A RESEARCH REPORT SUBMITTED TO **DUCKS UNLIMITED CANADA**

Water Quantity and Quality Benefits from Wetland Conservation and Restoration in the Broughton's Creek Watershed

WANHONG **YANG**[1]
XIXI **WANG**[2]
SHANE **GABOR**[3]
LYLE **BOYCHUK**[4]
PASCAL **BADIOU**[3]

1. Department of Geography, University of Guelph, Ontario, Canada
2. Department of Engineering and Physics, Tarleton State University, a member of the Texas A&M University System, Stephenville, Texas, U.S.A.
3. IWWR, Ducks Unlimited Canada, Stonewall, Manitoba, Canada
4. Ducks Unlimited Canada, Western Region, Regina, Saskatchewan, Canada

Ducks Unlimited Canada
Conserving Canada's Wetlands

OCTOBER 2008

A RESEARCH REPORT SUBMITTED TO **DUCKS UNLIMITED CANADA**

Water Quantity and Quality Benefits from Wetland Conservation and Restoration in the Broughton's Creek Watershed

WANHONG **YANG**[1]
XIXI **WANG**[2]
SHANE **GABOR**[3]
LYLE **BOYCHUK**[4]
PASCAL **BADIOU**[3]

1. Department of Geography, University of Guelph, Ontario, Canada
2. Department of Engineering and Physics, Tarleton State University, a member of the Texas A&M University System, Stephenville, Texas, U.S.A.
3. IWWR, Ducks Unlimited Canada, Stonewall, Manitoba, Canada
4. Ducks Unlimited Canada, Western Region, Regina, Saskatchewan, Canada

LEAD FUNDING FOR THE RESEARCH WAS PROVIDED BY **THE MURPHY FOUNDATION**.

Ducks Unlimited Canada
Conserving Canada's Wetlands

OCTOBER 2008

table of contents

figures

tables

executive summary

Wetlands serve important hydrologic, geochemical, and biological functions, and as such wetland conservation and restoration has been regarded as critical for sustainable watershed management. However, due to heterogeneity of landscape and wetland conditions, implementation of wetland conservation and restoration requires a good understanding of watershed hydrologic processes and corresponding water quantity and quality benefits.

Broughton's Creek is a 25,139-ha prairie watershed located in southwestern Manitoba that has experienced significant wetland loss and degradation. The purpose of this study was to develop and use a prototype modelling system to evaluate the environmental benefits of prairie wetlands at a watershed scale. The specific objectives were to: 1) use a "hydrologic equivalent wetland (HEW)" concept in the Soil and Water Assessment Tool (SWAT) to develop a prototype modelling system; 2) calibrate and validate the SWAT-based modelling system for the Broughton's Creek watershed; and 3) use the calibrated modelling system to assess the prospective wetland conservation and restoration scenarios in the Broughton's Creek watershed. The observed data on daily streamflows at the Oak River at Shoal Lake (05MG008) from 31 March 1990 to 31 May 1994 were transferred using an empirical equation to approximate the streamflows at the outlet of the Broughton's Creek watershed, where observed data are unavailable. The transferred data were used to validate the SWAT-based modelling system. The simulated streamflow pattern successfully captured the rising and recessing patterns exhibited by the daily streamflows, and the simulated annual average streamflow closely matched the corresponding computed value. Based on these results, the SWAT-based modelling system was judged to provide good simulation performance.

The SWAT-based modelling system was applied to examine the effects of wetland conservation and restoration in the Broughton's Creek watershed. The examination was conducted by analyzing six scenarios that have wetland areas ranging from 2,379 ha in the year of 2005 to 2,998 ha in the year 1968. For these six scenarios, the peak discharge at the watershed outlet was predicted to be reduced by 1.6 to 23.4%, and the sediment loading to be reduced by up to 16.9%. Senarios with wetland areas between 2,689 and 2,875 ha (i.e., restoration wetland areas of 310 to 497 ha) are probably most cost-effective. Also, the results indicated that restoring wetlands at targeted/selected subbasins within the study watershed will be more cost-effective. In addition, as a result of the scenario that has a total wetland area equivalent to that in the year of 1968, the wetland drainage area (i.e., the area directly drained into the wetlands) was determined to increase from 47.4% (11,906 ha) to 59.7% (15,009 ha) of the watershed area, whereas, the stream drainage area (i.e., the area directly drained into the streams) was determined to decrease from 52.6% (13,233 ha) to 40.3% (10,130 ha) of the watershed area.

Further, in terms of the drainage areas and empirical nutrient export coefficients, this study estimated reductions of total phosphorous (TP) and total nitrogen (TN) at the watershed outlet as a result of wetland restoration. The results indicated that for these six analyzed scenarios and on the annual average basis, the TP yield can be reduced by 79 to 785 kg/yr and the TN yield can be reduced by 423 to 4,219 kg/yr. These estimated reductions each are equivalent to 2.4 to 23.4% of the existing TP or TN export out of the study watershed. Because the Broughton's Creek watershed is nested within the Little Saskatchewan River watershed (LSR), this study reasonably assumed that these two watersheds share a similar wetland-drainage acreage ratio and extrapolated the aforementioned results to the LSR watershed. The extrapolation results indicated that restoring wetlands in the LSR watershed could reduce the TP yield by 3.4 to 34.1% (i.e., 992 to 9,892 kg/yr) and the TN yield by 1.9 to 18.9% (i.e., 5,334 to 53,163 kg/yr). Hence, restoring wetlands in the watersheds drained by the major tributaries (e.g., LSR) of the Red River of the North is likely to alleviate the eutrophication stresses being suffered by the Lake Winnipeg.

Keywords: *flood mitigation, HEW, hydrologic modelling, eutrophication, nutrients, sediment, SWAT, water quality, wetland conservation and restoration*

i

introduction

Wetlands serve important hydrologic, geochemical, and biological functions in a watershed (De Laney, 1995; Hart, 1995; National Research Council, 1995). Wetland functions include flood mitigation, groundwater recharge, water quality improvement, carbon sequestration and wildlife habitat. Unfortunately, Canada has lost more than 70% of its original wetlands in the prairie regions (DUC, 2007). In the United States, wetlands are disappearing at the rapid rate of 60,000 acres per year (Dahl, 1990, 2000). Since colonization, 50 to 70% of the nation's original wetlands have been drained, dredged, filled, leveled, and/or flooded (Dahl and Johnson, 1991). The loss percentage may be even higher for areas in the prairie pothole region. For example, the Red River of the North Basin, located in northwestern Minnesota, has lost more than 75% of its original wetlands (Gleason and Euliss, 1998).

In response to the alarming wetland losses, the Wetland Reserve Program (WRP) was established by the U.S. Congress in the 1990 Farm Bill (De Laney, 1995; Napier et al., 1995) and was reauthorized in 1996 and 2002 (Tweedy and Evans, 2003). WRP is a voluntary program offering financial incentives to landowners for protecting, restoring and enhancing wetlands on their property (USDA-NRCS, 2007). Similarly, in early 1990s, the Canadian federal government made policies for wetland conservation and protection, and the Manitoba government enacted a water protection act with wetlands as one of the important components. While the rationales are similar between the U.S. WRP and Canada's wetland conservation efforts, the Canadian policies mainly serve as guidelines and the governments provide little or no financial incentives for wetland restoration.

The growing concerns on adverse impacts of agricultural activities on the environment (in particular, water quality) necessitate that the federal and local governments take more consolidated measures (e.g., providing financial incentive) to protect and/or restore wetlands to improve regional environmental quality. In order to make a scientific decision, policy makers usually need information regarding the environmental benefits of a proposed wetland conservation or restoration effort. With this regard, watershed hydrologic models, such as the Soil and Water Assessment Tool (SWAT) developed by Arnold et al. (1993), can be used to generate 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.

For a wetland, its hydrologic function is the single greatest impetus (Tammi, 1994; Tweedy and Evans, 2003). The hydrologic conditions determine the wetland's geomorphology, habitat quality, water quality and biodiversity (Mitsch and Gosselink, 1993; Kadlec and Knight, 1996). For this reason, the hydrologic function of wetlands has been widely assessed using monitoring (e.g., Quinton et al., 2003; Hayashi et al., 2004) and/or modelling approaches (e.g., Padmanabhan and Bengtson, 2001; Vining, 2002). Hayashi et al. (2004) used the isotopic and chemical signatures of surface and subsurface water to estimate evaporation, evaluate the relative contribution of snowmelt water during spring runoff and examine the snowmelt storage capacity of wetlands for the Scotty Creek basin in the Northwest Territories of Canada. The results indicated that more than 70% of the average precipitation was lost to evapotranspiration in the study basin. The direct snowmelt contribution was less than 50% of the total runoff, and the water stored in the wetlands over winter was comparable to the average annual basin discharge. They concluded that considering wetland storage capacities in hydrologic models to simulate wetland-dominated basins such as the Scotty Creek basin is essential.

This result differed from Padmanabhan and Bengtson (2001), who used an 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. Wetlands cover 4.3 and 6.8% of the Maple River and Wild Rice River watersheds in terms of size, respectively. The authors ran the model for 10-day storms with return periods of 10, 25, 50 and 100 years. In the model, the wetlands were partitioned and aggregated on a subwatershed basis, and modeled as "flow diversions." The water with a maximum volume, estimated using an equation (Equation 2 in Bengtson and Padmanabhan, 1999) developed by the U.S. Bureau of Reclamation (USBR, 1999), was diverted at a subjective invariant rate and timing, and assumed to be lost from the drainage system. For a subwatershed, the equation defined the maximum volume as a function of the total surface area of the included wetlands. The results indicated that wetlands exerted only a negligible influence.

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 subbasin from 1981 to 1998. This is a major subbasin of the Devils Lake Basin, located in northeastern North Dakota. The modified PRMS model incorporated subroutines for snowmelt and wetland hydrology. However, it had no channel routing computation, did not account for frozen soil, and allowed only one wetland to be defined within each hydrologic response unit (HRU).

In the study, the subbasin was divided into 50 HRUs and thus 50 synthetic wetlands were defined to model the thousands of wetlands identified. A "synthetic wetland" for a HRU was defined as having the combined area and volumetric capacity of all the wetlands within the HRU. That is, the maximum surface area of the synthetic wetland was equal to the summation of the maximum surface areas of the component wetlands within the HRU, and the volumetric capacity of the synthetic wetland was estimated as a function of its maximum surface area. In addition, each synthetic wetland was partitioned into an "open part" and a "closed part." The closed part was defined as having no outlet with which to contribute water to the stream network, whereas the open part was defined as having an outlet with a spillage threshold beyond which water would flow into the stream network. The author assumed that each synthetic wetland consisted of 50% open and 50% closed parts in terms of capacity, and that each synthetic wetland intercepted 90% of the runoff generated within that HRU. In addition, six values, ranging from 0.2 to 1.0, were used to assess the simulation sensitivity to the spillage threshold.

The model was calibrated by adjusting a single parameter, namely the maximum available soil water in the soil profile. The calibrated model under predicted the annual peak discharges for all years except for 1983. The author attributed this under prediction to the lack of a subroutine in the model to account for frozen soil. The results indicated that more water was stored in the wetlands for the years with a higher annual streamflow than for the years with a lower streamflow. Further, the wetland areas were predicted to be greater for a larger spillage threshold value than for a smaller one because the implied physical effect of increasing spillage thresholds is filling of the spillways from the open part to permit the wetlands to hold more water.

These two modelling 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, even though they may have opposite correlations with runoff, as shown by Quinton et al. (2003).

These assumptions imply that hydrologic functions of wetlands within a watershed are linearly additive, which might be one reason why Padmanabhan and Bengtson (2001) reached a conclusion that contradicted that of Hayashi et al. (2004). Another reason might be that Padmanabhan and Bengtson (2001) used synthetic, low-frequency storms for their modelling study, whereas Hayashi et al. (2004) focused on spring snowmelt runoff in their monitoring study. In addition, the diversion rate and timing were likely to vary with the flow hydrographs generated from the storms, with the highest diversion rate probably occurring at some peak time. By failing to consider this functional relationship, Padmanabhan and Bengtson (2001) thus underestimated the influence of the wetlands. Further, the assumed partition of each synthetic wetland into 50% open and 50% closed portions, as well as the subjective spillage threshold, could have biased Vining's (2002) results, as indicted by the model's consistent underestimation of the annual peak discharges.

Recently, Wang et al. (2008) developed a "hydrologic equivalent wetland (HEW)" concept to solve the wetland modelling problems described above that arise as a result of these assumptions. A HEW has a hydrologic function identical to its component wetlands, and therefore substituting the HEW for the wetlands will not affect the precipitation-runoff process. Consequently, the HEW can reflect the nonlinear functional relations between runoff and wetlands that were revealed by Quinton et al. (2003). As with a regular wetland, a HEW is described by five parameters, namely the fraction of the subbasin area that drains into the HEW (frimp), the surface area at normal water level (SAnor), the volume of water stored in the HEW when it is filled to its normal water level (Vnor), the surface area at maximum water level (SAmax), and the volume of water stored in the HEW when it is filled to its maximum water level (Vmx). In contrast to both Padmanabhan and Bengtson (2001) and Vining (2002), these parameters should be determined through model calibration.

Despite the general agreement that wetland hydrologic functions are essential for modelling 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 the subject of much disagreement in the literature. The Soil and Water Assessment Tool (SWAT) developed by Arnold et al. (1993) 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 (e.g., 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 streamflows though wetlands might be an important land cover in some of the study watersheds (e.g., Du et al., 2005; Vazquez–Amábile and Engel, 2005).

The purpose of this study was to develop and use a prototype modelling system to evaluate environmental benefits of prairie wetlands at a watershed scale. The specific objectives were to: 1) use the HEW concept to develop a prototype of SWAT-based hydrologic modelling system; 2) calibrate and validate the model for the Broughton's Creek watershed; and 3) use the prototype modelling system to assess the prospective wetland conservation and restoration scenarios in the Broughton's Creek watershed.

study area

The 25,139-ha Broughton's Creek watershed is located within the Little Saskatchewan River Conservation District (LSRCD) in western Manitoba (Figure 1). The watershed is primarily in the Rural Municipality (RM) of Blanshard but involves the RM of Harrison to the north and the RM of Saskatchewan to the southeast in the vicinity of the watershed outlet. Originated on the headwaters of the Little Saskatchewan River watershed, the Broughton's Creek flows southeast into Lake Wahtopanah, which is located approximately 4.8 km upstream of the town of Rivers. The Little Saskatchewan River is a tributary of the Assiniboine River, which in turn flows east into the Red River of the North and finally to Lake Winnipeg.

The Broughton's Creek watershed experiences a 140 m drop over a distance of about 40 km (Figure 2a). The watershed is described as a hummocky till plain subdivided into two sub-regions in terms of a threshold value of 3.0 m for average topographic relief (WSRCD, 2005). The first sub-region comprises the northeast corner of the watershed, which shares a similar topography with elevations higher than 550 m above mean sea level (msl) and an average topographic relief greater than 3.0 m. In contrast, the second sub-region comprises the southern and southwest third of the watershed, which shares a similar topography with elevations lower than 550 m above msl and an average topographic relief less than 3.0 m.

