Journal of Civil Engineering (IEB), 45 (1) (2017) 19-40

Journal of Civil Engineering IEB

Role of goodwood marsh in basin hydrology

Ferdous Ahmed

Rideau Valley Conservation Authority
3889 Rideau Valley Drive, Manotick, Ontario, Canada K4M 1A5

Received 12 July 2016

Abstract

The role of wetlands on basin hydrology has been investigated for a small Canadian basin using the Mike11/NAM model of Danish Hydraulic Institute (DHI). The Franktown basin has an area of 99.72 km^2, 36% of which consists of wetlands of various size and shape, with Goodwood Marsh being the largest. The methodology involved long term continuous simulation of the basin with and without the wetlands. The water budget of this basin is significantly influenced by the presence of wetlands. On an annual basis, wetlands slightly reduce the total runoff and increase the evapotranspiration (by about 2%). Overland flow decreases 45% and base flow increases by 28% due to wetland presence. Groundwater recharge also increases by 28%. During individual runoff events, wetlands reduce both total runoff and overland flow by about 30-50% in terms of peak and volume. Wetlands also increase both the groundwater recharge and base flow by about 30-50% during individual runoff events. Flood peaks are attenuated by about 20%. The 1:100 year flood under current conditions would become a 1:15 year flood if wetlands were removed. We hope that this kind of site-specific technical analysis would be useful to decision making related to wetland functions and values.

Keywords: Wetland hydrology, goodwood marsh, wetland function, water budget, rideau valley, hydrologic modelling, mike11, runoff, flood, base flow, ground water recharge.

1. Introduction

A number of beneficial functions – such as flood attenuation, higher recharge, better water quality, greater biodiversity, etc. – have traditionally and intuitively been attributed to wetlands, although their quantification has proved difficult, if not impossible. Common hydrological functions of wetland include flood attenuation, groundwater recharge, low flow modification and base flow sustenance. As discussed by (Ahmed 2014), such intuitive arguments are routinely challenged in the real world, and opposing parties frequently want “proof” of any statement made by others regarding the role of wetlands. In other words, stakeholders now want more than “conventional wisdom”; they want scientific facts, measurable data, and thorough analyses. As a result, policy makers want to see site-specific studies – information that is quantifiable and verifiable, rather than vague generalities; it is also required that the analyses be presented in a way that is understandable to non-specialists, easily translatable into policy formulations, simple enough for effective communication, and conducive to conflict resolution.

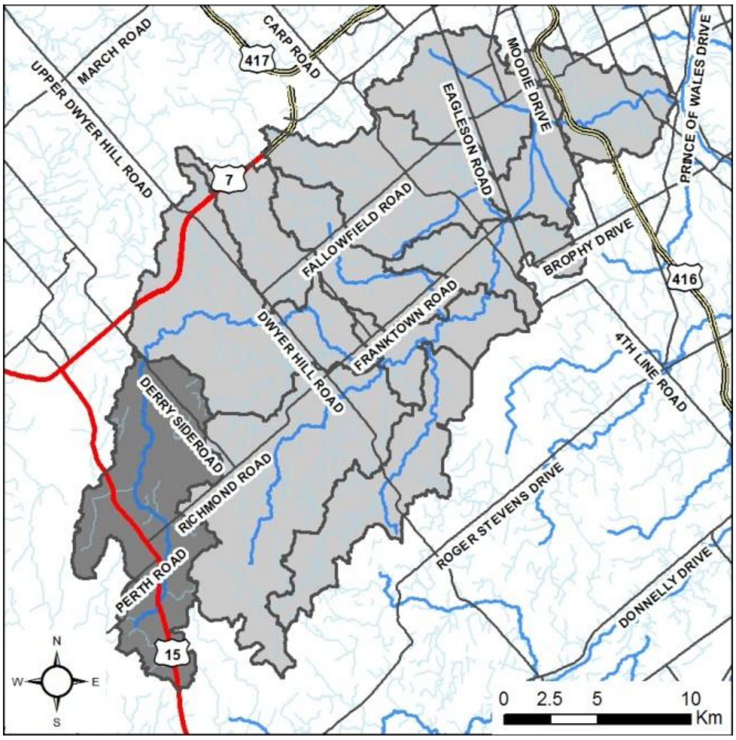


Fig. 1. Jock River sub watershed; Jock River is flowing northeast to the Rideau River; Franktown basin containing Goodwood Marsh is located in the headwaters of the Jock River; a Mike11 model was built for the whole Jock sub watershed.

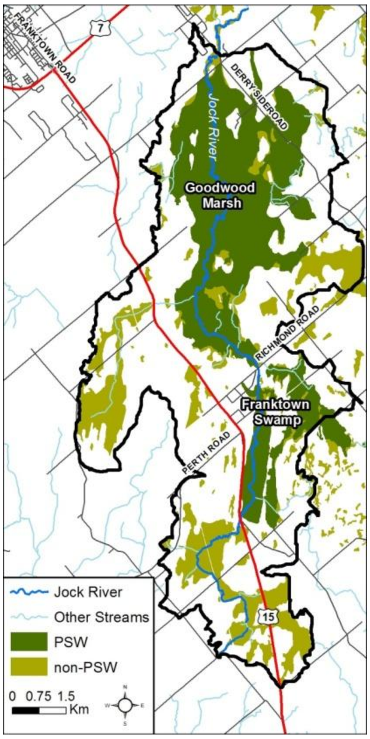


Fig. 2. Franktown basin; provincially significant wetlands (PSW) and non-PSW cover about 36% of basin area; Goodwood Marsh and Franktown Swamp constitute bulk of the wetlands.

(RVCA 2009) undertook a study to discern and quantify the hydrologic functions of wetlands within the context of Rideau River watershed, using an integrated hydrologic and hydraulic model (Mike11 of the Danish Hydraulic Institute). Continuation of that work is presented here.

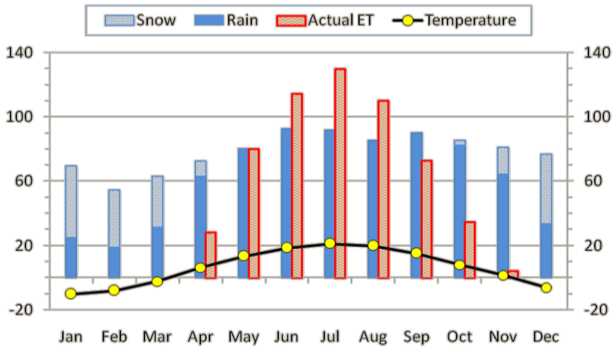


Fig. 3. Climate normal at Ottawa Airport; rainfall (mm), snow water equivalent (mm) and temperature (degree C) based on 1980-2009 data from Environment Canada; actual evapotranspiration (mm) based on the calculations of MRSWP (2011) for 1974-2003.

In this and a companion paper (Ahmed 2015a), we present the results of a numerical investigation into the role of wetlands in basin hydrology (Goodwood Marsh) and river hydraulics (Black Creek), respectively, both situated within the Rideau Valley watershed. This study is based on watershed modeling using the Mike11 platform of (DHI 2001, 2003, 2004), which was reported earlier (RVCA 2007 a; Ahmed 2010). The specific methodology used to discern and quantify wetland functions has previously been described in detail elsewhere (RVCA 2009; Ahmed 2014).

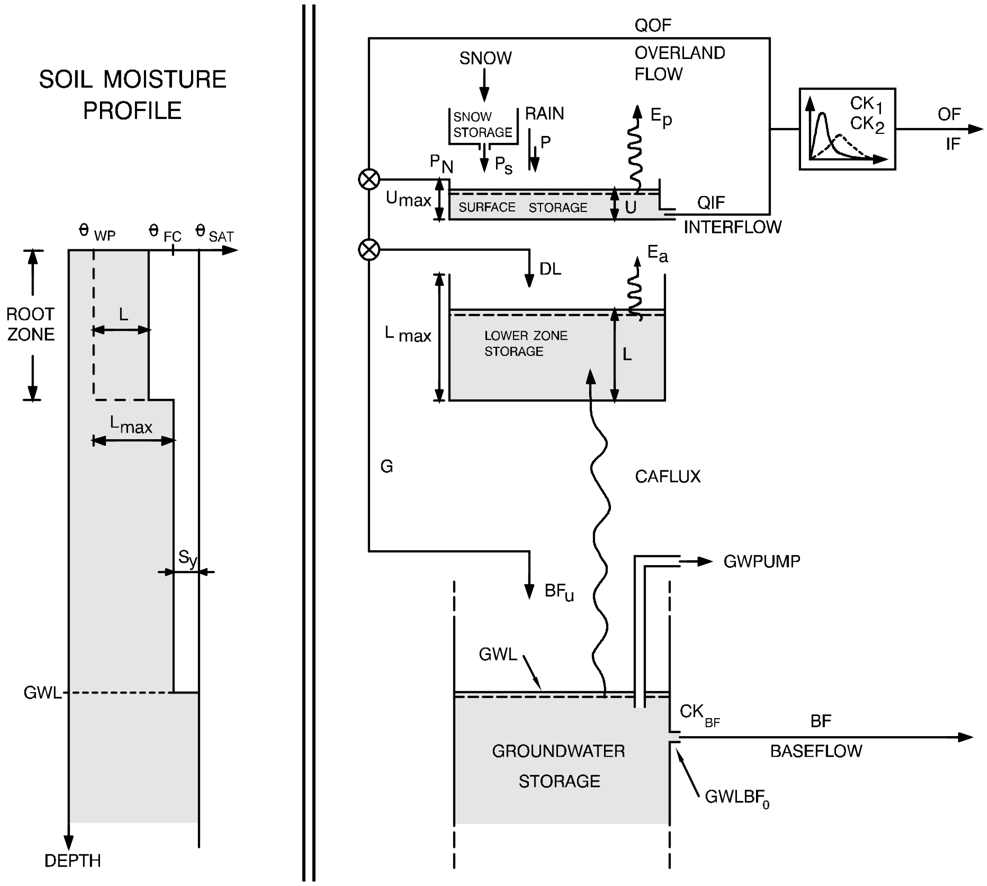


Fig. 4 Structure of the rainfall runoff (NAM) module of Mike11 (after DHI 2004);this is a lumped model based on the physical structures and known equations along with semi-empirical relationships; parameter values represent average values for the entire catchment; some of the parameters can be estimated from physical properties of the catchment, but final values are usually determined via calibration; the water balance components analyzed in this study are: evapotranspiration, total runoff, overland flow, interflow, groundwater recharge and base flow.

