

**Vermont Water Resources and Lake Studies
Center
Annual Technical Report
FY 2011**

Introduction

The following sections describe the activities of the Vermont Water Resources and Lake Studies Center in the project year just concluded (2011-2012).

Research Program Introduction

In the 2011-2012 project year the Vermont Water Resources and Lake Studies Center continued to address several broad aspects of water resources management in Vermont that are of direct interest to the Vermont Department of Environmental Conservation (VTDEC) and other collaborating stakeholder groups. These groups include the Lake Champlain Basin Program, the Lake Champlain Research Consortium, municipalities, and NGOs who have an interest in water resources management in Vermont. In the Vermont Water Center RFP process for 2011-2012 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. identify means to reduce sediment and phosphorus delivery to receiving waters in the state of Vermont; and
3. establish the socioeconomic justifications, costs, and benefits associated with or represented by water resources protection in Vermont.

The research projects supported USGS 103b funds in the 2011-2012 project year were:

1. Ross, D., E. Ishee, L. Morrissey, and B. Wemple. Determining phosphorus release potential from eroding streambank sediments in the Lake Champlain Basin of Vermont. (Final report)
2. Bowden, W. B., J. Shanley. Use of acoustic Doppler current profiler data to estimate sediment and total phosphorus loads to Lake Champlain from the Rock River. (Final report but the project will continue with separate funding)
3. Bomblies, A. and J. Hill. Advanced and Integrative Model of Phosphorus loading from High Runoff Events. (Continuing project, interim report)

As noted, two of these three projects (Ross et al. and Bowden and Shanley) are concluding and so the reports here are final reports. However, the project conducted by Bowden and Shanley will continue to a new phase with full support from the VTDEC. The funding provided by the Vermont Water Center in 2011-2012 was sufficient to justify continued investment by the VTDEC in 2012-2013. The project by Bomblies is continuing in 2012-2013 and so the report here is an interim report. These projects are described in detail in the sections that follow.

Determining phosphorus release potential from eroding streambank sediments in the Lake Champlain Basin of Vermont

Basic Information

Title:	Determining phosphorus release potential from eroding streambank sediments in the Lake Champlain Basin of Vermont
Project Number:	2011VT57B
Start Date:	3/1/2011
End Date:	2/28/2012
Funding Source:	104B
Congressional District:	First
Research Category:	Water Quality
Focus Category:	Nutrients, Non Point Pollution, Water Quality
Descriptors:	None
Principal Investigators:	Donald Ross, Leslie Morrissey, Beverley Wemple

Publications

1. Young, E.O., D.S. Ross, C. Alves, and T. Villars. 2012. Influence of soil series on phosphorus forms and availability at two riparian sites in the Lake Champlain Basin (Vermont). *J. Soil Water Conserv.* 67:1-7.
2. Ishee, E.I. 2011. Characterizing phosphorus in eroding streambank soils in Chittenden County, Vermont. M.S. Thesis, Dept. Plant & Soil Science, Univ. Vermont, 90 pp.

Final Report: Determining phosphorus release potential from eroding streambank sediments in the Lake Champlain Basin of Vermont

Principal Investigator: Donald S. Ross, Research Associate Professor, Department of Plant and Soil Science University of Vermont, dross@uvm.edu

Co-investigator: Eulaila Ishee, Graduate Research Assistant, Department of Plant and Soil Science University of Vermont

Collaborators:

Leslie Morrissey, Rubenstein School of Environment and Natural Resources, UVM.
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Abstract

Streambank erosion is a significant contributor of sediment and sediment-bound phosphorus (P) into Champlain Valley riverways and Lake Champlain, lowering water quality. Sediment and P load studies usually measure only total P (TP) and occasionally readily available P, such as Modified Morgans P (MM-P), yet neither concentration reflects the amount of P that will be released from sediments over time. Available P tests represent the fraction of P immediately bioavailable while TP includes occluded P that will likely never be released. Oxalate-extractable P (P-ox) has been shown to be more representative of P that is released over time in aquatic systems, measuring immediately available P as well as P complexed with Al and Fe oxides. In reduced environments such as lake sediments, Fe oxides readily release P that can be cycled into the water column. Recent work in the Lake Champlain Basin has shown that P-ox/TP ratios were strongly correlated with soil texture and therefore bioavailable P may be modeled throughout riparian landscapes using textural analysis. The objectives of this project were to: 1) quantify the slow-cycling P contribution (P-ox) from eroding streambank sediments into Lake Champlain and 2) further develop the relationships among P-ox, total P and soil texture. To meet these objectives, 400 archived soil samples representative of study extent, texture, and drainage (stratified random sample) were analyzed for P-ox and pH. These samples were collected as part of three past studies and have been analyzed for MM-P, TP, and texture. Soils were collected in the Basin along the corridors of six streams in three Vermont counties. Watershed averages for the amount of P extracted with oxalate ranged from 133 to 209 mg/kg and comprised 22 to 32% of the total P (P-ox/TP). The degree of phosphorus saturation (DPS), calculated from the ratio of P-ox to oxalate-extractable Al and Fe, averaged between 15 and 32%, but with 5 of the 6 watersheds < 20%. The P-ox/TP ratio, averaged by watershed, was linearly related to % silt ($R^2 = 0.81$, $n = 6$, $P = 0.01$). Samples taken from a stream restoration site on Lewis Creek were consistently highest in P-ox, DPS and the P-ox/TP ratio, whereas no statistical differences were found among the other 5 sites. On a broad scale, texture (% silt) may be able to model P-ox and DPS along riparian corridors of the Lake Champlain Basin, assuming accurate soils mapping. The DPS results suggest that many streambank soils may be capable of sorbing additional P. More research is needed on this aspect and also on potential P release dynamics once streambank soils are eroded and become stream or lake sediments.

Statement of regional or State water problem

Phosphorus (P) has long been recognized as the primary limiting nutrient for algal growth in fresh water systems. Along with an increase in P loading, Lake Champlain has seen an increase in algal blooms during summer months, with eutrophication recorded as early as 1977 (Budd and Meals, 1994). The majority of P from the landscape is sediment bound (e.g. Loeb, 2008; Sharpley, 1995). Streambank erosion has been identified as a potentially significant source of sediment and P into Lake Champlain and elsewhere, contributing 17-93% of total suspended sediments (TSS) to collecting water bodies (Sekely, 2002). In Chittenden County, DeWolfe et al. (2004) found streambank erosion to be highly variable in its contribution to suspended sediment, ranging from the least to the greatest single contributor. With 75% of stream reaches considered eroding by VT DEC (2007), the potential contribution of eroding streambank sediments is large and not well defined. While it is clear that not all eroded streambank sediments are transported downstream, streambank erosion may still actively release P into the hydrologic network without this transport.

The native P concentration of eroding streambank sediment is poorly understood both in quantity and form. Our ongoing research has shown that native soil P is variable through the riparian landscape, as is soil texture, topography and drainage. We found total soil P to be correlated with soil texture and, thus, it may be mapped according to soil type, assuming accurate soil maps (Young et al., 2012). However, predicting total P (TP) inputs will not adequately predict P release into the stream/lake system. It is important to understand the fraction of soil TP that will become bioavailable when soil becomes sediment and environmental conditions change. As sediments are exposed to reducing conditions, P bound to iron oxides releases (Young and Ross 2001; Heiberg, 2010). Recent studies in agricultural and floodplain systems have shown that oxalate-extractable P (P-ox) is representative of this P fraction that is released over time (Maguire, 2000; Koopman et al. 2004) and may be used as a proxy for bioavailable P as redox conditions change in the sediment environment. Oxalate has been shown to selectively extract the less crystalline and more easily reduced form of iron oxides (Maguire et al. 2000). Additionally, Young et al. (2012) found that the ratio of P_{ox} to TP was strongly correlated with texture, with decreasing P-ox/TP ratios with increasing sand content. This relationship was developed with soils from a limited number of sites and the present research greatly expanded the range of soils included.

Sediment transport is also related to sediment texture: smaller particles travel further with less force than larger particles. Increasing silt-clay content of soil increases the subaerial erodibility of the soil, especially in cohort with freeze-thaw cycles (Cooper, 2003) and it is largely assumed that all clay and some to all of the silt content of eroded streambank soils will be transported downstream (Law et al. 2007; Thoma et al. 2005). Therefore, our initial results indicated that smaller particles have a more bioavailable P fraction than do sand particles and are more transportable, compounding their effects in collecting water bodies.

Quantifying the portion of TP that will become bioavailable in aquatic systems is critical to understand the fate of sediment bound P from the landscape. This information will help soil and aquatic scientists understand the bioavailable contribution of P from sediments. Many studies have recognized the need to quantify the bioavailable fraction of TP entering aquatic systems (DeWolfe et al., 2004; Sharpley et al., 2005), yet little work has done so to date.

Nature, scope, and objectives of the project

This project evaluated the fraction of TP that is potentially bioavailable to algae over time (slow-cycling) as sediment redox conditions change. Using a statistically selected subset of samples collected from past and present projects (funded through the UVM Water Resources and Lake Studies Center by the USGS and the Vermont Agency of Natural Resource), oxalate extractable P, Al and Fe was determined. When combined with updated soils mapping, modeling efforts will enable spatially distributed estimates of potential P contribution from riparian corridors in the Lake Champlain Basin. The explicit objectives of this project were to i) quantify the slow-cycling P contribution (P_{ox}) from eroding streambank sediments into Lake Champlain and ii) further develop the relationships among P_{ox} , total P and soil texture.

Methods, procedures, and facilities

We used soil samples and associated data from our three Water Center funded studies, described in Young et al. (2012) and Ishee (2011). Two previous studies sampled riparian soils along Lewis Creek in Addison County and Rugg Brook and the Rock River in Franklin County (Young et al., 2012). In the most recent study, 75 streambank erosion features were sampled along 4 streams in Chittenden County: Allen Brook, Alder Brook, Indian Brook and LaPlatte River (Ishee, 2011). Of over 1500 samples collected from the three studies, a subset of 400 was selected to statistically represent the range of texture, drainage, and location. The subset samples were apportioned according to total number of samples from each stream; 35-40% of the total number of samples from each stream were selected at random and analyzed. These samples are comprised of 15-30 cm depth increments taken to a depth of 90-105 cm. Samples were extracted by acid ammonium oxalate solution in the dark (Burt, 2004) and P, Fe and Al determined by Inductively Coupled Plasma Atomic Emission Spectroscopy (ICP-AES) using standard methods. We also determined soil pH, 2:1 v:v in H_2O . Associated data, already analyzed, include total P by microwave assisted nitric acid digestion (TP), Modified Morgans soil test P (MM-P) and soil texture (determined using the hydrometer method). The degree of phosphorus saturation was calculated as follows:

$$DPS_{ox} = (P_{ox}/0.5[A_{lox} + Fe_{ox}]) \times 100\%, \text{ mmol/kg}$$

Statistical analysis was performed using SAS 9.2 (SAS Corp., Cary, NC). The general linear model (proc glm) was used for analysis of variance and the Student Newman Keuls (SNK) was used to contrast means. All data were initially checked for normality and log transformed if needed. Analysis of variance was performed using log transformed values for degree of P saturation, ratio of P-ox:TP and Modified Morgans P.

Findings

The number of samples analyzed from each watershed ranged from 21-120, varying proportionally to the total number of samples taken in the original studies (Table 1). Both Rugg Brook and Lewis Creek samples were taken from a relatively limited area at two stream restoration sites (Young et al. 2012), while the other four streams, all in Chittenden County, had more extensive sampling along much of their stream corridors.

The average amount of P extracted by ammonium oxalate (P-ox) in each watershed ranged from 133 to 209 mg/kg (Table 1, Fig. 1) and was significantly higher in samples from Lewis Creek. Watershed averages for total P ranged from 548 to 674 mg/kg (Table 1, Fig. 2) with Rugg Brook having significantly lower concentration than Lewis Creek and the other watersheds in between. Three additional measures of P availability were examined: i) the degree of P saturation (DPS), ii) the ratio of P-ox to total P, and iii) soil test (Modified Morgans) P. The DPS was consistently low in five of the watersheds (15-17%), while much higher (31.5%) in Lewis Creek samples (Table 1, Fig. 3). Change points between 20-30% DPS have been proposed as critical thresholds above which P is readily released into runoff, suggesting the Lewis Creek site may be above steady state DPS levels and releasing more P into the stream. Similar differences were found in the ratio of P-ox to total P with Lewis Creek samples being statistically higher. Modified Morgans P, an estimate of availability to crop plants, averaged low at all sites but, again, Lewis Creek was at the high end and Rugg Brook at the low end (Table 1). The optimum range for crop growth is 4-7 mg/kg and these watershed averages were all under 3 mg/kg.

