A decision support system approach for identifying pollutant source for optimization of beneficial management practices scenario modelling in Lake Winnipeg watersheds

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A decision support system approach for identifying pollutant source for optimization of beneficial management practices scenario modelling in Lake Winnipeg watersheds

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Abstract: The Soil and Water Assessment Tool (SWAT) results can be used to source trace loading "hotspots" for optimally locating beneficial management practices (BMP). It is possible to trace upstream and compute the relative contribution of each sub-basin to a point of interest, accounting for in-stream processes, reservoirs and point sources. A decision support system (DSS) framework was developed to run SWAT, perform the otherwise tedious process of source tracing "hotspots" and to optimize BMP locations. The "Crop to Hay" land use change BMP scenario was applied in an attempt to reduce annual loadings of total phosphorus (TP) for three Lake Winnipeg Basin watersheds: Boyne, La Salle and Little Saskatchewan. This BMP scenario was applied to all the sub-basins, starting from the highest TP contributing sub-basin to the lowest ("best case") and then applied starting from the smallest contributing sub-basin to the highest ("worst case"). When comparing the best case to the worst case to meet the 10% reduction target, the Boyne, La Salle, and Little Saskatchewan watersheds required 49, 57, and 63% less area of BMP to be applied, respectively. These results showed the importance of BMP placement in the watershed and the impact on pollutant reduction efficiency and, therefore, demonstrated the importance of the use of source tracing technique in developing efficient BMP scenarios.

Keywords: *beneficial management practices, scenario modelling, source tracing, decision support system, total phosphorus*

1 INTRODUCTION

Lake Winnipeg, the sixth largest Canadian freshwater lake, has experienced increasing levels of eutrophication and nutrient loading mainly due to agricultural activities. Nutrients such as phosphorus and nitrogen in fertilizers are commonly applied to enhance plant growth and to improve crop production. When excess nutrients are applied, some in soluble form or attached to soil particles are carried by overland water runoff from land into the aquatic ecosystems. Some of the resulting problems include excess algae growth which may be toxic, create a bad smell, reduce the enjoyment of water sports activities and fishing, and accelerate aging of the lake. In addition, these pollutants can be harmful to drinking water supply and wildlife. Therefore, it is an advantage to identify the source of these pollutants in order to provide valuable information as to where in the watershed corrective actions should be focused.

In the present paper, we discuss the use of the SWAT model results for source tracing loading "hotspots" to optimally locate BMP in the Lake Winnipeg Basin. From the model output, it is possible to trace the upstream sources and then compute the relative contribution of each sub-basin to a point of interest, usually the watershed outlet, accounting for all in-stream processes, reservoirs, dams and point sources. An environmental DSS framework is used to facilitate the source tracing process and to optimize BMP locations. The main advantage using the DSS approach is to remove the tedious source tracing process from an error prone manual exercise. Hence, such a DSS should be able to improve both reliability and efficiency in analyzing BMP.

2 MATERIALS AND METHODS

2.1 Study Areas

The three watersheds in this study, Boyne, La Salle and Little Saskatchewan, are located in Manitoba, Canada within the Lake Winnipeg Basin as shown in Figure 1. The La Salle watershed covers an area of 2,400 km^2 of which 80% (189,526 ha) is annual cropland. The Boyne watershed is the smallest of the three with a total area of 1,135 km^2. Cropland makes up 66% (74,857 ha) of the land use in the Boyne. The largest watershed of the three, the Little Saskatchewan, has a total area of 4,000 km^2, but has the smallest percentage of cropland at 37% (154,712 ha). Besides cropland, the other land types in the three watersheds include forest, pasture, urban and wetlands with percent compositions that range from 2-28%, 9-15%, 3-5% and 0.1-10%, respectively.

