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Spatial Optimization of Best Management Practices to Attain Water Quality Targets

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Abstract Diffuse nutrient loads are a common problem in developed and agricultural watersheds. While there has been substantial investment in best management practices (BMPs) to reduce diffuse pollution, there remains a need to better prioritize controls at the watershed scale as reflected in recent US-EPA guidance for watershed planning and Total Maximum Daily Load development. We implemented spatial optimization techniques among four diffuse source pathways in a mixed-use watershed in Northern Vermont to maximize total reduction of phosphorus loading to streams while minimizing associated costs. We found that within a capital cost range of 138 to 321 USD ha^{-1} a phosphorus reduction of 0.29 to 0.38 kg ha^{-1} year^{-1}, is attainable. Optimization results are substantially more cost-effective than most scenarios identified by stakeholders. The maximum diffuse phosphorus load reduction equates to 1.25 t year^{-1}using the most cost-effective technologies for each diffuse source at a cost of $3,464,260. However, 1.13 t year^{-1} could be reduced at a much lower cost of $976,417. This is the practical upper limit of achievable diffuse phosphorus reduction, above which additional

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spending would not result in substantially more phosphorus reduction. Watershed managers could use solutions along the resulting Pareto optimal curve to select optimal combinations of BMPs based on a water quality target or available funds. The results demonstrate the power of using spatial optimization methods to arrive at a cost-effective selection of BMPs and their distribution across a landscape.

Keywords Optimization · Watershed management · Best management practices · BMPs · Diffuse pollution

1 Introduction

Diffuse (or nonpoint source) pollution represents an aggregation of pollution that comes, often inadvertently, from activities spread across the landscape including urban stormwater, agricultural runoff, and erosion. Quantification of diffuse sources and pollutant transport mechanisms are challenging at the watershed scale due to difficulties in monitoring diffuse loads, the variety of factors (natural and human) that affect pollutant mobilization, and the complex pollutant pathway from sources to receiving waters. There is a need to improve prioritization of diffuse pollution controls at the watershed scale as funding is limited and pollution continues to increase.

Optimization algorithms provide a useful tool for developing cost-effective watershed plans to attain specific water quality targets, c.f. Seppelt (1999). Environmental simulation modeling with an application in optimization, generated under defined goals (e.g. a pollutant load reduction target) and specific constraints (e.g. available funds), can be incorporated into a tailored management plan (Seppelt 2000; Holzkämper and Seppelt 2007, and Eichhorn et al. 2012).

The optimization of management practices in a watershed context has been well explored (Randhir et al. 2000; Cerucci and Conrad 2003; Srivastava et al. 2002, 2003; Veith et al. 2003; Nikkami et al. 2002; Azzaino et al. 2002; Chang et al. 2009; Liu et al. 2011; Hsieh and Yang 2007). Recently, critical watershed source areas have been identified using spatial data as a proxy for landscape processes (Qiu 2009; Trevisan et al. 2010). There is a trade-off between problem complexity and computer run-time associated with all optimization efforts. For example, in our model simulations, the CPU runtime for a single 5-year simulation took 6 h and 45 min on an 8 node (64 bit) Opteron cluster in 2006. While run times will continue to improve, complete enumeration of the optimization problem posed in our study would require $16^{48,568}$ (16 unique combinations over 48,568 cells in the largest of the subwatersheds). The simulation model run-time is often reduced by eliminating or simplifying one or more level(s) of complexity such as the number of areas available for optimization, spatial neighborhood effects, the number of pollutant transport processes or sources (e.g. storm water only; Hsieh and Yang 2007), or the simulation time frame (e.g. a specific hydrologic event such as a 5-year storm; Srivastava et al. 2003). In some cases, optimization routines are tested on hypothetical rather than actual watersheds (Chang et al. 2009). Recent developments in computer software and data processing have expanded the use of optimization to simulation models that capture processes over both space and time. In this regard, spatial optimization holds exciting opportunities for watershed management.

The approach presented in this paper spatially optimizes BMPs over a watershed to maximize reduction of phosphorus loading to streams while minimizing costs. This approach benefits from the complex interactions captured by a raster-based landscape simulation model, while reducing the optimization problem by pre-running whole watershed scenarios. The approach was tested on the St. Albans Bay watershed in Northern Vermont as part of a state-led watershed planning effort with active stakeholder participation and real BMP costs and pollutant reduction estimates. The work supports water quality goals outlined in the Lake Champlain Total Maximum Daily Load (TMDL[1]) Study (VT ANR and NYDEC 2002). The optimization algorithm considers multiple landuse types and pollutant transport mechanisms such that BMP implementation is appropriately distributed throughout the watershed.

This paper represents one piece of a comprehensive watershed study. Other study components are reported elsewhere and include monitoring (Gaddis 2007), participatory scenario modeling with watershed stakeholders (Gaddis et al. 2009), and simulation modeling to quantify the relative importance of specific phosphorus sources and transport pathways in the watershed (Gaddis and Voinov 2010).

