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Landscape Modeling and Spatial Optimization of Management Practices to Restore Water Quality in the St. Albans Bay Watershed, Vermont

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Abstract: Diffuse (non-point source) pollution from urban stormwater and agricultural runoff are among the leading causes of water pollution in the United States. Currently, most management plans that address diffuse pollution are driven by dissociated economic, political and ecological interests that are difficult to reconcile. Integrated watershed management aims to protect and improve water resources while considering economic and social concerns in the community. Participatory environmental management requires tools, such as landscape models, that can be used to visualize and evaluate the possible outcomes of various management strategies. The overall objective of this project is to develop and implement a framework to examine the effectiveness of proposed solutions to diffuse phosphorus pollution. The Landscape Modeling Framework, implemented within the Spatial Modeling Environment, is used to build a hydro-ecological model from modular components, which captures both spatial relationships and temporal dynamics of urban and agricultural processes. Model development as well as watershed monitoring, necessary to calibrate and validate various modules, requires participation from many stakeholders in the community representing various governmental agencies, the agricultural community, the watershed association, and concerned citizens. This approach is being tested in the St. Albans Bay watershed, a small heterogeneous watershed, to determine the relative importance of different diffuse sources of phosphorus and to examine proposed policy scenarios to achieve Total Maximum Daily Load phosphorus reduction targets. Although the project is still a work in progress, preliminary results have identified specific areas of the watershed (both agricultural and developed) in need of attention. In addition, the systems approach taken in participatory model development have led to a better understanding of the entire hydro-ecological system and have created, we believe, a more cooperative approach to solving the problem.

Keywords: Landscape modeling; diffuse pollution; phosphorus; participatory modeling

1. INTRODUCTION

In the past decade, diffuse pollution has emerged as the remaining large untreated source of nutrient pollution in the United States. Diffuse pollution represents and aggregation of pollution that comes, often inadvertently, from residents, farmers, and businesses. The identification and quantification of diffuse sources and pollutant transport mechanisms has proven difficult. Even more difficult is quantifying the effectiveness of proposed policy, management, and technological solutions. As a result diffuse pollution is typically not regulated, leaving governmental bodies to implement change through education and incentives.

Lake Champlain, like many fresh water lakes, has received excess nutrient runoff for the past 50 years (Hyde et al., 1994; VTANR and NYDEC, 2002) due to changes in agricultural practices and rapid development of open space for residential and urban uses (Hyde et al., 1994). The effect of excess nutrients on the health of Lake Champlain has been most dramatically witnessed in bays such as St. Albans Bay, which exhibit eutrophic algal blooms every August (Hyde et al., 1994).

The watershed feeding St. Albans Bay is dominated by agriculture at the same time that development is burgeoning. Furthermore, the mixing rate of water in St. Albans Bay with the rest of the lake is low, resulting in accentuated nutrient build up. In the 1980s urban point sources of pollution were reduced by upgrading the St. Alban's sewage treatment plant. At the same time, agricultural non-point sources were addressed through implementation of 'Best Management Practices' (BMPs) on 60% of the farms in the watershed at a cost of $2.2 million (USDA, 1991). The outlets of the four major streams to the bay were monitored for 8 years by the Rural Clean Water Program (RCWP) following BMP implementation (USDA, 1991). Although the agricultural BMPs resulted in significant reductions in *E. coli* and suspended sediment in the streams, there was little reduction, and in some cases an increase, in the total phosphorus and total nitrogen loads (Meals, 1996).

Despite the considerable amount of money and attention paid to phosphorus loading in St. Albans Bay, it remains a problem today. The focus has remained primarily on agricultural landuses in the watershed, and as a result has caused considerable tension between farmers, city dwellers, and landowners with lake front property. Lake front housing prices are valued at 20% less than comparable property along other parts of Lake Champlain (Smeltzer, 2003).

