

Simulated environmental effects of wetland restoration scenarios in a typical Canadian prairie watershed

Wanhong Yang · Xixi Wang · Yongbo Liu ·
Shane Gabor · Lyle Boychuk · Pascal Badiou

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Abstract Wetland conservation and restoration contribute to improved watershed functions through providing both water quantity benefits in terms of flood attenuation and water quality benefits such as retention of sediment and nutrients. However, it is important to quantify these environmental benefits for informed decision making. This study uses a “hydrologic equivalent wetland” concept in the Soil and Water Assessment Tool to examine the effects of various wetland restoration scenarios on stream flow and sediment at a watershed scale. The modeling system was applied to the 25,139 ha Broughton’s Creek watershed in western Manitoba in Canada. As a representative prairie watershed, the Broughton’s Creek watershed experienced historic wetland losses from 2,998 ha in 1968 to 2,379 ha in 2005. Modeling

results showed that if wetlands in the Broughton’s Creek watershed can be restored to the 1968 level, the peak discharge and average sediment loading can be reduced by 23.4 and 16.9%, respectively at the watershed outlet. Based on wetland and stream drainage areas estimated by the model and empirical nutrient export coefficients, the corresponding water quality benefits in terms of reductions in total phosphorus and nitrogen loadings were estimated at 23.4%. The modeling results are helpful for designing effective watershed restoration strategies in the Broughton’s Creek watershed. The developed methodology can be also applied to other study areas for examining the environmental effects of wetland restoration scenarios.

Keywords Flood attenuation · HEW · Modeling · Nutrients · Sediment · SWAT · Wetland restoration

W. Yang (✉) · Y. Liu
Department of Geography, University of Guelph, Guelph,
ON N1G 2W1, Canada
e-mail: wayang@uoguelph.ca

X. Wang
Department of Engineering and Physics, Tarleton State
University, Stephenville, TX, USA

S. Gabor · P. Badiou
IWWR, Ducks Unlimited Canada, Stonewall,
MB, Canada

L. Boychuk
Ducks Unlimited Canada, Western Region,
Regina, SK, Canada

Introduction

With growing concerns about the adverse environmental effects of agriculture, wetland conservation and restoration have been considered as one of the important measures for improving watershed functions through providing environmental benefits in terms of flood attenuation and retention of sediment and nutrients (National Research Council 1995). In order to make a scientific decision regarding a

wetland conservation/restoration policy initiative or program, policy makers usually require information regarding the returned environmental benefits. With this regard, watershed hydrologic models need to be adapted to characterize wetland functions for examining wetland conservation and restoration scenarios and generating the information required by policy makers. However, the application of these models in practice requires specific considerations of the watershed of interest to generate useful as well as usable information.

It has been a challenge to characterize wetland functions using a watershed hydrologic model. Padmanabhan and Bengtson (2001) used the HEC-1 model (Hydrologic Engineering Center 1998) to assess the influence of wetlands on flooding in the North Dakota Maple River and Wild Rice River watersheds of the Red River of the North Basin. In the model, the wetlands were partitioned and aggregated on a subwatershed basis, and modeled as “flow diversions” (USBR 1999). The results indicated that wetlands exerted only a negligible influence on hydrologic processes of the studied watershed. In a separate study, Vining (2002) used a modified precipitation-runoff modeling system (PRMS) model (Leavesley and Stannard 1995; Leavesley et al. 2002) to simulate the water stored in the wetlands of the Starkweather Coulee sub-basin in northeastern North Dakota from 1981 to 1998. In the study, the sub-basin was divided into 50 hydrologic response units (HRUs) and thus 50 synthetic wetlands were defined to model the thousands of wetlands identified. The results indicated that more water was stored in the wetlands for the years with a higher annual stream flow than for the years with a lower stream flow.

These two modeling studies made common assumptions that: (1) the maximum surface area for a given “diversion” or synthetic wetland is equal to the summation of the maximum surface areas of the component wetlands; (2) the volumetric capacity of the diversion or synthetic wetland could be estimated as a function of its maximum surface area; (3) the percentage of the runoff intercepted by the diversion or synthetic wetland could be predetermined; and (4) different types of wetlands (e.g., channel fens versus flat bogs) had identical hydrologic functions. These assumptions imply that hydrologic functions of wetlands within a watershed are linearly additive,

which may not be a realistic characterization of wetlands in a watershed.

Recently, Wang et al. (2008) developed a “hydrologic equivalent wetland (HEW)” concept to address the aforementioned wetland modeling problems that arise as a result of these assumptions. A HEW has a hydrologic function equivalent to its component wetlands, and therefore substituting the HEW for the wetlands will not affect the precipitation-runoff process. Wetland HRUs and HEWs are different in that wetland HRUs do not have attenuation effects, whereas HEWs do. Consequently, the HEW can reflect the nonlinear functional relations between runoff and wetlands. As with a regular wetland, HEW is described by five parameters, namely the fraction of the sub-basin area that drains into the HEW, the surface area at normal water level, the volume of water stored in the HEW when it is filled to its normal water level, the surface area at maximum water level, and the volume of water stored in the HEW when it is filled to its maximum water level. In contrast to both Padmanabhan and Bengtson (2001) and Vining (2002), these parameters should be determined through model calibration.

