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Optimal implementation of green infrastructure practices to minimize influences of land use change and climate change on hydrology and water quality: Case study in Spy Run Creek watershed, Indiana

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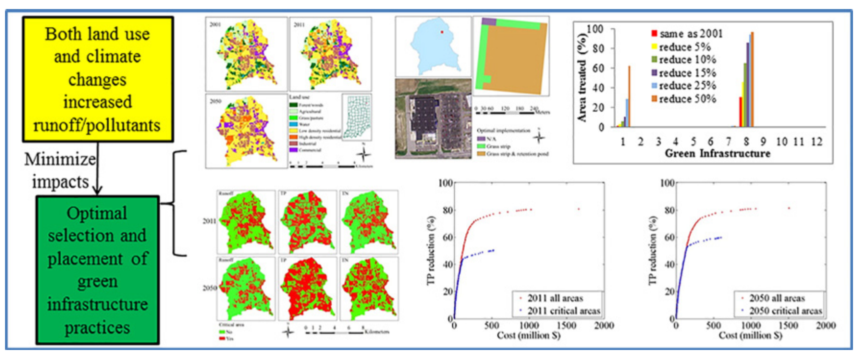
HIGHLIGHTS

- Both land use and climate changes increased runoff/pollutants from the watershed.
- Critical areas differed for various environmental concerns, land uses, and climates.
- Runoff/pollutants of 2011/2050 can be reduced to 2001 levels by green infrastructure.
- Critical area optimization can greatly decrease computational time.
- For higher reductions, critical area optimization results were not cost-effective.

GRAPHICAL ABSTRACT



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ABSTRACT

Nutrient loading from the Maumee River watershed is a significant reason for the harmful algal blooms (HABs) problem in Lake Erie. The nutrient loading from urban areas needs to be reduced with the installation of green infrastructure (GI) practices. The Long-Term Hydrologic Impact Assessment-Low Impact Development 2.1 (L-THIA-LID 2.1) model was used to explore the influences of land use (LU) and climate change on water quantity and quality in Spy Run Creek watershed (SRCW) (part of Maumee River watershed), decide whether and where excess phosphorus loading existed, identify critical areas to understand where the greatest amount of runoff/pollutants originated, and optimally implement GI practices to obtain maximum environmental benefits with the lowest costs. Both LU/climate changes increased runoff/pollutants generated from the watershed. Areas with the highest runoff/pollutant amount per area, or critical areas, differed for various environmental concerns, land uses (LUs), and climates. Compared to optimization considering all areas, optimization conducted only in critical areas can provide similar cost-effective results with decreased computational time for low levels of runoff/pollutant reductions, but critical area optimization results were not as cost-effective for higher levels of runoff/pollutant reductions. Runoff/pollutants for 2011/2050 LUs/climates could be reduced to amounts of 2001 LU/climate by installation of GI practices with annual expenditures of $0.34 to $2.05 million. The optimization scenarios that were able to obtain the 2001 runoff level in 2011/2050, can also reduce all pollutants to 2001 levels in this watershed.

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1. Introduction

LU change from natural LUs to urban areas increases impervious areas, resulting in increased runoff and impaired water quality (Chen and Chang, 2014; J. Chen et al., 2017; Fitzpatrick et al., 2007; Gitau et al., 2016; Liu et al., 2017a; Paul et al., 2017; Putro et al., 2016; Wang and Kalin, 2017; Zuo et al., 2016). Agricultural activities, such as applying fertilizer, can have adverse impacts on water quality (Arabi et al., 2008; H. Chen et al., 2017; Liu et al., 2017b; Psaltopoulos et al., 2017; Xu et al., 2017). Greenhouse gas emissions may result in climate change with varied precipitation features and air temperature (Stocker et al., 2013). Some studies found increased runoff/pollutants due to climate change (Bussi et al., 2016; Jenkins et al., 2017; Wang et al., 2017), while others reported decreased runoff/pollutants (Pruski and Nearing, 2002; Shrestha et al., 2017; Trotochaud et al., 2016). Best management practices (BMPs) and low impact development (LID) practices, which are also called GI practices in urban settings, can improve water quantity/quality in agricultural/urban areas (Ahiablame et al., 2013; Ahiablame and Shakya, 2016; Liu et al., 2015a, 2015b, 2016c; Scavia et al., 2016; Seo et al., 2017a, 2017b; Wallace, 2016; Wallace et al., 2017).

Spatial optimization can optimally apply GI practices to achieve the most environmental benefits with the lowest expenditures (Liu et al., 2016b, 2016c; Maringanti et al., 2009, 2011). A single optimization algorithm is usually combined with watershed models in spatial optimization. However, each optimization algorithm may be inefficient in finding optimal results. Liu et al. (2016b) developed an optimization tool using the L-THIA-LID 2.1 model, a multi-algorithm method (Vrugt and Robinson, 2007) (combines the strength of multiple optimization algorithms), and spatial optimization framework (Cibin and Chaubey, 2015) to efficiently obtain optimal results.

Nutrient loading from the Maumee River watershed is a major contributor to the harmful algal blooms (HABs) problem in Lake Erie (Lake Erie LaMP, 2011). Studies have explored strategies to reduce nutrient loading from agricultural areas in the watershed (e.g. Scavia et al., 2016; Wallace, 2016). However, nutrient loading from urban areas also needs to be reduced. LU/climate change impacts need to be explored as they may increase runoff/pollutants, resulting in more challenging conditions to achieve reduction goals in management plans. Various optimal GI practice implementation scenarios need to be explored to answer “what if” questions. Implementing GI practices focusing on critical areas (the greatest sources of pollutants) is a strategy commonly employed by watershed management agencies. How well this strategy would work with optimal application of GI practices needs to be explored.

The objectives were: (1) explore LU/climate change effects on runoff/pollutants in SRCW; (2) decide whether and where excess phosphorus loading existed in the watershed for 2011/2050 LUs/climates, and identify critical areas to understand where the greatest pollutant loads originated; (3) optimally apply GI practices to minimize LU/climate change effects on water quantity/quality with minimum expenditures; and (4) explore optimization results by studying various scenarios.

Hypotheses examined were: (1) both future LU/climate will increase runoff and nonpoint source (NPS) pollutants generated from the watershed; (2) critical areas will be different for various environmental concerns, LUs, and climates; (3) optimization results will differ for conducting optimization with yearly and spring rainfall; (4) runoff/pollutants for 2011/2050 conditions can be reduced to 2001 levels by applying GI practices; (5) optimal implementation scenarios of GI practices that can obtain 2001 runoff level for 2011/2050 LUs/climates, cannot reduce all pollutants to 2001 levels; and (6) compared to optimization considering all areas, critical area optimization can provide similar cost-effective results with decreased computational time for small reductions of runoff/pollutants, but critical area optimization results will not be as cost-effective for higher reductions of runoff/pollutants.

2. Background of models

2.1. Hydrologic/water quality model

L-THIA is a user friendly tool that can estimate field to watershed scales water quantity/quality (Harbor, 1994). The L-THIA-LID model (Ahiablame et al., 2012) is a LID version of L-THIA that can simulate LID practices, including bioretention system, green roof, rain barrel/cistern, porous pavement, and permeable patio. L-THIA-LID 2.1 is a newer version of L-THIA-LID that includes additional GI practices (including grassed swale, grass strip, wetland channel, wetland basin, detention basin, and retention pond) and enhanced methods to represent practices (Liu et al., 2015a, 2015b). In addition, the costs of practices and a framework to implement practices in series were added. The L-THIA and L-THIA-LID models were included in numerous research efforts (e.g. Jeon et al., 2014a, 2014b; Lim et al., 2010; Wright et al., 2016). For more information about the L-THIA-LID 2.1 model, readers should refer to previous publications (Liu et al., 2015a, 2015b, 2016a).

