

Scenarios to Investigate the Effect of Wetland Position in a Watershed on Nutrient Loadings

S.J. Melles^a, G. Benoy^b, B. Booty^a, L. Leon^a, J. Vanrobaeys^c, and I. Wong^a

^a*Environment Canada, 867 Lakeshore Rd., Burlington, ON, L7R 4A6, Canada
(Stephanie.Melles@ec.gc.ca, Bill.Booty@ec.gc.ca, Luis.Leon@ec.gc.ca, Isaac.Wong@ec.gc.ca)*

^b*Environment Canada and Agriculture and Agri-Food Canada, P.O. Box 20280, Fredericton,
NB, E3B 4Z7, Canada (Glenn.Benoy@ec.gc.ca)*

^c*Agriculture and Agri-Food Canada, 101 Route 100, Unit 200, Morden, MB, R6M 1Y5, Canada
(Jason.Vanrobaeys@agr.gc.ca)*

Abstract: Lake Winnipeg is Canada's 6th largest freshwater lake and is subject to an increasing rate of eutrophication as a result of nonpoint source pollution from numerous sources including farms and municipal wastewaters. We examine scenarios designed to compare the relative effects of wetland restoration and position on modelled nutrient loadings to Lake Winnipeg from a pilot watershed in the Lake's Basin, the La Salle River watershed. Scenarios were examined using the Soil and Water Assessment Tool (SWAT). SWAT is a well-known watershed scale hydrologic model designed to assess non-point source pollution loadings to contributing streams across a wide range of scales. Modelled results suggested that increasing wetland cover to historic levels decreased yearly nutrient loadings by 9-21% for both TN and TP. When 25% of historic wetland areas were restored at subwatershed outlets, equivalent or better nutrient reductions were attained. But placing all wetland area at the watershed outlet did not result in as substantial nutrient reductions. There was a larger range of uncertainty when wetlands were modelled across all subwatersheds than when the entire wetland area was modelled at the outlet. These results may indicate that wetland position is as important as wetland amount in terms of nutrient reductions.

Keywords: scenario evaluation, non-point source pollution, wetlands, watershed modelling, water quality, Lake Winnipeg

1 INTRODUCTION

The increasing prevalence of algal blooms along the shorelines of Lake Winnipeg (Manitoba, Canada) is a conspicuous example of excessive nutrient loadings. Agricultural run-off in Lake Winnipeg Basin is recognized as a major source of nonpoint source (NPS) nutrient pollution. NPS pollutants such as nitrogen (N), and phosphorus (P) cause accelerated eutrophication of inland waters and coastal "dead zones" around the world [Chambers et al., 1974; Scavia and Nassauer, 2007]. Lake Winnipeg is a fairly shallow freshwater lake with a drainage basin that spans four provinces and four states in Canada and the U.S.: the basin covers an area of approximately one million km². Half of the basin is dominated by agriculture and over half of the annual nutrient loads to the lake come from outside the Province of Manitoba.

Empirical research has demonstrated that the proportion of wetland in a watershed (i.e., up to 15%) is related to a reduction in nutrient pollution in receiving waters [Jones et al., 1976]. A variety of high profile SWAT modelling studies in Canada [Yang et al., 2008; Liu et al., 2008] and the U.S. [Vache et al., 2002] also suggest that wetlands can provide substantial nutrient reduction potential. Wetlands serve a variety of ecosystem purposes. They have known nutrient removal

capabilities. Both natural and constructed wetlands are commonly and effectively used to treat municipal and agricultural wastewater [White and Bayley, 2001]. Additionally, wetlands fulfill a variety of hydrologic functions, i.e. flood mitigation and reducing peak flows [Demissie and Khan, 1993] filtering and storage of snow-melt runoff [Hayashi et al., 2004]. Wetlands provide habitat for a diverse array of plants and animals [Mitsch and Gosselink, 2000], and they may help to ameliorate climate change by regulating temperature and storing CO₂ [Neave et al., 2008]. However, determining where to construct wetlands and what percent cover may be required to effectively reduce nutrient loadings are important yet unanswered questions.

