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AN OPEN SOURCE GIS-BASED DECISION SUPPORT SYSTEM FOR WATERSHED EVALUATION OF BEST MANAGEMENT PRACTICES[1]

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ABSTRACT: Economic costs, water quantity/quality benefits, and cost effectiveness of agricultural best management practices (BMPs) at a watershed scale are increasingly examined using integrated economic-hydrologic models. However, these models are typically complex and not user-friendly for examining the effects of various BMP scenarios. In this study, an open source geographic information system (GIS)-based decision support system (DSS), named the watershed evaluation of BMPs (WEBs), was developed for creating BMP scenarios and simulating economic costs and water quantity/quality benefits at farm field, subbasin, and watershed scales. This DSS or WEBs interface integrated a farm economic model, the Soil and Water Assessment Tool (SWAT), and an optimization model within Whitebox Geospatial Analysis Tools (GAT), an open source GIS software. The DSS was applied to the 14.3-km^2 Gully Creek watershed, a coastal watershed in southern Ontario, Canada that drains directly into Lake Huron. BMPs that were evaluated included conservation tillage, nutrient management, cover crop, and water and sediment control basins. In addition to assessing economic costs, water quantity/quality benefits, and cost effectiveness of BMPs, the DSS can be also used to examine prioritized BMP types/locations and corresponding economic and water quantity/quality tradeoffs in the study watershed based on environmental targets or budget constraints. Further developments of the DSS including interface transfer to other watersheds are also discussed. ***Editor's note****: This paper is part of the featured series on SWAT Applications for Emerging Hydrologic and Water Quality Challenges. See the February 2017 issue for the introduction and background to the series.*

(KEY TERMS: Soil and Water Assessment Tool; integrated economic-hydrologic modeling; best management practice evaluation; open source GIS; decision support system.)

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INTRODUCTION

In recent decades, governments have established various conservation programs to mitigate the adverse environmental effects of agriculture on water quantity and quality. These programs provide financial incentives to farmers to implement best management practices (BMPs) that attenuate flood peaks and reduce sediment and nutrient loadings to water bodies (Johnson *et al.*, 2015). However, the economic costs and water quantity/quality benefits resulting from

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agricultural BMPs likely vary spatially within a watershed. Furthermore, these economic and environmental data are typically not readily available. In agricultural conservation programs, farmers would benefit from knowing economic costs and environmental benefits from adopting BMPs. Conservation practitioners can also utilize these data to target BMP implementation in prioritized locations that minimize economic costs and/or maximize water quantity and quality benefits (Yang *et al.*, 2010).

In the literature, researchers have examined the economic costs, water quantity/quality benefits, and the cost effectiveness of agricultural BMPs at a watershed scale using farm economic, watershed hydrologic, and integrated economic-hydrologic modeling (Yang *et al.*, 2007, 2014; Ghebremichael *et al.*, 2013). These models, if well calibrated and validated, can be used to examine spatial variations of BMP cost effectiveness measured by the ratios of economic costs and water quantity and quality benefits, and prioritize spatial locations for BMP implementation. However, due to complexity of these models, farmers and conservation practitioners have difficulties on utilizing these models for evaluating various scenarios of agricultural BMP implementation (Osmond *et al.*, 1997; Miller *et al.*, 2004; Yang, 2011).

The demand for user-friendly decision support system (DSS) for watershed management has long been addressed by various developments of such systems for operationalizing one or more models (Lam *et al.*, 2004; Liu *et al.*, 2008; Volk *et al.*, 2010). In an agricultural context, databases or tools have been developed for providing BMP costs and/or effectiveness based on literature values and site-specific conditions (Gitau *et al.*, 2005; Merriman *et al.*, 2009). A web-based DSS has been developed to integrate the long-term hydrological impact assessment model, databases and geographic information system (GIS) for evaluating the water quantity and quality impacts of land use change (Engel *et al.*, 2003). GIS-based interfaces have been developed to set up, calibrate, and validate watershed hydrologic models such as the Soil and Water Assessment Tool (SWAT) (Olivera *et al.*, 2006) and apply the established models to evaluate water quantity and quality effects of agricultural BMPs (Maringanti *et al.*, 2009; Panagopoulos *et al.*, 2012). Furthermore, SWATShare, an innovative web platform has been developed for online sharing, simulation and visualization of SWAT models (Rajib *et al.*, 2016). However, there is a knowledge gap in developing DSS or interfaces for running integrated economic and hydrologic models to conduct rapid assessment of both BMP costs and effectiveness in agricultural watersheds.

The purpose of this study was to address this knowledge gap by developing an open source GIS-based interface for watershed evaluation of BMPs (WEBs). The WEBs interface was developed by integrating a farm economic model for quantifying the costs of BMPs, the SWAT (Neitsch *et al.* 2011; Arnold *et al.*, 2012) for estimating water quantity and quality benefits of BMPs, and an optimization model for examining the cost effectiveness of BMPs. SWAT was selected as part of the integrated modeling system because SWAT has been applied worldwide to assess water quantity and quality effects of agricultural BMPs at a watershed scale (Gassman *et al.*, 2007; Arnold *et al.*, 2012; Johnson *et al.*, 2015). In the WEBs interface, the farm economic model and SWAT were pre-calibrated and validated to fit into study watershed conditions. The integrated optimization model was used to examine prioritized BMP types/locations and corresponding economic and water quantity/quality tradeoffs based on environmental targets or budget constraints. The WEBs interface provides a DSS for evaluating agricultural BMPs by farmers and conservation practitioners in the study watershed.

FRAMEWORK OF THE WEBS INTERFACE

The framework of the open source GIS-based DSS or WEBs interface has four components including information, scenario, model, and display (Figure 1). These components are also the four steps taken by users to organize input data, design BMP scenarios, run models, and conduct results analysis.

Information Component

The information component of the WEBs interface includes geospatial data (DEM, landuse, soil, stream network, farm field and watershed boundary, and location of monitoring stations), climate data, flow and water quality data, agricultural management data, and economic data (such as crop yield, price, and production costs). These basic datasets are used to set up, calibrate, and validate the farm economic and watershed hydrologic models for a study watershed. Due to variations of economic and biophysical characteristics across landscapes, it is important to calibrate and validate these models to fit into conditions of specific watersheds.