2.2. Optimization tool

A multi-objective optimization tool (Liu et al., 2016b), that can find optimal GI practices to obtain the largest water quantity/quality benefits with the lowest costs, was created by combining the L-THIA-LID 2.1 model with an optimization algorithm (Vrugt and Robinson, 2007) using a multilevel simulation framework (Cibin and Chaubey, 2015). In the optimization tool, two levels of optimization are conducted. At the beginning, optimization is run in individual sub-areas (optimization level 1). A lookup table with optimization results in each sub-area is created. Then optimization is run in the entire watershed built on results of optimization in each sub-area (optimization level 2). For more information of the optimization tool, readers should refer to previous publications (Liu et al., 2016b, 2016c).

3. Materials and methods

3.1. Area of interest

SRCW (HUC 041000040606), urbanized watershed with an area of 39.4 km^2 in northeast Indiana, was studied. LU data used included National Land Cover Dataset (NLCD) 2001, NLCD 2011, and future Land Transformation Model (LTM) 2050 LUs (Pijanowski et al., 2014; Tayyebi et al., 2013). Fig. 1 shows the location and LUs (2001, 2011, and 2050) of SRCW. Table S.1 in supplementary materials shows sizes of LUs for 2001, 2011, and 2050, which indicates that LU change will greatly increase urban LUs while decreasing non-urban LUs from 2001 to 2050.

3.2. Input data

Several input data, including 7 years (2009–2015) of daily precipitation (USW00014827 from www.ncdc.noaa.gov), hydrologic soil group (HSG) (Soil Survey Geographic database), and LU (NLCD 2001/2001: www.mrlc.gov/; future LTM 2050: http://ltm.agriculture.purdue.edu/usgs.htm) are needed. Seven years (2009–2015) of streamflow data from USGS-04182808 were used for calibrating/validating the model. Other GIS data (www.indianamap.org) used to estimate drainage area, drainage slope, impervious, and sizes of specific LUs (roof top, patio, etc.) included GIS layers of streams, lakes, street centerlines, imperviousness, and digital elevation model (DEM).

LUs in NLCD 2001/2011 were reclassified into eight classes, as shown in Table S.1 (Liu et al., 2015b). Predicted LTM 2050 LUs, which include all categories of NLCD 2001/2011 and a new urban LU category, were also reclassified to the above eight LU categories. The final 2050 urban LUs were expected to be proportionally consistent to those of 2011, including 60.3% LDR, 11.7% HDR, 16.7% industrial, and 11.3%

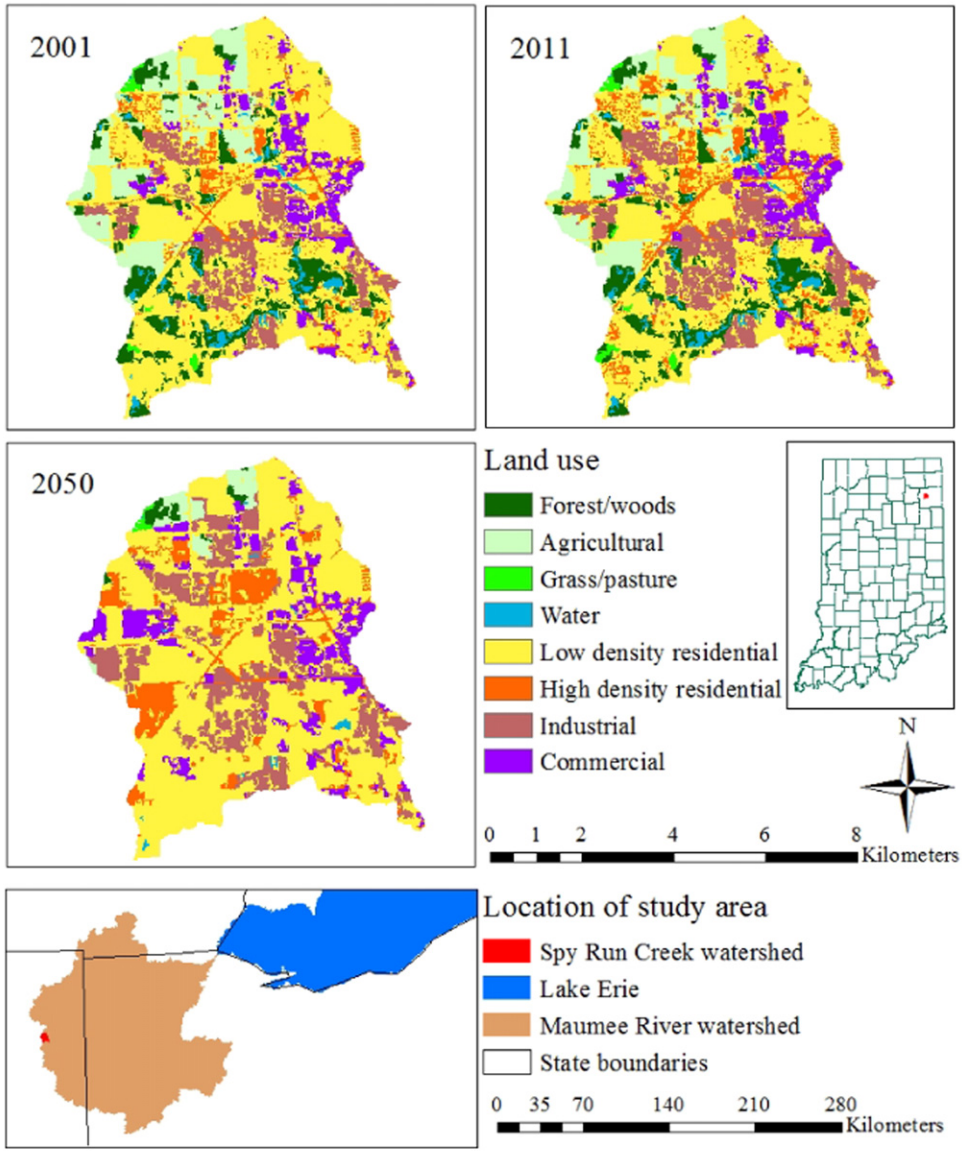


Fig. 1. Location and land uses (2001, 2011, and 2050) of Spy Run Creek watershed (SRCW).

commercial LUs. New urban LUs were reclassified using the following steps. First, contiguous new urban areas were created and ranked based on the sizes from the biggest to the smallest. Second, the new urban LU category was reclassified to detailed urban LUs by assigning the biggest contiguous areas to commercial LU first until 11.3% of the entire urban area was commercial LU. Third, the process was repeated for industrial (16.7%), then HDR (11.7%), and finally LDR (60.3%).

MarkSim web version (http://gisweb.ciat.cgiar.org/MarkSimGCM/) was used to obtain rainfall for climate change scenarios. When studying climate change impacts, at least 20 replicates were recommended (Wang et al., 2014). Therefore, WorldClim daily baseline precipitation was obtained for 30 replicates; and future precipitation data were obtained for 30 replicates for year 2050. 17 GCMs were used separately, and RCP 6.0 was used because it is an intermediate scenario (Ordonez et al., 2014; Wallace, 2016). The average annual rainfall depths of baseline and future were 963 and 991 mm, respectively.

