through the use of Enzyme-Hydrolysis Measures of Phosphorus Bioavailability") - Other Publications - Hill, Jane E. 2009, 1. Phytate: Movement and Transformation in the Landscape, Great Lakes Phosphorus Forum, Poster, July, 2009.

9. 2008VT36B ("Improvement of Phosphorus Load Estimates through the use of Enzyme-Hydrolysis Measures of Phosphorus Bioavailability") - Other Publications - Johnson, Nicholas R., and Jane E. Hill, 2009, 2. Phosphorus composition of wet and dried poultry litter-amended soil by enzyme hydrolysis and solution 31P-NMR, 238th ACS national meeting (presentation, Aug., 2009).

10. 2008VT36B ("Improvement of Phosphorus Load Estimates through the use of Enzyme-Hydrolysis Measures of Phosphorus Bioavailability") - Other Publications - Johnson, Nicholas R., Barbara Cade-Menun, and Jane E. Hill, 2009, 3. Hydrolysis as a Tool for Measuring Bioavailable P in Dairy Manure Storage and Treatment Systems, Soil Science Society of America Annual Meeting 2009 (presentation, Nov., 2009).

11. 2006VT25B ("Evaluating Quantitative Models of Riverbank Stability ") - Dissertations - Borg, J.L., 2010, Streambank Stability and Sediment Tracing in Vermont Waterways, M.S. thesis, Civil and Environmental Engineering, The University of Vermont, Burlington, Vermont.

12. 2006VT25B ("Evaluating Quantitative Models of Riverbank Stability ") - Articles in Refereed Scientific Journals - Borg, J. L., Dewoolkar, M. M., and Bierman, P. R., 2011, Quantitative analysis of the stability of Vermont streambanks, In Preparation for Engineering Geology.
13. 2006VT25B ("Evaluating Quantitative Models of Riverbank Stability ") - Other Publications - Borg, J. L., 2007, Vermont Streambank Stability, presentation at the Northeast Geotechnical Symposium at University of Massachusetts at Amherst.
14. 2006VT25B ("Evaluating Quantitative Models of Riverbank Stability ") - Other Publications - Borg, J. and Dewoolkar, M., 2007, presentation at the Lake Research Conference - Lake Champlain: Our Lake, Our Future, Burlington, VT.
15. 2008VT34B ("Tracing sources of eroded sediment with atmospherically produced 10-Be") - Articles in Refereed Scientific Journals - Borg, J. L., Bierman, P. R., Dewoolkar, M. M., Rizzo, D. M., and Rood, D., 2011, Meteoric 10Be adhered to suspended sediment: source and transport dynamics in a large New England watershed, Journal of Geophysical Research – Earth Surface, In Review.
16. 2008VT34B ("Tracing sources of eroded sediment with atmospherically produced 10-Be") - Dissertations - Borg, J. L., 2010, Streambank Stability and Sediment Tracing in Vermont Waterways, M.S. Thesis, Civil and Environmental Engineering, The University of Vermont, Burlington, Vermont.
17. 2006VT25B ("Evaluating Quantitative Models of Riverbank Stability ") - Other Publications - Borg, J. L., Dewoolkar, M. M., and Bierman, P. R., 2011, Borehole shear test for determining unsaturated soil strength, Geo-Congress 2012 State of the Art and Practice in Geotechnical Engineering Conference, In Preparation.