In this study, we examine the relative effects of restoring drained wetlands back to their historic (1870's) levels within the La Salle River watershed, and we test whether wetland position within a subwatershed had an effect on modeled nutrient loadings at the outlet using the SWAT model. We do so by creating a scenario of pre-settlement wetland cover (6.1%) merged with current land use practices in the La Salle watershed. We compare this scenario to a more realistic level of wetland restoration where one quarter of the historic wetlands are restored. We then test whether scenarios involving wetlands restored across all subwatersheds in the La Salle had a higher range of uncertainty in nutrient loadings at the outlet than a scenario that targeted wetland restoration at the watershed outlet alone to examine the effect of wetland position on nutrient loadings. Only the effect of parameter uncertainties in wetland nutrient chemistry were examined.

2 METHODS

2.1 Study area watershed

The La Salle River watershed of south central Manitoba is one of the most intensely drained landscapes in North America. Less than 0.1% wetland cover remains in the watershed according to 2001 LANDSAT derived, landcover classifications. Prior to European settlement, the area surrounding the current City of Winnipeg was covered by vast grassland habitats and extensive marshes, which supported a diverse community of wildlife [Bossenmaier and Vogel, 1974]. The La Salle river drains an area of approximately 2460 km² over an elevational change of 103 m (Fig. 1a). Much of the watershed (76%) is now intensively cultivated agricultural land [Jones and Armstrong, 2001], and livestock operations found throughout the watershed use grassland cover for pasture (8%). The main crops grown are: wheat, barley, canola, flax, legumes, and forages.

2.2 Model details

SWAT was designed to simulate watershed management decisions on hydrology and water quality over a wide range of scales and various periods of time [Arnold et al., 1998; Gassman et al., 2007]. SWAT combines physical, process-based algorithms with empirically-based hydrologic knowledge to model hydrology and water quality. Model inputs included: a digital elevation model (DEM) derived from SRTM (<http://www2.jpl.nasa.gov/srtm/>); soil, and landuse GIS layers obtained from the Manitoba Land Initiative (<https://mli2.gov.mb.ca/>); water quality data provided by Manitoba Water Stewardship [Stewardship, 2009]; flow data obtained from the Water Survey of Canada (<http://scitech.pyr.ec.gc.ca/waterweb/>), and climate data from Environment Canada's daily climate data (<http://climate.weatheroffice.gc.ca/>). The model was manually calibrated prior to this study, and calibration and validation tests are currently underway using SWAT-CUP (an autocalibration tool) and GLUE (Generalized Likelihood Uncertainty Estimation). Preliminary performance indices (root mean square error and the Nash-Sutcliffe coefficient of efficiency) measuring the correspondence between simulated discharge and measured monthly flow at a gauge station near the outlet were 0.73 (R^2) and 0.72 (R^2_{NS}) respectively. Please refer to [Leon et al., 2010, this issue] for more details on model setup and calibration. As the model is still undergoing calibration and validation, the results of this study must be interpreted very cautiously, however only the relative effects of changing wetland position and modifying wetland nutrient chemical parameters are of interest at any rate.