Soil pH varied widely across all samples, with a range between 3.8 and 8.6. Watershed averages ranged between 5.6 and 6.8 (Table 1). No effect of pH on DPS was found. Aluminum and Fe are generally more extractable at lower pH but we found only weak trends in our data. The maximum DPS values in individual samples (> 50%) were found at a pH of ~6.0. Relatively high concentrations of oxalate extractable Al and Fe were found in samples above pH 7.0, resulting in low DPS (< 20%).

Soil texture varied between sandy loam at Allen and Indian Brooks, loam at Rugg Brook and LaPlatte, and silt loam at Alder Brook and Lewis Creek (Fig. 4). Overall, the % sand was inversely related to % silt ($R^2 = 0.84$) with much less variation in % clay. Similar to our past studies (Young et al., 2012), we found a significant relation between P-ox:total P and % silt (Fig. 5). The concentration of P-ox increased with increasing silt content whereas the ratio of P-ox to total P displayed an even tighter relationship (Fig. 5). The relationship between P-ox and % silt in all individual samples was less robust than the watershed averages but still showed a significant trend (Fig. 6). Because sand and silt were inversely related, a similar but opposite trend was found with P-ox vs. % sand (Fig. 7).

We also examined the link between total P and other measurements and again found an interesting relationship with total Ca (Fig 8). This relationship showed much more scatter above pH 7.0, likely because of the presence of CaCO_3 . The relatively good fit suggests that some of the total P is in the form of apatite, a Ca-phosphate mineral. While not the focus of this study, the finding suggests an interesting avenue for research into the nature of total P in these soils. Any P present as apatite would likely not become available for algal growth even under reducing conditions in lake sediments.

In addition to comparisons among watersheds, we also examined differences among soil depth increments. The majority of the samples came from one of three depths, 0-15 cm (surface horizons), 15-30 cm (usually B horizon) and 60-90 cm (usually C horizon). We found significantly lower P-ox and total P at lower depths but no difference in the DPS (Table 2). Soil texture, total Ca and soil test P also did not change with depth whereas pH was higher at 60-90 cm (Table 2). This pH trend is consistent with soil profile development. Overall the differences among watersheds were more striking than the differences among depths.

Discussion

Sediment from streambank erosion can be an important source of P inputs into lake systems. Streambank erosion accounted for 1-78% of non-point source TP from the landscape into ten Lake Champlain Basin stream reaches in Vermont, reflecting variation in soil P levels, erosion rates, and other non-point P sources (DeWolfe et al., 2004). While streambank erosion represents a major source of sediment and associated P into hydrologic networks (McDowell et al., 2002; Kalma and Ulmer, 2003; DeWolfe et al., 2004), the characterization of this P is largely unknown, particularly in regard to the fraction of TP that will become bioavailable over time (DeWolfe et al., 2004).

The measurement of potentially bioavailable P in erodible soils requires a method that will simulate conditions once the soil is in the stream/lake system. Total P is routinely determined because it is a straightforward test but it can greatly overestimate the potential P contribution to the lake (DeWolfe et al., 2004; Sharpley et al., 2005). Environmental P tests such as water or weak-salt extractable only measure immediately available P. Soil test procedures, using various extractants designed for fertility assessment, remove greater P but were not designed to mimic sediment conditions. These extractants appear well correlated with the simple environmental tests (Magdoff et al., 1999). Anoxic conditions develop in stream and lake sediments, and release of P is a function of reduction of Fe oxides (Druschel et al., 2005; Heiberg et al., 2010; Young and Ross, 2001). Phosphate readily substitutes into the Fe oxide's structure, where it is stable under aerobic conditions but released when Fe reduction occurs under anaerobic conditions, seasonally variable but common in eutrophic systems. The most poorly crystalline forms of Fe oxides are both the best scavengers of phosphate aerobically and the most easily reduced under changing conditions. The oxalate extraction, acid ammonium oxalate, was actually designed to assess podzolization processes in soils (McKeague, 1967). Poorly crystalline Fe oxides can be translocated downward through a soil profile and accumulate in lower horizons. The oxalate extraction preferentially removes this form of Fe (and Al), along with organically complexed forms (Ross and Wang, 1993). Thus, this procedure will quantify both the oxide sequestered P and any organic-metal (Fe, Al)-phosphate, another poorly understood but important form. Recent studies (Maguire, 2000; Koopman et al., 2004) have used the oxalate extraction specifically to derive an estimate of potentially bioavailable P.

Smaller sized particles will preferentially be transported downstream under lower flow conditions than coarser particles (Cooper, 2003; Law et al., 2007; Thoma et al., 2005). However, sediments that settle prior to lake deposition may still transfer P into the water column through dissolution or other chemical transfer mechanisms (Heiberg et al., 2010; Young and Ross, 2001). In our previous studies, P variation in three Basin riparian corridors was well correlated with soil texture; soils with finer textures had higher TP than soils with coarse textures (Young et al., 2012). The relationship between texture and P has been found in a number of other studies (e.g. Truog, 1936; O'Halloran et al., 1987). Thus, smaller particles erode preferentially, are transported farther, and carry more TP than coarser particles.

Oxalate extractable P provides a measure of desorbable P representative of the TP fraction that will become bioavailable (Maguire et al., 2000; Pote et al., 1996; Young et al., 2012). The ratio of P-ox/TP was found to strongly correlate with soil texture for 27 soil samples along two tributaries of Lake Champlain (Young et al., 2012). The degree of P saturation (DPS) has been proposed as an indicator of P release in runoff (Koopmans, 2004; Maguire et al., 2002) with DPS change points identified above which P releases more readily. In Florida sandy soils, Nair et al.

(2004) found a change point of 20 or 28% (depending on runoff method), regardless of sample depth. These change points are consistent with critical thresholds identified in the Netherlands and Quebec (Beauchemin, 1999). In our data set, 72% of the individual samples had a DPS < 20%, suggesting that immediate release of P from these soils is not likely. The overall mean for the ratio of P-ox to TP was 24% and an average of 150 mg/kg P was oxalate extractable. The fraction of this P that is associated with Fe oxides would become bioavailable under reducing conditions in the lake. More detailed research is needed on both sediment transport and P release mechanisms.

Table 1. Watershed averages of phosphorus analyses, texture, pH and calcium. Values in a column not followed by the same letter are significantly different ($P < 0.05$). Before statistical treatment, values for DPS, Ox-P:TP, MM-P and clay were log transformed.

Watershed	n	Oxalate P	Total P	Degree of P saturation	Ratio of Ox-P to Total P	Modified Morgans P	sand	silt	clay	pH	Total Ca
		mg/kg	mg/kg	%		mg/kg	%	%	%		mg/kg
Allen Brook	112	133^B	592^{AB}	15.7^B	0.22^B	1.9^{AB}	55.6^A	32.9^D	11.4^{BC}	6.25^B	3684^A
SE		6	16	0.7	0.01	0.1	1.7	1.0	0.9	0.10	239
Indian Brook	120	146^B	619^{AB}	16.2^B	0.23^B	1.8^B	53.0^A	36.9^{CD}	10.1^C	5.65^C	2396^B
SE		9	17	0.9	0.01	0.1	3.4	2.5	1.5	0.13	132
Rugg Brook	21	139^B	548^B	15.4^B	0.24^B	1.1^C	38.6^B	43.3^{BC}	18.1^A	6.80^A	3032^A
SE		6	14	0.4	0.01	0.1	1.9	1.4	0.8	0.08	83
LaPlatte	59	164^B	674^A	15.8^B	0.25^B	2.8^A	35.2^B	43.6^{BC}	21.1^A	6.29^B	3321^A
SE		8	30	0.9	0.01	0.3	1.8	1.5	2.0	0.10	149
Alder Brook	60	160^B	608^{AB}	17.3^B	0.27^B	1.5^B	35.6^B	47.2^{AB}	17.2^{AB}	5.64^C	2376^B
SE		22	29	3.2	0.02	0.5	4.2	3.3	1.3	0.07	102
Lewis Creek	26	209^A	627^{AB}	31.5^A	0.32^A	2.8^A	37.0^B	51.9^A	11.1^{BC}	5.83^C	2313^B
SE		16	32	1.6	0.02	0.1	4.1	3.5	1.3	0.09	147

Table 2. Analytical results averaged by soil depth. Thirty seven samples from other depths are not included in these averages. Values in a column not followed by the same letter are significantly different ($P < 0.05$). Before statistical treatment, values for DPS, Ox-P:TP, MM-P and clay were log transformed.

Depth	n	Oxalate P	Total P	Degree of P saturation	Ratio of Ox-P to Total P	Modified Morgans P	sand	silt	clay	pH	Total Ca
		mg/kg	mg/kg	%		mg/kg	%	%	%		mg/kg
0-15 cm	112	168^A	671^A	17.0^A	0.25^A	2.7^A	48.0^A	40.2^A	11.8^A	5.69^B	3070^A
		8	17	0.6	0.01	0.2	1.9	1.4	0.8	0.08	129
15-30 cm	134	154^A	607^B	15.5^A	0.25^A	1.6^B	47.7^A	39.0^A	13.3^A	5.84^B	2929^A
		6	16	0.6	0.01	0.1	1.8	1.2	0.9	0.09	160
60-90 cm	115	128^B	573^B	17.1^A	0.22^B	1.6^B	44.8^A	39.3^A	15.9^A	6.26^A	2633^A
		5	12	0.7	0.01	0.1	2.3	1.6	1.4	0.08	123

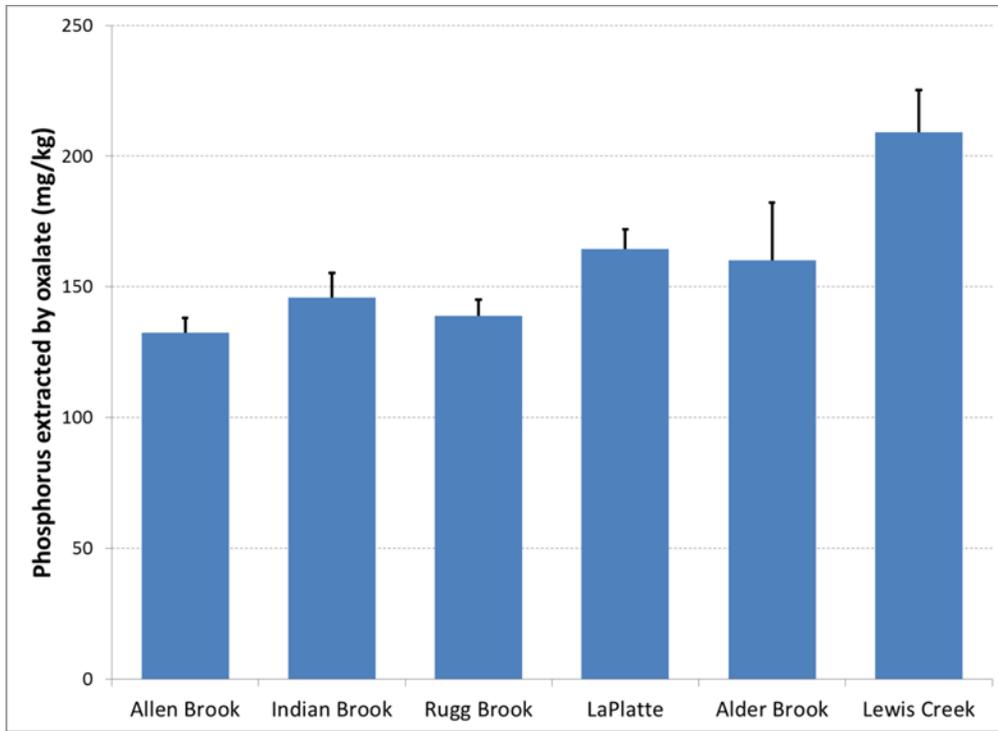


Figure 1. Oxalate extractable P averaged by watershed. Error bars represent the standard error of the means.