With geological settings formed by the Assiniboine glacial lobe retreat started about 20,000 to 12,000 B.C., the Broughton's Creek watershed has numerous undrained depressions ranging from potholes to large sloughs (WSRCD, 2005). Compared with potholes, sloughs are relatively large, shallow, elongated, and often northwest to southeast. In addition, there are also lakes present. Limited by the available detailed information, this study did not differentiate potholes, sloughs, and lakes, and modeled them as general wetlands. Based on the data obtained from the Manitoba Land Initiative (http://mlidata.gov.mb.ca/WPMLI/framesetup.asp) and DUC, the land uses in the Broughton's Creek watershed consist of 71.8% agriculture, 10.8% range land, 9.5% wetland, 4.0% forest, 2.5% transportation, 1.4% alfalfa and 0.1% other (Figure 2c and Table 1). The wetlands are scattered across the watershed. Soils of the Newdale association are dominant in the Broughton's Creek watershed (Figure 2b). These soils are dominantly well drained in upslope locations. Other minor soils belong to the Dorset, Drokan, Eroded SI and Jaymar associations. These minor soils are predominantly located in the areas adjacent to the streams.

A weather station situated in the city of Brandon, (station number 5010480), has data on daily precipitation and minimum and maximum temperatures for the selected simulation period from 1 January 1987 to 31 December 2004. The data were obtained from the Environment Canada and used in this study. There is no station where continuous data on daily streamflow and water quality (e.g., sediment and nutrient concentrations) are available. The Little Saskatchewan Conservation District (LSCD) conducted grab sampling in the years from 2003 to 2005 at 13 sites shown in Figure 1. However, we only obtained summarized water quality sampling data. In this study, the grab sampling data were used only as a point of reference because there were too few samples for model verification. In addition, as suggested by DUC, the data on daily streamflows at the Oak River at Shoal Lake (05MG008), collected by the Environment Canada from 31 March 1990 to 31 May 1994, were transformed using Equation (1) to estimate the corresponding daily streamflows at outlet of the Broughton's Creek watershed. In this study, the transformed data were used to verify the model performance.

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

Where Q_{2AB} is the estimated daily streamflow at outlet of the Broughton's Creek watershed, $Q_{05MG008}$ is the observed daily streamflow at station 05MG008, AR is the ratio of the drainage area of the Broughton's Creek watershed to the drainage area upstream of station 05MG008 and equals 0.7293.

The Soil and Water Assessment Tool (SWAT), developed by the U.S. Department of Agriculture, was selected to simulate hydrologic processes of the Broughton's Creek watershed. The model was 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, as discussed below. The model was verified using the computed daily streamflows for the period from 31 March 1990 to 31 May 1994.

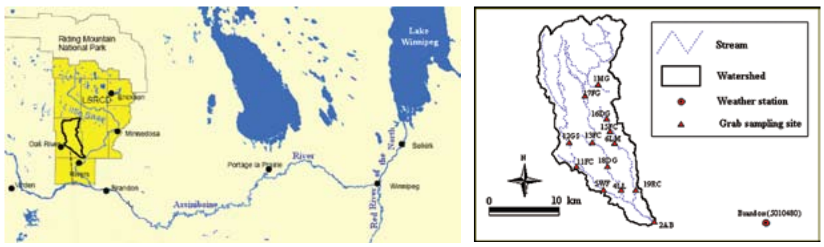


Figure 1. Map showing location and boundary of the Broughton's Creek watershed *(source: LSRCD 2005)*

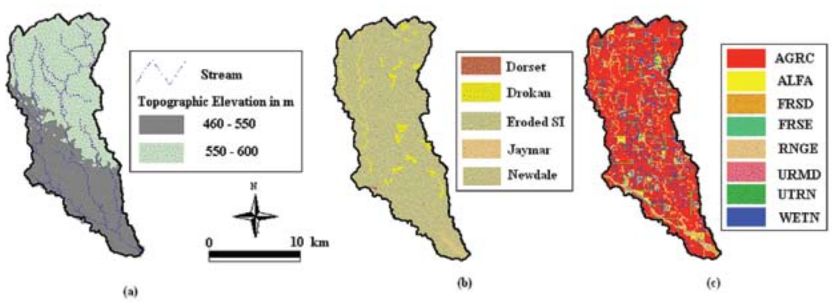


Figure 2. The Broughton's Creek watershed (a) topography, (b) soils, and (c) land uses

Land	SWAT Code	Area (ha)	Percentage
Agriculture	AGRC	18,036.0	71.8
Range Grasses	RNGE	2,713.1	10.8
Wetland	WETN	2,378.2	9.5
Deciduous Forest	FRSD	1,036.5	4.0
Transportation	UTRN	621.9	2.5
Alfalfa	ALFA	339.9	1.4
Residential	URMD	12.5	0.0
Evergreen Forest	FRSE	0.9	0.0
Total		**25,139**	**100%**

Table 1. Land use/land cover in the Broughton's Creek watershed (2000)

set-up of the SWAT model

The basic inputs to the SWAT model included data on topography, soils, and land cover/land use. A 15-m digital elevation model (DEM; Figure 2a) was used to delineate the boundary of the Broughton's Creek watershed and its drainage network. In order to improve the delineation accuracy, a hydrography data layer, provided by DUC and showing the streams and road ditches, was used as the reference. Herein, the basic assumption was that the drainage network presented by the data layer has a sufficient accuracy for modelling purposes. This data layer was provided as the digitized stream through the burn-in option in the AvSWAT-X for SWAT 2005 interface. The threshold area for stream definition was adjusted to 260 ha to make the delineated drainage network closely match the one presented by the hydrography data layer. As a result, the Broughton's Creek watershed was subdivided into 58 subbasins (Figures 3a, b, c, d). Some small-size subbasins (e.g., Subbasin 43 in Figure 3d) were delineated using grab sampling sites as outlets in order to obtain simulated results for these locations.

The soil GIS layer obtained from Manitoba Land Initiative (Figure 2b) 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 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 documentations. The SWAT soil database for the Broughton's Creek watershed is shown in Table 2.

Using the aerial photographs taken in 2005, DUC generated a wetland data layer for the Broughton's Creek watershed. This data layer was overlaid with a 2000 land use/land cover data layer obtained from the Manitoba Land Initiative. The mismatched areas, which were presented as wetlands in the 2000 land use/land cover data layer but were not delineated as wetlands by DUC, were reclassified as agricultural lands. Herein, the basic assumptions were that: 1) there was a negligible change of wetlands between 2000 and 2005; 2) the DUC generated data layer presented more accurate information on wetlands than the 2000 landuse/landcover data layer; and 3) the predominant land use in the watershed was agriculture and thus agriculture was the most probable land use for the mismatched areas. The result was a land use/land cover dataset that represents the best available information on wetlands and other land use types in the Broughton's Creek watershed. For description purposes, this dataset was designed "2000/2005 LULC" and was used as base layer in this study. Figure 2c and Table 1 illustrate the land classes presented in 2000/2005 LULC.

The soil map and 2000/2005 LULC were overlaid to define hydrologic response units (HRUs) for the subbasins. A threshold value of 10% was used for land use and soil class to eliminate HRUs with a tiny size. As a result, this study defined 177 HRUs, with 1 to 8 for each subbasin (Table 3). 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 subbasins, indicating that wetlands are largely scattered across the watershed (Figure 2c). Based on the rating curve provided by DUC, the storage volumes of the wetlands were estimated as a linear function (Figure 4) of the corresponding areas defined in 2000/2005 LULC.

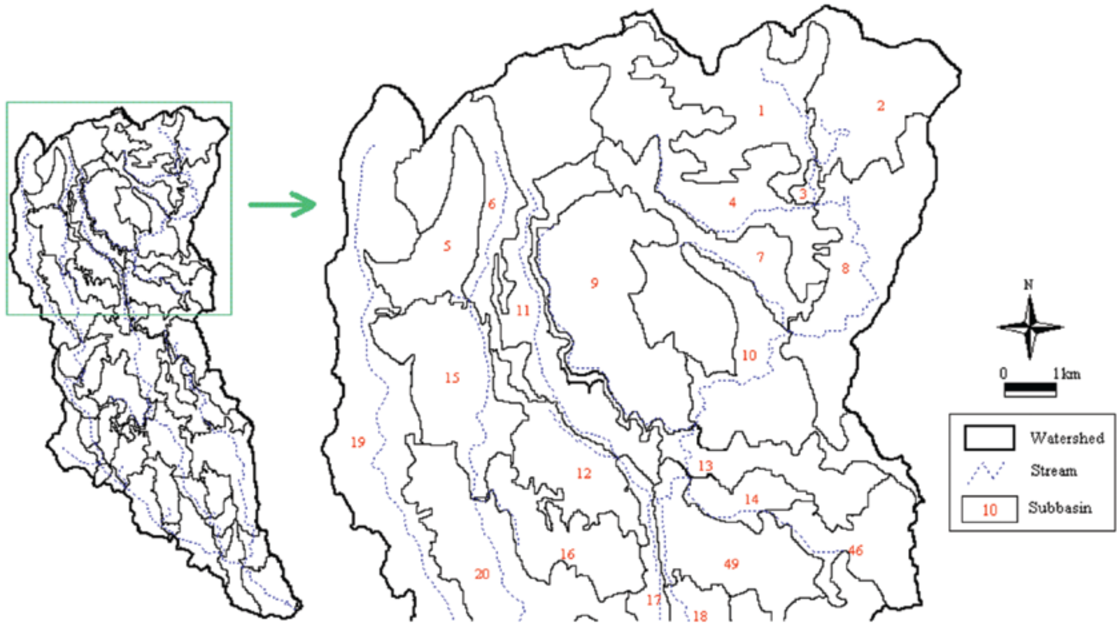


Figure 3a. The delineated subbasins in the uppermost portion of the Broughton's Creek watershed

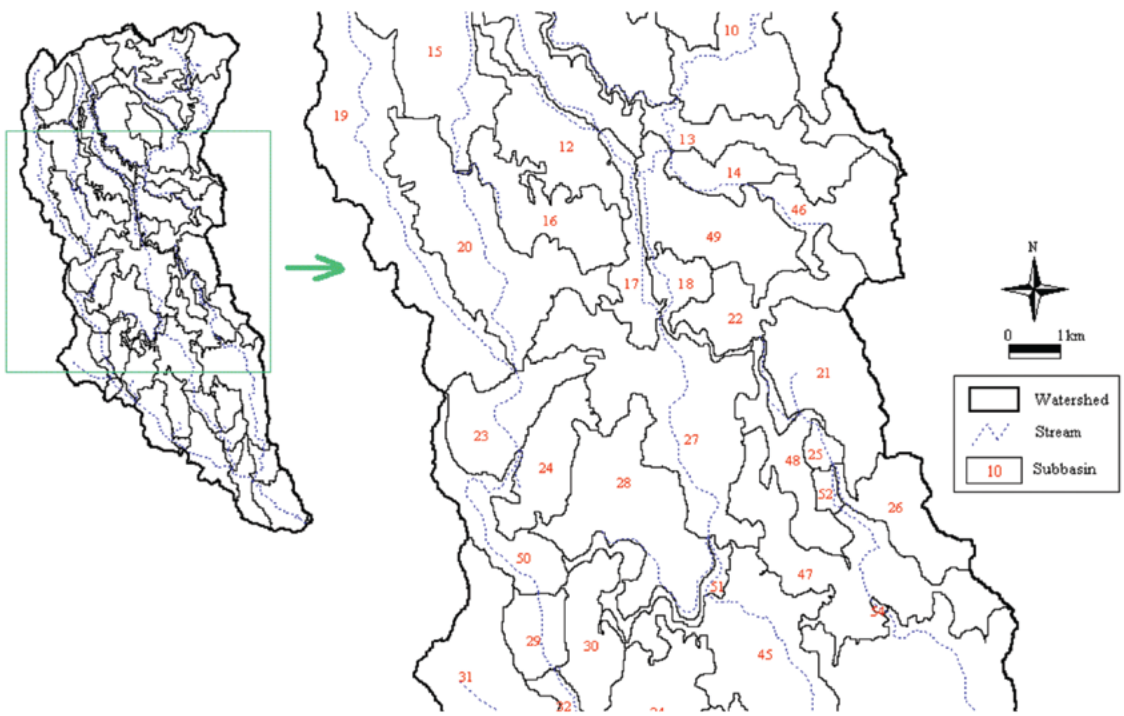


Figure 3b. The delineated subbasins in the middle upper portion of the Broughton's Creek watershed

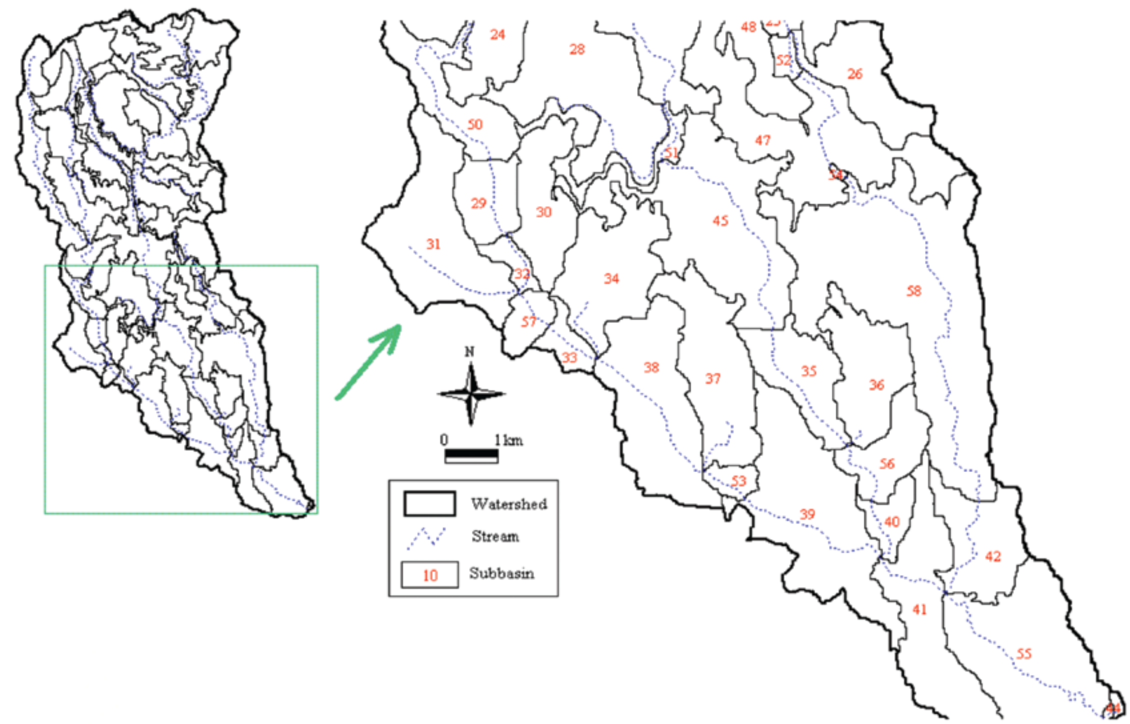


Figure 3c. The delineated subbasins in the middle lower portion of the Broughton's Creek watershed