Scenario Component

The scenario component of the WEBs interface is designed to operate on pre-calibrated and validated farm economic and watershed hydrologic models. The

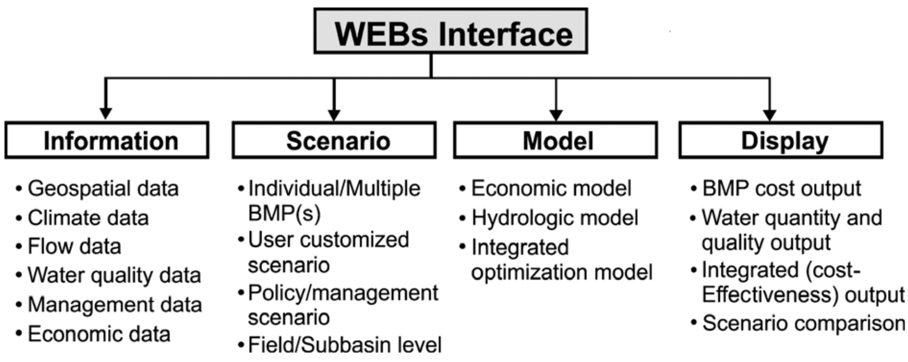

FIGURE 1. Framework of the Open Source GIS-Based Decision Support System for Watershed Evaluation of BMPs (WEBs). BMPs, Best Management Practices.

scenario component has two modules. In the first module, users can construct customized "what if" scenarios to simulate the impact of one BMP or multiple BMPs at a single location or for multiple locations. Users have the option of specifying BMPs on a watershed map or a table with farm field and BMP location data. User selections of BMP locations and types are saved in a database. A computer program links user BMP selections to the farm economic model and SWAT and corresponding parameters are modified for the BMP scenario. Users can then run the two models to examine economic costs, water quantity/quality benefits, and benefit-to-cost ratios of specific BMP scenario using maps, charts, and tables.

In the second module, users can specify an area of interest (multiple fields or subbasins, or the entire watershed) and evaluate cost effectiveness of all possible combinations of BMPs. User selections are linked to an integrated optimization model to prioritize BMP policy/management scenarios based on environmental targets or budget constraints. The module can generate an optimal set of BMPs with locations and types within the area of interest to achieve the environmental target with minimized BMP costs. The module can also identify an optimal set of BMPs to maximize environmental benefits with a specified budget constraint.

The WEBs interface has two baseline scenarios including (1) the "historical" baseline scenario characterizing the historical or existing BMP distribution and (2) the "conventional" baseline scenario in which no BMPs exist within the landscape. The "conventional" baseline scenario is developed by replacing historical/existing BMPs with conventional practices (*e.g.*, mouldboard plough tillage and high fertilizer application rates in conventional agriculture). All user-defined "what if" scenarios and policy/management scenarios can be compared to the two baseline scenarios, or to each other. These comparisons allow users to identify BMP scenarios to meet various economic and environmental targets.

Modeling Component

The modeling component is used to conduct computational task of the WEBs interface. This component includes the verified farm economic model and calibrated/validated SWAT model for estimating BMP costs and water quantity and quality benefits. Furthermore, an integrated optimization model is developed with either environmental targets or budget constraints as objective functions. A suite of computer programs are developed to link the scenario component with the farm economic model, SWAT, and integrated model to generate outputs of economic costs, water quantity and quality benefits, and cost effectiveness for "what if" BMP scenarios in the user customization module. The integrated model with optimization further supports prioritizing BMPs based on benefit-to-cost ratios and identifying a set of BMPs to meet environmental targets or budget constraints in the policy/management module.

Display Component

The display component of the WEBs interface is developed to visualize and analyze modeling outputs of various BMP scenarios in an interactive manner. BMP economic costs are associated with locations (for location-specific BMPs such as water and sediment control basin) and farm fields (such as conservation tillage). BMP water quantity and quality benefits are linked to hydrologic response units (HRUs) or subbasins (Arnold *et al.*, 2010). In this component, a look-up table is developed between HRUs and farm fields in the study watershed using GIS. An area-weighted procedure is developed to convert field-specific BMP costs to subbasins or interpolate HRU-based water quantity and quality benefits into farm fields. Based on this setup, users have the options to display BMP economic costs, water quantity and quality benefits, and benefit-to-cost ratios at site, field, subbasin, and watershed scales for the study watershed. Comparisons can be made to examine differences between BMP scenarios by contrasting a user-defined BMP scenario and a baseline scenario or two BMP scenarios.

DEVELOPMENT OF THE GULLY CREEK VERSION OF THE WEBS INTERFACE

The WEBs interface framework was applied to the 14.3-km^2 Gully Creek watershed, which is a representative shoreline watershed of Lake Huron basin in southern Ontario, Canada (Figure 2). The watershed has an undulating landscape and is dominated by agriculture (70% of the watershed area). The typical crop rotation includes corn, soybean, and winter wheat. With growing concerns about near-shore water quality of Lake Huron, BMP implementation in shoreline watersheds has become one of the important measures for mitigating these negative effects. Representative BMPs in the Gully Creek watershed include conservation tillage, nutrient management, cover crop, and water and sediment control basins (WASCoBs).

Farm economic modeling was developed to quantify input and output relationships of crop production in the Gully Creek watershed. The costs for land management BMPs including conservation tillage, nutrient management, and cover crop were defined as net return differences under the conventional baseline scenario and a BMP scenario. Inputs to the

