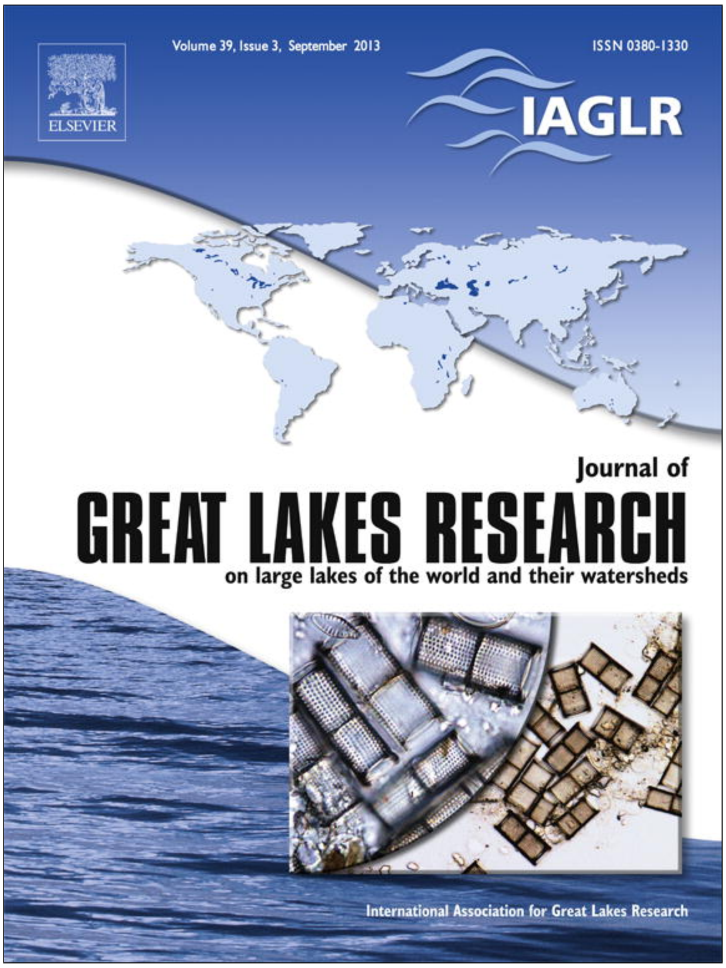
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Scenario-testing of agricultural best management practices in Lake Erie watersheds

Nathan S. Bosch [a,*], J. David Allan [b,1], James P. Selegean [c,2], Donald Scavia [d,3]

[a] Environmental Science, Grace College, Winona Lake IN 46590, USA
[b] School of Natural Resources and Environment, University of Michigan, Ann Arbor MI 48109, USA
[c] Great Lakes Hydraulics and Hydrology Office, U.S. Army Corps of Engineers, Detroit District, Detroit MI 48226, USA
[d] Graham Environmental Sustainability Institute, University of Michigan, Ann Arbor, MI 48104, USA

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ABSTRACT

Current research has shown that reductions in nonpoint nutrient loading are needed to reduce the incidence of harmful algal blooms and hypoxia in the western and central basins of Lake Erie. We used the Soil and Water Assessment Tool (SWAT) to test various sediment and nutrient load reduction strategies, including agricultural best management practice (BMP) implementation and source reduction in various combinations for six watersheds. These watersheds, in order of decreasing phosphorus loads, include the Maumee, Sandusky, Cuyahoga, Raisin, Grand, and Huron, and together comprise 53% of the binational Lake Erie Basin area. Hypothetical pristine nutrient yields, after eliminating all anthropogenic influences, were estimated to be an order of magnitude lower than current yields, underscoring the need for stronger management actions. However, cover crops, filter strips, and no-till BMPs, when implemented at levels considered feasible, were minimally effective, reducing sediment and nutrient yields by only 0–11% relative to current values. Sediment yield reduction was greater than nutrient yield reduction, and the greatest reduction was found when all three BMPs were implemented simultaneously. When BMPs were targeted at specific locations rather than at random, greater reduction in nutrient yields was achieved with BMPs placed in high source locations, whereas reduction in sediment yields was greatest when BMPs were located near the river outlet. Modest nutrient source reduction also was minimally effective in reducing yields. Our model results indicate that an "all-of-above" strategy is needed to substantially reduce nutrient yields and that BMPs should be much more widely implemented.

Introduction

Lake Erie has a long history of water quality concerns related to cultural eutrophication stemming from tributary inputs of sediments and nutrients (Boyce et al., 1987; Rosa and Burns, 1987). Past efforts to quantify inputs have evaluated both nonpoint and point source loading (De Pinto et al., 1986; Dolan, 1993; Richards, 1985), resulting in management actions that have had some success in reducing both types of inputs, especially point sources (Dolan and McGunagle, 2005). Recent work indicates that nonpoint source loading is currently the major contributor to nutrients in Lake Erie (Bosch and Allan, 2008; Dolan and Chapra, 2012; Ohio Lake Erie Phosphorus Task Force Final Report, 2010), although point source loading has been shown to be important in certain situations as well (Nemery et al., 2005). In recent years the extent of hypoxia (Zhou et al., 2012) and harmful algal blooms (Michalak et al., 2013; Stumpf et al., 2012) has drawn attention to the potential importance of land-derived nutrients in a resurgence of eutrophication symptoms in Lake Erie.