Despite the general understanding that wetland hydrologic functions are essential for modeling wetland-dominated watersheds (SCS 1981; Napier et al. 1995; USBR 1999; Hayashi et al. 2004), the exact method that should be used to incorporate wetlands into hydrologic models is still a debated subject with much agreements and disagreements. The Soil and Water Assessment Tool (SWAT) has been widely used to predict the impact of land management practices on water, sediment, and agricultural chemical yields in large and complex watersheds with varying soil types, land use, and management conditions over long periods of time (Arnold et al. 1993; Srinivasan and Arnold 1994; Rosenthal et al. 1995; Bingner 1996; Peterson and Hamlett 1998; Sophocleous et al. 1999; Spruill et al. 2000; Weber et al. 2001; Gitau et al. 2002; Van Liew and Garbrecht 2003; Chu and Shirmohammadi 2004; Du et al. 2005; Vazquez-Amábile and Engel 2005). However, few of these applications have considered the influence of wetlands on simulating stream flows, even though wetlands might be an important land cover in some of the study watersheds (Du et al. 2005; Vazquez-Amábile and Engel 2005).

The objective of this study was to develop and apply a prototype modeling system to evaluate water quantity and quality benefits of various wetland restoration scenarios in a representative prairie watershed. The specific objectives were to: (1) use the HEW concept to develop a prototype of SWAT-based hydrologic modeling system; (2) calibrate and validate the model for the Broughton's Creek watershed; and (3) use the prototype modeling system to assess the prospective wetland restoration scenarios in the Broughton's Creek watershed.

Study area

The 25,139 ha Broughton's Creek watershed is located in south-western Manitoba, Canada with latitudes 100.2–100.4 degrees west and longitudes 50.0–50.3 degrees north (Fig. 1). The Broughton's Creek links to the Little Saskatchewan River, a tributary of the Assiniboine River that in turn flows east into the Red River of the North and finally to Lake Winnipeg. Based on the data obtained from the Manitoba Land Initiative (<http://mldata.gov.mb.ca/WPMLI/framesetup.asp>), the 2000 land use pattern in the Broughton's Creek watershed consist of 71.4% agriculture, 10.8% range land, 9.8% wetland, 4.0% forest, 2.5% roads, 1.4% forage, and 0.1% others. As a representative prairie watershed, the Broughton's Creek watershed experienced historic wetland losses from 2,998 ha in 1968 to 2,379 ha in 2005. Wetland restoration will contribute to provide water quantity and quality benefits to the Broughton's Creek watershed, and potentially lead to the improvement of Lake Winnipeg conditions.

Methods

In this study, the HEW and SWAT coupled modeling system was firstly setup and calibrated to fit into the conditions of the Broughton's Creek watershed. The model performance was evaluated based on both visualization plots and statistical measures. Secondly, wetland restoration scenarios were formulated and two indicators were developed to evaluate wetland effects on streamflow peak and sediment loadings at watershed outlet. Lastly, the wetland and stream drainage areas were combined with empirical nutrient

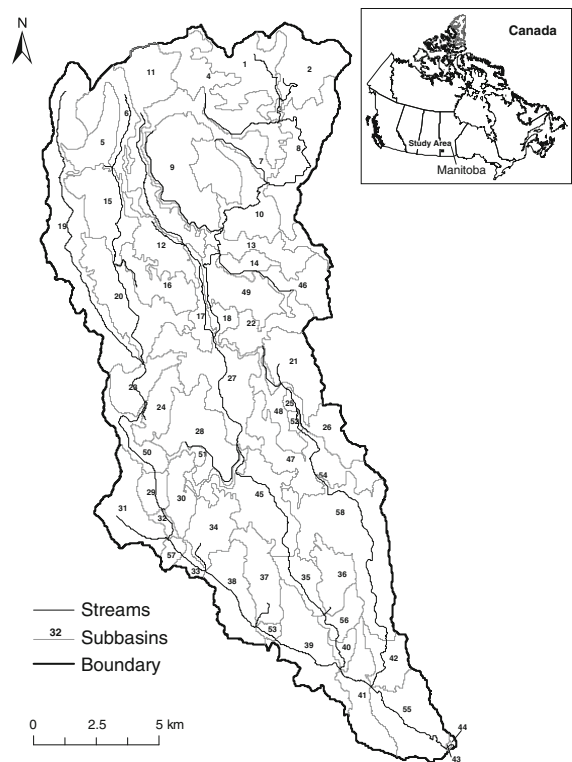


Fig. 1 Location and sub-basins of the Broughton's Creek watershed

transport coefficients to estimate the impacts of wetland restoration and conservation on total phosphorus and nitrogen loadings at watershed outlet.