2 Study Area and Watershed Model Description

2.1 Study Watershed

Lake Champlain, like many freshwater lakes, has received excess nutrient runoff for at least the past 50 years (VTANR and NYDEC 2002) due to changes in agricultural practices and rapid development of open space for residential uses (Hyde et al. 1994). The effect of excess nutrients on lake health has been most dramatically witnessed in bays that are not well mixed with the main lake such as St. Albans Bay (Fig. 1; hereafter referred to as the Bay) that exhibit eutrophic algal blooms in late summer or early fall (Hyde et al. 1994; LCBP 2012). The watershed is dominated by agriculture; yet at the same time, urban development is growing. Despite considerable monetary investment and attention paid to phosphorus loading to the Bay, the problem remains (Smeltzer 2003; LCPB 2012).

In 2002, the US Environmental Protection Agency (EPA) approved a TMDL for phosphorus to Lake Chaplain (VTANR and NYDEC 2002)[2]. Under this TMDL, the St. Albans Bay watershed (hereafter referred to as the watershed) was allocated a total annual nonpoint source phosphorus load of 4.2 t $year^{-1}$, which requires a 33 % annual reduction based on current load estimates. As with most TMDLs that address diffuse sources, there is considerable uncertainty in quantifying the relative phosphorus load associated with specific sources and transport processes in the watershed. This challenge, a primary focus of this study, requires tools that prioritize and target management actions for attainment of TMDL allocations.

2.2 Flow and Nutrient Transport Simulation Model

A spatially explicit landscape simulation model was developed for the watershed to simulate the dynamics of phosphorus transport from diffuse sources in the watershed (Gaddis and Voinov 2010). The primary goal of the simulation model was to quantify the most critical processes, locations, and times associated with phosphorus transport to streams.

The simulation model couples the dynamic nature of ecological and hydrologic process models with GIS software in a distributed landscape partitioned into a grid of square cells

[1] A TMDL is a water quality study required by the Clean Water Act, in the United States, that identifies the total pollutant load that a water body can accept and still meet water quality standards. The TMDL also allocates the acceptable load for categories of diffuse pollutant sources and regulated point sources in the watershed. Implementation plans that often accompany TMDLs outline critical sources and locations of diffuse pollutants in a watershed and a plan to reduce them to the loads identified in the TMDL.

[2] In 2011, EPA rescinded its approval of the Lake Champlain TMDL. Revisions to this TMDL by EPA are pending. The load allocations described in the 2002 TMDL are used for purposes of setting optimization targets in this study.

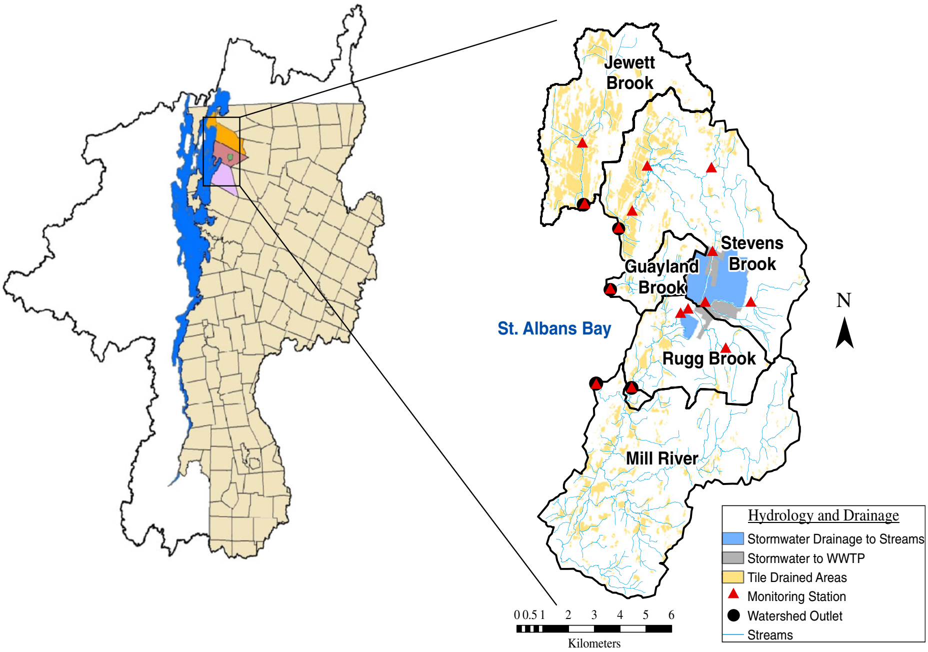

Fig. 1 Maps showing the location of St. Albans Bay in the Lake Champlain Basin (**a**) and the hydrology and subwatersheds draining to St. Albans Bay (**b**). The total watershed area is 12,500 ha and 30 % of the area is in the Stevens Brook subwatershed, the focus of the optimization study

(Fig. 2). The complete model captures four diffuse phosphorus transport processes: surface erosion, tile drainage, dissolved phosphorus in surface runoff, and road sand wash-off. Modules for hydrology, erosion, sediment, plant growth and phosphorus transport were developed or modified from the Hydro-Ecological Modules Library (Voinov et al. 2004) using Stella software (Version 9). Parameter inputs to the five modules include:

- spatial inputs at a 30 m grid cell scale (e.g., slope, drainage network, landuse, soil);
- time series data (e.g. meteorology, timing of fertilizer and road sand application);
- landuse dependent parameters (e.g. impervious cover, fertilizer rates, crop production);
- soil dependent parameters (e.g., soil phosphorus concentration, soil porosity);
- and constants related to process such as erosion, hydrology, vegetative growth, and phosphorus dynamics.