Recently, the Vermont Agency of Natural Resources and the New York Department of Environmental Conservation completed a Total Maximum Daily Load (TMDL) limit for phosphorus which was approved by the Environmental Protection Agency (EPA) in 2002 (VTANR and NYDEC, 2002). Under this TMDL the St. Albans Bay watershed has been allocated a total annual non-point source load of phosphorus of 4.2 metric tons/year, which will require an estimated reduction of 33%. The TMDL estimates that 80% of the non-point source phosphorus load in the St. Albans watershed comes from agricultural sources, whereas only 19.3% comes from developed landuses. However, these coefficients have not been directly validated for specific landuse types in the Lake Champlain Basin as a whole, nor in the St. Albans Bay watershed in particular (Cassell et al., 1998; Hegman et al., 1999; Hughes et al., 1999). The 1980s and 1990s were a time of significant population growth in Franklin County. The population increased by 34% from 34,788 people in 1980 to 46,694 people in 2000 (USCB, 2004). Estimated population growth in the watershed itself from 1970 to 2000 is estimated to be 32% (13,063 to 17,349) (VTANR, 2003). Along with this population growth has been significant suburban and residential development.

2. OBJECTIVES

The primary objective of this research is to develop and implement a framework to examine the effectiveness of proposed solutions to diffuse phosphorus pollution. This requires that we first identify the relative importance of different sources (spatially and temporally) and transport processes of phosphorus in the watershed. Furthermore, we aim to identify optimal spatial allocations of management practices to maximize reduction of diffuse pollution at a minimal cost. This framework will be developed specifically for use in the heterogeneous watershed of St. Albans Bay. To achieve these objectives, we are developing computer models using a participatory modeling approach. The most complex model is a spatially explicit landscape model simulating hydrology, erosion, plant growth, and phosphorus transport. Mass balance models quantify aggregated processes that are not captured spatially. Citizen involvement is maximized by engaging citizens in monitoring programs that capture missing data inputs for the models.

3. METHODS

3.1 Landscape Model Development with Stakeholders

A small group of stakeholders has joined a working group to participate in the development of the models that will be used to achieve our objectives. Stakeholders participate in the model development process in the following ways:

1. *Building the Models:* Stakeholders are very helpful in identifying whether there are processes or pollution sources which we have neglected. In the St. Albans watershed stakeholders identified migratory birds, tile drains, road sand/salt, and in-stream erosion as transport mechanisms for phosphorus.
2. *Model Assumptions:* Stakeholders are critical to checking that the assumptions we make about soils, landuse, and especially land management are correct for this area. We approach this topic with the assumption that those who live and work in a system are well informed about its processes and may have observed phenomena that would not be captured by university researchers.
3. *Data Availability:* Many stakeholders have access to data that we do not have access

to. This is especially the case for the agricultural landscape. In addition, some stakeholders are aware of data sources that are more specific to the watershed such as locally collected climatic data.

4. *Scenario Modeling:* Stakeholders are best placed to pose solution scenarios to the problem. Many of them have decision making power in the community and understand the relative feasibility of proposed ideas.

The working group meets every few months and includes decision makers from the town of St. Albans, the City of St. Albans, the town of Georgia, Northwest Regional Planning Commission, Vermont Agency of Natural Resources, Vermont Agency of Agriculture, and the Natural Resources Conservation Service (USDA). In addition, scientists from the University of Vermont, farmers, a local high school teacher, and watershed association members are involved. We have conducted 5 meetings thus far and will hold our final meeting for a presentation of results in May 2006.

The Landscape Modeling Framework (LMF), developed by the Gund Institute for Ecological Economics, couples the dynamic nature of ecological and hydrologic process models with GIS software in a distributed landscape partitioned into a spatial grid of square unit cells. Process models are built with modules composed in Stella and implemented within each grid cell in the landscape. The Library of Hydro-Ecological Modules was used as a template for developing a landscape model appropriate for use in the St. Albans Bay watershed. This library includes modules for hydrology, nitrogen dynamics, phosphorus dynamics, plant growth, and organic matter decomposition. These models are currently being adapted for Vermont and refined. Adaptations include the addition of snow melt processes, tile drain dynamics, erosion (based on the RUSLE model version 1.06), and phosphorus processes specific to Vermont (i.e. road sand and manure spreading application rates).

