MODELLING THE RAINFALL-RUNOFF RESPONSE FROM A HEADWATER WETLAND

by

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ABSTRACT

In southern Ontario, treed headwater swamps are a common watershed feature. These headwater swamps commonly exist at groundwater discharge sites and represent a significant link between the underlying groundwater system and the surface drainage system. In contrast to the volumes of literature pertaining to the hydrologic modelling of agricultural and forest land classes, relatively little attention has been focused on the development and testing of numerical simulation models suitable for predicting the stormflow response from these headwater wetland sites. If required to predict the rate of outflow from a wetland-dominated catchment, the hydrologist or engineer has few numerical tools and little data available to assist in the prediction.

From a modelling perspective, wetlands ecosystems represent a unique and complex hydrologic setting. The rainfall-runoff response from wetlands is shaped by numerous factors including the size and shape of the wetland, the topography of the wetland, the available air-filled pore space within the sediments and the characteristics of the drainage network. The movement of water through the wetland occurs as a combination of subsurface flow through the organic sediments and surface flow within the hummock terrain common to most wetlands.

The objective of this research is to investigate the feasibility of applying a numerical model to simulate the rainfall-runoff response from a treed headwater wetland site. A first-generation wetland model is developed in order to provide an operational tool capable of reproducing the hydrologic behaviour of the headwater wetlands common to southern Ontario. The process representations incorporated in the model structure are consistent with the data-poor environment typical of wetland systems and the computational requirements appropriate to modelling at the catchment or watershed scale. The wetland model utilizes a field hydrology model coupled to the stream routing model. The field hydrology model incorporates process representations for the horizontal movement of water through the wetland sediments and surficial hummock terrain. The channel routing model provides an accounting of the lateral exchange of water with the wetland sediments and simulates the transport of water through the wetland drainage network.

The development and testing of the wetland model is made in conjunction with a data collection program where hydrometric and meteorologic data were obtained at a 400 hectare first-order headwater swamp located within the Teeswater River watershed in southern Ontario. Field surveys of the wetland drainage network and a streamgauging program provide data pertaining to the open channel flows within the wetland. The observed rainfall-runoff response of the wetland clearly reveals a remarkable variability in the stormflow response.

A split sample approach is used to calibrate the model parameters and validate the model performance. The ability of the model to simulate the runoff response from the headwater swamp is investigated for discrete storm events and for monthly simulations. Properly calibrated and initialized, the wetland model provides a useful tool for simulating the stormflow response for short to medium length simulations. As a result of the long response time associated with the drainage of wetlands and the difficulty of quantifying the role of the underlying groundwater system, long-term simulation of the wetland stormflow dynamics is a more challenging task.

The sensitivity of the model output to changes in the calibrated model parameters is reported for two storm events: one event dominated by flows within the organic sediments and another storm in which the response is dominated by surface flows within the hummock layer. The results of the analysis indicate that the stormflow response from the wetland is significantly influenced by the antecedent wetland saturation and the precipitation input.

Overall, the use of an idealized wetland representation involving a stream routing function coupled to a wetland field model appears to hold promise for the simulation of the stormflow response of low-gradient headwater wetlands. However, the testing of the proposed model has been limited to a single wetland site. A true measure of the usefulness of the developed wetland model can only be assessed through continued application of the model to other wetland sites as additional hydrologic data are made available.

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CHAPTER 1

1. Introduction

1.1 General

In accordance with 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 among the most important ecosystems on the Earth (Mitsch and Gosselink, 1986), providing valuable hydrologic functions and unique habitats for a wide variety of flora and fauna. Wetlands improve water quality, protect shorelines from erosion, provide a measure of flood control, and offer social and economic benefits. The value of these wetland systems is becoming increasingly recognized by scientists, engineers and regulators.

It is estimated that wetlands comprise approximately 1,270,000 km^2 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 km^2. In recognition of the importance of wetlands, the Province of Ontario has developed a comprehensive wetland management program. The goals of the *Wetlands Policy Statement* (Ministries of Natural Resources and Municipal Affairs, 1992) are to ensure that wetlands are identified and adequately protected through the land use planning process and to prevent further loss of provincially significant wetlands. It has been estimated that over 75% of southern Ontario's original wetlands have been lost since European settlement (Ministries of Natural Resources and Municipal Affairs, 1992). The dominant cause of wetland loss in southern Ontario involves the reclamation of agricultural land use (Bardecki, 1981). In addition to wetlands lost to agriculture, wetlands are also lost due to encroachment resulting from urban development. At the time of this writing, current policy in the Province of Ontario requires that, for all planning jurisdictions - including municipalities and planning boards, protection of provincially significant wetlands must be reflected in official plans, zoning bylaws and any other development decisions.

The role of wetlands in regulating stormflow has been the subject of debate in wetland literature. The hydrologic response of wetlands is the result of a complex interaction of many factors, including: the size and location of the wetland relative to the watershed; the degree of interaction between the wetland and the channel network; the microtopography of the wetland and the available air-filled pore space within the wetland sediments. Research has shown that wetlands can often have a large impact on the stormflow response of a catchment and that the magnitude of the impact can vary significantly with region and season. Many wetland research efforts have involved water balance and process-related studies conducted at individual wetland sites (for example: Woo and Valverde, 1981; Roulet, 1990; Gerla, 1992). Although some of these studies have presented contradictory results, these studies have proven valuable in identifying and quantifying the primary mechanisms influencing the stormflow response from wetland basins.

Advances in data acquisition and computer technology have helped influence the current trend towards the use of physically-based distributed hydrologic models (Systeme Hydrologique Europeen (SHE), Abbott *et al.*, 1986; WATFLOOD, Kouwen, 1988). The routine availability of precipitation and streamflow data, and the ever increasing availability of remotely sensed land cover data provided by airborne and satellite sensors now allows the collection of detailed hydrologic information on a watershed scale. In recent years, there has been increasing interest in the development and application of physically-based distributed hydrologic models towards a variety of watershed types. One noticeable exception involves the application of process-based modelling efforts towards wetland basins. Although wetlands can significantly impact the stormflow response of a catchment, hydrologic modelling efforts applied to wetland systems are not well represented in wetland literature.

1.2 Research Objectives

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, there has been little research conducted into the numerical simulation of the stormflow response associated with these wetland systems.

The primary objective of this research is to develop a first-generation numerical model capable of simulating the stormflow response from the swamp wetland systems characteristic of the temperate region of southern Ontario. This research is motivated by the need to develop a predictive tool suitable for simulating the primary stormflow mechanisms governing the runoff response from wetland systems at the watershed scale. The ultimate end use of the wetland model will be its implementation into an existing distributed hydrologic model (WATFLOOD, Kouwen, 1996).

The underlying philosophy behind the model development is to construct a process-based model that is compatible with the scarcity of field data typical of wetland basins while utilizing a minimal number of fitting parameters. Many hydrologic models are specific to either surface or subsurface flow processes. Since the surface and subsurface hydrologic processes within wetland ecosystems are inseparable (Roulet, 1990), an important feature of the proposed wetland model involves the coupling of the surface hydrologic processes within each wetland with the subsurface flow transport and storage mechanisms associated with the wetland sediments.

A major task involved with the development of any hydrologic model is the assessment of the predictive capabilities of the model against measured and observed field data. As such, an essential objective of this research is to develop and present applications of the wetland model using observed precipitation events. A data collection program was established to collect the hydrometric data necessary to calibrate and validate the model. An effort was made to apply the wetland model over the wide range of seasonal vegetative states and wetland antecedent moisture conditions. An analysis was conducted to evaluate the sensitivity of the wetland model output to the modelling parameters and the representation of the runoff processes.

1.3 Thesis Organization

Chapter 2 presents general background information relevant to this research effort. The reader is introduced to the Canadian Wetland Classification System and its hierarchical approach to differentiating the numerous types of wetlands found across Canada. An introduction into the hydrologic aspects of wetland hydrology and the hydrologic functions attributable to wetland ecosystems is provided. The stormflow mechanisms identified through past wetland research efforts are outlined. Finally, a brief discussion of previous modelling efforts associated with wetland systems is provided.

Chapter 3 outlines the goals of the model development effort and the idealized wetland representation adopted by the model. The reader is introduced to the various components of the wetland model including interception, evapotranspiration and horizontal surface and subsurface flows. A full description of the numerical formulations utilized for the channel routing model and the wetland field hydrology model is provided.

A first-order headwater wetland site within the Teeswater River watershed was chosen to be the focus of the model testing. Chapter 4 provides details regarding the collection of meteorologic and hydrometric data utilized to evaluate the model performance. Streamflow hydrographs are presented to illustrate the seasonal variability in the rainfall-runoff response of the study wetland site. A brief analysis of the stormflow hydrograph characteristics associated with the wetland site is included.

Chapter 5 provides details regarding the calibration and validation of the wetland model. The sensitivity of the model output with respect to the model parameters is evaluated in Chapter 6. Finally, conclusions drawn from the research and recommendations for future study are provided in Chapter 7.

CHAPTER 2

2. Literature Review

2.1 Wetland Classification

The intent of wetland classification is to group together the various kinds of wetlands that are similar in as many respects as possible (Zoltai and Pollett, 1983). Classification of wetlands is required for the evaluation, inventory and management of wetland systems. Within the wetland literature, a variety of classification schemes have been introduced for wetlands. Most of the early wetland classification schemes were developed for the northern peatlands of Europe and North America (Mitsch and Gosselink, 1986).

In the United States, the U.S. Fish and Wildlife Service (USFWS) developed a wetland and deepwater habitat classification scheme utilizing hierarchical classes of wetlands with systems, subsystems, classes and subclasses. A full description of the USFWS classification scheme is provided by Mitsch and Gosselink (1986).

In Canada, a wetland classification scheme was developed by the National Wetlands Working Group (NWWG) based on ecological parameters that influence the growth and development of wetlands. Information pertaining to wetlands is organized in a hierarchical fashion, beginning with broad generalized categories and progressing to more specific levels of detail. A brief summary of the Canadian Wetland Classification System is provided below. For a complete description of the classification system, the reader is referred to *Wetlands of Canada* (NWWG, 1988).

2.1.1 Wetland Class

The most general category involves the definition of *wetland class*, based on hydrology, water quality and vegetation physiognomy. Under the Canadian Wetland Classification System, five wetland classes are recognized:

i) bog
ii) fen
iii) swamp
iv) marsh, and
v) shallow open water.

Bogs are peat-covered wetlands, typically with the water table at or near the surface. The bog surface, which may be raised or level with the surrounding terrain, is isolated from the mineral soil water. The associated soils are Fibrisols, Mesisols and Organic Cryosols. Bogs may be treed with black spruce or treeless, usually covered with sphagnum mosses.

Fens also exhibit high water tables but, in contrast to bogs, their groundwaters are nutrient-rich minerotrophic waters hydraulically connected to the underlying mineral soils. The soils are Mesisols, Humisols and Organic Cryosols. The vegetation typically consists of sedges, grasses, mosses and possibly a poor tree cover.

A *swamp* is a peatland or mineral wetland with standing water or water gently flowing through pools or channels (NWWG, 1988). The water table is usually at or near the surface. In many swamps, peat formation is minimal. If peat is present, it is mainly well-decomposed woody peat, underlain at times by sedge peat. The soils are typically Mesisols, Humisols and Gleysols. The vegetation typically consists of a dense cover of deciduous or coniferous trees, with a surface cover of shrubs, herbs and some mosses.

A *marsh* is a mineral wetland or peatland that is periodically inundated by standing or slowly moving water. The substratum typically consists of mineral material, although it may consist of well-decomposed peat. The soils are primarily Gleysols, with some

Mesisols and Humisols. Marshes may be bordered by trees and shrubs but the dominant vegetation consists of emergent sedges, grasses, rushes and reeds.

Shallow open water wetlands consist of open expanses of intermittently or permanently flooded areas. Under summer conditions, shallow water wetlands have open water zones occupying 75% or more of the wetland surface area. In the open water zone, vegetation is limited to submerged vegetation and floating aquatic plant forms.

2.1.2 Wetland Form

In addition to the wetland class, the classification of wetlands can be further differentiated based on *wetland form*. Wetland form is established from:

i) the surface form of the wetland
ii) the proximity to water bodies, and
iii) the drainage characteristics of the basin.

As of 1988, 18 bog forms, 17 fen forms, 15 marsh forms, 7 swamp forms and 13 shallow open water forms have been identified (NWWG, 1988). Of particular interest in this research are the various swamp forms. These forms include:

i)	Basin Swamp	A swamp developed in a topographically defined basin where the water is locally derived.
ii)	Flat Swamp	A swamp existing in areas of poorly drained lowlands.
iii)	Floodplain Swamp	A valley swamp inundated by a seasonal flooding river.
iv)	Peat Margin Swamp	A swamp existing in a narrow zone between a peatland and the mineral uplands. Drainage from the upland regions provide water to the swamp.
v)	Shore Swamp	A swamp located along the shores of a permanent water body.
vi)	Spring Swamp	A swamp maintained by a discharge of groundwater.
vii)	Stream Swamp	A swamp existing along a permanent stream and subject to periodic inundation.

2.1.3 Wetland Type

Finally, wetland forms are divided into *wetland types* on the basis of vegetation morphology. Wetland types include:

i) treed (coniferous and hardwood)
ii) shrub (tall, low and mixed)
iii) forb (non-grassy herbs)
iv) graminoid (grass, reed, tall rush, low rush and sedge)
v) moss
vi) lichen
vii) aquatic (floating and submerged)
viii) non-vegetated

2.2 Wetland Regionalization

The distribution of wetlands is strongly influenced by climate related processes and local physiography. North of the tree line, the relatively cold climate and low precipitation are not favourable to the development of wetlands. In comparison, a significant concentration of wetlands exists as a broad band extending from central Labrador, passing through northern Ontario and extending north-west across the northern prairie provinces. Throughout this region, moderate precipitation levels, cool climate and flat terrain combine to form a favourable environment for the development of these extensive wetlands complexes.

In Canada, regional differences in the development of wetlands are well recognized (Zoltai and Pollett, 1983). To date, twenty *wetland regions* have been delineated in Canada (NWWG, 1986). These wetland regions are zones where characteristic wetlands exist within given climatic boundaries. The major wetland regions include: Arctic, Prairie, Temperate, Subarctic, Boreal, Oceanic and Mountain. For each major wetland region, several subzones have been identified. For example, the Temperate Wetland Region is further subdivided into the Eastern temperate and the Pacific Temperate Regions.

2.2.1 Eastern Temperate Wetland Region

The study site selected for this research is located within the Eastern Temperate Region. Wetlands of the Eastern Temperate Region span southern Ontario, Quebec and portions of New Brunswick. The Eastern Temperate Wetland Region is associated with two physiographic regions: the St. Lawrence Lowlands in southwestern Ontario and the Appalachian Highlands occupying portions of Quebec and New Brunswick. In southern Ontario, the St. Lawrence Lowlands are characterized by relatively flat relief associated with the underlying sedimentary bedrock. The Wisconsin glaciation produced extensive areas of lacustrine clay and fluvial sand deposits. Erosion and glaciation formed numerous shallow and poorly drained basins, providing sites where wetlands have developed. On the morainal plains, the underlying bedrock often prevents the development of deep and extensive drainage systems, resulting in poorly drained upland regions. Figure 2.1 illustrates the distribution of wetlands in southern Ontario.

The Eastern Temperate Region contains all five of the wetland classes identified within the framework of the Canadian Wetland Classification System. Swamps are the most frequently encountered wetland class of the Eastern Temperate Wetland Region in southern Ontario (NWWG, 1988). The swamp forms most commonly occurring in southern Ontario include peat margin, basin, stream, shore and spring swamps. The swamps exhibit both treed and shrub (thicket) vegetation. Soft maple, elm and black ash are indicative of hardwood swamps while white cedar, tamarack and black spruce are associated with coniferous treed swamps.

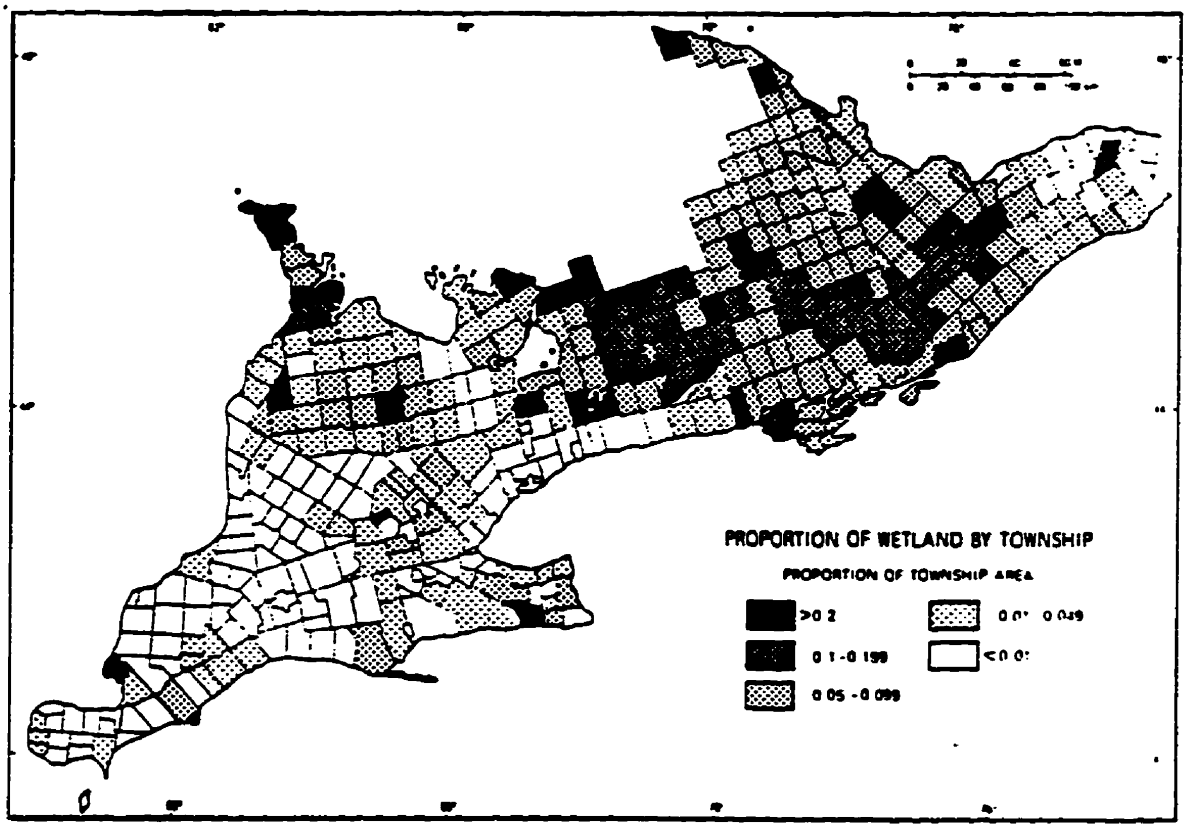


Figure 2.1 Distribution of wetlands in southern Ontario (Bardecki, 1981)

2.3 Wetland Hydrology

It is well recognized that a knowledge of wetland hydrology is essential to understanding and quantifying wetland functions and processes (Carter *et al.*, 1979). 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 particular site is strongly influenced by climate, geology and local topography.