The parameter configurations were handled using the Spatial Modeling Environment (Maxwell and Costanza 1997; Maxwell 1999; Costanza and Voinov 2004) software (Fig. 2). A daily timestep was selected because more than half of the nutrient pollution is delivered to the lake during a small percentage of the year in a few large storms or with snowmelt runoff (Jordan-Meille et al. 1998). See Gaddis and Voinov (2010) for additional discussion on the simulation model set-up, calibration, uncertainties and results.

2.3 Summary of Simulation Model Results

The simulation model outputs are user-defined maps of a variable at a given timestep (e.g. 5 years) or daily time-series output for a variable at a particular location on the landscape. For

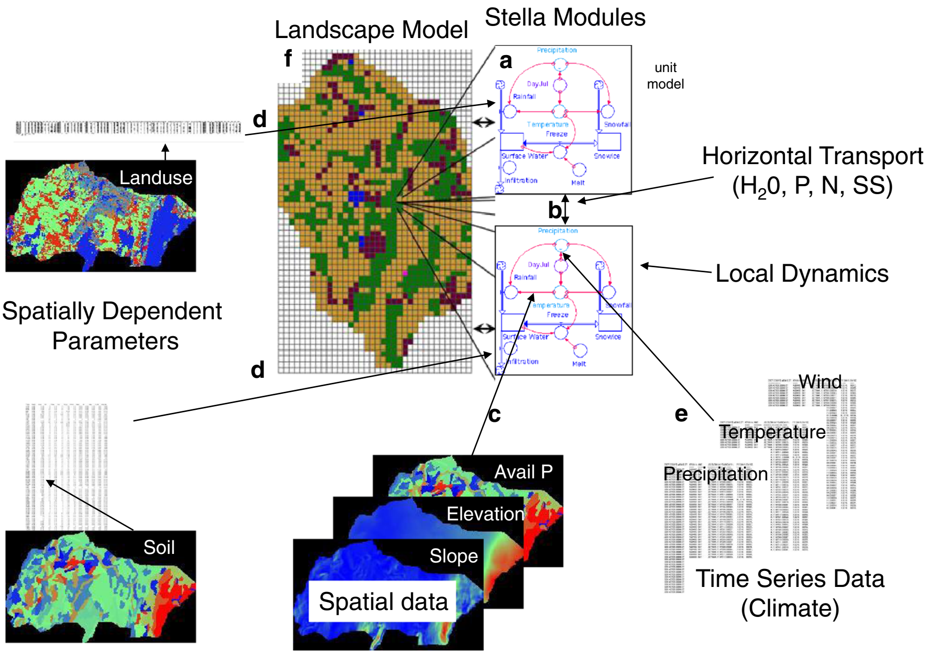

Fig. 2 Conceptual diagram of the St. Albans Bay spatially-explicit simulation model including process models, spatial inputs, and time series inputs. The Spatial Modeling Environment (SME) converts Stella generated modules (**a**) capturing processes and dynamics in each grid cell into a C++ driver allowing the user to run the modules spatially. Exchange of water, nutrients, and suspended sediment between grid cells (**b**), is captured at a daily time step. These simulations are driven by spatially-explicit data related to landuse, slope, elevation, etc. (**c**), spatially dependent parameters such as soil and landuse attributes (**d**), and time series climate data (**e**). A simulation run within the landscape model gives a visual representation of the landscape (**f**) as it evolves over time reflecting changes in hydrology, water quality, and material flows between adjacent cells

our application, spatial outputs included total phosphorus transported to stream outlets from each cell over the course of the 5-year simulation and phosphorus loading time series (Gaddis and Voinov 2010). The outputs were separated for each major transport pathway: surface erosion, tile drainage, dissolved phosphorus in surface runoff, and road sand wash-off.

The flow and transport simulation model, calibrated to measured stream flow and water quality data, shows phosphorus loading to streams could be as high as 10.57 t year^{-1}, which is 32 % greater than the 8.0 t year^{-1} reported in the original Lake Champlain Phosphorus TMDL (VTDEC and NYDEC 2002). The majority of the stream phosphorus loading is diffuse (8.06 t year^{-1}; 76 %). Dissolved phosphorus in surface runoff from agricultural fields accounts for 41 % (4.37 t year^{-1}) of the total landscape load to streams and is the single most important diffuse source of those modeled. Other important diffuse sources in order of magnitude are sand wash-off from roads and parking lots (1.26 t year^{-1}; 12 % of total load), surface erosion from agricultural fields (0.85 t year^{-1}; 8 % of total load), and tile drainage from agricultural fields (0.77 t year^{-1}; 7 % of total load). Detailed model results are described in Gaddis and Voinov (2010).

