Modeling the Flood Modification Effects of a Mid-Sized Unregulated Wetland

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In contrast to the extensive literature on hydrologic modeling of agricultural and urban land classes, relatively little attention has been focused on the prediction of the stormflow response from wetland ecosystems. If required to predict the rate of outflow from a wetland system, the hydrologist or engineer has few numerical tools and little available data to assist in the prediction. This chapter presents the application of a numerical wetland model using synthetic precipitation events. The wetland model consists of a field hydrology model fully coupled to a stream routing model. The field hydrology model incorporates two distinct layers, one representing the surficial hummock terrain common to many wetlands and the other representing the organic layer characteristic of all wetland sites. The hydrology model includes process representations for the quickflow responses associated with overland flows through the surficial hummock terrain and long-term subsurface interflow mechanisms within the wetland organics. Antecedent saturation states dictate the amount of storage available for temporarily storing meteorologic inputs. Under low saturation levels, the stormflow response is controlled by subsurface stormflow mechanisms. Under high saturation levels, overland flow mechanisms shape the response. Over the past few years, the integration of wetland sites and adjacent urban land use has been a focus of discussion. The results of this study illustrate the complexity and variability of the hydrologic response at a wetland site, even to a single precipitation input.

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18.1 Introduction

According to the Wetland Policy Statement (Ministries of Natural Resources and Municipal Affairs, 1992) wetlands are defined as *lands that are seasonally or permanently covered with shallow water, as well as lands where the water table is close to or at the surface. In either case, the presence of abundant water has caused the formation of hydric soils (soils in which there is an abundance of moisture) and has favoured the dominance of either hydrophytic or water tolerant plants.* Wetlands are very important ecosystems, providing valuable hydrologic functions and unique habitats for a wide variety of flora and fauna (Mitsch and Gosselink, 1986). Wetlands improve water quality, protect shorelines from erosion, provide a measure of flood control, and offer social and economic benefits.

The importance of protecting and preserving these wetland systems is being increasingly recognized by the general public, water resources engineers and regulators. It is estimated that wetlands currently comprise 1,270,000 km² or 14% of Canada's land surface (National Wetlands Working Group, 1988). In Ontario, wetlands occupy approximately 33% of the land area or 290,000 km², predominantly within the northern regions of the province. In southern Ontario, it has been estimated that over 75% of the wetland sites have been lost since European settlement (Ministries of Natural Resources and Municipal Affairs, 1992). In the past, the dominant cause of wetland loss in southern Ontario has been the reclamation of agricultural land use (Bardecki, 1981).

At any wetland site, the hydrologic response is influenced by numerous factors. These include: the size and shape of the wetland, the microtopography of the wetland, the properties of the organic sediments, the interaction between the wetland and the channel network, the nature of the water inputs and amount of storage space available within the organic sediments. It is recognized that the stormflow response of wetlands is strongly influenced by seasonal variations in both water inputs and evapotranspiration demand. Most of the wetland literature reports that the modification of peak flows at wetland-dominated basins is a function of percentage of wetland in the watershed, the location of the wetland within the basin, the volume of the precipitation input and the storage capacity at the wetland sites. Novitski (1979) reported that flood flows can be as much as 80% lower in basins with significant wetland networks as compared to similar sized basins with little or no wetland sites. Regressed equations by Conger (1971) indicated that 50% of the flood peak reduction resulted from the first 5% of lakes and wetland in the basin. Mitsch and Gosselink (1986) cite two studies involving riverine floodplain wetlands. The floodplain wetlands on the Charles River in Massachusetts were found to be extremely effective for flood control. It was estimated by the U.S. Army Corps of Engineers (1972) that the loss of 3400 ha would increase flood damages by \$17,000,000 per year. In a study of the

bottomland hardwood forests along the Mississippi River, Gosselink et al. (1981) reported that, prior to settlement, these wetlands stored the equivalent of sixty days of river discharge. After the construction of levees and drainage of the floodplain, the storage capacity was reduced to approximately twelve days.

In southern Ontario, headwater streams commonly originate from groundwater discharge zones. These discharge areas often exist in the form of treed swamps where the sustained influx of groundwater plays an important role in maintaining swamp saturation and stream baseflow (Roulet, 1991). Although these spring-fed swamps are a common watershed feature and their presence can significantly impact the stormflow response of a catchment, there has been relatively little research conducted into the numerical simulation of the stormflow response associated with these wetland systems.

18.1.1 Study Objectives

The purpose of this chapter is to examine the variability in the hydrologic response of headwater wetland sites common to southern Ontario. A calibrated numerical wetland model was used to simulate the response of a wetland study site to varying precipitation inputs within a design storm context. By incorporating synthetic storms, the hydrologic response of a headwater wetland was examined with regard to: (i) the wetland response to precipitation input, (ii) the length of the stormflow response associated with the wetland site, (iii) event stormflow runoff volumes (runoff coefficients) and (iv) a comparison of the wetland response with that of a comparably sized urban development.