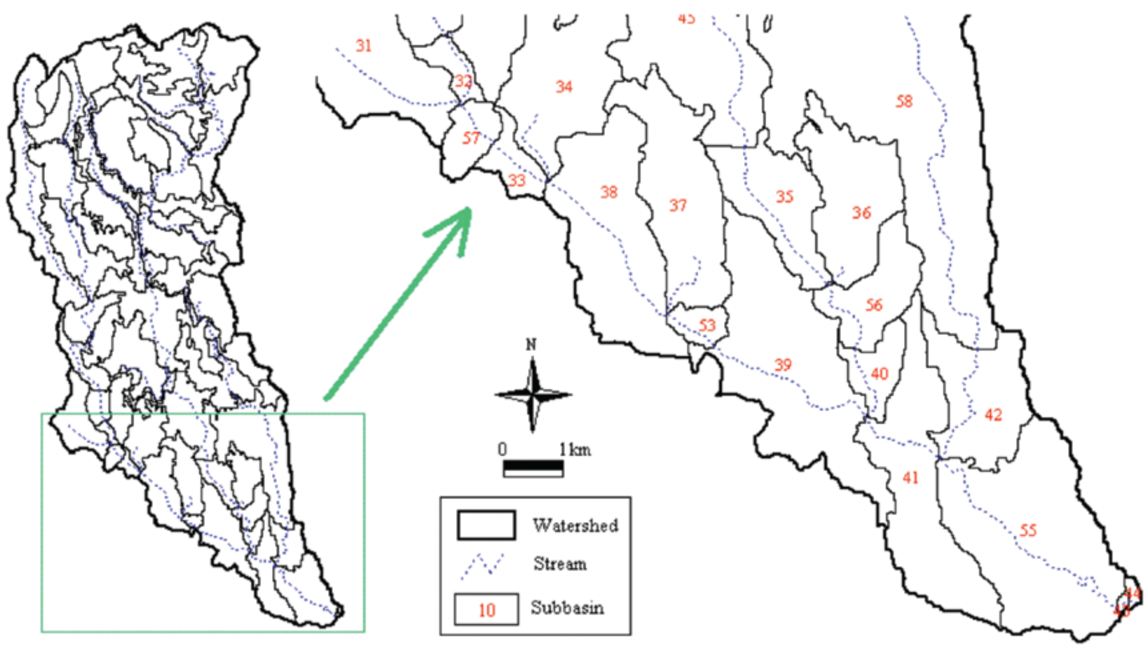


Figure 3d. The delineated subbasins in the lowermost portion of the Broughton's Creek watershed

Soil Name	HYDGRP	SOL_ZMX	Total Layers	No. of Layer	SOL_Z	SOL_BD	SOL_AWC	SOL_K	SOL_CBN	CLAY	SILT	SAND	ROCK	SOL_ALB	USLE_K	SOL_EC
Dorset	A	1000	5	1	40	0.15	0.11	100	17	15	20	65	0	0.175	0.2897	-
				2	190	1.47	0.07	250	3.7	11	16	73	0	-	0.2878	-
				3	340	1.74	0.01	250	1	8	12	80	0	-	0.3512	-
				4	440	1.8	0.01	600	0.3	4	4	92	0	-	0.3535	-
				5	1000	1.8	0.01	600	0	3	4	93	0	-	0.369	-
Drokan	C	1000	3	1	200	1.3	0.13	30	4.7	37	38	25	0	0.175	0.2945	-
				2	300	1.4	0.14	30	1.4	36	39	25	0	-	0.3286	-
				3	1000	1.5	0	19.5	0.2	38	44	18	0	-	0.4028	-
Eroded Sl	C	1000	1	1	1000	1.5	0.13	30	0.2	30	40	30	0	0.175	0.4032	-
Jaymar	B	1000	5	1	150	1.25	0.15	30	3.9	20	25	55	0	0.175	0.2897	-
				2	300	1.35	0.15	30	3.5	20	25	55	0	-	0.2897	-
				3	450	1.45	0.15	30	1.6	19	26	55	0	-	0.3114	-
				4	650	1.7	0.01	600	0.2	2	6	92	0	-	0.4001	-
				5	1000	1.55	0.01	30	0.1	26	37	37	0	-	0.4029	-
Newdale	C	1000	5	1	150	0.99	0.14	30	4.5	34	36	30	0	0.175	0.2936	-
				2	250	1.42	0.12	13	3	28	30	42	0	-	0.2891	-
				3	450	1.53	0.14	30	1	31	35	34	0	-	0.3617	-
				4	550	1.6	0.01	30	0.8	31	34	35	0	-	0.3739	-
				5	1000	1.63	0.01	19.5	0.1	26	36	38	0	-	0.4009	-

Table 2. Estimated parameters of soils in the Broughton's Creek watershed

Note: 1. HYDGRP: soil hydrologic group; SOL_ZMX: maximum rooting depth of the soil profile (mm); SOL_Z: depth from soil surface to bottom of the soil layer (mm); SOL_BD: moist bulk density of the soil layer (g/cm3); SOL_AWC: available water capacity of the soil layer (mm water/mm soil); SOL_K: saturated hydraulic conductivity of the soil layer (mm/hr); SOL_CBN: organic carbon content of the soil layer (% soil weight); CLAY: clay content of the soil layer (% soil weight); SILT: silt content of the soil layer (% soil weight); SAND: sand content of the soil layer (% soil weight); ROCK: rock fragment content of the soil layer (% soil weight); SOL_ALB: moist soil albedo; USLE_K: USLE equation soil erodibility factor (0.013 metric ton-m2-hr/m3-metric ton-cm); SOL_EC: electrical conductivity (dS/m).

2. The parameters labeled as "-" are not used by the current version of SWAT.

Table 3. Summary information of the defined hydrologic response units (HRUs)

Subbasin	Area (ha)	Total HRUs	Avg. HRU Size (ha)	Land Use			Soils	
				Number	*Dominant*	*Wetland?*	*Number*	*Dominant*
1	627.5	3	209.2	2	AGRC	yes	2	Newdale
2	632.8	1	632.8	1	AGRC	yes	1	Newdale
3	31.9	2	16.0	2	AGRC	yes	1	Newdale
4	789.3	4	197.3	3	AGRC	yes	2	Newdale
5	342.4	2	171.2	2	AGRC	yes	1	Newdale
6	488.6	4	122.2	2	AGRC	yes	2	Newdale
7	676.2	3	225.4	2	AGRC	yes	2	Newdale
8	781.7	4	195.4	3	AGRC	yes	2	Newdale
9	814.9	1	814.9	1	AGRC	yes	1	Newdale
10	629.6	5	125.9	3	AGRC	yes	2	Newdale
11	873.6	1	873.6	1	AGRC	yes	1	Newdale
12	397.0	1	397.0	1	AGRC	yes	1	Newdale
13	521.2	1	521.2	1	AGRC	yes	1	Newdale
14	164.5	3	54.8	3	AGRC	yes	1	Newdale
15	573.8	3	191.3	2	AGRC	yes	2	Newdale
16	387.6	1	387.6	1	AGRC	yes	1	Newdale
17	211.0	1	211.0	1	AGRC	yes	1	Newdale
18	142.4	3	47.5	2	AGRC	yes	2	Newdale
19	1471.6	4	367.9	2	AGRC	yes	2	Newdale
20	784.7	3	261.6	2	AGRC	yes	2	Newdale
21	510.2	1	510.2	1	AGRC	yes	1	Newdale
22	375.0	1	375.0	1	AGRC	yes	1	Newdale
23	356.9	1	356.9	1	AGRC	yes	1	Newdale
24	298.5	3	99.5	3	AGRC	yes	1	Newdale
25	50.4	1	50.4	1	AGRC	yes	1	Newdale
26	294.4	6	49.1	3	AGRC	yes	2	Newdale
27	918.8	7	131.3	3	AGRC	yes	3	Newdale
28	678.1	2	339.1	2	AGRC	yes	1	Newdale
29	175.8	2	87.9	1	AGRC	yes	2	Newdale
30	282.9	3	94.3	3	AGRC	yes	1	Newdale
31	552.9	4	138.2	3	AGRC	yes	2	Newdale
32	58.0	5	11.6	3	RNGE	yes	2	Newdale
33	81.7	7	11.7	4	AGRC	yes	2	Newdale
34	408.2	6	68.0	3	AGRC	yes	2	Newdale
35	262.0	4	65.5	2	AGRC	yes	2	Newdale
36	322.1	2	161.1	2	AGRC	yes	1	Newdale
37	434.8	2	217.4	2	AGRC	yes	1	Newdale
38	553.4	5	110.7	3	AGRC	yes	2	Newdale

Note: 1. STD: standard deviation;
2. "-" indicates that the computation does not make sense.

(continued on next page)

Table 3. Summary information of the defined hydrologic response units (HRUs)

Subbasin	Area (ha)	Total HRUs	Avg. HRU Size (ha)	Land Use			Soils	
				Number	*Dominant*	*Wetland?*	*Number*	*Dominant*
39	705.5	3	235.2	2	AGRC	yes	2	Newdale
40	99.0	3	33.0	2	AGRC	yes	2	Newdale
41	481.7	4	120.4	2	AGRC	yes	3	Newdale
42	303.1	3	101.0	2	AGRC	yes	2	Newdale
43	5.4	4	1.4	2	RNGE	no	2	Eroded Sl
44	10.5	5	2.1	3	FRSD	no	2	Jaymar
45	776.9	5	155.4	3	AGRC	yes	2	Newdale
46	373.9	1	373.9	1	AGRC	yes	1	Newdale
47	729.2	4	182.3	3	AGRC	yes	2	Newdale
48	267.2	1	267.2	1	AGRC	yes	1	Newdale
49	487.2	2	243.6	2	AGRC	yes	1	Newdale
50	314.8	3	104.9	2	AGRC	yes	2	Newdale
51	153.8	1	153.8	1	AGRC	yes	1	Newdale
52	38.4	2	19.2	2	AGRC	yes	1	Newdale
53	54.0	3	18.0	2	AGRC	yes	2	Newdale
54	6.0	2	3.0	2	AGRC	no	1	Newdale
55	705.8	8	88.2	3	AGRC	yes	3	Newdale
56	196.7	1	196.7	1	AGRC	yes	1	Newdale
57	91.4	8	11.4	4	RNGE	yes	3	Newdale
58	1382.5	2	691.3	2	AGRC	yes	1	Newdale
Sum.	**25139.4**	**177**	**11903.4**	-	-	-	-	-
Min.	**5.4**	**1**	**1.4**	**1**	-	-	**1**	-
Max.	**1471.6**	**8**	**873.6**	**4**	-	-	**3**	-
Ave.	**433.4**	**3**	**205.2**	**2**	-	-	**2**	-
STD	**319.6**	**2**	**199.2**	**1**	-	-	**1**	-

Note: 1. STD: standard deviation;
2. "-" indicates that the computation does not make sense.

Another input to the SWAT model is the observed data on daily precipitation and maximum and minimum temperatures. These data were obtained from the Environment Canada (http://www.ec.gc.ca), and preprocessed into two database files with formats required by AvSWAT-X. One database file stores the daily precipitation, while another file stores the daily maximum and minimum temperatures. Figure 5 shows the monthly total precipitation and monthly average maximum and minimum temperatures in the Broughton's Creek watershed for the model evaluation period from 1 March 1990 to 31 May 2004.

As mentioned above, because there were no observed data on daily streamflows in the Brought Creek watershed, Equation (1) was used to transfer the observed daily streamflows at the Oak River at Shoal Lake. The computed values using Equation (1) were assumed to be the corresponding daily streamflows at the outlet of the Broughton's Creek watershed. For the model evaluation period, the observed streamflows for the Oak River at Shoal Lake

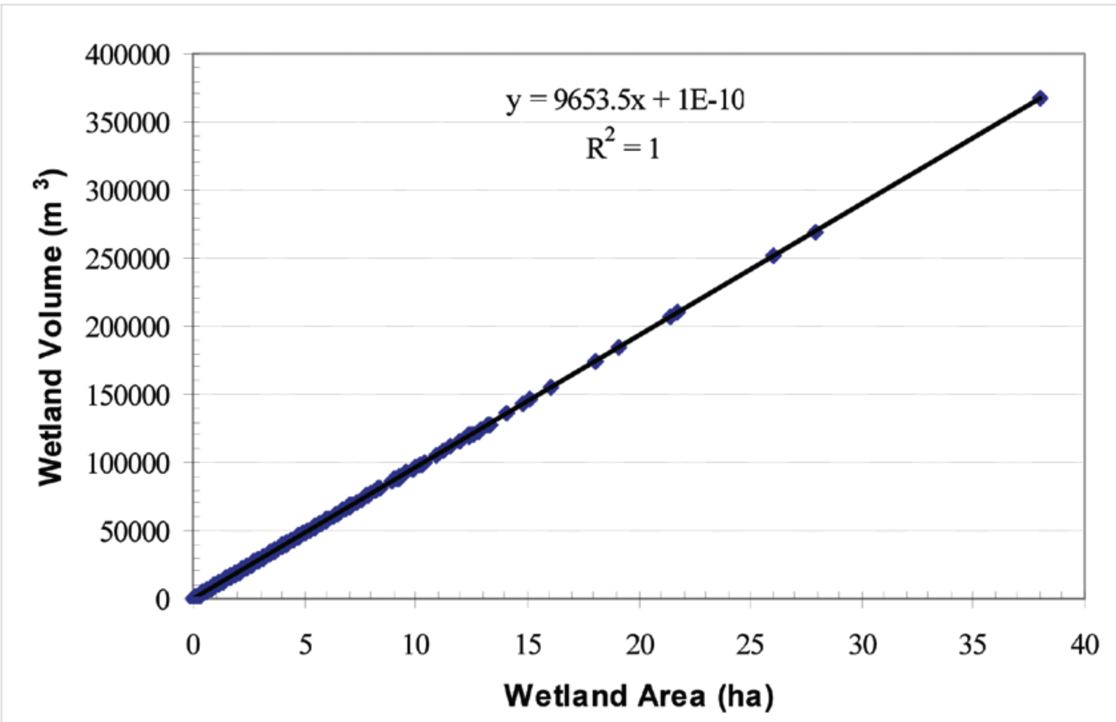


Figure 4. Plot showing the linear relationship between storage volumes and areas of the wetlands

from 1 March 1990 to 31 May 1994 were transferred to compute daily streamflows at the outlet of the Broughton's Creek watershed (Figure 6). The few summarized data at the 13 grab sampling sites were restrictively used for references. Thus, the computed daily streamflows from 1 March 1990 to 31 May 1994 were the only observed values that could be used to calibrate the model.

The SCS-CN (curve number) method was used to simulate the precipitation-runoff processes, while the Muskingum method was used for channel routing. The readers should be reminded that the Muskingum method in SWAT was different from the one described in textbooks because it considers both low and high flow conditions. The details about this improved Muskingum method can be found in the SWAT documentations. The potential evapotranspiration (PET) was estimated using the Priestley-Taylor method, which again is described in detail in the SWAT documentations. The Priestley-Taylor method was used 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-level parameters, namely SFTMP (Snow fall temperature), SMTMP (Snow melt temperature), SMFMX (Melt factor for snow on June 21), SMFMN (Melt factor for snow on December 21), TIMP (Snowpack temperature lag factor), ESCO (Soil evaporation compensation factor), SURLAG (Surface runoff lag factor), MSK_CO1 (Muskingum storage time constant for normal flow), and MSK_CO2 (Muskingum storage time constant for low flow), and the HRU-level parameter, namely CN2 (SCS curve number for AMC II). Particularly, snowmelt and frozen soil conditions have been accounted for in model calibration based on Wang and Melesse (2005). The definitions and calibrated values for these parameters are presented in Table 4.