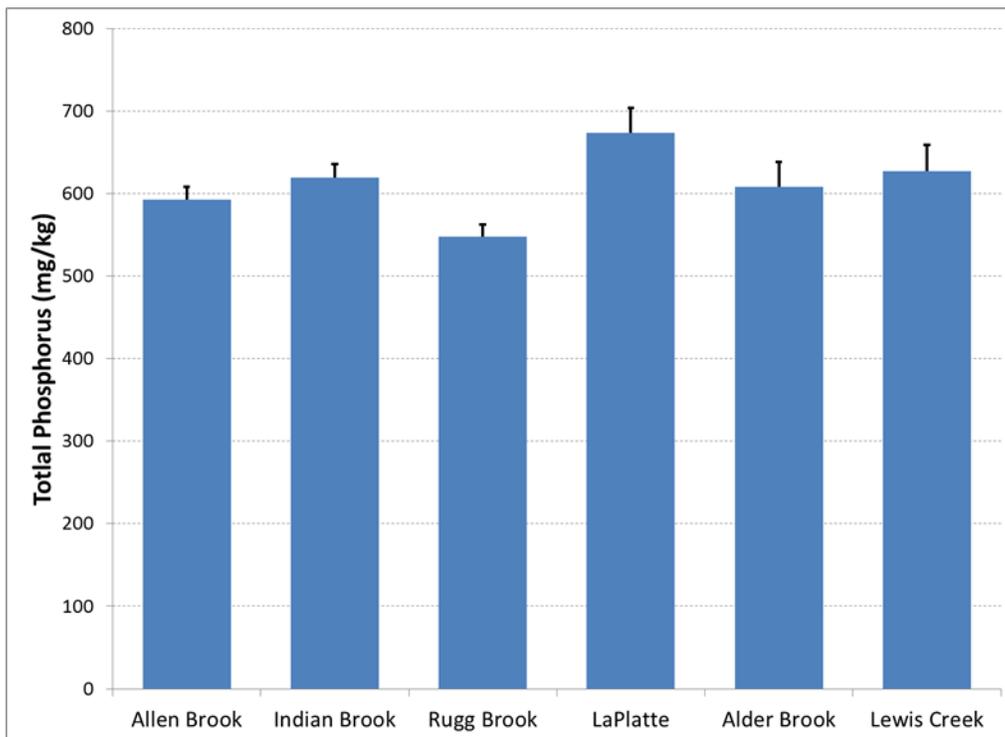


Figure 2. Total P averaged by watershed. Error bars represent the standard error of the means.

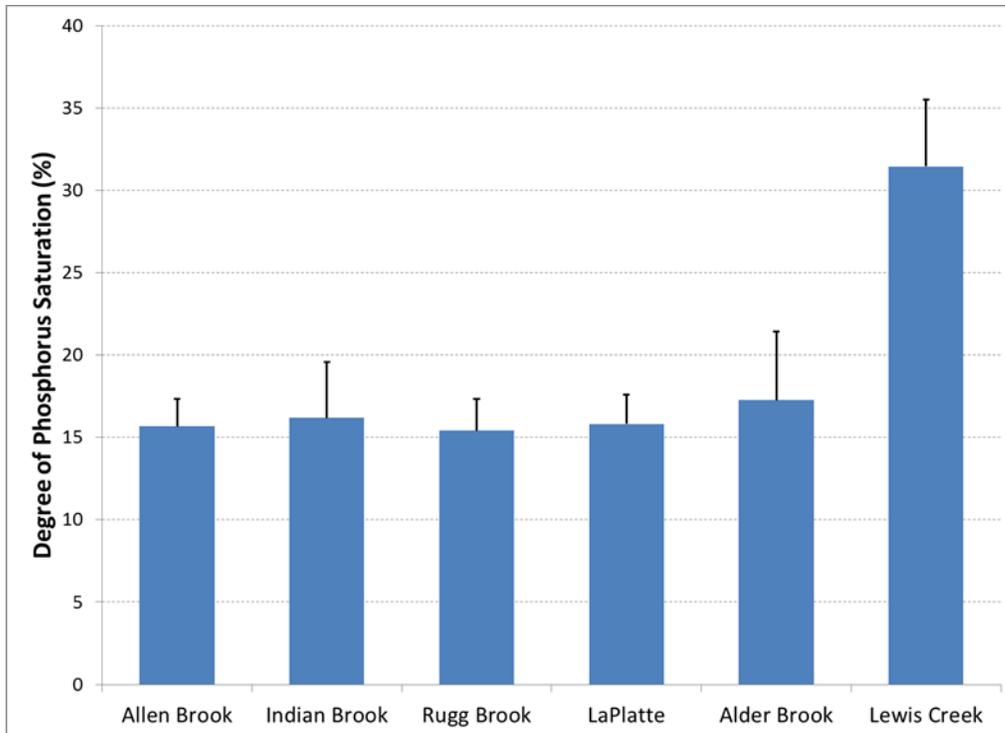


Figure 3. Degree of phosphorus saturation (DPS) from the oxalate extraction results. Error bars represent the standard error of the means.

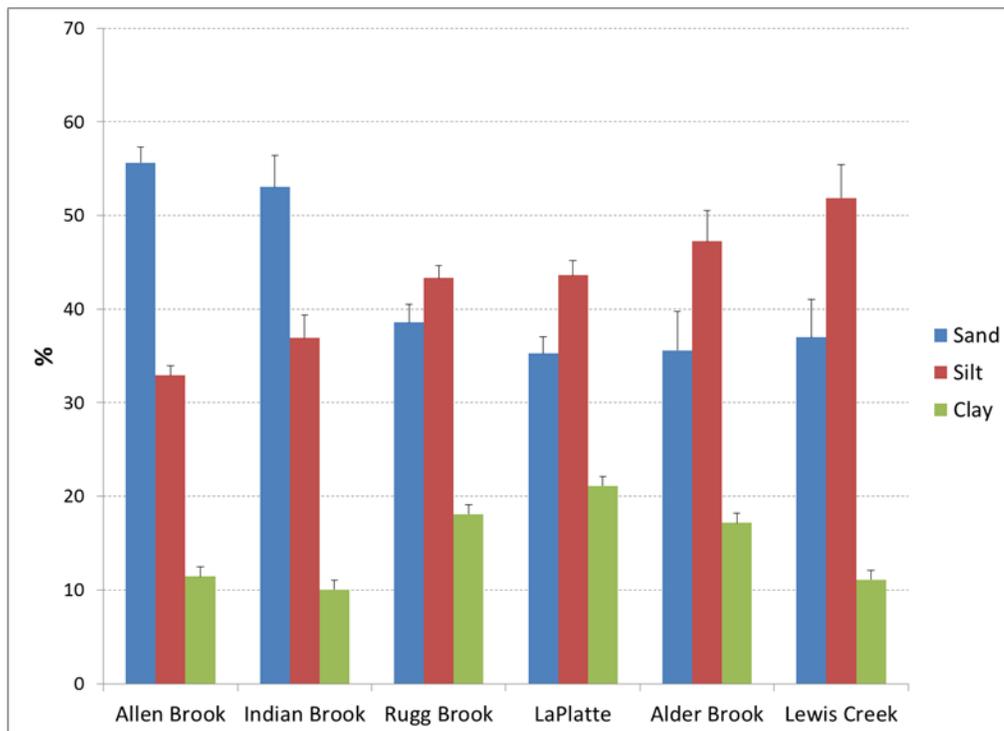


Figure 4. Soil texture (sand, silt and clay) averaged by watershed. Error bars represent the standard error of the means.

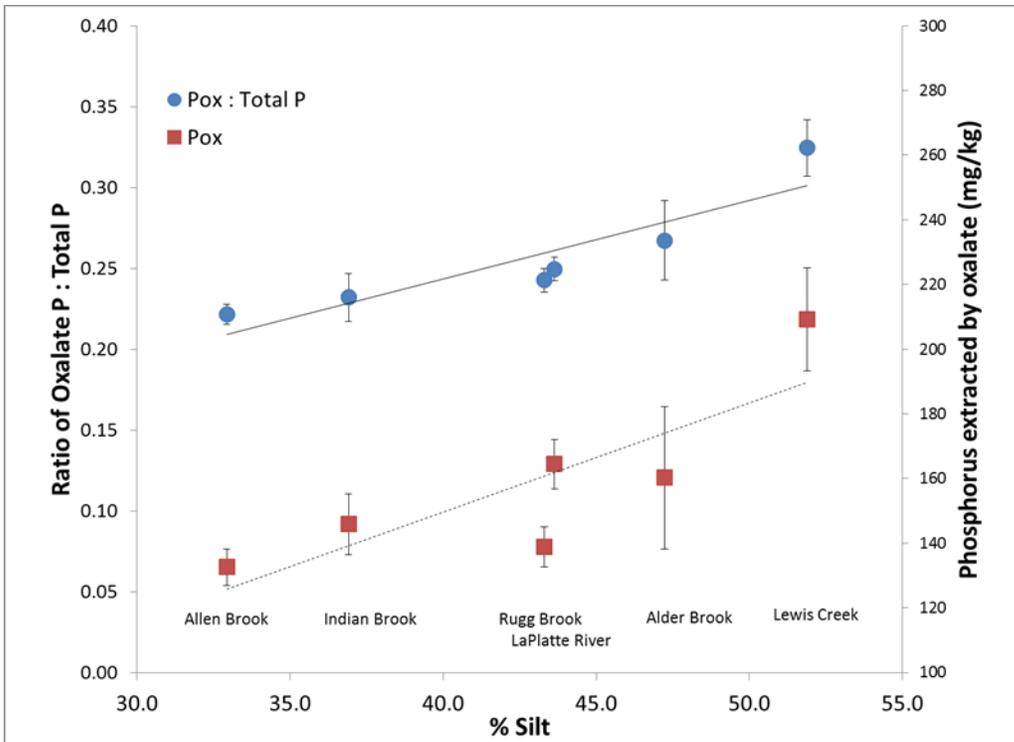


Figure 5. Watershed averages of P-ox and P-ox:Total P vs % silt. Error bars represent the standard error of the means.

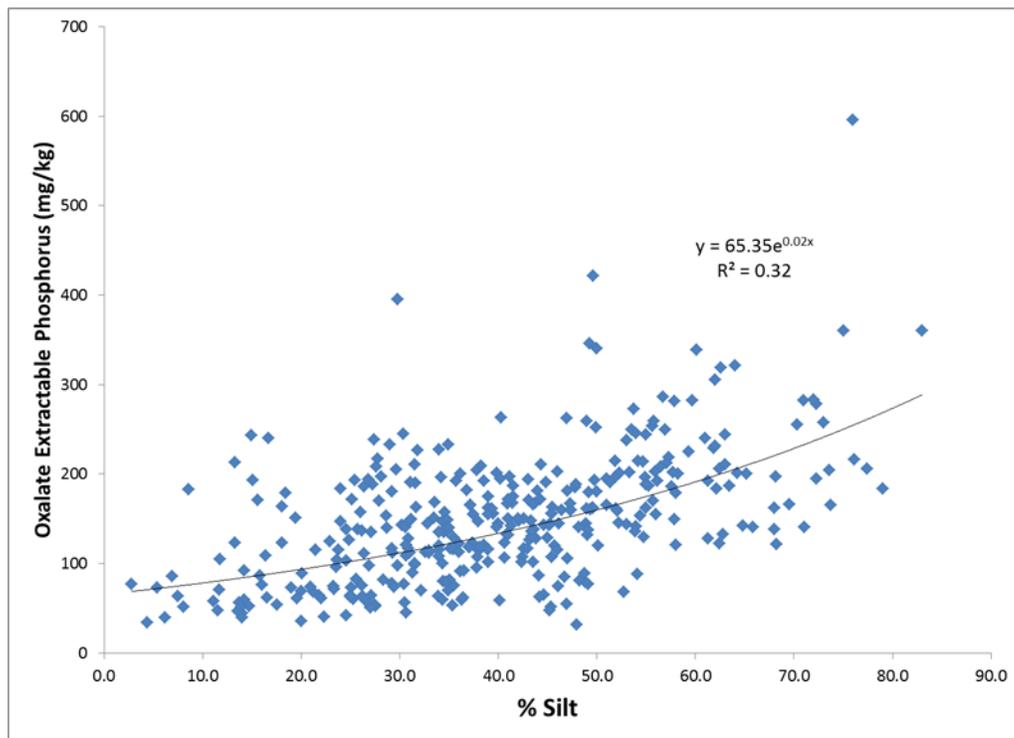


Figure 6. Oxalate extractable P vs % silt for all samples.