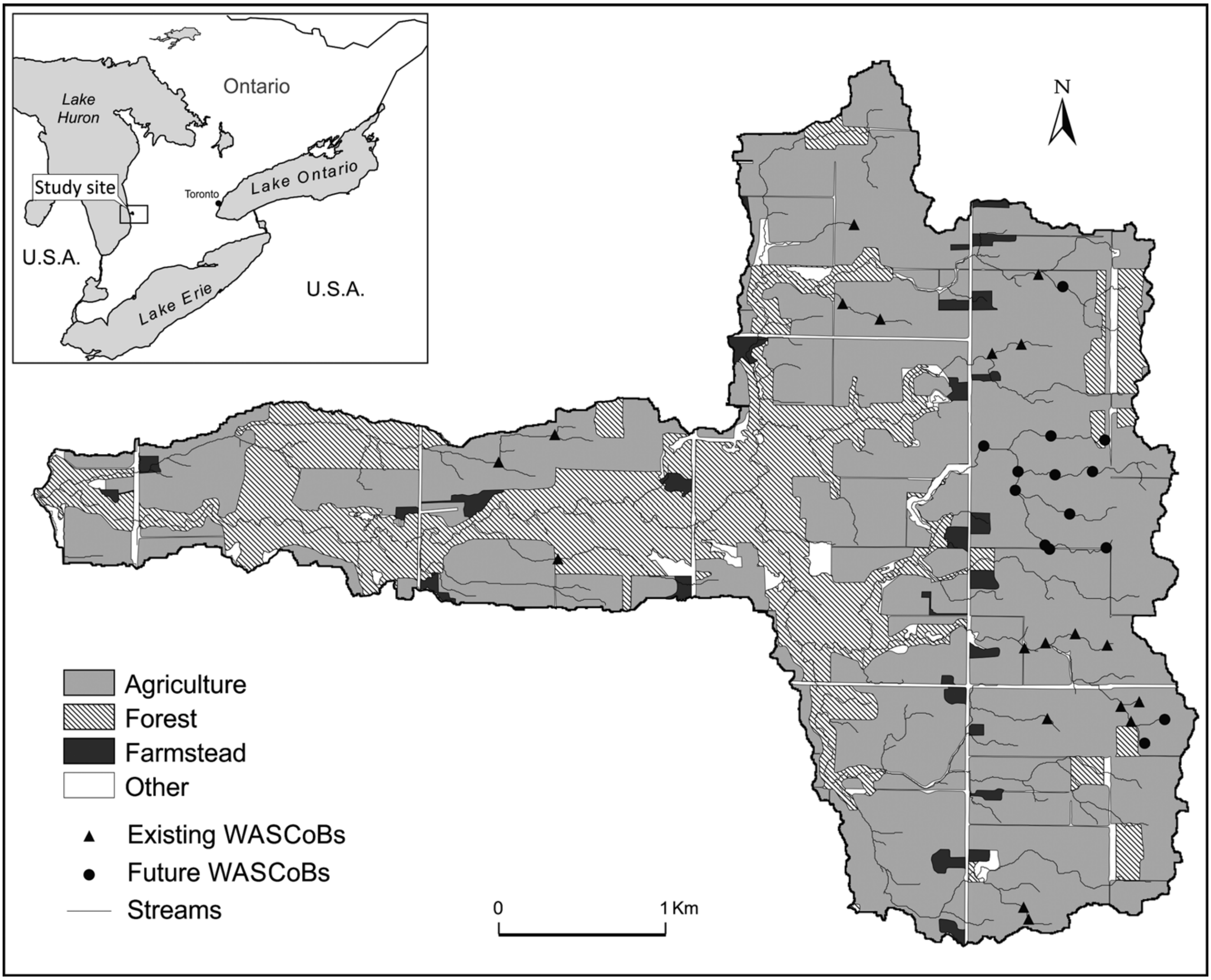

FIGURE 2. The Gully Creek Watershed in Southern Ontario, Canada. WASCoBs, Water and Sediment Control Basins.

farm economic model included crop price and yield, machinery, tillage, seed rate and price, fertilizer rate and price, and other items. These data were collected through a farm survey and were supplemented with farming business data from government sources (Ontario Ministry of Agriculture, Food and Rural Affairs, 2013). Net returns for conventional and BMP scenarios were calculated by subtracting production costs from revenues (crop yields multiplied by prices). Net returns under BMP scenarios were subtracted from those under the conventional scenario to calculate the economic costs of BMPs. The BMP costs for WASCoBs were estimated based on engineering costs associated with earthwork and outlet installation. The validity of farm economic modeling was verified by comparing simulated net returns with county level data and reasonable agreements were achieved (Oginskyy, 2014).

SWAT was set up based on climate, DEM, soil, landuse, and land management data including seeding and harvesting dates, tillage types and timing, and fertilizer rates and timing (Neitsch *et al.*, 2011). In addition to parameterize land management BMPs, WASCoB locations were defined as subbasin outlets to characterizing inflows from drainage areas in order to evaluate retention effects of water, sediment and nutrients. SWAT modeling was calibrated and validated based on observed flow and water quality data at multiple stations in the watershed and satisfactory performance was achieved (Yang *et al.*, 2013).

The farm economic and SWAT modeling can be used to estimate BMP costs, water quantity/quality benefits, and benefit-to-cost ratios. The two models were run for all possible scenarios including individual BMP and combinations of the four BMPs at farm field or subbasin scale (with interpolations between the two scales). The modeling output database was used to construct an integrated optimization model with either minimizing BMP costs as the objective function subject to a target constraint of water quantity/quality benefits or maximizing water quantity/quality benefits subject to a budget constraint. The optimization model can be used to identify a set of BMPs based on cost effectiveness subject to an environmental target or a budget constraint.

Whitebox geospatial analysis (GAT), a Java-based open source GIS software (Lindsay, 2016), was customized to develop the user interface in conjunction with SQLite (https://www.sqlite.org/), an open source database. In the WEBs interface, the information component (with input data to the models) and the modeling component were at the back end. The scenario and display components were at the front end for users to define BMP scenarios, run models, and display BMP assessment results (Figure 3). For the "what if" scenario module, a database was developed