2.3.1 Hydrologic Budget

A common approach to defining and quantifying the primary hydrologic components associated with wetland ecosystems is through the use of a simple hydrologic water budget (Ingram, 1983). Water can enter a wetland via precipitation, groundwater discharge, streamflow and surface water runoff (Figure 2.2). Wetlands lose water through streamflow, groundwater recharge, surface water runoff and evapotranspiration. Within the wetland system boundaries, inequalities of inflow and outflow can be interpreted as the variation in water storage over time. The storage capability of a wetland site will be determined by the topographic features of the wetland landscape, including the size or extent of the wetland and the depth and porosity of the wetland organics.

Defining ΔS as the change in storage, a general water balance statement can be expressed as:

$$\Delta S = Inflow - Outflow \tag{2.01}$$

Identifying the various boundary fluxes and internal flow processes, the water balance statement becomes:

$$\Delta S = P + GW_i + Q_i + SW_i - GW_o - Q_o - SW_o - ET \tag{2.02}$$

where P is precipitation; GW is groundwater flow; Q is streamflow, SW is surface water flow and ET is evapotranspiration. The inflow and outflow components in equation (2.02) are identified by the *i* and *o* suffixes respectively.

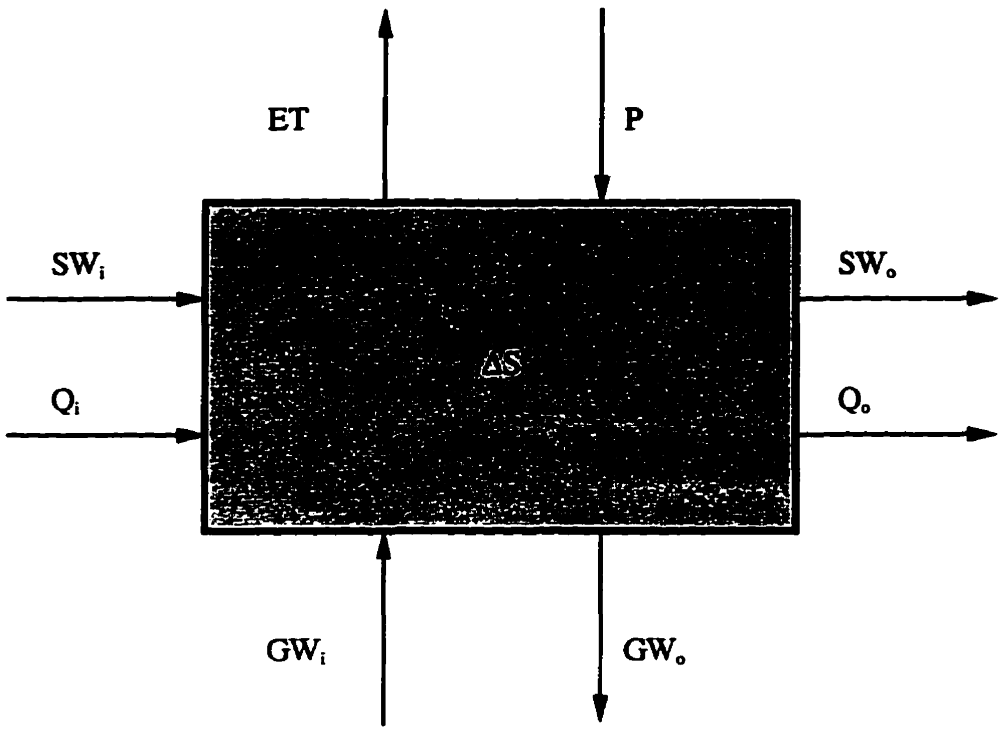


Figure 2.2 General wetland water budget

Although the water balance equation is conceptually simple, there are numerous difficulties involved in measuring the individual components (Carter, 1986). Computing the water balance for wetland sites is further complicated by the temporal variability of the wetland water table, the presence or absence of surface waters and the changes in the character of the wetland due to seasonality. From a modelling perspective, the relative importance of each component will vary depending on the individual characteristics of the wetland and the duration of the modelling. LaBaugh (1986) presents a good review of studies that have attempted to measure the individual components of the hydrologic budget. He concluded that very few studies have attempted to measure all components of the wetland water balance. Commonly, at least one major component is calculated as a difference between measured inputs and outputs.

Surface water input and output measurements are commonly made by establishing a relationship between discharge and measured flow levels across a weir or other control structure. From a practical perspective, the measurement of overland flow in wetlands is a significant problem. The flow paths across a wetland are strongly influenced by the local microtopography and vegetative state. Much of the available information pertaining to overland flows through wetland environments has been obtained from research associated with treatment wetlands, both natural and man-made.

For any land use, moisture losses to the atmosphere are a consequence of evaporation and transpiration by the existing vegetation. Transpiration implies water losses to the atmosphere through vegetation, while evaporation refers to the loss of water from the soil and water surfaces. In combination, these two processes are commonly referred to as evapotranspiration. It has been widely recognized that evapotranspiration losses represent a significant long term water loss in wetland systems (Verry and Boelter, 1979). The evapotranspiration losses from a wetland system varies according to plant and tree species, climate, vegetation density and available soil moisture.

A review of the wetland literature reveals that numerous approaches to evapotranspiration estimation have been applied to wetland sites. Past studies investigating the evapotranspiration loss in wetland systems have been summarized by Ingram (1983) and Carter (1986). In consideration of the variety of wetland sites and methods available for the measurement of evapotranspiration, it is not surprising that the reported results are somewhat confusing with many contradictory findings. A common index of evapotranspiration is the evaporation measured from standardized evaporation pans. An empirical formula is typically utilized to relate open water evaporation to an estimate of evapotranspiration. Traditionally, lake evaporation is understood to be approximately 0.6-0.8 of pan evaporation. However, for wetland systems, the relationship between evapotranspiration and free water evaporation is not clearly defined. During the growing season, estimates of evapotranspiration from different types of wetland vegetation have ranged from 0.5 to 5.3 times that of pan evaporation (Carter *et al.*, 1979).

The Priestley-Taylor approach has been found to work well in estimating evapotranspiration demand in water balance studies in wetland systems (Woo and Valverde, 1981; Price and Woo, 1988; Nuttle and Harvey, 1995, Neff, 1996). The Priestley-Taylor model (1972) is very attractive since its use requires only air temperature and radiation data. The model represents a special form of the Penman-Monteith combination model for evaporation:

$$ET = \alpha \frac{\Delta}{(\Delta + \gamma)} (R_n - G) \qquad (2.03)$$

where α is the Priestley-Taylor coefficient, Δ is the slope of the saturation vapour pressure curve (kPa/°C), γ is the psychrometric constant at the mean daily air temperature (kPa/°C), R_n is the net all-wave radiation (mm/day evaporative equivalent) and G is the soil heat flux (mm/day). The Priestley-Taylor coefficient, α, in part characterizes the control which the surface exerts on the yield of water to the atmosphere. For a surface that is wet and freely evapotranspiring, Priestley and Taylor (1972) found that an average value of α = 1.26 was appropriate. Use of the Priestley-Taylor equation essentially requires the local calibration of the α coefficient. When a soil moisture deficit exists, evapotranspiration is suppressed and the Priestley-Taylor coefficient typically falls to or below unity. In southern Ontario, Davies and Allen (1972) reported a similar value. McNaughton and Black (1973) found that a coefficient value of 1.05 was suitable for modelling the evapotranspiration of Douglas fir forest in British Columbia. For a shallow lake and wet sedge environment, Stewart and Rouse (1976) documented the successful application of α = 1.26 for characterizing the evaporation rate under a nonlimiting water supply. A hydrologic study of a small wet catchment in Connecticut (Stagnitti *et al.*, 1989) found a Priestley-Taylor coefficient of 1.22 to be suitable. Munro (1979, 1986) conducted an extensive evapotranspiration study involving the Beverly Swamp, located near Hamilton, Ontario. The results indicated that the forested wetland exhibited substantially smaller values (α near unity) in comparison to the standard Priestley-Taylor value of 1.26.

Kadlec *et al.* (1987) evaluated the predictive capabilities and site suitability of several alternative methods for the estimation of wetland evapotranspiration. The Thornthwaite, Christiansen and Penman methods (Penman 1948) were tested on two wetland sites, one in central Michigan and the other in Carson City, Nevada. The study results indicate that the evapotranspiration estimates proved to be highly site-specific.

Gerla (1992) used Turc's method to estimate the potential evapotranspiration from several wetland systems in North Dakota. Hammer and Kadlec (1986) applied the Thornthwaite method for evapotranspiration estimation during the application of a mathematical model for overland flow through a wetland at Houghton Lake, Michigan. O'Brien (1977) found that evapotranspiration estimated by the Thornthwaite approach compared favourably with measured values.

Although groundwater is a major component of the wetland water balance, the estimation or measurement of the fluxes entering or leaving wetland systems is very difficult and subject to large errors. Detailed hydrogeologic data are required in order to accurately assess the groundwater discharge/recharge relationship of any particular wetland. The collection of such data can be very expensive and, ideally, should be carried out over a relatively long period. In many cases, groundwater inflow is omitted because of the difficulty of its measurement, estimated from gradient and conductivity measurements (Huff and Young, 1980) or estimated as a residual term in the water balance.

There have been several detailed studies that have attempted to quantify the groundwater component associated with wetland systems. O'Brien (1980, 1977) investigated the hydrology associated with two small geographically different wetland basins in eastern Massachusetts. Both wetland study sites were part of the regional groundwater system and the study concluded that the wetlands represented highly efficient groundwater discharge sites. The study indicated that the groundwater accounted for up to 93% of the total annual discharge from the wetland sites.

Brown *et al.* (1987) investigated the interaction between groundwater and surface water at two wetland sites. The magnitude and relative contribution of the groundwater component to the water budget of each wetland site was significantly influenced by the hydrologic setting. At a groundwater slope wetland, groundwater accounted for 45% of the total water input. In comparison, at a surface water depression wetland site groundwater did not discharge into the wetland.

Roulet (1990) investigated the link between groundwater and surface hydrology in a small headwater drainage basin in southern Ontario. The results of the study indicated that the existence of the treed swamp is likely due to the large sustained groundwater input. The lack of a significant seasonal variation in the groundwater input produced a reasonably stable water table within the swamp. The large and sustained groundwater input led to the development of surface streamlets originating at permanently saturated seepage zones. The study estimated that, on average, over half of the groundwater entering the swamp was conveyed to the drainage channel via the surface streamlets.

Several researchers have investigated the groundwater flow at wetland sites from a hydrogeological perspective. Siegel (1988) presents the results of a study on the recharge-discharge function of a major freshwater wetland complex near Juneau, Alaska. The approach used in the study involved a hydrogeologic approach using a cross-sectional steady-state numerical simulation model to evaluate the recharge-discharge relationships. The study reports that, for the study site, the recharge-discharge function is highly dependent on the hydrogeologic setting. Gilvear *et al.* (1993) investigated the hydrogeological mechanisms associated with a small fen in England using a regional groundwater model (MODFLOW). The goal of the research was to quantify all water inputs and outputs from the Bradley Moor Fen and to investigate the sensitivity of the fen to changes in groundwater flow, climatological variables and aquifer characteristics. The study site was considered representative of wetlands overlying a leaky regional aquifer and they concluded that the existence of the fen is dependent on the unique geology that allows groundwater to maintain saturation of the surface layers. Hunt *et al.* (1996) estimated the groundwater inflows associated with a wetland site in southwestern Wisconsin using several alternative approaches: 1) traditional Darcy flux calculations based on observed gradient measurements, 2) stable isotope mass balance calculations, 3) temperature profile modelling and 4) numerical water balance modelling techniques. With the exception of the Darcy approach, the remaining three approaches produced results within the same order of magnitude. The report concludes that each method has strengths and weaknesses and no "best method" is likely to exist for any specific wetland site.

2.3.2 Organic Soils

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. Properties such as density, degree of humification, hydraulic conductivity and water storage commonly vary with vertical position. The upper layer, or *acrotelm,* represents the periodically aerated layer within which there are exchanges of moisture 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. Although not considered to be part of the wetland soils system, a leaf or root mat layer will often develop on the surface floor in many wetlands. This litter, or detrital layer typically consists of newly deposited plant material in various states of decomposition.

The physical 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 (ie: the dry weight of the material per unit volume) increases while the hydraulic conductivity decreases.

Humification takes place most rapidly within the acrotelm where oxygen is abundant. The average state of humification can be difficult to quantify. The most commonly referenced assessment approach is that of von Post scale (1926) for which a small amount of peat is inspected and manually squeezed. The degree of humification is graded on a scale from H_1 (no humification with clear water emerging) to H_{10} (completely decomposed with peat and water inseparable). Boelter (1969) proposed a scheme where soils were evaluated to determine the fraction of mass composed of fibres exceeding 0.10 mm is size. Soils with more than 67% fibres were classified as *fibric* while soils with less than 33% fibres were labeled as *saphic*. Fibre contents between 33% and 67% were classified as *hemic*.

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 (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. Hobbs (1986, quoted in Burt *et al.*, 1990) reported that the variation in saturated hydraulic conductivity within a single peat profile may range over eight orders of magnitude. 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.

Numerous studies have identified a relationship between the stormflow response from wetlands and the antecedent storage capacity of the wetland. The storage capacity of a wetland is influenced by the location of the water table. When the wetland sediments are inundated, storage of water occurs within the hollows of the hummocky terrain common to many wetland ecosystems. When the water table is located within the wetland sediments, air-filled pore space may be available within the unsaturated zone above the phreatic surface. The influence of the unsaturated zone within the acrotelm appears to vary with the type of wetland and the climatic conditions. For many undrained wetlands, the water table remains very close to the surface for most of the yearly cycle and available subsurface storage is limited. Burt *et al.* (1990) state that for many wetland sites, the unsaturated moisture conditions are of little importance in the study of peat hydrology. In wetland systems, the actual air-filled pore space available for infiltrating water may be only a few percent of the total porosity. With the organic soils existing at a state of near saturation, only small inputs of precipitation are required to raise the water table to the surface, producing source areas for surface runoff on peat terrain.

Most attempts at quantifying the relationship regarding the water storage associated with wetlands involve the concept of specific yield (S_y). The specific yield is defined as the volume of water released per unit area due to a unit decline of the phreatic surface. The above definition implies that the water released during a decline of the water table is only the water draining freely under the influence of gravity. The water yield represents the difference between the water content at saturation and the water content at field capacity.

Within the wetland literature, the reported values for specific yield encompass a wide range of values. Ingram (1983) reviewed several studies that have shown that specific yield decreases rapidly with increasing humification and depth. Boelter (1969) quotes the following general ranges for the specific yield of peat soils:

i) fibric soils $S_y > 0.42$
ii) hemic soils $S_y = 0.15 - 0.42$
iii) sapric soils $S_y < 0.15$

In their study of the Beverly Swamp, Woo and Valverde (1981) found a large variability in the specific yield within the site. In drier portions of the swamp, the specific yield was found to range from 0.06-0.09 throughout the depth of the peat. In the northern portion of the swamp where conditions were wetter, the specific yield decreased with depth, with the overall values ranging from 0.05-0.33.

In a subsequent study, Munro (1984) investigated the relationship between the soil moisture content and the water table in the Beverly Swamp. The study found that for a specified summer period, the soil moisture deficit within the peat column was reasonably correlated with the location of the water table. However, for each year of the study period, the relationship between soil moisture deficit and water table position was different. It was speculated that the differences in the relationships may be the result of yearly differences in the evapotranspiration efficiencies from one summer to the next.

2.3.3 Regulatory Role of Wetland Systems

It is widely recognized that 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 and the de-synchronization of flood peaks, recharge and discharge of groundwater, maintenance of baseflow, water quality regulation and reduction of shoreline erosion.

From a hydrologic modelling 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). The magnitude of these effects can vary significantly, depending on a number of factors including:

i) the class, form and type of wetland
ii) the size and location of the wetland relative to the drainage basin
iii) the available soil moisture storage
iv) the degree of interaction between the wetland and the adjacent drainage network, and
v) the magnitude and duration of the precipitation event.

Within the Eastern Temperate Region, many watersheds exhibit dendritic or tree-like drainage networks. The temporary storage of storm waters within the tributary wetlands and the resulting de-synchronization of the tributary and main channel flood peaks could play a major role shaping the runoff response from a watershed. As a result, any basin scale modelling of these watersheds must properly account for the timing of the runoff response from these tributary wetland complexes.

Relatively few studies have attempted to quantify the flood peak modification effects associated with wetland systems (Carter, 1986). 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 hectares 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 60 days of river discharge. After the construction of levees and drainage of the floodplain, the storage capacity has now been reduced to approximately 12 days.

It is recognized that the stormflow response of wetlands is strongly influenced by season and storage capacity (O'Brien, 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 the summer precipitation events, if air-filled pore space is available within the sediments for the retention of storm water, wetland outflows can be significantly reduced. Novitzki (1979) reported results on a study involving a statistical analysis of streamflows in Wisconsin that indicated that basins containing wetlands generally produced higher spring discharges and lower flood flows in comparison to basins with no wetlands.

2.3.4 Wetlands and Groundwater

Wetland sites exhibit a variety of relationships with the underlying groundwater regime (Carter and Novitzki, 1987). Depending on the local topography, the wetland may exist either above or below the local potentiometric surface. Wetlands perched above the regional or intermediate potentiometric surface may act to provide recharge to the underlying groundwater body. Alternatively, those wetland sites in contact with the underlying groundwater system serve as groundwater discharge sites. Hollands *et al.* (1986) state that the majority of freshwater wetlands in the northeastern United States are located on sites of groundwater discharge. Several recent studies have identified the importance of groundwater inflows with regard to the maintenance and stormflow characteristics of headwater swamp wetlands common to southern Ontario (Roulet, 1991; Waddington *et al.*, 1993). In some documented cases, wetland sites can function as both a discharge site and a recharge site over the annual cycle (O'Brien, 1977; Munro, 1984; Siegel, 1987). In either case, the wetland represents an important interface between the underlying groundwater flow system and the surface drainage features.

When reporting on the relationships between wetlands and groundwater, several researchers have categorized wetland sites as either lowland and upland wetlands (Holzer, 1986; Baker, 1986). Lowland wetlands occupy a position with major valleys underlain by glacial outwash or alluvium while upland wetlands are situated on glacial till. Most lowland wetlands exist in topographic depressions intercepting the regional water table and typically represent a groundwater discharge site. Upland wetlands exist in local topographic depressions intersecting the water table or potentiometric surface of an underlying aquifer. These upland wetland sites also represent groundwater discharge sites, with streamflows commonly being observed throughout the year.