18.1.2 Wetland Hydrology - A Primer

In order to properly manage these valuable ecosystems, regulators and planners must be aware of wetland hydrology and the particular hydrologic behaviour of wetlands. Hydrology is probably the single most important determinant for the establishment, extent and maintenance of specific types of wetlands and wetland processes (Mitsch and Gosselink, 1986). The type of wetland that will form on any given site is strongly influenced by climate, geology and local topography. It is well recognized that a knowledge of wetland hydrology is essential to understanding and quantifying wetland functions and processes (Carter et al., 1979). Wetlands provide a number of hydrologic functions and these functions have been well documented (Carter et al., 1979; O'Brien 1986; Carter 1986). The hydrologic functions attributable to wetland systems include peak flow reduction, delay of flood peaks, recharge and discharge of groundwater, maintenance of baseflow, water quality regulation and reduction of shoreline erosion. From a stormwater perspective, the most significant function associated with wetland systems is their ability to temporarily store or retain flood flows and as a result,

reduce flood peaks (Bay, 1969; Carter et al., 1979; Novitzki, 1979; Verry and Boelter, 1979; Woo and Valverde, 1981). In southern Ontario, most watersheds exhibit dendritic or tree-like drainage networks. The temporary storage of stormwaters within the tributary wetlands and the resulting delay of the tributary and main channel flood peaks can play a major role shaping the runoff response from a watershed. Past studies have indicated that during spring runoff events, most wetlands produce a flashy runoff response as a result of the saturated conditions within the wetlands. During the summer precipitation events, if air-filled pore space is available within the sediments for the retention of stormwater, wetland outflows can be significantly reduced.

A key characteristic of a wetland system is the existence of hydric soils. Hydric soils are those soils that experience saturation or frequent flooding for significant periods of time. Continuous or seasonal inundation combined with the production of relatively large amounts of dead organic material result in nearly perpetual soil anaerobiosis in many wetlands (Kadlec and Knight, 1996). The subsequent reduction in microbial activity and organic decomposition results in an accumulation of organic matter. When dealing with the properties associated with most wetland soils, a distinction is commonly made with regard to two identifiable layers within the wetland soil profile. The upper layer, or *acrotelm*, represents the periodically aerated layer within which there are exchanges of water with the atmosphere. The water table always lies within the acrotelm with the level of the water table fluctuating due to the varying meteorological influences. Underlying the acrotelm is the *catotelm*, an anaerobic, permanently saturated organic layer. The properties of organic sediments are very much related to the degree of humification. Humification refers to the decay or decomposition that occurs by biochemical oxidation of plant matter. As decomposition proceeds, the wetland soil undergoes a loss of organic matter and physical structure. In general, as the wetland soils decompose, the bulk density (i.e.: the dry weight of the material per unit volume) increases while the hydraulic conductivity decreases. The hydraulic characteristics of wetland sediments can vary significantly over very short vertical and horizontal distances. In most cases, there is a significant difference between the hydraulic conductivity associated with the acrotelm and that of the catotelm. Romanov *et al.* (1975) noted that the hydraulic conductivity associated with the upper layers of the acrotelm were in the order of 1 to 100 cm/s. At the lower boundary of the acrotelm, the hydraulic conductivity decreased to 0.001 cm/s. Several studies have reported hydraulic conductivity values associated with swamp wetlands in southern Ontario. Woo and Valverde (1981) reported values ranging from 4 to 22 m/day for the Beverly Swamp. In a study of the surface and groundwater hydrology at a small headwater drainage basin of the Duffin Creek watershed, Roulet (1990) reported hydraulic conductivity values ranging from over 10 m/day within the organic layer, to values less than 0.05 m/day in the underlying substrate. In a study of the

stormflow production in a forested swamp located northeast of Toronto, Ontario, Waddington et al. (1993) reported that the hydraulic conductivity of the peat near the drainage stream ranged from 0.03-0.17 m/day.

18.2 The Model

18.2.1 General

A brief description of the wetland model is provided in the following sections. A complete description of the wetland model development, numerical formulation, application and sensitivity analysis is provided by McKillop (1997). The wetland model consists of a channel routing model coupled to a wetland field hydrology model. The dynamics of the channel routing model determine the flow depths along the drainage system and the corresponding outflow from the wetland system. The wetland field hydrology model incorporates the process representations through which water is added, temporarily stored and subsequently removed from the wetland sediments. The primary inflow to the routing model is in the form of lateral discharge from the adjacent wetland organics. The horizontal water movement within the wetland field model is driven by the difference between the head in the wetland sediments and the head imposed at the stream banks by the fluctuating water levels within the wetland stream system. The process representations incorporated into the model are consistent with the data-poor environments typical of most wetlands.

18.2.2 Wetland Representation

Idealization of Wetland Drainage System

The model idealizes a wetland drainage system as a series of routing reaches, each coupled to an adjacent wetland field cell (Figure 18.1). The complexity of the routing network is dependent on the size of the modeling catchment, the data availability and the desired level of detail. The routing model can compute the flows along a main wetland channel and any specified number of tributaries.

Idealization of Wetland Soil System

The model idealizes the wetland using two storage zones (Figure 18.2). Zone 1 characterizes the hummocky terrain typically found in many wetland systems. The overland flow of stormwater is strongly influenced by the nonuniform bed shape (hummocks and hollows) and the emergent vegetation typical of wetlands. Zone 2 represents the organic sediments of the wetland. The model assumes that the saturated zone within the organic layer is hydraulically connected to the

Figure 18.1 Typical wetland reach segmentation.

Figure 18.2 Idealization of wetland channel and soil layers.

wetland channel. The wetland channel is idealized as fully penetrating the active layer of the wetland sediments. The wetland hydrology model characterizes each wetland field cell by overlaying a finite-difference mesh.