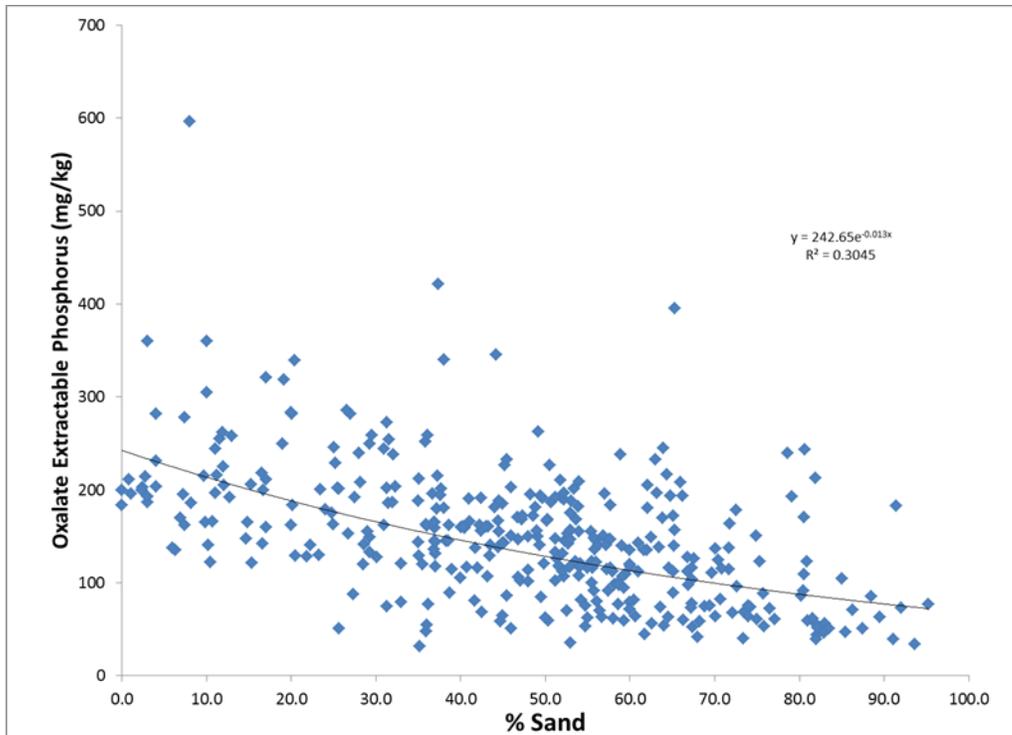


Figure 7. Oxalate extractable P vs % sand for all samples.

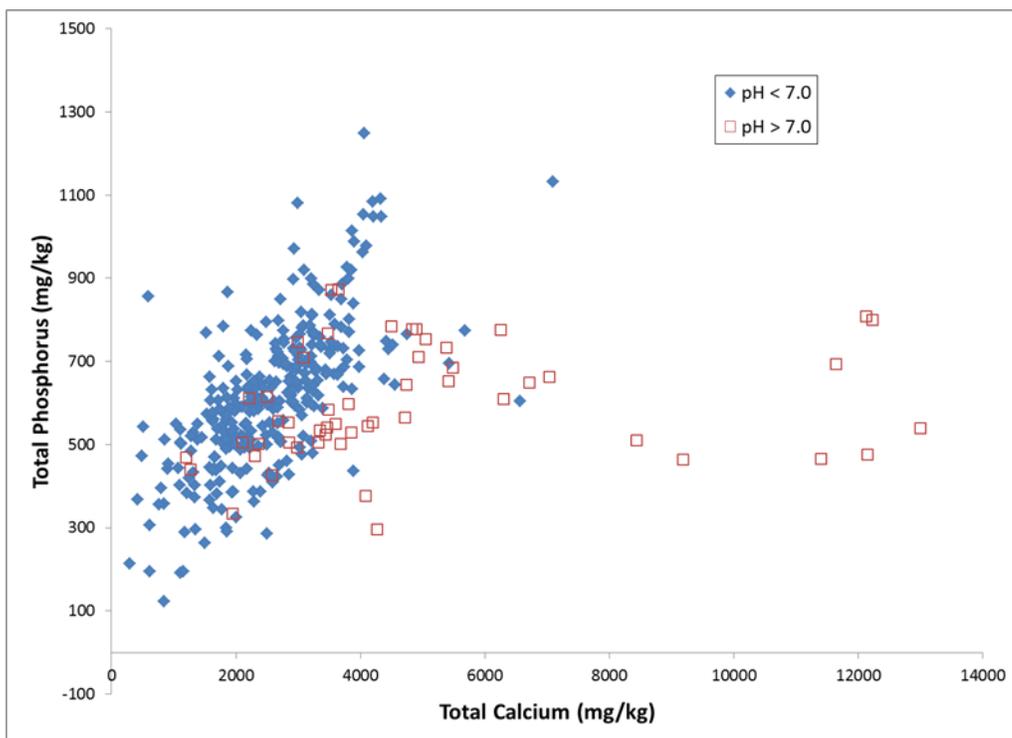


Figure 8. Total Ca vs. total P for all samples, separated by pH.

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Publications:

Ishee, E.I. 2011. Characterizing phosphorus in eroding streambank soils in Chittenden County, Vermont. M.S. Thesis, Dept. Plant & Soil Science, Univ. Vermont, 90 pp.

Young, E.O., D.S. Ross, C. Alves, and T. Villars. 2012. Influence of soil series on phosphorus forms and availability at two riparian sites in the Lake Champlain Basin (Vermont). *J. Soil Water Conserv.* 67:1-7.

Presentations:

Ishee, E.R. and D.S. Ross. 2011. Characterizing phosphorus in eroding streambank soils in Chittenden County, Vermont. H43F-1279, AGU Annual Meeting, San Francisco, CA, December.

Ishee, E. and D. Ross. 2011. Contribution of streambank erosion as a non-point source of phosphorus to Lake Champlain. Annual meeting of the Soil Science Society of America, San Antonio, TX, October.

Use of Acoustic Doppler Current Profiler data to estimate sediment and total phosphorus loads to Lake Champlain from the Rock River

Basic Information

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Principal Investigators:	Breck Bowden, James Shanley

Publications

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Project Annual Report

Title: Use of Acoustic Doppler Current Profiler data to estimate sediment and total phosphorus loads to Lake Champlain from the Rock River

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Abstract:

Reduction of phosphorus loading to Lake Champlain is a major management objective for the state of Vermont, so monitoring phosphorus transport to the lake is an essential task. For nearly twenty years this task has been accomplished by standard methods to estimate solute loads, based on manual sampling at discrete and relatively infrequent intervals. Most of the phosphorus is transported on sediments and so total suspended sediment (TSS) concentrations are an excellent surrogate of total phosphorus transport. TSS can be measured relatively easily and continuously with acoustic Doppler current profilers (ADCPs). This presents the opportunity to measure a surrogate of total phosphorus (TP) concentration at a finer scale of temporal resolution than has ever been practicable before. The objective of this project was to explore whether a new ADCP that has recently been installed on the Rock River near Highgate, Vermont could be calibrated to estimate TSS and thus TP. The instrument was installed primarily to measure discharge, but the data can be used for the purposes of this project if calibrated against manual TSS measurements. This one-year project was a feasibility analysis to test whether there was reasonable evidence that the ADCP could be used for this purpose. Initial data are encouraging and so the Vermont Department of Environmental Conservation has provided additional support to refine the initial results we report here. We expect that if the estimates of total sediment load calculated with the ADCP data prove to be useful then we will be able to use the continuous ADCP data to provide better estimates of suspended sediment and total phosphorus load than can be obtained with the current long-term monitoring program protocol which relies on intermittent, manual sampling.

Statement of regional or state water problem

Excessive phosphorus loading is widely viewed as one of the key water resource management issues affecting Lake Champlain, which defines the entire western boarder of Vermont. Phosphorus loading generally contributes to eutrophication of the lake and specifically may be responsible for algal blooms, especially of cyanobacteria that may at times create toxins that are of concern for human health. Excessive phosphorus loading from agricultural and urban land

uses regularly tops the list of priority environmental concerns expressed by regional managers, policy makers, NGO's, researchers, and residents. Transport of phosphorus is very tightly associated with transport of sediment; the relationship between total phosphorus and suspended sediment is linear and highly significant. Thus, quantification of sediment loading can be used as a surrogate for quantification of phosphorus loading. This is important because sediment can be measured relatively easily (gravimetrically or acoustically) while total phosphorus requires manual digestion followed by spectrophotometric analysis. These latter processes are time consuming, expensive, and require the use of materials that are dangerous to use and dispose.

The long-term water quality monitoring program for the Lake Champlain Basin is operated by the state of Vermont with support from the Lake Champlain Basin Program and in collaboration with the USGS. This program bases its estimates of phosphorus loading on intermittent sampling followed by manual analysis of total phosphorus as described above. Under the best of circumstances it is difficult to deploy sampling personnel during rapidly developing events. It is especially difficult when these events occur at night and over weekends and holidays. Equally important, due to the low frequency of sampling it is not clear how non-linear dynamics such as hysteresis during events or season-specific sediment generation processes (e.g. ice floes, farming practices) affect the total loading of sediment and thus the loading of phosphorus.

Acoustic Doppler Current Profiling (ADCP) is widely used to measure water velocity and discharge and more recently has been used to measure suspended as well as bed-load transport of sediment. ADCP has the benefits of being non-destructive, autonomous, continuous, and relatively robust. Therefore, it is a potentially useful method to estimate sediment transport as well as discharge. However, the use of ADCP to estimate sediment load is not entirely proven and is likely to be site-specific.

The Rock River is an especially useful focus for this study because it typifies the intensive agricultural landscape that is known to contribute significant TP loading to Lake Champlain. Rock River at the location of the ADCP gage is a small and hydrologically flashy stream, the type that poses the greatest challenge to characterize with traditional sampling techniques. It is not unusual for storm events to be over before personnel arrive to collect samples. Continuous monitoring in these circumstances is particularly valuable.

Finally, given the political and economic importance in Vermont placed on accurate estimates of phosphorus loading to Lake Champlain for the purposes of developing estimates of total maximum daily loads (TMDLs) it is imperative that we obtain accurate and defensible estimates of the TP loads. Related to this effort, the Lake Champlain Basin Program (LCBP) is supporting a Targeted Watershed Implementation Initiative in the Rock River Watershed. This project will provide concentrated funding and technical support for approximately 16 farms to implement best management practices within the sub-watershed of the Rock River monitored by the ADCP. The Basin Program has issued a contract for \$100,000 for the first phase of this work to develop farm-specific action plans and it is anticipated that a follow-on project will be funded at a substantially higher amount for the administration of financial incentives and disbursements to participating farmers. One purpose of the Targeted Watershed Implementation Initiative is to demonstrate that when agricultural producers implement a suite of priority conservation practices in a short period of time, measurable progress in water quality can be achieved. Thus, water

quality monitoring at this site is essential to achieve the purpose of the Targeted Watershed Implementation Initiative. This proposed project has the potential to provide more refined and quantitative estimates of changes in sediment and TP loading in response to the future implementation of the management practices.

The objective of this project was to calibrate the relationship between total suspended sediment (TSS) concentrations and estimates of particle transport based on data collected by Acoustic Doppler Current Profiling (ADCP). As a part of this effort we also began to explore the relationship between discharge and estimated particle transport based on the ADCP data, to determine whether there were inter-storm dynamics that could be important in assessing TSS and ultimately TP loads. In a separate but directly related project that has been funded by the VTDEC and that is currently under way, we will compare estimates of total sediment and total phosphorus loading in the Rock River based on the manual sampling method currently being used by the VTDEC and a new method based on continuous measurement of TSS by ADCP. In this follow-up project we will examine the fine-scale behavior of sediment loading during individual storm events to infer sources (from timing) and processes controlling sediment and phosphorus delivery to the Rock River. Our ultimate goal is to compare TP load estimates from the continuous proxy record to those from conventional estimates of TP load based on interpolation between intermittent manual samples to determine whether the conventional method introduces bias in estimates of event loads of sediment and TP. Thus, the project supported with USGS 103b funds and reported here has provided critical feasibility information for the project that is currently under way with VTDEC funding.