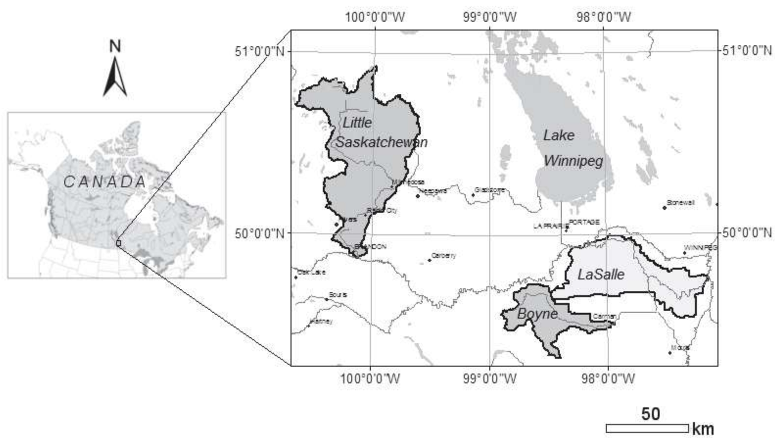

Figure 1. Map of the Boyne, La Salle and Little Saskatchewan watersheds in Manitoba Canada.

2.2 Baseline and BMP scenarios

Yang et al. (2014) analyzed the impact of four BMP scenarios, based on land use changes, on surface water quality, including total suspended sediment (TSS), total phosphorus (TP) and total nitrogen (TN), in the studied watersheds. Their results showed that when compared to the baseline case (i.e. current conditions), the annual cropland to hay land scenario had the biggest impact in reducing the annual TSS (33-65%), TP (38-72%) and TN (58-82%) average loadings at the watershed scale. The “Crop to Hay” scenario changed all of the available cropland areas in each of the three watersheds into perennial forage (hay land).

Other studies have shown that the choice of BMP as well as their placement play an important role in the effectiveness of pollution reduction. Subhasis et al. (2012) observed that different targeting methods of locating BMP produced varying results in pollution reduction, and recommends that the selection of proper targeting method and BMP be based on the needs and goals of the project. Tuppad et al. (2010) found that a strategic targeted approach to BMP placement was more effective, with less than half the land area required, than random placement in reducing 10% of overland and watershed outlet pollutant loads. Results from White et al. (2009) indicated that implementing BMP at critical source areas can potentially be more effective in reducing pollutants. Their study showed that only 5% of the watershed produced on average 22% of the sediment and TP loads from agricultural practices.

In this paper, we used the “Crop to Hay” BMP scenario as a proof of concept for TP load reduction, since phosphorus is considered to be the most important pollutant for the Lake Winnipeg basin.

Specifically, the study investigates the problem of optimizing the placement of the BMP scenario within the watershed to reduce the outlet TP loads to specified reduction levels. Two metrics were used to compare and rank solutions: the total area of cropland converted into hay land and the unit area loading reduction. A smaller value for the total area of BMP is desirable to meet the target load using the minimal amount of cropland conversion. The unit area loading reduction is a measure of the loading change per unit area and is calculated by dividing the amount of change in TP load, compared to the baseline scenario, by the total area of BMP. A higher value is more desirable for this metric as it measures the effectiveness of the land use change (i.e. how much reduction in TP load is produced by each unit area of land use change). For the proof of concept, this study focuses on three proposed TP reduction target levels of 10%, 20% and 30%.

2.3 Source Tracing Method using SWAT

Studies exist on source tracing using the SWAT model results; for example Sagahafiana et al. (2012) used a unit response approach to remove a contributing unit and then determined the change at the watershed outlet for runoff and sediment yield. This approach effectively accounts for in-stream processes and allowed for prioritizing the sub-basins with the most impact at the watershed outlet. However, the drawback of this approach is the excessive labour required when there are a large number of sub-basins to run through and could be impractical if results were required for different land use or hydrological response unit's (HRU). Shang el al. (2012) employed a similar method for TN load but changed the unit production of certain agricultural activities in one location to see the change in TN load at the watershed outlet. The approach has the same drawbacks as the Saghafiana method and only used TN load related to agricultural activities. Pai et al. (2011) used SWAT's "output.rch" file to determine the differences between upstream to downstream sub-basins. However, this sometimes results in net sink or negative loads from a sub-basin, which are set to zero.