2.4 Stakeholder Derived Scenarios

The simulation model identified relative comparisons between landscape sources and transport pathways to those offering the greatest opportunity for phosphorus load reduction. Feasible phosphorus control options were developed with stakeholder input for each process identified as significant. Control options ranged from structural changes implemented on a centralized scale (e.g., stormwater treatment) to behavioral changes of individual homeowners and farmers, such as changing fertilizer application rates. The simulation model assessed a variety of whole watershed scenarios proposed by stakeholders to reduce phosphorus load to streams in the short-term (5-years) and long-term (15-years) (Online Resource 1; Gaddis et al. 2009). The short-term scenarios are included for comparative purposes in the optimization results that follow.

3 Spatial Optimization of BMPs for Diffuse Sources

The water quality optimization problem for the watershed reconciles two, opposing goals. The first aims to maximize phosphorus load reduction to surface waters. The second aims to minimize capital expenditures for BMPs used to reduce phosphorus load. The Lake Champlain Phosphorus TMDL aims to reduce diffuse phosphorus load to the Bay by 3 t year^{-1} (VTANR and NYDEC 2002). If we select this as a constraint, we could then optimize for the costs. Alternatively, since, the Vermont Agency of Natural Resources had allocated \$625,000 to improving water quality in the Bay in the 2004 *Clean and Clear Action Plan* (VTANR 2004), we might consider the funding to be the constraint, and optimize for the load reduction. Instead, we use an unconstrained multi-objective optimization approach to combine objectives using a user-defined weight to create a heuristic balance between the water quality goals and the economic constraints. A similar approach has been successful in solving other spatial optimization problems (Rizzo and Dougherty 1996; Seppelt and Voinov 2002). We focus on capital costs because calculations are straightforward and more water quality funding is readily available for project capital costs. However, the method could be applied to amortized operation and maintenance costs.

The optimization method described below was first applied to the Stevens Brook watershed, a subwatershed within the St. Albans watershed that includes the majority of St. Albans City as well as a large agricultural area. The importance of the four phosphorus transport processes (surface erosion, dissolved phosphorus in surface runoff, tile drainage, and road sand wash-off) is captured in the variety of landuses and landscape conditions present in Stevens Brook. The subwatershed represents 30 % of the entire watershed area and 27 % of the total phosphorus load to the Bay. Stevens Brook watershed is representative of the landuse distribution in the entire St. Albans watershed with approximately half of the land in agricultural uses, a quarter as forested, and one fifth as developed.

3.1 Formalization of the Optimization Problem

The Stevens Brook watershed is represented by a set of gridded cells. For each cell, there are 16 combinations of BMPs, BMP_m (m=1,…,16), that could be employed to reduce phosphorus transport to streams. The most cost-effective BMPs for reducing phosphorus load from each of the four modeled transport processes were preselected for each landuse type and transport pathway combination (see Section 3.2 for BMP effectiveness and costs). BMPs, which address each of the four processes individually, comprise the first 4 possible BMP options. The remaining 12 options represent all combinations of these 4 BMPs, including a "no implementation" option. Sixteen map pairs were produced, one pair for each combinations of BMPs, representing both annual phosphorus load reduction P_m (g cell^{-1} year^{-1}) and total capital costs

C_m(dollar cell^{-1})[3]. Phosphorus load reduction maps show results using 5-year simulations and post-processed to account for flow distance from streams. Cost estimates were derived from the scenario modeling phase in collaboration with watershed stakeholders that had access to cost information (Gaddis et al. 2009). The costs were divided among the total number of cells associated with a particular watershed landuse type. Net overlap in phosphorus reduction or cost associated with solutions that yield multiple BMPs was considered in the phosphorus load and cost maps resulting in more cost-effective BMP groupings. Thus, the local optimization task for each cell, z, in the watershed W, can be described as follows:

$$\max_{m=1,\dots,16} F_m(z) \;\text{ for }\; z \in W \tag{1}$$

where $F_m(z)$ is the objective function defined as:

$$F_m(z) = P_m(z) - \lambda C_m(z) \tag{2}$$

m is the particular combination of BMPs applied at cell z for a specific landuse-transport process combination (e.g. road sand wash-off from urban areas or surface erosion from agricultural fields). As $P(z)$ and $C(z)$ are incommensurable in units, we introduce λ which represents the reciprocal of the shadow costs in average grams reduced per year per capital cost (g year^{-1} dollar^{-1}), i.e. expected phosphorus load reduction per dollar spent. Varying λ leads to different optimal solutions depending upon the weighting or desired tradeoffs between costs and phosphorus load reduction. The local optimal combination of BMPs for each grid cell varies for each λ, and each solution is associated with a specific cost and load.

As λ changes, the total watershed phosphorus load reduction, P, and the total associated cost, C, are calculated for each solution by summing the total cost and phosphorus reduced associated with the set of watershed interventions over each cell, z, in the watershed, W.

$$\begin{aligned} P &= \sum_{z \in W} P(z) \\ C &= \sum_{z \in W} C(z) \end{aligned} \tag{3}$$

A suite of optimal solutions was generated for 25 values of λ, ranging from 0.01 to 10^9. This range results from the different orders of magnitude in units selected for costs (dollar cell^{-1}) and load reduction (g cell^{-1} year^{-1}). Each λ generates an optimal combination of interventions across the urban and agricultural landscape of the Stevens Brook watershed, and has an associated cost and total phosphorus load reduction as well as optimal BMP allocation maps (Fig. 3; Online Resource 3). These solutions illustrate the range of options available to watershed managers depending on available funds. A graph of P and C values illustrates the bounds of expected phosphorus reduction for a given expenditure (Fig. 3). Each solution informs decision makers as to where, in the landscape, implementation will be most cost-effective.