In studying the hydrologic characteristics of wetlands in Wisconsin, Novitzki (1979) classified wetlands according to hydrologic setting. Differences in hydrology and the degree of the groundwater-wetland interaction were established for four hydrologic wetland settings:

i) surface water depression wetland
ii) surface water slope wetland
iii) groundwater depression wetland
iv) groundwater slope wetland

A *surface water depression wetland* exists where precipitation and overland stormflows collect in a surface depression. The bottom of the wetland is situated above the local water table and, as a result, the site does not receive groundwater inputs. With no drainage outlet, water entering these depressional wetlands leaves the wetland by downward leakage to the underlying soils or through evaporation. Surface water depression wetlands are associated with pond and marsh environments.

A *surface water slope wetland* occurs along the slopes located margins of lakes and streams. These wetlands exchange water with the adjacent lake or stream during a flood event. Surface water slope wetlands include marshes, swamps and floodplain forests.

A *groundwater depression wetland* occurs at sites where a topographic depression intercept the local water table. The wetland can receive water from precipitation, overland flow and inflow from the underlying groundwater system. Groundwater depression wetlands are characteristic of marshes, fens and sedge meadows.

A *groundwater slope wetland* exists where groundwater discharges to the surface as springs or seeps. These wetland sites have a constant groundwater discharge with surplus water draining via overland flow. Much of the character associated with these wetlands is determined by the magnitude of the groundwater input. Groundwater slope wetlands include fens, meadows and cedar swamps.

2.4 Wetland Stormflow Processes

2.4.1 Background

Stormflows may arrive at a drainage channel by any number of pathways; 1) direct precipitation falling onto the channel surface, 2) overland surface flow, 3) shallow subsurface flow and 4) deep subsurface flow. In watershed hydrology literature, the mechanisms of stormflow production have been a subject of considerable research and debate. In general, disagreement has centred around the factors influencing the development of overland flow and the relative contribution of subsurface flows with regard to the hydrologic response of a drainage basin.

The classic concept of streamflow generation through overland flow is attributable to Horton (1933). Overland flow consists of stormwater failing to infiltrate to the subsurface regime and travelling along the ground surface towards the drainage channel system as sheet flow or as flow collecting within surface rivulets. The Hortonian approach to runoff implies that the surficial soils partition precipitation events into two components: one portion of the precipitation is infiltrated into the soil while the remainder of the precipitation develops overland flow along any available surface paths. The partitioning rule involves the infiltration capacity at the soil surface. When rain falls at a rate greater than the rate at which it can infiltrate, there will be an excess of precipitation which will travel along the surface in the form of overland flow. Alternatively, no overland flow will develop if, for the duration of the event, the rainfall intensity is lower than the infiltration capacity associated with the surficial soils. The Hortonian hypothesis is most likely to be applicable under conditions of sparse vegetation cover and where soils exhibit crusting.

Subsequent researchers have observed that the heterogeneities in soil types and vegetation cover result in an irregular runoff response. These findings led to the concept of *partial contributing areas*. It was recognized that only certain portions of a watershed contributed overland flow. It was found that storm hydrographs originated from small upstream source areas, often less than 10 percent of the drainage basin (Dunne and Black, 1970). The size of these partial areas is influenced by the rainfall intensity, rainfall depth, and the antecedent moisture conditions associated with the catchment.

Refinements to the partial-contributing area concept have led to the *variable-source area* model (Hewlett and Nuttle, 1970; Ward, 1984). The variable-source areas are located in low-lying lands immediately adjacent to streams and rivers and are concentrated near basin outlets. The extent of these variable-source areas is a function of the antecedent soil moisture conditions, soil moisture storage capacity and rainfall intensity. The variable-source area model represents a dynamic version of the partial-contributing area model. The dynamics of the variable-source areas are reflected in the seasonal changes in soil moisture and the character of the precipitation events (intensity, duration and depth of rainfall). These source areas generate overland stormflows whenever the upper soil horizon becomes saturated.

Numerous researchers, particularly in forest hydrologic studies, have promoted the concept of *subsurface stormflow* as a major source of stormflow. The essential requirement for subsurface storm flow is a shallow soil horizon of high permeability (Freeze, 1974). Using a mathematical simulation model, Freeze (1972) concluded that the mechanism of subsurface stormflow is only applicable to convex hillslopes that feed deeply incised channels in conjunction with very high permeability soils.

More recent studies into stormflow generation have employed the use of environmental isotopes such as oxygen-18 and deuterium. These studies have indicated that stormflow generated during snowmelt and precipitation events is supplied by pre-event or old water that is in the catchment prior to the event (Sklash and Farvolden, 1979; Sklash *et al.*, 1986; Buttle and Sami, 1992). Several processes have been suggested to explain the large and sudden response of surface waters to an impulse of snowmelt or rainwater including groundwater ridging and macropore or pipe flow through the upper layer of the soil sediments.

According to the groundwater ridging hypothesis, rapid variations in pre-event discharge indicate the development and subsequent dissipation of groundwater ridges adjacent to the stream channels. These ridges increase the groundwater fluxes to the surface stream due to increased gradients and expanded seepage faces. Previous research efforts into rapid groundwater input to surface water have observed the formation of groundwater ridges at the base of hillslopes adjacent to stream channels (Sklash and Farvolden, 1979; Abdul and Gillham, 1989).

Buttle and Sami (1992) conducted combined hydrometric and isotopic techniques to test the groundwater ridging hypothesis of streamflow generation during snowmelt in a forested catchment on the Canadian Shield. Hydrograph separation methods indicated that pre-event water contributions dominated streamflow, providing up to 69 percent of the total flow from the wetland. The results are typical of those reported by other researchers involved with shield watersheds (Bottomley *et al.*, 1986; Moore, 1989). The report concluded that groundwater ridging in the near-stream zone was not responsible for the displacement of pre-event water into the channel. The formation of a groundwater mound beneath the channel was observed following the initiation of surface saturation in the wetland, suggesting that water left the wetland as saturation overland flow and infiltrated the channel bed. The water table subsequently rose until it intersected the ground surface, at which time, stream flow was recorded at a downstream gauge. The authors suggest that the variations in total stream flow and pre-event runoff may be indicative of the role played by surface storage in the wetland. The isotopic signature of water held in surface storage was intermediate between that of event and pre-event water. Variations in snowmelt and precipitation inputs to the wetland appear to have resulted in a displacement of the mixed water to the stream.

Several recent studies have focused on the concept of *macropore flow* within the upper soil horizons. Short circuiting of the subsurface flows through naturally occurring seeps and soil pipes has been hypothesized by numerous researchers (Nieber and Warner, 1991). Flow through *soil pipes* or *seeps* has been observed in peaty forested systems (Weyman, 1970; O'Brien, 1980; Thomas and Beasley, 1986; Waddington *et al.*, 1993). O'Brien (1980) noted the presence of pipes between a peat and muck interface at two New England forested wetlands. Measured discharges from individual seeps ranged from 50 l/day to 2,700 l/day, large enough to account for the observed streamflows.

2.4.2 Stormflow Production From Swamp Environments

Over the past decade, several studies pertaining to the stormflow production of wetland systems specific to the Eastern Temperate Region have shed light on mechanisms which appear to regulate stormflow behavior of riverine and palustrine wetlands (Whiteley and Irwin, 1986). The stormflow characteristics from a wetland system are dictated by numerous factors including: the wetland topography, the magnitude of the groundwater input relative to precipitation, the level of the water table, the local drainage network and the size of the wetland complex relative to the contributing drainage basin. A review of the findings reported by researchers is useful in illustrating the complexity of the stormflow processes in wetland basins.

O'Brien (1980) investigated the relative importance of direct surface runoff versus subsurface drainage in two small wetland controlled basins in Eastern Massachusetts. The author concluded that subsurface flows played a significant role in the generation of the flood peaks. At one of the wetland sites, the study estimated that nearly the entire baseflow of the stream could be provided by pipe or seep discharge. At both wetlands, total runoff amounted to approximately 48% of the recorded precipitation with the wetland discharge exhibiting considerable seasonal variation. On average, the spring months (March, April and May) accounted for roughly 70% of the total annual discharge.

Woo and Valverde (1981) conducted a hydrologic study of Beverly Swamp, a treed swamp covered predominantly by white cedar, tamarack and red maple. The swamp can be classified as a riverine wetland with two creeks traversing its limits. The study concluded that the regulatory role of the swamp is governed by the subsurface storage capacity and the degree of interaction between the groundwater and the streamflow.

Taylor (1982) reported on a study of the runoff processes in two small watersheds near Peterborough in south-central Ontario. In both watersheds, he reported that stormflow was produced principally as saturation overland flow from contributing areas which vary in size during and between precipitation events. The extent and duration of the contributing zones also appeared to vary on a seasonal basis. One of the study watersheds drained an ephemeral swamp that was considered typical of headwater basins in the region (Taylor, 1982). Taylor stated that these wetlands contribute most of the storm runoff from the headwater stream and that the storm-to-storm variations in stormflow response can be explained using the variable-source area saturation model as a framework.

Taylor summarized the stormflow response of the headwater swamp watershed as follows. During the winter period, the stormflow response is almost non-existent because contributing zones are small and moisture input is in the form of snowfall. In the spring, the release of stored water within the snowpack combines with the spring rainfall to expand the contributing zones as the water table within the wetland rises to the surface. After the spring melt period and throughout the summer period, interception and evapotranspiration losses result in significant available storage within the wetland soil horizon. As a result, stormflow response from the basin is at a minimum during the summer months. Into the fall period, evapotranspiration rates decline, allowing a recharge of the soil moisture and raising the groundwater levels. As a result, contributing zones during the fall period expand again and stormflow from the wetland system is observed following precipitation events. This seasonal pattern in stormflow response has been reported by other researchers (Bay, 1969; O'Brien, 1977).

Burt and Gardiner (1984) performed a multiple regression analysis of hydrograph characteristics for two subcatchments at Shiny Brook. The authors concluded that, for the study site, the antecedent soil moisture conditions were essentially constant due to permanently saturated pools. These pools provide fixed source areas for surface runoff and thus the rise of the storm hydrograph was controlled primarily by the precipitation input.

In southern Ontario, one of the most comprehensive research efforts to investigate the stormflow and runoff mechanisms of a headwater swamp involves a study of a forested groundwater discharge wetland located north of Toronto (Roulet, 1990; Roulet, 1991; Waddington *et al.*, 1993). The swamp is considered representative of the groundwater-connected wetlands commonly found in areas of glacial deposition in southeastern Canada and the northeastern United States (Roulet, 1990). The swamp is located on a first and second order stream valley and occupies approximately 2 percent of a headwater basin which measured 1.6 km^2. The results demonstrated that the wetland had little impact on stream baseflow. This is contrary to many previous wetland studies (see Carter, 1986 for review) which state that wetlands generally utilize stored water for evapotranspiration at the maximum potential rates at the expense of base flow (Verry and Boelter, 1979). In contrast to the stormflow response in the variable saturated swamp reported by Taylor (1982), runoff from the headwater swamp was proportional to the depth of rainfall. Roulet concluded that the consistency of the saturated contributing areas in this study was a result of the persistent and large groundwater input. Rainfall input represented approximately 7 percent of the total water input and, as such, had no significant impact on the areal extent of the saturated areas.

2.5 Past Wetland Modelling Efforts

Carter *et al.* (1979) identified five urgent research needs for the identifying and quantifying the hydrologic functions characteristic of wetlands. One of the research recommendations involved the need to continue the development of hydrologic models based on hydrologic data in order to generate better analysis and predictive capabilities. In a later publication (Carter, 1986), it was reported that little progress had been made in meeting the research recommendations.

A review of the recent wetland literature reveals that modelling efforts pertaining to wetland ecosystems in North America are becoming more common. These modelling efforts provide valuable information regarding the hydrologic processes unique to wetland systems while allowing new hypotheses to be formulated and tested. In general, the individual wetland modelling efforts can be generalized into two categories: 1) modelling efforts utilizing existing models and 2) efforts involving the construction of new models, developed specifically for wetland systems.

With respect to the first category, several groundwater studies have used the MODFLOW program to evaluate the groundwater regime associated with wetlands (Siegel, 1988; Gilvear *et al.*, 1993; Bromley and Robinson, 1995; Lloyd and Tellam, 1995; Bradley, 1996; Hunt *et al.*, 1996). The DRAINMOD model (Skaggs, 1982) was originally developed as a water management model capable of the design and evaluation of field scale facilities for subsurface drainage, surface drainage and irrigation. The DRAINMOD simulation model has been applied to wetland systems to evaluate peat-mining (Konyha *et al.*, 1988) and to investigate pocosin hydrology (Skaggs *et al.*, 1991).

Huff and Young (1980) reported on the development of a marsh hydrology water budget model to simulate the surface and subsurface discharge from a marsh wetland in response to urban inflows. The model was applied to a marsh adjacent to Lake Wingra in Madison Wisconsin. The model was used to compute daily water budget totals for the marsh over a seven year period. The model was capable of reproducing the daily water table fluctuations in the marsh and estimating the correct levels to within ± 10 cm.

Hammer and Kadlec (1986) presented a mathematical model for flow through wetland ecosystems. The model was based on a pair of mass balance equations, one characterizing surface flows when the free surface is above the sediment surface and a second equation appropriate to horizontal subsurface movement when the free surface is below the sediment surface. The model was applied to the Porter Ranch treatment facility (Houghton Lake, Michigan) to estimate daily water levels within the wetland.

One recent predictive model (Guertin *et al.*, 1987) is the Peatland Hydrologic Impact Model (PHIM). The PHIM is a lumped parameter, deterministic, continuous simulation model developed to predict the hydrologic response of natural or mined wetlands, mineral soil uplands or a combination of the land classes. The natural wetland model utilizes a two layer soil system, analogous to the acrotelm and the catotelm. Actual evapotranspiration (AET) is considered to be a function of the potential evapotranspiration (PET) and the water table depth. The streamflow response from the wetland is considered comparable to that of an unregulated reservoir. The wetland outflows are determined using a water table versus available storage relationship and a water table versus discharge relationship incorporated into a reservoir routing algorithm. The relationships are established from the peat profile and simultaneous field observations of water table elevation and discharge. Barten and Brooks (1988) presented the results from a modified version of the PHIM model in which a physically based upland land-type model for mineral uplands was tested on a 9.7 ha and 23.3 ha watershed.

Kittelson (1988) applied conventional hydrologic methods towards the analysis of several depressional wetlands in Minnesota and Wisconsin. Runoff from the upstream watersheds was estimated using the Soil Conservation Service (SCS) approach. The wetland sites were assumed to function as a conventional reservoir with a specified stage-discharge relationship. Outflow hydrographs from the depressional wetlands were obtained using a modified Puls routing procedure. Return period storms were applied to the model in order to evaluate the impact of the depression with respect to peak flows. The results indicated that the influence of the wetland sites on peak flow modification varied with available storage at the site and the nature of the wetland outlet.

Recently, Walton *et al.* (1996) developed and applied a dynamic water budget model to a large field investigation of the processes in the Black Swamp wetlands of the Cache River in Arkansas. The model incorporates three modules, providing representations of surface water flow, horizontal groundwater flow and the primary vertical processes. The model is based on an explicit link-node technique and includes concepts and approaches used in commonly applied programs. The model was applied to the Cache River wetland system using the surface flow module. The horizontal groundwater flow module was not utilized. The study concluded that inundation of the riverine wetlands was produced by several downstream constrictions, rather than the downstream advance of the flood waves.

2.6 Chapter Summary

In Canada, large regional differences in climate and landform have resulted in the development of numerous and diverse wetland ecosystems. In southern Ontario, treed headwater swamps are a common watershed feature. Recent process-related studies, conducted at several swamp sites in southern Ontario, have identified the dominant stormflow processes associated with these wetlands. Many of these wetlands represent groundwater discharge sites with the groundwater input playing an important role in establishing the degree of saturation in these systems.

Wetlands provide some measure of flood control. The low gradients and available storage within the sediments provide wetlands with the ability to temporarily retain stormflows. The magnitude of the peak flow reduction is influenced strongly by the drainage characteristics of the wetland site and the seasonal variability in available storage space within the sediments.

As our knowledge and understanding of wetland processes grows, increased interest is being focused on the application of numerical simulation models to wetland environments. However, studies involving the application of simulation models to swamp environments are not well represented in the wetland literature.

CHAPTER 3

3. Description of Wetland Model

3.1 Introduction

3.1.1 Background

From a mathematical perspective, the term *model* describes a system of assumptions, equations and procedures intended to characterize the behaviour of a prototype system (Linsley *et al.*, 1982). With respect to the science of hydrology, a *hydrologic model* represents an assemblage of models, with each model corresponding to an individual component of the hydrologic cycle. The relative importance of each component of the hydrologic cycle incorporated in the model is dependent on the model application. For any given application, the complexity of each model component will vary with the model requirements and data availability.

Event-based streamflow simulation (EBSS) models incorporate the hydrologic processes that dominate the rainfall-runoff response over short time periods. These event-based simulation models focus on the partitioning of rainfall into the infiltration and runoff components. Long-term processes such as evapotranspiration, soil moisture storage and groundwater flow are commonly neglected. Alternatively, continuous streamflow simulation (CSS) models maintain a continuous accounting of the water held in storage within the watershed. As a result of the long simulation periods, hydrologic processes such as evaporation and subsurface flow take on more significance.

3.1.2 Goals Of The Model Development

The construction of any simulation model must begin with a full recognition of the ultimate end-use of the model and its data requirements. For this research the development of the wetland model is driven by the need to provide a streamflow model capable of simulating the rainfall-runoff response from headwater swamps at the watershed scale. When modelling hydrologic processes at the meso to macro scale, extensive field work to obtain model inputs is not feasible and as such, the conceptualization and parameterization of the wetland model must be consistent with the anticipated amount of available data.

The goal of this research is to develop a numerical model capable of simulating the rainfall-runoff response at headwater wetland sites. The model must be capable of operating as both an event-based streamflow simulation (EBSS) model and as a continuous streamflow simulation (CSS) model. The intent of the EBSS modelling exercise is to evaluate the ability of the model to simulate the short-term rainfall-runoff behaviour exhibited by wooded headwater swamps common to southern Ontario. The goal of the CSS wetland modelling effort is to evaluate the ability of the wetland model to simulate the wetland streamflows over long periods where groundwater interaction and evapotranspiration play a dominant role in the wetland hydrologic budget.

3.2 Programming Software

3.2.1 General

The development of the wetland model was completed using the *Visual Basic for Windows Professional Edition* (Version 3.0). Microsoft *Windows*™ has become the graphical user interface (GUI) of choice for many engineering users. The *Windows* software provides a consistent user interface for many applications and supports excellent screen graphical displays. In 1991, Microsoft introduced the *Visual Basic*™ program development software. *Visual Basic* allows the user to develop large programs using a modular approach and allows the use of the graphical features commonly associated with *Windows* applications (scroll bars, pull-down menus, check boxes, etc.). The program display can contain multiple windows and has the capability of communicating with other *Windows* applications. The speed of the *Visual Basic* software is comparable with *C++* or *Turbo Pascal for Windows* (Walton, 1995).