3.3. Simulation scenarios

Simulation scenarios and methods used are shown in Table 1. The simulations started from no GI practices implemented in the watershed. Environmental concerns included runoff volume (RV), total phosphorus (TP) loads, and total nitrogen (TN) loads. The scenarios were conducted in the entire watershed unless specified (some scenarios were conducted in critical areas). GI practices simulated included retention pond, detention basin, wetland basin, rain barrel/cistern, permeable patio, green roof, grassed swale, grass strip, wetland channel, bioretention system, porous pavement, green roof with rain barrel/cistern. GI practices were represented using default values documented in previous studies (Ahiablame et al., 2012; Liu et al., 2015a, 2015b).

4. Results and discussion

4.1. Influences of LU/climate change

An increase of curve numbers by 1% gave the best simulation results. The combined calibration/validation results had an R^2 value of 0.81 and Nash Sutcliffe Coefficient value of 0.79, indicating the model had good performance in estimating annual RV (Engel et al., 2007).

Table 2(A) shows influences of LU/climate changes on yearly mean RV/pollutants. LU change resulted in more RV/pollutants, due to increased urban LUs. Other studies also reported increased runoff/pollutants when exploring the effects of LU changes on RV/pollutants (Kim et al., 2002; Liu et al., 2016c). Future climate increased RV/pollutants compared to

Table 1
Scenarios studied and methods used for each objective.

Objectives	Scenarios studied and methods used
Influences of changes in land use (LU)/climate	The influences of LU/climate change on average annual water quantity/quality were studied with six scenarios, including 2001 LU and baseline precipitation (BP), 2001 LU and future precipitation (FP), 2011 LU and BP, 2011 LU and FP, future 2050 LU and BP, and future 2050 LU and FP. Annual runoff volume (RV) simulation by the L-THIA-LID 2.1 model was used for calibration (2009–2012) and validation (2013–2015). Curve number values were altered by 1% increments to match simulated RV with observed results. Streamflow data were explored using the Baseflow Filter Program (BFLOW) (Arnold and Allen, 1999) to obtain observed RV data. Model simulation was evaluated by calculating R^2 and Nash-Sutcliffe efficiency coefficient (NSE). The L-THIA-LID 2.1 model after calibration and validation in Spy Run Creek watershed (SRCW) was used in this study for all scenarios. For baseline climate, the simulation was conducted using 30 replicates of baseline rainfall data. For future climate, the modeling was conducted using future rainfall data obtained from each of the 17 GCMs, and then the ensemble average results of runoff/pollutants were obtained based on all simulation results.
Identification of critical areas	Two scenarios studied were whether and where excess total phosphorus (TP) loading existed in 2011/2050, and critical areas in 2011/2050. The goal of 40% reduction in spring TP loads compared to 2008 Maumee River baseline is recommended by the watershed management plan (USEPA, 2016). The Maumee River was estimated to contribute 1800 tons/year of phosphorus load to Lake Erie (Lake Erie LaMP, 2011). Based on the information, the goal of TP load/area was estimated and used as the threshold to designate areas with excess TP loading. For modeling, Hydrologic Response Units (HRUs) were used and defined as areas with the same combinations of LU and soil type. HRUs with the highest runoff/pollutant load per area were selected until the total area of selected HRUs was at least 25% of the watershed area. The selected areas were defined as critical areas because they generated the highest runoff/pollutant amount per area.
Optimization of implementing GI practices	The following scenarios for optimal selection and placement of GI practices in SRCW were conducted: (1) reduce runoff/pollutants for NLCD 2011 with current rainfall; (2) reduce runoff/pollutants for LTM 2050 with future rainfall; (3) reduce TP in critical areas of the watershed using NLCD 2011 and current rainfall; (4) reduce TP in critical areas of the watershed using LTM 2050 and future rainfall; and (5) reduce TP using NLCD 2011 and current spring rainfall only (model simulations for March through July only, same definition as in Scavia et al. (2016)). The implementation of GI practices in SRCW was optimized using the multi-objective optimization tool by exploring two objective functions (Eq. 1). The objective functions were to minimize the cost of implementing GI practices (objective 1), and at the same time to minimize cumulative runoff/pollutant values (CRPV) with practices applied (objective 2). Variables used in optimization were percentages of suitable areas in the watershed for each type of GI practice. CRPV values were defined as runoff/pollutants after application of GI practices divided by runoff/pollutants before application of practices. CRPV values for RV (Runoff_CRPV), TP loads (TP_CRPV), and TN loads (TN_CRPV) were minimized in this study, as shown in Eqs. 2 to 4. $Objective\ \ function = MINIMIZE\ \ (Cost \wedge CRPV)$ (1) $Runoff\ CRPV = \frac{Runoff_{after}}{Runoff_{before}}$ (2) $TP\,CRPV = \frac{TP_{after}}{TP_{before}}$ (3) $TN\,CRPV = \frac{TN_{after}}{TN_{before}}$ (4) The efficiencies of GI practices over their life (assumed to be 20 years) were assumed to be constant; construction and maintenance expenditures with a 4.5% interest rate were used to estimate the cost of practices (Liu et al., 2015b, 2016b, 2016c). Population sizes and generations were altered to advance the performance of optimization tool, and other parameters were suggested by (Vrugt and Robinson, 2007).
Exploring Optimization results	Six scenarios were explored, including spring TP optimization vs. yearly TP optimization, attaining 2001 runoff/pollutant levels in 2011/2050, reducing 2011/2050 influences to multiple levels compared to 2001, critical area optimization vs. optimization considering all areas, exploring optimized scenarios vs. watershed management plan, and exploration of amount of urban runoff treated. The optimization results of implementing GI practices in SRCW were explored to answer "what if" questions. First, results of TP optimizations using current spring rainfall (model simulations for March through July only) and current yearly rainfall for NLCD 2011 were compared. Second, optimization results for implementing GI practices to attain 2001 runoff/pollutant levels for 2011/2050 LUs/climates were explored. Third, optimization results for implementing GI practices were explored to reduce 2011/2050 impacts to the same levels as 2001, and reductions of 5%, 10%, 15%, 25%, and 50% compared to the 2001 levels. Fourth, optimizations conducted only in critical areas and optimizations considering all areas of the watershed were compared. Fifth, optimized scenarios were explored based on the watershed management plan (USEPA, 2016), which has a goal of 40% reduction in spring TP loads compared to 2008 baseline from the Maumee River. The 2008 baseline of TP load was calculated using 2008 rainfall, NLCD 2011, and the L-THIA-LID 2.1 model. Sixth, the Great Lakes Restoration Initiative Action Plan II (GLRI, 2014) indicated the need to report amount of runoff treated from urban areas. Amount of runoff treated was calculated for the runoff optimized scenario to reduce 2011 runoff to the same level as 2001, and reductions of 5%, 10%, 15%, 25%, and 50% compared to the 2001 level.

baseline climate. This is due to increased annual rainfall depth (from 963 to 991 mm) and increased overall depths of rainfall in bigger rainfall events; smaller rainfall events would not result in as large of portions of rainfall becoming runoff as bigger rainfall events. Wang et al. (2017) studied climate change impacts on hydrology in the St. Joseph River watershed, and found average stream discharge under future climate (2021–2050) were 1.2%–10.3% higher than baseline values. LU change generally had higher influences on RV/pollutants than climate change. The scenario of 2050 LU and future rainfall had the biggest challenge in reducing runoff/pollutants to achieve management plan goals. Therefore, this scenario was included in the optimization part of the study to simulate the most challenging scenario.