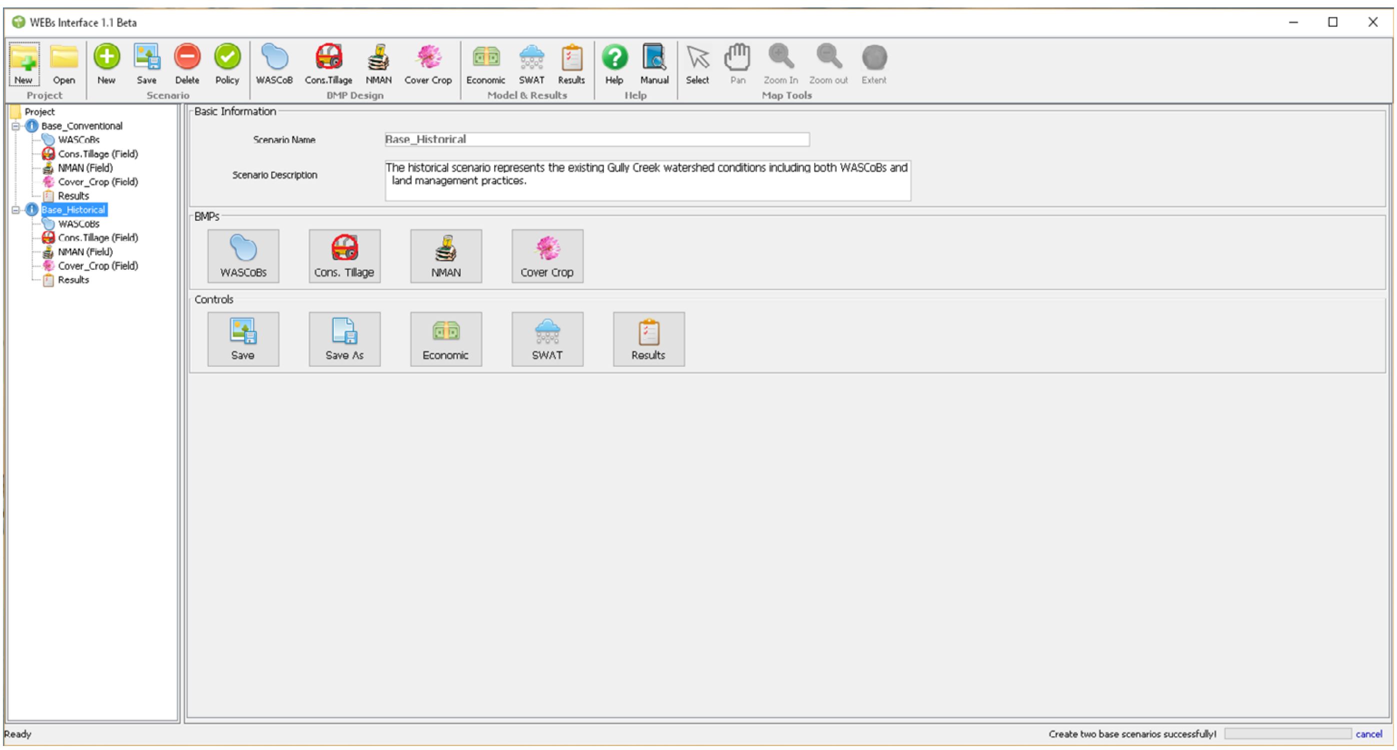

FIGURE 3. User BMP Setup View of the WEBs Interface. Two baseline scenarios (historical and conventional) are created after the project setup.

to store user scenarios with field IDs and BMP types. A suite of Java programs was developed to link user selections with farm economic and SWAT models. The Java programs operate farm economic model to estimate net returns under a user scenario and calculate BMP costs. The Java programs also operate SWAT management files and WASCoB files to calculate water quantity and quality benefits for a user scenario. For "Policy/Management" scenario module, a suite of Java programs were developed to set up constraints and objectives of the integrated optimization model. The optimization model, based on an open-source mixed integer linear programming solver (lp_solve version 5.5, http://lpsolve.sourceforge.net/5.5/), is run to identify BMP types and locations based on environmental targets or budget constraints.

FUNCTIONALITY OF THE GULLY CREEK VERSION OF THE WEBS INTERFACE

The Gully Creek version of the WEBs interface has a suite of functions to assist users with watershed evaluation of agricultural BMPs. In the interface, users start with setting up a new project or opening an existing project. For a project, the two baseline scenarios, *i.e.*, the historical and conventional scenarios, are pre-run before users start to define a BMP scenario and farm economic and SWAT modeling results for the baseline scenarios were stored in databases for comparison with a user defined BMP scenario. The project tree on the left panel of the project window houses baseline scenarios and user defined BMP scenarios (Figure 3).

Within a project, the first module is for users to examine "what if" BMP scenarios. Users can select a BMP to bring up the watershed map in the main window and the table on the right panel. Users will be prompted to select either "historical" or "conventional" as the baseline scenario. Then users can select one or multiple farm fields from either the map or table to define a land management BMP scenario (including conservation tillage, nutrient management, and/or cover crop) or they can select one or multiple locations to define a WASCoB BMP scenario. Figure 4 presents a "what if" scenario for conservation tillage in multiple farm fields for illustrative purposes. After selections (for one or multiple BMPs), users can save the scenario, run the farm economic model, and run SWAT.

After the model has run, users can display the modeling results (Figures 5 and 6). The project window is refreshed to house user options in the right panel, the map in the main window, and the chart in

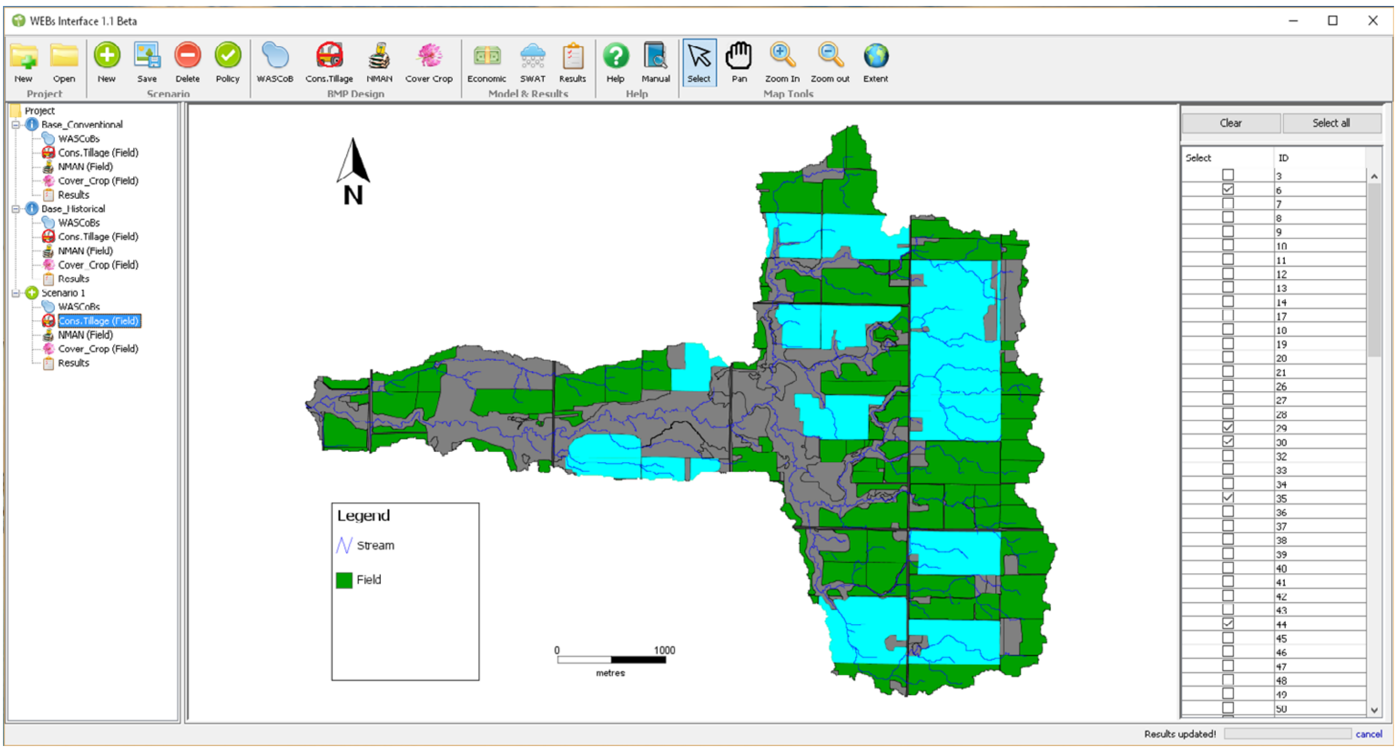

FIGURE 4. User Conservation Tillage Selection on the WEBs Interface. The user can select multiple locations from map or table for BMP implementation and run models to examine BMP effects.