3.2.2 User Interface

The current wetland program provides menu-driven access to each component of the model. The program provides numerous interactive display screens that allow the user to:

- i) specify the modelling events
- ii) modify the wetland process parameters
- iii) modify the wetland channel parameters
- iv) specify the model mesh
- v) initialize the model to steady-state
- v) optimize the model parameters
- vi) execute a model simulation
- vii) display mass balance calculations
- vii) compare simulated streamflows against historical streamflows
- viii) display phreatic surface within the finite-difference grid
- ix) display a summary of streamflow statistics
- x) generate daily evapotranspiration estimates (Thornthwaite or Turc method)

A sample listing of several of the program display screens is provided in Appendix A.

3.3 Wetland Representation

3.3.1 General

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 rate 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.

3.3.2 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 3.1). The complexity of the routing network is dependent on the size of the modelling catchment, the data availability and the desired level of detail. The routing model computes the channel flows along a main wetland channel and any specified number of tributaries.

3.3.3 Idealization of Wetland Soil System

The current model idealizes the wetland using two storage zones. 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. As indicated in Figure 3.2, the organic sediments of Zone 2 extend from the lower limit of the hummock layer down to the invert of the wetland stream system.

The model assumes that the saturated zone within the organic layer is hydraulically connected to the wetland channel. The wetland channel is idealized as fully penetrating the active layer of the wetland sediments.

3.4 Precipitation

The wetland model requires precipitation data in the form of hourly values. The model currently is limited to precipitation inputs as no snow-melt routine has been implemented at the time of this writing. The current model assumes a uniform rainfall distribution within the wetland boundaries.

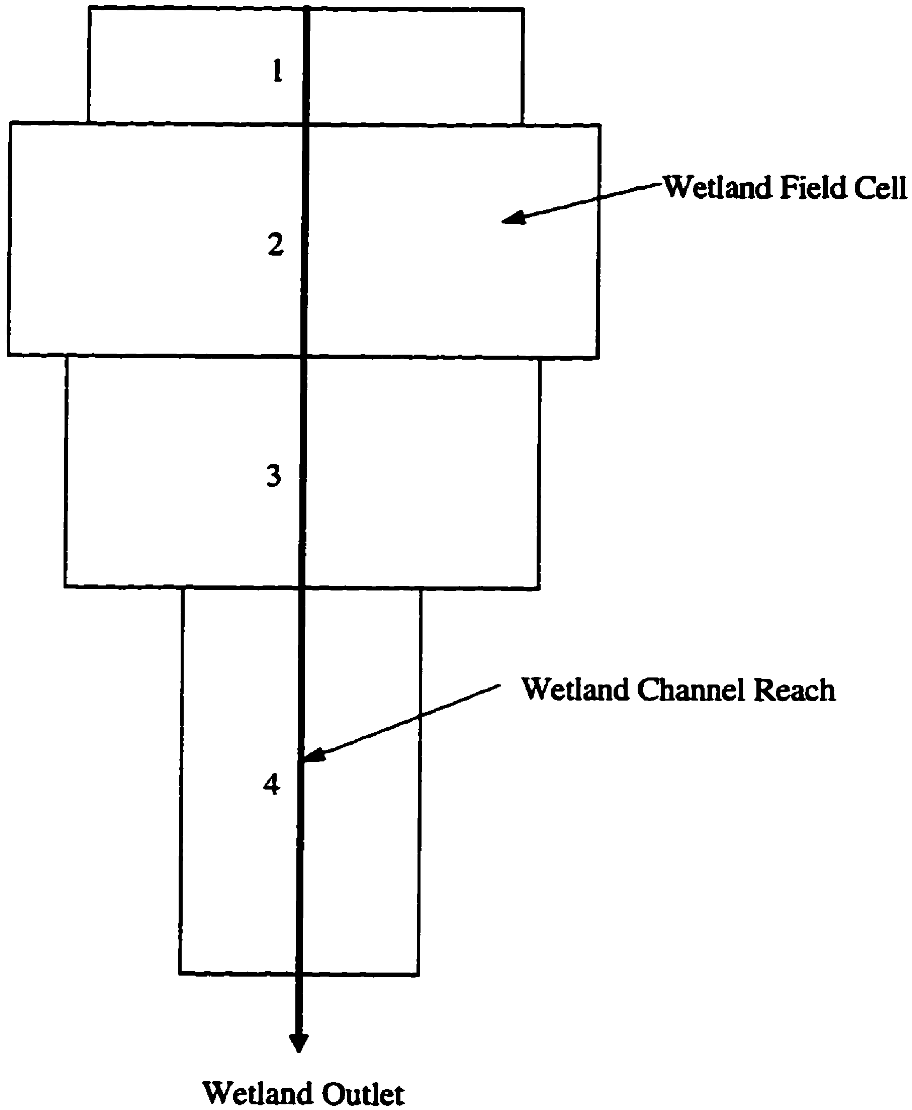


Figure 3.1 Typical wetland reach segmentation

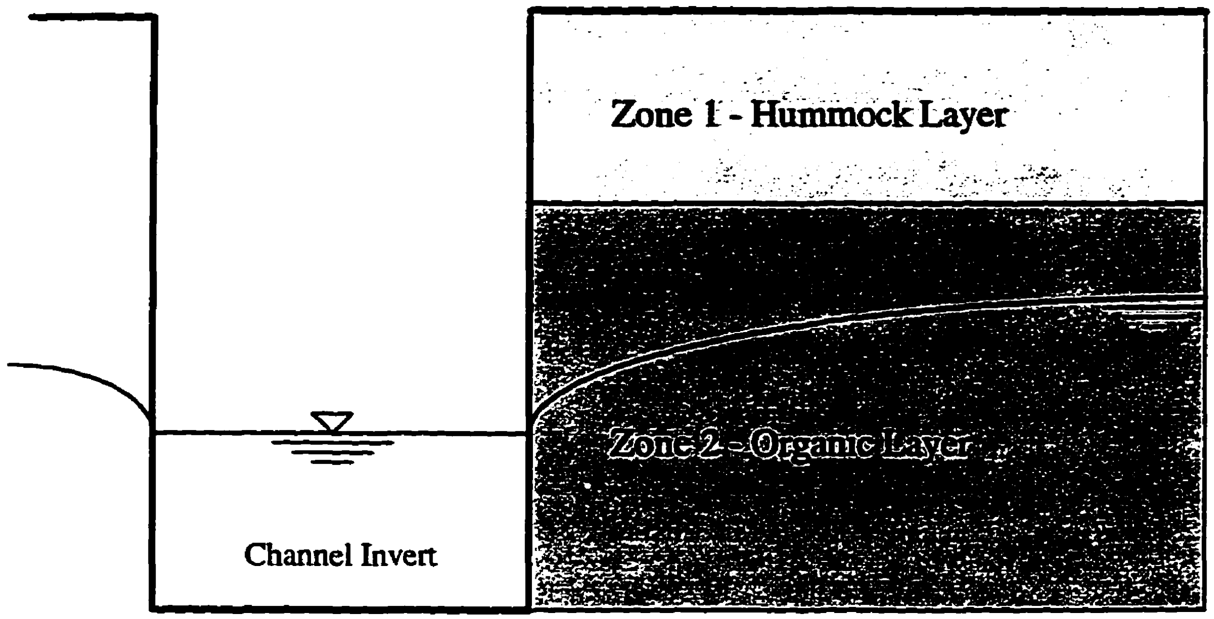


Figure 3.2 Idealization of wetland channel and soil layers

3.5 Estimation of Evapotranspiration

3.5.1 Background

As described in Chapter 2, evapotranspiration can represent a significant long-term water loss in the water budget associated with wetland ecosystems. Evapotranspiration can be distinguished into two components: transpiration from vegetation and evaporation of the moisture existing within the surficial soils and precipitation intercepted by the vegetation. The relationship between evapotranspiration and climatic factors, geographic location and vegetative cover has been investigated by numerous researchers.

Much of the work conducted on measuring and predicting evapotranspiration has been developed with respect to agricultural land uses and irrigation practices (Jensen *et al.*, 1990). Many of these techniques for estimating evapotranspiration are not directly applicable to forests and wooded wetlands. Wooded areas are aerodynamically rougher resulting in lower wind speeds and smaller temperature and humidity gradients above the canopy (Spittlehouse and Black, 1981). In addition, wooded areas generally have different leaf stomatal resistance characteristics and reflect less solar radiation. The estimation of evapotranspiration is often performed using the concepts of potential evapotranspiration (PET) and actual evapotranspiration (AET). The concept of potential evapotranspiration was first presented by Thornthwaite and later reinforced by Blaney and Penman (Mustonen and McGuinness, 1968). Potential evapotranspiration is defined as the rate at which water can be removed from soil and plant surfaces when the system is not water-limited. The hydrologic literature contains numerous techniques for the estimation of PET and AET.

Several rigorous physically-based evapotranspiration models have been presented in literature (Bouten *et al.*, 1992; Verseghy *et al.*, 1993). However, these models typically require a significant amount of data regarding atmospheric conditions, vegetation and soil moisture state. While these models satisfy a research need, they are not convenient for operational use on a watershed scale at this time. As a result, numerous empirically-based evapotranspiration models have been developed that rely on a minimal amount of data. However, many of these models are applicable only to the climate and region in which they were developed (Spittlehouse and Black, 1981). Many of these methods are based on empirical formulas containing one or more climatological data such as temperature, solar radiation, relative humidity or wind speed. Some of the more commonly applied empirical approaches include the Thornthwaite method, the U.S. Weather Bureau approach, the Blaney-Criddle method (Blaney and Criddle, 1945), the Turc formula (Turc, 1961) and the Hargreaves approach (Hargreaves, 1966).

The selection of a suitable evapotranspiration estimation technique must take into account the data availability, the intended use and the required accuracy of the estimate. With regard to estimating catchment scale evapotranspiration estimates, application of the Thornthwaite approach and the Turc formula have been presented within the wetland literature.

3.5.2 Estimation Methods

The wetland model requires values of daily potential evapotranspiration. The current version of the model has an internal capability of providing potential evapotranspiration estimates using the Thornthwaite and Turc methods. The methods require a minimum of data and are well suited for application at the catchment scale.

3.5.2.1 Thornthwaite Model

Thornthwaite (1948) developed a method for estimating potential evapotranspiration from climatological data. Monthly potential evapotranspiration (PET) is estimated using:

$$PET = 1.6\left(\frac{10T}{I}\right)^{a} \tag{3.01}$$

where T is the mean monthly air temperature (°C). I represents an annual heat index computed by summing a series of monthly heat indexes i as follows

$$i = \left(\frac{T}{5}\right)^{1.514} \tag{3.02}$$

and a is a cubic function of I given by

$$a = 6.75x10^{-7} I^{3} - 7.71x10^{-5} I^{2} + 1.79x10^{-2} I + 0.49 \tag{3.03}$$

Using the Thornthwaite approach, temperature records and latitude are sufficient to estimate the potential evapotranspiration at any location. Although the Thornthwaite model is highly empirical, it nevertheless provides an estimate of potential evapotranspiration by an indirect reference to the radiation component of evapotranspiration through the use of the mean monthly air temperature.

3.5.2.2 Turc Formula

The Turc formula (Turc, 1961) utilizes temperature, relative humidity and solar radiation to provide estimates of potential evapotranspiration over 10 day intervals. The Turc formula involves two expressions for the potential evapotranspiration estimate, depending on the value of the average relative humidity:

$$PET = 0.13\left(\frac{T}{T+15}\right)(R_a + 50) \qquad \text{when } W_a < 50\%$$

$$PET = 0.13\left(\frac{T}{T+15}\right)(R_a + 50)\left[\frac{1.20 - W_a}{0.70}\right] \qquad \text{when } W_a \geq 50\% \qquad (3.04)$$

where W_a is the average relative humidity, T is the mean temperature (^{0}C) and R_a is the total incoming radiation (cal/cm^2/day). The incoming radiation can be approximated by:

$$R_a = I_a\left[0.18 + \left(0.62\frac{h}{H}\right)\right] \qquad (3.05)$$

where I_a is the direct solar radiation at the top of the atmosphere (cal/cm^2/day), h is the measured amount of sunshine in hours per day and H is the maximum amount of possible sunshine hours per day. Based on a comparison of evapotranspiration models, Saeed (1986) reported that the Turc formula is a good estimator of potential evapotranspiration.

3.5.3 Temporal Distribution

The current model provides two alternative distribution patterns;

i) daily potential evapotranspiration demand distributed uniformly over the 24 hour period, or
ii) a sinusoidal function over the daylight period.

3.5.4 Estimation of Actual Evapotranspiration

Many operational hydrologic models limit the amount of evapotranspiration from the upper soil layer through an accounting of the soil moisture content. Typically, evapotranspiration is allowed to occur at the potential rate whenever the soil moisture is at field capacity. Below field capacity, the ability of the soil to provide water for the evapotranspiration demand is typically assumed to be a function of the soil moisture content.

The present version of the wetland model assumes that the wetland organic layer maintains a moisture content essentially at field capacity. The evapotranspiration demand is assumed to occur at some user-specified fraction of the potential rate:

$$AET = f \cdot PET \tag{3.06}$$

where f is a specified constant. A value of unity implies that the water lost due to evapotranspiration occurs at the potential rate. Based on a study of the Beverly Swamp, Munro (1979, 1986) found support for the existence of an equilibrium evaporation regime in which vegetative control could be ignored in long-term evaporation work. Adopting an equilibrium model, the actual evapotranspiration demand would be approximately 79% of the potential demand ($f = 0.79$).

3.6 Canopy Processes

3.6.1 Background

In forested areas, interception of precipitation by canopy storage can represent a significant component of the water balance (Rutter *et al.*, 1971; Gash, 1979). For a continuous or long-term hydrologic simulation, the processes of interception and evaporation must be represented in some manner. Over the past two decades, various canopy models have been developed. Typically, the models can be classified as either research or operational models. In general, the models differ with respect to the estimation of the canopy storage depth, when canopy throughfall (drip) is initiated, how the evaporation potential is applied to the removal of moisture stored on the foliage and the computational and data requirements.

The water balance for a forest canopy can be expressed (Rutter *et al.*, 1971) by:

$$P_i - FT_i - D_i - CE_i = \Delta S_i \tag{3.07}$$

where P_i is the total precipitation over time period i, FT_i is the free throughfall, ie: the rainfall that reaches the ground surface without coming into contact with the vegetation,

D_i is the canopy drip - the precipitation that is initially intercepted by the vegetation and subsequently falls to the ground surface, CE_i is the evaporation from the wetted vegetation over the time period and ΔS_i is the change in interception storage over the time period.

3.6.2 Canopy Storage

The wetland model allows the user to characterize the vegetation interception storage capacity using two common methods:

i) Several models have utilized the concept of a leaf area index (LAI), the ratio of the vegetative leaf area (all sides) to the ground area (m^2/m^2). The interception storage capacity (S_{max}) is computed using the appropriate LAI and an interception capacity coefficient (S_{int}):

$$S_{max} = S_{int} \cdot (LAI) \tag{3.09}$$

A typical value for the interception capacity coefficient is 0.2 mm (McCarthy *et al.*, 1992; Spittlehouse and Black, 1981). The appropriate value of a LAI is dependent of the type of vegetation, the density of the stand, and the seasonal variation in foliage growth. Table 3.1 provides a representative summary of LAI values reported by Verseghy *et al.* (1993).

Table 3.1 LAI values for various vegetation types (from Verseghy *et al.*, 1993)

Vegetation Class	LAI Values
Evergreen needleleaf	4.0-5.0
Evergreen broadleaf	10.0
Deciduous needleleaf	0.5-4.0
Deciduous broadleaf	0.5-6.0
Evergreen shrub	4.0
Deciduous shrub	0.5-4.0

ii) The alternative approach is to simply assign a mean canopy storage capability (mm) based on the class of vegetation and coverage fraction. In general, a storage capacity of 1 mm is generally applicable to most deciduous stands in leaf and a value of 0.5 mm is suitable for leafless stands. Values of the maximum canopy storage for conifers typically ranges from 1-2 mm, depending on the density of the vegetation.

The wetland model regards the wetland canopy as having a surface storage capacity, S, that is filled through precipitation and released by evaporation. Water is assigned to the canopy storage at a rate, I, given by:

$$I = P(1-p) \qquad (3.09)$$

where P is the rainfall intensity and p is the coefficient of free throughfall. Drip from the canopy storage volume does not occur until precipitation has satisfied the canopy storage.

3.6.3 Canopy Evaporation

Moisture detained by interception is removed through the process of evaporation. When the amount of water on the canopy, S, equals the surface storage capacity, S_{max}, moisture is removed at the potential evaporation rate:

$$E_{canopy} = PET \qquad (3.10)$$

For a partially wet canopy, the actual evaporation rate, E_{canopy}, is given by:

$$E_{canopy} = PET\left(\frac{S}{S_{max}}\right) \qquad (3.11)$$

3.7 Groundwater Input

In the temperate regions of North America, many wetland systems exist at groundwater discharge areas, taking the form of spring-fed treed headwater wetlands. These wetland sites often represent a surface feature of a large and complex intermediate or regional groundwater flow system. If the wetland sites are connected to a local groundwater system, the hydrologic behaviour and stormflow response can vary in conjunction with the seasonal nature of the groundwater flows.

In order to model those wetland systems, an estimate of the groundwater contribution to the streamflow is required for any long-term modelling effort. As reported in Chapter 2, quantifying the groundwater component of the wetland water budget is a very difficult endeavour. For single wetland sites, a hydrogeological investigation is required to quantify the groundwater fluxes entering or leaving a wetland site. However, when modelling at the watershed scale, the estimation of the groundwater interactions associated with a suite of wetland sites will generally require a simpler approach. An estimate of the groundwater contribution can be obtained from:

i) an externally-determined, user-specified value, or
ii) a value obtained through calibration of the wetland model against historical streamflow data.

The current version of the wetland model incorporates two simplifying assumptions regarding the interaction between the wetland surface processes and the underlying groundwater regime:

i) The model currently adopts a constant steady-state groundwater flux, applied over the duration of the simulation. If data were to exist, the model could easily be modified to allow the specified groundwater flux to change temporally (ie: on a daily, weekly or monthly basis).

ii) The wetland model applies the vertical flux uniformly over the areal extent of the wetland sediments. Studies involving several small, well instrumented wetland sites have indicated that groundwater often enters the wetland along preferential pathways, producing localized saturated zones. If such data were available, the model could easily be modified to account for the areal distribution of the groundwater inflows.

3.8 Wetland Field Hydrology Model

3.8.1 General

In order to predict the stormflow response from wetland systems, it is essential to understand the internal transport processes that control the movement of water within the wetland boundaries. Horizontal movements of water through a wetland are influenced by numerous factors including the nature of the wetland vegetation, the surface topography, the degree of 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 and through the wetland vegetation. It is recognized that the presence of a significant microtopography (hollows and hummocks) can be important to the wetland's capacity to contribute to stormflow. Hammer and Kadlec (1986) proposed that the wetland surface could be idealized as a doubly porous medium, with a fine scale porosity associated with plant stems, leaves and litter, and a coarse scale porosity due to the presence of hammocks and channels.