In addition, based on the HEW concept (Wang et al., 2008), the parameters related to wetlands, namely WET_FR (Fraction of subbasin area that drains into wetlands), WET_NSA (Surface area of wetlands at normal water level), WET_NOVL (Volume of water stored in wetlands when filed 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 (Table 5). The parameter WET_K, the hydraulic conductivity of bottom of wetlands, was empirically specified as 0.5 mm/hr. Further, the field trip conducted in August 2006 indicated that most of the channels in the Brought Creek watershed were fairly covered by vegetation. Based on scientific judgment, the parameter CH_COV, the channel cover factor, was empirically specified as 0.3 for all channel reaches because using different values for different reaches can only be justified by collecting more detailed, site-specific data. The parameter CH_EROD, the channel erodibility factor, was specified to be 0.35, the average USLE erodibility of the soils in the watershed. The other two sediment-related parameters, SPCON (the coefficient for calculating maximum sediment reentrained) and SPEXP (the exponent for calculating maximum sediment reentrained), were empirically specified as 0.0001 and 1.0, respectively. A description of HEW setup is presented in Appendix A.

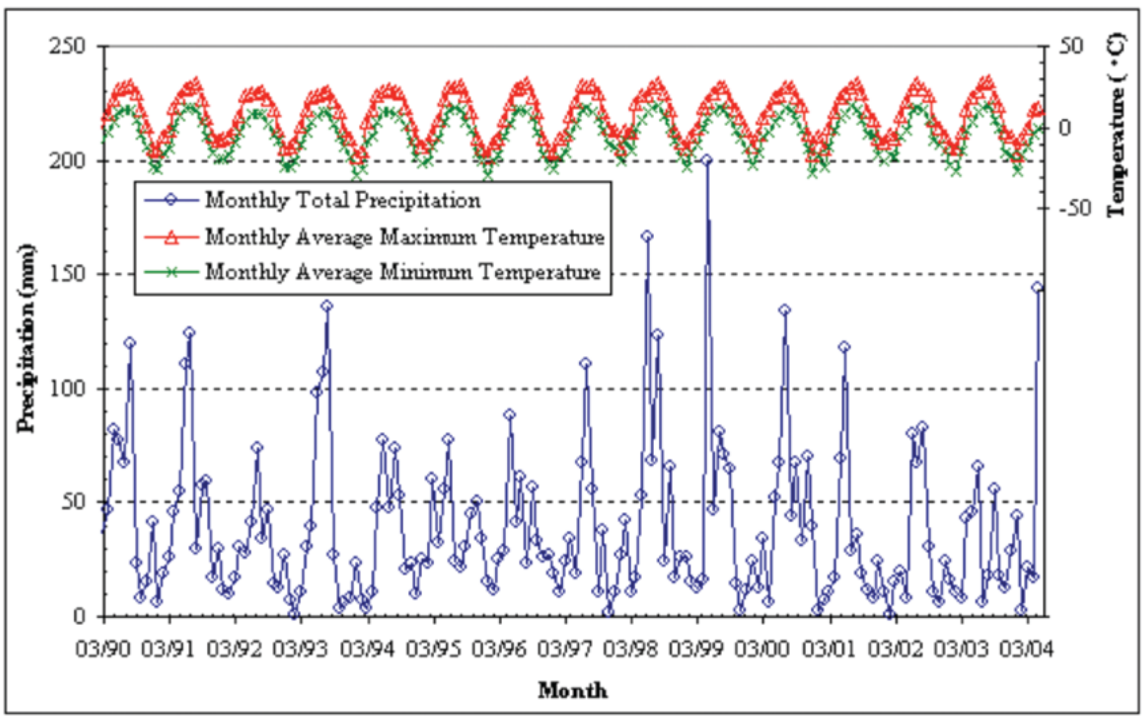


Figure 5. Precipitation and temperatures during the evaluation period from 1 March 1990 to 31 May 2004

Given the uncertain errors of the derived daily streamflows at the outlet of the Broughton's Creek watershed, the SWAT model was empirically judged to have very good simulation performance (Figure 6). The model captured the rising and recessing patterns exhibited by the computed daily streamflows. The noticeable overestimation of the 1991 peak might be because for this year, the climatic conditions in the Oak River watershed were probably different from those in the Broughton's Creek watershed. For the five years from 1990 to 1994, the SWAT simulated annual average streamflow at the outlet of the Broughton's Creek watershed ($0.1m^3/s$) matches the computed annual average streamflow ($0.1m^3/s$), indicating that the computed water quantity can be accurately reproduced by the model. In this study, the model was used to evaluate various wetland conservation and restoration scenarios.

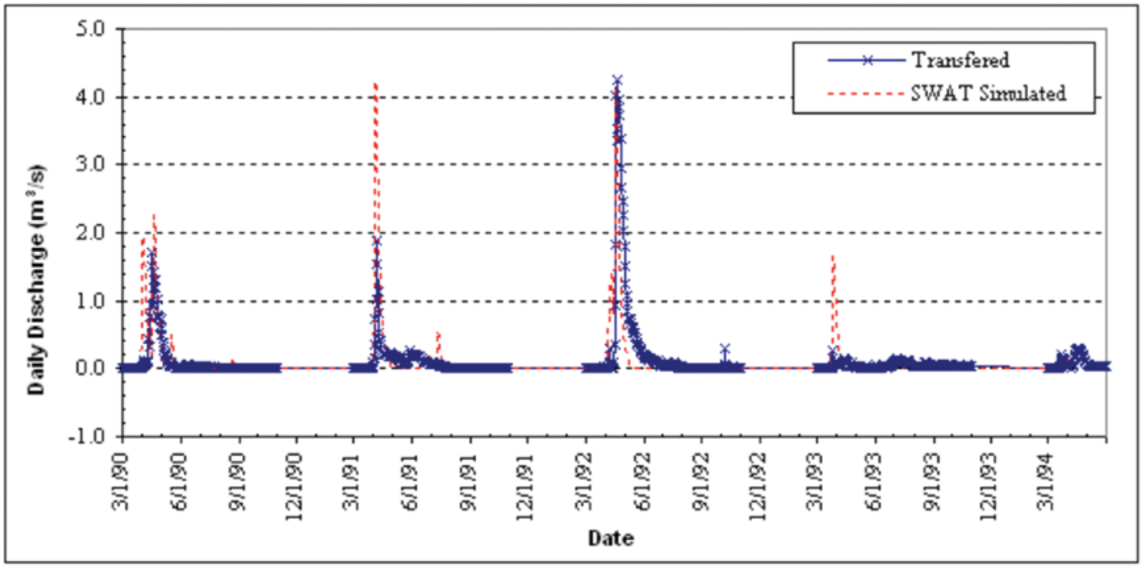


Figure 6. Plot showing the transferred and SWAT simulated daily streamflows at the outlet of the Broughton's Creek watershed

Parameter	Definition	Calibrated Value
SFTMP (°C)	Snow fall temperature	0.5
SMTMP (°C)	Snow melt temperature	2.5
SMFMX (mm H_2O/°C-day)	Melt factor for snow on June 21	6.5
SMFMN (mm H_2O/°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_CO1 (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-hr/ 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

Table 4. Watershed parameters for calibration and adjusted values

Table 5. Wetland-related parameters and adjusted values

Subbasin	WET_NSA = WET_MXSA (ha)	WET_NVOL = WET_MXVOL (10_4m_3)	WET_FR
1	50.24	48.5029	0.401
2	35.59	34.3560	0.282
3	1.42	1.3732	0.226
4	103.38	99.7933	0.655
5	36.67	35.4025	0.536
6	47.95	46.2840	0.492
7	126.04	121.6682	0.932
8	85.59	82.6258	0.549
9	67.50	65.1634	0.414
10	68.53	66.1595	0.545
11	28.19	27.2088	0.162
12	21.59	20.8467	0.272
13	27.66	26.7021	0.265
14	17.45	16.8431	0.531
15	28.98	27.9744	0.253
16	31.96	30.8566	0.413
17	15.17	14.6448	0.360
18	10.49	10.1285	0.369
19	88.25	85.1887	0.300
20	74.55	71.9623	0.475
21	42.74	41.2573	0.420
22	33.95	32.7759	0.453
23	25.06	24.1927	0.352
24	38.45	37.1165	0.645
25	2.09	2.0156	0.210
26	43.66	42.1455	0.743
27	100.91	97.4154	0.550
28	127.04	122.6402	0.937
29	13.10	12.6464	0.374
30	35.05	33.8342	0.620

(continued on next page)

Subbasin	WET_NSA = WET_MXSA (ha)	WET_NVOL = WET_MXVOL (10_4m_3)	WET_FR
31	52.67	50.8431	0.477
32	3.09	2.9815	0.266
33	10.32	9.9667	0.634
34	76.00	73.3688	0.931
35	13.25	12.7933	0.254
36	51.23	49.4523	0.795
37	67.15	64.8256	0.772
38	48.59	46.9084	0.440
39	42.99	41.5022	0.305
40	3.25	3.1387	0.165
41	16.85	16.2648	0.175
42	19.23	18.5643	0.318
43	0.00	0.0000	0.000
44	0.00	0.0000	0.000
45	82.50	79.6431	0.532
46	13.91	13.4311	0.186
47	114.72	110.7495	0.787
48	25.77	24.8769	0.482
49	68.13	65.7732	0.699
50	20.55	19.8400	0.328
51	15.00	14.4780	0.488
52	7.24	6.9938	0.948
53	1.40	1.3491	0.130
54	0.00	0.0000	0.000
55	29.84	28.8034	0.212
56	9.55	9.2194	0.243
57	9.45	9.1232	0.518
58	146.77	141.6853	0.531
Total	**2378.72**	**2296.30**	

Note: 1. WET_NSA: surface area of wetlands at normal water level; WET_NVOL: volume of water stored in wetlands when filled to normal water level; WET_MXSA: surface area of wetlands at maximum water level; WET_MXVOL: volume of water stored in wetlands when filled to maximum water level; WET_FR: fraction of subbasin area that drains into wetlands.

2. Assume WET_NSA = WET_MXSA, and WET_NVOL = WET_MXVOL.

iv

wetland conservation and restoration scenarios

DUC provided data on the wetland inventory developed from a 1:40,000-scale photography flown in 1968 and 2005. The wetland data were used to updated landcover data for the Broughton's Creek watershed in 1968 and 2000. The immersed landcover data indicate 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 subbasins as:

$$A_{i,j} = (1-\alpha_{i,j}) \cdot A_{i,2005} + \alpha_{i,j} \cdot A_{i,1968} \qquad (2)$$

Where $A_{i,j}$ is the wetland area in subbasin i for scenario j; $A_{i,2005}$ is the wetland area in subbasin i in 2005; $A_{i,1968}$ is the wetland area in subbasin i in 1968; and $\alpha_{i,j}$ is the coefficient of restoration level in subbasin i for scenario j. $\alpha_{i,j}$ can range from 0 to 1, with a value of 0 indicating no restoration and a value of 1 indicating a 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 wetlands in size (i.e., holds as that shown in Figure 4), this study analyzed six uniform wetland conservation and restoration scenarios listed in Tables 6 through 11. 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). This means that more wetlands will have to be restored, mandating a larger amount of financial investment. Considering these two contradict counterparts, this study developed and used two indexes, designated "peak reduction efficiency (η_{peak})" and "sediment loading reduction efficiency (η_{sed})," to evaluate these scenarios. An optimal scenario would have minimum values for these two coefficients or a minimum value for either of them.

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

$$\eta_{peak,j} = \frac{1-\frac{Q_{p,j}}{Q_{p,existing}}}{1-\frac{A_{existing}}{A}} \qquad (3)$$

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

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

$$\eta_{sed,j} = \frac{1-\frac{L_{sed,ave,j}}{L_{sed,ave,existing}}}{1-\frac{A_{existing}}{A_i}} \qquad (4)$$

Where $L_{sed,ave,j}$ is the average annual average sediment loading for scenario j; and $L_{sed,ave,existing}$ is the average annual average sediment loading for the existing condition.

Both $\eta_{peak,j}$ and $\eta_{sed,j}$ 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. When a wetland restoration scenario has near-zero values for these two coefficients, this scenario should be judged to be infeasible in accordance with the benefit-cost (i.e., B/C) ratio. In addition, a scenario that can result in a larger increase for either $\eta_{peak,j}$ or $\eta_{sed,j}$ or both should be judged to be more beneficial. Otherwise, this scenario may be least beneficial.

Table 6. Scenario I: Coefficient of restoration level $\alpha_{i,j} = 0.10$ for all subbasins

Subbasin	WET_NSA = WET_MXSA (ha)	WET_NVOL = WET_MXVOL ($10^4 m^3$)	WET_FR
1	57.30	55.31	0.457
2	41.61	40.17	0.330
3	1.81	1.75	0.289
4	106.74	103.04	0.676
5	37.60	36.30	0.549
6	48.52	46.83	0.498
7	126.71	122.32	0.937
8	89.79	86.68	0.576
9	71.36	68.89	0.438
10	70.25	67.82	0.559
11	30.77	29.70	0.176
12	24.30	23.46	0.306
13	29.45	28.43	0.283
14	18.67	18.03	0.569
15	32.38	31.26	0.282
16	34.89	33.68	0.450
17	15.17	14.64	0.360
18	10.68	10.31	0.376
19	90.75	87.61	0.309
20	75.37	72.76	0.480
21	43.34	41.83	0.425
22	34.84	33.64	0.465
23	27.08	26.14	0.380
24	38.45	37.12	0.645
25	2.17	2.10	0.218
26	44.18	42.65	0.752
27	102.73	99.17	0.560
28	127.86	123.43	0.943
29	13.10	12.65	0.374
30	35.35	34.12	0.625

(continued on next page)

Subbasin	WET_NSA = WET_MXSA (ha)	WET_NVOL = WET_MXVOL ($10^4 m^3$)	WET_FR
31	52.67	50.84	0.477
32	3.09	2.98	0.266
33	10.32	9.97	0.634
34	76.00	73.37	0.931
35	14.39	13.89	0.276
36	51.98	50.18	0.807
37	68.16	65.80	0.784
38	48.59	46.91	0.440
39	43.50	42.00	0.309
40	3.31	3.20	0.168
41	17.52	16.92	0.182
42	19.23	18.56	0.318
43	0.00	0.00	0.000
44	0.00	0.00	0.000
45	82.50	79.64	0.532
46	15.38	14.84	0.206
47	114.72	110.75	0.787
48	26.63	25.70	0.498
49	68.13	65.77	0.699
50	20.55	19.84	0.328
51	15.54	15.00	0.506
52	7.24	6.99	0.948
53	1.40	1.35	0.130
54	0.00	0.00	0.000
55	30.23	29.19	0.215
56	9.76	9.42	0.248
57	9.45	9.12	0.518
58	147.15	142.05	0.533
Total	**2440.69**	**2356.12**	**—**

Note: 1. WET_NSA: surface area of wetlands at normal water level; WET_NVOL: volume of water stored in wetlands when filled to normal water level; WET_MXSA: surface area of wetlands at maximum water level; WET_MXVOL: volume of water stored in wetlands when filled to maximum water level; WET_FR: fraction of subbasin area that drains into wetlands.