Agricultural best management practices (BMPs) are an important mechanism to reduce delivery of nutrients and sediments from nonpoint sources. Best management practices include changes in agricultural practices such as reducing tillage or planting cover crops as well as structural changes such as the addition of edge-of-field filter strips or bioswales. Despite widespread implementations of BMPs, there are few field-based, watershed-scale studies of their effectiveness, and existing studies show mixed results. Best management practices led to reductions in dissolved phosphorus loads from watersheds in a dairy farming region of New York (Easton et al., 2008) and reduced both sediments and nutrients in a study of six small agricultural watersheds in New York (Makarewicz et al., 2009). On the other hand, a paired watershed study in central Illinois found no significant changes in sediments, nitrate, total phosphorus, or dissolved reactive phosphorus in response to BMP implementation (Lemke et al., 2011). A study in three oxbow lakes of the Mississippi Delta showed consistent sediment decreases

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[*] Corresponding author. Tel.: +1 574 372 5100x6447.
E-mail addresses: boschns@grace.edu (N.S. Bosch), dallan@umich.edu (J.D. Allan), james.p.selegean@usace.army.mil (J.P. Selegean), scavia@umich.edu (D. Scavia).
[1] Tel.: +1 734 764 6553.
[2] Tel.: +1 313 226 6791.
[3] Tel.: +1 734 615 4860.

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of 34–59% with implementation of both cultural and structural BMPs, but results with nutrients were inconsistent (Cullum et al., 2006). Field studies of BMP implementation are impractical in large watersheds, and even small watershed results may be inconclusive because of the limited scale of BMP implementation relative to watershed area (Makarewicz, 2009) or due to other confounding factors. Thus models provide the most feasible approach for estimating impacts of alternative BMPs for improving water quality. The Soil and Water Assessment Tool (SWAT) is often used to evaluate the water quality benefits of agricultural conservation practices because it offers a number of management alternatives and is the basis of EPA-BASINS, the EPA hydrologic model used in many watershed TMDL studies. In addition, SWAT is capable of simulating many of the crop and tillage practices likely to be used, allowing one to test alternative scenarios aimed at reducing sediment and nutrient export from watersheds.

SWAT is a semi-empirical hydrologic and water quality model that was developed by the USDA and runs at a daily time step (Arnold et al., 1998). A continuous-time, watershed-scale model (Gassman et al., 2007), it includes hydrology, sediment, and nutrient processes in both upland and water-routing phases (Neitsch et al., 2005). Several forms of nitrogen and phosphorus are modeled separately with mechanistic representations of transport, uptake, loss, and transformation. SWAT includes a spatially explicit parameterization at the subwatershed scale (Bosch et al., 2011).

SWAT has been successfully applied to Lake Erie watersheds in previous studies (Bosch, 2008; Bosch et al., 2011; Grunwald and Qi, 2006; Hargreaves and Hobbs, 2009; Qi and Grunwald, 2005). Bosch (2008) used SWAT to show that impoundments reduced riverine sediment and nutrient export from two Lake Erie watersheds, the Huron and Raisin. A SWAT application in the Sandusky watershed demonstrated the importance of hydrology calibration (Qi and Grunwald, 2005) and identified critical source areas of sediments, phosphorus, and nitrogen (Grunwald and Qi, 2006). SWAT scenarios were used to optimize future development based on both economic and ecological objectives in the Chagrin watershed of Ohio (Hargreaves and Hobbs, 2009). In a recent SWAT application, Bosch et al. (2011) compared calibration and validation results for six Lake Erie watersheds of differing agricultural, forested, and urban land use. Using 4 years of calibration data and 4 years of validation data for river discharge, sediment, and nutrient loads, that study found best model performance in agricultural and forested watersheds, relative to two urban watersheds, and established model reliability based on multiple criteria such that further scenario testing was appropriate.

The present study uses the six SWAT models previously calibrated for the Huron, Raisin, Maumee, Sandusky, Grand, and Cuyahoga (Bosch et al., 2011) to evaluate BMP effectiveness in reducing sediment and nutrient loads emanating from watersheds that comprise a substantial fraction (53%) of the binational Lake Erie basin area. Moreover, these six watersheds dominate nutrient inputs to the Western and Central Basins and contribute the major share of nonpoint runoff to Lake Erie. First, we ask whether extending BMP implementation to levels deemed feasible by agriculture conservation staff will appreciably reduce sediment and nutrient loss. We test three BMPs (filter strips, cover crops, and no-till), singly and in combination, that are currently in use and considered effective by conservation staff. Second, we ask whether location placement of BMPs within watersheds can be adjusted to increase their effectiveness. Third, we consider whether source reduction rather than BMP implementation is more likely to decrease tributary sediment and nutrient loads. Finally, we examine these options under moderate vs. more aggressive levels of implementation. Our results point to the need for more aggressive implementation of multiple strategies to substantially reduce tributary nutrient loading to Lake Erie. To our knowledge no previous effort using SWAT or similar models has evaluated multiple BMP strategies together with source reduction to address nutrient management over such a broad region responsible for nonpoint runoff to Lake Erie.