3.8.2 Friction Models

There has been relatively little research conducted on the numerical simulation of overland flow through wetland ecosystems (Kadlec and Knight, 1996). The rate of flow through most wetland environments is very low and as a result, the inertial and acceleration terms in the momentum balance are negligible in comparison to the gravitational and friction terms. With the frictional and gravity effects in balance, flows through a wetland environment can be modelled using an appropriate mass balance and a relationship between velocity and gradient.

Kadlec *et al.* (1981) reported on a field study to evaluate the appropriate friction law governing overland flows through wetland environments. As part of the study, four alternative friction laws were investigated; Darcy's laminar flow through porous medium, a v^2 power law appropriate to turbulent flow through porous media, a laminar flow model with a depth-variable porosity to reflect the presence of hummocks, and finally, a square of the depth power law. The study concluded that the flow rates are strongly governed by the material balance and are relatively insensitive to the adopted friction law.

3.8.2.1 Manning's Law

Kadlec and Knight (1996) report on a series of emergent marsh studies in Florida whose results make up a large volume of the available wetland friction data. In general, Manning's n is highly dependent on flow depth and vegetation density. Based on the Florida data and research at the Houghton Lake site in Michigan (Kadlec *et al.* 1981; Hammer and Kadlec, 1986; Kadlec, 1990), preliminary recommendations were offered regarding the estimation of Manning's n for flow through emergent marshes. For sparse vegetation systems:

$$n = \frac{0.20}{h^{1.7}} \qquad \text{where } 0.05 < h < 1.0 \text{ metres} \qquad (3.12)$$

where h represents the depth of flow (m). For dense vegetation environments, the appropriate relationship is given by:

$$n = \frac{1.0}{h^{1.7}} \qquad \text{where } 0.10 < h < 1.0 \text{ metres} \qquad (3.13)$$

3.8.2.2 Power Law

For many wetland sites the use of Manning's equation is not appropriate for several reasons. 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 the Manning's open channel friction equation to wetland systems, several researchers have adopted a more relaxed power law formulation:

$$Q = W\alpha d^{\beta+1} S^{\chi} \tag{3.14}$$

where Q is the volumetric flow rate (m^3/s), W is the wetland width (m), d is the water depth (m), S is the energy gradient (m/m), α is the friction law coefficient, β is the hydraulic depth exponent and χ is the energy slope exponent. When β equal to 0.67 and χ is equal to 0.5, equation (3.14) is applicable to a turbulent open channel flow regime.

For application to wetland systems, Kadlec and Knight (1996) recommend a laminar flow formulation (χ=1.0) until further research data becomes available. Kadlec and Knight (1996) report a range of $1.0 < \beta < 2.4$ for the hydraulic depth exponent. Past studies (Kadlec 1981; Hammer and Kadlec, 1986) have indicated that the computed water surface profiles are not sensitive to the selection of beta within normal operating ranges. Until more research is conducted, a depth exponent of 2 is recommended (Kadlec and Knight, 1996).

The friction law coefficient is influenced by vegetation and litter density. Until further data becomes available, Kadlec and Knight (1996) recommend a coefficient value of 116 m^{-1}/s for densely vegetated marshes and 580 m^{-1}/s for sparsely vegetated marshes.

3.8.3 Overland Flow Model

The wetland model utilizes the laminar friction law model as proposed by Kadlec (1986). Adopting the power law formulation, the overland flow velocity (v_x) can be expressed by:

$$v_x = \alpha d^{\beta}\left(-\frac{dh}{dx}\right) \tag{3.15}$$

where dh/dx is the slope of the water surface within the hummock layer.

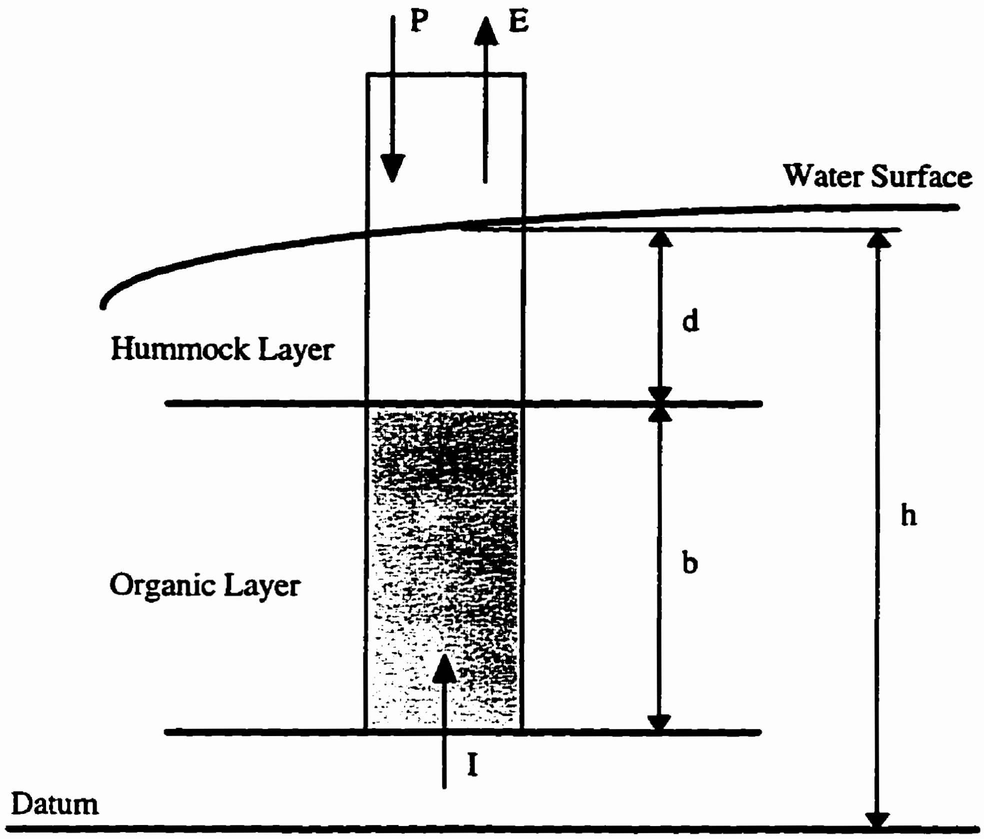


Figure 3.3 Representative element of wetland

Using a representative element (Figure 3.3), Hammer and Kadlec (1986) presented a mathematical model for overland flow through vegetated wetland areas. A one-dimensional mass balance formulation of the surface flow utilizing equation (3.15) is described by:

$$\phi_s \frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(\alpha d(h)^{\beta+1} \frac{\partial h}{\partial x} \right) + (P - E \pm I) \quad (3.16)$$

where h is the head elevation relative to some arbitrary datum, $d(h)$ is the depth of flow within the hummock layer, ϕ_s represents the specific yield or drainable porosity, P is the net precipitation rate (m/s), E is the evapotranspiration rate (m/s) and I represents the rate of vertical leakage associated with the underlying sediments (m/s).

3.8.4 Subsurface Flow Model

An additional term can be added to equation (3.16) to account for the movement of water within the wetland sediments. The specific discharge (q_x) within the wetland sediments is related to the gradient in head through Darcy's law (Bear, 1979)

$$q_x = -K(h)\frac{dh}{dx} \tag{3.17}$$

where K(h) is the depth-averaged hydraulic conductivity associated with the organic sediments. Incorporating equation (3.17) into the mass balance expression yields:

$$\phi_s \frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(\left[b(h)K(h) + \alpha d(h)^{\beta+1}\right]\frac{\partial h}{\partial x}\right) + (P - E \pm I) \tag{3.18}$$

where $b(h)$ is the thickness of the saturated flow within the organic layer. Equation (3.18) provides a general depth-averaged mass balance representation for combined surface and subsurface flow through a wetland environment.

For the one-dimensional formulation, the rate of flow per unit width per unit hydraulic gradient (or transmissivity, T_x) is given by:

$$T_x = b(h)K(h) + \alpha d(h)^{\beta+1} \tag{3.19}$$

The transmissivity value integrates the effects of micropore flow, macropore flow, surface flow within the hummock terrain and preferential surface flow along surface streamlets or channels.

Implicit with the use of equation (3.18) 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 application of a one-dimensional depth-averaged groundwater flow representation has been successfully applied to several studies involving the lateral water movement in tidal marshes. Nuttle (1988) utilized a model of depth-averaged model to study the horizontal water fluxes in a tidal marsh near Boston, Massachusetts. In the marsh studied, the semidiurnal tidal influences were limited to a region within 15 metres of the creek bank. Harvey *et al.* (1987) applied a numerical model to simulate the subsurface hydraulics in the vicinity of a creek bank subjected to regular tidal flooding. Observed changes in hydraulic head over complete tidal cycles were accurately predicted by the model.

The specific yield or drainable porosity, ϕ_s can be defined as the change in water content per unit change in head, per unit surface area. The value of the drainable porosity is dependent on the position of the hydraulic head within the wetland. When the phreatic surface is located entirely above the hummock layer, the drainable porosity is set equal to unity. When the phreatic surface is located within the organic layer, the drainable porosity is equivalent to the drainable porosity associated with the organic sediments.

3.8.5 Numerical Formulation of the Wetland Flow Model

3.8.5.1 Governing Equation

The wetland model utilizes the one-dimensional mass balance formulation for surface and subsurface flow through a wetland environment (equation 3.19). Expressing in terms of transmissivity:

$$\phi_s \frac{\partial h}{\partial t} = \frac{\partial}{\partial x}\left(T_x \frac{\partial h}{\partial x}\right) + R(x,t) \tag{3.20}$$

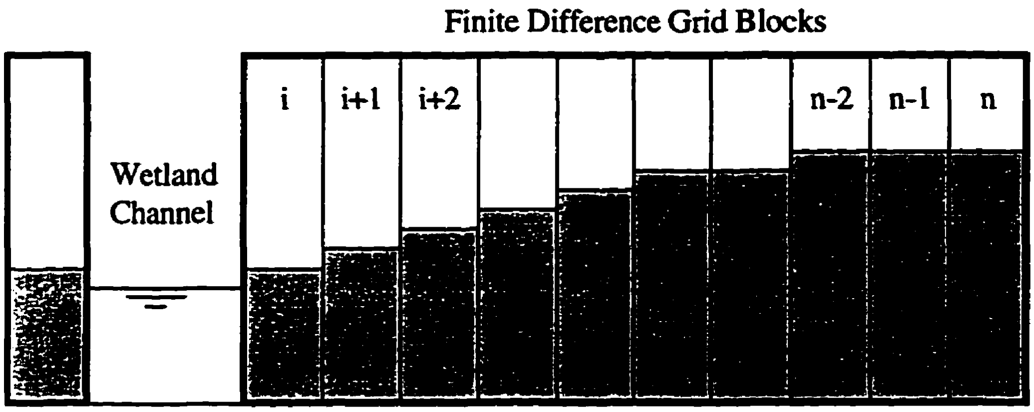
where:

φ_s	-the drainable porosity
h	-hydraulic head (m)
x	-flow length in the direction of flow (m)
T_x	-horizontal transmissivity (m^2/s)
$R(x,t)$	-source/sink term accounting for recharge or withdrawal

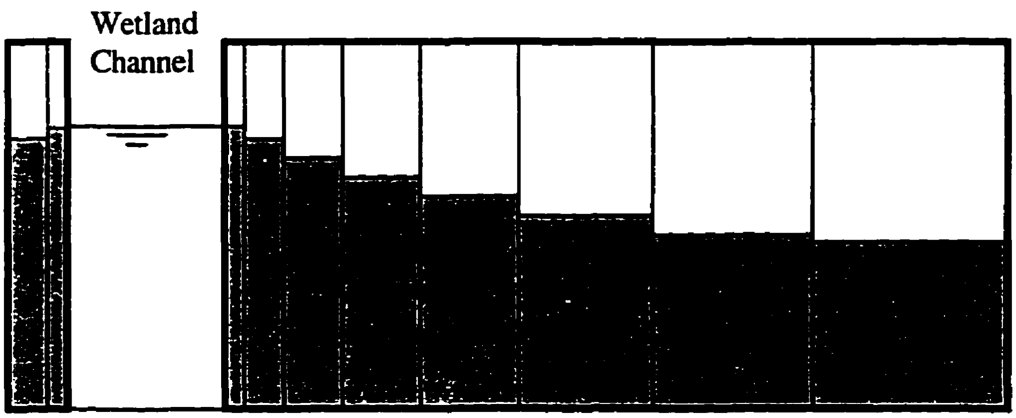
The use of equation (3.20) assumes that the direction of water movement in both the sediment layer and hummock layer is perpendicular to the wetland stream. At each grid, the dominant hydrologic processes (ie: precipitation, canopy interception, evapotranspiration and groundwater input) are specified or simulated and subsequently incorporated into the source/sink term in equation (3.20).

3.8.5.2 Model Mesh

The application of the wetland hydrology model consists of idealizing each wetland field cell into a series of finite-difference grids located adjacent to a stream routing reach and solving the appropriate mass balance equation appropriate to each grid block. The wetland program provides a pre-processor to generate the finite-difference mesh and assign elevation data to each grid block. The wetland model has the capability of utilizing either a uniform or variable grid mesh (Figure 3.4). The variable mesh is generated using:



a) Uniform grid (shown with an effluent stream)



b) Variable grid (shown with an influent stream)

Figure 3.4 Finite-difference model meshes

$$D_n = L\left(\frac{n-1}{N}\right)^2 \tag{3.21}$$

where D_n is the distance from the wetland stream to the left edge of grid block *n*, *L* is the width of the wetland field cell and *N* is the number of grid blocks contained in the model mesh.

The variable grid mesh established using equation (3.21) provides a smaller grid resolution near the wetland streams while incorporating a coarser grid near the wetland margin. To illustrate, a 500 metre wetland field cell characterized using a variable mesh involving 30 grid blocks will incorporate a 0.60 metre grid block immediately adjacent to the stream while providing a 32.8 metre grid block at the wetland margin.

3.8.5.3 Finite-Difference Representation

Adopting a block-centred, finite-difference formulation, equation (3.20) may be approximated by:

$$\frac{\phi_s}{\Delta t}\left(h_i^{t+\Delta t} - h_i^t\right) - R_i^t = \frac{1}{\Delta x_i}\left[\left(T_{i+1/2}\frac{\left(h_{i+1}^{t+\Delta t} - h_i^{t+\Delta t}\right)}{\Delta x_{i+1/2}}\right) - \left(T_{i-1/2}\frac{\left(h_i^{t+\Delta t} - h_{i-1}^{t+\Delta t}\right)}{\Delta x_{i-1/2}}\right)\right] \tag{3.22}$$

where

Δt	-is the time increment
Δx	-is the space increment in the x direction
i	-is the index in the x direction
$T_{i+1/2}$	-the horizontal transmissivity between block i and block i+1
$T_{i-1/2}$	-the horizontal transmissivity between block i and block i-1
$\Delta x_{i+1/2}$	-the distance between the centre of block i and block i+1
$\Delta x_{i-1/2}$	-the distance between the centre of block i and block i-1

Figure 3.5 illustrates the representation of saturated flow between two finite-difference grid blocks.

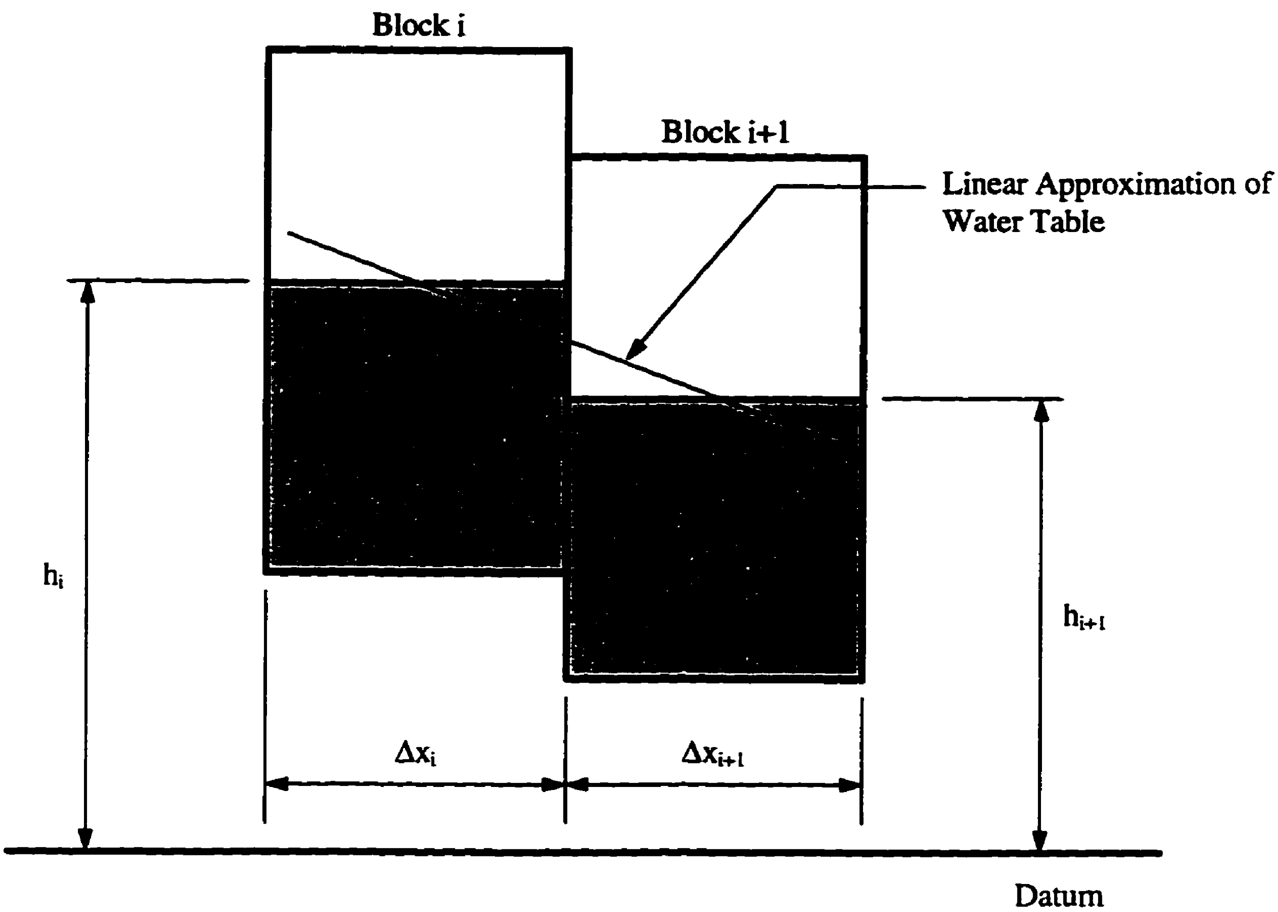


Figure 3.5 Flow between two adjacent grid blocks

Utilizing the harmonic mean of the transmissivity between grid blocks:

$$T_{i+1/2} = \frac{\frac{\Delta x_i}{2} + \frac{\Delta x_{i+1}}{2}}{\frac{\frac{\Delta x_i}{2}}{T_i} + \frac{\frac{\Delta x_{i+1}}{2}}{T_{i+1}}} \tag{3.23}$$

$$T_{i-1/2} = \frac{\frac{\Delta x_i}{2} + \frac{\Delta x_{i-1}}{2}}{\frac{\frac{\Delta x_i}{2}}{T_i} + \frac{\frac{\Delta x_{i-1}}{2}}{T_{i-1}}} \tag{3.24}$$

Equation (3.22) can be simplified as:

$$\frac{\phi_s}{\Delta t}\left(h_i^{t+\Delta t} - h_i^t\right) - R_i^t = C_i\left(h_{i+1}^{t+\Delta t} - h_i^{t+\Delta t}\right) - D_i\left(h_i^{t+\Delta t} - h_{i-1}^{t+\Delta t}\right) \tag{3.25}$$

with

$$C_i = \frac{\dfrac{2T_i T_{i+1}}{T_i \Delta x_{i+1} + T_{i+1}\Delta x_i}}{\Delta x_i} \tag{3.26}$$

and

$$D_i = \frac{\dfrac{2T_i T_{i-1}}{T_i \Delta x_{i-1} + T_{i-1}\Delta x_i}}{\Delta x_i} \tag{3.27}$$

Use of the harmonic mean of the block transmissivities ensures continuity across block boundaries if a variable grid size is used. With respect to the boundary conditions associated with the finite-difference grid, the coefficients expressed in equations (3.26) and (3.27) become zero for a no-flow boundary condition.