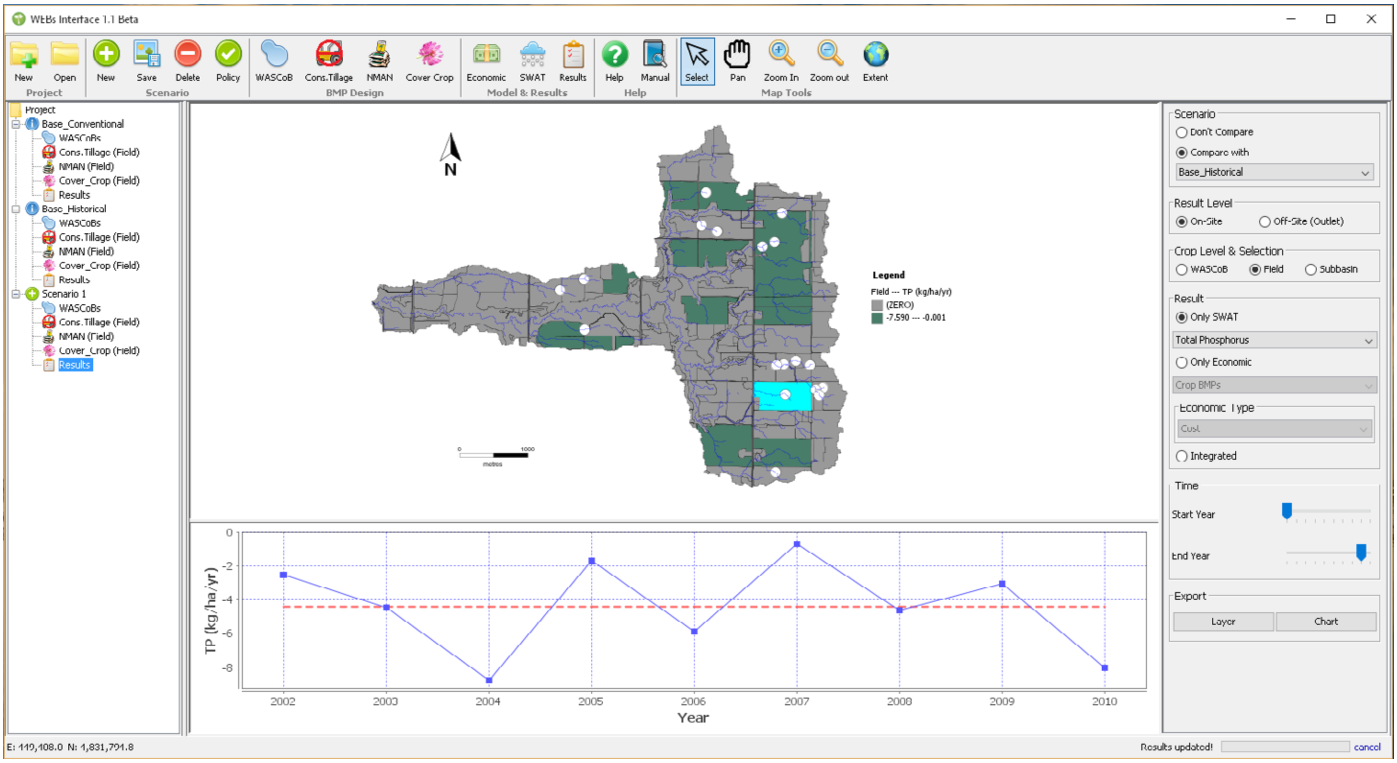

FIGURE 5. “On-Site” Results of User Defined Conservation Tillage Scenario in Comparing to “Historical” Baseline Scenario. The solid line in chart indicates the annual total phosphorus (TP) reductions of the selected field. The dotted line shows the average value of annual TP reductions.

the lower panel. A suite of options are provided for users to display BMP assessment results, including:

1. Users firstly click on “Don’t compare” radio button to display modeling results for the current BMP scenario, which include both selected BMPs and the rest of the watershed. Users can also click on “Compare with” radio button to display differences in modeling results between the current BMP scenario and another scenario including historical or conventional baseline scenario, or a different BMP scenario with the same baseline scenario. This comparison option displays modeling results only for those user defined BMP locations as no change happens in the rest of the watershed (Figure 5).
2. With either “Don’t compare” or “Compare with” option, users can click on a location or multiple locations on the map to display “On-Site” modeling results. Users have a further option of choosing WASCoB (location), field or subbasin for results display. User selected locations or fields will be highlighted and a chart appears in the lower panel to display a time-series of the economic or hydrologic modeling results. For multiple selections, the chart displays area-weighted average results for those locations or fields (Figure 5). Users can also choose to display “Off-Site” modeling results in chart, which represent aggregate economic results for selected BMPs and/or cumulative environmental effects at watershed outlet (Figure 6).
3. Based on the aforementioned selections, users can further have one of the three options: (1) display “Only SWAT” modeling results, which include water yield, sediment, particulate N, dissolved N, total N, particulate P, dissolved P, and total P for a scenario (“Don’t compare” option) or differences in SWAT modeling results between the current BMP scenario and another scenario (“Compare with” option); (2) display “Only Economic” modeling results, which include production costs, revenue, net returns, or WASCoB costs for a scenario (“Don’t compare” option) or differences in economic modeling results between the current BMP scenario and another scenario (“Compare with” option), and; (3) display “Integrated” modeling results. This option is only available to “Compare with” option, which shows BMP benefit-to-cost ratios in terms of water quantity/quality benefits per $1,000 BMP costs. The ratios can be displayed for both On-Site and Off-Site options (Figures 5 and 6).