Based on published research (described in the next section), it appears that wetland functions could be profitably investigated and quantified by using integrated hydrological models. Difficulties exist in hydrometric measurement, which would keep the study of wetlands by using measured data rather limited for the time being. Therefore, numerical modeling offers a feasible – and perhaps preferred – way of studying wetland hydrology.

Such a modeling study is presented here. Out of the four main hydrological functions of wetlands, (flood attenuation, low flow modification, groundwater recharge, and base flow sustenance), (RVCA 2009) studied the flood attenuation and low flow modification at the watershed scale (an area of about 4000 km^2). Here we look at the entire water budget process, but at a local basin scale (area < 100 km2), and also conduct a water budget analysis based on simulated hydrologic quantities. Runoff, overland flow, evapotranspiration, groundwater recharge, base flow as well as floods are investigated here.

2. Literature review

Review of existing literature indicates that, while a qualitative understanding of wetland functions is more or less agreed upon, quantification of specific functions remain largely unstudied (Bullock and Acreman 2003; Price and Waddington 2000; Price et al. 2005; Fisher and Acreman 2004). This can and usually does lead to disputes on the magnitude of wetlands' hydrologic functions, if not their very existence. This lack of quantification of wetland function is a gap that we hope to fill.

The hydrology of a wetland, i.e. the occurrence and movement of water within it, creates unique physiochemical conditions that make wetland ecosystem different from well-drained and deep-water aquatic systems. Water depth, flow patterns, and the duration and frequency of flooding, which results from the hydrologic inputs and outputs, influence the biochemistry of the soils and are the major factors in the ultimate selection and sustenance of wetlands. Hydrology is therefore often described as the single most important determinant of the establishment and maintenance of specific types of wetlands and wetland process (Mitsch and Gosselink 2007). The intimate connection of wetland hydrology to the physical, chemical and biological features is now an established fact (Trochlell and Bernthal 1998).

The exhaustive review of 169 studies on wetland hydrology by (Bullock and Acreman 2003) led to the conclusion that most, but not all, studies (23 of 28) show that floodplain wetlands reduce or delay floods; the same conclusion applies to headwater wetlands, but less conclusively (30 out of 66). Two thirds of the studies indicate that wetlands increase evaporation. More than 80% of the studies indicated that wetlands influence some or all components of the water budget. In view of the complexity of wetland systems and sometimes contradictory findings of various studies, generalized and simplified statements of wetland functions are discouraged. In another review of 57 studies, (Fisher and Acreman 2004) found that in about 80% of the cases, wetlands exhibit significant nutrient retention function. The retention process is complex involving enhanced sedimentation, sorption of nutrients to sediment particles, plant uptake of nutrients, and de nitrification. Not surprisingly, phosphorous and nitrogen, the main two nutrients, undergo different degrees of retention by the same wetlands under the same hydrologic condition.

Although hydrological regime of a wetland, whose slight change may result in significant alteration of wetland ecology, has been recognized as a key factor in characterizing wetlands, the actual job of studying it is by no means easy. (Acreman and Miller 2006) proposed a hydrological impact assessment approach for wetlands based basically on estimating various components of the water budget equation starting from a conceptual understanding of the hydrology of the wetland in question. They pointed out that "It is not possible to measure any rates of water transfer exactly, and thus it is inevitable that quantification of the water balance will not be precise. Although uncertainty is often perceived as a negative issue (often associated in people's minds with user error), it is a fact of life, especially when dealing with natural systems, and should be presented explicitly rather than hidden. Where possible, the uncertainty (or level of confidence) associated with any water transfer mechanism should be estimated. Future efforts can then be focused on the better measurement of the most uncertain mechanisms. One approach to the estimation of uncertainty is to quantify the rate of flow in each water transfer mechanism using various different methods. The range in results generated using different methods helps define the certainty with which the water transfer mechanism has been defined." Obviously, the major difficulty in understanding wetland hydrology is associated with various water budget components, some of which such a groundwater recharge are very difficult to measure if not impossible. Estimating uncertainties, which is important due to the wide variation in magnitude of different water budget components, is an addition challenge. As a result, indirect estimation or modeling is what many researchers turn to. (Gaska-Tucker et al. 2007) made direct measurements of evapotranspiration from a wet grassland (a particular type of wetland in the UK) and found that the actual evapotranspiration was actually higher than the potential evapotranspiration calculated by standard methods (presumably the upper limit). The applicability of standard methods in wetland environment is limited by the fact that they preclude the effect of soil saturation, a common feature of wetland hydrology. An estimation error in evapotranspiration, usually the largest component in the water budget equation, can obviously mask the smaller components and skew the hydrological picture. It follows that we have to be extra careful in deploying the standard measurement and calculation tools, and verify that the tools are appropriate.

Functions and values of individual wetlands is important and have been studied by many researchers (Bullock and Acreman 2003; Price and Waddington 2000; Price et al. 2005; and references therein). However, wetland clusters within a watershed or “wetland complexes”, whose combined effect can transcend individual wetlands’ values, have not received much attention. Wetland impacts that may seem minor when considered individually may become major if considered collectively over time and space (Trochlell and Bernthal 1998). This is an area where a gap in research is apparent. The (RVCA 2009) study was an attempt to understand the cumulative effects of many wetlands within a watershed context. Using stream flow records from 30 gagging stations monitoring watersheds in Illinois with variable wetland areas, (Demissie and Khan 1993) used regression analysis to assess the influence of wetlands on stream flow. They concluded that peak flood flows and flood volumes decrease and low flow increases with increasing percentage of wetlands in the watershed. The influence of wetlands was more noticeable on peak flow and low flow than on flood volume. For all the gagging stations analyzed, the peak flow to average precipitation ratio decreased on the average by 3.7%, flood volume to total precipitation ratio decreased by 1.4%, and low flow (represented by Q95) increased by 7.9% for an increase of one percent wetland area in a watershed. There were, however, significant regional and seasonal differences in the rate of change.

Since experiments involving elimination or creation of wetlands are impractical, study of wetland functions does of necessity involve some kind of calculation of water movement. Simple water budget calculation is most common, although usually done at crude spatial and temporal scales. Distributed hydrological modeling, increasingly detailed and user friendly now-a-days, offers hope in investigating wetland functions in a more rigorous fashion (as rigorously as possible in the less than perfectly understood world of hydrological sciences).

Several commercially available models, such as Mike11 of DHI used in this study, can simulate basin hydrology, river hydrodynamics, structure operation and pollutant transport in an integrated fashion. This enables the simulation of the whole system to the extent permitted by the model’s ability to represent various physical processes. Use of GIS-based data in digital format, user friendly graphical interface, and efficient input/output visualization allows virtually as fine discretization as desired. Complex hydrological systems, including those involving wetlands, can be simulated using such integrated modeling platforms. Such models, once calibrated and validated (to the extent possible), can then be used to investigate specific aspects of a system, discern and isolate functions of specific system components, and to probe ‘what if’ scenarios.

Many models with different degrees of complexity – from HEC-1, HEC-HMS, HEC-RAS and SWMM to HSPF, Mike11 and Mike SHE – have been used to simulate and analyze wetlands. Here we confine our discussion to a few applications of the Mike11/Mike SHE platform of DHI, one of the most versatile and widely used modeling platforms at this time. (Thompson et al. 2004) reported a coupled MIKESHE/MIKE 11 model built and applied toa wet grassland (the Elmley Marshes in the UK). Model results were generally consistent with observed data and reproduced the seasonal dynamics of groundwater and ditch water. The close association between flooding and both groundwater and ditch water levels was demonstrated. Topographic depressions were found to be important for the initiation of flooding and responsible for much of the shallow surface water in areas isolated from ditches. Deeper flooding was found to spread from the ditches.

This model was later used to investigate the effect of climate change on wetland hydrology (Thompson et al. 2009). Their results indicated drier conditions through the progressively higher emissions scenarios when compared to contemporary conditions; summer water tables would be lower and the duration of high winter water tables would be reduced; lower groundwater and ditch water levels would result in declines in the magnitude and duration of surface inundation. It was claimed that the changes in hydrological conditions simulated by the model were of sufficiently fine resolution to infer ecological impacts, which are likely to include the loss of some grassland species adapted to high water tables. Reductions in the extent of surface water in spring are likely to reduce suitability for wading birds including lapwing and redshank for which these marshes are internationally renowned.

(Cui et al. 2005) combined the Mike SHE hydrological model of the forests and wetlands of Gator National Park in Florida with a water quality model named Wetland-DNDC, which could simulate the biogeochemical processes and estimate greenhouse gases produced from wetlands. It was found that the water table changes had a remarkable effect on greenhouse gas fluxes. Anaerobic conditions in forested wetland soils reduce organic matter decomposition and stimulate methane production. Decrease in the water table from the wetland surface decreases methane flux, while carbon dioxide emission was lower with a rise in the water table. When there is a drop in water availability, wetlands can become a net source of atmospheric carbon dioxide as photosynthesis is decreased and respiration loss enhanced. This was an excellent example of how wetland hydrology could be related to biogeochemistry, and their mutual interdependence.