18.2.3 Wetland Hydrology Model

The purpose of the wetland hydrology model is to maintain an accounting of the utilized storage within the wetland while simulating the input and withdrawal of water stored within the wetland. The model requires specification of the dominant vertical water fluxes: precipitation input, groundwater input (or output) and

evapotranspiration demand. The model simulates the horizontal movement of water along both subsurface and surface flow paths. Horizontal movements of water through a wetland are influenced by numerous factors including the nature of the wetland vegetation, the surface topography, the channelization, the properties of the wetland sediments, the presence of macropore flow and the gradient of the shallow groundwater system. Water can move through a wetland system along several parallel paths. Under non-submerged conditions, horizontal water movement is limited to micropore and macropore flow through the wetland sediments. Numerous researchers have identified the importance of the highly permeable upper organic layer in discharging water to the wetland streams (Ivanov, 1981; O'Brien, 1980). Overland flow movements can occur along any available drainage channels.

With regard to the numerical simulation of overland flow through wetlands, there has been relatively little research (Kadlec and Knight, 1996). The rate of flow through most wetlands is low and as a result, the inertial and acceleration terms in the momentum balance are negligible in comparison with gravitational and friction terms. With the frictional and gravity effects in balance, flows through a wetland can be modeled using an appropriate mass balance and a relationship between velocity and gradient. For wetlands, it can be argued that the use of Manning's equation is not appropriate. Manning's equation applies to turbulent flow conditions controlled by bottom friction whereas wetland overland flows are nearly always in the laminar or transitional flow regime, controlled by vegetative resistance (Kadlec and Knight, 1996). Secondly, the typical flow depths within many wetlands are shallow and as a result, the microtopography of the surface is of importance. For overland flows across a wetland, the depth of flow would be highly variable. Finally, for many types of wetland vegetation, there is a pronounced vertical distribution in vegetation density. As a result of the difficulties inherent in the application of Manning's equation to wetlands, several researchers have adopted a more general power law:

$$Q = W\alpha d^{\beta+1} S^{\chi} \quad (18.1)$$

where:

- Q = the volumetric flow rate (m^3/s),
- W = the wetland width (m),
- d = the water depth (m),
- S = the energy gradient (m/m),
- α = the friction law coefficient ($\text{m}^{1-\beta}\text{s}^{-1}$),
- β = the hydraulic depth exponent, and
- χ = the energy slope exponent.

When $\beta = 0.67$ and $\chi = 0.5$, Equation 18.1 is applicable to a turbulent open channel flow regime. The friction law coefficient is influenced by vegetation and litter density. Until further data becomes available, Kadlec and Knight (1996)

reported coefficient values of $116 \text{ m}^{-1}/\text{s}$ for densely vegetated marshes and $580 \text{ m}^{-1}/\text{s}$ for sparsely vegetated marshes. Kadlec and Knight (1996) report a range of $1.0 < \beta < 2.4$ for the hydraulic depth exponent. Past studies (Kadlec et al., 1981; Hammer and Kadlec, 1986) have indicated that the computed water surface profiles are not sensitive to the selection of β within normal operating ranges. For application to wetland systems, Kadlec and Knight (1996) recommend a laminar flow formulation ($\chi = 1.0$), unless additional research data becomes available.

The wetland model utilizes a laminar friction law model as proposed by Hammer and Kadlec (1986). Overland flow velocity (v_x) can be expressed:

$$v_x = \alpha d^\beta \left(-\frac{dh}{dx} \right) \quad (18.2)$$

where:

- h = head elevation relative to some arbitrary datum,
- dh/dx = slope of water surface in the hummock layer.

In order to account for the movement of water in the wetland sediments, a groundwater component is incorporated. The specific discharge (q_x) within the wetland sediments is related to the gradient in head through Darcy's law (Bear, 1979):

$$q_x = -K(h) \frac{dh}{dx} \quad (18.3)$$

where $K(h)$ is the depth-averaged hydraulic conductivity associated with the organic sediments. Using a representative wetland element (Figure 18.3), the one-dimensional mass balance formulation of the surface flow is:

$$S_y \frac{\partial h}{\partial t} = \frac{\partial}{\partial x} \left(\left[b(h)K(h) + \alpha d(h)^{\beta+1} \right] \frac{\partial h}{\partial x} \right) + (P - ET \pm I) \quad (18.4)$$

where:

- $b(h)$ = the thickness of the saturated flow within the organic layer (m),
- $d(h)$ = the depth of flow within the hummock layer (m),
- S_y = represents the specific yield or drainable porosity,
- P = the net precipitation rate (m/s),
- ET = the evapotranspiration rate (m/s) and
- I = represents the rate of vertical leakage associated with the underlying sediments (m/s).

Equation 18.4 provides a general depth-averaged one-dimensional mass balance representation for combined surface and subsurface flow through a wetland. For the one-dimensional formulation, the rate of flow per unit width per unit hydraulic gradient (or transmissivity, T_x) is:

$$T_x = b(h)K(h) + \alpha d(h)^{\beta+1} \tag{18.5}$$

The transmissivity integrates the effects of micropore flow, macropore flow, surface flow within the hummock terrain and preferential surface flow along surface streamlets or channels. In any grid block, overland flow does not occur until complete saturation of the underlying organic layer. Implicit with the use of Equation 18.4 is the assumption that the pressure is hydrostatically distributed such that the gradient in head is the same above and below the wetland surface.