2. Assume WET_NSA = WET_MXSA, and WET_NVOL = WET_MXVOL.

Table 7. Scenario II: Coefficient of restoration level $\alpha_{i,j} = 0.25$ for all subbasins

Subbasin	WET_NSA = WET_MXSA (ha)	WET_NVOL = WET_MXVOL ($10^4 m^3$)	WET_FR
1	67.88	65.52	0.542
2	50.64	48.89	0.401
3	2.40	2.32	0.382
4	111.78	107.91	0.708
5	38.99	37.64	0.570
6	49.37	47.66	0.507
7	127.72	123.30	0.945
8	96.10	92.77	0.616
9	77.16	74.48	0.473
10	72.83	70.31	0.579
11	34.64	33.44	0.198
12	28.35	27.37	0.357
13	32.15	31.03	0.308
14	20.51	19.80	0.625
15	37.49	36.19	0.327
16	39.28	37.92	0.507
17	15.17	14.64	0.360
18	10.97	10.59	0.386
19	94.51	91.24	0.322
20	76.60	73.95	0.488
21	44.23	42.70	0.434
22	36.18	34.92	0.483
23	30.10	29.06	0.422
24	38.45	37.12	0.645
25	2.30	2.22	0.231
26	44.97	43.41	0.766
27	105.45	101.80	0.574
28	129.08	124.60	0.952
29	13.10	12.65	0.374
30	35.80	34.56	0.633

(continued on next page)

Subbasin	WET_NSA = WET_MXSA (ha)	WET_NVOL = WET_MXVOL ($10^4 m^3$)	WET_FR
31	52.67	50.84	0.477
32	3.09	2.98	0.266
33	10.32	9.97	0.634
34	76.00	73.37	0.931
35	16.09	15.53	0.308
36	53.10	51.26	0.824
37	69.68	67.27	0.801
38	48.59	46.91	0.440
39	44.27	42.74	0.314
40	3.40	3.29	0.173
41	18.54	17.90	0.193
42	19.23	18.56	0.318
43	0.00	0.00	0.000
44	0.00	0.00	0.000
45	82.50	79.64	0.532
46	17.57	16.96	0.235
47	114.72	110.75	0.787
48	27.91	26.94	0.522
49	68.13	65.77	0.699
50	20.55	19.84	0.328
51	16.36	15.79	0.532
52	7.24	6.99	0.948
53	1.40	1.35	0.130
54	0.00	0.00	0.000
55	30.83	29.76	0.219
56	10.08	9.73	0.256
57	9.45	9.12	0.518
58	147.71	142.59	0.535
Total	**2533.65**	**2445.86**	**—**

Note: 1. WET_NSA: surface area of wetlands at normal water level; WET_NVOL: volume of water stored in wetlands when filled to normal water level; WET_MXSA: surface area of wetlands at maximum water level; WET_MXVOL: volume of water stored in wetlands when filled to maximum water level; WET_FR: fraction of subbasin area that drains into wetlands.

2. Assume WET_NSA = WET_MXSA, and WET_NVOL = WET_MXVOL.

Table 8. Scenario III: Coefficient of restoration level $\alpha_{i,j} = 0.50$ for all subbasins

Subbasin	WET_NSA = WET_MXSA (ha)	WET_NVOL = WET_MXVOL ($10^4 m^3$)	WET_FR
1	85.51	82.54	0.683
2	65.70	63.42	0.520
3	3.38	3.27	0.538
4	120.19	116.02	0.762
5	41.31	39.88	0.604
6	50.80	49.04	0.522
7	129.41	124.92	0.957
8	106.60	102.91	0.683
9	86.81	83.80	0.533
10	77.13	74.46	0.613
11	41.10	39.67	0.235
12	35.11	33.90	0.443
13	36.63	35.36	0.351
14	23.58	22.76	0.718
15	46.00	44.40	0.401
16	46.60	44.98	0.602
17	15.17	14.64	0.360
18	11.45	11.05	0.403
19	100.77	97.28	0.343
20	78.66	75.94	0.501
21	45.73	44.14	0.449
22	38.40	37.07	0.512
23	35.14	33.93	0.493
24	38.45	37.12	0.645
25	2.51	2.42	0.252
26	46.28	44.67	0.788
27	109.99	106.18	0.599
28	131.11	126.57	0.967
29	13.10	12.65	0.374
30	36.55	35.28	0.647

(continued on next page)

Subbasin	WET_NSA = WET_MXSA (ha)	WET_NVOL = WET_MXVOL ($10^4 m^3$)	WET_FR
31	52.67	50.84	0.477
32	3.09	2.98	0.266
33	10.32	9.97	0.634
34	76.00	73.37	0.931
35	18.92	18.27	0.363
36	54.97	53.07	0.853
37	72.21	69.71	0.830
38	48.59	46.91	0.440
39	45.55	43.97	0.323
40	3.55	3.43	0.180
41	20.23	19.53	0.210
42	19.23	18.56	0.318
43	0.00	0.00	0.000
44	0.00	0.00	0.000
45	82.50	79.64	0.532
46	21.23	20.49	0.284
47	114.72	110.75	0.787
48	30.05	29.01	0.562
49	68.13	65.77	0.699
50	20.55	19.84	0.328
51	17.72	17.10	0.576
52	7.24	6.99	0.948
53	1.40	1.35	0.130
54	0.00	0.00	0.000
55	31.82	30.72	0.226
56	10.60	10.24	0.269
57	9.45	9.12	0.518
58	148.65	143.50	0.538
Total	**2688.57**	**2595.41**	**—**

Note: 1. WET_NSA: surface area of wetlands at normal water level; WET_NVOL: volume of water stored in wetlands when filled to normal water level; WET_MXSA: surface area of wetlands at maximum water level; WET_MXVOL: volume of water stored in wetlands when filled to maximum water level; WET_FR: fraction of subbasin area that drains into wetlands.

2. Assume WET_NSA = WET_MXSA, and WET_NVOL = WET_MXVOL.

Table 9. Scenario IV: Coefficient of restoration level $\alpha_{i,j} = 0.75$ for all subbasins

Subbasin	WET_NSA = WET_MXSA (ha)	WET_NVOL = WET_MXVOL ($10^4 m^3$)	WET_FR
1	103.14	99.57	0.823
2	80.75	77.95	0.640
3	4.37	4.21	0.695
4	128.59	124.14	0.815
5	43.62	42.11	0.637
6	52.22	50.41	0.536
7	131.09	126.55	0.970
8	117.11	113.05	0.751
9	96.46	93.12	0.592
10	81.43	78.61	0.647
11	47.55	45.91	0.272
12	41.87	40.42	0.528
13	41.11	39.69	0.394
14	26.64	25.72	0.811
15	54.51	52.62	0.475
16	53.91	52.04	0.696
17	15.17	14.64	0.360
18	11.93	11.51	0.419
19	107.04	103.33	0.364
20	80.72	77.92	0.514
21	47.22	45.58	0.464
22	40.63	39.22	0.542
23	40.18	38.79	0.564
24	38.45	37.12	0.645
25	2.71	2.62	0.273
26	47.59	45.94	0.810
27	114.53	110.56	0.624
28	133.14	128.53	0.982
29	13.10	12.65	0.374
30	37.30	36.01	0.660

(continued on next page)

Subbasin	WET_NSA = WET_MXSA (ha)	WET_NVOL = WET_MXVOL ($10^4 m^3$)	WET_FR
31	52.67	50.84	0.477
32	3.09	2.98	0.266
33	10.32	9.97	0.634
34	76.00	73.37	0.931
35	21.76	21.01	0.417
36	56.84	54.87	0.882
37	74.74	72.15	0.859
38	48.59	46.91	0.440
39	46.83	45.21	0.332
40	3.71	3.58	0.188
41	21.92	21.16	0.228
42	19.23	18.56	0.318
43	0.00	0.00	0.000
44	0.00	0.00	0.001
45	82.50	79.64	0.532
46	24.88	24.02	0.333
47	114.72	110.75	0.787
48	32.19	31.07	0.603
49	68.13	65.77	0.699
50	20.55	19.84	0.328
51	19.07	18.41	0.621
52	7.24	6.99	0.948
53	1.40	1.35	0.130
54	0.00	0.00	0.000
55	32.81	31.67	0.233
56	11.13	10.74	0.283
57	9.45	9.12	0.518
58	149.59	144.41	0.541
Total	**2843.49**	**2744.97**	—

Note: 1. WET_NSA: surface area of wetlands at normal water level; WET_NVOL: volume of water stored in wetlands when filled to normal water level; WET_MXSA: surface area of wetlands at maximum water level; WET_MXVOL: volume of water stored in wetlands when filled to maximum water level; WET_FR: fraction of subbasin area that drains into wetlands.

2. Assume WET_NSA = WET_MXSA, and WET_NVOL = WET_MXVOL.

Table 10. Scenario V: Coefficient of restoration level $\alpha_{i,j} = 0.90$ for all subbasins

Subbasin	WET_NSA = WET_MXSA (ha)	WET_NVOL = WET_MXVOL ($10^4 m^3$)	WET_FR
1	113.72	109.78	0.908
2	89.78	86.67	0.711
3	4.95	4.78	0.788
4	133.63	129.00	0.847
5	45.02	43.46	0.658
6	53.08	51.24	0.545
7	132.11	127.53	0.977
8	123.42	119.14	0.791
9	102.25	98.71	0.627
10	84.01	81.10	0.668
11	51.43	49.64	0.295
12	45.93	44.33	0.579
13	43.81	42.29	0.420
14	28.48	27.50	0.867
15	59.61	57.55	0.520
16	58.30	56.28	0.753
17	15.17	14.64	0.360
18	12.21	11.79	0.430
19	110.80	106.96	0.377
20	81.95	79.11	0.522
21	48.12	46.45	0.472
22	41.97	40.51	0.560
23	43.21	41.71	0.606
24	38.45	37.12	0.645
25	2.84	2.74	0.285
26	48.37	46.70	0.824
27	117.26	113.19	0.639
28	134.37	129.71	0.991
29	13.10	12.65	0.374
30	37.75	36.44	0.668

(continued on next page)

Subbasin	WET_NSA = WET_MXSA (ha)	WET_NVOL = WET_MXVOL ($10^4 m^3$)	WET_FR
31	52.67	50.84	0.477
32	3.09	2.98	0.266
33	10.32	9.97	0.634
34	76.00	73.37	0.931
35	23.46	22.65	0.449
36	57.97	55.96	0.900
37	76.26	73.62	0.877
38	48.59	46.91	0.440
39	47.60	45.95	0.338
40	3.80	3.67	0.193
41	22.93	22.14	0.238
42	19.23	18.56	0.318
43	0.00	0.00	0.000
44	0.00	0.00	0.001
45	82.50	79.64	0.532
46	27.08	26.14	0.363
47	114.72	110.75	0.787
48	33.47	32.31	0.627
49	68.13	65.77	0.699
50	20.55	19.84	0.328
51	19.89	19.20	0.647
52	7.24	6.99	0.948
53	1.40	1.35	0.130
54	0.00	0.00	0.000
55	33.40	32.24	0.237
56	11.45	11.05	0.291
57	9.45	9.12	0.518
58	150.15	144.95	0.544
Total	**2936.45**	**2834.70**	—

Note: 1. WET_NSA: surface area of wetlands at normal water level; WET_NVOL: volume of water stored in wetlands when filled to normal water level; WET_MXSA: surface area of wetlands at maximum water level; WET_MXVOL: volume of water stored in wetlands when filled to maximum water level; WET_FR: fraction of subbasin area that drains into wetlands.

2. Assume WET_NSA = WET_MXSA, and WET_NVOL = WET_MXVOL.

Table 11. Scenario VI: Coefficient of restoration level $\alpha_{i,j} = 1.00$ for all subbasins

Subbasin	WET_NSA = WET_MXSA (ha)	WET_NVOL = WET_MXVOL ($10^4 m^3$)	WET_FR
1	120.77	116.59	0.964
2	95.80	92.48	0.759
3	5.35	5.16	0.851
4	137.00	132.25	0.868
5	45.94	44.35	0.671
6	53.65	51.79	0.551
7	132.78	128.18	0.982
8	127.62	123.20	0.818
9	106.11	102.44	0.651
10	85.73	82.76	0.682
11	54.01	52.14	0.309
12	48.63	46.94	0.613
13	45.60	44.02	0.437
14	29.71	28.68	0.905
15	63.02	60.84	0.550
16	61.23	59.11	0.790
17	15.17	14.64	0.360
18	12.40	11.97	0.436
19	113.30	109.38	0.386
20	82.78	79.91	0.527
21	48.71	47.03	0.478
22	42.86	41.37	0.572
23	45.22	43.66	0.634
24	38.45	37.12	0.645
25	2.92	2.82	0.294
26	48.90	47.20	0.833
27	119.07	114.95	0.649
28	135.18	130.49	0.997
29	13.10	12.65	0.374
30	38.05	36.73	0.673

(continued on next page)

Subbasin	WET_NSA = WET_MXSA (ha)	WET_NVOL = WET_MXVOL ($10^4 m^3$)	WET_FR
31	52.67	50.84	0.477
32	3.09	2.98	0.266
33	10.32	9.97	0.634
34	76.00	73.37	0.931
35	24.60	23.74	0.471
36	58.71	56.68	0.911
37	77.27	74.59	0.888
38	48.59	46.91	0.440
39	48.11	46.44	0.342
40	3.86	3.72	0.196
41	23.61	22.79	0.245
42	19.23	18.56	0.318
43	0.00	0.00	0.000
44	0.00	0.00	0.001
45	82.50	79.64	0.532
46	28.54	27.55	0.382
47	114.72	110.75	0.787
48	34.32	33.13	0.643
49	68.13	65.77	0.699
50	20.55	19.84	0.328
51	20.43	19.73	0.665
52	7.24	6.99	0.948
53	1.40	1.35	0.130
54	0.00	0.00	0.000
55	33.80	32.63	0.240
56	11.66	11.25	0.296
57	9.45	9.12	0.518
58	150.53	145.31	0.545
Total	**2998.42**	**2894.52**	**—**

Note: 1. WET_NSA: surface area of wetlands at normal water level; WET_NVOL: volume of water stored in wetlands when filled to normal water level; WET_MXSA: surface area of wetlands at maximum water level; WET_MXVOL: volume of water stored in wetlands when filled to maximum water level; WET_FR: fraction of subbasin area that drains into wetlands.

2. Assume WET_NSA = WET_MXSA, and WET_NVOL = WET_MXVOL.

The aforementioned six scenarios assume uniform percentages of wetland conservation and restoration across subbasins within the Broughton's Creek watershed. That is, for a given scenario, the increase percentage of wetland area is identical for all 58 subbasins. Hereinafter, those six scenarios are designated "uniform wetland restoration scenarios" for description purposes. In order to examine impacts of wetland restoration locations on streamflow and sediment loadings, these subbasins were aggregated into six nested groups from the lower to upper portions of the watershed to formulate six targeted wetland restoration scenarios (Table 12; Figure 7). Assuming the total wetland area within each subbasin is equal to that in the year of 1968, these targeted scenarios have the accumulated wetland acreage starting from the lowest section: (1). A-I; (2). A-I+A-II; (3) A-I+A-II +A-III; (4). A-I+A-II +A-III+A-IV; (5). A-I+A-II +A-III+A-IV+A-V; (6). A-I+A-II +A-III+A-IV+A-V+A-VI. A display of the six targeted wetland restoration is shown in Figure 7.