SWAT results can be used to source trace loading "hotspots" upstream and compute the relative contribution of each sub-basin to a point of interest, typically at the watershed outlet. SWAT version 2009 (revision 445) was used for the study in this paper. In our method, in general we extracted runoff loadings from each sub-basin or HRU using SWAT's "output.hru" file. Then we use the "output.rch" values to get the effective sub-basin or HRU loading, at a point of interest. This modification does not have any issue with negative loads. In addition, our method also includes the effects of reservoirs by extracting results from SWAT's "output.rsv" file. Hence, accounting for in-stream processes, reservoirs and point sources is included. This method requires the reading of SWAT's "fig.fig" file to determine the drainage system of sub-basins and the location of point sources and reservoirs. More specifically, the loads in and out of each reach from SWAT's "output.rch" file are compared to determine the ratio of increase or decrease through each reach. A ratio less than 1 indicates losses/sinks are greater than gains/sources in the reach; for example losses could be settling or decay, and gains could be re-suspension or growth. Similarly, the ratios for reservoirs can be estimated using loadings in and out of each reservoir from the output.rsv file. These ratio adjustments are then applied to all upstream sub-basin loads and point sources. Then the effective contribution of a particular sub-basin or point source is the combined ratios (i.e. product) from all downstream reaches and reservoirs. The loadings at the watershed outlet should match the sum of the effective contributions of all upstream sub-basins and point sources. This process can be applied to any parameter and time step: in this paper we focus on yearly loadings of TP.

SWAT's "output.hru" file is also used to obtain the sediment and nutrient loads for each HRU. For parameters such as TP, the individual phosphorus components of organic (ORGP), sediment (SEDP), soluble (SOLP), and ground water (GWP) are summed. Although this paper only focuses on TP, the same method can be applied to other parameters such as TSS and TN. Sub-basin loads are obtained by summing the loads for each HRU in the sub-basin. Also, the loads for different land use or soil type can be obtained by summing the appropriate HRU values. Point source loads are obtained from the SWAT point source input files. The effective loads for these sub-basins, land uses and soil types, are computed by applying the effective contribution factor for the appropriate sub-basin. The percent of total load at the watershed outlet can then be calculated by dividing these loads by the total load at the watershed outlet. Also, the effective unit area load can be calculated by dividing the loads by the area of their sub-basins.

2.4 BMP Scenario Modelling Decision Support System

The process to apply source tracing techniques using the SWAT model to identify high polluted areas in agricultural watersheds and to target BMPs in these areas to meet pollutant reduction objectives is a complex one. It requires many data inputs, repetitive runs of the SWAT model for scenario optimization, and results analysis and visualization. Thus, it is desirable to use a decision support system (DSS) framework (Booty and Wong 2010) to minimize manual inputs to the model and human interactions in the multiple model runs to reduce errors and increase productivity. Figure 2 is a schematic diagram of the BMP Scenario Modelling DSS showing its components and linkages. The model input data reside in the data management component, which provide inputs to the source tracing and scenario optimization processes, which run within a SWAT model execution component. Source tracing results and BMP information data (from the BMPs configuration component) are passed into the optimization process to produce scenarios that meet target objectives. These optimized scenarios are reviewed in the results analysis component and a visualization component is available to view input data and source tracing and scenario results in multiple formats such as tables, charts and maps.