Methods, procedures, and facilities

The acoustic method is relatively new automated stream discharge measurement technique whereby a high-frequency sound wave is propagated through the water column and the Doppler shift in the signal frequency backscattered from particles in the water is used to quantify the particles' velocity, which is assumed to be equal to the water velocity. These velocities are then summed over the cross-section to yield discharge. ADCP also measures the amount of backscatter and attenuation in the sound wave. These properties are strongly affected by the quantity, composition, and size distribution of the suspended sediment in the stream. Backscatter is affected primarily by the sand fraction, while attenuation is affected primarily by clay and silt. Recent research has validated that these measurements, when calibrated to a specific stream, can yield robust estimates of the sand and silt/clay fractions of total suspended sediment (TSS) concentration at the time step of the measurement (Gray and Gartner, 2009; Wall et al., 2006), in this case every 15 minutes. Total phosphorus (TP), in turn, is closely linked to TSS. Thus, the ADCP installation will enable us to measure TP transport and thus estimate TP loads. In addition, the high-frequency record will allow us to identify conditions and infer processes controlling TP export by examining the detailed record of TSS and total phosphorus shifts over the hydrograph.

In fall 2010, USGS established a stream gage on the Rock River in Highgate, Vermont (<http://waterdata.usgs.gov/nwis/uv?04294140>). Discharge at the gage is measured using a Sontek SL-3000 Acoustic Doppler Current Profiler (ADCP). It is currently recording acoustic backscatter and velocity in 5 bins of about 1 m per bin, across the river at the gage site. This data

is being served in real time to the USGS website. The 5 bins appear to be adequate to estimate attenuation based on a preliminary analysis of data from a similar instrument and installation on the Barton River. The SL-3000 has the capability of dividing the cross-section into 10 bins as well but we would not be able to serve this data in real-time given the current installation.

We programed the ADCP to measure and store the average backscatter and attenuation over the entire acoustical beam length, as well as a subset of backscatter values for at least 5 segments (bins) along the beam length. Post-processing of the ADCP signal includes compensation for physical characteristics like temperature as well as loss in signal strength with distance from the transducers due to beam spreading, absorption by the water, and attenuation by the sediment. Acoustic backscatter (ABS) is strongly controlled by the sand fraction of the suspended sediment whereas beam attenuation is strongly controlled by the clay and silt fractions. In most cases, one can quantify these two components of the TSS (and total TSS, by addition) using a single acoustical instrument at a single frequency. These relations were assessed from discrete samples over a range of TSS concentrations, by targeting storms and snowmelt when TSS concentrations are most likely to be high and changing.

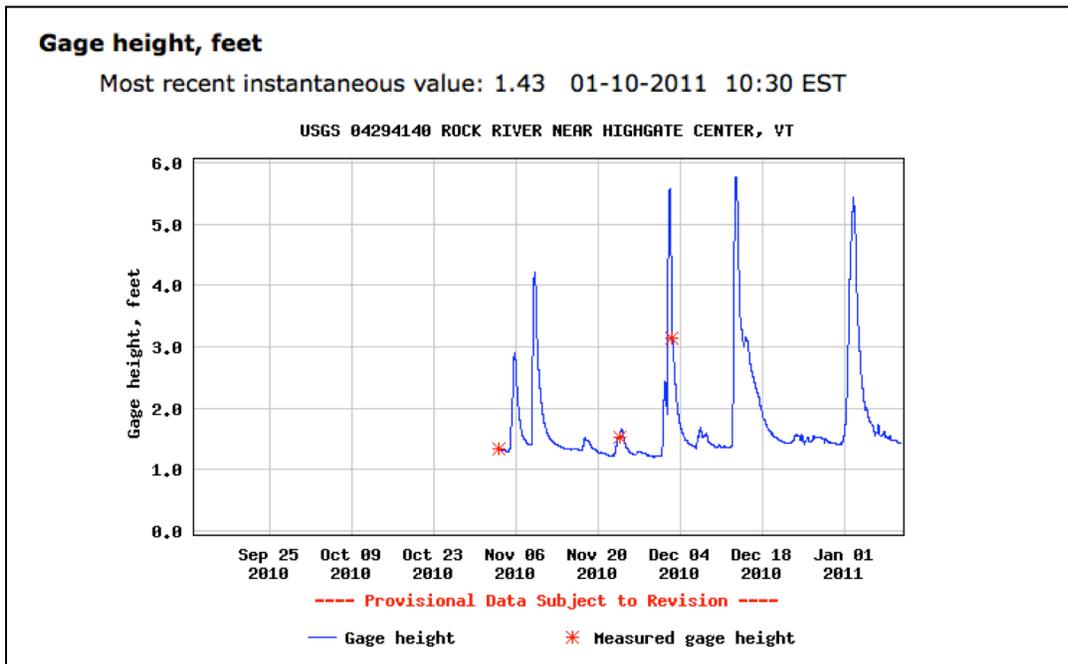


Figure 1. Stage record at Rock River from start-up in early November 2010 through early January 2011. Red stars indicate manual measurements of stage for comparison.

The relatively small Rock River watershed has flashy hydrology (Figure 1), so a stage-activated automatic water sampler was deployed to ensure that large storms are not missed. For grab samples, standard USGS protocols for sampling stream water were followed—the equal-width increment method if stream velocity was at least the 1.5 ft/sec minimum required for isokinetic sampling, or fewer integrated verticals if stream velocity was less than 1.5 ft/sec. Integrated samples were compared to simple grab samples at the centroid of flow to evaluate the validity of the automated sampling, which was constrained to a fixed intake. We expected that the Rock

River is sufficiently well-mixed that we should find little difference between the two sampling methods.

The water samples for suspended sediment analysis and ADCP data were analyzed to determine if a relationship existed that would allow prediction of TSS and ultimately TP loading. Data was used from the time of ADCP installation, November 3, 2010 until January 25, 2012. Water samples were collected during that time period by the Friends of Northern Lake Champlain volunteer group as well as samples that were collected using an autosampler that was installed by USGS in October 2011. The Friends of Northern Lake Champlain collected samples on a regular basis throughout the year, with a goal to collect at least once during storm event as well as once per week during baseflow. The autosampler was programmed to collect samples on timed intervals during storm events and to baseflow samples during the period noted.

Water samples were analyzed for TP and TSS. A small number of suspended sediment samples were saved for a full particle-size analysis later. This information on grain size distribution is not critical to the project reported here, but will help fine-tune the empirical relations and will help interpret seasonal deviations from the empirical relations should they occur. Analysis of TSS was done at the Rubenstein Ecosystem Science Lab at the University of Vermont. All TP samples were analyzed by the Vermont Environmental Laboratory in Waterbury VT as an in-kind contribution to the study. All measured parameters and empirically-derived quantities (TSS, TP) will be stored in the National Water Information System (NWIS) and displayed on the USGS real-time website.

Findings

The relationship between discharge and log total suspended sediment concentration (log TSS) was variable ($r^2 = 0.41$) and was driven by a few discharge events that had high concentrations (Figure 2). The nature of this variation in TSS concentrations was expected.

The relationship of average signal-to-noise ratio (SNR) and log TSS was significant ($p < 0.001$, $r^2 = 0.26$, Figure 3). The relationship between attenuation corrected SNR and log(TSS) was also significant, though the relationship had less explanatory power ($p < 0.001$, $r^2 = 0.12$, Figure 4)). Theoretically an increase in suspended sediment should cause the signal-to-noise ratio to increase. Normally, the SNR data need to be corrected for losses due to water and sediment attenuation, based on water temperature and distance from the face of the ADCP. However, we found that after these corrections the strength of the relationship between SNR and TSS decreased rather than increased and so in the calculations reported here we have used the uncorrected SNR values. We used SNR rather than acoustic backscatter because the composition of the sediment in the Rock River is silt and clay rather than coarser particles for which acoustic backscatter would be more appropriate (Wall et al. 2006).

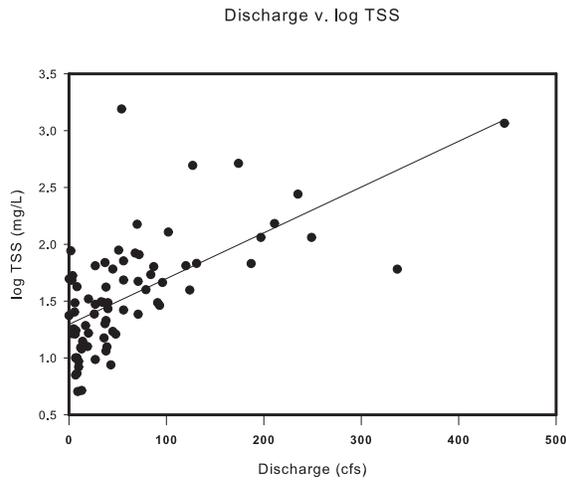


Figure 2. Discharge (cfs) v. log TSS (mg/L) for samples collected 5 Nov 2010 to 20 Jan 2011. Linear regression equation is $y=0.00x+1.29$ with an r^2 of 0.41

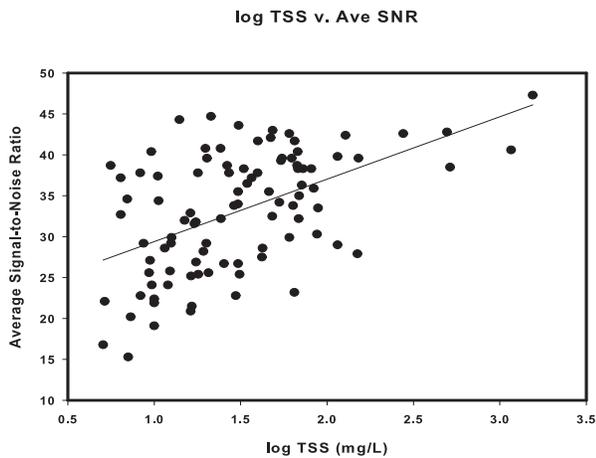


Figure 3. Log TSS versus average SNR values for samples collected 5 Nov 10-20 Jan 11. Linear regression equation is $y=7.62x+21.72$ with an r^2 of 0.26 ($p<0.001$).

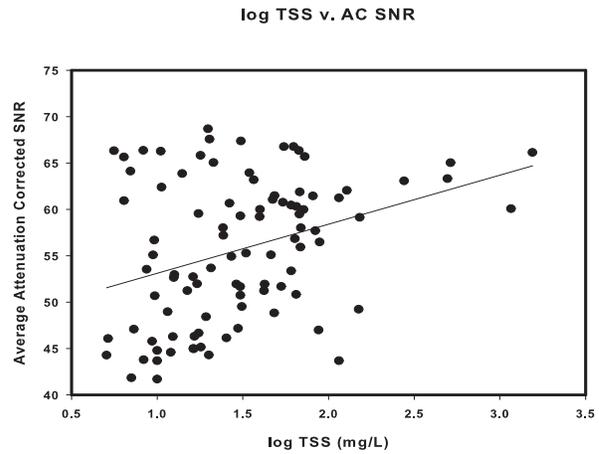


Figure 4. Log TSS versus average attenuation corrected SNR values for samples collected 5 Nov 10-20 Jan 11. Linear regression equation is $y=5.29x + 47.84$ with an r^2 of 0.12 ($p<0.001$).

There was not a strong relationship between the attenuation corrected signal-to-noise ratio of the ADCP at the time that TSS samples were taken and the amount of TSS measured in the water. However, the ADCP signal typically contained a considerable amount of structure that is not captured in the manual TSS sampling. Hysteresis in the ADCP data made it difficult to interpret the relationship with TSS because the same discharge value could have very different signal-to-noise ratio values depending on previous conditions, such as storms.

To deal with hysteresis, it was necessary to examine the ADCP data based on individual storm events rather than as a whole. Some patterns emerge as seen in the figure for a storm December 5-9, 2011 (Figure 5). In this storm TSS followed the SNR closely, including an unexpected peak in SNR near the end of the event (point D) were sampling also identified a high concentration of

TSS. At this point discharge was continuing to decrease in the falling limb of the hydrograph. The correspondence of the high TSS sample with the high SNR data suggest that other fine structure in the SNR signal might relate to patterns in TSS concentration. If this is the case, then the current protocol of intermittent, manual sampling likely misses much of this fine structure.