3.2 Phosphorus Reduction and Cost Maps

Optimal BMPs for a given landuse and phosphorus transport process were pre-selected to achieve the most phosphorus reduction for the least cost. An array of BMP options was

[3] Note: All costs are given in 2006 USD. Although the costs values are relatively old, the study is comparative and therefore unit consistency is the most important concern for costs. Recent changes in unit costs associated with inflation may change the absolute costs but do not affect the shape of the pareto curve.

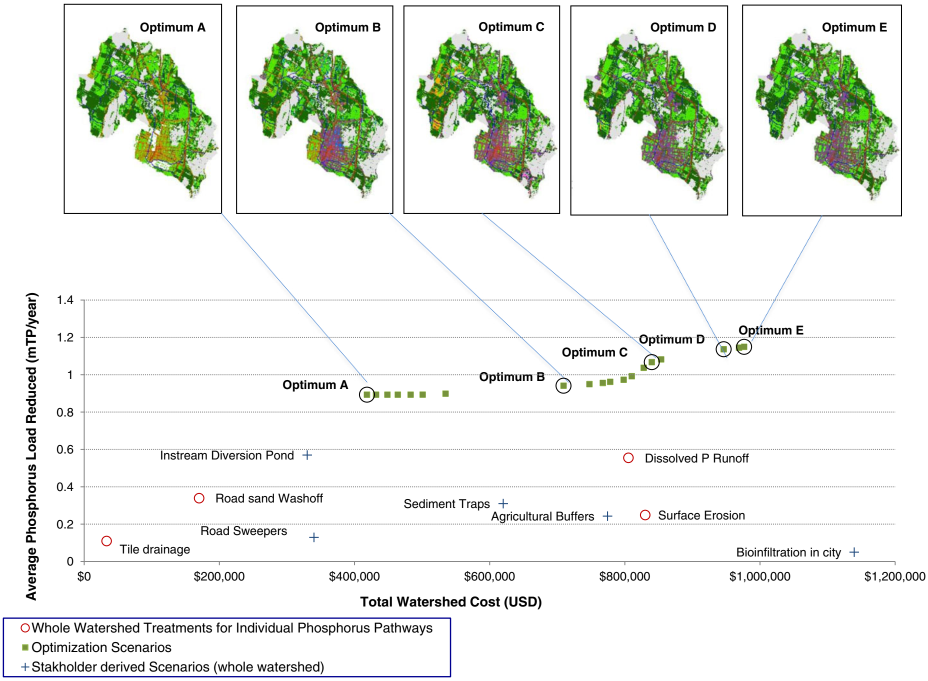

Fig. 3 Summary of full optimization modeling results. Plot of the Pareto frontier space of phosphorus load reduction versus costs locating the considered optimized landscapes as well as the Pareto frontier that translates into several spatially explicit locations of BMPs shown in the maps. The maps show optimal watershed intervention combinations for specific landuses at varying costs and reductions of diffuse phosphorus load and are detailed in Online Resource 3

considered for each landuse and transport pathway combination in consultation with stakeholders. The rationale for each selected BMP combination is described below and in Online Resource 2. Selected BMPs range from commonly-used practices (i.e., infiltration basins for erosion control in urban areas) to innovative technologies (e.g. EAF steel slag barriers to control dissolved phosphorus from agricultural fields). Some transport pathways are assumed to occur only on specific landuse types (e.g. tile drained fields); therefore, BMPs are not identified for all landuses for all transport pathways in Online Resource 2.

3.2.1 Surface Erosion

The most cost-effective practice for reducing surface erosion on agricultural land was riparian buffers and filter strips down gradient of cells with high surface erosion; buffers were assumed to reduce particulate phosphorus by 84 % (Watzin et al. 2003). Scenario modeling estimated a 6.7 % net reduction of phosphorus loading to streams accounting for this transport pathway (Gaddis 2007). The $150 per acre cost associated with vegetative riparian buffers was an estimated minimum for installation (personal communication with Kathy Hakey, NRCS September 2005), which equates to $6.06 per cell. This cost does not include land costs or the opportunity costs of converting land from agriculture to conservation.

The most cost-effective practices for reducing surface erosion on developed lands are BMPs that retain water during storms. We assumed 90 % of the rainfall would be retained in the landscape per storm; the Vermont Stormwater manual (VTANR 2002) defines this as the *water quality volume*. The associated phosphorus load reduction, if implemented watershed wide, would reduce loading to streams by 0.5 % (Gaddis 2007). On residential lands, the most cost-effective decentralized practice is a grass swale, which could be installed for $0.49m^{-2}$ of impervious cover (RAN 2005). For all other forms of developed landuses, infiltration basins are the most cost-effective and can be installed for $2.11 m^{-2} of impervious cover (RAN 2005).