(Wen et al. 2013) built a coupled 1D/2D MIKE FLOOD floodplain hydrodynamic model of Macquarie Marshes in Australia based on high quality digital elevation data. Hydrological characteristics of key constituent wetlands – such as the correlation between water level and inundation area, relationships between stream and wetlands and among wetlands – were estimated using time series extracted from hydrodynamic simulations, which were then introduced into a separate hydrological model (IQQM) of the wetlands. The model was used to simulate the daily behavior of inflow/outflow, volume, and inundated area for key wetlands under natural conditions and recent water management practices. The modeling results revealed that the recent water management practices have induced large changes to wetland hydrology. The most noticeable changes include the dramatic reductions in high flows, areal inundation extent, and flow rising/falling rates.

3. Study area: Franktown basin and Goodwood marsh

The Franktown catchment studied here is one of the 106 within the Rideau Valley Conservation Authority delineated during the modeling of the entire RVCA watershed. It is situated in the headwaters of the Jock River (Figure 1 and 2), one of the major rivers within RVCA. It has an area of 99.72 km^2, streams totaling up to about 55 km in length, and about 36.05km^2 of wetlands (about 36% of the basin area). The Goodwood Marsh, the largest of the wetlands, covers an area of 22.51 km^2. In the present context, the combined effect of all wetlands is discussed, although for convenience, we collectively lump them together as the Goodwood Marsh. As described in a recent watershed report (RVCA 2010), the Franktown sub watershed is located within the regional Smiths Falls limestone plain; the local terrain includes areas of peat and muck, shallow exposed bedrock, glacial deposits and Champlain Sea deposits. The soil is predominantly peat and muck (51%), limestone and sandstone (41%), with minor patches of sand, gravel and clay. The climate is a typical Canadian cold one, summarized in Figure 3.

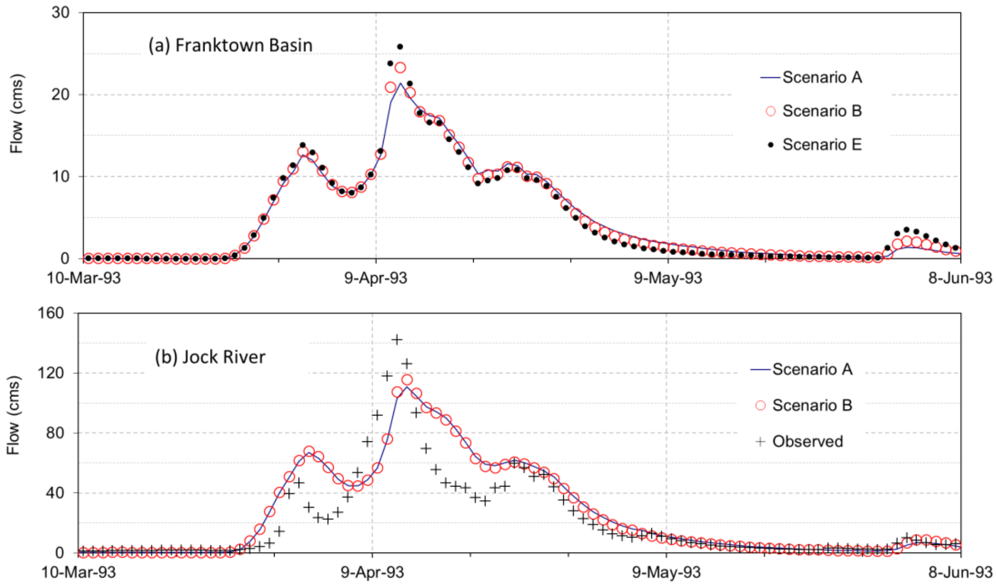


Fig. 5. Typical spring-time hydrographs at (a) Franktown basin and (b) Jock River near its outlet at Moodie Drive; Scenarios A, B and E illustrate the effect of wetland removal; the measured values indicate the ability of Mike11 model to simulate Jock basin hydrology.

The Rideau Valley Conservation Authority (RVCA) is one of the 36 watershed-based agencies in Ontario, Canada; these agencies have as their mandate the overall management of the watershed, including water resources, fisheries, forestry, ecology and land use planning. Since 2004, using the Mike11 modeling system of the Danish Hydraulic Institute (DHI 2001, 2003, 2004), a detailed model of the Rideau Valley Watershed has been constructed. It includes 532 km of rivers and lakes, 106 basins, 122 bridges and culverts, and 20 water control structures. The model was calibrated using measured stream flow data for a time period of five years; additional five years of data was used for validation. Various methods – both qualitative and quantitative – were used to evaluate the model performance. It was found that the model can simulate the hydrological response with a reasonable to high degree of accuracy. Details on the watershed characteristics and modeling are presented elsewhere (RVCA 2007a, Ahmed 2010); interested readers are referred to them for the full details. Since the overall modeling of the entire Rideau watershed, a number of smaller, more detailed models at local scale have also been built to study area-specific issues.

Modeling in RVCA was initiated with the intention of using it in its day-to-day task of watershed management as well as special, in-depth technical investigations. One such application of the model was the investigation the hydrologic impacts of wetland loss at a watershed scale, which has been reported earlier (RVCA 2009; Ahmed 2014). The present study is an extension of it, where we look at the impact of wetland functions in more detail, as permitted by Mike11's capability of simulating various components of the hydrological cycle.

About 15% of RVCA is covered by wetlands, which have been classified into three categories:

- Provincially Significant Wetland (PSW) – covering 9.0% of the watershed area – delineated and recognized by the Ministry of Natural Resources (MNR 1993) – already covered by RVCA regulations – not at risk of being lost.
- Locally Significant Wetland (LSW) – 0.7% of the watershed area – not covered by RVCA regulations – at risk of being lost.
- Non-Evaluated Wetland (NEW) – 5.3% of the watershed area – not covered by RVCA regulations – at risk of being lost.

The last two categories – LSWs and NEWs – together are usually called non-PSWs. Six percent of the watershed area is within non-PSWs. Therefore, the total wetland area within RVCA – both PSWs and Non-PSWs – is 15%. More information on wetlands within RVCA can be found in (RVCA 2007 b).

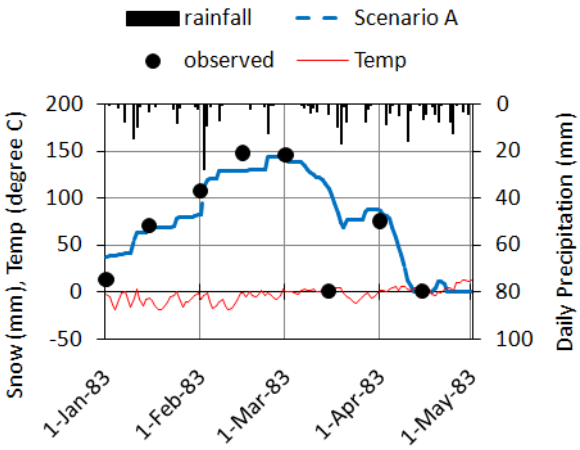


Fig. 6. Simulated snow water equivalent (SWE) of the Franktown basin; the observed values are from Ashton, some 10 km northeast from the basin center.

It is the non-PSWs that are not currently protected by RVCA regulations and are at risk of being lost (meaning being converted to other land uses, usually agricultural or urban settlement). The hydrological functions of non-PSWs, and the effect of their removal, have been previously studied (RVCA 2009; Ahmed 2014). Subsequently, the modeling was repeated to include all wetlands (both non-PSW and PSW), in recognition of the fact that the hydrologic functions of wetlands are the same irrespective of their policy-based classification. And it is important to include all wetlands to evaluate the role played by them. Using the categorization of (Bullock and Acreman 2003), most of the wetlands in RVCA can be called "surface water slope" (no hydraulic connectivity with groundwater; outlet has direct connectivity with river system) or "floodplain" (inputs are dominated by upstream river flows) type. Goodwood Marsh and associated wetlands within Franktown basin are of this type.

4. Methodology

As shown in Table 1, the overall methodology involves three modeling scenarios. Scenario A, the base condition, is essentially the Mike11 model of the entire Rideau Basin that was calibrated and validated in 2007 based on existing conditions (RVCA 2007 a). This model was run for a long time period, from December 16, 1943 to December 31, 2003, as permitted by the availability of climate data at Ottawa Airport. Since the structure (i.e. dam) operation data was not available for this entire period, it was assumed to follow the "rule curve" (defined as the targeted water level behind the dams; Acres 1994) where applicable, or a typical year's actual data elsewhere. The structure operation (SO) module of Mike11 (DHI 2001) was used for this purpose.