4.2. Critical areas

Based on methods in Section 3.3, TP load/area goal was 63.5 kg/yr/km^2. HRUs in the watershed with values bigger than 63.5 kg/yr/km^2 indicate that this HRU has TP loading in excess of mean loading per unit area.

Fig. 2(A) shows whether and where excess TP loading existed for 2011/2050. Areas with excess TP loading are red. There were more areas with excess TP loading in 2050 than 2011, due to LU/climate change resulting in higher runoff/pollutants generated from the watershed. Fig. 2(B) shows critical areas in 2011/2050 for runoff, TP, and TN, respectively. Red represents critical areas. Critical areas were different for different environmental concerns, LUs, and climates. To implement GI practices in critical areas, different critical areas would be considered for each environmental concern.

4.3. Optimization results exploration

4.3.1. Spring TP optimization vs. yearly TP optimization

Optimal results of implementing GI practices to reduce TP using 2011 LUs with spring and yearly rainfall are shown in Fig. 3(A). The right side figure is the zoomed in display of the left side figure. X-axes show cost of GI practices for 20 years, and Y-axes show TP reduction percentages after implementing practices. Red and blue dots represent optimization results for yearly and spring rainfall, respectively. The optimal fronts, which represent optimization results of implementing GI practices, were similar for conducting optimization with yearly and spring rainfall.

Table 2
Land use (LU)/climate change impacts and optimization results exploration.

A. Influences of LU/climate change on average yearly water quantity/quality

LU	Rainfall	Runoff volume (RV) ($\times10^7$ m^3)	Total phosphorus (TP) load (ton)	Total nitrogen (TN) load (ton)
2001	Baseline	1.07	6.92	19.78
	Future	1.08	7.01	20.02
2011	Baseline	1.13	6.99	20.22
	Future	1.14	7.08	20.49
2050	Baseline	1.26	7.56	21.59
	Future	1.28	7.66	21.91

B. Results of achieving yearly mean water quantity/quality of 2001 in 2011

Concerns	2001 (Original)	2011 (Original)	Reductions needed to attain 2001 levels (%)	Corresponding yearly expenditure of optimization scenarios to obtain 2001 levels (million)	Capability of RV optimization scenario in reducing pollutants (%)
RV ($\times10^6$ m^3)	10.5	11.1	5.4	\$0.80	5.4
TP (ton)	6.8	6.9	1.2	\$0.34	4.3
TN (ton)	19.4	19.9	2.5	\$0.36	6.7

C. Results of achieving yearly mean water quantity/quality of 2001 in 2050

Concerns	2001 (Original)	2050 (Original)	Reductions needed to attain 2001 levels (%)	Corresponding yearly expenditure of optimization scenarios to obtain 2001 levels (million)	Capability of RV optimization scenario in reducing pollutants (%)
RV ($\times10^6$ m^3)	10.5	12.8	17.5	\$2.05	17.5
TP (ton)	6.8	7.7	11.6	\$0.79	18.6
TN (ton)	19.4	21.9	11.6	\$0.67	20.7

D. Results of applying 2011 TP optimized scenario to reach management plan goal of 40% TP reduction compared to 2008 level

Concerns	2008 (Original)	2011 (Original)	After applying 2011 TP optimized scenario	Reduction when applying 2011 TP optimized scenario (%)	Corresponding annual cost (million)
TP (ton)	5.4	6.8	3.3	40	\$6.1
TN (ton)	15.8	19.9	13.9	12	

E. Results of applying 2050 TP optimized scenario to reach management plan goal of 40% TP reduction compared to 2008 level

Concerns	2008 (Original)	2050 (Original)	After applying 2011 TP optimized scenario	Reduction when applying 2050 TP optimized scenario (%)	Corresponding annual cost (million)
TP (ton)	5.4	7.7	3.3	40	\$8.1
TN (ton)	15.8	21.9	14.4	9	

F. Examples of average annual urban runoff treated in optimization results to reduce 2011 runoff compared to 2001 level

2011 optimization to reduce runoff compared to 2001 level	Urban runoff captured (10^6 m^3)	Urban runoff treated but not captured (10^6 m^3)	Urban runoff treated including captured (10^6 m^3)
Same as 2001	0.6	2.2	2.8
5%	1.1	2.8	3.9
10%	1.6	3.3	4.9
15%	2.1	3.9	6.1
25%	3.2	4.3	7.4
50%	5.6	4.4	10.1

In Fig. 3(B), X-axis represents various GI practices, and Y-axis shows differences between percentages of suitable areas treated with each GI practice in yearly and spring optimized scenarios to reduce 2011 TP. The differences were between −11.9% and 8.8% (with an average of −0.2%). Based on a paired two sample *t*-Test with α of 0.05, the differences were not significant for each TP reduction level. In this particular case, optimization results of implementing GI practices were similar due to similar distributions of daily rainfall depths during spring and annually. However, in areas with obviously different distributions of daily rainfall depths during spring and annually, optimal results would be potentially different.

4.3.2. Attaining 2001 runoff/pollutant levels in 2011/2050

Tables 2(B) and 2(C) show the results to attain yearly mean water quantity/quality of 2001 in 2011 and 2050, respectively. To attain 2001 levels of RV, TP, and TN, the reductions required in 2011/2050 scenarios were 1.2%–17.5%, and corresponding annual costs of GI practices of \$0.34–\$2.05 million. Optimized scenarios that can minimize RV can reduce TP and TN by 4.3%–20.7%. To achieve RV/pollutants of 2001 levels, further reductions were needed in 2050 compared to 2011. The corresponding annual costs in 2050 were higher than 2011 due to additional GI practices needed in 2050.

By applying RV optimized scenarios (most expensive scenarios in 2011 and 2050, respectively) to the watershed, they also reduce all pollutants to 2001 levels. This was due to percent reductions of TN/TP needed to attain 2001 levels in SRCW being lower than that of RV; and many GI practices further reduce pollutant loads beyond that for RV as some practices reduce both RV and pollutant concentrations. However, this differed from results in Trail Creek watershed (TCW) (Liu et al., 2016c), which found greater percent reductions of pollutants needed than for RV, and therefore RV optimized scenario failed to reduce all pollutants in 2050 to 2001 levels. The results differed due to varied conditions of LU, HSG, and climate in the two watersheds, which resulted in different RV/pollutant reduction (%) needs to obtain 2001 levels.

In Fig. 4(A) and 4(B), X-axes show GI practices considered, while the Y-axes show percentages of suitable areas treated with each practice to achieve the yearly mean water quantity/quality (RV, TP, and TN) of 2001 in 2011/2050. Grass strip was implemented the most because it was the lowest cost per unit of RV/pollutants reduction among simulated practices. The amounts of chosen practices in each optimization scenario were higher in 2050 than 2011 due to the greater need to reduce runoff/pollutants in 2050. All optimized scenarios had different rankings of most implemented GI practices, due to cost-effective practices differing for different environmental goals. In 2011/2050, rankings of the most