The landscape model is driven with climatic data sets, spatial data including soil, slope, and landuse. It will be calibrated with hydrologic and nutrient loading data collected in the 1980s and validated with current water quality and flow measurements currently being collected by a citizens monitoring group. In the future, we also hope to implement optimization algorithms to prioritize implementation of management practices (MPs) across a landscape between agricultural and developed areas at three time scales such that *both* spatial and temporal dynamics are accounted for. This will require documentation of the costs and benefits associated with each MP. Stakeholder participation will be used to refine the models and methods in an attempt to increase their impact on decision making and education.

The Landscape Modeling Framework (LMF) is implemented with the use of the Spatial Modeling Environment (SME) (Costanza and Voinov, 2004; Maxwell and Costanza, 1995; Maxwell and Costanza, 1997a; Maxwell and Costanza, 1997b; Maxwell and Costanza, 1994; SME3, 2003) software, which automatically converts Stella generated modules into a C++ driver, which allows the user to run the modules as one complete process model which is run in each cell of the landscape at every time step (usually daily). Horizontal fluxes of water and nutrients are accounted for with cell-cell head differences of surface water and groundwater or through vector-based piped networks for stormwater and tile drainage transport (Voinov et al., Unpublished). SME executes the simulation of landscape processes by reading spatial data layers in the form of maps prepared in GIS and time-series data, such as climatic data. The Spatial Modeling Environment essentially executes multiple models across a landscape and calculates all of the horizontal transport at a user defined time step (usually daily). Feedback among the biological, chemical and physical model components are important structural attributes of this framework (Maxwell, 1999; Maxwell and Costanza, 1995; Voinov et al., 2004). A simulation run within the LMF gives a visual representation of the landscape as it evolves over time reflecting changes in hydrology, water quality, and material flows between adjacent cells.

The landscape model is calibrated using climatic data from the 1980s (using an old landuse map) for which extensive daily data is available for hydrology (flow), nutrient and sediment loads (Meals, 2004.). The general reliability of the hydrologic model is also evaluated by comparing rainfall-runoff data from nearby watersheds for which USGS collects discharge data.

3.2 Citizen Involved Watershed Monitoring

At the beginning of this project, one of our first observations was that there was a dearth of recent data regarding the general state of the watershed including water quality, discharge, and soil phosphorus concentrations. This was despite all the attention and effort to reduce nutrient pollution to the bay. At the same time, there was a highly motivated group of citizens organized through the St. Albans Area Watershed Association which was motivated to begin "doing" something in the watershed immediately. We worked with the group to apply for grant money to conduct citizen based monitoring of water quality and soil test P in the urban areas.

Twenty four water quality monitoring sites were established around the watershed to collect water quality and discharge data for Stevens Brook and Rugg Brook. Some of these sites were established in streams based on location in the watershed and dominant landuse in the subwatershed. Stevens and Rugg Brooks begin in the forested hills above St. Albans and both flow through the city and residential sections and then through an agricultural region before flowing into the bay. Other sites were used to monitor the quality of water from stormwater collection outfalls as well as tile drains and ditches in the agricultural areas of the watershed.

Stage height readings and water quality samples were collected with the help of citizen volunteers simultaneously with stormwater sample collection. Water quality samples were collected biweekly from June 9, 2004 – October 15, 2005 by citizen volunteers. These samples were analyzed for total phosphorus, total nitrogen, total suspended solids, and turbidity using standard methods by a water quality laboratory selected by the Agency of Natural Resources (Clesceri et al., 1995). Volunteers collected over 550 samples and