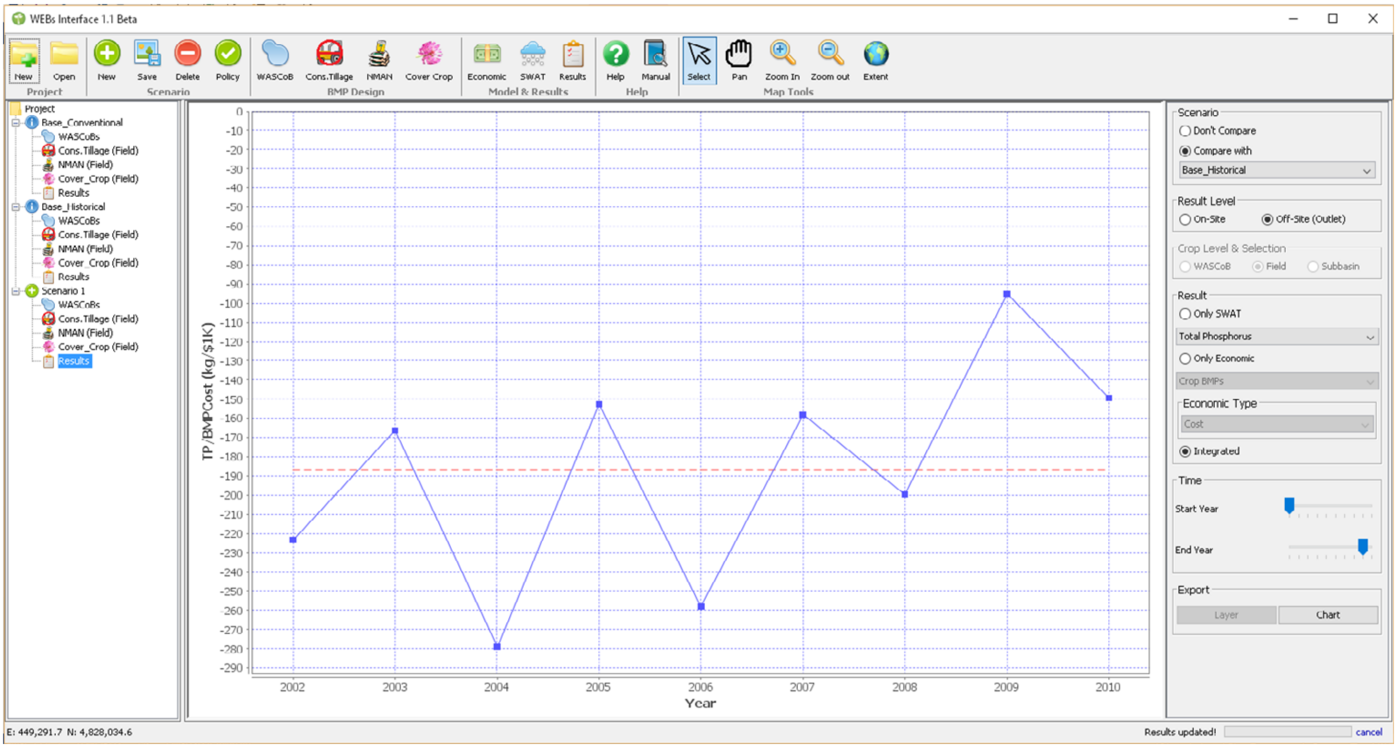

FIGURE 6. “Off-Site” Benefit-to-Cost Ratios of User Defined Conservation Tillage Scenario in Comparing to the “Historical” Baseline Scenario. The solid line in chart indicates the annual TP reductions at the watershed outlet per $1,000 costs. The dotted line shows the average value of the annual TP reductions.

4. Users can move the markers on the “Start Year” and “End Year” rulers to define the display of modeling results for partial or the entire modeling simulation period (Figures 5 and 6).
5. Users can also click on “Layer” or “Chart” button to export modeling results into a comma separated values (CSV) text file for further data analysis (Figures 5 and 6).

In the project window, users can click on the “Policy” icon on the top panel to enter into the interface for the second module of the scenario component (Figure 7). In this module, users have the option to choose either “historical” or “conventional” baseline scenario, which indicates the optimization of BMPs will be based on historical/existing or conventional conditions. Users can also choose to run the model and display the optimized land management BMP set using farm field or subbasin as spatial units. After these options, the application of the BMP optimization model is as follows (Figure 7):

1. Define an area of interest by clicking on multiple fields or subbasins. If no selection is made, the BMP optimization will be defaulted to the entire watershed.
2. Specify either budget constraint or environmental target as the objective function.
3. Select one BMP or multiple BMPs for optimization.
4. Define a time period based on starting and ending years.
5. Choose a pollutant (such as sediment, total nitrogen [TN] or total phosphorus [TP]).
6. Define the specific target (such as a budget level or a pollution reduction level) in an absolute number or in a percentage.
7. Select “increment mode” to define the number of increments (points) within the target range and run the BMP optimization model.

After these definitions, the optimization model will run for each of the increments to develop a tradeoff curve between BMP costs and benefits. Users can click on a point on the curve (corresponding to an increment) and the corresponding set of optimized BMPs will be displayed in the map window. Users can also export the BMP optimization results as a CSV text file for further data analysis. For illustrative purposes, we have developed a policy scenario with TP reductions between 10 and 20% at the watershed outlet for WASCoB and conservation tillage BMPs. The project window shows a tradeoff curve of