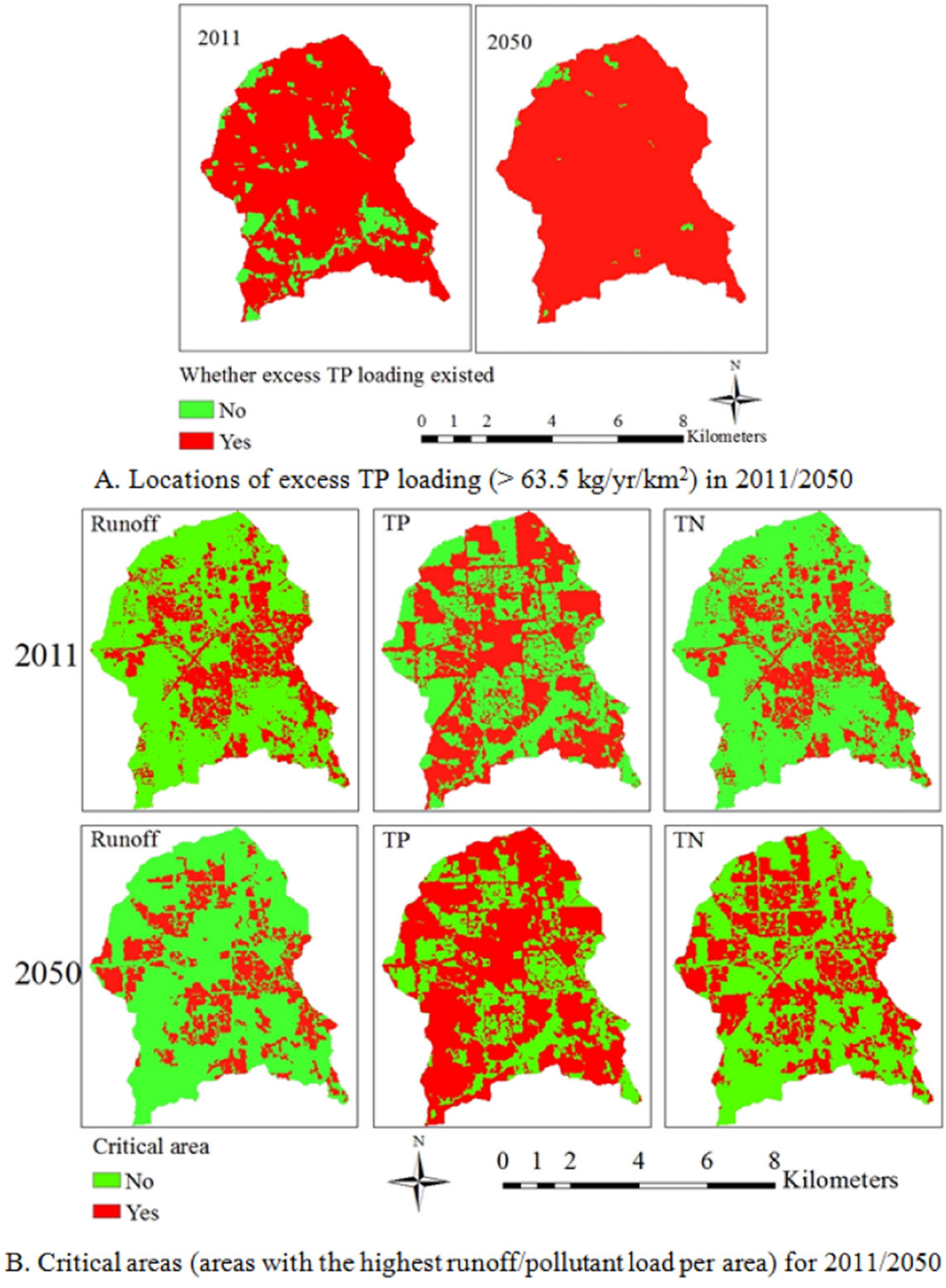


Fig. 2. Pollutant sources and critical area identification (Total phosphorus—TP, Total nitrogen—TN).

implemented practice types were identical for the same environmental concerns. Although RV optimized scenarios reduced all pollutants to 2001 levels, optimization work should still be conducted for each environmental goal individually due to favored GI practices being different for individual RV/pollutants reduction goals. Liu et al. (2016c) found similar results in TCW, which suggested that optimization work should be conducted for each RV/pollutant reduction goal. Liu et al. (2016b) analyzed the hydrologic response unit (same LU and HSG) level optimization results in Crooked Creek watershed, and found that optimal application of GI practices varied for individual goals of reducing total suspended solids and RV.

4.3.3. Reducing 2011/2050 influences to multiple levels compared to 2001

In Fig. 5(A), X-axes show reductions of 2011/2050 RV/pollutants to identical levels as 2001, and reductions of 5%, 10%, 15%, 25%, and 50% compared to the 2001 levels; the primary Y-axes show yearly costs of GI practices; and secondary Y-axes show runoff/pollutants levels with GI practices installed. To reduce runoff/NPS pollutants to multiple levels

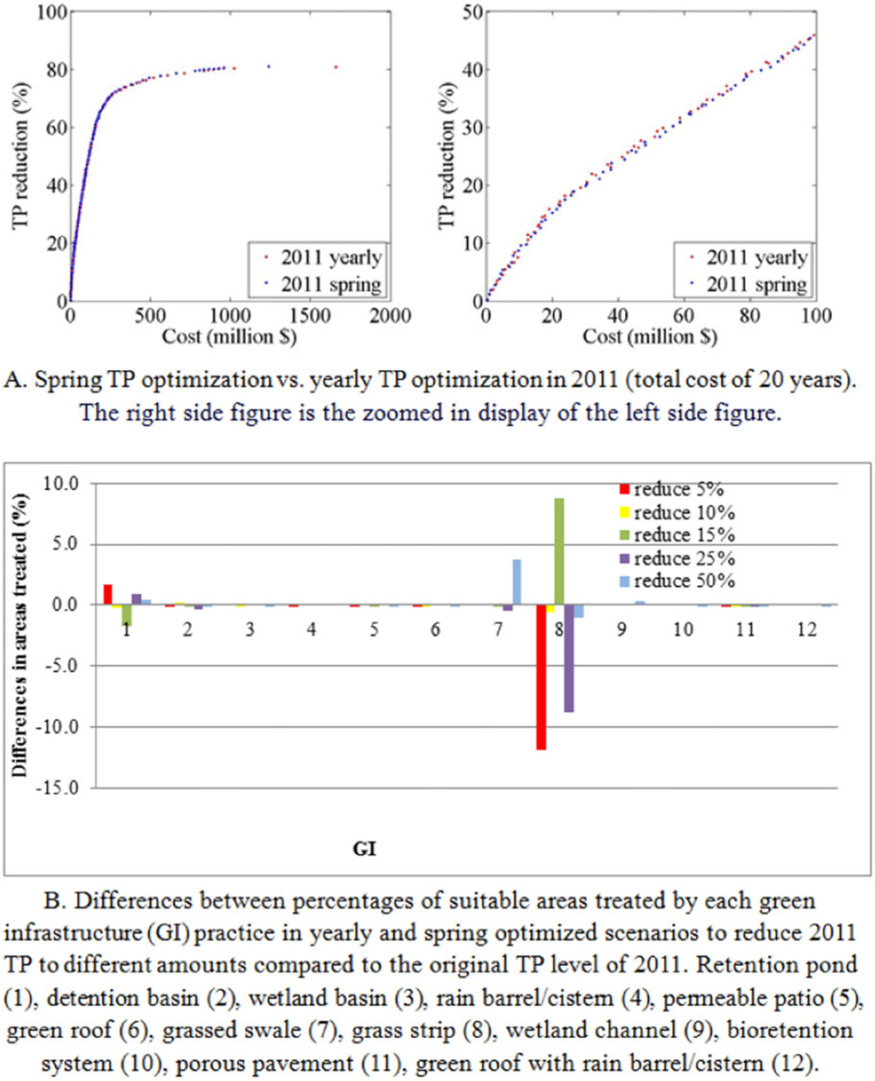


Fig. 3. Results for spring Total phosphorus (TP) optimization vs. yearly TP optimization.