Methods

Study area

The Huron, Raisin, Maumee, and Sandusky watersheds drain into the western basin of Lake Erie; the Cuyahoga and Grand watersheds drain into the central basin (Fig. 1). The six watersheds vary widely in watershed size, precipitation, and land cover (Table 1). Average annual precipitation increases slightly from west to east due to increasing lake-effect precipitation in the eastern watersheds. The Raisin, Maumee, and Sandusky are predominantly agricultural, while the Huron and Cuyahoga are more urbanized. The Grand watershed is mostly forested (Bosch et al., 2011).

Model parameterization and calibration

Several types of input data were used to parameterize the six models using ArcSWAT (version 2.1.5). Required data included elevation, stream network, land cover, soil type, weather, point source discharges, tile drainage, impoundment (reservoir, lake, or pond) characteristics, atmospheric N deposition, and land management practices. As previously described in more detail (see Supplemental Information Appendix A and Bosch et al., 2011), all six models were run for 1995–2005, including 3 years for model spin-up (1995–1997), 4 years for calibration (1998–2001), and 4 years for validation (2002–2005). Stream flow discharge, sediment loads, and nutrient loads (TP, SRP, TN, nitrate) were included in calibration and validation (Table 2 and Supplemental Information Appendix A). USGS gage stations near the river mouth of each watershed were used for daily mean stream discharge. The National Center for Water Quality Research at Heidelberg College provided near-daily sediment, TP, SRP, TN, and nitrate loads for most watersheds. For the Huron watershed, approximately biweekly TP, SRP, TN, and nitrate concentration data were collected for 3 years of the study period (Bosch et al., 2009). Owing to limited data, 2003 and 2004 loads were used for calibration, and 2005 loads were used for validation in the case of the Huron watershed.

Comparative scenario testing across all six watersheds

We first simulated modest implementation of three common agricultural BMPs randomly across all six watersheds (Table 3a). These “modest implementations” represented the judgment of local agricultural conservation staff for a “feasible” suite of improvements in agricultural practices above current efforts. The baseline scenario included current watershed conditions as simulated in the models without any alteration to parameter values derived from previous calibration and validation work (Bosch et al., 2011). The no-till scenario simulated a cessation of any tillage practices related to corn and soybean crops across an additional randomly selected 25% of row-crop land. This was accomplished in SWAT by decreasing curve number (CN2), increasing overland Manning's roughness coefficient (OV_N), and omitting tillage operations in the. Mgt input file following the procedure described by Arabi et al. (2008). Field cultivator tillage in preparation for winter wheat planting was retained in crop rotation operations. We inserted a cover scenario across a randomly selected 25% of row-crop land to include a cereal rye grass cover crop planted immediately after soybean harvest and killed immediately before corn planting the next year. Our filter strip scenario was applied across a randomly selected 20% of row-crop land. We utilized the equations and methods described in Arabi et al. (2008) to represent a 10-m wide edge-of-field vegetative strip with a 25% trapping efficiency. A 25% trapping efficiency was used as a conservative estimate for Lake Erie watersheds due to work done with similar soil textures in southeastern Norway (Syversen and Borch, 2005). Finally, we simulated a combined scenario in which all three BMPs were implemented to the same row-crop area which was chosen randomly. Because the filter strip BMP was applied to only

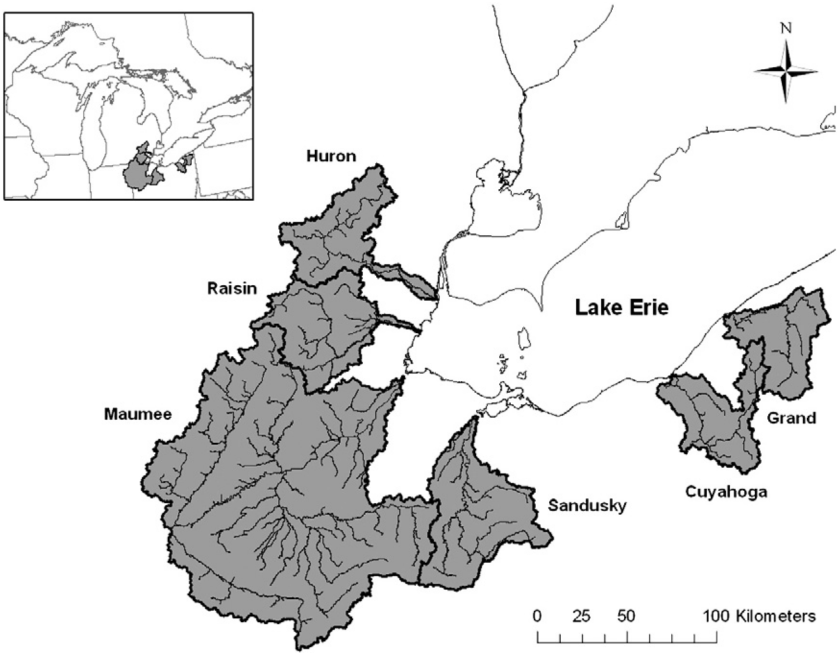

Fig. 1. The Huron, Raisin, Maumee, Sandusky, Cuyahoga, and Grand watersheds draining into western and central Lake Erie as delineated in SWAT models.