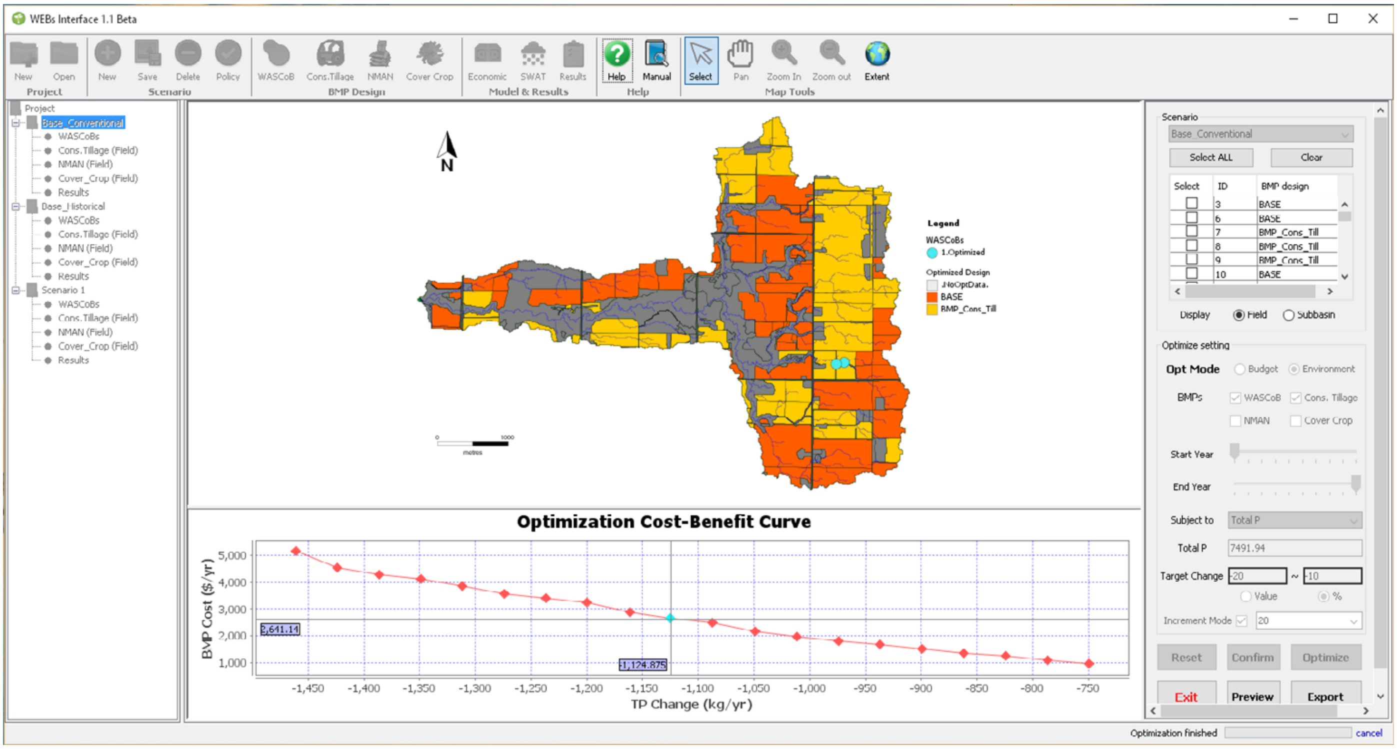

FIGURE 7. Optimization Result for Two BMPs (WASCoB and Conservation Tillage) with Total Phosphorous Reduction Targets Ranging between 10 and 20%. Each dot on the "Optimization Cost-Benefit Curve" indicates a recommended BMPs set (BMP type/location).

BMP costs and TP reduction benefits and a map of the optimal BMP set for a 15% TP reduction target (Figure 7).

DISCUSSION

The Gully Creek version of the WEBs interface is a user-friendly DSS that enables nonmodelers to interact with complex integrated economic-hydrologic modeling to conduct BMP assessment in the study watershed. Based on pre-calibrated models, the WEBs interface is an interactive tool for farmers and conservation practitioners to examine BMP costs, benefits, and cost effectiveness at field, farm, and subbasin scales. The improved understanding between proposed "on-ground" BMP actions and economic and environmental outcomes at field and watershed scales can facilitate farmer decision making on implementing BMPs. Conservation practitioners can use the WEBs tool to evaluate the cost effectiveness of various BMP scenarios. Particularly, the integrated optimization model in the WEBs tool can be used to rank individual BMPs and various BMP combinations within the landscape and the ranking scheme can be used to identify priority areas for program implementation at the watershed scale. Users can also use the SWAT modeling option of the WEBs tool to identify critical source areas (CSAs) with high pollutant export and to evaluate water quantity and quality effects of BMPs in CSAs.

Currently there exist GIS interfaces for setting up, calibrating and validating watershed hydrologic models such as SWAT (Olivera *et al.*, 2006). However, operationalizing these established models for BMP assessment is challenging for farmers and conservation practitioners due to model complexity and related technical expertise requirements. In this study, the WEBs interface or DSS was designed and developed based on pre-calibrated and validated farm economic and SWAT models for rapid WEBs. Note that the Gully Creek version of the WEBs interface was site-specific and BMP-specific. As the Gully Creek watershed is representative of Lake Huron basin of Ontario in terms of landscape and land management characteristics, the WEBs interface has the potential to be transferred to similar watersheds in this region based on three key steps:

1. Basic datasets need to be prepared for topography, landuse, land management, soil, climate, water quantity and quality, and BMPs.

2. Farm economic, watershed hydrologic and integrated optimization models need to be set up, calibrated and validated.
3. The open source GIS interface needs to be transferred to the new study watershed by linking the three modeling components with the interface.

Transferring the WEBs interface outside the Lake Huron basin of Ontario may take considerable efforts. Due to spatial variations of economic, biophysical, and BMP characteristics across landscapes, it is reasonable to expect that the farm economic and watershed hydrologic models will be different to certain extent across watersheds. Therefore it would be challenging to develop a "plug-in and play" type interface for running these models. However, sharing the design and source code may facilitate the efforts to transfer the WEBs interface to other watersheds. Interested readers may contact the corresponding author to discuss the acquisition of the Gully Creek version of the WEBs interface. In the future, procedures or protocols need to be developed to standardize input data preparation, model construction, BMP characterization, and interface development to improve the transferability of the WEBs interface.

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LITERATURE CITED

Arnold, J., D. Moriasi, P. Gassman, K. Abbaspour, M. White, R. Srinivasan, C. Santhi, R. Harmel, A. Van Griensven, and M. Van Liew, 2012. SWAT: Model Use, Calibration, and Validation. Transactions of the ASABE 55(4):1491-1508, DOI: 10.13031/2013.42256.

Arnold, J.G., P.M. Allen, M. Volk, J.R. Williams, and D.D. Bosch, 2010. Assessment of Different Representations of Spatial Variability on SWAT Model Performance. Transactions of the ASABE 53(5):1433-1443, DOI: 10.13031/2013.34913.

Engel, B.A., J. Choi, J. Harbor, and S. Pandey, 2003. Web-Based DSS for Hydrologic Impact Evaluation of Small Watershed Land Use Changes. Computers and Electronics in Agriculture 39:241-249.

Gassman, P.W., M.R. Reyes, C.H. Green, and J.G. Arnold, 2007. The Soil and Water Assessment Tool: Historical Development, Applications, and Future Research Directions. Transactions of the ASABE 50(4):1211-1250, DOI: 10.13031/2013.23637.