The model requires the specification of two storage parameters. When the phreatic surface is located within the hummock layer, changes in storage are characterized by a drainable porosity term applicable to the wetland hummocks and vegetation. When the phreatic surface is located within the organic layer, changes in hydraulic head are related to the drainable porosity parameter associated with the organic sediments.

Figure 18.3 Representative element of wetland.

18.2.4 Wetland Stream Model

In the literature, little attention has been focused on the influence of the wetland drainage system on stormflow response. During storm events, the wetland drainage system and its interaction with the wetland sediments can play an important role in governing the rainfall-runoff response. In order to accurately compute the saturation of the wetland sediments and the travel time along the drainage network, the variation in stream levels within the wetland drainage channels must be adequately simulated. The selection of a suitable routing model is strongly influenced by the availability of data, the computational expense and the overall purpose of the model. For most applications, the availability of stream data within wetland systems is expected to be low. As a result, the use of a data-intensive channel routing model is generally not suitable. The wetland routing

model incorporates a simple storage routing model. The primary purpose of the wetland routing model is to maintain an accounting of the stream levels along the reaches adjacent to the wetland sediments and to characterize the open channel flow travel times within the drainage network. Storage routing is based on the conservation of mass:

$$I - O = \frac{\Delta S}{\Delta t} \quad (18.6)$$

where:

- I = the average rate of inflow into the channel reach,
- O = the average rate of outflow from the reach, and
- ΔS = the change in storage within the channel reach over some time increment Δt .

The solution of Equation 18.6 requires the specification of a relationship between stage and discharge. The wetland model utilizes the Manning expression to relate the channel outflows with the flow depth within the wetland routing reach:

$$Q = \frac{1}{n} A R^{2/3} S_0^{1/2} \quad (18.7)$$

where :

- n = the Manning's roughness parameter,
- A = the cross-sectional area of flow within the channel (m^2),
- R = the hydraulic radius (m), and
- S_0 = the bed slope of the wetland channel (m/m).

The coupling of the Manning equation for uniform flow with the continuity equation has proved successful for meso-scale routing schemes (Kouwen, 1996).

18.2.5 Coupling of Routing Model and Wetland Flow Model

An important component of the wetland model is the coupling of the water levels within the drainage channels and the phreatic surface levels within the wetland organic sediments. The runoff response from the wetland organics is strongly influenced by the flow depths in the drainage channel. At the beginning of any time step, the water levels in the wetland stream and wetland field cells are known and the lateral inflow to the stream along any reach, is known from the solution of the previous time step. The solution at time $t + \Delta t$ is initiated by solving the channel storage routing model with the lateral flow component set equal to the previous value. The new surface water levels are then used as a prescribed head boundary condition for the solution of the wetland flow model along all routing reaches. Based on the revised groundwater heads, an improved estimate of the

lateral exchange between the wetland and the stream is computed. The wetland channel routing is then solved again using the revised lateral flow estimates. The iterative process is then continued until successive estimates of the lateral flow between the wetland field hydrology model and the channel routing model are within a predetermined error.

18.3 Study Site

18.3.1 Description

An isolated, treed headwater swamp located in the central portion of the Teeswater River watershed (4885000 N, 476000 E) was used in this study. The wetland is located on a first-order tributary of the Teeswater River and occupies an area of approximately 420 hectares. The wetland exists primarily as a groundwater discharge area with streamflow observed throughout the year. The wetland is drained by approximately 6 km of drainage channel at a gradient of approximately 0.001 m/m. The wetland sediments consist of a surficial detrital layer consisting of matter in various states of decomposition and occupying the topmost 5 to 10 cm. The sediments underlying the surficial matter consist primarily of muck with the thickness ranging from 0.3-0.6 m. The surface topography of the wetland takes the form of an irregular pattern of hummocks and hollows. Numerous natural depressions or streamlets provide a preferential flow path for surface waters. In the wetland, the natural drainage patterns are disturbed by the presence of several Township roadways.

18.3.2 Stormflow Response

Over a two-year study period (1994-1995) hydrometric and meteorologic data were collected at the wetland. The response of the wetland site to precipitation inputs was significantly influenced by the antecedent saturation and the volume of the rainfall. Figure 18.4 illustrates the response of the wetland to two precipitation events. During periods of low flow, the wetland attenuates the stormflow hydrograph peak and reduces the runoff volume discharged. Figure 18.4(a) illustrates the rainfall-runoff from the wetland for a high-intensity, short-duration precipitation event in late June of 1995. The event produced approximately 26 mm of rainfall over a three hour period. Storage within the wetland organics was low prior to the event due to a span of 22 days without any rain. As indicated in Figure 18.4(a), the response to the precipitation was relatively insignificant. Under saturated conditions, the response of the wetland is shaped by overland flow through the hummock terrain. The response under saturated conditions is shown in Figure 18.4(b) for a 31 mm rainfall over 6 hours on

Figure 18.4 Observed rainfall-runoff response (a) June 25, 1995, (b) April 21, 1995.

April 21, 1995. Inundation of the wetland sediments resulted in charging of the channel system. The corresponding streamflows exhibited an initial rise in the flow rate followed by a plateau in the streamflow hydrograph as the channel flowed full for a period of approximately 50 hours, followed by a decline in the wetland outflow rate.

18.3.3 Parameterization of Study Site

For the purposes of this study, the wetland was idealized as a single unit, draining symmetrically to a wetland drainage channel (Figure 18.5). Parameters were obtained from mapping, aerial photography, site reconnaissance and field surveys. The depth exponent (b) was set at 2 as recommended by Kadlec and Knight (1996). A listing of the wetland parameters is provided in Table 18.1.