SWAT setup

The SWAT, developed by the U.S. Department of Agriculture, was selected to simulate hydrologic processes of the Broughton's Creek watershed. Based on data availability, the model was set up and run from 1 January 1987 to 31 December 2004. The period from 1 January 1987 to 28 February 1990 was used to stabilize the initial values of the model parameters (e.g., initial soil moisture), whereas, the period from 31 March 1990 to 31 May 2004 was used to evaluate the model performance and analyze effects of wetland restoration scenarios. The model was verified using the computed daily stream flows for the period from 31 March 1990 to 31 May 1994.

The basic inputs to the SWAT model included data on topography, soils, and land cover/land use (Fig. 2). A 15-m digital elevation model (DEM)

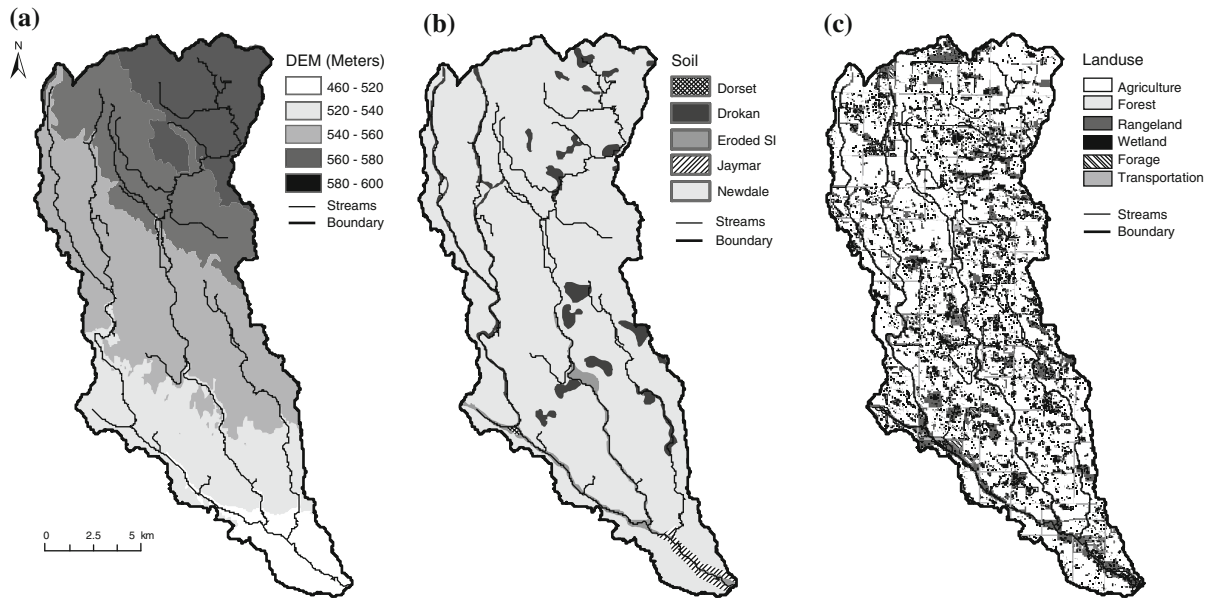


Fig. 2 The Broughton's Creek watershed **a** topography, **b** soils, and **c** land uses

was used to delineate the boundary of the Broughton's Creek watershed and its drainage network. The threshold area for stream definition was adjusted to 260 ha to make the delineated drainage network closely match the one in the hydrography data layer. As a result, the Broughton's Creek watershed was subdivided into 58 sub-basins. The soil GIS layer obtained from Manitoba Land Initiative was preprocessed to develop a user soil database in the format required by AvSWAT-X. Values for some of the soil parameters were obtained from the Manitoba soil database. For those soil parameters with missing values (e.g., hydraulic conductivity, bulk density, and available water capacity), the parameter values were estimated using the formulas presented in the SWAT documentation.

A 2005 wetland layer for the Broughton's Creek watershed was generated using aerial photographs. The wetland layer was overlaid with a 2000 land use/land cover data layer obtained from the Manitoba Land Initiative to generate the "2000/2005 LULC" dataset and was used as the base layer in this study. The soil and 2000/2005 LULC layers were overlaid to define hydrologic response units (HRUs) for the sub-basins. A threshold value of 10% was used for land use and soil class to eliminate very small HRUs. As a result, this study defined 177 HRUs, with 1–8 for each sub-basin. The HRUs have

an average size of 205 ha, a dominant land use of agriculture, and a dominant soil of Newdale. Wetland HRUs were defined by overlaying wetlands with soils. Wetland HRUs appeared in 55 out of 58 sub-basins, indicating that wetlands are largely scattered across the watershed.