Ghebremichael, L.T., T.L. Veith, and J.M. Hamlett, 2013. Integrated Watershed- and Farm-Scale Modeling Framework for Targeting Critical Source Areas While Maintaining Farm Economic Viability. Journal of Environmental Management 114:381-394, DOI: 10.1016/j.jenvman.2012.10.034.

Gitau, M.W., W.J. Gburek, and A.R. Jarrett, 2005. A Tool for Estimating Best Management Practice Effectiveness for Phosphorus Pollution Control. Journal of Soil and Water Conservation 60 (1):1-10.

Johnson, M.-V.V., M.L. Norfleet, J.D. Atwood, K.D. Behrman, J.R. Kiniry, J.G. Arnold, M.J. White, and J. Williams, 2015. The Conservation Effects Assessment Project (CEAP): A National Scale Natural Resources and Conservation Needs Assessment and Decision Support Tool. IOP Conference Series: Earth and Environmental Science 25:012012, DOI: 10.1088/1755-1315/25/1/012012.

Lam, D., L. Leon, S. Hamilton, N. Crookshank, D. Bonin, and D. Swayne, 2004. Multi-Model Integration in a Decision Support System: A Technical User Interface Approach for Watershed and Lake Management Scenarios. Environmental Modelling & Software 19:317-324, DOI: 10.1016/S1364-8152(03)00156-7.

Lindsay, J., 2016. Whitebox GAT: A Case Study in Geomorphometric Analysis. Computers & Geosciences 95:75-84, DOI: 10.1016/j.cageo.2016.07.003.

Liu, Y., H. Gupta, E. Springer, and T. Wagener, 2008. Linking Science with Environmental Decision Making: Experiences from an Integrated Modeling Approach to Supporting Sustainable Water Resources Management. Environmental Modelling & Software 23:846-858, DOI: 10.1016/j.envsoft.2007.10.007.

Maringanti, C., I. Chaubey, and J. Popp, 2009. Development of a Multiobjective Optimization Tool for the Selection and Placement of Best Management Practices for Nonpoint Source Pollution Control. Water Resources Research 45:W06406, DOI: 10.1029/2008WR007094.

Merriman, K.R., M.W. Gitau, and I. Chaubey, 2009. A Tool for Estimating Best Management Practice Effectiveness in Arkansas. Applied Engineering in Agriculture 25(2):199-213, DOI: 10.13031/2013.26333.

Miller, R.C., D.P. Guertin, and P. Heilman, 2004. Information Technology in Watershed Management Decision Making. Journal of the American Water Resources Association 40:347-357, DOI: 10.1111/j.1752-1688.2004.tb01034.x.

Neitsch, S.L., J.G. Arnold, J.R. Kiniry, and J.R. Williams, 2011. Soil and Water Assessment Tool Theoretical Documentation Version 2009. Texas Water Resources Institute Technical Report No. 406, Texas A&M University System, College Station, Texas.

Oginskyy, A., 2014. Integrated Hydrologic-Economic Optimization Modeling for Watershed Evaluation of Agricultural BMPs and Policies. Ph.D. Dissertation, University of Guelph, Guelph, Ontario. https://atrium.lib.uoguelph.ca/xmlui/handle/10214/8660, *accessed* January 2017.

Olivera, F., M. Valenzuela, R. Srinivasan, J. Choi, H. Cho, S. Koka, and A. Agrawal, 2006. ArcGIS-SWAT: A Geodata Model and GIS Interface for SWAT. Journal of the American Water Resources Association 42:295-309, DOI: 10.1111/j.1752-1688.2006.tb03839.x.

OMAFRA (Ontario Ministry of Agriculture, Food and Rural Affairs), 2013. Cost of Production and Budgets. http://www.omaf ra.gov.on.ca/english/busdev/production.html, *accessed* January 2017.

Osmond, D.L., R.W. Cannon, J.A. Gale, D.E. Line, C.B. Knott, K.A. Phillips, M.H. Thrner, M.A. Foster, D.E. Lehning, S.W. Coffey, and J. Spooner, 1997. WATERSHEDSS: A Decision Support System for Watershed-Scale Nonpoint Source Water Quality Problems. Journal of the American Water Resources Association 33:327-341, DOI: 10.1111/j.1752-1688.1997.tb03513.x.

Panagopoulos, Y., C. Makropoulos, and M. Mimikou, 2012. Decision Support for Diffuse Pollution Management. Environmental Modelling & Software 30:57-70, DOI: 10.1016/j.envsoft.2011.11.006.

Rajib, M.A., V. Merwade, I.L. Kim, L. Zhao, C. Song, and S. Zhe, 2016. SWATShare – A Web Platform for Collaborative Research and Education through Online Sharing, Simulation and Visualization of SWAT Models. Environmental Modelling & Software 75:498-512, DOI: 10.1016/j.envsoft.2015.10.032.

Volk, M., S. Lautenbach, H. van Delden, L.T.H. Newham, and R. Seppelt, 2010. How Can We Make Progress with Decision Support Systems in Landscape and River Basin Management? Lessons Learned from a Comparative Analysis of Four Different Decision Support Systems. Environmental Management 46:834-849, DOI: 10.1007/s00267-009-9417-2.

Yang, W., 2011. Developing Open Access in Conservation Research. Journal of Soil and Water Conservation 66(1):6A-8A.

Yang, W., B.A. Bryan, D.H. MacDonald, J.R. Ward, G. Wells, N.D. Crossman, and J.D. Connor, 2010. A Conservation Industry for Sustaining Natural Capital and Ecosystem Services in Agricultural Landscapes. Ecological Economics 69(4):680-689, DOI: 10.1016/j.ecolecon.2009.11.028.

Yang, W., W. Liu, Y.B. Liu, R.C. Corry, and R.D. Kreutzwiser, 2014. Cost-Effective Targeting of Riparian Buffers to Achieve Water Quality and Wildlife Habitat Benefits. International Journal of River Basin Management 12(1):43-55, DOI: 10.1080/15715124.2014.880710.

Yang, W., Y.B. Liu, J. Simmons, A. Oginskyy, and K. McKague, 2013. SWAT Modelling of Agricultural BMPs and Analysis of BMP Cost Effectiveness in the Gully Creek Watershed. http://www.abca.on.ca/downloads/WBBE-Huron-SWAT-Modelling-2013-08-21.pdf, *accessed* January 2017.

Yang, W., A.N. Rousseau, and P. Boxall, 2007. An Integrated Economic-Hydrologic Modeling Framework for the Watershed Evaluation of Beneficial Management Practices. Journal of Soil and Water Conservation 62(6):423-432.