Figure 18.5 Idealization of wetland.

Table 18.1 Parameterization of wetland.

Parameter	Parameter
Length of wetland-stream interface (m)	6000
Width of wetland (m)	700
Mean thickness of organic sediments (m)	0.50
Slope of wetland hummock layer	0.0005
Channel width (m)	2.0
Channel roughness	0.045
Channel slope	0.001

18.3.4 Calibration/Validation of Site-Specific Model Parameters

For the wetland, the parameters were found through an optimization exercise conducted as part of a previous study (McKillop, 1997). A process-oriented calibration procedure was employed. The process-oriented approach to calibration involves splitting the calibration period into subgroups, within which certain identifiable processes dominate the production of runoff. In this manner, the parameters are only evaluated over periods where they are active and contribute to the model output. The aim of the process-oriented approach is to attempt to minimize the effects of parameter interaction during calibration.

Two sub-periods were identified based on the flow processes occurring within the wetland. During the last half of August 1994 (Figure 18.6), the wetland streamflows incorporated a period of low flows associated with the recession of

Figure 18.6 Comparison between observed and calibrated outflow hydrograph - 1994 calibration period.

a significant precipitation event that occurred on August 04, 1994. The stormflow response during the 1994 calibration period was governed by the subsurface storage and flow processes. The calibration period spanning late April and early May (Figure 18.7) involved multiple precipitation events applied to the study wetland under fully saturated conditions. The stormflow response was influenced by overland surface flows within the uppermost organic sediments and across the hummock layer. Subsequent to an initial manual optimization, a series of automatic optimization runs were performed in order to arrive at the optimal parameter values. The initial calibration of the model using the 1994 calibration period was followed by a similar calibration of the model using the 1995 period. The model calibration over the 1994 period was then repeated using the revised parameters optimized from the 1995 period. Based on the revised parameters found from the 1994 calibration, the model was re-calibrated over the 1995

Figure 18.7 Comparison between observed and calibrated outflow hydrograph - 1995 calibration period.

Table 18.2 Optimized model parameters for wetland site.

Description	Value
Drainable porosity of organic sediments	0.12
Drainable porosity of hummock sediments	0.95
Hummock flow coefficient (m^{-1}/s)	350
Conductivity - litter layer (m/s)	0.0051
Conductivity - lower organic boundary (m/s)	0.0001

period. This iterative procedure, alternating from the 1994 calibration period to the 1995 calibration period, was repeated until an optimal parameter set was established. A full description of the calibration procedure is presented by McKillop (1997). Table 18.2 summarizes the optimized parameter values.

The calibrated organic layer drainable porosity is an average over the range in heads encountered during the calibration period. In general, the drainable porosity lies within the range typically reported for swamp systems in southern Ontario (for example, Woo and Valverde, 1981). The hummock storage is an average reflecting the effective porosity corresponding to the vegetation and hummock/hollow topography. As a result of the coarse model discretization, the calibrated hydraulic conductivities are higher than those corresponding to typical point-scale measurements of organic soils. With respect to the modeled processes, the effective hydraulic conductivity parameters incorporate not only micropore flow through the soil matrix but integrate macropore flow and depressional streamlet flow to deliver stormflow to the channel system in excess of the amount possible by micropore flow alone. The surface flow coefficient characterizes surface flow in hummock terrain, the size and density of surface streamlets, the nature of the surface vegetation, and the availability of overland flow paths. The calibrated value lies within the range reported by Kadlec and Knight (1996), intermediate between dense and sparse emergent vegetation.

Figure 18.8 illustrates a validation data set, comparing the observed and simulated continuous streamflows generated for the 1994 study period using the calibration data set.

18.4 Numerical Simulations

18.4.1 Methods

All runs had a simulation length of 20 days (480 hours). For this study, a 3-hour uniform rainfall distribution was utilized throughout. Precipitation volumes ranged from 10 mm to 100 mm. From a previous study (McKillop, 1997) a

Figure 18.8 Comparison between observed and validation hydrographs - 1994 period.

constant groundwater inflow of approximately 1 mm/day was found to be appropriate for the site. A canopy interception depth of 1.5 mm was adopted. For all simulations, a uniform evapotranspiration (ET) demand of 3 mm/day was utilized. With evapotranspiration demand exceeding the groundwater input, a net loss of stored water within the wetland occurred during all recession periods.

Wetland researchers generally agree that the hydrologic response at wetlands is strongly influenced by the ability of the wetland to retain stormwater inputs. In order to examine the behaviour of the site under various saturation states, the model was initialized for two distinct saturation states. For the study wetland, an antecedent streamflow of $0.010 \text{ m}^3/\text{s}$ corresponds to low water table levels within the wetland sediments. Initialization of the model resulted in the phreatic surface being located entirely within the wetland organics, utilizing approximately 50% of the available pore space. For the purposes of comparison, a high saturation scenario was also established. Initializing the model for an antecedent streamflow rate of $0.100 \text{ m}^3/\text{s}$ resulted in saturation of the organic soils and steady-state water levels located within the hummock terrain.