Another input to the SWAT model is the observed data on daily precipitation and maximum and minimum temperatures. These data were obtained from Environment Canada (<http://www.ec.gc.ca>), and preprocessed into two database files with formats required by AvSWAT-X. Because there were no observed data on daily stream flows in the Broughton's Creek watershed, the data on daily stream flows at a nearby location, the Oak River at Shoal Lake (05MG008), collected by Environment Canada from 31 March 1990 to 31 May 1994, were transformed using Eq. (1) to represent the corresponding daily stream flows at outlet of the Broughton's Creek watershed.

$$Q_{2AB} = Q_{05MG008} \cdot AR^{0.679} \quad (1)$$

where Q_{2AB} —estimated daily stream flow at outlet of the Broughton's Creek watershed; $Q_{05MG008}$ —observed daily stream flow at station 05MG008; AR —ratio of the drainage area of the Broughton's Creek watershed to the drainage area upstream of station 05MG008 and equals 0.7293.

The Broughton's Creek watershed and the Oak River watershed are two adjacent watersheds with similar characteristics in terms of climate, landuse, soil, topography, and wetland distribution (Land Resource Unit 1998). Based on the analysis of various GIS datasets, both watersheds have a dominant landuse of agriculture and dominant medium texture (loams to clay loams) soils. Both watersheds also have a relatively flat terrain. The Broughton's Creek watershed has an average slope of 1.7%, while the Oak River watershed has an average slope of 2.3%. In Broughton's Creek watershed planning, the recorded flows and volumes of the gauging station along the Oak River at Shoal Lake were used to estimate the surface water flow characteristics of the Broughton's Creek watershed (Little Saskatchewan River Conservation District 2002). Thus, the transformed stream flow data were judged to have the accuracy required for comparing relative changes of water quantity and water quality as a result of different scenarios (i.e., what-if analyses), which is the focus of this study. The transformed data were used to verify the model performance.

A close examination of the transformed flow hydrograph (Fig. 3) revealed that the base flows for the simulation period were negligible. In addition, because the water table in the region, where the Oak River and Broughton's Creek watersheds are located, is very deep (>30 m on average; Little Saskatchewan River Conservation District 2002), the aquifer has very limited contributions to the stream flows even during low flow periods. Thus, this study calibrated the model using the total stream flows without differentiating the base flows and the direct flows.

Data on sediment were not available. According to the field visits carried out, most of the stream

channels in the Broughton's Creek watershed are fairly protected by vegetation and riparian trees. Based on professional judgment, SWAT channel and related sediment transport parameters (Table 1) were specified empirically. Again, because what-if analyses are the focus of this study, the empirically calibrated sediment component of the model probably had a minor influence on evaluating relative changes of water quality as a result of different wetland restoration scenarios.

The SCS-CN (curve number) method was used to simulate the precipitation-runoff processes, while the Muskingum method was used for channel routing. The potential evapotranspiration (PET) was estimated using the Priestley–Taylor method because Wang et al. (2006) showed that this method performs well in the prairie region in which the Broughton's Creek watershed is located. The calibration adjusted the watershed, HRU, and wetland parameters (Table 1). Particularly, snowmelt and frozen soil conditions have been accounted for in model calibration based on Wang and Melesse (2005). In addition, based on the HEW concept (Wang et al. 2008), the parameters related to wetlands, namely WET_FR (fraction of sub-basin area that drains into wetlands), WET_NSA (surface area of wetlands at normal water level), WET_NOVL (volume of water stored in wetlands when filled to normal water level), WET_MXSA (surface area of wetlands at maximum water level), and WET_MXVOL (volume of water stored in wetlands when filled to maximum water level), were also adjusted. These physical parameters affect wetland hydrologic processes of infiltration, evaporation, and routing, and are theoretically sensitive, as indicated by Wang et al. (2008). For example, the predicted peak discharges and sediment loadings

Fig. 3 Transferred and SWAT simulated daily stream flows at the outlet of the Broughton's Creek watershed