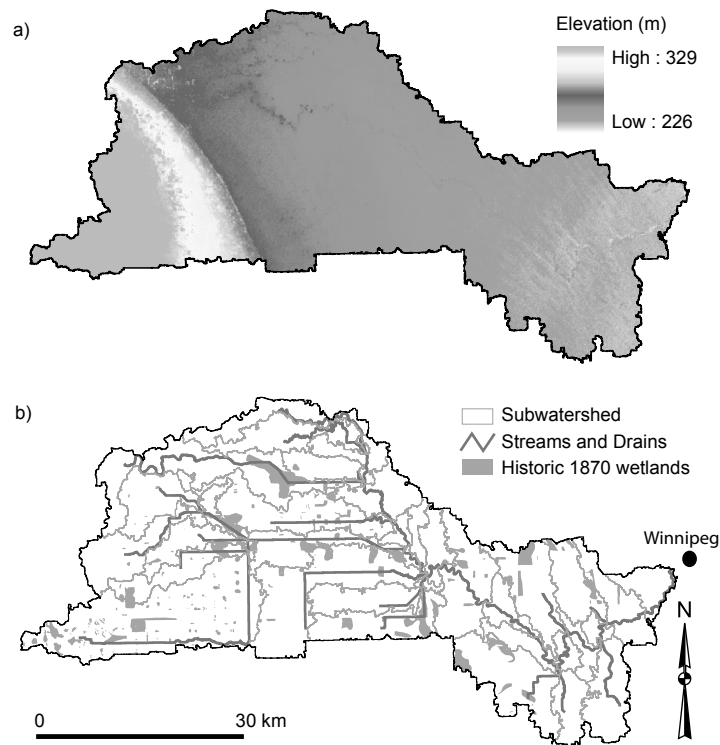


Figure 1: Study area watershed ($49^{\circ}36'56''$ N, $97^{\circ}44'35''$ W) within the Lake Winnipeg Basin, MB, Canada. a) Elevation derived from Shuttle Radar Terrain Mission data, and b) Watershed map of historic (1870) wetland coverage, current streams and drains, and subwatershed delineation.

2.3 Scenarios

The *current* scenario for the La Salle was based on 2001 landcover data derived from LANDSAT imagery. A landscape reconstruction of historic wetland cover (*W1870*) was provided by Hanuta [2006] and was created using the original Dominion Land Survey township maps (Fig. 1b). As some areas of the La Salle watershed were missing from Hanuta [2006], these areas were digitized from Figure 1 of Bossenmaier and Vogel [1974]. The original township maps suggest that 6.1% of the La Salle remained as wetland in 1870 (Fig. 1b). Historic wetland levels were compared with a scenario where one quarter (25% by area) of the 1870's wetlands were restored at all of the historic locations (*QWR*). Then, this scenario, which restored wetlands over 1.5% of the watershed was modified such that wetlands in each subwatershed were positioned at the mouth of the subwatershed (*QWRsuboutlets*). Our rationale for placing wetlands at subwatershed outlets was to target wetland placement where the wetland should intercept a maximal amount of overland flow in the subwatershed. The fifth scenario compared the relative effects of restoring the same area of wetland (1.5% of the watershed) entirely at the watershed outlet (*QWRoutlet*). In order to model these scenarios, modifications were made to the .PND input files of all subwatersheds. Corresponding changes were not made to the landcover layers because in the majority of cases, the amount of wetland coverage within each subwatershed was below the threshold used to create homogeneous hydrologic response units (HRU's), which are the basic landcover modelling units in SWAT.

2.4 Parameter uncertainty

SWAT requires that 19 parameters be set for each wetland modelled per subwatershed. Six of these parameters can be set using a GIS, model-inference and visual estimation, including wetland surface area (normal and maximum), volume (normal, initial, and maximum), and the fraction of

Table 1: SWAT wetland nutrient parameters and range of parameter uncertainty values considered.

Parameter name	Description	High removal capacity	Medium removal capacity	Low removal capacity
WETSED	Initial sediment concentration [mg/l]	1	2500	5000
WETNSED	Normal sediment concentration [mg/l]	4300	4300	4300
WETK	Hydraulic conductivity of bottom [mm/hr]	0	0	0
PSETLW1	Phosphorus settling rate for summer months [m/year]	20	10	1
PSETLW2	Phosphorus settling rate for winter months [m/year]	20	10	1
NSETLW1	Nitrogen settling rate for summer months [m/year]	20	10	1
NSETLW2	Nitrogen settling rate for winter months [m/year]	20	10	1
CHLAW	Chlorophyll a production coefficient	1	0.5	0
SECCIW	Water clarity coefficient [m]	1	0.5	0
WETNO3	Initial concentration of NO ₃ -N [mg N/l]	1	50	100
WETSOLP	Initial concentration of soluble P [mg P/l]	1	25	50
WETORGN	Initial concentration of organic N [mg N/l]	1	37.5	75
WETORGP	Initial concentration of organic P [mg P/l]	1	25	50

the subwatershed that drains into the wetland [Liu et al., 2008]. Maximum surface area was set to the historic wetland area calculated from the GIS layer, and surface area at normal water level was set to 30% of the maximum [as per Liu et al., 2008]. Considering that many areas in the La Salle watershed are dry for much of the year, this seems like a reasonable level.