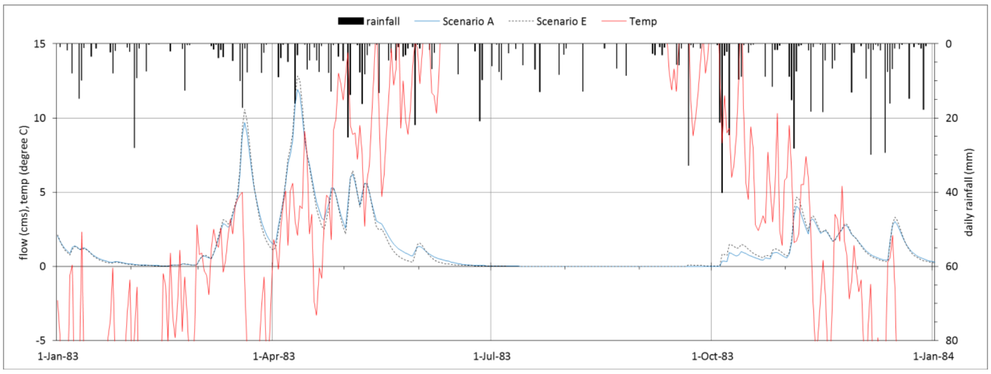
Table 1
Modeling scenarios

Model Scenario	Description	Type of analysis done	Expected results
A	- existing or baseline condition - based on RVCA's 2007 watershed model - all wetlands intact - simulation period: 1945-2003	- comparison of water budget components (runoff, evapotranspiration, overland flow, groundwater recharge, base flow) - duration curve comparison - flood frequency analysis	- comparison of A and B reveals the impacts of non-PSW removal - comparison of A and E reveals the impacts of all wetlands removal (both PSWs and non-PSWs)
B	- hypothetical condition - all PSWs intact - all non-PSWs lost - simulation period: 1940-2007		
E	- hypothetical condition - all PSWs lost - all non-PSWs lost - simulation period: 1940-2007		

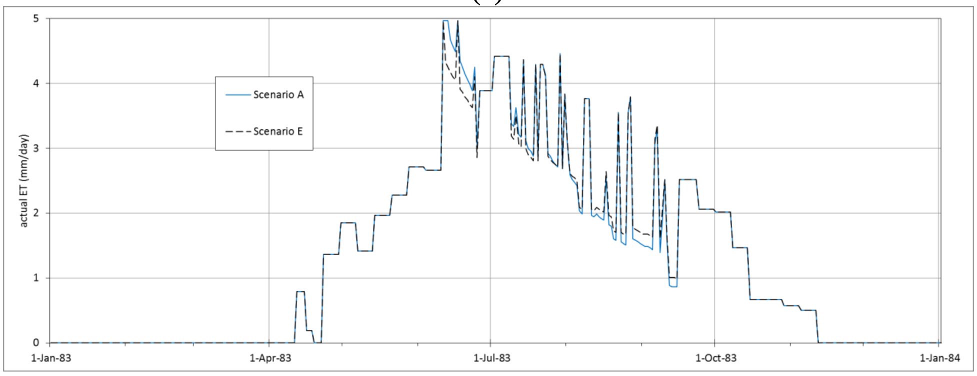
Table 2
Original (Scenario A) and changed (Scenario E) NAM parameters for basins within Jock sub watershed

Basin	Area (km^2)	Original Parameters (Scenario A)			Wetland (% of basin area)	Changed Parameters (Scenario E)		
		Umax (mm)	Lmax (mm)	CQOF (-)		Umax (mm)	Lmax (mm)	CQOF (-)
Franktown	99.72	38.50	226	0.542	36.05	24.62	307	0.933
Jock D1	89.02	38.50	260	0.540	12.99	33.50	294	0.680
Kings Creek	94.89	39.30	257	0.560	18.08	32.19	303	0.763
Nichols Creek	62.83	39.30	190	0.570	44.49	21.82	275	0.990
Hobbs Drain	33.99	39.10	295	0.550	16.00	32.84	342	0.726
Jock C1	11.04	39.50	252	0.550	10.64	35.30	279	0.667
Jock C2	3.15	39.50	139	0.550	80.24	7.80	251	0.990
Jock B1	5.82	39.20	95	0.542	86.92	5.13	178	0.990
Jock B2	4.81	39.20	234	0.542	9.57	35.45	256	0.646
Jock B3	11.36	39.50	248	0.550	28.12	28.39	318	0.859
Jock A1	17.93	39.20	239	0.570	13.14	34.05	270	0.720
Flowing Creek 1	48.53	39.20	267	0.560	6.80	36.53	285	0.636
Flowing Creek 2	3.08	39.50	214	0.560	0.00	39.50	214	0.560
Leamy Creek	5.64	39.40	207	0.550	0.00	39.40	207	0.550
Jock A2	12.02	39.50	201	0.560	0.20	39.42	201	0.562
Monahan Drain 1	27.45	39.40	227	0.550	1.26	38.90	230	0.564
Monahan Drain 2	3.45	39.30	231	0.540	0.28	39.19	232	0.543
Monahan Drain 3	11.87	39.50	212	0.540	0.00	39.50	212	0.540

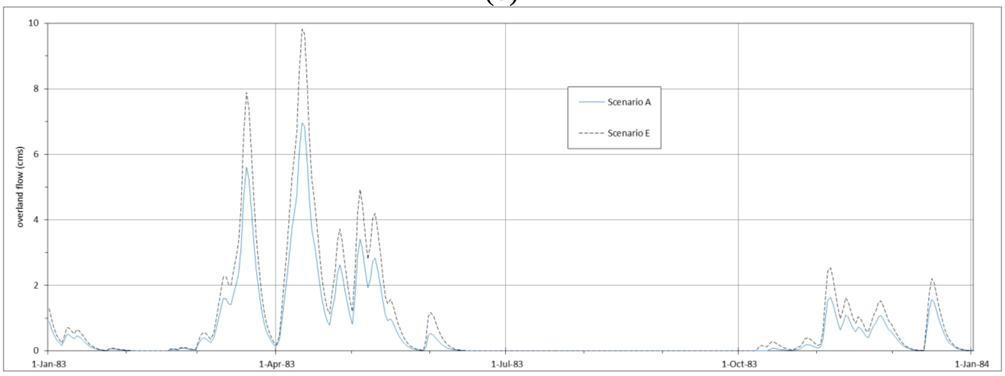
The first one year of simulation were ignored in the subsequent analysis in order to avoid the influence of initial conditions. Thus, all analyses are based on the simulated results from January 1, 1943 to December 31, 2003.Scenario A is considered to represent the existing condition – the way the watershed is now. The 59 years of simulation period is considered long enough for the statistical analyses and the inferences drawn there from. The same applies to all other scenarios, which are based on and are variations of Scenario A.



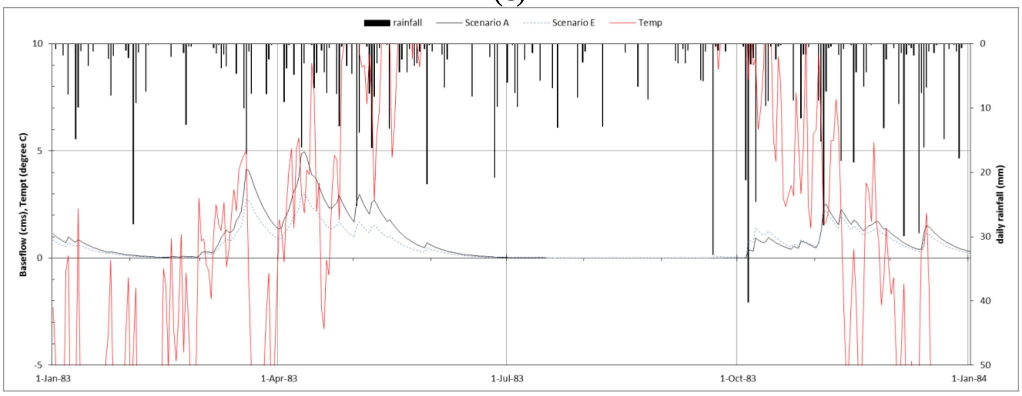
(a)



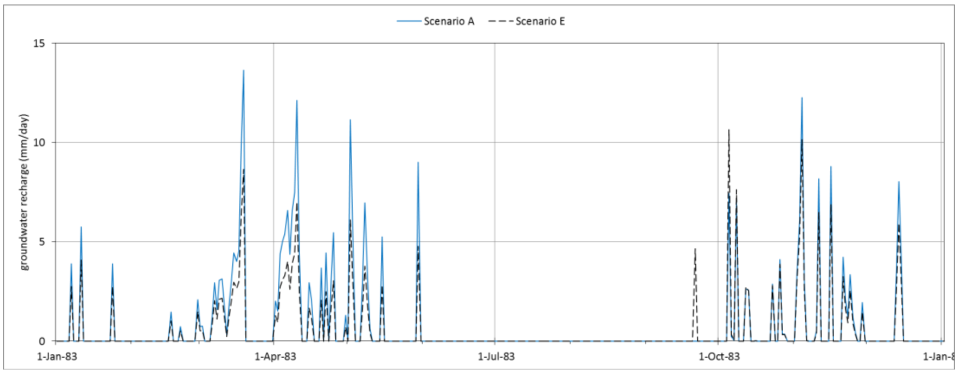
(b)



(c)



(d)



(e)

Fig. 7 Main water balance components of Franktown basin as simulated by Mike11 NAM model for a typical year of 1983; (a) total runoff (cms) reaching the stream along with daily precipitation (mm) and daily mean temperature (degree C); (b) actual evapotranspiration (mm/day); (c) overland flow (cms); (d) base flow (cms); and (e) groundwater recharge (mm/day); precipitation and temperature are input to the model; all others are output as computed by the model.

Scenario B (Table 1) is a hypothetical situation where all non-PSWs have been "lost", which really means that, by virtue of being drained and filled; they no longer serve the functions of storage and infiltration. In most cases, the wetlands are replaced by agricultural fields or, in some cases, urban development. This is a basic assumption in the present analysis.