Table 12. Subbasins formulating the six targeted restoration scenarios.

A-I	A-II	A-III	A-IV	A-V	A-VI
35	32	26	17	9	1
36	33	28	18	10	2
39	34	29	21	11	3
40	37	30	22	12	4
41	38	31	23	13	5
42	45	47	24	14	6
43	53	48	25	15	7
44	54	50	27	16	8
55	57	51	46	19	
56	58	52	49	20	

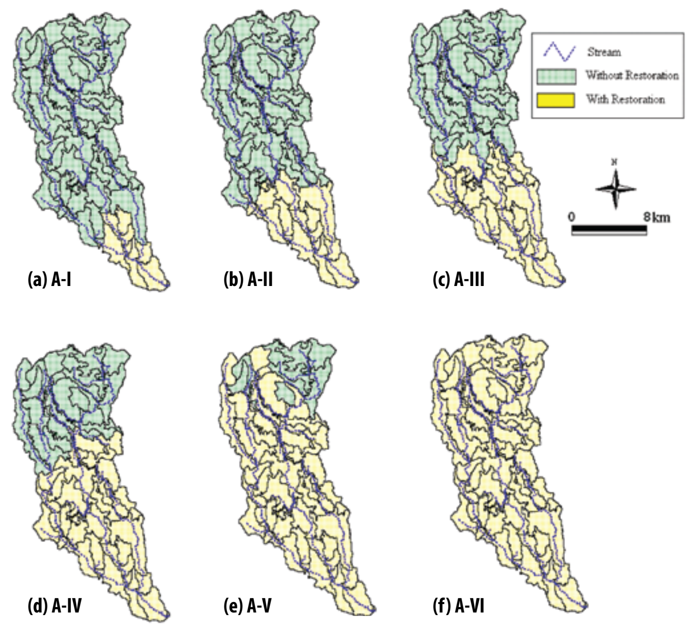


Figure 7. Spatial distribution of the six targeted wetland restoration scenarios

effects on stream flow and sediment loading

For the six uniform wetland restoration scenarios, the simulation results are summarized in Table 13. As expected, with the increase of the coefficient of restoration level α, the flows and sediment loadings were predicted to decrease. The reduced peak discharges will be good for flood reduction in the watershed, whereas, the reduced sediment loadings will be beneficial for the water quality improvement. The average annual peak discharges were predicted to be reduced by 1.6 to 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.

Table 13. Effects of the six uniform 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	2378.72	2.972	0.097	19.332	0.472
I	0.10	2440.69	2.962	0.096	19.268	0.463
II	0.25	2533.65	2.885	0.092	18.519	0.442
III	0.50	2688.57	2.758	0.086	17.693	0.405
IV	0.75	2843.49	2.637	0.080	16.726	0.369
V	0.90	2936.45	2.564	0.077	16.058	0.348
VI	1.00	2998.42	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 sediment loading for scenario j; $L_{sed,ave,j}$: average annual average daily sediment loading for scenario j.

Based on peak reduction efficiency η_{peak}, the optimal restoration scenario was determined to have a coefficient of restoration level α of 0.90, which is Scenario V (Table 13 and Figure 8). However, the 75% restoration level (i.e., Scenario IV) is likely to be a turning point, beyond which a small decrease of peak discharges would incur a large increase of costs in terms of wetland acreage. Therefore, in practice, a scenario with α value between 0.50 and 0.80 is probably most cost-effective in terms of benefit to wetland acreage ratios. The sediment reduction efficiency η_{sed} exhibits a similar pattern with η_{peak} (Figure 8). A scenario with α value between 0.50 and 0.80 would result in 8 to 15% reduction of the sediment loadings (Table 13), which was judged to be both environmentally and economically sound for most watershed management practices in terms of benefit to wetland acreage ratios.

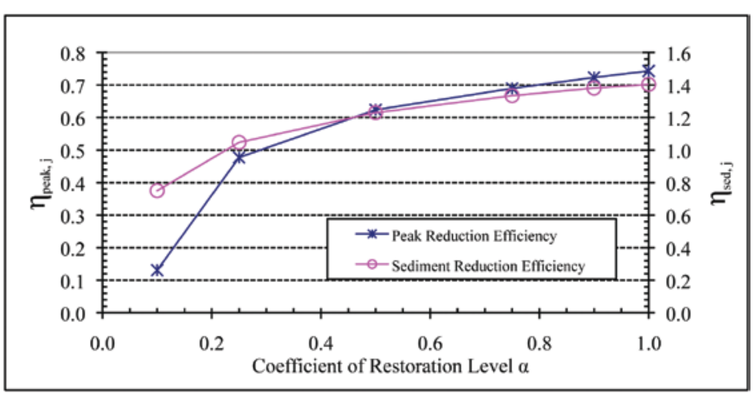


Figure 8. Plot showing the peak reduction efficiency η_{peak} (Equation 3) and sediment reduction efficiency η_{sed} (Equation 4) versus the coefficient of restoration level α (Equation 2) for the six uniform restoration scenarios

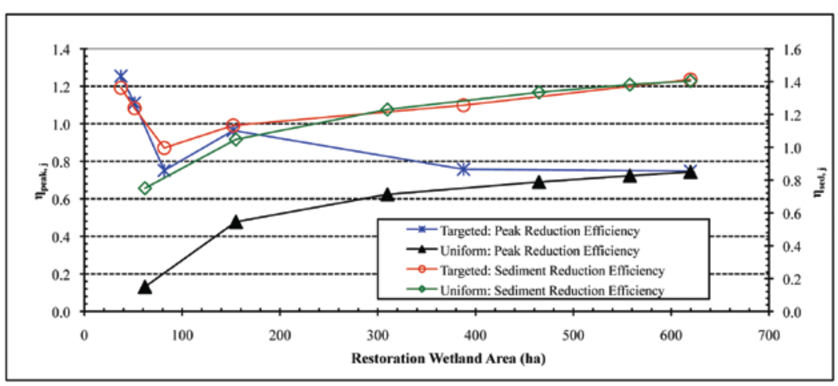
The predicted reductions were larger for a targeted wetland restoration scenario than for a uniform wetland restoration scenario while the total restoration acreages for these two scenarios are identical (Tables 13 and 14). For example, the scenario A-I has a restoration wetland area of 37.4 ha and the scenario I has a restoration wetland area of 62.0 ha, but the predicted peak discharge and sediment loading for the former scenario were smaller than the corresponding values for the latter scenario. In addition, the efficiencies for the six targeted and the six uniform wetland restoration scenarios are plotted in Figure 9. That the efficiencies do not monotonically increase with the restoration wetland area reveals that the effects of wetlands are also dependent upon their spatial locations. For the Broughton's Creek watershed, the wetland restoration in the A-II subbasins (Table 12) may not be cost-effective, as indicated by the decreased efficiencies with these subbasins being taken into account (Figure 9). Nevertheless, the efficiencies for the targeted restoration scenarios are consistently higher than those for the uniform restoration scenarios, indicating that for a given total wetland restoration area, it may be wise to implement the restoration in the targeted/selected subbasins. In addition, for the targeted scenarios, the additional wetland restoration beyond 400 ha will be least efficient in further reducing the peak discharge at the watershed outlet. In terms of reduction of sediment loading, the targeted scenarios were predicted to be slightly better than the uniform scenarios, with 300 ha as the approximate merging point beyond which the effects of these two types of scenarios converge (Figure 9).

Table 14. Effects of the six targeted wetland restoration scenarios

Targeted Scenario	Restoration Area (ha)	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	2378.72	2.972	0.097	19.332	0.472
A-I	37.39	2435.27	2.915	0.096	18.679	0.462
A-II	51.27	2449.15	2.903	0.095	18.613	0.460
A-III	81.64	2479.52	2.898	0.095	18.564	0.457
A-IV	152.21	2550.09	2.801	0.092	17.880	0.440
A-V	387.67	2785.55	2.659	0.084	16.723	0.390
A-VI	619.70	2998.42	2.515	0.074	15.763	0.335

Note: A_j: total wetland area 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.

Figure 9. Plot showing the peak reduction efficiency η_{peak} (Equation 3) and sediment reduction efficiency η_{sed} (Equation 4) versus the restoration wetland area for six targeted and the six uniform restoration scenarios.



effects on total phosphorus and nitrogen loadings

As discussed above, a SWAT model was set up and used to predict streamflows and sediment loadings at the outlet of the Broughton's Creek watershed both for the existing conditions and conditions with various wetland restoration scenarios. However, limited by the available data on fertilizer management and stream water quality, we could not justify the use of the model to conduct a similar simulation of phosphorus (P) and nitrogen (N) processes within the study watershed. Alternatively, we used empirical export coefficients for total phosphorus (TP) and total nitrogen (TN) reported by Bourne et al. (2002) in conjunction with the modeled change in effective drainage area to estimate the annual average amounts of TP and TN exported from the Broughton's Creek watershed as a result of wetland drainage. Additionally, restoration benefits were evaluated relative to the existing condition by estimating the increase in the mass of TP and TN trapped within the watershed as a result of the various wetland restoration scenarios.

6.1. The approach to estimate water quality benefits

The nutrient export coefficients are defined as nutrients transported to the edge of field and loaded into water bodies such as wetlands or streams from different land use classes. The approach was based on four assumptions. First, nutrients entering into wetlands are proportional to divisions of runoff and drainage areas in a subbasin, i.e., 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. Second, nutrients are uniformly mixed within wetlands and corresponding transports are proportional to the flow and/or sediment into and out of wetlands. Third, nutrient removal rates can be used to estimate the amount of nutrients trapped by wetlands based on wetland areas. Fourth, nutrients transported to the watershed outlet through streams are defined by a delivery ratio. Based on these assumptions, wetland reductions of nutrient export to streams are defined as the differences between nutrient inputs and outputs of wetlands. Nutrient export reductions associated with wetland restoration are represented by additional nutrient removal contributed by increased wetland areas through restoration. Water quality benefits of wetland restoration can be defined as reductions of nutrients delivered to the watershed outlet and transported to downstream watersheds.

6.2. Nutrient export coefficients and delivery ratio for the study watershed

Nutrient export coefficients for various landuse classes were adopted from Bourne et al. (2002). In order to simplify the calculation, we lumped pasture and forest export coefficients together to derive non-crop land nutrient export coefficients. The TP export coefficients for cropland and non-cropland are 0.65 kg/ha/yr and 0.17 kg/ha/yr respectively, while the corresponding TN coefficients are 3.15 kg/ha/yr and 1.72 kg/ha/yr respectively (Table 15). This is a reasonable pattern because nutrient exports on cropland are much higher than non-cropland due to nutrient applications. TN export rates are much higher than TP export rates due to typically higher TN application rates and proportions of dissolved TN in transport. Based on these coefficients we can estimate nutrient exports from each subbasin based on cropland and non-cropland areas. We also assumed a 0.5 nutrient delivery ratio within streams, 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 Broughton's Creek watershed outlet. 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 two to three week 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.

Table 15. Nutrient export coefficients in Manitoba (Bourne et al., 2002)

	TP (kg/ha/yr)	TN (kg/ha/yr)
Cropland	0.65	3.15
Non-cropland	0.17	1.72

6.3. Wetland and stream drainage areas within the study watershed

Based on hydrologic equivalent wetland (HEW) concept, wetland drainage area for each subbasin under existing conditions or no wetland restoration scenario is estimated based on outflow from the specific subbasin and scientific judgments. Wetland drainage area for each subbasin 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 16, 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 ha to 15,009 ha) due to wetland restoration.

Table 16. Wetland and stream drainage areas for the six uniform restoration scenarios

Scenario	α_j [1]	Wetland Area (ha)	Restoration Wetland (ha)	Wetland Drainage (ha)	Wetland Drainage (%) [2]	Direct Drainage (ha)	Direct Drainage (%) [2]
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

[1] α_j: coefficient of restoration level for scenario j.

[2] computed as the ratio of the drainage area to the total watershed area of 25,139 ha.

6.4. Nutrient removal rates of wetlands in the study watershed

Literature on wetland nutrient removal is very sparse for prairie wetlands. We reviewed available journal articles on wetland nutrient budgets of constructed wetlands or natural marshes in cold and warm areas (Tables B1 and B2 in Appendix B). The P removal rates are quite variable and range from 0.2 to 156 g/m^2/yr. N removal rates are also quite variable and range from 5 to 60 g/m^2/yr. A study in a constructed wetland in Québec (Kroeger et al. 2007) showed a P removal rate of 1.7 g/m^2/yr and an N removal rate of 49.2 g/m^2/yr. For the Broughton's Creek watershed, we assume TP and TN removal rates of 0.5 and 5 g/m^2/yr or 5 and 50 kg/ha/yr respectively. We used these conservative nutrient removal rates in order not to overestimate the nutrient removal efficiencies of wetlands. Based on the removal rates, the existing 2,379-ha wetlands in the Broughton's Creek watershed have a capacity of removing TP 11,895 kg/yr and TN 118,950 kg/yr respectively. With a full wetland restoration to 1968 level, wetlands in the Broughton's Creek watershed are 2,998 ha. These wetlands have a capacity of removing TP 14,990 kg/yr and TN 149,900 kg/yr respectively.

6.5. Nutrient export and delivery under the existing conditions

Based on the developed methodology, the mass of nutrients exported to streams on an annual basis is estimated by multiplying the land use specific nutrient export coefficients by their respective areas within the direct stream drainage areas. Under the base scenario, we estimate nutrient loading to Broughton's Creek to be 6,696 kg/yr of TP and 35,988 kg/yr of TN. Similarly, nutrients exported to wetlands are estimated by multiplying nutrient export coefficients by cropland and non-cropland areas within wetland drainage areas. In nutrient export calculation, wetland areas were subtracted from wetland drainage areas because these areas don't generate nutrients. Under base scenario or existing condition, 4,821 kg/yr of TP and 25,910 kg/yr of TN are exported into wetland basins. It is important to note here that these estimated nutrient loads are substantially lower than the estimated wetland nutrient removal capacity of TP 11,895 kg/yr and TN 118,950 kg/yr.

With an empirical in-stream delivery ratio of 0.5, the nutrient loadings at Broughton's Creek watershed outlet under existing condition are TP 2,348 kg/yr and TN 17,994 kg/yr. SWAT modelling results showed that the average daily streamflow at Broughton's Creek watershed outlet under base scenario is 0.097 m^3/s, which is equivalent to annual water yield of 3,058,992 m^3 (0.097 x 3,600 x 24 x 365). Based on streamflow 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 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 and the comparison supports that our methodology for estimating nutrient export to streams and delivery to watershed outlet is reasonable.