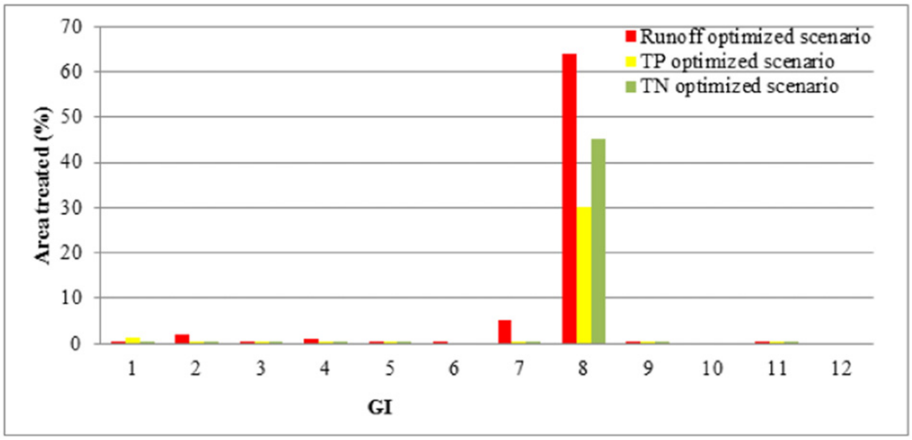
compared to 2001 levels, yearly expenditures of optimally implementing GI practices in 2011/2050 were \$0.3–\$21.0 million. To reduce RV/pollutants further, annual cost of implementing GI practices greatly increased for 2011/2050, due to implementation of additional practices to achieve the goals. The annual cost of reducing 2050 impacts to each RV/pollutants level was higher than that of 2011, due to the original RV/pollutants being higher in 2050.

In Fig. 5(B), X-axis represents each GI practice in the simulation, Y-axis represents percentages of suitable areas treated by individual GI practice in 2011 TP optimization scenarios to multiple levels compared to the 2001 level. Grass strip and retention pond were the most implemented practices, as they were more cost-efficient than other practices to reduce TP. To reduce TP further, the implementation levels of the two favored practices increased, while implementation levels of other less cost-efficient practices remained low. This was due to the most cost-efficient GI practices in reducing TP being selected during optimization and implementation level of that practice increasing until reaching its highest implementation level (100%); other practices would also be selected one by one based on the cost-effectiveness of each practice. Liu et al. (2016c) conducted a study to determine the portions of the entire watershed treated by individual GI practice in optimization scenarios that can decrease 2050 RV to multiple amounts compared to 2001 in TCW; the favored practices to reduce RV were detention basin, grassed swale, grass strip, and rain barrel/cistern. The application percentages of favored practices also increased to reduce RV further, and the implementation levels of other practices also remained low. GI practices selected were the most cost effective ones, indicating that for the small areas in which less favored practices were implemented due to these practices were more cost effective than implementing favored practices in remaining areas.

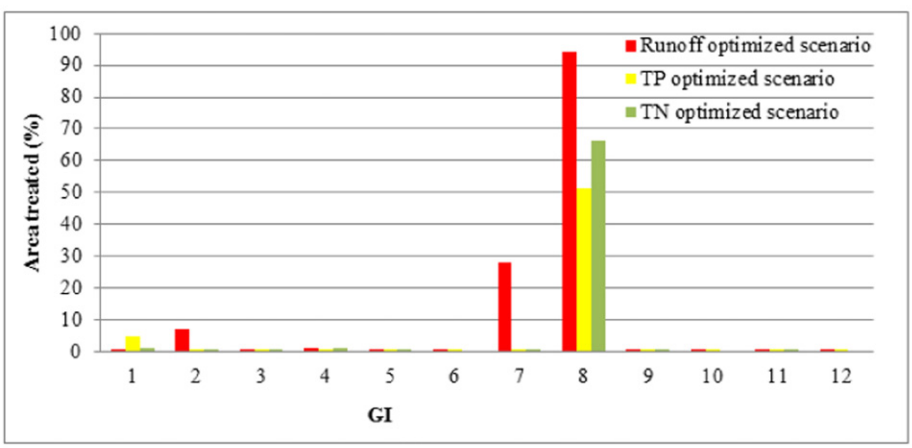
4.3.4. Critical area optimization vs. optimization considering all areas

In Fig. 6(A) and 6(B), X-axes show the cost of implementing GI practices over 20 years to reduce TP in critical area optimization vs. optimization considering all areas, and Y-axes show percent reductions of TP after implementing practices. Blue dots are critical area optimization results, and red dots are results of optimization considering all areas. The right side figure is the zoomed in display of the left side figure.

Twelve parallel Matlab workers on one Intel Xeon-E5 processor were used for the first level optimizations, while one Matlab worker on the same processor was used for the second level optimizations. The computational time of optimization considering all areas in 2011 was 102 h, while critical area optimization in 2011 only needed 0.8 h to complete. For 2050 scenarios, the computational time of optimization considering all areas was 75 h, while critical area optimization only required 0.7 h to run. This was due to the reduced search space for critical area optimization, making it faster to find optimal combinations compared to optimization considering all areas. To obtain small TP reductions, results of critical area optimization and optimization considering all areas were similar. The



A. Percentages of suitable areas treated by each GI practice to obtain yearly mean water quantity/quality of 2001 in 2011. Retention pond (1), detention basin (2), wetland basin (3), rain barrel/cistern (4), permeable patio (5), green roof (6), grassed swale (7), grass strip (8), wetland channel (9), bioretention system (10), porous pavement (11), green roof with rain barrel/cistern (12). Total Phosphorus—TP, Total Nitrogen—TN.