18.4.2 Response to Precipitation Input

Background

Although it is recognized that the stormflow response of wetlands is strongly influenced by season and storage capacity (O'Brien, 1986) relatively few studies have attempted to quantify flood peak modification (Carter, 1986). Past studies

indicate that during spring runoff events, most wetlands produce a flashy runoff response as a result of the saturated conditions within the wetlands. During summer precipitation events, if air-filled pore space is available within the sediments for the retention of stormwater, wetland outflows can be significantly reduced. In general, the greater the depth to saturation the more storage capacity is available for temporary storage of the precipitation inputs. Bay (1969) related the peak stormflow from a bog watershed to water table position and precipitation volume. Relationships between precipitation volume and peak discharge were established for low, medium and high water table conditions.

Site Data

At the study site, the wetland response to precipitation input was strongly linked to the storage status in the wetland. Figure 18.9 illustrates the relationship between the precipitation and the observed streamflow as a function of three ranges in antecedent streamflow. Under low antecedent streamflow ($Q < 0.01 \text{ m}^3/\text{s}$), significant storage capacity resulted in peak flows being strongly suppressed. With comparable precipitation volumes, under high antecedent saturation, the observed peak flow values were significantly higher. The observed response of the wetland to a 40 mm precipitation input ranged from $0.06 \text{ m}^3/\text{s}$ to $0.35 \text{ m}^3/\text{s}$, depending on the antecedent storage capacity of the site. The results of this study reinforce the findings of Bay (1969). Precipitation inputs and the resulting peak flow rates were well correlated under low water table conditions. When the wetland sediments were saturated prior to the precipitation inputs, considerable variation in the peak flow response was observed.

Figure 18.9 Relationship between precipitation input and observed peak discharge at wetland site. ■ $Q < 0.010 \text{ m}^3/\text{s}$, ▼ $0.010 < Q < 0.050 \text{ m}^3/\text{s}$, ● $Q > 0.050 \text{ m}^3/\text{s}$

Modeling Results

The wetland model was used to compute the stormflow from the study site for a precipitation time-series. Table 18.3 and Table 18.4 summarize the peak flow rates and total runoff volumes for each precipitation volume under the low and high antecedent saturation scenarios respectively.

Table 18.3 Impact of precipitation volume on wetland response (low antecedent streamflow).

Precipitation Volume (mm)	Peak Discharge (m ³ /s)	Total Wetland Outflow Volume (mm)
5	0.008	1.5
10	0.015	2.2
20	0.034	4.1
30	0.057	6.6
40	0.097	9.3
60	0.169	19.8
80	0.355	37.7
100	0.446	56.6

Table 18.4 Impact of precipitation volume on wetland response (high antecedent streamflow).

Precipitation Volume (mm)	Peak Discharge (m ³ /s)	Total Wetland Outflow Volume (mm)
5	0.056	12.2
10	0.072	13.8
20	0.107	17.7
30	0.131	23.4
40	0.207	31.2
60	0.412	49.3
80	0.465	67.7
100	0.503	85.3

Previously, the variation in the relationship between the precipitation inputs and the corresponding observed peak outflows was provided in Figure 18.9. Figure 18.10 provides a comparison between the relationships observed at the site and the relationships generated by the model for three antecedent streamflow values. For a low initial streamflow ($Q_{init} = 0.006 \text{ m}^3/\text{s}$), there was good

Figure 18.10 Comparison of observed and simulated peak discharges at wetland site. ■ $Q < 0.010 \text{ m}^3/\text{s}$, ▼ $0.010 < Q < 0.050 \text{ m}^3/\text{s}$, ● $Q > 0.050 \text{ m}^3/\text{s}$

correspondence between the observed and simulated peak flow for low precipitation volumes. However, as the precipitation volume increased, the model tended to overestimate the hydrograph peak. During periods of low flow, it would be reasonable to expect a soil moisture deficit to exist within the unsaturated region of the wetland organics. However, the current wetland model assumes that the unsaturated zone is at field capacity and thus overestimates the stormflow response. At the wetland site, an antecedent streamflow (Q_{init}) of $0.049 \text{ m}^3/\text{s}$ corresponds to the onset of ponding within the hummock terrain. Figure 18.10 shows that the computed peak discharge-precipitation relationship compares favourably with the observed discharge-precipitation relationship under medium wetness conditions.

Figure 18.11 provides a plot of the computed streamflow hydrographs under the low antecedent saturation state. For low precipitation inputs, the wetland suppresses the hydrograph peak. The computed response exhibits a distinct hydrograph peak followed by a well-defined recession period. With increasing precipitation inputs, saturation of the wetland sediments occurs, overland flow mechanisms shape the stormflow response and the wetland outflow hydrographs exhibit significantly higher peaks and higher stormflow volumes.

Figure 18.12 illustrates the computed hydrographs for the wetland under high saturation conditions. In comparison to the results obtained for the low saturation scenario, under high antecedent wetness, the computed rainfall runoff response at the wetland resulted in larger and more sustained peak flows and significantly greater runoff volumes.

Figure 18.11 Computed influence of precipitation volume under low antecedent streamflow.

Figure 18.12 Computed influence of precipitation volume under high antecedent streamflow.

18.4.3 Length of Wetland Response

Background

Few studies have attempted to quantify the length of the hydrologic response associated with wetlands. The response of the wetland can be conveniently characterized by the length of time taken for the wetland to drain the stored stormwater and allow the wetland streamflow to return to the value immediately prior to the precipitation (Figure 18.13).