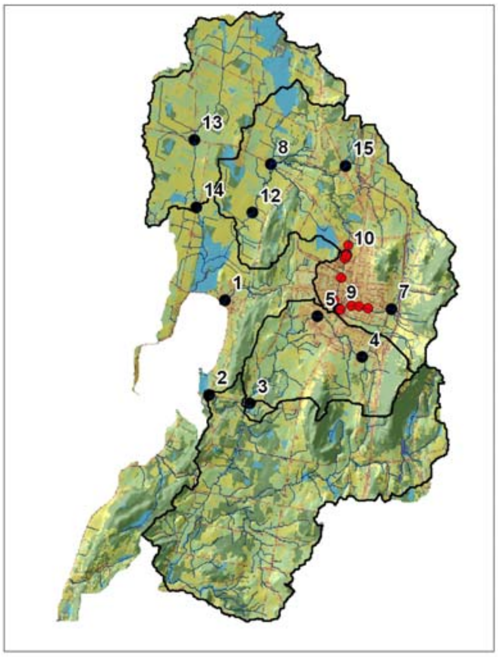


Figure 1. Monitoring points in the St. Albans watershed. Black points are in streams. Red points are stormwater outfalls. Agricultural sampling locations are not shown due to privacy restrictions. Landuse is illustrated using common colors of green for forest, red-orange for developed, yellow for agricultural, and blue for water/wetlands.

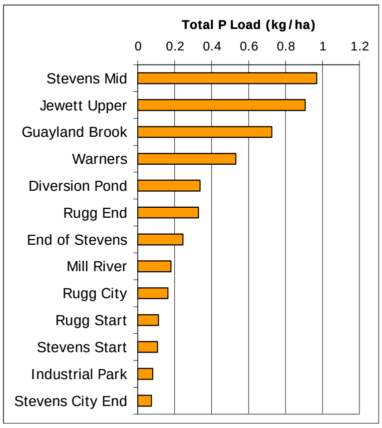
350 gage height readings, in addition to collecting samples during 5 storm events.

In a separate effort, soil test kits were offered free of charge to 300 homeowners in the City of St. Albans. This work was completed in partnership with the St. Albans Area Watershed Association, the Lake Champlain Basin Program, the Bellows Free Academy high school, and the UVM Master Gardener extension service. Over 90 samples were collected from local residences, parks, athletic fields, and commercial properties with participation from local Master Gardeners and high school students. The results of these data, in addition to helping homeowners better manage their lawns, were interpolated using a GIS based on soil type into a map and used to estimate phosphorus loads from fertilizers in residential areas.

4. PRELIMINARY RESULTS

4.1 Water Quality Monitoring

During the 2004 – 2005 sampling period, 325 storm samples were collected during 5 storm events and 365 samples were collected during calculate annual load, however preliminary results



	Agriculture	Developed	Forest
Stevens Mid	59%	14%	18%
Jewett Upper	71%	5%	8%
Guayland	53%	26%	16%
Warners	64%	14%	17%
Diversion Pond	40%	42%	18%
Rugg End	70%	15%	14%
Stevens End	66%	7%	20%
Mill River	52%	7%	37%
Rugg city	45%	40%	14%
Rugg Start	35%	22%	42%
Stevens Start	33%	16%	51%
Industrial Park	7%	93%	0%
Stevens City End	6%	85%	9%

Figure 2. Area weighted phosphorus loads for subwatersheds. Associated table shows respective landuse proportions.

indicate that 65% of the annual phosphorus load non-storm periods. In addition, 181 stream gage readings were made for 14 sites permitting the development of discharge curves for many stream reaches. These data are still being analyzed to occurs during storm periods, 17% during baseflow, and 9% and 11% during post-storm and spring runoff respectively. Figure 2 shows which subwatersheds appear to have the highest annual TP loading (kg/ha) and the landuse proportions associated with each subwatershed.