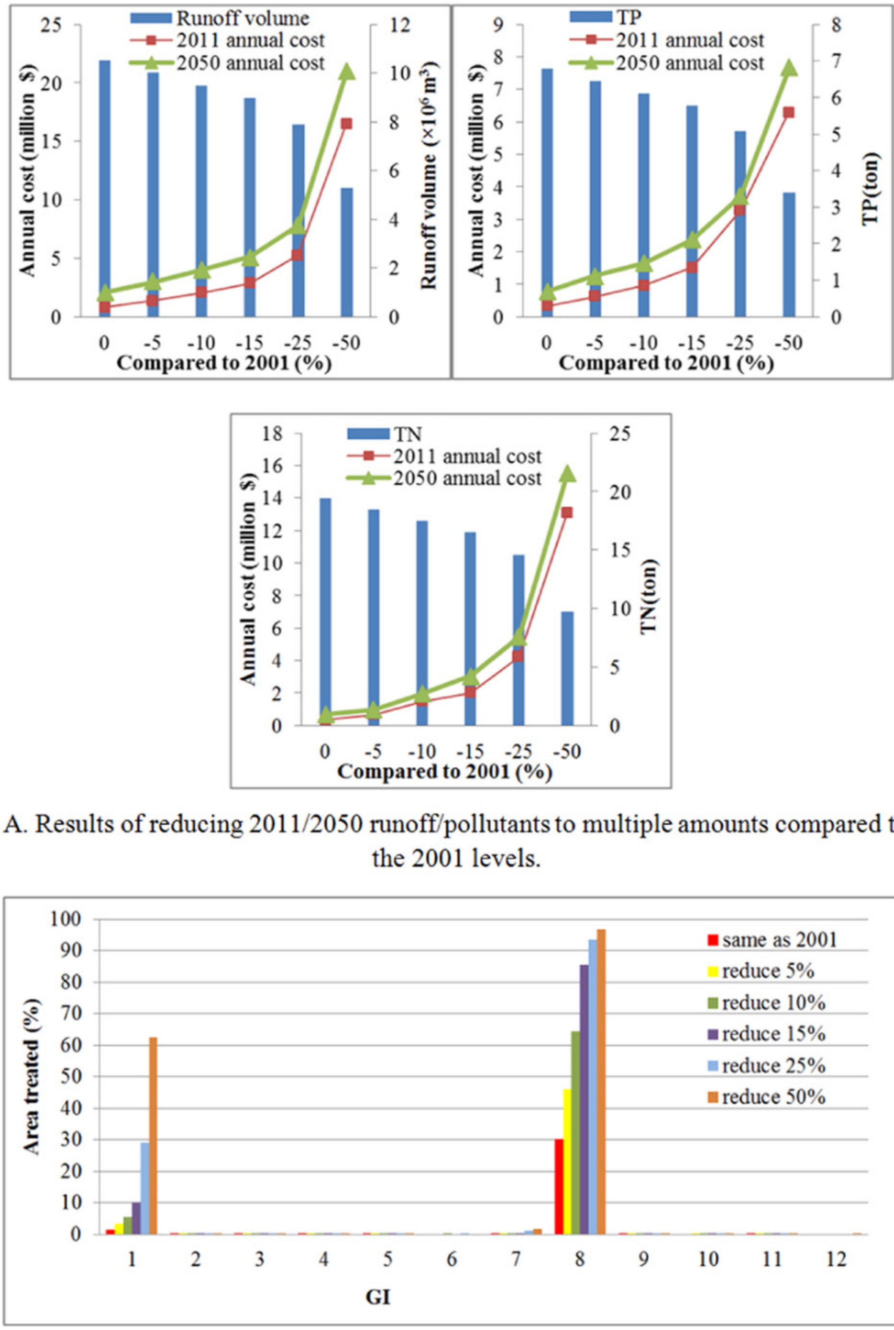


B. Percentages of suitable areas treated by each GI practice to obtain yearly mean water quantity/quality of 2001 in 2050.

Fig. 4. Suitable areas (%) treated by individual green infrastructure (GI) practice in optimization scenarios.

figures on the right side in Fig. 6(A) and 6(B) show the blue and red dots (representing optimization results) did not overlap, indicating these solutions were close to optimal rather than optimal results. The results were not expected to be optimal due to the large search space in the selection and placement of GI practices. However, after certain reduction levels, critical area results were not as cost-efficient as results of optimization considering all areas, and the highest reductions obtained for critical area were lower than those for the entire watershed. This was due to critical areas generating only a portion of TP loads (68.2% for 2011 and 75.9% for 2050), and therefore this percentage was the highest potential that critical area optimization can achieve. The costs of per unit TP reduction were lower for other areas of the watershed at some point, resulting in less cost-efficient results for critical area optimization. This indicates that critical area optimization could greatly reduce computational time in identifying solutions for lower level reductions of runoff/pollutants compared to that of optimization considering all areas. However, for greater runoff/pollutant reductions, critical area optimization results would not be as cost-efficient as results of optimization considering all areas.

Fig. 6(C) shows percentages of suitable areas treated by individual GI practices to remove TP for 2011 critical areas with yearly rainfall to multiple amounts compared to the 2001 level. X-axis represents all GI practices simulated, and Y-axis represents suitable areas (%) treated by individual GI practice. Compared to the figure that shows percentages of suitable areas treated by individual GI practice to minimize TP in 2011 for the entire watershed (Section 4.3.3), optimized scenarios to reduce TP in 2011 critical areas show the same most favored practices, including retention pond and grass strip. Implementation levels of most favored practices also increased to reduce TP further. For lower TP reductions, the implementation levels of favored practices were similar in both figures, since they can obtain similar results for lower reduction goals. However, implementation levels of practices for greater TP reductions were quite different since critical area optimization had lower maximum TP reduction potential and had fewer areas to implement the most cost-efficient practices, less cost-efficient practices needed to be implemented, resulting in less cost-efficient results.



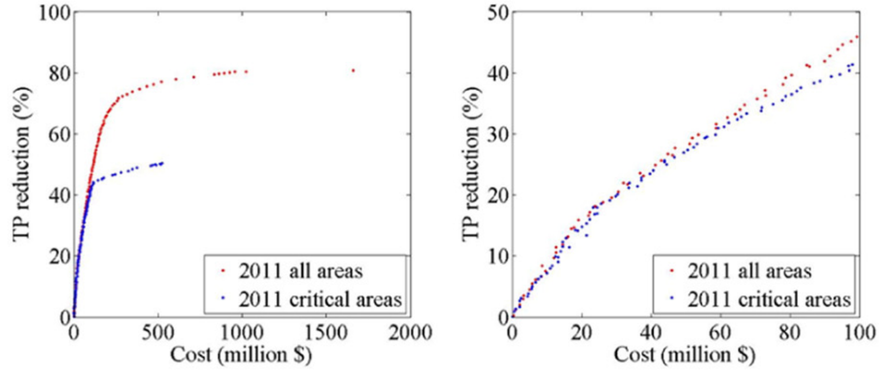
A. Results of reducing 2011/2050 runoff/pollutants to multiple amounts compared to the 2001 levels.

B. Percentages of suitable areas treated by individual GI practice in 2011 TP optimized scenarios to multiple amounts compared 2001 level. Retention pond (1), detention basin (2), wetland basin (3), rain barrel/cistern (4), permeable patio (5), green roof (6), grassed swale (7), grass strip (8), wetland channel (9), bioretention system (10), porous pavement (11), green roof with rain barrel/cistern (12).

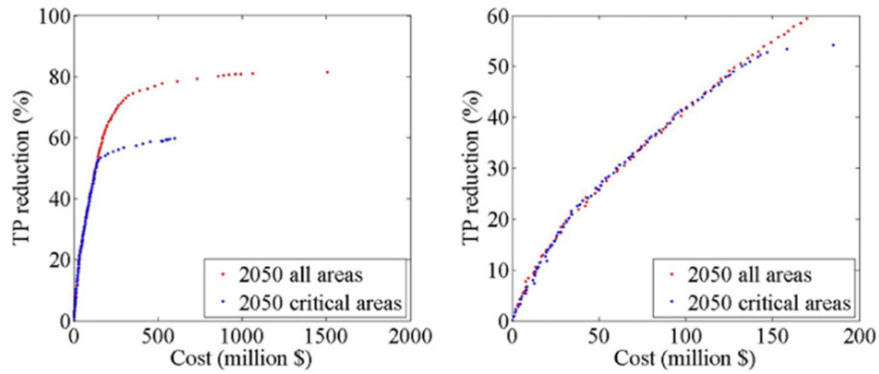
Fig. 5. Results of reducing 2011/2050 influences to multiple amounts compared to 2001.