Thirteen additional parameters must be set for each wetland to define nutrient concentrations and removal rates in the wetland (Table 1). Both nitrogen and phosphorus removal rates tend to be highly variable [Yang et al., 2008]. Moreover, the nutrient removal capacity of wetlands varies both seasonally and as the wetland ages. Wastewater wetlands can even begin to export phosphorus following saturation of their sediments [White and Bayley, 2001]. Not to mention that it is impossible to estimate what the nutrient concentrations and removal capabilities were for historic wetlands of 1870. To account for this source of uncertainty, we tested the extremes of nutrient removal capabilities to put upper and lower bounds around the range of nutrient parameter uncertainty. The values selected and shown in Table 1 represent SWAT model extremes (for saturated and unsaturated wetlands) as well as midpoint values. Hydraulic conductivity (WETK) was set to 0 because seepage is not expected to occur in the watershed given that the dominant soil type is clay. However, coarse textured soils do exist in the western portions of the watershed, so a comprehensive uncertainty analysis might also consider this parameter in addition to normal sediment concentrations. Normal sediment concentrations were inferred from a study on the effect of cultivation on sediment composition and deposition in prairie wetlands [Martin and Hartman, 1987], and these values were not allowed to vary in this preliminary study.

3 RESULTS AND DISCUSSION

Increasing wetland cover to historic levels decreased simulated yearly average nutrient loadings at the outlet by up to 21% (range 8.6 - 21%). Figure 2 shows a comparison of the five wetland scenarios for TP only, but results were consistent for both TN and TP. When one quarter of the area in each historic wetland was restored within all original subwatersheds (*QWR*), yearly nutrient loadings decreased by a lesser amount, as expected. The mean annual decrease in TP was between 2.2 and 5.2 % on average for scenario *QWR* (Fig. 2). This was also true for the scenario where the full quarter of historic wetland area (i.e., 1.5% of watershed area) was positioned at the watershed outlet (*QWRoutlet*). In this case, the decrease in simulated mean annual TP was between 1.8 and 2.6%. Surprisingly, however, when historic wetlands were restored at the outlet of each of their respective original subwatershed positions, there was a very large decrease in mean annual nutrient loadings, even when only 25% of historic wetland area was restored. Indeed, the decrease was similar in magnitude to the decrease in nutrients found by restoring all 1870's wetlands in their original subwatershed positions (range 7.9 - 39%).

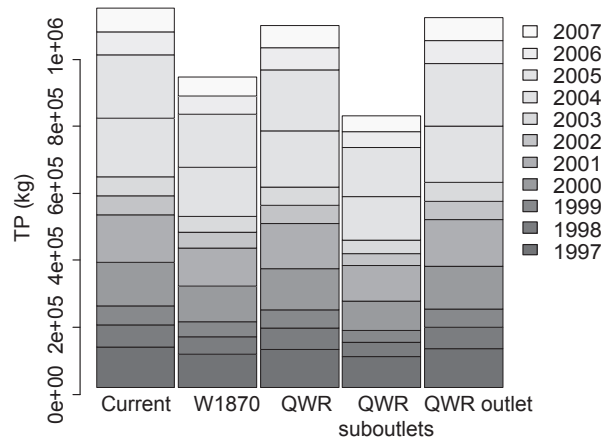


Figure 2: Differences in total phosphorus loadings at the La Salle Manitoba watershed outlet over the period 1997 to 2007, for the current scenario and various wetland reference and restoration scenarios. *W1870* is the scenario for historic 1870's wetland cover; *QWR* represents a scenario where 25% by area of the historic 1870's wetlands are restored at all of the historic locations; *QWRsuboutlets* represents a scenario where 25% of historic wetland areas are restored at each of the watershed suboutlets; *QWRoutlet* represents a scenario where 25% of the historic wetland area is restored, but the entire wetland area is located at the watershed outlet.

The largest nutrient loadings occurred during the month of peak flow or spring snow-melt (Fig. 3 and Fig. 4). Figures 3 and 4 depict mean monthly total phosphorus and total nitrogen loadings respectively for all scenarios examined. The relative differences in mean monthly nutrient loadings even out across all scenarios during the fall and winter months, which is related to changes in the flow regime. The main differences between the scenarios that were evident in figure 2 are most apparent during the months of April and July when snow-melt and summer storms increase flow. Wetlands distributed throughout the watershed had the largest effect on relative nutrient loadings during these two periods, indicating that they were reducing peak flows of nutrients. What is also interesting to note about these figures is that the effect of nutrient parameter uncertainty had a larger impact on nutrient loadings when wetlands were restored at all subwatershed outlets than when a single large wetland was restored at the watershed outlet. This finding suggests that distributing wetlands across the watershed may have a larger potential impact on nutrient loadings, but the level of impact may be more variable, and depends on wetland nutrient removal capabilities.