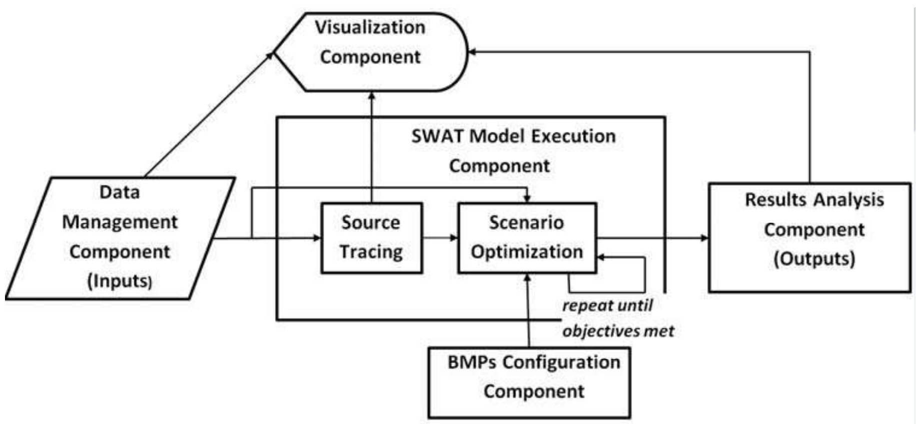

Figure 2. Schematic diagram of the components in the BMP Scenario Modelling DSS

Logically, areas of the watershed that contribute higher amounts of unit area TP loads to the watershed outlet ought to be the ones first selected for applying BMP. The output from the source tracing method is used to identify these areas. As described in an earlier section, the method computes the unit area TP loads that each of the SWAT sub-basins contributes to the watershed outlet. Sorting the sub-basins in descending order of unit area load contributions from the sub-basin that contributed the highest unit area TP load to the sub-basin that contributed the lowest unit area TP load prioritizes the sub-basins where to apply the BMP (i.e. “Crop to Hay”) scenario. The DSS framework was used to assess whether this hypothesis would hold true and if this would be a good method to “target” BMP adoption.

The DSS goes through the list of sub-basins (ordered from highest contributing to lowest contributing) resulting from the source tracing analysis and applies the BMP scenario. More specifically, the DSS firstly applied the BMP scenario only to the first sub-basin in the list (i.e. the one that contributed the largest unit area TP load to the watershed outlet). All cropland within this sub-basin was converted into hay land. The “Crop to Hay” scenario is implemented in the SWAT model by replacing the management file of each cropland HRU with the management schedule for hay land. These schedules included planting/begin growing, fertilizer application, harvesting and kill/end growing operations. Also, the SWAT parameters CN2 (SCS runoff curve number) and OV_N (Manning’s n value for overland flow) were adjusted to the values associated with hay. After the BMP scenario was setup by the DSS, it executed the SWAT model and calculated the average annual TP load at the watershed outlet. Then, the DSS applied the BMP scenario to the first two sub-basins in the list (i.e. the sub-basins that contribute the most and the second most unit area TP loads). SWAT was run again and the average annual TP loads calculated. Then, the first three sub-basins in the list from the source tracing analysis (i.e. the sub-basins that contributed the three highest unit area TP loads) had their cropland converted into hay land and so on until the BMP scenario was applied to all sub-basins in the list. At each step, the average TP loads were checked to see if any of the proposed target reductions were met and, the first time this occurred for a target, the total area of BMP deployed and the corresponding unit area loading reduction were recorded. This prioritizing of sub-basins from largest unit area TP load to smallest via the SWAT source tracing method formed the source tracing case ("best case") of the study.

Performing the analysis (i.e. source tracing, setting up BMP scenarios, running SWAT model and summarizing results) in the DSS improved overall efficiency and reduced errors compared to if it was done manually. The DSS also executed multiple SWAT models in parallel and this improved the model run-time an order of magnitude when compared to running the models sequentially.

The scenarios produced by the source tracing case method in the DSS are near optimal, but the advantage of the method over others is that it is less computationally intensive. For a watershed with *n* sub-basins, the method requires at most *n* executions of the SWAT model to produce a scenario meeting the objective if a solution exists. Thus, the method has order of *n*. On the other hand, we may use a brute-force approach to systematically apply BMP to every possible combination of sub-basins in the watershed to achieve optimum results, but this is highly computationally intensive. Hence, it is not practical in our application. Another advantage of the source tracing procedure is it can be executed by itself without performing any scenario optimization due to the component-based structure of the DSS. Information on high load areas of the watershed alone is valuable to land managers and policy makers.

Two other cases were created to test whether the "best case" method implemented in the DSS produced scenarios that required less total areas of BMPs applied to meet reduction targets and had higher unit area loading reductions. These test cases consisted of the source tracing case with sub-basin priority in reverse order ("worst case") and a Monte Carlo case ("average case"). Both of these test cases are not included within the final DSS and are solely for the purpose of comparison.

In the "worst case" test, the list of sub-basins from the source tracing analysis was sorted in ascending order (reverse order) of unit area TP load contributions from the sub-basin that contributed the lowest unit area TP load to the sub-basin that contributed the highest unit area TP load. Similar to the best case, the BMP scenario was applied to the first sub-basin in the list (i.e. this time the one that contributed the least unit area TP load), SWAT was executed and the average annual TP load calculated. Then, the BMP scenario was applied to the first two sub-basins in the list (i.e. the sub-basins that contributed the smallest and second smallest unit area TP loads), SWAT was run and the average annual TP load computed. Then, the BMP scenario was applied to the three sub-basins that contributed the smallest unit area TP loads and so on until all sub-basins were processed. The first time when each of the percentage reduction targets was achieved, the total area of BMP application and the unit area loading reduction were recorded.