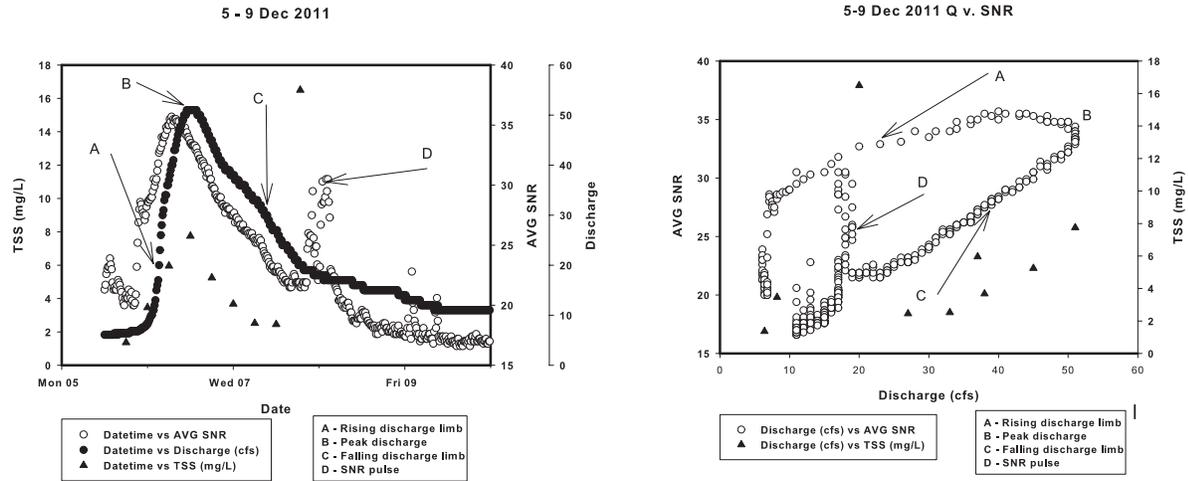


Figure 5. Left: TSS, average signal to noise ratio (SNR) and discharge for an event on 5-9 December 2011. Specific points the hydrograph are noted by letters. In particular note the unexpected peak in average SNR at the point marked D. Right: The relationship between average SNR and discharge with points in the hydrograph as noted on the panel on the left. Note the strong hysteresis in the average SNR data.

A storm on 15-18 May 2011 (Figure 6) illustrates the complexity of the relationship between average SNR, TSS, and discharge. This storm had three discharge peaks with each succeeding peak larger than the previous. However, the average SNR was greater at the beginning of the

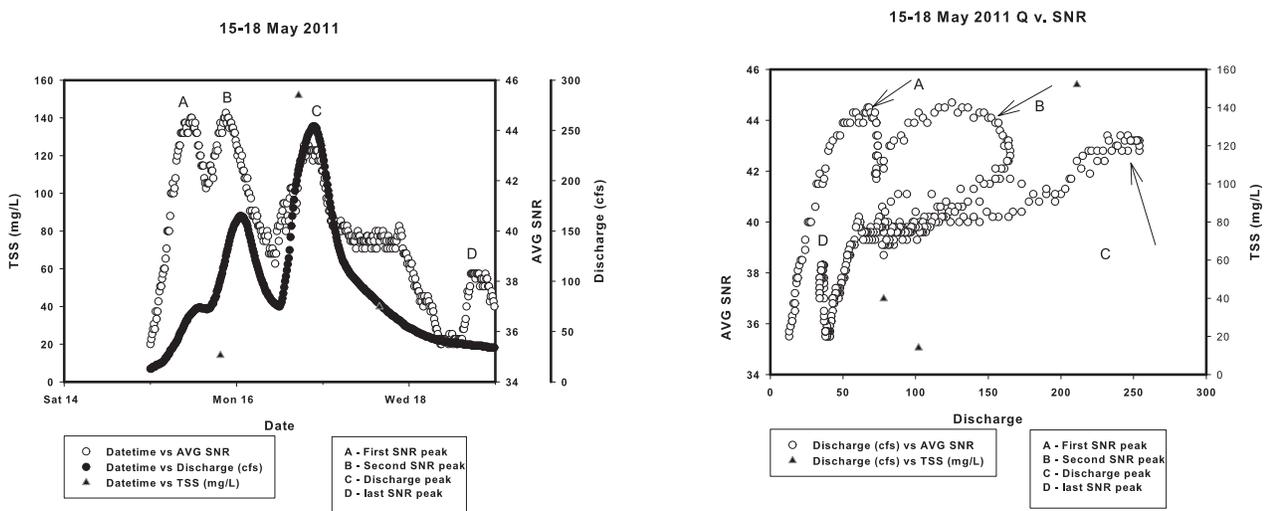


Figure 6. Left: Concentrations of TSS, average SNR, and discharge for a storm event on 15-18 May 2011. This storm has three distinct peaks in discharge that related to three distinct peaks in average SNR, identified by the letters A-D. Right: Average SNR versus discharge for the same storm. Note the unique hysteresis signatures of each of the three sub-peaks in discharge and associated SNR.

storm before the second discharge peak. The SNR also decreased at a different rate than the discharge at the end of the storm, with a small pulse in SNR after discharge had returned to baseflow. Unfortunately, only three TSS samples were taken during this event and so relationship between SNR and TSS is not clear. The relationship between average SNR and discharge is complex, with three distinct hysteresis loops related to the three discharge peaks during the event.

Discussion

The use of optical and acoustical proxy measurements for TSS has blossomed in recent years (Christensen et al., 2000; Kostaschuk et al., 2005; Merkelbach, 2006; Elci et al., 2009; Gray et al., 2010; Landers, 2010; Simmons et al. 2010). Acoustical measurements have some advantages over optical methods in that they measure over a broad swath of the water column rather than a single point, they are minimally affected by biofouling, and they enable TSS determination with the same instrument used to measure stream discharge (Gray and Gartner, 2009). Most previous studies that investigated acoustical proxy measurements were either strictly methodological (Wall et al., 2006), or sited on large streams with a narrow focus on sediment concentration and composition (Topping et al., 2007; Topping et al., 2010; Wall et al., 2008). Our study focusses on a relatively small agricultural stream. Previous studies have demonstrated the effectiveness of optical turbidity measurements as a proxy for phosphorus in these types of streams (Grayson et al. 1996). But to our knowledge, acoustical methods of TSS determination have not been extended to phosphorous.

The data that we have collected to date provide two important pieces of information. First, it is clear that the relationship between average SNR and discharge is complex. If, as we suspect the average SNR signal is related to TSS (and thus to TP), then the relationship between TSS (and TP) with discharge must be equally complex. We are encouraged to think this is the case by the results from the storm event of 5-9 Dec 2011 (Figure 5) where by chance we obtained a water sample with a high concentration of TSS at the same time that a peak in the average SNR ratio occurred. It is not clear why this peak in average SNR occurred. One intriguing possibility is that a bank failure event upstream instantaneously added sediment to the same discharge.

If it is the case that the average SNR signals are indeed related to TSS concentrations, then our ADCP data suggest that the dynamics of TSS – and by extension TP – during storm events are considerably more complex than we have imagined previously. Clearly, a single grab sample of water for analysis of TSS would miss most of this complexity. It is highly unlikely that manual or even automated sampling could be devised to capture this complexity and so some other means like the ADCP data may be needed.

It remains to be established, however, that the ADCP signal is reliably correlated with changing TSS during storm events. To establish this relationship it is necessary to sample with much higher frequency during a number of different storm events. That is the subject of our current research supported by the VTDEC.

Training opportunities

This project supported three undergraduate students: Genna Waldvogel, Kelsey McAuliff, and Evelyn Boardman. Their involvement on this project gave them experience and training in stream processes and laboratory research as well as an understanding of an emerging new technology (ADCP for sediment analyses). The project also supported a technician, Elissa Schuett, to attend a workshop sponsored by the USGS and the Consortium of Universities for the Advancement of Hydrologic Research, Inc. (CUAHSI) on the ADCP technology and data analysis.

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Advanced and Integrative Model of Phosphorus loading from High Runoff Events

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Publications

There are no publications.

Advanced and Integrative Model of Phosphorus loading from High Runoff Events

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Abstract

Lake Champlain Basin (LCB) non-point pollution control factors heavily into the environmental health of the lake, because excessive nutrient loading has resulted in a number of harmful algal blooms. Agricultural activity within the watershed is largely responsible for the phosphorus (P) and nitrogen (N) pollution, which originates in fields within the LCB. Critical source areas (CSAs) have been defined as nonpoint phosphorous sources that contribute disproportionately higher amounts of P to the watershed (Ghebremichael, 2010). The high P loss stemming from CSAs has been attributed to unusually high P concentration within a CSA resulting from soil types and management practices (Pote et al., 1996, 1999; Sharpley, 1995; Sharpley et al., 1996), and areas susceptible to high volumes of runoff and erosion (Pionke et al., 1997; Gburek and Sharpley, 1998). P source areas are locally controlled, but transport in the watershed depends on hydrological processes. In the LCB, studies have looked at P transport within the watershed using the curve-number based SWAT model (e.g. Gebremichael 2010), but process-based models have not been applied with much success. Since sediment-bound P transport plays a major role in nutrient transport, and because runoff generation processes are variable in time and space in a watershed, a process-based model representing sediment mobilization from individual fields may be better suited to simulate the changes expected from alterations of management of those fields that are small components of subwatersheds. Moreover, because much sediment transport occurs during discrete high precipitation events, a process-based model should be better suited to simulate the impacts of changes in the precipitation regime expected from climatic change on LCB nutrient loading, as well as anomalously high loading stemming from spring flush events and other extreme hydrological events. In synergy with the recent Vermont EPSCoR grant that aims to model regional adaptation to climate change within the LCB, *we propose to continue to build process-based models that can help determine CSAs, both present and future, from hydrological characteristics including intrafield topographic variability. This will allow the simulation of runoff and nutrient response to future precipitation regimes that differ from the previously-observed rainfall regime on which much watershed management is based.*

Statement Of Regional Or State Water Problem

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Multiple studies have focused on the importance of CSA identification and remediation to mitigate nonpoint P loss (e.g. Pionke et al., 1997; McDowell et al., 2001; Weld et al., 2001). Opportunities for Action generated by the Lake Champlain Steering Committee, November 2010, addresses the importance of CSA identification through acknowledgment of current projects and future research:

- ID (4.6.1) - Continue the IJC* project, *Identification of Critical Source Areas of Phosphorus Pollution in the Missisquoi Bay Watershed* (Vermont, Québec, USDA-NRCS, LCMB)
- ID (4.6.7) - Seek funding sources to support analysis of Critical Source Areas in the New York portion of the South Lake watershed, similar to the Missisquoi Bay initiative funded by the IJC.
- ID (4.9.2) Explore management tools that can be used to identify critical source areas and effective interventions.

*International Joint Commission

Phosphorous sources and transport factors that drive disproportionate P contributions to the watershed lead CSA identification strategies to combine complex site specific variability of topography, hydrology, soil and management practices (Ghebremichael, 2010). Sediment transport from CSAs to the watershed can act as a conduit for P migration. Early approaches to estimating soil erodibility at concentrated flows were made using an erodibility factor generated from the Universal Soil Loss Equation (USLE) which describes the combined response to both sheet and rill erosion as an approximation (Knapen, 2007). The suitability of the USLE 'K' factor was rejected (Line and Meyer, 1989; Laflen et al., 1991; Zhu et al., 1995) due to the consideration that soil erosion is a process-specific concept and that intrinsically different processes are responsible for concentrated flow erosion compared to combined sheet and rill erosion and erodibility (Bryan, 2000; Sheridan et al., 2000a,b). Two major tools have been developed to address the need for watershed and subwatershed modeling: the Soil and Water Assessment Tool (SWAT) and the Water Erosion Prediction Project (WEPP). SWAT, generated by the U.S. Department of Agriculture's, Agricultural Research Service, was developed to predict the impact of land management practices on water, sediment and agricultural chemical yields in large complex watersheds with varying soils, land use and management conditions over long periods (Neitsch et al., 2005). WEPP, developed by the USDA-ARS National Soil Erosion Research laboratory, is a process-based continuous simulation program that predicts sediment yields and deposition from overland flow on hill slopes, sediment yield and deposition from concentrated flow in small channels, and sediment deposition in impoundments. WEPP computes spatial and temporal distributions of sediment yield and deposition, and provides

explicit estimates of when and where in a watershed or on a hill slope erosion occurs so that conservation measures can be selected to most effectively control soil erosion (Flanagan and Nearing, 1995). Comparisons of SWAT and WEPP for watershed hydrology and erosion prediction have been performed (Shen et al., 2009; Boll et al., 2011). The outcomes have indicated that SWAT is useful for large scale watershed assessment due to the convention that areas with the same soil type and land use form a Hydrologic Response Unit (HRU), a basic computational unit assumed to be homogeneous in hydrologic response to land cover change, and that WEPP is an appropriate tool for medium to small watersheds. SWAT is not an appropriate tool for smaller watersheds and field specific use because of the soil module, Modified Universal Soil Loss Equation (MUSLE) which is an empirical equation and not appropriate to be used where detailed physical parameters are necessary to describe erosion and sediment yields mechanistically for determination of change impacts (Williams et al., 1985; Shen et al., 2009).