6.6. Water quality benefits of wetland restoration in the study watershed

Similar to the base scenario, nutrients exported to wetlands under various wetland restoration scenarios are far less than nutrient removal capacity of these wetlands. For example, with 2,998 ha of wetlands under full restoration scenario, nutrients exported to wetlands are TP 4,947 kg/yr and TN 26,588 kg/yr while these wetlands have a nutrient removal capacity of TP 14,990 kg/yr and TN 149,900 kg/yr respectively. A major portion of water quality benefits due to wetland restoration can be defined as the difference between nutrients exported to wetlands under a wetland restoration scenario and the base scenario. In addition, the aforementioned water quality benefits can be increased by reduced nutrient generation from increments of wetland acreage in comparing to wetland area under base scenario because these increased wetland areas do not generate nutrients.

Under the base scenario, 6,696 kg/year of TP and 35,988 kg/year of TN are delivered to surface waters directly contributing to the outlet of the Broughton's Creek watershed. With a delivery ratio of 0.5, the reduced nutrient loadings at Broughton's Creek watershed outlet are TP 3,348 kg/yr and TN 17,994 kg/yr. 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 ha to 12,922 ha. This reduction in contributing area due to wetland restoration reduces nutrient export by 158 kg/yr for TP and 847 kg/yr for TN compared to the base scenario. With a delivery ratio of 0.5, the reduced nutrient loadings at Broughton's Creek watershed outlet under scenario I relative to the base scenario are TP 79 kg/yr and TN 423 kg/yr. 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 ha to

10,130 ha. This reduction in contributing area due to wetland restoration reduces nutrient export by 1,570 kg/yr for TP and 8,439 kg/yr for TN compared to the base scenario. With a delivery ratio of 0.5, the reduced nutrient loadings at Broughton's Creek watershed outlet under scenario VI relative to the base scenario are TP 785 kg/yr and TN 4,219 kg/yr. Under scenario VI, Water quality benefits are represented by a 23.4% reduction in TP and TN at the watershed outlet relative to the base scenario (Table 17).

Table 17. Reductions of nutrient exports to streams and nutrient loadings at watershed outlet under various wetland restoration scenarios

Scenario	a_j	TP Export Reduction (kg/yr)	TN Export Reduction (kg/yr)	TP Load Reduction (kg/yr)	TN Load Reduction (kg/yr)	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 kg/yr and 35,988 kg/yr respectively, TP and TN Loadings at outlet are 3,348 kg/yr and 17,994 kg/yr respectively.

2. Load at outlet = 0.5 x Export to streams.

6.7. Nutrient export and delivery due to wetland drainage

In 1968, the Broughton's Creek watershed had a wetland area of 2,998 ha. In 2005, wetland area was 2,379 ha. During this period, 619 ha of wetland area was lost or degraded due to drainage activity, which is equivalent to 20.6% of the 1968 wetland area. With this trend, wetland drainage areas decreased from 15,009 ha to 11,906 ha and direct stream drainage areas increased from 10,130 ha to 13,223 ha. Therefore, nutrient exports to streams and nutrient loadings at the watershed outlet have increased considerably. The 1968 nutrient exports to streams is estimated at 5,126 kg/yr of TP and 27,549 kg/yr of TN. Nutrient loadings at watershed outlet are 2,563 kg/yr of P and 13,775 kg/yr of N respectively. In 2005, nutrient exports to streams increased to 6,696 kg/yr of TP and 35,988 kg/yr of TN. As a result, nutrient loadings at the watershed outlet increased to 3,348 kg/yr of TP and 17,994 kg/yr of TN respectively. Using the above information we estimate that there has been a 30.6% increase in the mass of nutrients exported out of the Broughton's Creek watershed between 1968 and 2005 as a result of wetland drainage (Table 18).

6.8. Water quality benefits of wetland restoration in the Little Saskatchewan River watershed

Average nutrient loads (1994-2001) from the Little Saskatchewan River (LSR) to the Assiniboine River are estimated to be 29 and 281 T/yr for TP and TN, respectively (Bourne et al. 2002). Assuming nutrients exported from the Broughton's Creek outlet are exported to the LSR, the various wetland restoration scenarios would yield load reductions to the Assiniboine River of 79 to 785 kg/yr of TP and 423 to 4,219 kg/yr of TN. These nutrient reductions in Broughton's Creek would reduce nutrient loading from the LSR to the Assiniboine River by 0.3 to 2.7% for TP, and by 0.2 to 1.5% for TN.

Table 18. Nutrient exports to streams and loadings at watershed outlet under different wetland drainage scenarios

Scenario	a_j	TP Export (kg/yr)	TN Export (kg/yr)	TP Load (kg/yr)	TN Load (kg/yr)	TP Increase (%)	TN Increase (%)
Existing (2005)	**0.00**	**6,696**	**35,988**	**3,348**	**17,994**	**30.6**	**30.6**
I	0.10	6,538	35,141	3,269	17,571	27.5	27.6
II	0.25	6,304	33,880	3,152	16,940	23.0	23.0
III	0.50	5,911	31,771	2,956	15,886	15.3	15.3
IV	0.75	5,519	29,664	2,760	14,832	7.7	7.7
V	0.90	5,282	28,390	2,641	14,195	3.0	3.1
VI (1968)	**1.00**	**5,126**	**27,549**	**2,563**	**13,775**	**0.0**	**0.0**

Note: Load = 0.5 x Export

The LSR watershed has an area of 317,701 ha (not including Riding Mountain National Park), which is 12.6 times the Broughton's Creek watershed area of 25,139 ha. Assuming wetland restoration potential in the LSR watershed is proportional to the potential in the Broughton's Creek watershed and assuming land use patterns are similar, we can scale up the results from Broughton's Creek to the LSR watershed. Based on these assumptions, wetland restoration potential in the LSR watershed ranges from 781 ha to 7,799 ha. Scaling up the wetland restoration scenarios to the entire LSR watershed would reduce nutrient loading from the LSR to the Assiniboine River by 992 to 9,892 kg/yr (3.4-34.1%) for TP and 5,334 to 53,163 kg/yr (1.9-18.9%) for TN (Table 19).

Table 19. Nutrient loading reductions in the Little Saskatchewan River watershed under various wetland restoration scenarios

Scenario	a_j	Broughton's TP Loading Reduction (kg/yr)	Broughton's TN Loading Reduction (kg/yr)	Broughton's TP Load Reduction in LSR (%)	Broughton's TN Reduction in LSR (%)	TP Load Reduction in LSR (%)	TN Load Reduction in LSR (%)
I	0.10	79	423	0.3	0.2	3.4	1.9
II	0.25	196	1,054	0.7	0.4	8.5	4.7
III	0.50	392	2,108	1.4	0.8	17.0	9.5
IV	0.75	588	3,162	2.0	1.1	25.6	14.2
V	0.90	707	3,799	2.4	1.4	30.7	17.0
VI	1.00	785	4,219	2.7	1.5	34.1	18.9

Note: Under existing condition pollution loads from the Little Saskatchewan River (LSR) to the Assiniboine river are TP 29 T/year and TN 281 T/year. The Broughton's Creek watershed has 25,139 ha while the LSR watershed has 317,701 ha. The TP and TN load reduction in the LSR watershed is calculated by multiplying the rates in the Broughton's Creek watershed by 12.6, assuming that all other portions of the LSR watershed will have the same wetland restoration rates and water quality impacts as the Broughton's Creek watershed.

vii

conclusions

This study set up a SWAT model for the Broughton's Creek watershed, with the wetlands lumped into the HEWs on the subbasin basis. In accordance with the daily streamflows transferred from the observed data on daily streamflows at the Oak River at Shoal Lake (05MG008) from 31 March 1990 to 31 May 1994, the model was judged to have a very good simulation performance. The model captured the rising and recessing patterns exhibited by the computed daily streamflows, and the simulated annual average streamflow closely matches the corresponding computed value.

In addition, this study evaluated six uniform wetland restoration scenarios, which have coefficients of restoration level α from 0.1 to 1.0 (or 10% to 100% wetland restoration). 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%. Further, based on the peak reduction efficiency and sediment reduction efficiency, scenarios with α value of 0.5 to 0.8 (i.e., 50% to 80% wetland restoration) can be judged to be cost-effective in terms of benefit to wetland acreage ratios.

With full restoration, the wetland drainage area increases from 47.4% (11,906 ha) to 59.7% (15,009 ha) of the watershed area, while the stream drainage area decreases from 52.6% (13,233 ha) to 40.3% (10,130 ha) of the watershed area. Based on the wetland and stream drainage areas estimated by the modelling system and nutrient export coefficients from the literature, we estimated water quality benefits from wetland conservation and restoration in the Broughton's Creek watershed. The results indicated that these scenarios could remove TP and TN by 79 to 785 kg/yr and 423 to 4,219 kg/yr respectively, which are each equivalent to 2.4% to 23.4% of the TP or TN yield under the existing conditions. If we assume that other watersheds in the Little Saskatchewan (LSR) River watershed have a similar wetland-watershed acreage ratio, the wetland conservation and restoration within the LSR watershed will probably be able to reduce 3.4% to 34.1% of the existing TP yield and 1.9% to 18.9% of the existing TN yield. This will greatly benefit the ongoing efforts to alleviate the eutrophication of the Lake Winnipeg.

references

Arnold, J. G., P. M. Allen, and G. Bernhardt. 1993. A comprehensive surface-groundwater flow model. *J. Hydrol*. 142: 47-69.

Bengtson, M.L., and G. Padmanabhan. 1999. Hydrologic model for assessing the influence of wetlands on flood hydrographs in the Red River Basin development and application. A Report to the International Joint Commission Red River Task Force, North Dakota State Water Commission, and Minnesota Department of Natural Resources Division of Waters. Fargo, ND: North Dakota Water Resources Research Institute, North Dakota State University.

Bingner, R. L. 1996. Runoff simulated from Goodwin Creek watershed using SWAT. *Trans. ASAE* 39(1): 85-90.

Bourne, A., N. Armstrong, and G. Jones. 2002. A preliminary estimate of total nitrogen and total phosphorus loading to streams in Manitoba, Canada. Water Quality Management section. Manitoba Conservation Report No. 2002-04.

Chu, T. W., and A. Shirmohammadi. 2004. Evaluation of the SWAT model's hydrology component in the Piedmont physiographic region of Maryland. *Trans. ASAE* 47(4): 1057-1073.

Dahl, T.E. 1990. Wetlands losses in the United States, 1780s to 1980s. Washington D.C.: Department of the Interior, Fish and Wildlife Service, 13pp. Available at: http://www.npwrc.usgs.gov/resource/wetlands/wetloss/wetloss.htm.

Dahl, T.E. 2000. Status and trends of wetlands in the conterminous United States, 1986 to 1997. Washington D.C.: Department of the Interior, 82pp. Available at: http://www.npwrc.usgs.gov/resource/wetlands/wetloss/wetloss.htm.

Dahl, T.E., and G.E. Johnson. 1991. Status and trends of wetlands in the conterminous United States, mid-1970s to mid-1980s. Washington D.C.: Department of the Interior, Fish and Wildlife Service, 28pp. Available at: http://www.npwrc.usgs.gov/resource/wetlands/wetloss/wetloss.htm.

De Laney, T.A. 1995. Benefits to downstream flood attenuation and water quality as a result of constructed wetlands in agricultural landscapes. *J. Soil and Water Conservation* 50(6): 620-626.

Du, B., J.G. Arnold, A. Saleh, and D.B. Jaynes. 2005. Development and application of SWAT to landscapes with tiles and potholes. *Trans. ASAE* 48(3): 1121 – 1133.

DUC (Ducks Unlimited Canada). 2007. DUC – Dedicated to Wetland and Wildlife Conservation. Available at http://www.ducks.ca/conserve/index.html, Accessed on December 24, 2007.

Gitau, M. W., W. J. Gburek, and A. R. Jarrett. 2002. Estimating best management practice effects on water quality in the Town Brook watershed, New York. In *Proc. Interagency Federal Modeling Meeting Las Vegas*, 2: 1–12. The United States Department of Agriculture, Agricultural Research Service.

Gleason, R.A., and N.H. Euliss, Jr. 1998. Sedimentation of prairie wetlands. *Great Plains Res*. 8(1): 97-112.

Hart, R.A. 1995. Mussel (bivalvia: unionidae) habitat suitability criteria for the Otter Tail River, Minnesota. MS Thesis. Fargo, ND: North Dakota State University, Department of Agriculture and Applied Science.

Hayashi, M., W.L. Quinton, A. Pietroniro, and J.J. Gibson. 2004. Hydrologic functions of wetlands in a discontinuous permafrost basin indicated by isotopic and chemical signatures. *J. Hydrol*. 296: 81-97.

Hydrologic Engineering Center (HEC), U.S. Army Corps of Engineers. 1998. HEC-1 Flood Hydrograph Package; User's Manual. (Computer program manual). U.S. Army Corps of Engineers, Hydrologic Engineering Center, Davis, CA.

Kadlec, R.H., and R.L. Knight. 1996. *Treatment Wetlands.* Boca Raton, FL: Lewis Publishers.

Kroeger, A.C., C. A. Madramootoo, P. Enright, C. Laflamme 2007. Efficiency of a small constructed wetland in southern Québec for treatment of agricultural runoff water. In conference proceedings "Wastewater Biosolids Sustainability: Technical, Managerial, and Public Synergy", June 24-27, 2007, Moncton, New Brunswick, Canada, pp. 1057-1062.

Leavesley, G.H., and L.G. Stannard. 1995. The precipitation-runoff modeling system – PRMS. In *Computer Models of Watershed Hydrology: Water Resources Publications*, 281-310. V.P. Singh, ed. Highlands Ranch, CO.

Leavesley, G.H., S.L. Markstrom, P.J. Restrepo, and R.J. Viger. 2002. A modular approach to addressing model design, scale, and parameter estimation issues in distributed hydrological modeling. *Hydrol. Process.* 16(2): 173-187.

LSRCD (Little Saskatchewan River Conservation District). 2005. Sustainable Communities Initiative Final Project Report.

Mitsch, W.J., and J.G. Gosselink. 1993. *Wetlands*. New York, NY: John Wiley & Sons.

Napier, T.L., S.E. McCarter, and J.R. McCarter. 1995. Willingness of Ohio land owner-operators to participate in a wetlands trading system. *J. Soil and water Conservation* 50(6): 648-656.

National Research Council. 1995. *Wetlands, Characteristics, and Boundaries*. Washington D.C.: National Academy Press.

Padmanabhan, G., and M.L. Bengtson. 2001. Assessing the influence of wetlands on flooding. In *Proc. Wetlands Engineering & River Restoration 2001.* Reno, NV.

Peterson, J. R., and J. M. Hamlett. 1998. Hydrologic calibration of the SWAT model in a watershed containing fragipan soils. *J. AWRA* 34(3): 531-544.

Quinton, W.L., M. Hayashi, and A. Pietroniro. 2003. Connectivity and storage functions of channel fens and flat bogs in northern basins. *Hydrol. Process.* 17: 3665-3684.

Rosenthal, W. D., R. Srinivasan, and J. G. Arnold. 1995. Alternative river management using a linked GIS-hydrology model. *Trans. ASAE* 38(3): 783-790.

SCS. 1981. Flood hazard analyses: Maple River in Cass and Ransom counties. Washington D.C.: U.S. Department of Agriculture, Soil Conservation Service.

Sophocleous, M. A., J. K. Koelliker, R. S. Govindaraju, T. Birdie, S. R. Ramireddygari, and S. P. Perkins. 1999. Integrated numerical modeling for basin-wide water management: The case of the Rattlesnake Creek basin in south-central Kansas. *J. Hydrol.* 214: 179-196.