4.2 Soil Tests

The average concentration of phosphorus in soils collected and analyzed from residential, commercial, and public properties in the city was 16 ppm. This is higher than the average soil P found in agricultural soils in the same watershed (11 ppm). Assuming that 5 ppm is optimal (on average) for soils to grow turf grass, 67% of the samples from the city were above optimal and only 9% were considered to be low (less than 2.5 ppm). The maximum concentration was 87 ppm and the minimum 1 ppm. These data have been used in an educational campaign to introduce phosphorus free fertilizer into nurseries that supply the city and to educate local residents about the importance of soil testing prior to fertilizer application. The soil map produced from these data is also used as a spatial input to the phosphorus module.

4.3 Model Development

All of the modules required for scenario analysis have been developed including hydrology, snow melt, erosion, plant growth, and phosphorus. The models are currently being calibrated and prepared for scenario simulations.

The modeling approach taken in this study has already benefited many of the stakeholders in the St. Albans watershed even before results of the modeling work are completed. The systems approach taken in this project, and worked through with stakeholders, has helped many stakeholders better understand the entire hydro-ecological system and has even led to some resolution of conflict arising from misunderstanding of hydrologic or nutrient transport processes. In addition, the participatory modeling approach has stimulated additional activity around diffuse pollution issues in the watershed and increased involvement of concerned citizens through monitoring and model development. By allowing stakeholders and citizens to become part of the research process we have created a sense of ownership over the problem and raised awareness about the uncertainty associated with modeling and monitoring. We hope this will lead to more careful application and interpretation of the model results in the future. In addition, our participatory modeling efforts have already resulted in a mass-balance modeling exercise that has addressed some concerns and allowed stakeholders to refocus their attention on the larger contributors of nutrients to the bay. For example, we have encouraged members of the watershed association to examine diffuse sources of phosphorus from the developed landscape in addition to the agricultural landscape and have confirmed that waterfowl are not a significant new source of nutrients. Finally, the process has identified missing information that has led to side projects and grants aimed at filling data gaps.

4.4 Scenarios

The following is an abbreviated list of scenarios developed by the stakeholder group. These scenarios were selected by the stakeholder group because, in their estimation, these are feasible proposed changes to the watershed for which funding is available. These scenarios are currently being evaluated for the feasibility of testing them using the model structure that we have developed. We expect the results of the scenario simulations to be available in May 2006.

1. Stormwater separation (from sewers) in the city.
2. Replacing road sand with a no-P alternative.
3. Treatment of city stormwater with bioinfiltration.
4. Low impact v. standard practices used in constructing new developments.
5. Reduced fertilizer usage in the agricultural landscape and/or developed landscape.
6. Erosion reduced to soil tolerance level as defined by NRCS.
7. Installation of buffers in the city and the agricultural landscape.
8. Treatment (80%) of all manure and silage leachate from farmsteads.
9. Installation of sediment traps in stormwater pipes in the city.
10. Installation of the proposed diversion structure on Stevens Brook.
11. Treatment of tile drain effluent.

5. CONCLUSIONS AND FUTURE WORK

This project is still in progress. Thus, the conclusions reported here are by nature preliminary. Generally we have found the participatory approach to model development and watershed monitoring to be highly effective in developing more effective models, creating interest and trust for our process and results within the watershed community, collecting more water quality and soil samples than we could have alone on a small budget, and educating the public about diffuse phosphorus pollution while informing participants about the uncertainties associated with modeling, statistics, and scenario predictions.

From our water quality sampling efforts we can conclude that the majority of phosphorus runs off during storm events, rather than during spring runoff as was previously hypothesized. In addition, the agricultural landscape appears to be the largest contributor followed by the urban stormwater of phosphorus to streams. We can say with some certainty that the most important transport process from the agricultural landscape comes as direct discharges from barns and barnyards followed by erosion, dissolved runoff (as expected) as well as tile drains, a process that had not previously been targeted but appears to be important. However these conclusions will be validated when the simulation modeling has been completed.

Our soil test results indicate that residential and commercial properties are significantly over fertilized with phosphorus. Turf lawn may be responding to nitrogen fertilizer; however the phosphorus component of the fertilizer could be eliminated for most properties. This could significantly reduce the net import of chemical fertilizer to the watershed.

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