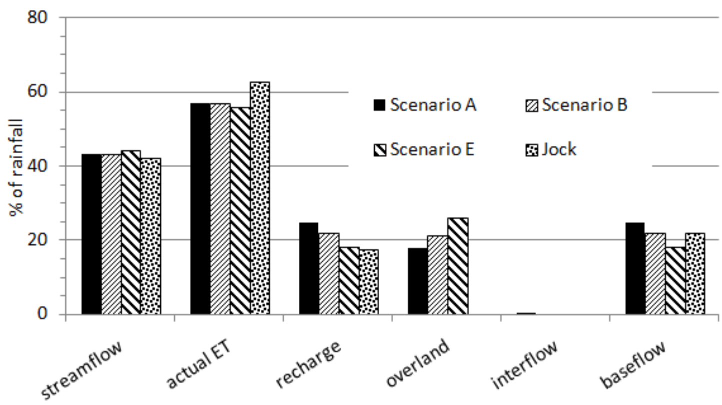


Fig. 8. Overall annual water budget components of Franktown basin as computed from 59 years of model output (1945-2003); the Jock basin values were computed for 1974-2003 by MRSPR (2011) and provide a yardstick for comparison; note that simulated interflow is very small and was not available for Jock.

Scenario E is another hypothetical situation where all wetlands (PSW and non-PSW) have been removed. For this scenario the model was run from January 1, 1940 to December 31, 2007. Excluding the first three years in order to avoid initial condition effects, there was 65 years of data for analysis. For the present study, with discerning the role of all wetlands in the Franktown basin as the goal, we have preliminary compared Scenarios A and E with occasional use of Scenario B results.

In order to incorporate the effect of wetland loss in the model, the inputs to the rainfall-runoff or NAM module of Mike11 has been modified (Figure 4).This module represents various components of runoff generation process by continuously accounting for the water content in four storages. Each storage represents a different element of the catchment. The NAM model has been successfully used in many parts of the world under different hydro-climatic regimes, and is now widely considered a well-tested engineering tool. The hydrologic response of the land use change (wetland to agricultural or urban) at the single basin scale (roughly in the order of 20-100km^2) has therefore been modeled here. After closely scrutinizing the model structure (DHI 2003, 2004), three NAM parameters have been identified, which, when suitably modified, can simulate the effect of the type of land use change under consideration (RVCA 2009; Ahmed 2014). They are:

– Maximum Water Content in Surface Storage, U_{max}[mm]: U_{max} defines the maximum water content in the surface storages. This storage is interpreted as including the water content in the interception storage, in surface depression storages, and in the uppermost layer of the ground. The water in the surface storage is continuously diminished by evaporation as well as by horizontal leakage or interflow. When the surface storage exceeds U_{max}, some of the water enters the stream as overland flow, whereas the remainder is infiltrated into the lower zone and groundwater storage. As a rule, $U_{max} = 0.1\ L_{max}$ can be used unless special basin characteristics or hydrograph behavior indicate otherwise. However, the final value is usually obtained via calibration. The presence of wetland means higher value of U_{max}.

– Maximum Water Content in Root Zone Storage, L_{max} [mm]: The soils moisture in the root zone, a layer below the surface from which the vegetation can draw water for transpiration, is represented by the lower storage zone (Figure 4). Moisture in this zone is depleted by transpiration as well as deep percolation into the groundwater storage. L_{max} denotes the upper limit of this storage. This parameter depends on the vegetative transpiration and soil classification. It can be estimated by multiplying the difference between field capacity and the wilting point of actual soil (water holding capacity of soil) with the effective root depth. Since the model is lumped, in order to find one representative value for the basin, these values were weighted according to soil type and land use. From the root zone, water generally rises to the surface by capillary action of the soil pores and plant stems, and evaporates. The presence of wetland prevents this mechanism, and therefore reduces the value of L_{max}.

– Overland Flow Runoff Coefficient, CQOF [dimensionless]: CQOF determines the distribution of excess rainfall into overland flow and infiltration. It depends on soil and moisture content in saturated and unsaturated zones. CQOF is a dimensionless number with a value between 0 and 1. Small values are expected for flat catchments with coarse sandy soils and a large unsaturated zone. Large values are for catchments with low permeable soils such as clay and bare rocks. CQOF was computed based on available soil texture information and the presence of water bodies. The presence of wetlands facilitates an early onset of the overland runoff process, and therefore results in lower values of CQOF.

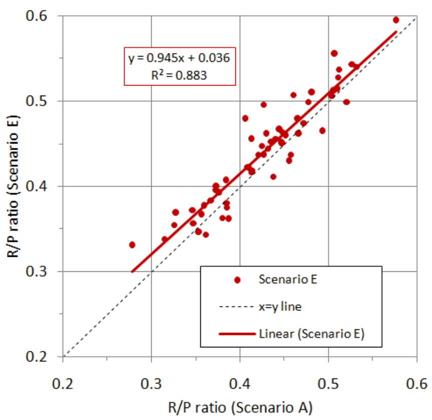


Fig. 9. Annual runoff to precipitation ratio for Franktown basin under existing condition (Scenario A) and when all wetlands are removed (Scenario E).

Since the primary impact of wetland is manifested through enhanced surface storage, reduced unsaturated zone depth, and reduced infiltration during runoff events, the loss of wetlands was modeled by a decrease in U_{max}, an increase in L_{max}, and an increase in CQOF. The change in each parameter – obviously related to the amount of wetland lost – was computed as follows:

$$changed\ U_{\max} = original\ U_{\max}\left(1 - \frac{wetland\ area}{watershed\ area}\right) \tag{1}$$

$$changed\ L_{\max} = original\ L_{\max}\left(1 + \frac{wetland\ area}{watershed\ area}\right) \tag{2}$$

$$changed\ CQOF = original\ CQOF\left(1 + 2\frac{wetland\ area}{watershed\ area}\right) \tag{3}$$

This computational procedure was somewhat subjective and was arrived at after considerable scrutiny of local watershed response and a number of tests runs (RVCA 2009). However, considering the model structure and the information available in the current literature, it is considered to be appropriate and useful for the present investigation. The original and changed parameters for all basins are documented in (RVCA 2009); here parameters for only the Jock sub watershed are listed in Table 2 as an example. The original parameters are the ones determined during calibration of the original model (RVCA 2007 a), and are used in Scenario A where all wetlands are intact; the changed parameters are used when the wetlands are removed, i.e. in Scenario E (Scenario B parameters are not included in this Table). The 'wetland area' in the above equations is equal to 'non-PSW area' for Scenario B and 'all wetlands' for Scenario E.

Table 3
Model performance during calibration and validation (Jock River at Moodie Drive; 02LA007)

Performance indicator	Calibration (1 Jan 1983 to 31 Dec 1987)				Validation (1 Jan 1988 to 31 Dec 1992)			
	Daily Flow	unit	Monthly Runoff	unit	Daily Flow	unit	Monthly Runoff	unit
MAE	3.588	cms	12.357	mm	3.790	cms	13.427	mm
%BIAS	11.195	[-]	11.195	[-]	26.754	[-]	26.789	[-]
RMSE	7.515	cms	21.195	mm	9.238	cms	24.992	mm
RRMSE	1.124	[-]	0.674	[-]	1.708	[-]	0.982	[-]
NSE	0.566	[-]	0.700	[-]	0.163	[-]	0.537	[-]
R^2	0.690	[-]	0.816	[-]	0.582	[-]	0.830	[-]
PCC	0.831	[-]	0.903	[-]	0.763	[-]	0.911	[-]
IA	0.901	[-]	0.937	[-]	0.836	[-]	0.918	[-]
EI	0.853	[-]	0.820	[-]	0.713	[-]	0.710	[-]
RSR	0.659	[-]	0.548	[-]	0.915	[-]	0.681	[-]

MAE mean absolute error, %BIAS percentage bias (%BIAS) or water balance error (%WBL), RMSE root mean square error, RRMSE relative root mean square error, R^2 coefficient of determination, PCC Pearson correlation coefficient, NSE Nash-Sutcliffe coefficient of efficiency, EI flow duration error index, IA index of agreement; RSR RMSE-observation standard deviation ratio; (Ahmed 2010) for details; taken from (Ahmed 2015 b).

The rainfall-runoff module (NAM) of Mike11computes runoff as well as several other components of the water budget (Figure 4). The time series of these parameters were analyzed in various ways to discern and quantify the role of wetlands on basin hydrology. The long term flow or runoff hydrograph was closely scrutinized. In addition to visual inspection of the hydrographs, the time series was also used for standard flood frequency analyses. The flood frequency was conducted on the annual maximum daily flow values using the Consolidated Frequency Analysis (CFA) software, standard software available from Environment Canada and used widely in Canada (Pilon and Harvey 1993).

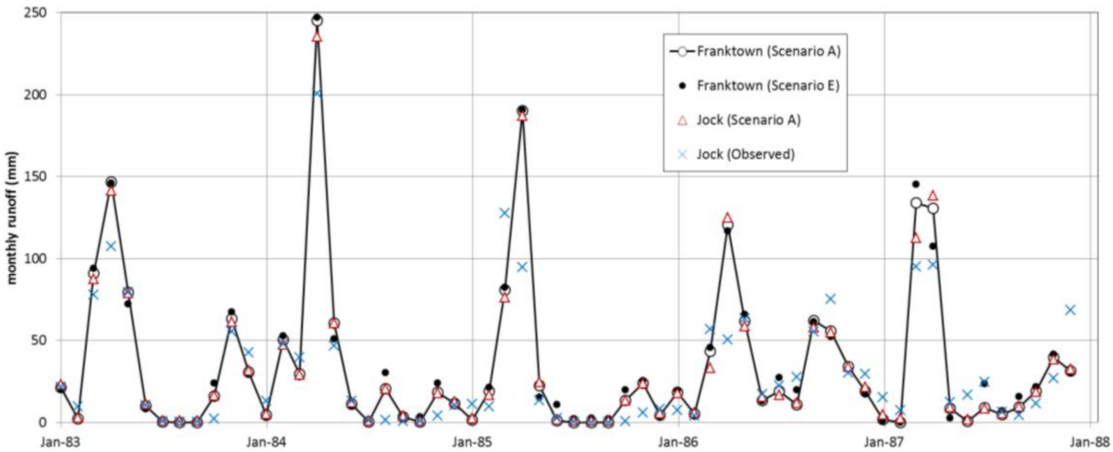


Fig. 10. Variation of monthly runoff for Franktown basin and Jock watershed at Moodie Drive; the effect of wetland removal is evident between Scenarios A and E; the Jock values provide and benchmark for comparison and also give an indication of the accuracy of simulated values.