Modeling Results

The computed results illustrate the significant variability in the response of the wetland. Table 18.5 summarizes the results for 10, 40 and 100 mm precipitation volumes. Under low antecedent saturation conditions, the computed recovery time of the wetland was roughly double the values found for the high antecedent

Figure 18.13 Definition diagram for wetland response time.

Table 18.5 Summary of computed wetland recovery time.

Precipitation Volume (mm)	Antecedent Streamflow (m³/s)	
	0.01	0.10
10	116 hours (4.8 days)	46 hours (1.9 days)
40	387 hours (16.1 days)	211 hours (8.8 days)
100	591 hours (24.6 days)	310 hours (12.9 days)

saturation scenario. Under saturated conditions, the computed wetland recovered from a 10 mm input in less than 2 days. Under low antecedent saturation conditions, the computed wetland required almost 5 days to return to the initial streamflow value after a 10 mm input. Under a low antecedent saturation condition, the computed wetland would require almost 25 days of continuous drainage in order to return to the streamflow level prior to a 100 mm precipitation input. Figure 18.14 illustrates the computed streamflows under both antecedent saturation states for a 40 mm rainfall event. Figure 18.15 provides a similar comparison for the 100 mm precipitation event.

18.4.4 Event Runoff

Background

In the literature, total runoff hydrographs are commonly separated into two components: baseflow and direct runoff. Base flow is the component of the channel discharge comprising groundwater inflows and delayed interflow. Direct runoff comprises surface runoff and quick interflow. The separation of the

Figure 18.14 Computed streamflow hydrographs for 40 mm rainfall.

Figure 18.15 Computed streamflow hydrographs for 100 mm rainfall.

baseflow component from the total runoff hydrograph is highly subjective and numerous techniques are available. For this study, the total runoff hydrograph was separated into a baseflow drainage component and an event runoff component using the wetland model. The model was used to generate a hypothetical baseflow drainage hydrograph where the computed wetland was allowed to drain over the length of the simulation period with no precipitation inputs (Figure 18.16). The computed drainage of the wetland would represent a combination of the gravity drainage of water stored within the wetland sediments, the local groundwater inflows and the evapotranspiration uptake by the wetland vegetation over the length of the simulation. The event runoff hydrograph was then constructed by subtracting the baseflow drainage streamflows from the computed total streamflow hydrograph.

Modeling Results

Table 18.6 summarizes the computed response of the wetland to a 40 mm precipitation input. With respect to the 40 mm precipitation input, the event runoff volume ranged from 8.3 mm under low antecedent saturation conditions to 20 mm of runoff under high initial wetness conditions. At the end of the 480

Figure 18.16 Computed streamflow hydrographs - 40 mm precipitation total and baseflow hydrograph under antecedent streamflow of 0.10 m³/s.

Table 18.6 Comparison of computed wetland response (40 mm precipitation event).

	Antecedent Streamflow (m ³ /s)	
	0.01	0.10
Maximum peak - total runoff (m ³ /s)	0.097	0.207
Maximum peak - event runoff (m ³ /s)	0.092	0.169
Total runoff volume (m ³)	39200 (9.3 mm)	131000 (31.2 mm)
Event runoff volume (m ³)	34800 (8.3 mm)	84200 (20.0 mm)
Runoff coefficient	0.22	0.52

hour simulation, the stormflow runoff computed under the low saturation scenario corresponded to a runoff coefficient of 0.22. A runoff coefficient of 0.52 resulted from the high antecedent saturation state.

Table 18.7 provides a similar summary for a 100 mm precipitation volume. Under well saturated conditions, a 100 mm precipitation input resulted in more than 74 mm of computed runoff being discharged from the site.

Table 18.7 Comparison of computed wetland response (100 mm precipitation event).

	Antecedent Streamflow (m ³ /s)	
	0.01	0.10
Maximum peak - total runoff (m ³ /s)	0.446	0.503
Maximum peak - event runoff (m ³ /s)	0.441	0.461
Total runoff volume (m ³)	237900 (56.6 mm)	358300 (85.3 mm)
Event runoff volume (m ³)	233500 (55.6 mm)	311500 (74.2 mm)
Runoff coefficient	0.56	0.75

18.4.5 Stormflow Production

Background

Wetland literature contains several conflicting field studies regarding the mechanisms of stormflow production in wetlands. O'Brien (1980) studied two swamps in Massachusetts and concluded that the dominant stormflow mechanism was subsurface stormflow. Taylor (1982) reported that the stormflow response at a wetland complex near Peterborough, Ontario could be explained using a variable-source area, saturated overland flow concept. At a valley-bottom, spring-fed swamp in southern Ontario, Roulet (1991) reported that the stormflow volume was directly proportional to the precipitation input due to the presence of constant saturated zones maintained by a steady groundwater input.

Modeling Results

Figure 18.17 provides a comparison between the precipitation input volume and the corresponding outflow volume computed for both the low and high antecedent saturation states. The figure illustrates how the computed dominant stormflow mechanism at the study site can in fact, progress from a subsurface stormflow mechanism to a saturated overland flow framework. The slope of the precipitation-runoff plot characterizes the change in computed runoff volume resulting from a unit change in the precipitation input. For low precipitation inputs to the site, the shallow slope of the computed precipitation-runoff plot is characteristic of a subsurface stormflow mechanism. The case where the stormflow yield is

Figure 18.17 Comparison of computed direct runoff volume and precipitation input.

directly proportional to the precipitation input is consistent with a saturation overland flow conceptual framework. For both antecedent saturation states, the slope of each plot increases with increasing precipitation input, eventually approaching a 1:1 slope where a unit precipitation input produces a unit increase in computed runoff.