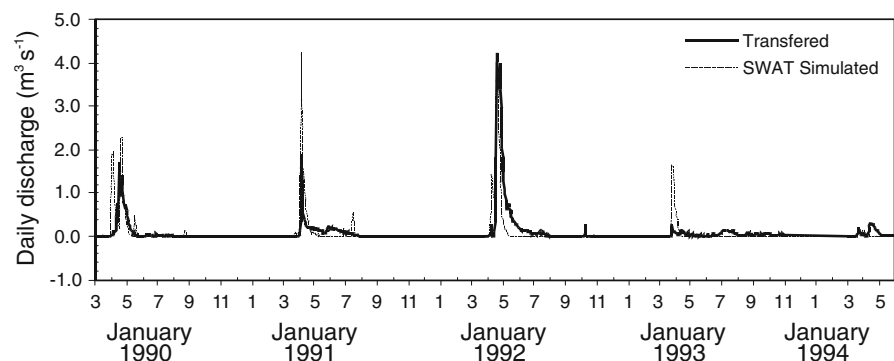


Table 1 Watershed and wetland parameters for calibration and adjusted values

Parameter	Definition	Calibrated value
SFTMP (°C)	Snow fall temperature	0.5
SMTMP (°C)	Snow melt temperature	2.5
SMFMX (mm H ₂ O/°C-day)	Melt factor for snow on June 21	6.5
SMFMN (mm H ₂ O/°C-day)	Melt factor for snow on December 21	1.5
TIMP	Snowpack temperature lag factor	0.35
ESCO	Soil evaporation compensation factor	0.45
SURLAG	Surface runoff lag coefficient	1.0
CN2	SCS curve number for AMC II	Reduce by 3
MSK_CO1 (day)	Muskingum storage time constant for normal flow	2.5
MSK_CO2 (day)	Muskingum storage time constant for low flow	2.5
CH_COV	Channel cover factor	0.3
CH_EROD (0.013 metric ton-m ² -h/m ³ -metric ton-cm)	Channel erodibility factor	0.35
SPCON	Coefficient for calculating maximum sediment reentrained	0.0001
SPEXP	Exponent for calculating maximum sediment reentrained	1.0
WET_K (mm/h)	Hydraulic conductivity of bottom of wetlands	0.5

were very sensitive to WET_NSA, WET_NOVL, WET_MXSA, and WET_MXVOL (Fig. 4; Tables 2, 3). Based on the rating curve provided by Ducks Unlimited Canada, the storage volumes of the wetlands were estimated as a linear function ($y = 9,653.5x$) of the corresponding areas defined in 2000/2005 LULC.

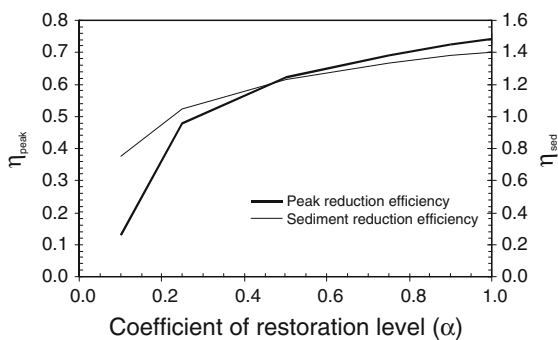


Fig. 4 Plot showing the peak reduction efficiency η_{peak} (Eq. 4) and sediment reduction efficiency η_{sed} (Eq. 5) versus the coefficient of restoration level α (Eq. 3) for the six restoration scenarios

Measure of model performance

The model performance was examined using visualization plots showing the predicted versus transformed stream flows. In addition, the model performance is further evaluated by the Nash–Suttcliffe coefficient (NSC; Nash and Suttcliffe 1970). NSC indicates how well the model reproduces the time evolution of stream flows, and can be computed as:

$$NSC = 1 - \frac{\sum_{i=1}^N (Q_{s_i} - Q_{o_i})^2}{\sum_{i=1}^N (Q_{o_i} - \overline{Q_o})^2} \tag{2}$$

where Q_{s_i} and Q_{o_i} are the simulated and observed stream flows on day i (m³/s), and N is the number of days over the simulation period.

The NSC can be computed for daily, monthly and yearly simulations. The value of NSC can range from $-\infty$ to 1.0, with higher values indicating a better overall fit and 1.0 indicating a perfect fit. A negative NSC indicates that the simulated stream flows are less reliable than if one had used the average of the observed stream flows, while a positive value

Table 2 Effects of the six wetland restoration scenarios

Scenario j	α_j	A_j (ha)	$Q_{p,j}$ (m ³ /s)	$Q_{ave,j}$ (m ³ /s)	$L_{sed,p,j}$ (tonne/day)	$L_{sed,ave,j}$ (tonne/day)
Existing	0.00	2,378.72	2.972	0.097	19.332	0.472
I	0.10	2,440.69	2.962	0.096	19.268	0.463
II	0.25	2,533.65	2.885	0.092	18.519	0.442
III	0.50	2,688.57	2.758	0.086	17.693	0.405
IV	0.75	2,843.49	2.637	0.080	16.726	0.369
V	0.90	2,936.45	2.564	0.077	16.058	0.348
VI	1.00	2,998.42	2.515	0.074	15.763	0.335

Note A_j , total wetland area for scenario j ; α_j , coefficient of restoration level for scenario j ; $Q_{p,j}$, average annual maximum daily flow for scenario j ; $Q_{ave,j}$, average annual average flow for scenario j ; $L_{sed,p,j}$, average annual maximum daily sediment loading for scenario j ; $L_{sed,ave,j}$, average annual average daily sediment loading for scenario j