Our methodology (long term integrated watershed simulation, followed by statistical analysis of simulated flow series) does not exactly correspond to any of the methodologies reviewed and classified by (Bullock and Acreman 2003); the closest ones were based on conceptual catchment modeling and water balance analysis – considerably less elaborate than our method. However, the "with-without" comparison used here is rather common. As pointed out by (Acreman et al. 2007) in connection with wetland restoration projects, hydrological modeling have proved invaluable in identifying and quantifying wetland functions under existing as well as projected conditions.

5. Model building and calibration

The calibration and validation of the Jock sub watershed model, encompassing Franktown basin and Goodwood Marsh, is documented in detail elsewhere (RVCA 2007; Ahmed 2010, 2015 b); here, only a skeletal description is given. The Jock sub watershed model – with 18catchments, 62 km of streams and 30 bridge and culverts – was built using available data (such as river geometry, soil, land use, etc.) collected from various sources. The model was calibrated using the Jock River flow data at Moodie Drive, the only location where good data is available since 1970. Five years data was used for calibration and another five years for validation. The model was evaluated using a matrix of numerical indicators (Table 3), yielding a mean absolute error (MAE) of 3.6 cms, Nash-Sutcliff coefficient of efficiency (NSE) of 0.16 to 0.70, and a coefficient of determination (R^2)of 0.53 to 0.83 (Table 3). Hydrographs during a typical spring freshet (Figure 5) compares simulated runoff to measurements, thus giving an idea of model's capability. It also indicates the nature and magnitude of runoff response due to wetland removal; the difference in runoff for various scenarios indicates how easy or difficult it would be to discern and quantify the effect of wetland removal. Moving from particular events to the whole simulation period (1945 to 2003), we found that the modeling results can be used to estimate the 1:100 floods within

10% accuracy. The snow on the ground, representing accumulated snowfall and melt, is another measure of the model (Figure 6).

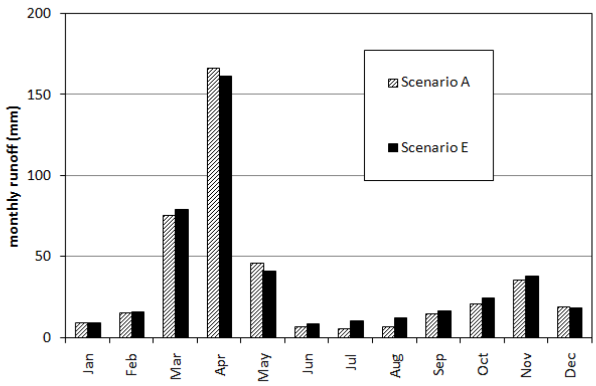


Fig. 11. Effect of wetland removal on monthly runoff generated from Franktown basin.

6. Results: impact on water budget

6.1 Overall water budget

The NAM model computes the major components of the water budget on a daily time step (Figure 4). In this study, we have scrutinized the simulated time series of total runoff, comprising of overland flow, interflow and base flow. The groundwater recharge, which eventually manifests as the base flow, was tracked. So was the actual evapotranspiration. Figure 7 (a-f) shows these components for Scenarios A and E for a typical year (1983); this gives the overall idea of the seasonal variation of the water budget components as well as the effect of wetland removal on them.

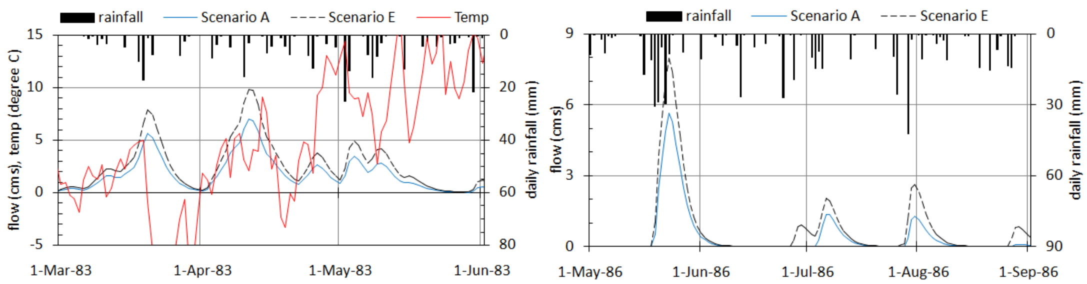


Fig. 12. Simulated overland flow in Franktown basin during (a) 1983 spring freshet and (b) 1986 summer months.

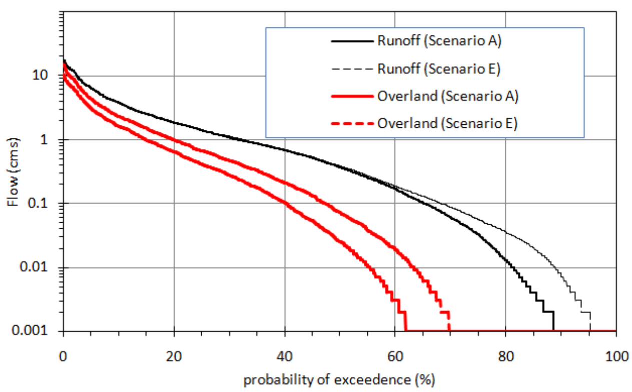


Fig. 13. Flow duration curves for total runoff and overland flow; comparison of Scenarios A and E reveal the effect of wetland removal.

For example, the total runoff is impacted profoundly during the beginning (May-June) and end of summer (October), whereas during the winter and spring months (November-April) the effect is rather subdued. The evapotranspiration decreases during June and July, but increases in August and September. The increasing effect on overland flow is evident throughout the year. The decreasing effect on recharge and base flow is perineal, although more pronounced during the spring freshet when temperature fluctuates around the freezing point.

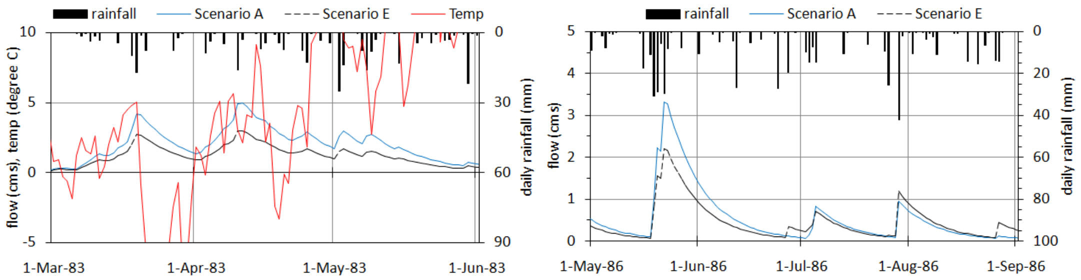


Fig. 14. Simulated base flow in Franktown basin during (a) 1983 spring freshet and (b) 1986 summer months.

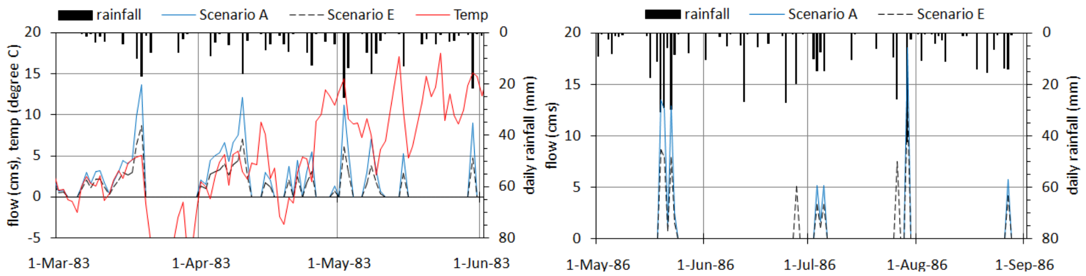


Fig. 15. Simulated groundwater recharge at Franktown basin during (a) 1983 spring freshet and (b) 1986 summer months (bottom).

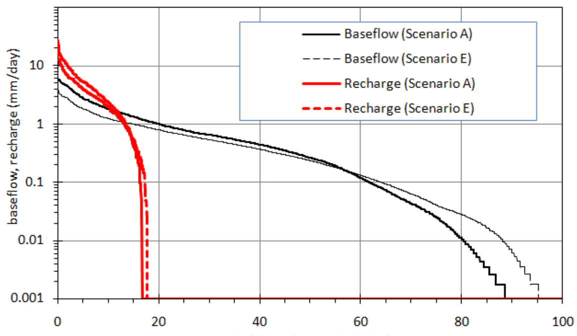


Fig. 16. Flow duration curves for base flow and groundwater recharge; comparison of Scenarios A and E reveals the effect of wetland removal.