20% of cropland while cover crops and no-till to 25% of cropland, a small portion (5%) of the total area under the combination scenario had only no-till and cover crop applied.

We tested these scenarios among the different BMPs and across the watersheds based on comparison to the baseline scenario over the years 1998–2005. Yields were calculated at the outlet of each watershed, and these annual yields were then averaged for comparison of scenario outcomes for water, sediment, TP, SRP, TN, and nitrate. All results are presented as yields because this adjusts for watershed area and discharge, thus making comparisons among watersheds and scenarios direct and intuitive. The total quantity of sediments or nutrients that reach Lake Erie is the load, which equals yield times drainage area (see Table 1 for drainage area). While the impact of watershed runoff on lake processes is best evaluated based on the total load of materials entering the lake, BMP effectiveness is best represented as yields.

Detailed scenario testing of Maumee watershed

As the largest of the six study watersheds and with the greatest sediment and nutrient loads delivered to Lake Erie, the Maumee watershed was chosen for a more detailed analysis of BMP implementation location and extent, as well as source reduction (Table 3b). The Maumee watershed was delineated in SWAT with 203 subwatersheds, allowing considerable flexibility in spatial positioning of BMPs in scenario testing. The first series of scenarios tested three options for optimizing BMP placement. The random-combined scenario was identical to the combined scenario tested for all six watersheds. In the source-combined scenario, we applied BMPs to the 25% of the row-crop land which had the highest loading rates (i.e., sources of inputs) of sediment, TP, and TN. The 203 Maumee subwatersheds were ranked based on loading rates for these three parameters, and then BMPs were added to these subwatersheds in rank order until 25% of the row-crop land was selected. In the river mouth-combined scenario, we placed BMPs in subwatersheds that represented 25% of land located closest to the watershed outlet at the Maumee River mouth.

To test the influence of more aggressive BMP implementation in the Maumee watershed, each individual BMP and the combination of all three were simulated as 100% implementation in all row-crop land (Table 3b). Additional scenarios were developed and tested for the combined BMP situation, with implementation extents of 0% (baseline), 12.5%, 25% (moderate), 50%, and 100% (full).

We also assessed the effect of moderate source reduction in manure and fertilizer application and point loads for comparison with various BMP strategies (Table 3b). We simulated a 25% reduction in manure application rates across all hay and row-crop agriculture land in the Maumee watershed, leaving all manure spreading operations otherwise

Table 1
Characteristics of the Huron, Raisin, Maumee, Sandusky, Cuyahoga, and Grand watersheds for the modeled areas determined at the watershed outlet location.

	Watershed Size (km^2)	Precipitation (mm/yr)	Landcover (%)			
			Row-crop	Hay	Urban	Forested
Huron	2379	896	13	13	34	37
Raisin	2784	861	53	19	11	16
Maumee	17030	934	76	5	11	8
Sandusky	3455	962	80	3	9	8
Cuyahoga	2100	1039	8	7	47	35
Grand	1896	1093	27	10	10	52

Table 2
Calibration and validation results for monthly total phosphorus loads (Mg P) for the six modeled watersheds. Coefficient of determination (R^2), Nash–Sutcliffe simulation efficiency (NSE), and percent bias (PBIAS) are used as evaluators of model performance. Statistics taken from Bosch et al. (2011). Mg = metric tonnes.

	Observed Mean (Mg P)	Simulated Mean (Mg P)	R^2	NSE	PBIAS (%)
(a) Calibration					
Huron	1	1	0.53	−2.55	−2
Raisin	11	8	0.52	0.47	29
Maumee	149	149	0.72	0.72	0
Sandusky	23	24	0.66	0.64	−1
Cuyahoga	14	14	0.41	0.11	1
Grand	6	7	0.71	0.68	−7
(b) Validation					
Huron	1	3	0.16	−46.12	−220
Raisin	9	8	0.50	0.49	11
Maumee	182	137	0.86	0.74	25
Sandusky	43	30	0.87	0.77	29
Cuyahoga	29	16	0.68	0.39	44
Grand	13	9	0.30	0.28	25

Table 3
SWAT scenario descriptions for testing with all six watersheds (a) and only the Maumee (b).