It can also be noted that as the precipitation input increases, the computed rainfall-runoff response of the highly saturated wetland approaches a 1:1 slope earlier than the low antecedent saturation simulations. This is consistent with the perception that the high antecedent saturation state would generate saturated overland flow more quickly than a wetland site with significant subsurface storage.

18.4.6 Comparison with Urban Stormflow Response

Background

It is well known that urbanization generally results in increased stormwater runoff volumes as well as greater peak rates of runoff. In southern Ontario, urban expansion is constantly encroaching upon wetland sites. Modern best management practices require urban development sites to coexist with wetland systems. It is important for land use planners and urban engineers to be aware of the significant differences in the hydrologic responses from urban and wetland land classes.

Modeling Results

Estimates of the urban runoff were generated using the SWMM engines. Developed and maintained by the U.S. Environmental Protection Agency, SWMM is a widely accepted urban simulation model. A hypothetical residential development was adopted. The site occupied an area of 420 hectares and was assumed to have an impervious fraction equivalent to 30% of the site. The Horton infiltration equation ($f_o = 50$ mm/hr, $f_c = 7.5$ mm/hr and $k = 2$ hr⁻¹) was used to estimate the infiltration of stormwater on the pervious portions of the catchment. The site was modeled using a trapezoidal channel bisecting the catchment and installed at the same gradient as the original wetland channel network (0.001 m/m).

Table 18.8 provides a comparison of the computed peak runoff rates and runoff volumes corresponding to the urban development and the wetland site. The table indicates that for the 40 mm precipitation volume, uncontrolled runoff from a comparably sized residential development would result in a peak discharge rate of 4.0 m³/s. In comparison, the peak flows from the wetland site are significantly lower. Under the high antecedent saturation condition, the peak flow was only 0.207 m³/s, approximately 5% of the peak flow value generated from the residential development. The table also reveals the variation in computed runoff volume associated with the swamp. Neglecting any groundwater

Table 18.8 Comparison of computed urban and wetland response (40 mm precipitation).

	Residential Development	Wetland Site	
		$Q_0=0.01\text{ m}^3/\text{s}$	$Q_0=0.10\text{ m}^3/\text{s}$
Peak Flow (m^3/s)	4.0	0.097	0.207
Event Runoff Volume (mm)	11.5	8.3	20.0

contribution, the residential development generated approximately 11.5 mm of computed storm runoff, corresponding to a runoff coefficient of 0.30, typical of a residential development. Under low saturation conditions, the swamp suppressed the computed stormflow response and generated 8.3 mm of computed stormflow volume. However, under high antecedent saturation conditions with little storage volume available, the swamp site discharged 20.0 mm of computed runoff, representing a 74% increase over the volume produced by the residential development.

Figure 18.18 provides a plot of the computed streamflow hydrographs for a 40 mm precipitation input. As discussed earlier, the computed recession period associated with the wetland is many hundreds of hours in length. In comparison, the urban development discharges most of the computed storm runoff in less than a day.

Figure 18.18 Comparison of computed urban and wetland response to a 40 mm precipitation input.

18.5 Conclusions

Although it is generally understood that the presence of a swamp ecosystem attenuates peak flows and elongates recessions, few studies have attempted to quantify these flood modification effects. In this study, a calibrated numerical wetland model was used to examine the response of a wetland to various precipitation inputs applied to differing saturation states.

The runoff generated at the wetland site was strongly influenced by the initial saturation state and the precipitation input. Runoff coefficients ranged from 0.22 for a 40 mm precipitation input under low saturation conditions to 0.75 for a 100 mm rainfall volume applied to a highly saturated wetland. Under low antecedent saturation, a 40 mm precipitation input resulted in 8 mm of runoff. However, the same 40 mm precipitation volume produced 20 mm of runoff when the wetland was saturated prior to the precipitation event.

The results indicate that the wetland stormflow response can be explained using a subsurface stormflow framework when antecedent saturation levels and precipitation volumes are low. However, under highly saturated conditions, increases in the stormflow yield will be directly proportional to the increase in meteorologic input, consistent with a saturation overland flow mechanism.

The length of time taken for the wetland outflows to return to antecedent levels was influenced by the dominant stormflow mechanism. Under a subsurface stormflow response, a 40 mm rainfall input produced a response time of 387 hours. In comparison, applied to a saturated wetland where overland flow mechanisms enabled stormflows to traverse the wetland more quickly, a 40 mm rainfall resulted in a 211 hour response time.

The wetland behaviour was compared to the hydrologic response of a hypothetical residential development of comparable size. The results indicated that the wetland site significantly suppressed the peak outflow rates in comparison to the urban development. With regard to the overall stormflow volume, under high antecedent saturation conditions, the wetland site generated a runoff volume greater than the volume produced by the urban development. The results also illustrate the significant variation in the length of the hydrologic response associated with the wetland and urban land classes. While an urban stormflow response from a 40 mm precipitation input lasted less than one day, a comparably sized wetland site generated a response lasting over 16 days.

In summary, it is evident that the stormflow response from treed swamp ecosystems is complex and highly variable. The results presented in this chapter have significant implications for the management of swamp ecosystems. In southern Ontario, many swamp sites are threatened by urban expansion and a complete understanding of the hydrologic behaviour of these valuable natural resources is essential for proper management by planners and regulators.

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