For instances where the wetland head in a grid block is below the hummock surface, subsurface flow prevails and the horizontal transmissivity associated with the organic layer is computed as:

$$T_i = \left(K_i b_i\right) \tag{3.28}$$

where b_i is the thickness of the saturated flow within grid block i. Inundation of the organic sediments allows water to traverse the wetland as a combination of surface and subsurface flow. For any grid block where the organic sediments are inundated with the free surface located within the hummock layer, the transmissivity is computed as:

$$T_i = \left(K_i b_i + \alpha d_i^{\beta+1}\right) \tag{3.29}$$

where b is the thickness of the saturated organic layer and d is the depth of overland flow. Rearranging equation (3.25) such that the known terms are collected on the left-hand side of the equation:

$$C_i h_{i+1}^{t+\Delta t} - C_i h_i^{t+\Delta t} - D_i h_i^{t+\Delta t} + D_i h_{i-1}^{t+\Delta t} - \frac{\phi_s}{\Delta t} h_i^{t+\Delta t} = -\frac{\phi_s}{\Delta t} h_i^t - R_i^t \qquad (3.30)$$

or

$$D_i h_{i-1}^{t+\Delta t} + E_i h_i^{t+\Delta t} + C_i h_{i+1}^{t+\Delta t} = -\frac{\phi_s}{\Delta t} h_i^t - R_i^t \qquad (3.31)$$

where

$$E_i = -\left(\frac{\phi_s}{\Delta t} + C_i + D_i\right) \qquad (3.32)$$

The source term, R_i, accounts for the primary vertical fluxes associated with each grid block including:

i) recharge from net precipitation,
ii) evapotranspiration,
iii) discharge to or from the underlying sediments and,
iv) runoff across the wetland margin from adjacent land uses.

In the wetland model, the source term is computed as:

$$R_i^t = qp_i^t + qg_i^t + qr_i^t - qe_i^t \qquad (3.33)$$

where

qe_i -evapotranspiration flux per unit area (m/s)
qp_i -effective precipitation flux per unit area (m/s)
qg_i -flux per unit area associated with underlying sediments (m/s)
qr_i -recharge per unit area along wetland margin blocks (m/s)

3.8.5.4 Boundary Conditions

The exterior blocks associated with the finite-difference grid are used to introduce the boundary conditions. The interface between the wetland sediments and the wetland channel is modelled as a specified head boundary (Dirichlet) condition. The wetland stream is assumed to be hydraulically connected to the shallow groundwater system and, for each routing reach, the surface water elevation within the channel is used to specify the head boundary condition at the wetland-stream interface for that time step.

At the wetland boundary, a no-flow boundary is employed. The current model does not allow water stored within the sediments to exit the wetland at the margin. Depending on the topography of the surrounding basin, some wetlands may receive inflow from surface runoff and interflow from the adjacent land use. Runoff from any adjacent land uses is simulated as an additional recharge along the boundary nodes as indicated in equation (3.33).

3.8.5.5 Depth-Variable Hydraulic Conductivity

It is generally recognized that the hydraulic conductivity associated with wetland organic sediments varies with the degree of humification and depth. As reported in Chapter 2, within a single peat column the conductivity can vary by several orders of magnitude. The current wetland model requires two values of hydraulic conductivity, corresponding to the values at the top (K_{TOP}) and bottom of the organic layer (K_{BOT}).

The model incorporates a simple linear relationship between the two conductivity values (Figure 3.6). The depth-variable conductivity representation results in a rapid increase in transmissivity as the saturated depth of the wetland sediments is increased. If distributed data are available, the wetland model can easily be modified to use a non-linear variation in the conductivity values.

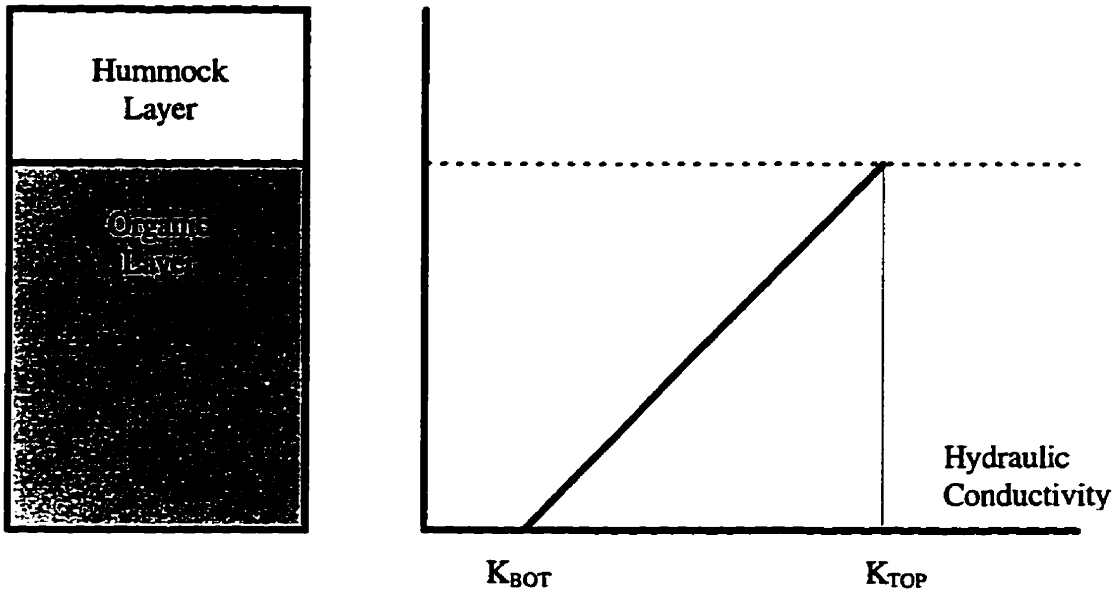


Figure 3.6 Variation of hydraulic conductivity within organic layer

3.8.6 Solution of the Wetland Flow Model

In matrix notation, equation (3.31) can be expressed as:

$$[COEF]^t [h]^{t+\Delta t} = \left[-R - \frac{\phi_s}{\Delta t} h \right]^t \qquad (3.34)$$

For the one-dimensional representation of the wetland flows, the coefficient matrix [COEF] in equation (3.34) is tridiagonal and solution is solved readily using the well-known Thomas algorithm. However, in unconfined aquifer systems, the transmissivity associated with any grid block is a function of the head in that grid block. The solution of equation (3.34) is accomplished through an iterative process. At the beginning of a time step, the transmissivity associated with each grid block is based on the previous solution of the head within the block. Following the groundwater solution, the revised head elevation in each grid block is compared to the previous estimate used to compute the transmissivity. If the difference in head is within a specified tolerance for all grid blocks, the model proceeds to the next time step. If the head difference is greater than the tolerance in any grid block, the groundwater model is re-solved with the transmissivities revised to reflect the most recent head estimates as shown below:

$$\left(T_i^{t+\Delta t}\right)^{k+1} = \left(K_i b_i^{t+\Delta t} + \alpha\left(d_i^{t+\Delta t}\right)^{\beta+1}\right)^k \tag{3.35}$$

where k represents an iteration counter. With the exception of the time periods involving significant amounts of precipitation, solution of the groundwater model was typically accomplished in one or two iterations.

3.8.6.1 Storage Conversion

The storage term requires special treatment at grid blocks when, during a time step, a conversion occurs from subsurface flow within the organic layer to free surface flow through the hummock layer, or vice versa. For the case where the saturation state of a grid block changes from a water table condition within the organic layer to free surface flow within the hummock layer (Figure 3.7), the appropriate storage term is given by:

$$\phi_s \frac{h_i^{t+\Delta t} - h_i^t}{\Delta t} = \frac{\phi_{organic}}{\Delta t}\left[TOPORG_i - h_i^t\right] + \frac{\phi_{hummock}}{\Delta t}\left[h_i^{t+\Delta t} - TOPORG_i\right] \tag{3.36}$$

where $TOPORG$ represents the elevation corresponding to the top of the organic layer. For the case where a grid block is draining and the saturation state changes from free surface flow within the hummock layer to a water table condition within the wetland organic layer, the storage term becomes:

$$\phi_s \frac{h_i^{t+\Delta t} - h_i^t}{\Delta t} = \frac{\phi_{hummock}}{\Delta t}\left[h_i^{t+\Delta t} - TOPORG_i\right] + \frac{\phi_{organic}}{\Delta t}\left[TOPORG_i - h_i^t\right] \tag{3.37}$$

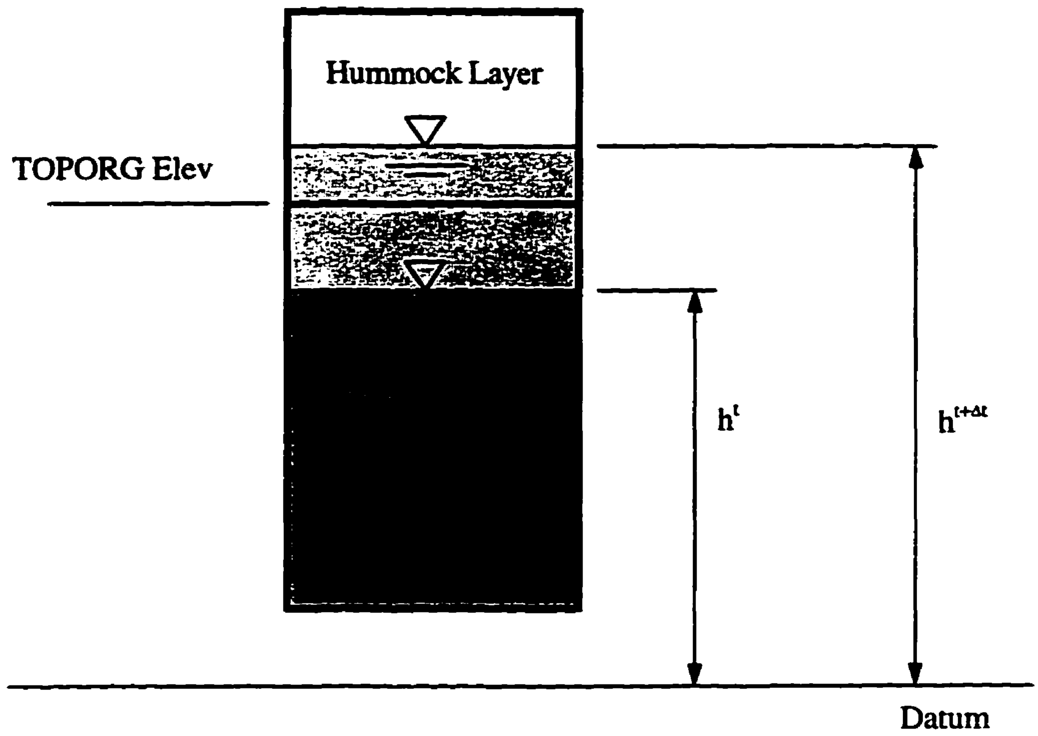


Figure 3.7 Inundation of organic layer

3.8.7 Water Balance Calculations

A water balance calculation is a necessary component of any groundwater modelling exercise. A typical water balance calculation involves the computation of all flows across the system boundaries, flows to and from sources or sinks and an accounting of the storage within the system. The difference between the total inflow and outflow is divided by the total inflow to provide an estimate of the error in the water balance. An error of 1% is typically considered acceptable. A small error in the water balance provides additional assurance that the code is correctly solving the governing mathematical model.

The wetland model provides a display screen providing a summary of the water balance calculations for the most recent simulation. The display provides a listing of the water balance error for each wetland field cell over each time step of the simulation. In addition, the model computes an overall water balance error associated with the entire simulation.

3.9 Wetland Channel Routing Model

3.9.1 General

In the wetland 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 will play an important role in governing the nature of the rainfall-runoff response from wetland systems. In order to accurately predict 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.

3.9.2 Background

Channel routing involves the mathematical simulation of open channel flow conditions along natural river or stream systems using established hydraulic principles. Our present day modelling techniques find their origin in the 19^{th} century work of St. Venant and Boussinesq, who formulated the equations of unsteady flow. Significant theoretical concepts were established during the first half of this century but the first engineering applications of these principles did not occur until the development of the computer.

The mathematical flood routing models currently available can be generalized into models adopting a conceptual or systems approach, commonly referred to as *hydrologic models*, or process-type models, often called *hydraulic models*. Over the past two decades, numerous models have been developed within both groups. Developments in computer technology and numerical techniques have prompted an increase in the application of process-type models for flood routing simulations. The practical application and efficiency of such models is limited however by the high input data requirements and the high demands on computer resources. In certain situations, computational difficulties can arise when the physical flow depths are small, typically during long inter-storm periods. At a section that is subject to shallow depth, supercritical flow may develop and, if the modelling system is based on an implicit finite-difference scheme, unstable numerical oscillations may develop (Cunge *et al.*, 1980).

Numerous approximate routing models have been developed and presented in past flood routing literature. Hydrologic routing employs an equation of continuity coupled with either an analytical or an assumed relationship between discharge and storage. Although there are numerous hydrologic routing approaches, they generally differ in their formulation of the discharge-storage relationship. While providing results at considerably lower expense, the accuracy of such a model is dependent on the particular simplifications inherent in the model and the specific application for which the model is used.

The advantage of low data requirements is an important consideration in selecting a storage routing technique over a complete hydraulic approach based on the St. Venant equations. The storage routing methods also provide an advantage with respect to computational expense. Typically, flow simulations in natural rivers utilizing the complete Saint Venant equations require computational increments of the order of 1 kilometre or less, while storage routing methods can successfully use routing reaches of 10-50 kilometres.

3.9.3 Selection of Routing Model

With regard to the implementation of any continuous routing scheme, 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 anticipated to be very low. As a result, the use of a data-intensive channel routing model is not suitable for the modelling of stream flows through wetland systems at the watershed scale.

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. Based on the above considerations, the wetland routing model incorporates a simple storage routing model. Storage routing is based primarily on the conservation of mass equation:

$$I - O = \frac{\Delta S}{\Delta t} \qquad (3.38)$$

where I is the average rate of inflow into the channel reach, O is the average rate of outflow from the reach, and ΔS is the change in storage within the channel reach over some time increment Δt. The solution of equation (3.38) 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:

$$O = \frac{1}{n} A R^{2/3} S_o^{1/2} \tag{3.39}$$

where A is the cross-sectional area of flow within the channel, R is the hydraulic radius and S_o is the bed slope of the wetland channel. The coupling of the Manning equation for uniform flow with the continuity equation has proved successful in the routing schemes incorporated into the WATFLOOD model (Kouwen, 1996).

3.9.4 Representation of Channel Geometry

The current wetland routing model incorporates a simple rectangular channel configuration with streamflows limited to channel flow between the bank stations. Overbank flow, parallel to the drainage channel, is not accounted for in the current version of the wetland model.

The rectangular representation of the channel geometry provides a reasonable approximation, suitable for the limited data associated with wetland systems. Characterization of the channel conveyance capabilities of each routing reach is provided by the following parameters:

- i) channel width
- ii) channel depth
- iii) channel roughness, and
- iv) channel slope.

3.9.5 Numerical Formulation of the Channel Routing Model

Expressed in a centred finite-difference form, equation (3.38) becomes:

$$\frac{I_t + I_{t+\Delta t}}{2} - \frac{O_t + O_{t+\Delta t}}{2} = \frac{S_{t+\Delta t} - S_t}{\Delta t} \tag{3.40}$$

Rearranging equation (3.40) to solve for $O_{t+\Delta t}$, the outflow from the wetland channel reach at the end of the modelling time step, the continuity equation becomes:

$$O_{t+\Delta t} = I_t + I_{t+\Delta t} + \frac{2S_t}{\Delta t} - O_t - \frac{2S_{t+\Delta t}}{\Delta t} \tag{3.41}$$

For any time step, the inflow into a given channel reach is obtained by summing the discharge entering the channel at the upstream boundary and the lateral inflow associated with the reach:

$$I_t = Q_t + q_t \tag{3.42}$$

$$I_{t+\Delta t} = Q_{t+\Delta t} + q_{t+\Delta t} \tag{3.43}$$

where Q represents the channel discharge and q represents the lateral inflow to the channel reach. Adopting a double subscript notation where i is the cross section identifier and j is the time increment corresponding to the solution domain shown in Figure 3.8, equation (3.41) can be expressed as:

$$Q_{i+1,j+1} = Q_{i,j} + q_{i,j} + Q_{i,j+1} + q_{i,j+1} + \frac{2S_{i,j}}{\Delta t} - Q_{i+1,j} - \frac{2S_{i,j+1}}{\Delta t} \tag{3.44}$$

Equation (3.44) cannot be solved directly since $O_{i+1,j+1}$ and $S_{i,j+1}$ are unknown. A second relationship or storage function is required to relate the reach storage and reach outflow at the end of the modelling time step. The wetland channel storage routing model assumes that the channel outflow is a function of the channel storage. The channel outflow is related to the channel storage through Manning's equation for uniform flow:

$$O_{i+1,j+1} = \frac{1}{n_i} A_{i,j+1} R_{i,j+1}^{2/3} S_{0i}^{1/2} \tag{3.45}$$

where n_i is the Manning coefficient for the routing reach, $A_{i,j+1}$ is the mean cross-sectional area of flow corresponding to the reach at the end of the time step, $R_{i,j+1}$ is the mean hydraulic radius corresponding the channel reach and S_{oi} is the bed slope corresponding to the channel reach.