	Scenario name	Scenario description
a)	Baseline	Actual conditions simulated
	No-till	No-till corn and soybean implemented in random 25% of row-crop agricultural land
	Cover	Rye cover crop planted between soybean and corn crop in random 25% of row-crop agricultural land
	Filter	Filter strip (10 m with 25% trapping efficiency) in random 20% of row-crop agricultural land
	Combined	Combination of three BMPs on same randomly distributed row-crop agricultural land
b)	Random combined	Combination of three BMPs on same 25% of Maumee row-crop agricultural land; randomly distributed among subwatersheds
	Source combined	Combination of three BMPs on same 25% of Maumee row-crop agricultural land; distributed in high source subwatersheds
	Mouth combined	Combination of three BMPs on same 25% of Maumee row-crop agricultural land; distributed in subwatersheds near river mouth
	100% no-till	No-till corn and soybean implemented in 100% of Maumee row-crop agricultural land
	100% cover	Rye cover crop planted between soybean and corn crop in 100% of Maumee row-crop agricultural land
	100% filter	Filter strip (10 m with 25% trapping efficiency) in 100% of Maumee row-crop agricultural land
	100% combined	Combination of three BMPs on 100% of Maumee row-crop agricultural land
	Manure	Manure application rates reduced 25% across all Maumee subwatersheds for hay and row-crop agricultural land
	Fertilizer	Fertilizer application rates reduced 25% across all Maumee subwatersheds for urban and row-crop agricultural land
	Point	Point source (municipal and industrial) effluent rates reduced 25% across all Maumee subwatersheds
	All source	Combination of three 25% source reductions across all Maumee subwatersheds
	Pristine	Agriculture and urban replaced by forest and wetland; point and atmospheric nutrient sources omitted; tile drains removed

unmodified. We also simulated a 25% reduction in fertilizer application rates in all urban and row-crop lands. The point input scenario simulated a 25% reduction in effluent rates of both municipal and industrial point sources. An all-source scenario combined all three types of source reduction.

As a reference and baseline we created a “pristine” scenario for the Maumee watershed that returned all agriculture and urban land cover back to forest and wetland (Table 3b). This scenario simulates what yields from the Maumee watershed might have been prior to European settlement. For this pristine scenario, we also removed all point sources and tile drainage from the watershed and eliminated atmospheric sources of nitrogen. Based on soil hydrology, wet areas (soil types included in the C and D hydrology group categories) previously classified as row-crop, hay, or urban were simulated as wetland; similarly, dry areas were simulated as forests.

Results and discussion

Watershed characteristics

Moderate BMP implementations across the six diverse watersheds resulted in varied but limited reductions in flow, sediment, and nutrient yields (Table 4). Water yields decreased less than 2% for all watersheds and BMP conditions. Sediment and nutrient yield reductions varied across watersheds and BMP conditions, with declines ranging from 0–11%. Among individual BMPs, cover crop was the most effective in

Table 4
Average annual riverine yields for the six modeled watersheds for various BMP implementation conditions. Nutrient parameters include total phosphorus (TP), soluble reactive phosphorus (SRP), total nitrogen (TN), and nitrate. Mg = metric tonnes.

	BMP scenario	Flow (mm/y)	Sediment (Mg/km^2)	TP (kg P/km^2)	SRP (kg P/km^2)	TN (kg N/km^2)	Nitrate (kg N/km^2)
Huron	Baseline	206	1.2	15.5	4.9	220	195
	No-till	206	1.2	15.3	4.7	219	194
	Cover	205	1.2	14.8	4.5	216	192
	Filter	206	1.2	15.3	4.8	220	195
	Combined	205	1.2	14.9	4.5	216	192
Raisin	Baseline	263	20.7	32.8	12.2	1656	1346
	No-till	263	19.1	32.6	12.5	1650	1354
	Cover	261	20.1	31.8	11.8	1606	1305
	Filter	263	20.1	32.2	11.9	1637	1332
	Combined	261	18.4	31.7	11.8	1592	1300
Maumee	Baseline	328	52.6	101.5	26.0	2377	1995
	No-till	328	50.9	104.5	25.6	2401	2013
	Cover	322	48.9	97.2	25.1	2262	1901
	Filter	328	51.0	98.5	25.2	2312	1942
	Combined	322	47.1	99.2	24.4	2239	1875
Sandusky	Baseline	313	20.5	81.2	25.1	2593	2405
	No-till	313	20.5	78.0	24.3	2549	2370
	Cover	307	19.9	76.4	24.0	2449	2278
	Filter	313	20.5	78.5	24.1	2523	2340
	Combined	307	19.8	73.5	22.9	2377	2210
Cuyahoga	Baseline	511	35.2	110.3	80.7	2078	1658
	No-till	511	35.2	110.7	81.1	2074	1657
	Cover	511	35.1	110.2	80.7	2077	1658
	Filter	511	35.2	109.8	80.3	2077	1658
	Combined	511	35.1	110.0	80.5	2074	1657
Grand	Baseline	411	52.7	40.0	5.0	669	374
	No-till	410	52.3	39.3	4.9	659	376
	Cover	410	52.5	39.6	5.0	662	370
	Filter	411	52.7	39.6	4.9	660	371
	Combined	409	52.1	38.8	4.8	646	368

Table 5
Average annual riverine yields for the Maumee watershed for various BMP placement strategies. Nutrient parameters include total phosphorus (TP), soluble reactive phosphorus (SRP), total nitrogen (TN), and nitrate. Mg = metric tonnes.