A large number of studies in Canada and the U.S. have used calibrated models built with the Soil and Water Assessment Tool [Gassman et al., 2007, and references therein]. A modelling approach is necessary in situations where data are lacking or sparse and when large areas are under investigation [Lindenschmidt et al., 2007]. Nutrient reduction potentials reported in several of these studies seem comparable to the values reported here [e.g., Yang et al., 2008]. We realize, however, that all model results are subject to uncertainty, particularly when historic or future scenarios are under consideration and when the model itself has only undergone preliminary calibration. We cannot really model what has never been measured, nor can we make accurate projections about what the future will look like. Even when data are available, results may be subject to measurement errors and biases or systematic sampling errors. Moreover, natural ecosystem variability leads to parameter uncertainties in space and time. The nutrient removal efficiencies of wetlands are not static through time, nor are all wetlands alike. For example all wetlands are not equally capable of water storage. Additional sources of uncertainty stem from a mismatch between the model and the system being modelled (model uncertainty) and uncertainty in subjective judgements that are made along the way.

Several of the SWAT studies reported on by Gassman et al. [2007] suggest that wetlands were adequately represented by the model. However, there are limitations to the way SWAT depicts

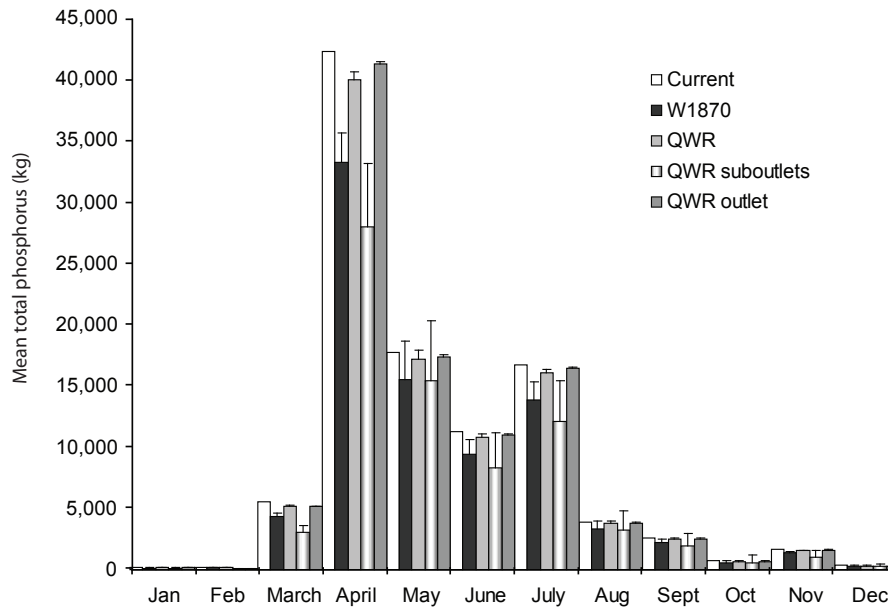


Figure 3: Mean monthly total phosphorus loadings at the La Salle Manitoba watershed outlet over the period 1997 to 2007 for five scenarios. Acronyms as in Fig. 2. Error bars for each scenario represent the range of nutrient loadings at the outlet, given uncertainty in input parameters for wetland nutrient chemistry (refer to Table 1 for the range values considered).

wetlands [Liu et al., 2008; Hatterman et al., 2006]. For example, only a single wetland per subwatershed can be modelled, so all wetlands in a subwatershed must be depicted as a single 'pseudo' wetland positioned somewhere within the subwatershed. Moreover, riparian wetlands, adjacent or connected to waterbodies, lakes, and streams, are not well represented by the model [Liu et al., 2008; Hatterman et al., 2006]. The latter authors each created extension modules for SWAT and SWIM (Soil and Water Integrated Model) that better represent riparian area wetlands, but these modules cannot be used for non-riparian wetlands and we were not able to implement them in the present study.