For the second test case, "average case", a Monte Carlo simulation of 1,000 runs was used to estimate "average" values for the total area of BMP deployment and the unit area loading reduction at each of the three percentage reduction targets. A random ordering of the sub-basins was first generated (sub-basins were selected from a uniform distribution). Then, the same methods used to calculate the best case were performed on this ordering of sub-basins. This process was repeated 1,000 times where the ordering of the sub-basins was randomized each time. At the end of the Monte Carlo simulation, each of the percentage reduction targets had sets of area values and unit area loading values. The median of the 1,000 simulations was taken to represent the "average" case.

3 RESULTS AND DISCUSSION

The calibrated SWAT models for the Boyne, La Salle and Little Saskatchewan watersheds from Yang et al. (2014) were used as the baseline scenarios for this study. The annual average TP loads from 1990 to 2007 at the watersheds' outlets were used as the basis of comparison. The annual average TP loads of the baseline scenario for Boyne, La Salle and Little Saskatchewan were 20,888, 55,832 and 27,606 kg, respectively.

Source tracing of TP was performed on the three watersheds to locate the “hotspots”. Figure 3 shows maps of the unit area TP loads contributed by each sub-basin to the outlets of the Boyne, La Salle and Little Saskatchewan watersheds. Sub-basins in the Boyne, La Salle and Little Saskatchewan watersheds contributed unit area TP loads that ranged from 0 to 2.24 kg/ha, 0.01 to 0.62 kg/ha, and from 0.01 to 0.21 kg/ha, respectively. In all three watersheds, higher unit area TP loads were generally found in the outlet sub-basin or at nearby upstream sub-basins.

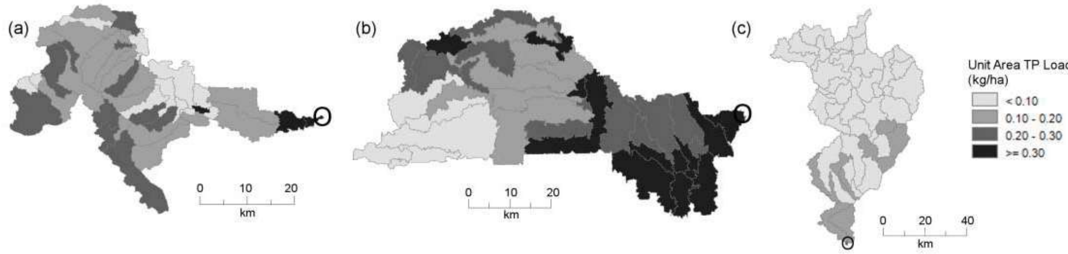

Figure 3. Source tracing results for the (a) Boyne, (b) La Salle and (c) Little Saskatchewan watersheds. Darker shading represents sub-basins contributing higher unit area TP loads. Circled areas are the watershed outlets.

The best case, average case and worst case analyses were performed for each of the 3 watersheds. Figure 4 highlights the sub-basins that had BMP applied to meet each of the percentage reduction targets for the best, average and worst cases.

The results show that the best case required the least total area of BMP scenario application to meet each of the proposed target reductions (i.e. 10%, 20% and 30%) and had the biggest unit area TP loading reductions. Conversely, for the worst case, the largest total area of BMP was necessary in order to meet the targets and the unit area TP loading reductions were the smallest. Table 1 shows that the areas and unit area loading reductions from the average case fell in between those from the best and worst cases.