Scenario	Flow (mm/y)	Sediment (Mg/km^2)	TP (kg P/km^2)	SRP (kg P/km^2)	TN (kg N/km^2)	Nitrate (kg N/km^2)
Baseline	328	52.6	101.5	26.0	2377	1995
Random combined	322	47.1	99.2	24.4	2239	1875
Source combined	321	45.9	92.6	23.4	2161	1813
Mouth combined	321	42.8	98.4	25.4	2280	1931

reducing flow, sediments, and nutrients. No-till was least effective and nutrient yields actually increased slightly in some instances. The combined BMP scenario resulted in greater decreases in yields than any of the individual BMPs.

The effectiveness of BMP scenarios differed across the six watersheds (Table 4). The three agricultural watersheds, the Raisin, Maumee, and Sandusky, generally showed the largest yield reductions in sediment and nutrients. The combined BMP scenario reduced sediment yields by 11% and 10% for the Raisin and Maumee watersheds, respectively. The Sandusky watershed showed the greatest reductions for TP (9%), SRP (9%), TN (8%), and nitrate (8%) in response to the combined BMP scenario.

This moderate level of BMP implementation, randomly located throughout the six watersheds, was only minimally effective in reducing sediment and nutrient yields. With implementation affecting only about 25% of cropland area, it appears that sediment and nutrient yields will decrease by about 10% at most. Assuming that BMPs at their most effective are likely to reduce but not eliminate nutrient losses, this is not surprising. Our comparisons showed that reductions in yield were most pronounced in agricultural watersheds as expected since these BMPs were only applicable to cropland. Urban-oriented BMPs would likely be more effective at reducing sediment and nutrient yields in the Huron and Cuyahoga watersheds.

Influence of BMP location

To determine if greater reductions in sediment and nutrient yields could be obtained through targeting BMP location, we tested several placement options for the Maumee watershed for comparison to random placement (Table 3b). Implementing BMPs in subwatersheds near the mouth of the Maumee River resulted in greater reduction in sediment yields (19%, vs 10% with random distribution, Table 5). However, the greatest reduction in nutrient yields occurred when BMPs were placed in subwatersheds that delivered the largest inputs from land to streams. Total phosphorus yields, for example, were only reduced by 2% with random distribution and 3% with distribution near river mouth, while a reduction of 9% was predicted by SWAT if BMPs were located in high nutrient source areas.

These results are likely due to the different soil types and topographies across the watershed, different pathways that sediments and nutrients travel from land to streams, and transport through the stream network. Soil types and distributions change across the Maumee watershed as does the slope of the landscape, leading to potentially very different BMP impacts among subwatersheds. Soil eroded from the headwaters of the Maumee watershed, even with high erosion rates in certain subwatersheds, can be deposited in stream channels long before it reaches the river terminus. This is less likely for excess sediment entering the channel near the river mouth, which could explain why BMP implementation near the river mouth is most effective in reducing sediment yields. Model results for nutrients, in contrast, indicate that in-stream removal as modeled by SWAT is less important than loading from the landscape in deterring loads at the river mouth. Controlling nutrient loading from major source areas, therefore, may be the most effective approach. However, it should be acknowledged that simplified modeling of instream transport and removal processes by SWAT, particularly in a large watershed, may limit the robustness of these findings.

Increased BMP implementation

When BMP implementation rates were increased from the moderate level considered feasible by agricultural specialists to 100% across all row-crop land in the Maumee watershed (Table 3b), substantially greater yield reductions were observed (Table 6 vs. Table 4). Yields of water, sediments, and nutrients were reduced from 0–43% across the various BMPs. Cover crop was the most effective single BMP of those tested, generating declines in yield of 28, 16, and 18% for sediment, TP, and TN, respectively. Combining all three BMPs led to even more substantial yield reductions in model outcomes — sediment, TP, and TN yields decreased 43, 30, and 28%, respectively.

Across BMP implementation levels from moderate to full, sediment yields showed greater declines than nutrients (Fig. 2). This is expected because the principal goal of the current suite of BMPs has been to reduce runoff of sediment with associated particulate phosphorus. Indeed, when a series of BMPs were implemented in six small watersheds in New York, sediments showed the greatest decline (Makarewicz et al., 2009). Fig. 2 also implies that achieving a 25% reduction in yields of all constituents would require implementation of BMPs on at least 50% of agricultural lands in the Maumee watershed.

Model output for BMPs implemented across varying extents of agricultural land is consistent with other scenario results from the present study. Sediment yields decrease more than water and nutrient yields, which is as expected because the three BMPs chosen for this analysis are intended to reduce sediment loading to stream channels. Cover crops are consistently found to be the most effective individual BMP tested. These results also show that higher implementation rates are needed to substantially reduce sediment and nutrient yields in these watersheds.

Similar BMP testing conducted in other systems (Arabi et al., 2008; Lee et al., 2010; Tuppad et al., 2010) has shown comparable results (Table 7). At the full implementation extent, or 100% coverage

Table 6
Average annual riverine yields for the Maumee watershed under 100% implementation of several BMP conditions. Nutrient parameters include total phosphorus (TP), soluble reactive phosphorus (SRP), total nitrogen (TN), and nitrate.