Figure 8 shows the long term averages of various NAM-generated annual water budget components for the Franktown basin under Scenarios A, B and E (values averaged over 1945-2003). This gives time-averaged magnitude of various quantities and how they would be affected by progressive wetland removal. While the effects are in general in line with expectation, their quantification is the novelty of this study. We notice that the annual runoff and evapotranspiration varies relatively slightly compared to groundwater recharge, base flow and overland flow. On the long run, the recharge eventually converts to base flow and are almost identical in their reduction with wetland removal. This reduction in recharge (or base flow) is compensated by an increase in overland flow. Same parameters for the larger Jock sub watershed, based on measured stream flow of the Jock River at Moodie Drive and rainfall at Ottawa Airport and averaged over 1971-2000 (MRSPR 2011), are also included in Fig. 8 for comparison. The groundwater recharge was calculated using a methodology advocated by (MOEE 1995) using the water balance calculation procedure of (Thornthwaite and Mather 1957). The base flow was calculated using a recent USGS methodology (Neff et al. 2005). Comparison of the simulated values to this set of data from an independent source serves two purposes. First, it confirms that the simulated values are in the right range. Second, it confirms that the relative magnitudes of various water budget components for Franktown basin and the Jock sub watershed can be explained by watershed characteristics. For instance, Franktown basin, with more wetlands, has higher recharge and base flow.

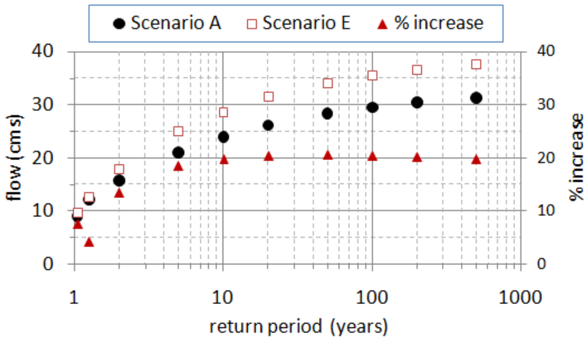


Fig. 17. Frequency analysis of total runoff or stream flow generated by Franktown basin; wetland removal is expected to increase the 1:100 flood by 20%.

6.2 *Total runoff*

In addition to hydrograph inspection, the total runoff (or stream flow as this is the part of precipitation that eventually reaches the stream) was analyzed in several other ways. First, the annual runoff to precipitation ratios for Scenarios A and E, when plotted (Figure 9), indicate higher runoff after wetland removal. However, the considerable scatter suggests a more complicated phenomenon involving evapotranspiration and runoff generation process. Second, monthly runoff from Franktown basin plotted for 1983-87 (Figure 10) shows the seasonal variation as well as the impact of wetland removal, within the context of Jock sub watershed, for which both simulated and observed values are included. The 5-year average of monthly runoff, as shown in Figure 11, indicates the overall annual variation of the impact of wetland removal. It appears that wetlands slightly increase the total monthly runoff (not the peak flow events) during spring freshet (perhaps due to enhanced baseflow), and decrease it during the rest of the year.

6.3 *Overland flow*

The role of wetlands on overland flow can be clearly seen in Figure 12. During spring thaw, snowmelt-generated overland peak flow as well as runoff volume can increase by 30-50% as a result of wetland removal. Similar increase can take place during summer storm events, when even higher increase is possible for smaller storm events. The role of wetlands in attenuating the overland flow volume and peak is therefore apparent.

Flow duration curves (Figure 13) indicate that the overland flow is influenced by the wetlands throughout the whole spectrum, while the total runoff is affected only during frequent events (when the probability of exceedance is greater than 50%) and during extremely rare events (probability of exceedance less than 2%). This is perhaps due to the direct effect of wetlands on reducing the overland flow and increasing infiltration; however a good part of the infiltrated water does eventually come to the surface through capillary action of the soil and evaporates, thus leaving a lesser impact on the total runoff reaching the stream. This apparently leaves a large part of total runoff, in between the 2% to 50% range of the probability of exceedance, more or less unaffected by wetlands.

6.4 Baseflow and groundwater recharge

Typical plots of base flow and groundwater recharge are shown in Figure 14 and 15. We can see a clear influence of wetlands on both. The base flow is attenuated by wetlands by about 30-50% by volume and peak values during the spring freshet and summer months. The recharge is enhanced by wetlands by about 40-60% during both spring freshet and summer months, except that during summer wetlands seem to induce extra recharge events. The recharge also aligns with the rising limb of the base flow hydrographs; no recharge generally takes place during base flow recession.

Duration curves (Figure 16) indicate that base flow greater than 0.2 mm/day is substantially reduced by the presence of wetlands, whereas the lower, more frequent flows are somewhat increased. The intermittent nature of the groundwater recharge is evident by the confinement of its non-zero values within about 17% of the probability of exceedance (in other words, during 83%of the time there is no recharge). The recharge enhancement induced by the presence of wetlands is evident for rates larger than 0.8 mm/day.

6.5 Results: impact on flood

If there is an aspect of wetland function with the least amount to controversy, it is the fact that wetlands attenuate flood hydrographs and reduce the magnitude of flood peaks. Daily rainfall data and thus a 24 hour time step in the NAM model were used in this study; this precluded any quantitative analysis of hydrograph attenuation, which, for small basins like this one, has a time scale of hours and minutes. However, daily hydrographs (Figure 5) clearly captured the flood peak attenuation both at basin and sub watershed scale.

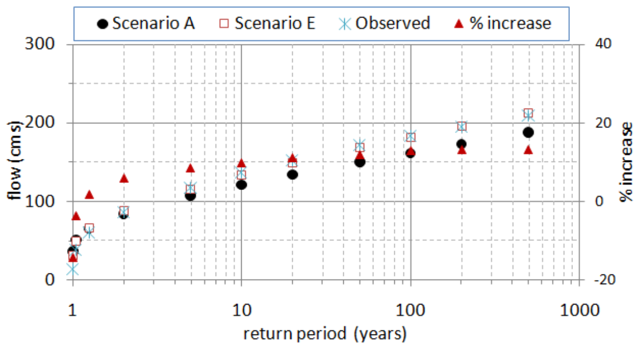


Fig. 18. Frequency analysis of stream flow of the Jock River at Moodie Drive; wetland removal is expected to increase the 1:100 flood by 12%; flood quantiles based the simulated values under existing conditions (Scenario A) are about 10% lower than those based on observation.

Annual flood peaks at the outlet of Franktown basin and Jock sub watershed were extracted from the model and analyzed. Flood frequency analysis was performed on the simulated data series for Scenarios A, B and E, and the floods with specific return periods were estimated. The CFA program of Environment Canada was used and the 3-parameter log-normal distribution was fitted to all data sets, for consistency and also because this distribution was found to better fit the stream flow data in Ontario (Pilon and Harvey 1993). The results, plotted in Figure 17 and 18, clearly indicate the flood reduction function of wetlands.

For the Franktown basin (Figure 17), it appears that the removal of Goodwood Marsh and other wetlands (about 36% of the basin area) would increase the peak flood by about 20% for larger flood events (return period of 10 years and more). For smaller flood events, the increase gradually diminishes down to about 5%. At Moodie Drive (Figure 18), the outlet of Jock sub watershed, the removal of wetlands (15% of basin area) would increase the peak floods, which gradually varies with the return period of the event; for the 1:100 year flood, the increase is about 13%. It is noted that the annual flood peaks at Moodie Drive were extracted from the hydrodynamic (HD) module and, being in a downstream location, it reflects the contribution of several NAM modules and routing along several streams. The observed data at Moodie Drive shows that the flood peaks based on Mike11 simulation (Scenario A) underestimates the flood peak by about 10%; this is indicative of the accuracy of flood quantiles based on long term simulation with the Jock sub watershed.

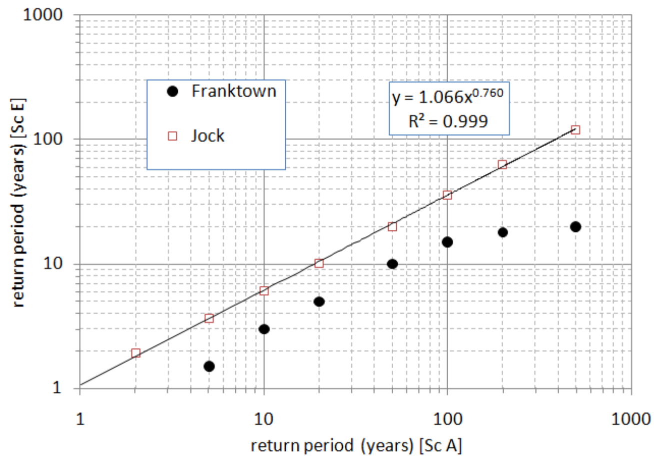


Fig. 19. Recurrence reduction at Franktown basin and Jock watershed; the return period of a flood quantile under existing condition (Scenario A, plotted along the x axis) reduced considerably when wetlands are removed (Scenario E, plotted along y axis); for instance, the existing 1:100 year flood for Franktown basin becomes only a 1:15 year flood.

An alternate way to describe the increase in flood magnitude is to use the notion of recurrence reduction (Vogel et al. 2011). This concept is illustrated in Figure 19 with the Franktown and Moodie Drive data derived from Figure 17 and 18. Here, for instance, we see that the 1:100 year flood at Franktown basin becomes a 1:15 year flood when wetlands are removed; in other words, this extreme event will occur more frequently. For the Jock River, the 1:100 year flood would become a 1:35 year flood, a lesser reduction of recurrence, which is expected because of the lesser amount of wetlands removed (15% vs. 36%).

7. Closure

Using a ‘with vs. without’ methodology and numerical modeling, we have discerned and quantified wetlands’ role in the hydrology of Franktown basin. About 36% of this basin is covered by wetlands of various size and shape, with Goodwood Marsh being the largest. The wetland functions investigated here include various water budget components and floods. Our computation indicates that wetlands help maintain higher groundwater recharge and base flow reduce total runoff and overland flow, and attenuate floods. This is in line with the prevailing conventional wisdom about wetland functions. Quantification of these functions at basin scale is, however, the novelty of this study.