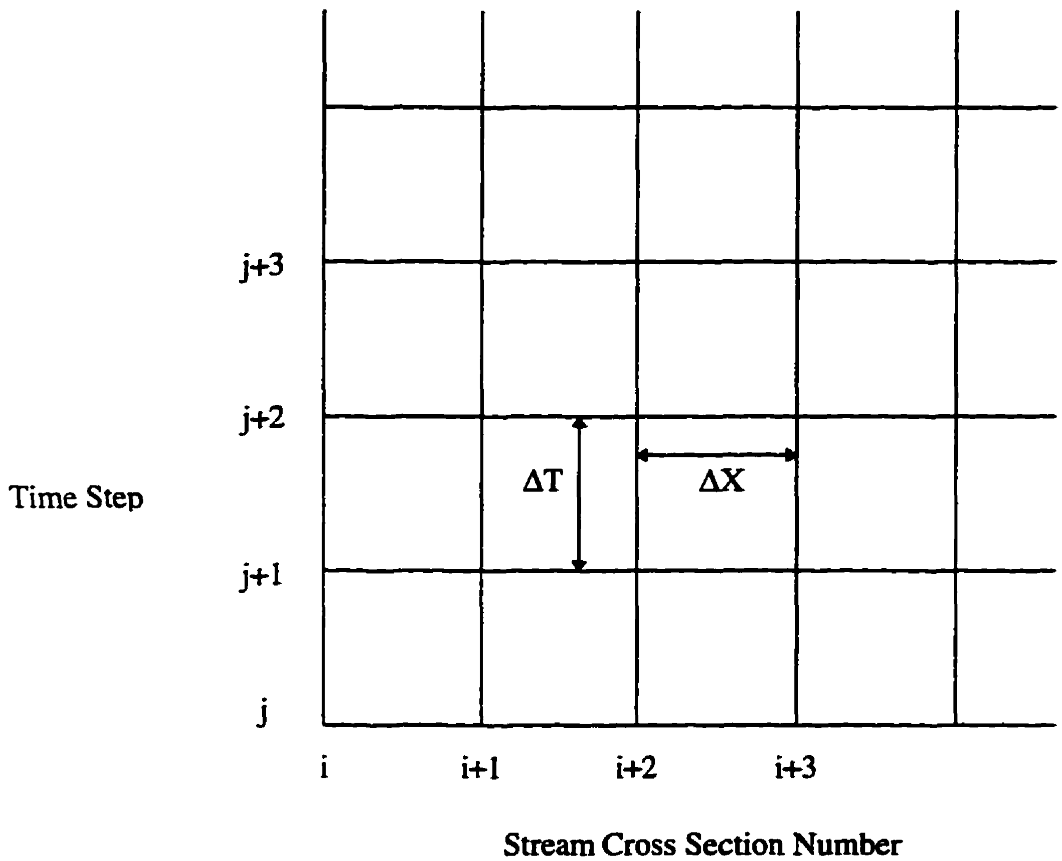


Figure 3.8 Discretization of the space and time domain for the solution of the finite-difference routing scheme

The current routing model utilizes the mean flow depth within the routing reach to establish a corresponding channel outflow. Expressing equation (3.45) in terms of $y_{i,j+1}$, the normal flow depth along routing reach *i*:

$$O_{i+1,j+1} = \frac{1}{n_i} w_i y_{i,j+1} \left[\frac{w_i y_{i,j+1}}{w_i + 2y_{i,j+1}} \right]^{2/3} S_{oi}^{1/2} \tag{3.46}$$

where w_i is the representative width of the wetland channel along reach *i*.

Expressing the channel storage at the end of the time step, $S_{i,j+1}$, as a function of the normal depth associated with the channel reach:

$$S_{i,j+1} = (w_i \Delta x_i) y_{i,j+1} \tag{3.47}$$

where Δx_i is the longitudinal length of routing reach *i*. Substituting equations (3.46) and (3.47) into equation (3.44):

$$\frac{1}{n_i} w_i y_{i,j+1} \left[\frac{w_i y_{i,j+1}}{w_i + 2y_{i,j+1}} \right]^{2/3} S_{oi}^{1/2} = Q_{i,j} + q_{i,j} + Q_{i,j+1} + q_{i,j+1} + \frac{2S_{i,j}}{\Delta t} - Q_{i+1,j} - \frac{2\left((w_i \Delta x_i) y_{i,j+1}\right)}{\Delta t} \tag{3.48}$$

3.9.6 Solution of the Channel Routing Model

Over any time step, equation (3.48) can be simplified by defining several constants:

$$C1 = \frac{S_{oi}^{1/2}}{n_i} \tag{3.49}$$

$$C2 = Q_{i,j} + q_{i,j} + Q_{i,j+1} + q_{i,j+1} + \frac{2S_{i,j}}{\Delta t} - Q_{i+1,j} \tag{3.50}$$

$$C3 = \frac{2(w_i \Delta x_i)}{\Delta t} \tag{3.51}$$

Substitution of the constants C1, C2 and C3 results in the following channel routing equation:

$$C1\left[w_i y_{i,j+1} \left[\frac{w_i y_{i,j+1}}{w_i + 2y_{i,j+1}} \right]^{2/3} \right] = C2 - C3(y_{i,j+1}) \tag{3.52}$$

Equation (3.52) represents the routing function implemented into the wetland routing model. The function is implicit in the variable $y_{i,j+1}$, the normal depth associated with the routing reach at the end of the modelling time step.

The solution of the routing function is accomplished using the Newton-Raphson technique. In order to use the Newton-Raphson approach, the derivative of the function must be developed. Differentiating equation (3.52) with respect to the normal flow depth:

$$f(y) = C2 - C3\left(y_{i,j+1}\right) - C1\left[w_i y_{i,j+1}\left[\frac{w_i y_{i,j+1}}{w_i + 2y_{i,j+1}}\right]^{2/3}\right] \tag{3.53}$$

and

$$f'(y) = -C3 - C1\left(\frac{5w}{3}\right)\left[\frac{w_i y_{i,j+1}}{w_i + 2y_{i,j+1}}\right]^{2/3} + \frac{4}{3}C1\left[\frac{w_i y_{i,j+1}}{w_i + 2y_{i,j+1}}\right]^{5/3} \tag{3.54}$$

Equations (3.53) and (3.54) represent the wetland routing function and the corresponding derivative. The Newton-Raphson technique involves evaluating both the function and the derivative at some initial estimate of y. A new approximation of the root is then obtained using:

$$y^{k+1} = y^k - \frac{f\left(y^k\right)}{f'\left(y^k\right)} \tag{3.55}$$

where the index k represents the iteration counter, y^k is the initial estimate of the normal depth, and y^{k+1} represents the improved estimate. The procedure is repeated until successive values of the revised root estimate are less than a prescribed tolerance.

3.10 Coupling of Routing Model and Wetland Flow Model

3.10.1 General

The development of many flood routing schemes have been presented under the assumption of negligible lateral inflows along the study reaches with lateral inflows limited to tributary flows at river or stream confluences. An important component of the wetland model involves 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 within the drainage channel.

3.10.2 Solution Scheme

The wetland routing model and the wetland field cell model are coupled through the use of Equation (3.50) developed previously:

$$C2 = Q_{i,j} + q_{i,j} + Q_{i,j+1} + q_{i,j+1} + \frac{2S_{i,j}}{\Delta t} - Q_{i+1,j} \tag{3.50}$$

The routing model requires the average rate of inflow resulting from the lateral exchange between the channel and the wetland organic sediments. During the advancement of the solution, the lateral flow corresponding to the end of the time step $q_{i,j+1}$, is initially unknown.

The coupling of the open channel flows and the horizontal flows within the wetland is performed as described by Pinder and Sauer (1971). At the beginning of any time step, the water levels within the wetland stream and wetland field cells are known, and the lateral inflow to the stream along any reach, $q_{i,j}$, 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 function (equation 3.52) with the lateral flow component set equal to the previous value:

$$q_{i,j+1}^{k+1} = q_{i,j}^{k} \tag{3.56}$$

where k represents the iteration count. The new surface water levels are then used as a prescribed head boundary condition for the solution of the wetland flow model (equation 3.31) along each reach. 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 model (equation 3.52) is then re-solved 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 tolerance.

3.11 Initialization of Wetland Model

An important step in any unsteady flow problem is the initialization of the model. With respect to the wetland routing component, at time t=0 the water elevation and discharge associated with all routing reaches must be specified. In addition, the distribution of the heads within all grid blocks defining the wetland field hydrology model must be specified.

The current version of the wetland model allows two alternative methods for the initialization of the model:

i) the wetland site can be initially filled to saturation of the hummock layer and allowed to drain until some specified wetland outflow is reached; or

ii) the wetland can be run until a steady-state, equilibrium condition is established at a specified wetland outflow

3.12 Model Limitations

Prior to the application of any model, it is essential that the user be aware of the assumptions and simplifications incorporated into the model. All operational hydrologic models involve a number of simplifications made necessary by incomplete understanding of processes involved and lack of available data. Depending on the application, the simplifications of the various processes inherent to a model can significantly limit or restrict the ultimate end-use of the model.

In order to be operational at a watershed scale, the current version of the wetland model incorporates a number of simplifying assumptions. These include:

i) The horizontal movement of water within the wetland sediments is formulated as a one-dimensional representation with flows directed perpendicular to the wetland drainage channels. The model formulation incorporates the well known Dupuit-Forchheimer assumptions: 1) neglecting the flow in the vertical direction, 2) assuming that the flow velocity is proportional to the slope of the water table and 3) the flow is horizontal and vertically uniform.

The current model assumes that the wetland channel is hydraulically connected to the saturated groundwater within the wetland sediments. It is well recognized that the Dupuit-Forchheimer approximations are not strictly valid where there is pronounced radial flow as would occur if the drainage channel does not penetrate the organic sediments to depth.

ii) Although the wetland model incorporates a subsurface flow component, the model is not explicitly linked to the underlying groundwater system. The model requires an external estimate of the exchange of water between the wetland and the underlying groundwater flow system. The current version of the model adopts a constant groundwater flux over the simulation period.

iii) The current model adopts a uniform rainfall distribution over the areal extent of the modelled wetland. In reality, uniform rainfall almost never occurs. The assumption of uniform rainfall is reasonably valid when modelling small wetland sites.

iv) The wetland model provides a highly idealized representation of the wetland soil system. The model does not account for any variation of moisture content within unsaturated zone and does not incorporate a rigorous infiltration representation. Water removed from the wetland through evapotranspiration is removed directly from the saturated zone.

The model partitions the stormwater inputs into the surface flow component after full saturation of the wetland sediments. The response of the water table to a precipitation input is controlled by the drainable porosity parameter characterizing the available pore space within the sediments.

v) The wetland routing module incorporates simple storage routing. The routing procedure does not explicitly account for backwater influences produced by downstream controls or local culvert structures.

3.13 Chapter Summary

This chapter describes the components of the numerical wetland model. The model recognizes the dominant hydrologic features affecting the stormflow response from swamp wetland environments. The parameterization of the model is consistent with the poor data environments typical of wetland systems.

The wetland model consists of a field hydrology model fully coupled to a channel routing model. The field hydrology model is based on an idealization of the processes governing the flow of water over and through the wetland soil system. The model utilizes a depth-averaged mass balance formulation to simulate the horizontal movement of stormwater through or over the wetland sediments. An effective or depth-averaged hydraulic conductivity integrates the dominant horizontal flow processes, including both micropore and macropore flow paths within the wetland sediments as well as surface flows across the hummock terrain.

A storage routing model is used to simulate the transport of the streamflows along the wetland drainage system and to allow the exchange of water between the stream system and the wetland sediments.

CHAPTER 4

4. Data Acquisition and Analysis

4.1 General

The goal of this research is the development and application a wetland hydrologic model capable of simulating the runoff response from wetland ecosystems at a watershed scale. As with all physically-based hydrologic models, a critical evaluation of the wetland model requires measured data for calibration and validation. For this research, a data collection program was completed over an 18 month period, extending from June 1994 to October 1995.

This chapter provides a general description of the wetland study site and outlines the methods and sources utilized to obtain the meteorologic and hydrometric data required for the evaluation of the model. The nature of the observed runoff response and the characterization of observed stormflow hydrographs are presented.

4.2 Study Site

4.2.1 Description

A treed headwater swamp located in the central portion of the Teeswater River watershed was selected as the study site during this research (Figure 4.1). Located in south-western Ontario, the Teeswater River basin has a contributing drainage area of approximately 760 square kilometres and forms a tributary of the Saugeen River. The study wetland occupies an area of approximately 400 hectares and exists primarily as a groundwater discharge area with streamflow observed throughout the year. The wetland is drained by approximately 6 kilometres of drainage channel at an approximate gradient of 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 metre. 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. Within the wetland, the natural drainage patterns are disturbed by the presence of several Township roadways. At several sites, culverts have been installed to aid the natural drainage.

Figures 4.2-4.6 illustrate the vegetation and surface features typical of the wetland site.

4.2.2 Climate and Physiographic Setting

The wetland lies within the borders of the physiographic and climatic region known as the Huron Slopes (Saugeen Valley Conservation Authority, 1979). According to Brown et al. (1968), the local climate of the Huron slopes is influenced by the close proximity to the Great Lakes. The region experiences a predominantly westerly wind direction with a mean annual precipitation of 800-1000 mm. The mean annual potential evapotranspiration associated with the region is 600 mm. The historical start of the growing season for the region is April 17. The mean date of last frost is May 20 and the mean date of first frost is September 30. Table 4.1 provides a summary of the average climatic characteristics of the study area based on 1961-1990 data collected at Paisley, located approximately 16 km. north of the study site.