Scenario	Flow (mm/y)	Sediment (Mg/km^2)	TP (kg P/km^2)	SRP (kg P/km^2)	TN (kg N/km^2)	Nitrate (kg N/km^2)
Baseline	328	52.6	101.5	26.0	2377	1995
100% no-till	328	45.6	95.9	24.2	2361	2000
100% cover	302	38.0	85.1	22.9	1949	1649
100% filter	328	44.7	85.5	22.2	2052	1733
100% combined	303	30.0	71.5	19.3	1721	1469

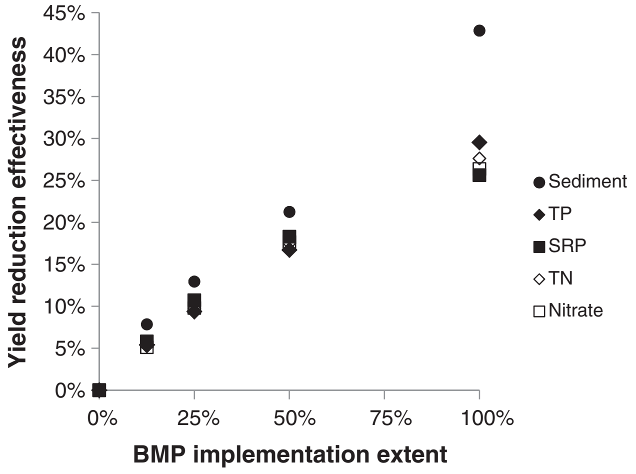

Fig. 2. Average annual reductions (in %) in riverine yields for the Maumee watershed under various implementation extents of combined BMP conditions. Nutrient parameters include total phosphorus (TP), soluble reactive phosphorus (SRP), total nitrogen (TN), and nitrate.

of BMPs, there is variation in outcomes, and the present study fits within the range seen across these other studies. Which BMPs are most effective also varies among studies, indicating that the most effective BMPs likely depend on specific circumstances of individual watersheds.

Nutrient source reduction

SWAT simulations that reduced nutrient source inputs in the Maumee watershed resulted in minimal decreases in nutrient yield (Table 8), similar in magnitude to the outcome under moderate BMP implementation (Table 4). Changes to fertilizer input and point sources resulted in greater reduction in nutrient yields than manure reductions, and combined source reductions led to 4–12% decreases in nutrient yields. Point source reductions were most effective for decreasing P yields, while fertilizer source reductions were most effective for decreasing N yields.

Simulation of pristine conditions

The scenario intended to simulate reference conditions and approximate the "pristine" state of the Maumee watershed (Table 3b) showed a dramatic decrease in yields of sediment (84%), TP (87%), SRP (91%), TN (91%), and nitrate (92%) (Table 9). These results are consistent with previous studies involving pristine or least disturbed watersheds. Several estimates of riverine TN export from pristine watersheds suggest a likely range of 100–200 kg N/km^2, consistent with our estimate of 206 kg/km^2. Lewis (2002) estimated an average of 260 kg/km^2 based on 20 minimally disturbed U.S. rivers (but receiving modern levels of atmospheric deposition of N). Minimally disturbed watersheds of the Lake Michigan Basin (LMB) have a present-day average TN yield of 236 kg/km^2 (Han and Allan, 2008). Several authors have modeled pristine river yields of TN, arriving at estimates of 110 for watersheds of the northeastern U.S. (Howarth et al., 2002), 130–190 for watersheds of the LMB (Han and Allan, 2012) and 45–110 kg/km^2 for the Seine (Billen et al., 2007).

Table 7
Comparison of average reduction in riverine loads (in %) between this study and similar SWAT BMP studies.

BMP	Parameter	Present study	Lee et al. (2010)	Tuppad et al. (2010)	Arabi et al. (2008)
Filter	Sediment	15	25	9	3
	Total phosphorus	16	5	17	21
	Total nitrogen	14	6	16	24
No-till	Sediment	13		3	15
	Total phosphorus	5		−3	23
	Total nitrogen	1		3	35
Cover	Sediment	28			3
	Total phosphorus	16			10
	Total nitrogen	18			14

Riverine TP export from pristine watersheds of the region is likely in the range of 5–15 kg P/km^2. Estimates of TP export in tributaries of Lake Simcoe, Ontario, were from 6 to 7 kg/km^2 for forested catchments (Winter et al., 2002). Similarly, TP export from the most northerly and forested tributaries of the LMB ranged from 5 to 10 kg/km^2 (Han et al., 2011). Riverine TP export from relatively undisturbed watersheds such as those in northern LMB or Lake Simcoe may not be suitable for extrapolation to previous pristine watershed conditions of Lake Erie because of differences in geology and climate. Nonetheless, SWAT estimates of 14 kg/km^2 TP export from LE watersheds under pristine conditions are consistent with monitoring data from the region.