The resulting phosphorus load reductions and costs for the respective developed and agricultural landscape simulations are combined to create comprehensive maps representing the best pre-selected interventions on all landuses.

3.2.2 Tile Drainage

The BMP selected for reducing phosphorus from tile drains was "EAF steel slag barriers for surface runoff P reduction". This technology, under development in 2007 at the University of Vermont, uses electric arc furnace steel slag (EAFSS), which is an industrial by-product from steel production, to chemically adsorb and precipitate dissolved phosphorus. The EAFSS is placed in filter units in field ditches or streams that receive both tile drainage and surface runoff from adjacent fields. Phosphate is retained through chemical adsorption and precipitation reactions with calcium and iron oxides present in the EAFSS (Drizo et al. 2006). The combined annual phosphorus load reduction from tile drainage and surface runoff was assumed to be 40 % for this technology (personal communication with Aleksandra Drizo, University of Vermont, May 11, 2006). The material cost of implementing the BMP across the watershed was estimated at $134,000, which equates to $0.026 per gram of phosphorus load calculated by dividing $134,000 by the total phosphorus load from tile drainage and surface runoff in agricultural areas of the watershed (5.19 t year^{-1}). In addition, the tile drained design cost of $120,000 for the watershed (estimated to be 25 farms) equates to $6.04 per cell when divided across all tile-drained cells in the watershed. Thus, the estimated EAFSS installation cost per cell is:

$$C_{td}(z) = 0.026 * L_{td}(z) + 6.04 \tag{4}$$

where, $C_{td}(z)$ is the installation cost in cell z and L_{td} is the phosphorus load from tile drains (g cell^{-1} year^{-1}), a spatial output from the simulation model. The disaggregation of the cost estimates across individual cells represents our assumptions on how cost might reasonably be distributed across the landscape based on the cell-specific phosphorus loading estimates produced with the simulation model.

3.2.3 Dissolved Phosphorus in Surface Runoff

The "EAF steel slag barriers for surface runoff P reduction" BMP selected for reducing phosphorus surface runoff from agricultural landuses again assumes a 40 % phosphorus reduction. Capital costs for implementation across the watershed are estimated using (4) and the phosphorus load from dissolved runoff, L_{ds}, for cells that are not tiled. The design costs for tiled cells are assumed to be spread equally between surface and tile drained pathways; thus, the design costs have been reduced by 50 % to $3.02 per cell for those cells.

$$C_{ds}(z) = 0.026 * L_{ds}(z) + 3.02 \tag{5}$$

The BMP selected for reducing dissolved phosphorus in surface runoff from developed landuses is the elimination of phosphorus fertilizers used on lawns and gardens. Total phosphorus load reduction to streams was estimated at 0.25 % over 5 years using scenario modeling (Gaddis et al. 2009). The cost for replacing typical commercial fertilizers with phosphorus free fertilizers is estimated to be \$0.23 m^{-2} of lawn based on the differential costs of phosphorus-free fertilizer, assumed to be \$29.95 for 116 m^{-2} of lawn and commercial fertilizer, assumed to be \$15.99 for 465 m^{-2} of lawn, based on published fertilizer costs in 2006. The cost per cell for this change is based on the average area of lawn in each cell, a parameter with landuse specific values.

Again, the phosphorus load reduction and costs for the respective developed and agricultural landscape simulations are combined to create watershed-wide maps representing the best pre-selected intervention for all landuses.

3.2.4 Road Sand Wash-Off

BMPs to reduce road sand wash-off are only applied to roads, parking lots, and commercial landuses. The most cost-effective BMP was street sweepers that recover up to 74 % of sand applied to roads during winter storms (USDOT 2006). For St. Albans town and City, this represents an upgrade from the current 33 % and 50 % recovery using existing sweepers. The cost of purchasing a new sweeper is \$170,000, which is spread across all road cells in the town and city for an average cost per cell of \$23.30.

3.3 Whole Watershed Solutions

The simulation model was first used to estimate the cost and load reduction attainable for each 'whole watershed' solution represented by the 16 maps of landuse and transport specific BMP combinations. These local control optima for each individual transport process as well as all combinations of transport processes (e.g. tile drainage, tile drainage + surface erosion, tile drainage + surface erosion + road sand wash-off, etc.) were then compared to scenarios derived by stakeholders and those derived using the spatial optimization algorithm described below.

3.4 Optimization Algorithm and Software

An optimization algorithm identified the optimal set and spatial configuration of BMPs for each cell, by maximizing Eq. (2) for each grid cell depending on the weighting of cost versus phosphorus reduction represented by lambda (λ). As this spatial configuration is key for identifying optimal solutions, the combinatorial problem is computationally expensive and not solvable by exhaustive search. We thus make use of an optimization code originally developed to maximize water quality and agricultural yields; see (Seppelt and Voinov 2002, 2003). The optimized watershed solutions are the result of a combinatorial search that selects the best combination of local cell-by-cell BMP applications. This requires computation of potentially optimum BMP maps based on the set of 16 map pairs pre-analyzed and indentified by the watershed simulation model. Given a weighting lambda (λ) spatially optimal placement and combination of BMPs are generated quickly (see Seppelt and Voinov (2002) for details). Neighborhood effects are captured by the simulation model which generates the phosphorus load reduction to streams associated with BMPs specific to each landuse and transport pathway combination.