Although our findings suggest that wetland restoration may have a large impact on nutrient loadings and peak flows, Shultz and Leitch [2003] had divergent findings. These authors investigated the feasibility of restoring previously drained wetlands to reduce flood damage, and they question the utility of wetlands for reducing major springtime flood events in the Red River Valley because, according to Shultz and Leitch [2003], wetlands tend to already be at full water storage capacity in the spring due to excessive rainfall in the preceding year. We note that there is little evidence to support their contention that wetlands are at full storage capacity prior to spring snowmelt, but we did not investigate the effect of changing normal, maximum or initial wetland volumes. Future analyses should attempt to do so.

4 CONCLUSIONS AND RECOMMENDATIONS

We have made a simple preliminary assessment of five wetland restoration scenarios and a single type of uncertainty - parameter uncertainty in wetland nutrient water chemistry. Despite the limitations and uncertainties of these comparisons, we feel, as do others, [e.g., Vache et al., 2002; Gassman et al., 2007] that such analyses are useful because they allow us to compare the relative effect of various alternatives, given the assumptions of the model and what we know about the system. Indeed, the results have surprised us. The implications of our study suggest that it is not better to apply all wetland restoration efforts at the watershed outlet as common sense principles and economic limitations might indicate. Wetland position may be as important as wetland amount and this finding warrants further study.

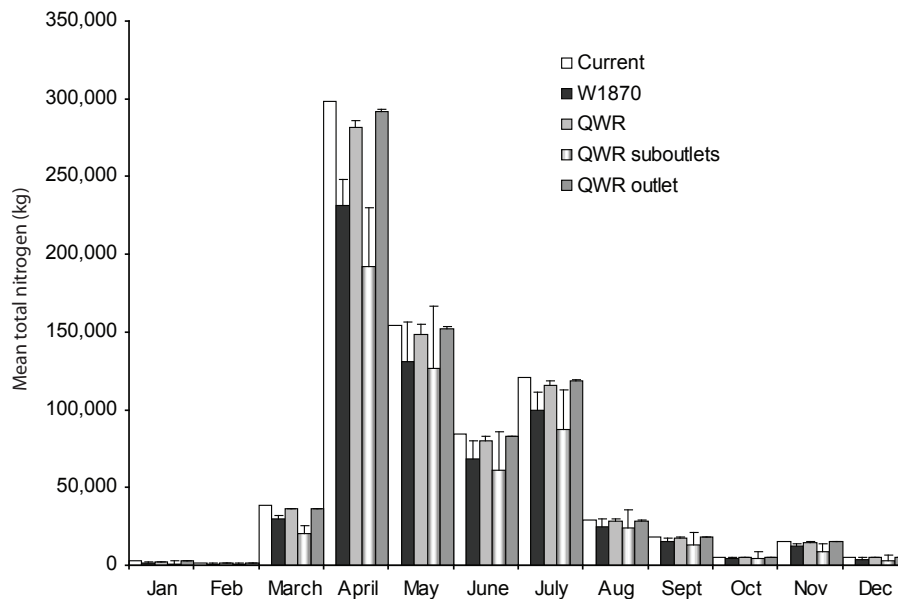


Figure 4: Mean monthly total nitrogen loadings at the La Salle Manitoba watershed outlet over the period 1997 to 2007 for five scenarios. Acronyms as in Fig. 2. Error bars for each scenario represent the range of nutrient loadings at the outlet given uncertainty in input parameters for wetland nutrient chemistry (refer to Table 1 for the range values considered).

A more comprehensive Monte Carlo uncertainty analysis that accounts for the relationships between parameters would help to substantiate the preliminary findings reported here. Several uncertainty analysis tools are available with SWAT2005, but these tools are designed to optimize parameter inputs by minimizing an objective function typically related to some measure of the difference between observed and simulated values. These methods assess and improve model fit. We are interested in studying the effect of parameter uncertainty on model outputs during model implementation. Ultimately we would like to optimize the position of wetlands in a watershed using multiple criteria [as in Maringanti et al., 2009] such as nutrient loadings and wetland ability to intercept water flow.

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