Table 3 Wetland and stream drainage areas for the six restoration scenarios

Scenario	α_j^a	Wetland area (ha)	Restoration wetland (ha)	Wetland drainage		Direct drainage	
				(ha)	(%) ^b	(ha)	(%) ^b
Existing	0.00	2,379	0	11,906	47.4	13,233	52.6
I	0.10	2,441	62	12,217	48.6	12,922	51.4
II	0.25	2,534	155	12,681	50.4	12,458	49.6
III	0.50	2,689	310	13,456	53.5	11,683	46.5
IV	0.75	2,843	464	14,231	56.6	10,908	43.4
V	0.90	2,936	557	14,699	58.5	10,440	41.5
VI	1.00	2,998	619	15,009	59.7	10,130	40.3

^a α_j , coefficient of restoration level for scenario j

^b Computed as the ratio of the drainage area to the total watershed area of 25,139 ha

indicates that they are more reliable than using this average. Based on Motovilov et al. (1999), the simulated stream flows are considered “good” for values of NSC > 0.75, while for values of NSC between 0.75 and 0.36, the simulated stream flows are considered “satisfactory”. This criterion of NSC has fewer ratings than the one suggested by Moriasi et al. (2007). Because NSC is dependent on a number of factors, including the evaluation time step (e.g., daily vs. monthly), the length of evaluation period (e.g., 5 vs. 10 years), and the data quality, and because NSC usually exhibits large variations and is somewhat subjective (Gassman et al. 2007), fewer ratings may be more feasible and preferred for certain applications. For this reason and because the criteria for evaluation time steps other than monthly have not been well established (Moriasi et al. 2007), this study used the aforementioned criterion suggested by Motovilov et al. (1999) for daily, monthly, and seasonal time steps alike, while we are aware that a stricter performance rating may be warranted as the evaluation time step increases. When different

criteria are to be used for different time steps, the cutoff values for satisfactory model performance may vary between 0.75 and 0.36, as reflected by a greater cutoff value of 0.5 in the criterion suggested by Moriasi et al. (2007) for monthly time step.

Formulation of scenarios

The 1968 and 2005 wetland layers showed that there were 2,998 ha of wetlands in 1968 and 2,379 ha of wetlands in 2005, with 619 ha of wetlands lost or degraded during this period due to drainage activity. In this study, the 1968 wetlands were taken as the upper limit for restoration, while the 2005 wetlands were considered as the baseline. The restoration scenarios were formulated by increasing the areas of the wetlands in the sub-basins as:

$$A_{i,j} = (1 - \alpha_{i,j}) \cdot A_{i,2005} + \alpha_{i,j} \cdot A_{i,1968} \quad (3)$$

where $A_{i,j}$ —wetland area in sub-basin i for scenario j ; $A_{i,2005}$ —wetland area in sub-basin i in 2005; $A_{i,1968}$ —wetland area in sub-basin i in 1968; $\alpha_{i,j}$ —coefficient

of restoration level in sub-basin i for scenario j , $\alpha_{i,j}$ ranges from 0 to 1, (0—no restoration; 1—full restoration to the 1968 condition).

Assuming that the relationship between the volume and area of a HEW does not change with the increase of wetland sizes, this study analyzed six wetland restoration scenarios with restoration coefficients of 0.10, 0.25, 0.50, 0.75, 0.90, and 1.00 as suggested by wetland specialists from Ducks Unlimited Canada. A scenario that is expected to have larger reductions of the peak discharges and sediment loadings will require a higher restoration level (i.e., a larger value for α), thereby requiring a larger amount of financial investment. Considering these two contradict counterparts, two indexes, designated as “peak reduction efficiency (η_{peak})” and “sediment loading reduction efficiency (η_{sed})”, were developed and used to evaluate the two scenarios. An optimal scenario would have maximum values for these two coefficients or a maximum value for either of them.

The peak reduction efficiency for scenario j , $\eta_{\text{peak},j}$, can be defined as:

$$\eta_{\text{peak},j} = \frac{1 - \frac{Q_{p,j}}{Q_{p,\text{existing}}}}{1 - \frac{A_{\text{existing}}}{A_j}} \quad (4)$$

where $Q_{p,j}$ —simulated average annual maximum daily flow for scenario j ; $Q_{p,\text{existing}}$ —simulated average annual maximum daily flow for the existing condition; A_j —total wetland area for scenario j ; A_{existing} —total wetland area for the existing condition (i.e., 2,378.7 ha for this study).

The sediment reduction efficiency for scenario j , $\eta_{\text{sed},j}$, can be defined as:

$$\eta_{\text{sed},j} = \frac{1 - \frac{L_{\text{sed,ave},j}}{L_{\text{sed,ave,existing}}}}{1 - \frac{A_{\text{existing}}}{A_j}} \quad (5)$$

where $L_{\text{sed,ave},j}$ —average annual average sediment loading for scenario j ; $L_{\text{sed,ave,existing}}$ —average annual average sediment loading for the existing condition.