While generation of agricultural runoff, erosion and sediment yields are an important function of CSA identification, phosphorous generation from soil P and sediment transport need to be quantified at a field scale to validate modeling outputs. It is our intention to use the WEPP model to identify critical source areas generating disproportionate P inputs at an individual agricultural field scale and to quantify total P generation at a field scale. A study site, of 3 agricultural fields, has been acquired through the generous support of Tim Camisa, Vermont Organics Reclamation, located in Georgia, Vermont. A mass balance of the site water budget has been performed for the summer and fall through the installation of impoundments at the field drainages, 3 weirs and 1 flume. Phosphorous quantification will be performed at the weirs and flume to indicate total P leaving the site. Identification of potential CSAs will take place over a three-step process;

- The WEPP model will be parameterized specific to the site for management practices, soil classification, climate generation, and slope.
- Model output will indicate location of maximum sediment detachment and deposition specific to field slope inputs.
- At the point of maximum detachment specific to field slope, Gerlach sediment samplers will be installed to quantify sediment mass and P concentration.

Maximum detachment locations will be identified for multiple percent slope elevations and sediment samples will be collected for 24-hour rain event periods.

Statement of Benefits

Because phosphorus is often associated with suspended solids (Gray and Glysson, 2002), erosion in agricultural watersheds can be a source of non-point phosphorous pollution that can adversely impact receiving water bodies. Critical source areas of phosphorus will be associated with runoff generation in a field as well as the potential mobilization of P at that point. Runoff generation in turn is related to degree of saturation of the soil as well as the topography of the field. The seasonal legislative ban on manure application in Vermont during winter periods when the soil is frozen and impermeable has addressed the recognized problem of high P loading during winter periods of low soil permeability. However, high phosphorus loading continues to be a problem in the Lake Champlain watershed, despite regulatory efforts. This may be partially due to spring-like conditions during the summer or late spring (post April 1) when periodic high precipitation events saturate soils, runoff is high, and manure spreading is not prohibited.

Topography can influence the amount of runoff from a field in addition to soil moisture. Higher angled slopes will produce more runoff than lower-angled slopes, and the effects of topography can thus influence the distribution of critical source areas. Topographic variability within a field may play a significant role in determining the phosphorus mobilization from that field. Topographically lower areas

where runoff water accumulates during spring-like conditions will contain deeper, faster flowing water whose greater scouring potential is expected to mobilize P more effectively.

We hypothesized that an understanding of the hydrological impacts of both topographic variability and the occurrence of soil saturation after the end of the manure spreading ban in Vermont (April 1) will help identify critical source areas of P pollution in the Lake Champlain Watershed. Consequently, a mechanistic model that simulates these potentially important processes, distributed in space, is of value as concerns about Lake Champlain water quality increase. Page et al. (2004) investigated a TOPMODEL-style distributed topographic index as a predictor for point P concentration, but the correlation was not good due to confounding factors such as uneven distribution of manure within the field. In this study, we aimed to understand the integrated impacts of topographic variability over an entire agricultural plot, during times when runoff is high. We measured point P concentrations throughout the field to characterize the spatial variability within the field. Our modeling approach allowed spatially distributed estimates of mobilized P concentrations based on such measurements, which differs from the topographic index approach employed by Page et al. (2004). They assumed that topographically induced wetness can be used as a proxy for mobilized P. Our modeling results explicitly simulate accumulated P at each location. These results were then validated with field sampling of suspended P across the plot during precipitation events and at the outlet.

To simulate the non-linear response of agricultural watershed P mobilization to changes in land use, freezing patterns, climate patterns, or other perturbations, detailed process-based models are preferred over empirical models and lumped-parameter models, despite distributed process-based models' needs for many distributed parameters. Mechanistic, process-based models are able to simulate the detailed causative pathways between perturbations and system response. The effects of individual variables can be teased apart if all known processes are simulated, and so the potential impacts of changes in timing of rainfall vs. spring melting of the ground surface can be accurately modeled. This detailed representation of the nonlinearities within the physics-based modeling of processes and the mechanistic insight that it allows is a primary intellectual merit of this research. This understanding of P mobilization under variable conditions during spring flush events can then be extended to other parts of the Lake Champlain watershed.

Project Objectives

The overall objective of the study is to develop a new model to simulate the suspended phosphorus loading from non-point sources in frozen or saturated fields during the high runoff events.

Objective 1: Watershed modeling of P transport. We developed a detailed, spatially explicit model to simulate the overland flow over the frozen, thawing or otherwise saturated field. This entailed simulations of snowmelt, precipitation and sediment transport to predict suspended P at the catchment outlet. One purpose of the model will be to study the role of intrafield topographic variability in determining sediment mobilization and potential role in CSA determination. We hypothesized that topographic variability can have a significant impact on runoff response to precipitation events. WEPP model output will be compared to SWAT model output to determine the efficacy of such a detailed process-based model for representing mechanisms of CSAs. Such a modeling approach is very detailed and highly parameterized, but also allows the detailed study of the mechanisms involved in sediment mobilization. The model is capable of representing spring flush events, which result from rainfall and snowmelt on saturated, recently thawed bare soil and often mobilize large amounts of P from agricultural fields.

Objective 2: Field studies of P mobilization. To parameterize the model we closely monitored a carefully chosen field site. As of December 2011, this field site has been in operation for eight months

(Georgia, Vermont). We set up automated monitoring at the catchment outlet and took repeated surveys of the catchment characteristics after April 1 and will continue through the summer.

Methods, Procedures, Statistics And Facilities

Objective 1: Model development.

We developed a highly detailed model that can accurately predict the dissolved and suspended phosphorus from a field undergoing high runoff events either during frozen conditions or saturated conditions. Topographic variability is explicitly represented to assess the role of topography as a determinant of critical source areas in the Lake Champlain Watershed. To this end, we used the Water Erosion Prediction Project (WEPP) model (Laflen et al., 1991; NSERL, 1995, Flanagan and Nearing, 1995). The WEPP model is a physics-based model designed to operate at the field scale spatially, and daily scales temporally. It was written to simulate the essential processes governing water erosion at field scales, however watershed-scale processes are supported as well. WEPP also simulates other hydrologic processes such as redistribution of water in the soil profile (negligible in frozen soils), evaporation and transpiration, freezing and thawing, and agricultural manipulation of the soil surface and vegetation. Due to its distributed and physics-based nature, the model is often criticized for being overly data-intensive, and the mismatch between the scale of parameter measurements and the scale of simulation often restricts the model to intensively studied research applications (Merritt et al., 2003). However, it is an appropriate model for our research objectives, because of the planned spatial resolution of field measurements including P concentrations and elevation, as well as the desired functionality of the model. For the goal of modeling suspended P attached to particulates, the use of WEPP is an improvement over the popular but empirical-based Universal Soil Loss Equation (USLE) for this site, because it allows continuous simulation of erosion and deposition along a hillslope to be simulated. This allows more accurate simulation of sediment load at the watershed outlet, provided the input data is sufficiently detailed. In addition, erosion and associated runoff are predicted for individual precipitation events. This capability allows detailed temporal analysis of individual hydrographs and sedigraphs.

Modeled precipitation is in the form of daily precipitation depth, duration and intensity, however field-measured meteorological data can also be used as model forcing. In this way, field-measured meteorological variables will be used to calibrate and validate the model for several events, and modeled climate variables can also be generated by WEPP to explore system response to various scenarios. Soil freezing and thawing is simulated on an hourly scale. Both sheet and rill flow are simulated, but gullies and channel erosion are not. In the subsurface, the model simulates infiltration, lateral flow, resurfacing and tile drainage, and at the surface both disturbances by tillage and natural processes are included (Fox et al., 2001).

Model meteorological input came from local meteorological measurements. Bomblies has a Campbell Scientific meteorological station that was installed on the site. This device measured rainfall, temperature, solar radiation, soil moisture, soil temperature and wind data at high temporal resolution, and stores these variables in a datalogger for periodic download. For topography input, we surveyed the site with survey-grade differential GPS equipment. Bomblies owns a Topcon Hiper Lite Plus system, with centimeter horizontal precision and 15-mm vertical precision. Bomblies also will provide associated data collectors and relevant software from Topcon. This is a state-of-the-art, highly accurate measurement system ideally suited for data collection for such a detailed study. Using this instrument, a highly detailed, hydrologically correct representation of watershed topography was generated. This is necessary input for credible simulation using the WEPP model.

The application of WEPP occurred in conjunction with a Geographic Information System (GIS), to allow management of input datasets, and survey locations. A digital elevation model (DEM) generated from the

topography data formed the basis for generating intra-field slope profiles and flow paths as needed in WEPP.

Facilities:

Modeling was done using the Bomblies lab's computer. This is a Dell T7500 workstation with two 3.5 GHz quad-core processors and 4GB of RAM. ArcGIS and WEPP are installed on the computer. The School of Engineering owns a license for the ESRI ArcGIS software used in conjunction with WEPP.

Objective 2. Field measurements.

Many detailed field studies are needed to parameterize and validate the WEPP model. The primary field data need is total P at the watershed outlet, in response to precipitation and/or snowmelt events. For this, we set up a flume at the catchment outlet, equipped with an automated depth gauge such as a pressure transducer. Bomblies has an automated pressure transducer available, and purchased a flume. The pressure transducer was wired to the automated datalogger located at the meteorological station. Periodic visits with a flow meter during flow events allow the rating curve to be developed, to allow continuous monitoring of the hydrograph.

During the high runoff events (high precipitation/saturation and snowmelt), detailed runoff samples were taken to parameterize the model. Before, during and after storm events, graduate student Joshua Tyler sampled the catchment outflow at hourly intervals, and quantify the total, suspended, and dissolved phosphorus concentrations. Filtered and unfiltered samples were measured for suspended and dissolved phosphorus as well as organic phosphorus composition using standard techniques such as molybdate-reactive phosphorus and total phosphorus from digestion and the high-throughput method developed by Hill, respectively.

In addition, regular surveys of the catchment surface were made. These surveys gather information on two key variables: the degree of snow cover or saturation throughout the test field and the spatial distribution of P-containing soil. These measurements were repeated in order to characterize the response to flushing events. The spatial variability of phosphorus in the source area (manure-covered field) was estimated with these samples. Each field sample at each location was repeated in triplicate, and the locations chosen in order to generate a distributed field of available P as model input.

Soil Sampling methods:

Soil and sediment samples were processed as follows. Total mass was measured directly. Particulate mass was quantified by drying at 55°C. Total P and metals (Fe, Al, Mg, Ca, Mn) were calculated from a digested sample (Parkinson and Allen, 1975) using inductively-coupled plasma-optical emission spectroscopy. Total C and total N was determined on an Elemental Analyzer. Inorganic P was calculated via a modified molybdate blue assay (Dick and Tabatabai, 1977; He et al, 2007). Organic P was determined via the plate assay developed by Johnson and Hill (2010).

Runoff sampling methods:

Surface runoff samples were collected during rainfall events. Liters of sample were collected and analyzed as follows. The filtrate from 0.45 μm samples was assayed for molybdate-reactive phosphorus (He et al, 2007) and total P was measured directly using inductively-coupled plasma-optical emission spectroscopy. Unfiltered samples were assayed for total P and metals after digestions as well as molybdate-reactive P and organic P in the same manner as soil samples.

Progress to date

We (J. Tyler, M.S. student of J. Hill and A. Bomblies) have instrumented a field site near Georgia Center. Figures 1, 2 and 3 (all figures are at the end of the report) show the field site at various times of the year, with the variable topography across the site (an important determinant of P mobilization) accentuated in

Figure 3. We have installed a meteorological station (Figure 4) and have monitored the site from May 2011 until the present. During this time, we have witnessed manure application, plowing, planting and harvest of the crops. In short, we have taken note of the land management for an entire growing season using typical techniques, and have monitored the inflows and outflows of water at the site (to determine runoff generation). This was done using a 6" Parshall flume at the catchment outlet (Figure 5), which includes a pressure transducer with which the stage is continuously recorded. The flume was installed using sand bags instead of concrete, because we wanted the installation to be temporary, and also because it was installed while the ground was still frozen in March. The standard rating curve is used to convert stage to flow, and periodic pygmy meter measurements are used to verify accuracy of this measurement. In addition, the small amount of flow onto the site is gauged by three v-notch weirs (Figure 6), each instrumented with a pressure transducer to measure flow continuously. Together, these measurements allow a good estimate of runoff generation from the study site to be made.