4 Results

The total optimized costs for implementing BMPs ranged from \$418,400 to \$3,464,260 and represent phosphorus load reductions ranging from 0.89 to 1.25 t $year^{-1}$. Optimized scenarios were more cost-effective than the whole watershed scenarios representing landuse-specific interventions applied to the entire landscape (Fig. 2). The five optima (Fig. 3 and Online Resource 3) also show changes in spatial patterns of implementation at increasing costs. For each landuse, only a subset of BMPs results in meaningful phosphorus load reduction (Online Resource 2). For example, tile drain BMPs do not apply to the urban landscape. Therefore, not all BMP and landuse combinations are shown on Fig. 3. Regardless of the priority (choice of λ) assigned to load reduction versus cost, the solutions are considerably more efficient when the BMPs are spatially tailored and distributed.

The most expensive scenario includes all interventions implemented across the watershed for a cost of $3,464,260 and a phosphorus load reduction of 1.25 t year^{-1}. Stevens Brook represents one third of the watershed area and phosphorus load to streams; therefore, this reduction is consistent with the 2.3 to 5 t year^{-1} load reduction goal for the entire watershed. However, additional optimization work would be required to apply the approach to the entire watershed. The 1.25 t year^{-1} load reduction represents the maximum achievable diffuse phosphorus reduction for the Stevens Brook watershed. In comparison, the lowest cost associated with a whole watershed intervention is the treatment of water from agricultural tile drains at an estimated cost of $33,161, resulting in a phosphorus load reduction of 0.11 t year^{-1}. Solutions to the right of Optimum E (Fig. 3) offer very small gains in phosphorus reduction achieved at a substantial cost. Between Optima A and E, the most cost-effective combinations occur on the steep side of the Pareto frontier, which has a sigmoid shape. This means that marginal costs for further phosphorus load reduction are lowest in this area of the curve.

Similar spatial patterns are evident for each optimum (Fig. 3). At the optimal cost combination (Optimum A), almost all of the agricultural landscape was selected for “EAF steel slag barriers for surface runoff P reduction” to address surface runoff; and most of the roads were selected for improved road sweepers (Fig. 4). In Optima B and C, agricultural buffers and “EAF steel slag barriers” for both surface runoff and tile drainage P reduction become more dominant only to drop off again in Optima D and E as the entire agricultural landscape is included in the implementation of surface runoff treatment. The lowest priority agricultural fields for BMPs are pastures with non-clay soils most distant from streams. Nearly all roads are selected for improved road sweeping under all optima. In the city, the combination of road sweeping and conversion to phosphorus free fertilizer become a more important intervention increasing steadily from Optima B to E. The phosphorus free fertilizer intervention is first selected on the steep slopes of the city, where runoff is highest, and eventually increases to include all residential, commercial, and industrial cells with lawns (Optimum E). The diversity of selected interventions is highest at a mid-level cost (Optimum C) and decreases as money is allocated and all agricultural land and roads receive their respective optimal interventions (Fig. 4).

5 Discussion

The optimization routine employed in this study identifies combinations of BMPs across the landscape that achieve the greatest phosphorus load reduction at the lowest cost. Multiple optima were discovered using the spatially explicit, multi-objective optimization algorithm. Watershed managers could use these results to select optimal combinations of watershed interventions along a Pareto optimal curve based on a target load reduction or funds available. Each solution could also be used to inform where, in the landscape, implementation will be most cost-effective through detailed analysis of the BMP map output with each optimum. The results demonstrate the power of using spatial optimization methods to arrive at a cost-effective distribution of BMPs