Both $\eta_{\text{peak},j}$ and $\eta_{\text{sed},j}$ can have a value ranging from zero to positive infinity, with a larger value indicating a higher efficiency in reducing peak discharge and/or sediment loading. A scenario that can result in a larger increase for either $\eta_{\text{peak},j}$ or $\eta_{\text{sed},j}$ or both, should be judged to be more beneficial. Otherwise, the scenario may be less beneficial.

Estimation of effects on total phosphorus and nitrogen loadings

As stated above, a SWAT model was set up for estimating stream flows and sediment loadings at the outlet of the Broughton’s Creek watershed, both for the existing conditions and various wetland restoration scenarios. However, limited by the available data on fertilizer management and stream water quality, the use of the model to conduct a similar simulation of phosphorus and nitrogen processes within the study watershed could not be justified. Alternatively, we used empirical export coefficients for total phosphorus (TP) and total nitrogen (TN) in conjunction with the modeled change in effective drainage area to estimate the reductions of annual average amounts of TP and TN exported from the Broughton’s Creek watershed as a result of wetland restoration efforts.

The nutrient export coefficients were defined as nutrients transported to the edge of field and loaded into water bodies such as wetlands or streams from different landuse classes. Based on Bourne et al. (2002), the TP export coefficients for cropland and non-cropland in Manitoba are 0.65 and 0.17 kg/ha/year, respectively, while the corresponding TN coefficients are 3.15 and 1.72 kg/ha/year, respectively. The amount of nutrients transported to wetlands can be estimated based on nutrient export coefficients and wetland drainage areas. Similarly, nutrients directly entering into streams can be also estimated based on nutrient export coefficients and stream drainage areas. Furthermore, a 0.5 nutrient delivery ratio within streams was justified, which means 50% of nutrients loaded to streams will be absorbed in the stream routing process and the remaining 50% of the nutrients will be delivered to the outlet of the Broughton’s Creek watershed. This is a relatively conservative assumption considering the fact that in Broughton’s Creek spring runoff contributes most of the annual stream flow over a 2–3 weeks period when opportunities for in-stream nutrient uptake are limited due to cold temperatures and high flow. Additionally, water quality data from past and ongoing studies in the Broughton’s Creek watershed indicate that most of the nutrients are present in soluble form during the spring runoff period. Based on these empirical relationships, water quality benefits of wetland restoration scenarios can be defined as reductions of nutrients delivered to the

watershed outlet and transported to downstream watersheds in comparison to the base scenario.

Results

Calibrated HEW-based SWAT model

Given the uncertain errors of the derived daily stream flows at the outlet of the Broughton's Creek watershed, the SWAT model was empirically judged to have very promising simulation performance (Fig. 3). The model captured the rising and recessing patterns exhibited by the computed daily stream flows. For the 5 years from 1990 to 1994, the SWAT simulated annual average stream flow at the outlet of the Broughton's Creek watershed ($0.1 \text{ m}^3/\text{s}$) matches with the computed annual average stream flow ($0.1 \text{ m}^3/\text{s}$), indicating that the transformed stream flows can be accurately reproduced by the model. The model had an acceptable simulation performance of the daily flows ($\text{NSC} = 0.20$), while the monthly ($\text{NSC} = 0.72$) and seasonal ($\text{NSC} = 0.70$) flows were reproduced with a satisfactory accuracy. The NSC for annual flows was not computed because of the short evaluation period of only 5 years. Thus, the calibrated model was judged to be accurate enough for evaluating the wetland restoration scenarios.

Effects on stream flow and sediment loadings

The simulation results for the six wetland restoration scenarios are summarized in Table 2. As expected, with the increase of the coefficient of restoration level α , the flows and sediment loadings were predicted to decrease (coefficients of determination $R^2 > 0.995$). The reduced peak discharges will be good for flood reduction in the watershed, whereas, the reduced sediment loadings will improve water quality. The average annual peak discharges were predicted to be reduced by 1.6–23.4%, and the sediment loadings were predicted to be lowered by up to 16.9%. The simulated yearly sediment loading reductions range from 3.3 to 50.0 tonnes.

Effects on total phosphorus and total nitrogen loadings

Based on the hydrologic equivalent wetland (HEW) concept, wetland drainage area for each sub-basin

under existing conditions or no wetland restoration scenario is estimated based on outflow from the specific sub-basin and scientific judgments. Wetland drainage area for each sub-basin under wetland restoration scenarios is estimated by wetland area multiplied by the ratio of wetland drainage area and wetland area under base scenario. As shown in Table 3, 2005 wetland drainage area in the Broughton's Creek watershed (base scenario) is 11,906 ha, which is 47.4% of the watershed area. Under the full wetland restoration scenario (1968 wetland acreage), wetland drainage area increased to 15,009 ha, which constitute 59.7% of the watershed area. This represents a 26.1% increase in wetland drainage area (from 11,906 to 15,009 ha) due to wetland restoration.