We have also taken within-field samples of overland flow, and quantified the mobilized P and sediment. These measurements were done using Gerlach samplers (troughs). Gerlach troughs capture surface runoff and channel flow into a sealed bucket that is used to document sediment yields from unbounded plots (Gerlach, 1967). These have been used by the USGS in New Mexico and Puerto Rico with successful results (Gellis et al., 2004; Gellis et al., 2006). The trough is an aluminum channel 20" long with a 3/4" hose connection for collection in a 5 gallon utility bucket. The top of the trough has a galvanized sheet metal rain cover. Installation consists of digging an area the width and length of the trough, creating a slight slope in the direction of the runoff hole. Gerlach troughs were placed in the furrows to collect sediment yield. The sediment yield will be used in conjunction with the rainfall data from an onsite meteorological station to couple rainfall events with sediment transport. Once sampling was completed the collection buckets were brought back to the University of Vermont soils lab, weighted, and analyzed for sediment and phosphorous concentration. Some samples from the latter part of the 2011 growing season were collected and analyzed. These sample locations are shown in Figure 7. Several more samples were taken, but were not used because the Gerlach samplers repeatedly were flooded. Ultimately, we chose to abandon those samples and use only two sample locations of Figure 13. During 2012, four more Gerlach samplers will be installed and monitored in order to determine the role of topographic variability in mobilizing sediment. The measurements will constitute a model calibration target for 2011, and will be validated using 2012 data.

Similar measurements of sediment and P were taken from water sampled above the impoundments of the V-notch weirs to determine background P and sediment in the water entering the site, and the flume to determine total sediment and P at the catchment outlet. These measurements commenced in July 2011, and yielded values that we are considering a baseline, because significantly higher concentrations are anticipated in the spring of 2012, beginning in late March or April. Surprisingly little rain fell at the site during the Tropical Storm Irene event of August 28, 2011 (3.8 inches over 24 hours), and the fully-cropped conditions during the event prevented significant sediment mobilization from the study fields. Low flows were observed in the flow gauges, that were significantly less than flows in the spring. This is in contrast to observations of severe sediment transport in larger rivers post-Irene, but based on our observations the sediment may have originated elsewhere, such as bank erosion for example. The results of water measurements taken from impoundments above flumes and weirs during the 2011 season are shown in Figure 8.

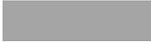
Because topography is expected to be a key determinant of sediment and nutrient mobilization, and intrafield topographic variability may be very important for sediment mobilization, we have measured field topography at 5-meter resolution using a Topcon HiperLite Plus differential GPS system. This allows for distributed topography to be used as a model input and predicted sediment at the Gerlach trough locations to be simulated.

Graduate student Josh Tyler has been working on building a process-based model using WEPP for the research site. This has involved gathering all of the necessary input and attempting calibration. Because we have not yet gathered data during the spring thaw and flush of nutrients and sediment, the model does not yet have sufficient data for calibration. We need to experience the spring of 2012 thaw, snowmelt, and possible flooding to obtain enough data for this.

Objectives for 2012

We aim to collect more field data throughout 2012, with a particular emphasis on the spring melt and subsequent expected high runoff and sediment and nutrient transport. Data collection and lab analysis of soil and water samples will continue until August 2012, when Josh Tyler aims to finish his MS research. During the entire time, model development and calibration will continue, and Tyler will write his thesis in the summer and prepare a journal article which we plan to submit to the Journal of the American Water Resources Association.

Timeline:

<i>Activity</i>	2012	
	<i>Feb - Apr</i>	<i>May - July</i>
MS student training	completed	
establishment of spring field sites	completed	
Objective 1 (model development)		
Objective 1 (model calibration)		
Objective 2 (field experiments)		
Publishing preparation		

Discussion

The goal of this research is to investigate the impacts of small-scale topographic and land use variability on non-point phosphorus pollution. The field component of this research was started in April 2011 by Arne Bomblied and Josh Tyler (MS student, Civil and Environmental Engineering), and is ongoing. Samples are being analyzed in the Hill lab where total P, metals, and inorganic & organic P are being quantified by Tyler. We are noticing minor effects of topography on P from soil samples and are measuring overland flow directly using Gerlach samplers. So far, those samples have not yielded any major findings, but are carefully monitoring the actual, mobilized sediment and sediment-bound P in overland flow at various points in our study fields. This is important for our overall P and water budget that we are conducting and modeling.

The most promising result so far is a series of samples that indicate that pooled water in topographic depressions within the study fields has much higher dissolved P than typical runoff because it has been stagnant. Light rain adds more water to these depressions and seems to temporarily dilute the P but it returns to equilibrium after some time with relatively high P concentration and does not lose water to the watershed. However, when a large storm flushes out these depressions the dissolved P is washed downstream and enters the watershed in a significant pulse, greater than it would be from overland flow

alone. This constitutes a mechanism by which P flushed from the fields depends nonlinearly on rainfall, and is dependent on microtopography that is smoothed over in many common models. Tyler and Bomblied are working on representing this effect using the WEPP model and will compare the results with the commonly-used SWAT. Field sampling and modeling are ongoing, and we are aiming to finish this research by the end of the summer.

Other ongoing research involves a careful water balance at the site, and an attempt at characterizing the groundwater contribution to both water and P into the stream draining the fields. It is thought that P in deeper soil from many years of past farming at the site can lead to a significant addition to the P budget when it is dissolved in moving groundwater. We are attempting to quantify this effect by sampling groundwater entering the streams using upside down buckets that sample only water from the flow lines entering the stream from below. A small amount of water may be due to hyporheic exchange from the channel flow as well. None of these findings are conclusive at this point, and we aim to generate useful results and publish the findings at the end of the summer of 2012.

Year 2 of this project will see a continuation of the sampling at the edges of the study fields (water samples for P and sediment), as well as within the fields themselves. We are still aiming to characterize topographically-driven differences in mobilized sediment, although if these are not evident we will still have good field data for use in our modeling. We will continue to focus on pooled water in depressions and will aim to quantify the nonlinear relationship and the cost of smoothing over microtopography in runoff models. Tyler and Bomblied will continue to work with Hill on this project as stated, with an anticipated completion of September 2012. Finally, we will aim to complete a water balance of this site including estimates of groundwater contribution to both flow and nutrient fluxes. We will begin at least one manuscript for publication in the fall of 2012, and possibly another one, depending on what our groundwater investigations yield.

Training Potential

This project is the MS degree research of Civil and Environmental Engineering graduate student Josh Tyler. He expects to finish his thesis in September 2012. This thesis will be published, and we are aiming for publication in the ASCE (American Society of Civil Engineers) journal "Journal of Hydrologic Engineering". Both the MS thesis and the research paper are in progress and will be completed by December 2012 at the latest.

Moreover, this project involves an undergraduate student in Civil and Environmental Engineering, Lindsay Taylor, who has won a summer grant from the Barrett Foundation at UVM. The travel money from this project is shared between Lindsay and Josh to travel repeatedly to the field site from Burlington, VT, to near St Albans, VT.

Figures



Figure 1 Field Site Pre Harvest - Georgia, Vermont 8-10-11



Figure 2 Field Site Post Harvest - 11-2-11



Figure 3 Field 1 8% Slope Model Input - 3-25-11



Figure 4 Meteorological Station Setup; Site-specific weather monitoring 4-17-11



Figure 5 Flume; minimal flow 5-20-11



Figure 6 South Weir; Minimal Flow - 9-30-11

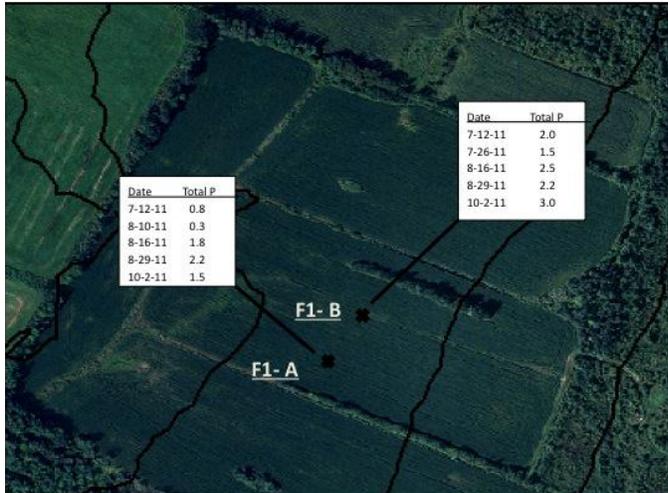


Figure 7 Intra field water samples reported in mg P/L - Samples collected from Gerlach Sediment Traps

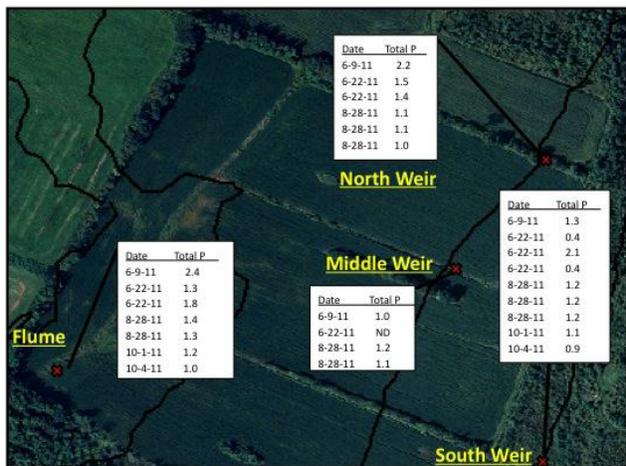


Figure 8 Impoundment water samples reported in mg P/L

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Theses And Articles

This project is the MS degree research of Civil and Environmental Engineering graduate student Josh Tyler. He expects to finish his thesis in September 2012. This thesis will be published, and we are aiming for publication in the ASCE (American Society of Civil Engineers) journal “*Journal of Hydrologic Engineering*”. Both the MS thesis and the research paper are in progress and will be completed by December 2012 at the latest.

Moreover, this project involves an undergraduate student in Civil and Environmental Engineering, Lindsay Taylor, who has won a summer grant from the Barrett Foundation at UVM. The travel money from this project is shared between Lindsay and Josh to travel repeatedly to the field site from Burlington, VT, to near St Albans, VT.

Information Transfer Program Introduction

The following section describes the Information Transfer activities of the Vermont Water Resources and Lake Studies Center in 2011-2012.

Information Transfer Activities

Basic Information

Title:	Information Transfer Activities
Project Number:	2008VT39B
Start Date:	3/1/2011
End Date:	2/28/2012
Funding Source:	104B
Congressional District:	First
Research Category:	Water Quality
Focus Category:	Education, Management and Planning, Methods
Descriptors:	None
Principal Investigators:	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. During the current project year we began a complete overhaul of the Water Center website structure and content and are in the process of deciding what functionality we want in the new site. We expect to complete this effort and launch the new site in the 2012-13 project year.

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. His activities on these committees also helps to inform the directions of the Water Center and has led to a number of productive partnership, including the current work on the use of ADCP technologies to measure sediment and ultimately total phosphorus loads in rivers.

From time to time the Center supports seminars, workshops, and conferences relevant to water resources management issues in Vermont. In the 2011-12 project year we proposed to support partial costs for eminent water scientists, engineers, and policy makers to visit different college campuses in Vermont as a new form of outreach and education supported by the Center. This new component did not progress as quickly as we hoped. However, we did ultimately plan for two visiting scholar seminars which were subsequently completed in the 2012-13 project period and will be reported more fully next year. In addition, we expect to support several more visitor seminars in 2012-13 using unexpended funds from 2011-12. We have also held some funds in reserve to provide partial support for an important conference on flood hazards in Vermont and future flood hazard mitigation. This conference was proposed by the Governors of Vermont and New York and the Premier of Canada after the devastating spring flooding caused by rain on unusually deep snow and the fall flooding caused by Tropical Storm Irene. This conference will occur on 4-5 June 2012 on the University of Vermont campus and the Vermont Water Resources and Lake Studies Center will be one of the key underwriters. We will report more fully on this conference next year.

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	1	0	0	0	1
Ph.D.	1	0	0	0	1
Post-Doc.	0	0	0	0	0
Total	6	0	0	0	6

Notable Awards and Achievements

Nothing to report.

Publications from Prior Years