Table 1. BMP area totals and % reductions and unit area TP loading reductions for the best case, average case and worst case for the Boyne, La Salle and Little Saskatchewan watersheds

	Best Case			Average Case			Worst Case		
		Reduction			Reduction			Reduction	
Target %	BMP Area (ha)	%	Unit Area TP Load (kg/ha)	BMP Area (ha)	%	Unit Area TP Load (kg/ha)	BMP Area (ha)	%	Unit Area TP Load (kg/ha)
Boyne Watershed									
10%	10,543	11.5%	0.228	14,285	11.3%	0.165	20,686	10.3%	0.104
20%	21,533	23.6%	0.229	24,651	21.4%	0.181	31,514	21.0%	0.139
30%	28,079	31.8%	0.237	35,570	31.3%	0.184	44,572	32.4%	0.152
La Salle Watershed									
10%	19,097	14.5%	0.423	26,371	11.4%	0.242	44,683	11.9%	0.149
20%	27,859	22.9%	0.460	48,789	21.6%	0.247	75,094	21.2%	0.157
30%	42,051	30.5%	0.405	71,390	31.5%	0.246	99,907	31.0%	0.173
Little Saskatchewan Watershed									
10%	22,513	10.9%	0.134	40,733	11.0%	0.074	60,795	12.4%	0.057
20%	53,073	20.1%	0.105	73,514	21.0%	0.079	86,951	21.0%	0.067
30%	89,330	30.0%	0.093	106,313	31.0%	0.081	126,497	32.0%	0.070

Furthermore, Table 1 also shows that the best case was the most efficient in reducing pollutants in terms of BMP areas required and unit area TP load reduced when compared to the average and worst cases. To illustrate this, we examine the 10% reduction case. The best case required 26, 28 and 45% less total area of BMP deployment than the average case for the Boyne, La Salle and Little Saskatchewan watersheds. The unit area TP loading reductions were improved by 38, 75, and 81% for the Boyne, La Salle and Little Saskatchewan, respectively. When the best case is compared to the worst case, the Boyne, La Salle and Little Saskatchewan watersheds required 49, 57, and 63% less total area of BMP deployment respectively to meet a 10% target reduction. Also, the unit area TP loading reductions were greater than 119, 184 and 135% for the Boyne, La Salle and Little Saskatchewan, respectively. Similar results were achieved at the 20% and 30% target reduction levels (Table 1). This reinforces the importance of employing a source tracing approach in targeting BMP applications to reduce the amount of BMP area required and to increase unit area reduction loadings.

These results show that the choice of where to implement BMP scenarios in the watershed affects the amount of BMP required (in terms of total area) to meet specified target loads and impacts the effectiveness in reducing pollutants. As expected, when the BMP scenario was applied to sub-basins that were ranked based on their TP contribution load from largest to smallest (the "best case") using source tracing analysis in the DSS, the target reductions were reached using the least amount of BMP area and it produced highest unit area TP loading reductions. This proof of concept shows that source tracing can be a crucial strategy for targeted BMP deployment for pollutant reduction scenarios.