Implications

Employing well-calibrated SWAT models for six watersheds of Lake Erie to test a variety of BMP scenarios, we show that substantial reductions in nutrient and sediment yields are possible, but BMPs must be much more widely implemented and strategically located to be fully effective. Moderate implementation of the three tested BMPs, at levels currently considered feasible by the agricultural community, are not likely to result in substantial reductions in sediment and nutrient yields. Indeed, the recent history of BMP implementation in some of these same watersheds is consistent with our results, in that agricultural BMPs presently are employed, although to varying degrees, and flow-weighted concentrations of particulate P show only modest declines (Richards et al., 2009), while concentrations of dissolved reactive P (DRP) are increasing. Ironically, the shift to no-till agriculture may contribute to the rise in DRP as fertilizer remains in the upper soil profile, and this may be exacerbated by fall fertilizer application, frequent absence of cover crops, and recent wet years (Daloglu et al., 2012). Present-day practices in these watersheds also indicate the need for more extensive implementation of both structural and cultural BMPs.

By optimizing the placement of BMPs within specific subwatersheds, specifically those with high nutrient inputs, it is possible to increase the effectiveness of even moderate BMP implementation in reducing sediment and nutrient yields. Using a SWAT model to evaluate BMP placement optimization in the Saginaw River (MI) watershed, Giri et al. (2012) found that results can be specific to the BMP, whether the aim is sediment or nutrient reduction. These results imply that BMPs and cropland placement could be optimized in certain subwatersheds, possibly allowing increased agricultural production while still reducing riverine nutrient transport from the watershed.

Our studies (including Bosch et al., 2011) and review of comparable work (citations in Table 7) indicate that watershed characteristics strongly influence the effectiveness of BMP implementation. As expected, sediment and nutrient yield reductions were greater in agricultural compared to more forested or urban watersheds because BMPs were applied to row-crop land. However, BMP effectiveness varies widely across the three agricultural watersheds as well. Another important factor in nutrient transport that differs across these watersheds is the number of impoundments connected to the stream network, ranging from over 20 impoundments in the Huron to none in the Sandusky. These factors imply that it is unlikely that uniform BMP implementation across watersheds of a region will yield similar sediment and nutrient yield reductions; rather each watershed may need to be considered individually.

Table 8

Average annual riverine yields for the Maumee watershed with 25% reductions in various watershed nutrient sources. Nutrient parameters include total phosphorus (TP), soluble reactive phosphorus (SRP), total nitrogen (TN), and nitrate.

Scenario	Flow (mm/y)	Sediment (Mg/km^2)	TP (kg P/km^2)	SRP (kg P/km^2)	TN (kg N/km^2)	Nitrate (kg N/km^2)
Baseline	328	53	101	26	2377	1995
−25% manure	328	53	101	26	2359	1978
−25% fertilizer	327	53	100	26	2205	1834
−25% point	328	53	99	24	2315	1939
−25% all sources	328	53	98	24	2126	1762

Table 9

Average annual riverine yields for the Maumee watershed under simulated pristine conditions. Nutrient parameters include total phosphorus (TP), soluble reactive phosphorus (SRP), total nitrogen (TN), and nitrate. Mg = metric tonnes.

Scenario	Flow (mm/yr)	Sediment (Mg/km^2)	TP (kg P/km^2)	SRP (kg P/km^2)	TN (kg N/km^2)	NO_3 (kg N/km^2)	N:P (kg/km^2)
Baseline	328	53	101	26	2377	1995	23
Pristine	176	8	14	2	206	159	15

Further research could address several issues that are beyond the scope of the present study. The three BMPs chosen for the present study are widely used, but the potential effectiveness of additional BMPs merits exploration, as well as the potential benefits of strategic placement of particular BMPs. Although our study includes 53% of the total land area runoff to Lake Erie, inclusion of Canadian watersheds and smaller U.S. watersheds in future modeling work would lead to a more comprehensive treatment. Finally, other modeling frameworks may have advantages for evaluating certain BMPs. For evaluating buffer strips, for example, using the Water Erosion Prediction Project (WEPP) model may be preferable to SWAT.

Conclusion

Using SWAT to test nutrient and sediment reduction scenarios for the six principal watersheds of the western and central basins of Lake Erie suggests only limited effectiveness can be anticipated under moderate levels of implementation. Model results indicate that both BMP implementations at increased levels currently considered feasible by the agricultural community and moderate reductions in fertilizer application rates are likely to be minimally effective. Moreover, current nutrient yields from agricultural watersheds are roughly an order of magnitude greater than our estimates of those expected from pristine landscapes. Taken together, these results imply the need for some combination of much wider implementation of BMPs, strategic targeting of locations, and source reduction in order to protect Lake Erie water quality. Measures in recent drafts of the Farm Bill that include new provisions for addressing critical conservation areas in a Regional Conservation Partnership Program and special attention for areas of "priority resource concern" may assist in that needed targeting. However, it is important to note that our results also show there may be tradeoffs to be made between targeting measures for lower nutrient yields vs. sediment yields, and this is particularly important as new efforts emerge focused on controlling SRP loads (Daloglu et al., 2012; Frankenberger et al., 2012).

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.jglr.2013.06.004.

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