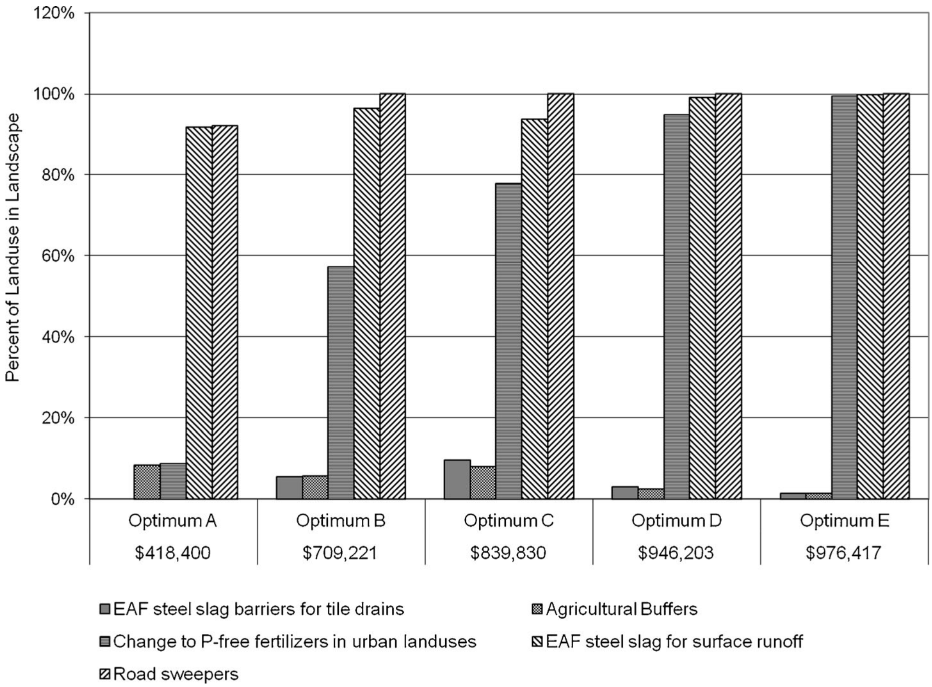

Fig. 4 Change in BMP implementation percentage across the landscape as optimum combinations increase in cost and diffuse phosphorus reduction

across a landscape. Whole watershed scenarios could achieve similar phosphorus reduction, but at costs up to 3.5 times the cost of the optimized spatially explicit solutions. The optimal solutions range in total cost for the watershed from $418,400 to $976,417 ($138 to $321 USD ha^{-1}) and represent a range of diffuse phosphorus load reduction from 0.89 to 1.13 t year^{-1} (0.29 to 0.38 kg ha^{-1}). The maximum diffuse phosphorus load reduction was 1.25 t year^{-1} using the most cost-effective technologies for each diffuse source at a cost of $3,464,260. However, 1.13 t year^{-1}could be reduced at a much lower cost of $976,417 using the interventions selected by the optimization routine. This solution represents the practical upper limit of achievable diffuse phosphorus reduction for the Stevens Brook watershed. That is, there is a clear threshold of cost-effectiveness around $1 million dollars, after which additional spending would not result in substantially more phosphorus reduction. Selecting solutions from the steep side of the Pareto curve provides the most cost-effective approach to reduce phosphorus at the watershed scale because the marginal costs for additional phosphorus reduction are the lowest.

The current load of diffuse phosphorus transported from the landscape to streams in the Stevens Brook subwatershed is 2.82 t year^{-1}. Thus, the maximum achievable annual phosphorus load reduction for the watershed is 46 %, using the interventions selected for the optimization routine. The total target reduction for the entire watershed, of which Stevens Brook is only one of five subwatersheds, ranges from 2 to 4.5 year^{-1} (Gaddis 2007; VTDEC and NYDEC 2002). Thus, combined with point source reductions and diffuse load reductions from the other four subwatersheds, the diffuse load reduction of Stevens Brook approximated of 1 t year^{-1} at a cost of $850,000 would be a significant step toward achieving TMDL targets. The optimal spatial patterns described for the Stevens Brook watershed could be applied to the other 4 subwatersheds to craft a cost-effective implementation plan for the entire St. Albans Bay watershed.

The optimization approach presented in this paper serves to target watershed areas with specific BMPs and provides a probable cost estimate for TMDL attainment. The results provide watershed managers with information to develop more tailored incentive and compensation plans and better direct volunteer efforts. States are increasingly drafting watershed plans as part of TMDL development that follow EPA's nine criteria for achieving water quality improvement and demonstrate TMDL attainability (EPA 2008). The approach described in this paper directly supports two of the nine criteria and could be used to develop watershed specific implementation plans. The approach could also be used for watershed planning in Europe, in support of the EU water directive that includes river basin planning at the catchment scale (EU 2000).

6 Conclusion

In the United States, TMDLs are required to identify the contribution of specific nonpoint sources of pollution to impaired waters. However, it is difficult to prioritize areas of a watershed or landuse types for implementation. In practice, nonpoint source control funding provided through agencies is typically allocated to willing landowners located in watersheds of impaired waters regardless of whether the land is in a priority area of the watershed. Recently, the Government Accounting Office (GAO) evaluated water quality improvement in watersheds with significant expenditures of nonpoint source control funds (GAO 2012). The study found that state programs need to be more discerning in the selection of water quality funded projects to ensure that they yield measurable water quality improvement (GAO 2012). Watershed level optimization could be used to better target funds to address the most cost-effective implementation for pollution sources and transport pathways. To maximize cost-effectiveness, optimization algorithms must account for sources, neighbor effects, and landuse specific implementation costs. Our approach is novel as it firstly links simulation modeling results derived through a participatory process with landscape optimization (Seppelt et al. 2013). It maximizes the information wrapped into the optimization routine, while minimizing computer run time by using pre-selected combinations of BMPs and running whole watershed scenarios to generate maps used in the optimization algorithm. The approach is applicable for any spatially explicit watershed model, including those that are vector based or run at larger scales, to analyze diffuse pollution.

The optimization approach described here is applicable to watersheds in which diffuse sources are significant contributors of pollution to an impaired water body, in cases where funding for BMP implementation is limited, and in watersheds in which varied sources and landscape factors create interactions that complicate pollutant transport analysis. The approach is strengthened by leveraging initial physics-based simulations of BMP scenarios at the watershed scale to reduce the size of the combinatorial problem used for follow-on optimization and could support existing adaptive watershed management and planning efforts.

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