Based on wetland/stream drainage areas and nutrient export coefficients, nutrient loadings to the Broughton's Creek are estimated to be 6,696 kg/year of TP and 35,988 kg of TN. With an empirical in-stream delivery ratio of 0.5, the nutrient loadings of TP and TN at Broughton's Creek watershed outlet under existing condition are 3,348 and 17,994 kg/year, respectively (Table 4). SWAT modeling results showed that the average daily stream flow at Broughton's Creek watershed outlet under base scenario is $0.097 \text{ m}^3/\text{s}$, which is equivalent to annual water yield of $3,058,992 \text{ m}^3$ ($0.097 * 3,600 * 24 * 365$). Based on stream flow volume and nutrient loadings, estimated nutrient concentrations at Broughton's Creek watershed outlet are 1.1 mg/l of TP and 5.9 mg/l of TN, respectively. These values are within the ranges measured by the Little Saskatchewan River Conservation District in the Broughton's Creek between 2002 and 2006. TP and TN concentrations measured across multiple sites within the Broughton's Creek watershed ranged from 0.08 to 8.9 (mean 1.2) mg/l and from 0.8 to 17.9 (mean 4.2) mg/l, for TP and TN, respectively. Therefore, the estimated nutrient concentrations are within the range of sampling results as evidenced by a two-sided *t*-test ($P\text{-value} = 0.002 < \alpha = 0.05$) and the comparison supports that the present methodology for estimating nutrient export to streams and delivery to watershed outlet is reasonable.

Under wetland restoration scenario I, 62 ha of wetlands are restored with a total wetland area of 2,441 ha. As a result of wetland restoration under this scenario, the area contributing to the outlet of the Broughton's Creek watershed is reduced from 13,233

Table 4 Reductions of nutrient exports to streams and nutrient loadings at watershed outlet under various wetland restoration scenarios

Scenario	α_j	TP export reduction (kg/year)	TN export reduction (kg/year)	TP load reduction (kg/year)	TN load reduction (kg/year)	TP removal (%)	TN removal (%)
I	0.10	158	847	79	423	2.4	2.4
II	0.25	392	2,108	196	1,054	5.9	5.9
III	0.50	785	4,217	392	2,108	11.7	11.7
IV	0.75	1,177	6,324	588	3,162	17.6	17.6
V	0.90	1,414	7,597	707	3,799	21.1	21.1
VI	1.00	1,570	8,439	785	4,219	23.4	23.4

Note 1. Under existing condition, TP and TN exported to streams are 6,696 and 35,988 kg/year, respectively, TP and TN loadings at outlet are 3,348 and 17,994 kg/year, respectively. 2. Load at outlet = 0.5* Export to streams

to 12,922 ha. Due to the reduction in direct contributing area, the reduced nutrient loadings at Broughton's Creek watershed outlet under scenario I relative to the base scenario are TP 79 and TN 423 kg/year. Under scenario I, water quality benefits are represented by an additional 2.4% of TP and TN reductions at watershed outlet relative to the base scenario. Under the full wetland restoration scenario (scenario VI), 619 ha of wetlands are restored with a total wetland area of 2,998 ha. As a result of wetland restoration under this scenario, the area contributing to the outlet of the Broughton's Creek watershed is reduced from 13,233 to 10,130 ha. This reduction in contributing area due to wetland restoration reduces nutrient loadings at Broughton's Creek watershed outlet by 785 kg/year of TP and 4,219 kg/year of TN relative to the base scenario. Under scenario VI, water quality benefits are represented by a 23.4% reduction in TP and TN (Table 4).

Discussions and conclusions

This study set up a SWAT model for the Broughton's Creek watershed, with the wetlands represented as the HEWs on the sub-basin basis. The model was then used to examine the impacts of various wetland restoration scenarios on stream flow and sediment loadings at the outlet of the Broughton's Creek watershed. While limited by the data availability, this study generated very useful information for determining optimal acreages for wetlands to be restored.

For the evaluated six wetland restoration scenarios, the results indicated that the peak discharges would be reduced by 1.6 to 23.4%, and the sediment loadings

would be reduced by up to 16.9%. Based on the peak reduction efficiency and sediment reduction efficiency, scenarios with α value of 0.5–0.8 (i.e., 50–80% wetland restoration) can be judged to be more efficient in terms of benefit to wetland acreage ratios. In addition, the results indicated that these scenarios could remove TP and TN by 79–785 and 423–4,219 kg/year, respectively, which are each equivalent to 2.4–23.4% of the TP or TN yield under the existing conditions. One probable generalization of these results is that the wetland restoration efforts in the watersheds drained by the Red River of the North and its tributaries may be one of the ultimate solutions to the eutrophication problem in the Lake Winnipeg.

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