We can summarize the role Goodwood Marsh and other wetlands play in Franktown basin hydrology as follows. With 36% of the basin area covered by wetlands, the water budget of this basin is significantly influenced by their presence. On an annual basis, wetlands reduce the total runoff by about 2% and increase the evapotranspiration by about the same amount.

However, the constituents of the total runoff, namely overland flow and base flow, are influenced more profoundly by wetlands. Overland flow decreases 45% and base flow increases by 28% due to wetland presence. Groundwater recharge also increases by 28%. During individual runoff events, wetlands reduce both total runoff and overland flow by about 30-50% in terms of peak and volume. Wetlands also increase both the groundwater recharge and base flow by about 30-50% during individual runoff events. Flood peaks are attenuated by about 20%. The 1:100 year flood under current conditions would become a 1:15 year flood if wetlands were removed. There is currently a heightened interest in wetland functions, how to preserve them, and how to incorporate them in land use planning. Many of the 36 conservation authorities in Southern Ontario are at various phases of formulating policies to protect wetlands within their jurisdictions by controlling land use and wetland interference. The present study, having demonstrated that wetland loss has a quantifiable adverse impact on water budget and flood risk, will provide a much-needed piece of scientific information.

There are several limitations of this study. First, we have used a particular, commercially available modeling platform (Mike11 of DHI, more specifically its NAM module). In doing so, we have implicitly assumed that this model adequately ‘represents’ or ‘mimics’ the hydrology of the subject basin. Although NAM has been widely used across the world and found adequate for specific purposes, and that we have calibrated our model for a larger sub watershed encompassing the subject basin, the fact remains that we have not been able to test the model at the local scale due to lack of data. Even our calibration at the larger sub watershed is based on only observed stream flow data; there was no data to check the internal working of the model such as overland flow, groundwater recharge or base flow. The second limitation relates to the methodology, e.i. the adjustment of NAM parameters to model wetland removal. As mentioned here and elsewhere (Ahmed 2014), this procedure was rather subjective and was based on a considerable amount of experimentation. We found it adequate for our purpose, but at the same time we realize that a different analyst would come up with a different approach.

Notwithstanding the above limitations, we believe that this study has achieved its goal of discerning and quantifying wetland functions for a specific basin using state-of-the-art computational techniques and available data. Our intention here is to understand the bigger picture that would be helpful in policy formulation, not to develop accurate computational tools. Confirmation of wetland functions based on an approximate quantitative analysis is no less valuable than precise analysis, considering the prevailing policy debate and the general paucity of data and analysis.

The modeling exercise done here is comparable to other published modeling done using the Mike11/Mike SHE platform (e.g. Refsgaard 1997; Refsgaard and Henriksen 2004). However, all models involve uncertainties and approximations (Beven 2009), which should be kept in mind when analyzing and interpreting model results.

Acknowledgments

This study builds on various projects that Icarried out at the RVCA. However, I did this study at my own initiative and at my own time – outside my official duties at RVCA. As such, the analyses and opinions presented in this paper are my own, and do not represent the position of RVCA in any way. I am grateful to N. Howladerand T. Ducrocq for assisting me with Mike11 model runs during the original RVCA projects.

References

Acreman, M., Fisher, J., Stratford, C. J., Mould, M. J., and Mountford, J. O.(2007). “Hydrological science and wetland restoration: Some casestudies from Europe.” Hydrol. Earth Syst. Sci., 11(1), 158–169.

Acreman, M. C., and Miller, F.(2006).“Hydrological impact assessment of wetlands.”International Symposium on Groundwater Sustainability, Alicanto, Spain, 225-255.
Acres (1994). Rideau Canal Water Management Study, prepared for Parks Canada by Acres International Limited, Canada.
Ahmed, F. (2010).“Numerical modeling of the Rideau Valley Watershed.”Nat. Hazards, 55(1), 63–84.
Ahmed, F. (2014). “Cumulative Hydrologic Impact of Wetland Loss: Numerical Modeling Study of the Rideau River Watershed, Canada.” Journal of Hydrologic Engineering 19(3):593-606.
Ahmed, F. (2015a).“Influence of wetlands on Black Creek hydraulics” [in preparation]
Ahmed, F. (2015b). “An integrated Mike11 model of the Jock River basin, Canada” [in preparation]
Beven, K. (2009). Environmental modelling: An uncertain future?,Routledge, Oxon, U.K.
Bullock, A., and Acreman, M. (2003).“The role of wetlands in thehydrological cycle.”Hydrol. Earth Syst. Sci., 7(3), 358–389.
Cui, J., Li, C., Sun, G. E., and Trettin, C. (2005).“Linkage of MIKE SHE to Wetland-DNDC forcarbon budgeting and anaerobic biogeochemistrysimulation.” Biogeochemistry 72:147-167.
Danish Hydraulic Institute (DHI).(2001). Mike 11–Control structures,Mike 11 training manual, Hørsholm, Denmark.
Danish Hydraulic Institute (DHI).(2003). Mike 11–A modeling system forrivers and channels, Reference manual, Hørsholm, Denmark.
Danish Hydraulic Institute (DHI).(2004). NAM – Technical reference andmodel documentation draft, Hørsholm, Denmark.
Demissie, M., and Khan, A. (1993). Influence of wetlands on streamflow inIllinois, Illinois State Water Survey, Champaign, IL.
Fisher, J., and Acreman, M. C.(2004). “Wetland nutrient removal: a review of the evidence.” Hydrol. Earth Syst. Sci., 8(4), 673-685.
Gasca-Tucker, D. L., Acreman, M. C., Agnew, C. T., and Thompson, J. R. (2007).“Estimating evapotranspiration from a wet grassland.”Hydrol. Earth Syst. Sci., 11(1), 270-282.
Johnston, C. A., Detenbeck, N. E., and Niemiet, G. J. (1990). “Thecumulative effect of wetlands on stream water quality and quantity:A landscape approach.” Biogeochemistry, 10(2), 105–141.
Mitsch, W. J., and Gosselink, J. G. (2007).Wetlands, Wiley, Hoboken, NJ.
Mississippi-Rideau Source Protection Region (MRSPR).(2011). Assessment Report – Rideau Valley Sources Protection Area.Manotick, Ontario, ON.
Neff, B. P., Day, S. M., Piggott, A. R., and Fuller, L. M. (2005).Base Flow in the Great Lakes Basin. US Geological Survey Scientific Investigations Report 2005-5217, Reston, VA.
Ontario Ministry of Natural Resources (MNR).(1993). Ontario WetlandEvaluation System, Southern Manual, NEST TM-002, Toronto, ON.
Ontario Ministry of Environment and Energy (MOEE).(1995). MOEE Hydrogeological Technical Information Requirements for Land development Applications. Toronto, ON.
Pilon, P. J., and Harvey, D. (1993).CFA–Consolidated Frequency Analysisversion 3.1.Environment Canada, Surveys and Information SystemsBranch, Ottawa, ON.
Price, J. S., Branfireun, B. A., Waddington, J. M., and Devito, K. J. (2005).“Advances in Canadian wetland hydrology, 1999–2003.”Hydrol.Process., 19(1), 201–214.
Price, J. S., andWaddington, J. M. (2000).“Advances in Canadian wetlandhydrology and biogeochemistry.”Hydrol.Process., 14(9), 1579–1589.
Refsgaard, J. C. (1997). “Parameterisation, calibration and validation ofdistributed hydrological models.” J. Hydrol., 198(1–4), 67–97.
Refsgaard, J. C., and Henriksen, H. J. (2004). “Modeling guidelines–Terminology and guiding principles.” Adv. Water Resour., 27(1),71–82.
Rideau Valley Conservation Authority (RVCA).(2007a). Rideau RiverWatershed Modeling Using Mike11, Draft rep., Manotick, ON.
Rideau Valley Conservation Authority (RVCA).(2007b). A prioritizationsystem for wetlands within the Rideau valley watershed, Manotick, ON.
Rideau Valley Conservation Authority (RVCA). (2009). Quantifying theimportance of wetlands in the management of floods and droughtsin the Rideau Valley Watershed, Manotick, ON.
Rideau Valley Conservation Authority (RVCA). (2010). Jock subwatershed report 2010: A report on the environmental condition of the Jock river. Manotick, ON.

Thompson, J. R.,Sørensonb, H. R., Gavina, H., and A. Refsgaard, A. (2004). “Application of the coupled MIKE SHE/MIKE 11 modellingsystem to a lowland wet grassland in southeast England.” J. Hydrol. 293:152-179.

Thompson, J.R., Gavin, H, Refsgaard, A., Sørenson, H. R., and Gowing, D. J. (2009). “Modelling the hydrological impacts of climate change on UKlowland wet grassland.”Wetlands Ecol. Manage. 17:503–523.

Thornthwaite, C., and Mather, J. (1957).Instructions and Tables for Computing Potential Evapotranspiration and the Water Balance.Laboratory of Climatology Publication 10(3), Drexel Institute of Technology, NJ.

Trochlell, P., and Bernthal, T. (1998). Small wetlands and the cumulativeimpacts of small wetland losses: A synopsis of the literature, PublicationFH266-98, Wisconsin Dept. of Natural Resources, Madison, WI.

Vogel, R. M., Yaindl, C., and Walter, M. (2011).“Nonstationarity: Flood Magnification andRecurrence Reduction Factors in the United States.” Journal of the American Water Resources Association(JAWRA) 47(3):464-474.

Wen, L., Macdonald, R., Morrison, T., Hameed, T., Saintilan, N., and Ling, J. (2013).“From hydrodynamic to hydrological modelling: Investigating long-term hydrological regimes of key wetlands in the Macquarie Marshes,a semi-arid lowland floodplain in Australia.” J. Hydrol. 500:45-61.