4.3.5. Exploring optimized scenarios vs. watershed management plan

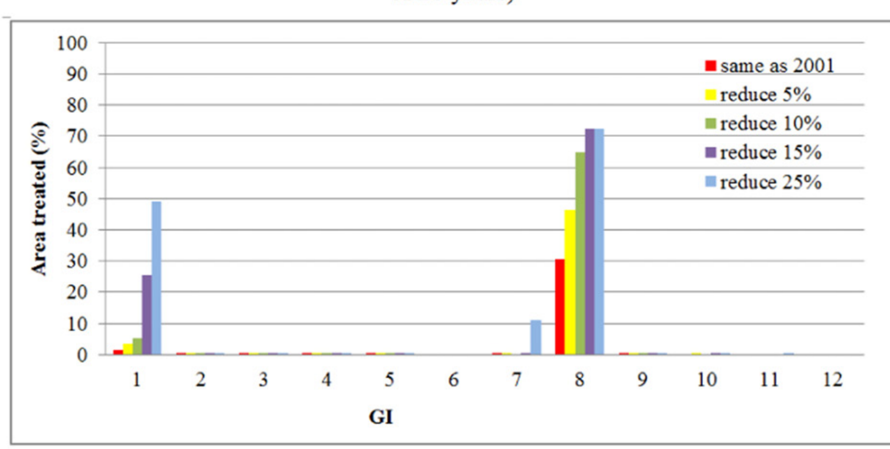
Tables 2(D) and 2(E) show the results of applying 2011/2050 TP optimized scenarios to reach the watershed management plan goal of 40% TP reduction compared to the 2008 level. Information in the tables includes environmental benefits (TP and TN), original pollutant loads (2008, 2011, and 2050), pollutants after applying 2011/2050 TP optimized scenarios that can reduce TP by 40% compared to the 2008 level, percent reductions of pollutants by applying the 2011/2050 TP optimized scenarios, and corresponding annual cost of the 2011/2050 TP optimized scenarios. Results show that 2011 TP and TN can be reduced to 3.3 ton and13.9 ton, respectively, which were 40% and 12% reductions compared to 2008 levels, respectively. The annual cost of the 2011 TP optimized scenario was $6.1 million. The 2050 TP and TN can be decreased to 3.3 ton and 14.4 ton, respectively, which were 40% and 9% reductions compared to 2008 levels, respectively. The annual cost of the 2050 TP optimized scenario was $8.1 million. As expected,



A. Critical area optimization vs. optimization considering all areas in 2011



B. Critical area optimization vs. optimization considering all areas in 2050 (total cost of 20 years)



C. Percentages of suitable areas treated by individual green infrastructure (GI) practice to minimize TP for 2011 critical areas with yearly rainfall to multiple amounts compared to 2001. Retention pond (1), detention basin (2), wetland basin (3), rain barrel/cistern (4), permeable patio (5), green roof (6), grassed swale (7), grass strip (8), wetland channel (9), bioretention system (10), porous pavement (11), green roof with rain barrel/cistern (12).

Fig. 6. Results for critical area optimization vs. optimization considering all areas (Total phosphorus—TP).

the 2050 TP optimized scenario cost more, and at the same time can reduce pollutants more compared to results of the 2011 TP optimized scenario. Due to LU/climate change, to attain the same level of TP load, the 2050 TP optimized scenario required more GI practices compared to that of 2011, and the additional GI practices implemented can reduce pollutants more compared to pollutant reduction capabilities of the 2011 TP optimized scenario. This indicates the importance of considering LU/climate change to achieve the goals of watershed management plans. Both 2011/2050 TP optimized scenarios were able to reduce TN to levels below those of 2008. Results indicate that TP optimized scenarios were not as effective in reducing TN. If the reduction goal of a watershed management plan was to reduce TP and TN to certain levels simultaneously, optimization would need to be conducted again with revised objective functions.

4.3.6. Exploring amount of urban runoff treated

The following results show how urban runoff treated by GI practices in optimization scenarios could be reported. Table 2(F) shows urban runoff treated for six optimized scenarios that can reduce 2011 runoff to the same level as 2001, and reductions of 5%, 10%, 15%, 25%, and 50% compared to the 2001 level. After the implementation of GI practices in six optimization scenarios, average annual urban RV captured was 0.6, 1.1, 1.6, 2.1, 3.2, and 5.6 million m^3; average annual urban runoff treated but not captured was 2.2, 2.8, 3.3, 3.9, 4.3, and 4.4 million m^3; and average annual urban runoff treated, including captured, was 2.8, 3.9, 4.9, 6.1, 7.4, and 10.1 million m^3.

4.4. Results of testing hypotheses

The study supported part of the hypotheses examined. First, we found that both LU and climate changes increased runoff/NPS pollutants generated from the watershed (Section 4.1). Second, we found that critical areas were different for various environmental concerns, LUs, and climates (Section 4.2). Third, RV and NPS pollutants of 2011/2050 can be reduced to 2001 amounts with implementation of GI practices (Section 4.3). Fourth, the study found that critical area optimization can provide similar cost-effective results with decreased computational time compared to optimization considering all areas for smaller runoff/pollutant reductions, but for higher levels of runoff/pollutant reductions, critical area optimization results were not as cost-effective (Section 4.3). However, other hypotheses were not supported by the findings of this study. The study found that optimization results were similar for yearly and spring rainfall in this particular watershed (Section 4.3); however, in areas with obviously different distributions of daily rainfall depths in spring and annually, optimal results could be different. Second, this study found that RV optimized scenarios, which can attain 2001 runoff level in 2011/2050, can also reduce all pollutants to 2001 levels (Section 4.3); however, optimization work should still be conducted for each environmental goal individually since favored GI practices were different for each runoff/pollutants removal goal.

5. Conclusions

The L-THIA-LID 2.1 model was applied to explore the influences of LU/climate change on water quantity/quality in SRCW. Locations of expected excess phosphorus loading in the watershed in 2011/2050 were calculated. Critical areas with the highest runoff/pollutant amounts per area in 2011/2050 were identified. GI practices were optimally selected and placed to minimize adverse effects of LU/climate change on water quantity/quality with minimum costs. Optimal results were explored through various scenarios.

Results indicate that changes in both LU and climate increased runoff/NPS pollutants. There were more areas with excess TP loading in 2050 compared to that of 2011. Critical areas were different for various environmental concerns, LUs, and climates. Optimization results were similar for yearly and spring rainfall in the area. However, in areas with obviously different distributions of spring and annual daily rainfall depths, optimal results may be different. To attain 2001 levels of RV, TP, and TN, the corresponding annual costs of implementing GI practices in 2011/2050 scenarios were \$0.34 to \$2.05 million. RV optimized scenarios cost the most compared to other optimization scenarios; by applying RV optimized scenarios to the watershed, they can also reduce TP and TN to 2001 levels. However, optimization work should still be conducted for each environmental goal individually since favored GI practices were different for each environmental concern. To reduce runoff/NPS pollutants to multiple levels compared to 2001 levels, yearly expenditures of optimally implementing GI practices in 2011/2050 were \$0.3 to \$21.0 million. To reduce RV/pollutant loads further, annual costs greatly increased, and the annual cost of reducing 2050 impacts to each runoff/pollutant level was higher than that of 2011. Critical area optimization reduced search space and decreased computational time compared to optimization considering all areas. Compared to optimization considering all areas, results of critical area optimization were similar for lower level TP reductions, but critical area optimization results were not as cost-efficient after certain reduction levels. Results of optimally implementing GI practices to reduce 2011 runoff to the same levels as 2001, and reductions of 5%, 10%, 15%, 25%, and 50% compared to the 2001 levels show that urban runoff treated including captured was 2.8 to 10.1 million m^3.

For future studies, optimization results of implementing GI practices should be expanded to all urban areas in the Maumee River watershed. Future research can be conducted to study the difference between optimization results using yearly rainfall and spring rainfall in another location with different rainfall features. To quantify the small runoff/pollutant reduction levels that critical area optimization can provide similar optimal results compared to optimization considering all areas, the transition points need to be explored in the future for different environmental concerns and critical area definitions. The LTM predicted all categories of NLCD 2001/2011 and a new urban LU category. In future studies, the LTM model should be improved to separate the new urban LU category into specific urban LUs.

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Appendix A. Appendix A Supplementary data.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.scitotenv.2017.06.015.

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