Spruill, C. A., S. R. Workman, and J. L. Taraba. 2000. Simulation of daily and monthly stream discharge from small watersheds using the SWAT model. *Trans. ASAE* 43(6): 1431-1439.

Srinivasan, R., and J. G. Arnold. 1994. Integration of a basin-scale water quality model with GIS. *Water Res. Bull.* 30(3): 453-462.

Tammi, C.E. 1994. Onsite identification and delineation of wetlands. In *Applied Wetlands Science and Technology* (2nd ed.), 35-54. D.M. Kent ed. Boca Raton, FL: Lewis Publishers.

Tweedy, K.L., and R.O. Evans. 2003. Hydrologic characterization of two prior converted wetland restoration sites in eastern North Carolina. *Trans. ASAE* 44(5): 1135-1142.

USBR, 1999. Pilot project: Wetlands inventory and drained wetlands water storage capacity estimation for the St. Joe-Calio Coulee subbasin of the greater Devils Lake Basin, North Dakota. Bureau of Reclamation Technical Memorandum No. 8260-99-02. Washington D.C.: Department of Interior.

USDA-NRCS. 2007. Wetland Reserve Program. Available at http://policy.nrcs.usda.gov/ViewerFS.aspx?id=2192, Accessed on August 19, 2007.

Van Liew, M. W., and J. Garbrecht. 2003. Hydrologic simulation of the Little Washita River experimental watershed using SWAT. *J. AWRA* 39(2): 413-426.

Vazquez-Amábile, G.G. and B.A. Engel. 2005. Use of SWAT to compute groundwater table depth and streamflow in the Muscatatuck River watershed. *Trans. ASAE* 48(3): 991 – 1003.

Vining, K.C. 2002. Simulation of streamflow and wetland storage, Starkweather Coulee Subbasin, North Dakota, water years 1981-98. Water-Resources Investigations Report 02-4113. Washington D.C.: Department of the Interior and U.S. Geological Survey.

Wang, X. and A. M. Melesse 2005. Evaluation of the SWAT Model's Snowmelt Hydrology in a Northwestern Minnesota Watershed. *Trans. ASAE* 48(4): 1359-1376.

Wang, X., A.M. Melesse, and W. Yang. 2006. Influences of potential evapotranspiration estimation methods on SWAT's hydrologic simulation in a northwestern Minnesota watershed. *Trans. ASAE* 49(6): 1755 – 1771.

Wang, X., W. Yang, and A.M. Melesse. 2008. Using hydrologic equivalent wetland concept within SWAT to estimate streamflow in watersheds with numerous wetlands. *Trans. ASAE* 51(1): 55-72.

Weber, A., N. Fohrer, and D. Moller. 2001. Long-term land use changes in a mesoscale watershed due to socio-economic factors: Effects on landscape structures and functions. *Ecological Modeling* 140: 125-140.

WSRCD (West Souris River Conservation District). 2005. *Sustainable Communities Initiative*. Winnipeg, Manitoba: Final Project Report.

appendix A: a documentation of HEW setup in SWAT

A HEW is defined to have equivalent hydrologic functions with its component, real wetlands on a subbasin basis. The subbasin data layer (Figure 3), generated using the AvSWAT GIS interface, was overlaid with the 2005 wetland data layer (Figure 2c), provided by DUC, to delineate the wetlands within each subbasin. For each subbasin, the total area of the inclusive wetlands was calculated and taken as the area of the corresponding HEW. The results from this calculation are shown in Figure A.1.

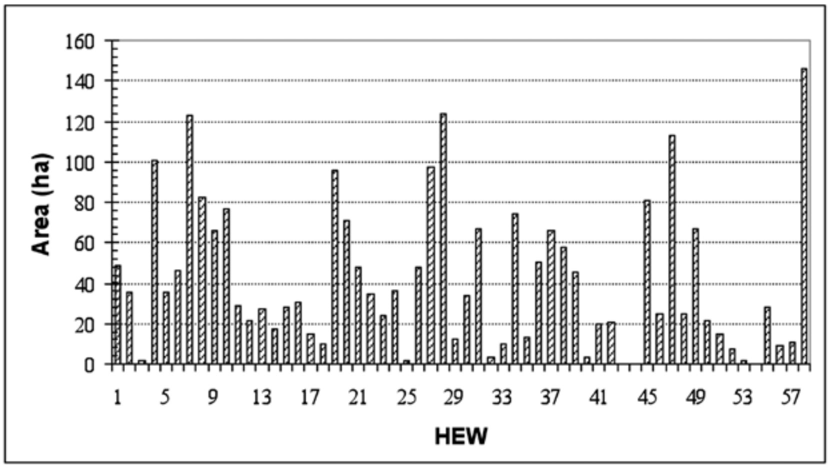


Figure A.1. Plot showing areas of the hydrologic equivalent wetlands (HEWs)

A regression analysis of the data provided by DUC indicated that for a wetland, its storage volume is approximately linearly correlated with its surface area (Figure A.2). The relationship can be expressed as:

$$V = 9653.5 \cdot A_s \qquad \text{(A1)}$$

Using Equation (A1) and the areas shown in Figure A.1, the volumes for the HEWs were calculated and are shown in Figure A.3.

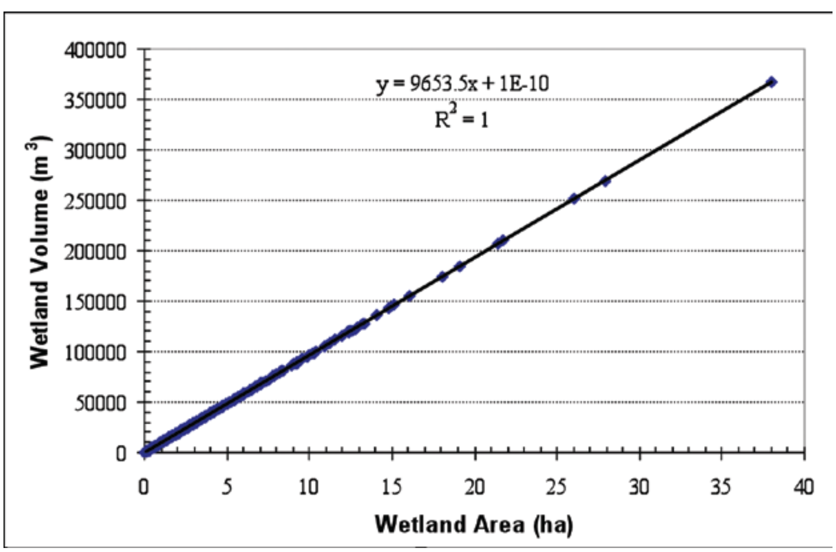


Figure A.2. Plot showing the approximately linear relationship between wetland storage volume and surface area

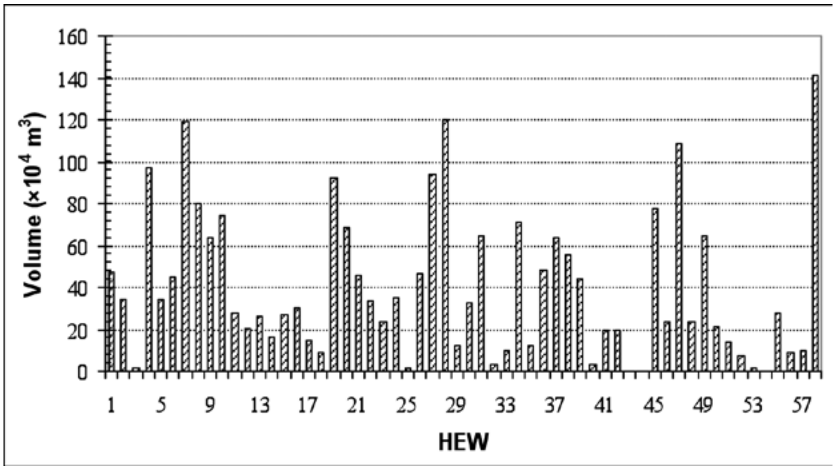


Figure A.3. Plot showing volumes of the hydrologic equivalent wetlands (HEWs)

Assuming that most of the wetlands are not controlled by hydraulic structures, we took the areas shown in Figure A.1 as the values for the two parameters of WET_NSA (Surface area of wetlands at normal water level) and WET_NOVL (Volume of water stored in wetlands when filed to normal water level). Similarly, the areas shown in Figure A.1 and Figure A.3 were taken as the values for another two parameters of WET_MXSA (Surface area of wetlands at maximum water level) and WET_MXVOL (Volume of water stored in wetlands when filed to maximum water level). For long-term simulations, the initial storages in the HEWs would not affect the results and thus were taken as zero. The parameter WET_K, the hydraulic conductivity of bottom of wetlands, was empirically specified as 0.5 mm/hr.

The parameter of WET_FR (Fraction of subbasin area that drains into wetlands) was taken as a calibration parameter. This parameter was empirically adjusted to have values shown in Figure A.4. The adjustment was to make reasonable the predicted streamflows and sediment loadings at the watershed outlet.

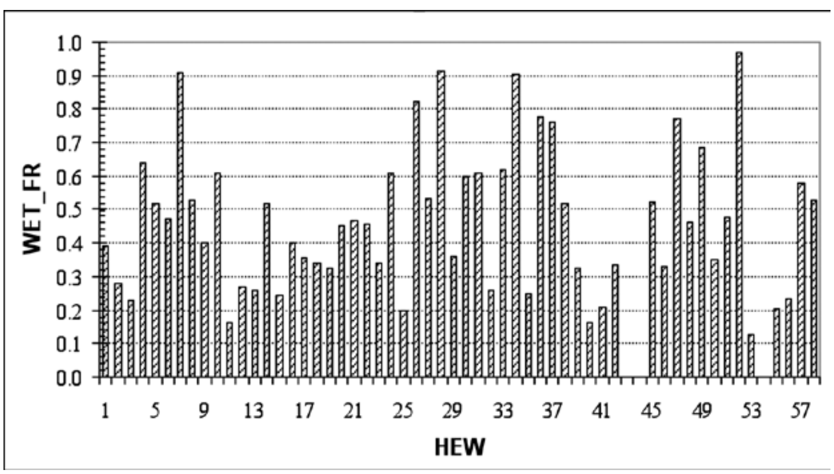


Figure A.4. Plot showing the fraction of a subbasin area, WET_FR, drained into its hydrologic equivalent wetland (HEW)

For the Broughton's Creek watershed, two subbasins (Subbasins 43 and 44) were determined to have no wetland, whereas, for each of the other 56 subbasins, one HEW was defined. The parameters for these HEWs were determined to have values shown in Figures A.1, A.3 and A.4. WET_FR was an important calibration parameter. At this stage, because observed data on streamflows and sediment were unavailable at the outlet or within the watershed, this parameter was empirically adjusted. When observed data are available in the future, the values for this parameter should be fine-tuned.

appendix B: a summary of literature review on N and P removal rates of wetlands

Table B.1. P budget and site information for various natural, restored, and constructed wetlands

Location	Wetland type [1] /soil type	Size (ha)	Drainage area (ha)	Year of data	Number of samples	Inlet and outlet concentration (mg/L)	Loading and Removal rate ($g/m^2/yr$)	Removal efficiency – conc./ loading (%)
Everglades Water Conservation Area (Richardson and Craft, 1993)	R/peat	350,000		1989	15 (sediment cores)	NA	0.40 (removal)	-
Frank Lake, northern prairie wetland (White et al. 2000)	R/mineral	1,246	34,200	1995	19 (sediment cores)	NA	24-38.5 (removal)	-
Constructed wetlands in cold temperate regions – Sweden, Norway, Finland, Switzerland, USA (Braskerud et al. 2005)	C/mostly mineral	0.03 - 1	5 - 929	1993 - 2004	17 constructed wetlands with intensive sampling	NA	0.7 - 307 (loading) 0.2 - 156 (removal)	1 - 88 (TP) -19 - 89 (DRP)
Norway (Braskerud 2002)	C/mineral	0.03 - 0.09	22 - 148	1992 - 1999	6 constructed wetlands with intensive sampling	0.17 - 0.43 (in) 0.10 - 0.27 (out)	97 - 191 (loading) 26 - 71 (removal)	21 - 44 (TP)
Everglades Water Conservation Area (Richardson et al. 1997)	R/peat	350,000		1989	15 (sediment cores)	NA	0.44 - 1.00 (removal)	-
Illinois, riparian marshes (Mitsch et al. 1995)	C/mineral	1.9 - 3.4	34 - 104 (low flow) 120 - 424 (high flow)	1990 - 1992	4 constructed riparian marshes with intensive sampling		0.46 - 2.08 (loading-low flow) 0.41 - 1.73 (removal-low flow) 1.68 - 4.01 (loading-high flow) 1.37 - 2.86 (removal-high flow)	81 - 99 (low flow) 53 - 96 (high flow)
North Carolina, estuarine marshes (Craft 1997)	N&C	0.2 - 5.0		1983 - 1985	4 constructed and 4 natural estuarine marshes	NA	1-2 (removal in natural wetlands) 3-30 (removal in restored wetlands during first 3 years, depending on loading)	-
Southern Québec, constructed wetland (Kroeger et al. 2007)	C	0.12		2003 - 2006	1 constructed wetland intensively monitored for 4 years (flow and chemistry)	0.078 (in - mean over 4 year operation) 0.052 (out - mean over 4 year operation)	5.0 (loading) 1.7 (removal)	34

N = Natural, R = Restored, C = Constructed

Table B.2. N budget and site information for various natural, restored, and constructed wetlands

Location	Wetland type [1] /soil type	Size (ha)	Drainage area (ha)	Year of data	Number of samples	Inlet and outlet concentration (mg/L)	Loading and Removal rate (g/m²/yr)	Removal efficiency – conc./ loading (%)
Everglades Water Conservation Area (Richardson and Craft, 1993)	R/peat	350,000		1989	15 (sediment cores)	NA	13.5	-
North Carolina, estuarine marshes (Craft 1997)	N&C	0.2 - 5.0		1983 - 1985	4 constructed and 4 natural estuarine marshes	NA	5-10 (removal in natural and constructed wetlands) >60 (removal in wetlands receiving high nitrogen loading)	-
Southern Québec, constructed wetland (Kroeger et al. 2007)	C	0.12		2003 - 2006	1 constructed wetland intensively monitored for 4 years (flow and chemistry)	3.4 (in [NO3] - mean over 4 year operation) 2.8 (out [NO3] - mean over 4 year operation)	258.9 (loading) 49.2 (removal)	19

N = Natural, R = Restored, C = Constructed

LEAD FUNDING FOR THE RESEARCH WAS PROVIDED BY **THE MURPHY FOUNDATION**.

Ducks Unlimited Canada
Conserving Canada's Wetlands

Ducks Unlimited Canada conserves, restores and manages wetlands and associated habitats for North America's waterfowl. These habitats also benefit other wildlife and people.

National Office
Oak Hammock Marsh Conservation Centre
P.O. Box 1160, Stonewall MB
R0C 2Z0

Tel:	1-204-467-3000
Toll-free:	1-800-665-3825
Fax:	1-204-467-9028
Email:	webfoot@ducks.ca

www.ducks.ca