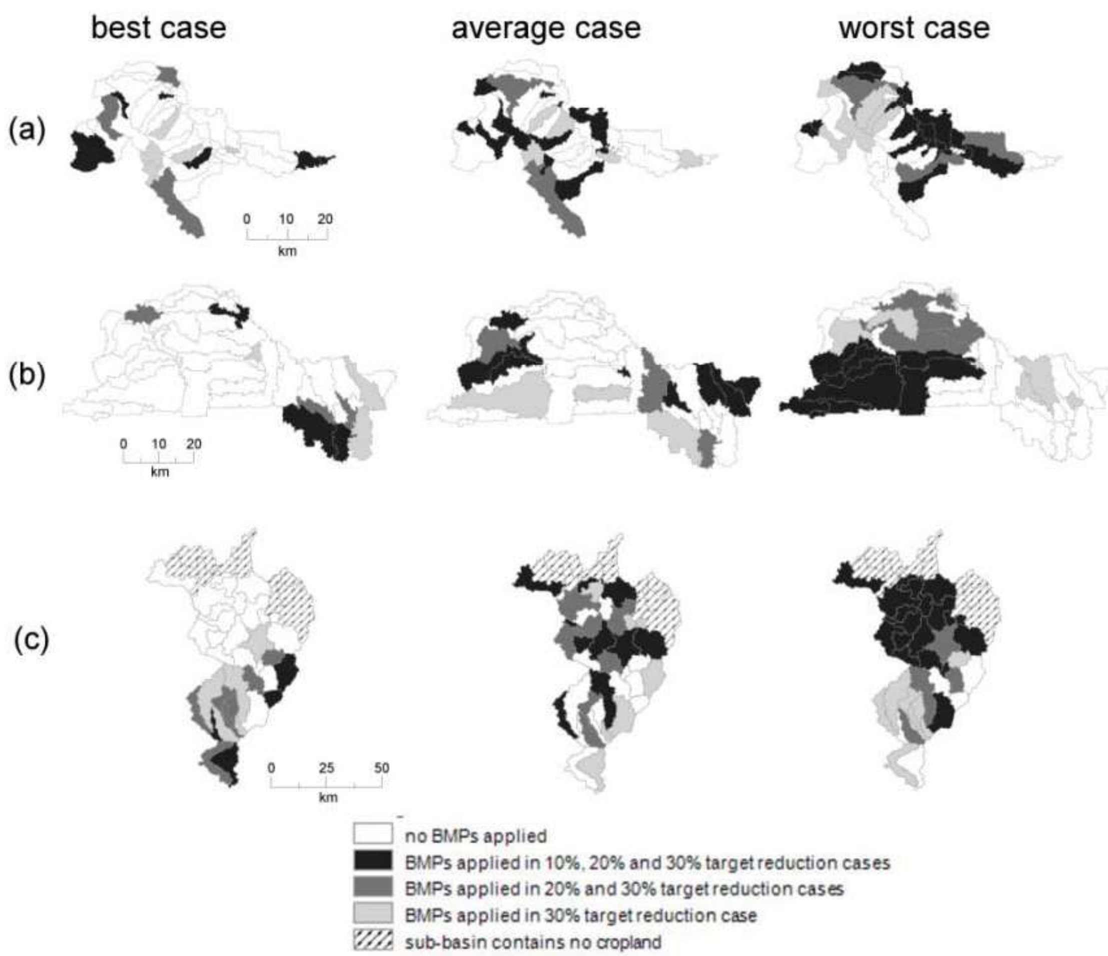

Figure 4. Sub-basins selected in the (a) Boyne, (b) La Salle and (c) Little Saskatchewan watersheds for BMP application in the best, average and worst cases to meet TP reduction targets of 10%, 20% and 30%.

4 CONCLUSIONS & RECOMMENDATIONS

The results of the study showed that source tracing using the SWAT results provides important information that can help guide the effective placement of BMP for watershed nutrient loading reduction. Applying a BMP scenario to “hotspots”, or areas with the highest yield of nutrients that reach the watershed outlet, produced the most optimal results in terms of the least area of BMP required and the most unit area loading reduction for the same target reduction percentage for the three study watersheds in the Lake Winnipeg Basin: Boyne, La Salle and Little Saskatchewan.

The use of source tracing in the DSS framework allows for effective and efficient assessment of the impacts of the “Crop to Hay” BMP scenario comparison with the baseline. This study opens up an opportunity for BMP scenario modellers to target high load areas for applying various BMP based on the HRU information.

In the future, we intend to introduce a suite of BMPs that is appropriate for various HRUs for evaluation and consideration. The BMPs in consideration are non-physically constructed such as nutrient management, land-use change and riparian buffers. As long as the percentage and composition of HRUs in the sub-basins are known, then there is sufficient information to modify SWAT input files for BMP implementation and to run SWAT for optimization of pollutant reduction scenarios. This approach allows specific BMPs that are most effective to be deployed on suitable HRUs based on land-use, soil and slope information. By combining the pollutant source tracing and the target BMP application strategy allows for more precise placement of BMPs in appropriate HRU areas. For example, riparian buffers BMP is most effective adjacent to a cropland HRU with high levels of surface runoff and is particularly effective where concentrated flow leaves these fields. Also, nutrient management BMPs are most relevant on cropland and in areas where fields have areas within them prone to chronic low yields and high runoff.

The optimization of combined BMPs that targets the characteristics of various sub-basins/HRUs using the DSS approach will assist watershed resource managers and planners to improve program efficiency and targeting of finite resources to improve watershed health. It will also benefit farmers and land managers by minimizing financial impacts due to lost revenue and BMP construction costs through targeting locations that are the most effective for nutrient reduction. Furthermore, the BMP scenario results can be used in the integrated lake and watershed modelling framework to predict the change of lake water quality due to the use of BMP implementation at the watershed level.

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