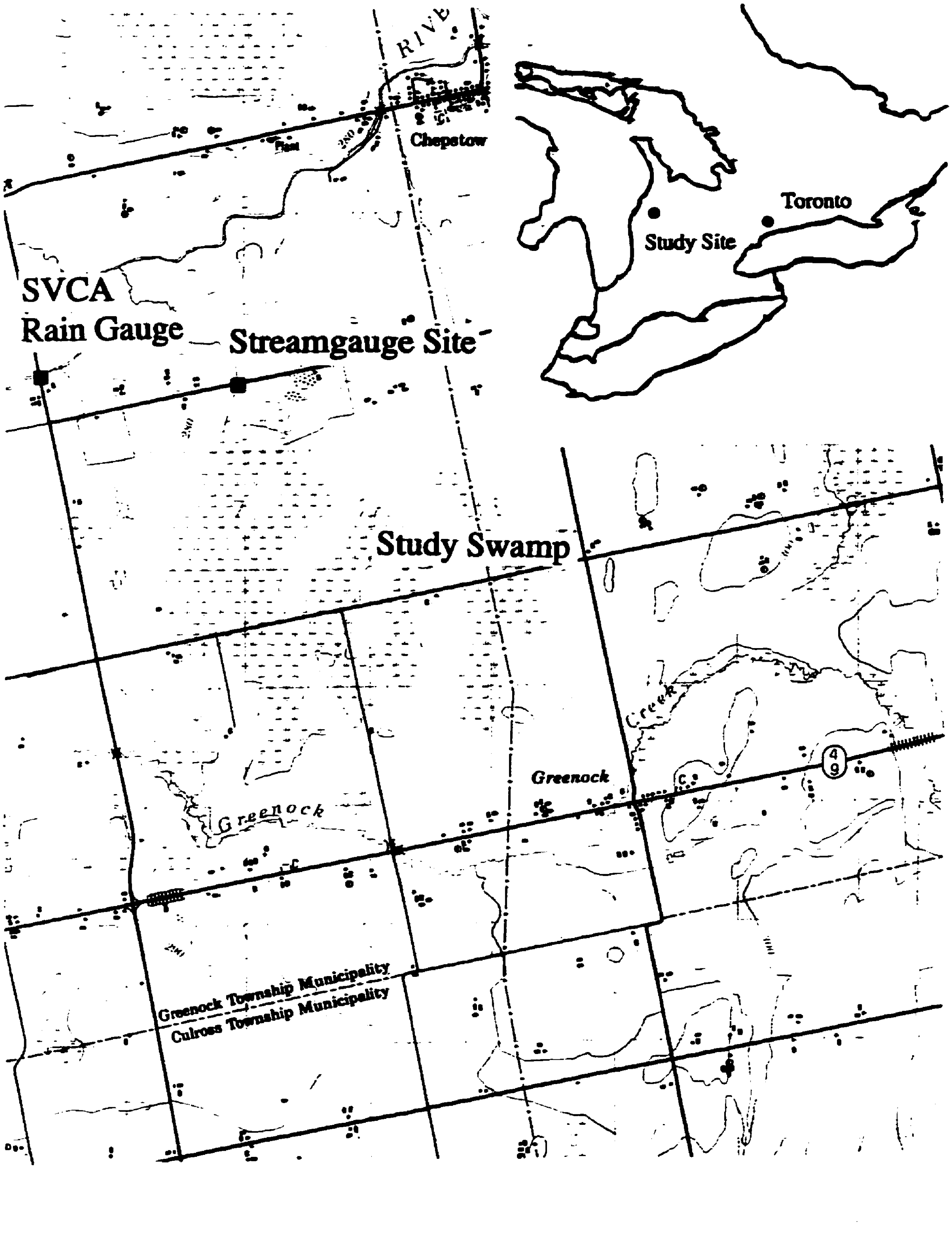


Figure 4.1 Wetland study site

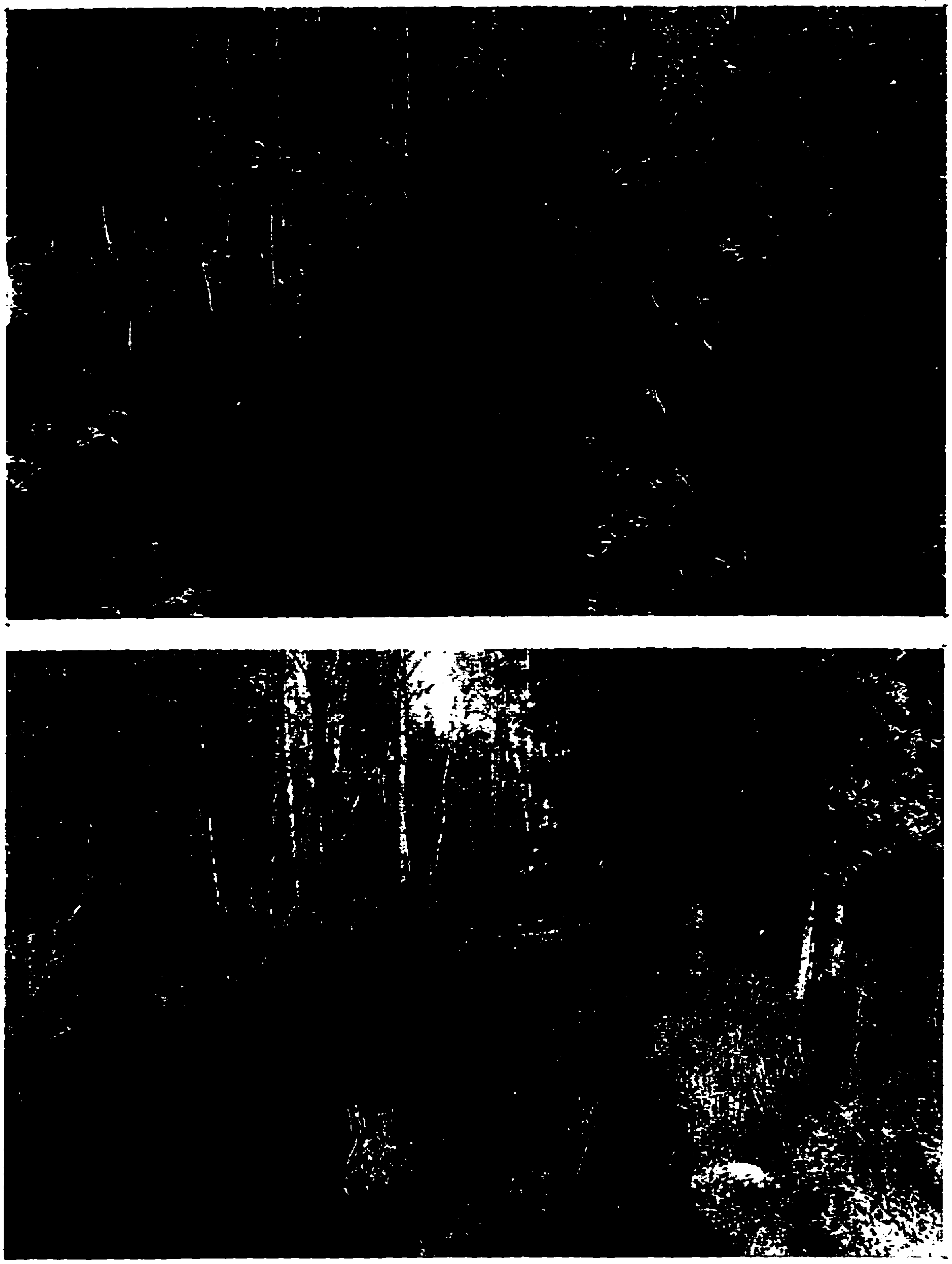


Figure 4.2 Typical near-stream conditions

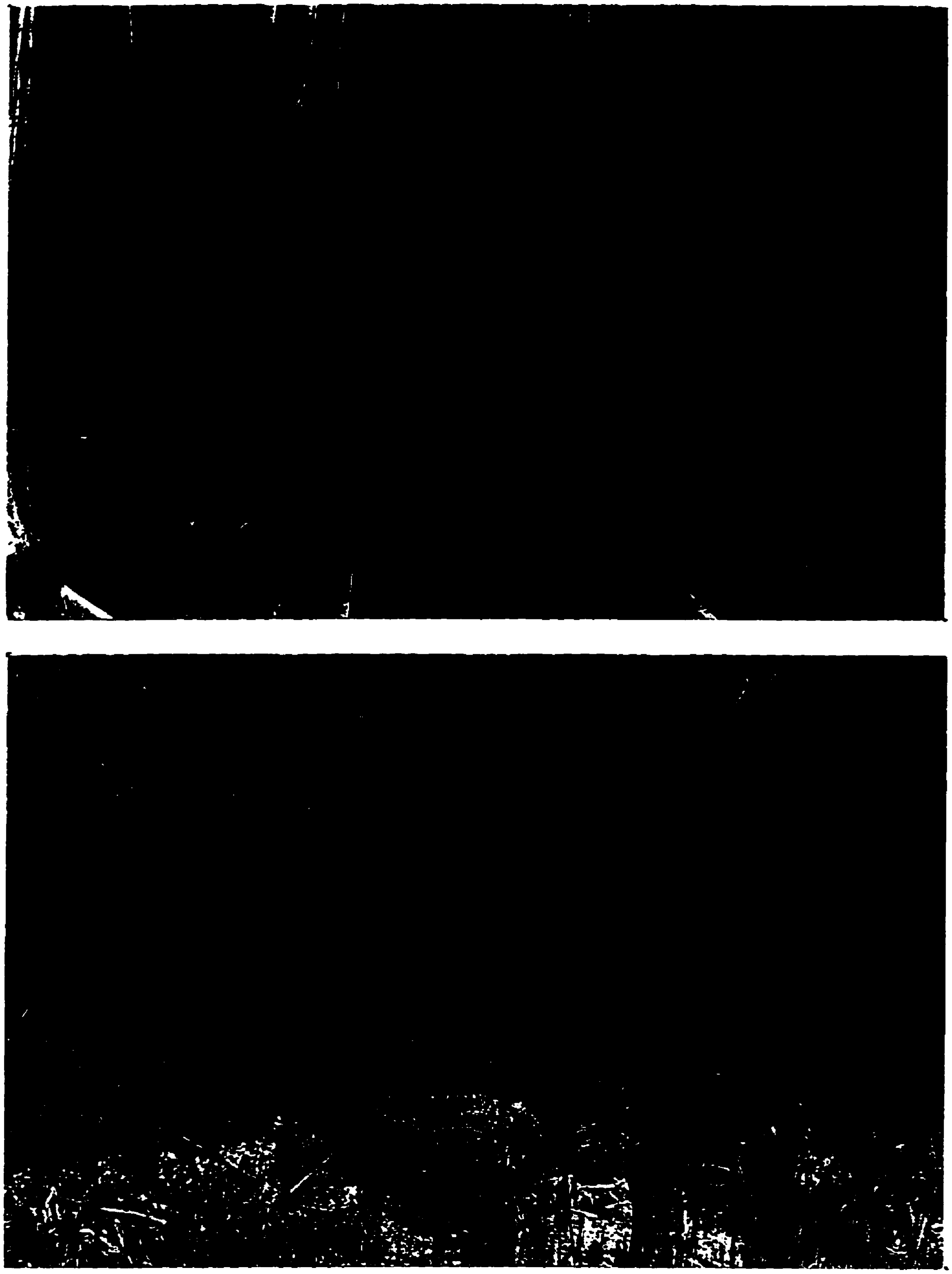


Figure 4.3 Typical wetland vegetation

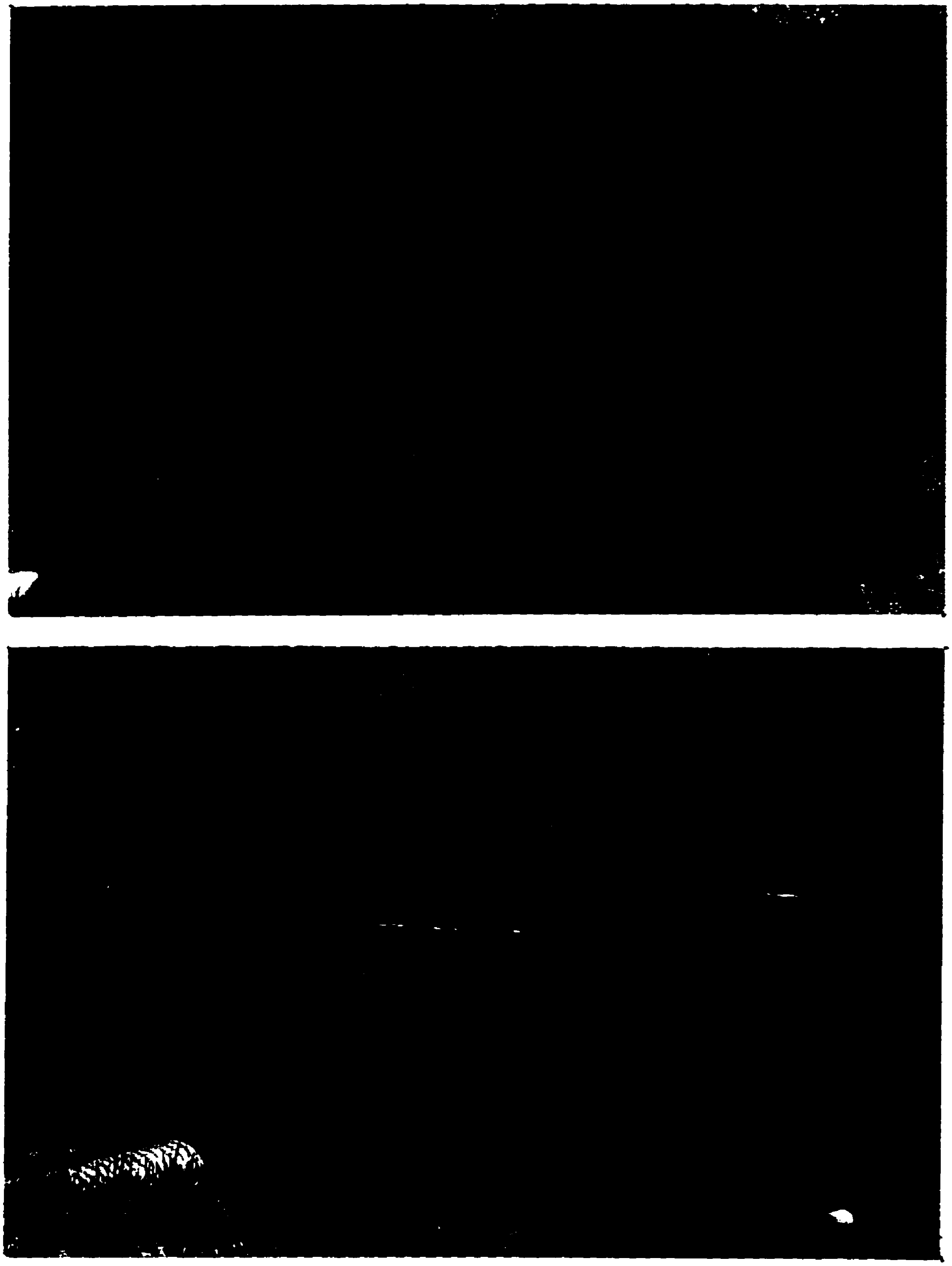


Figure 4.4 Surface water features

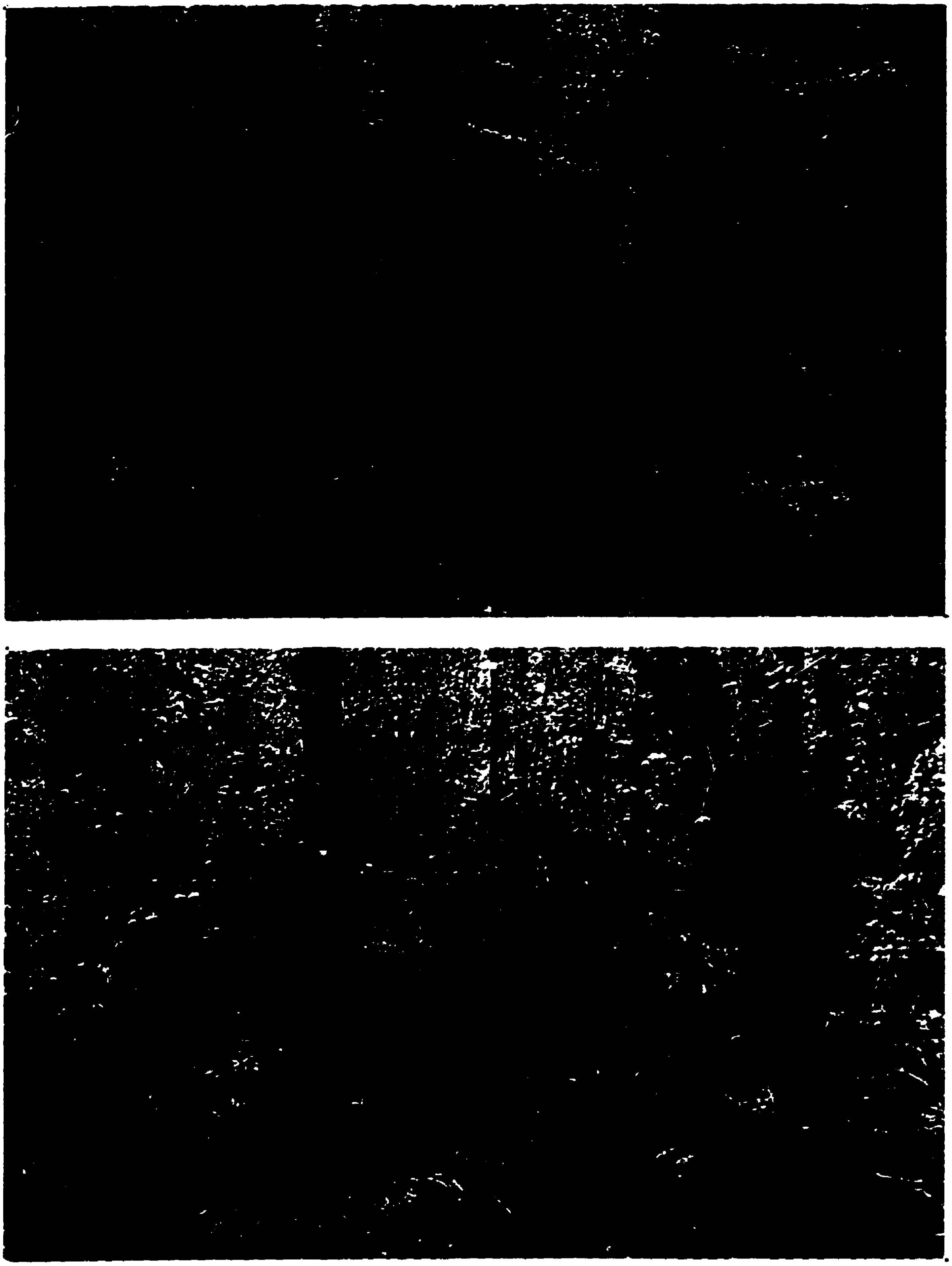


Figure 4.5 **Hummock features**

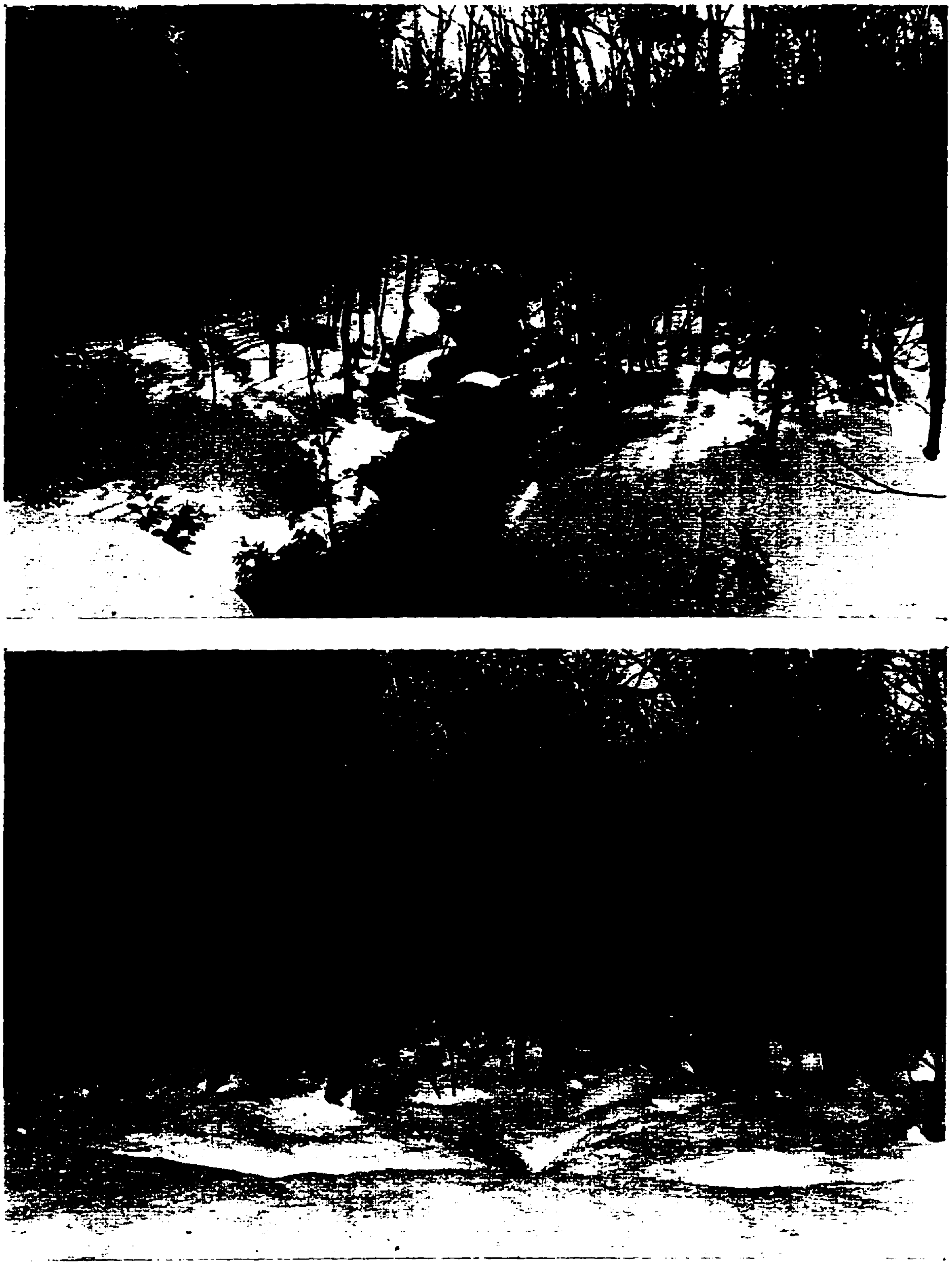


Figure 4.6 Winter conditions

Table 4.1 Climatic Summary (Paisley, Ontario, 1961-1990)

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Temperature													
Daily Max. (°C)	-3.4	-3.0	2.2	10.2	17.2	22.2	25.0	23.8	19.4	13.0	5.8	-0.7	11.0
Daily Min. (°C)	-11.1	-11.9	-7.1	-0.3	4.8	9.7	12.7	12.3	8.7	3.7	-0.8	-7.4	1.1
Daily Avg. (°C)	-7.2	-7.4	-2.4	5.0	11.0	16.0	18.9	18.1	14.1	8.4	2.6	-4.0	6.1
Snowfall (cm)	128	76	37	10	0	0	0	0	0	2	35	109	397
Precip. (mm)	147	96	78	67	71	76	75	96	106	94	106	150	1161
Month End Snow Cover (cm)	41	36	6	0	0	0	0	0	0	0	6	25	
Days with Measurable Precipitation	22	17	15	13	12	12	10	11	14	16	18	22	182
Wind (km/hr)	18	16	16	16	13	12	11	11	12	14	17	17	14

4.3 Meteorological Data

4.3.1 Sources of Data

In December 1994, a weather station containing a multi-channel Chart-Pac™ data recording module was installed near the Greenock Swamp complex. The weather station consisted of an instrument tower capable of providing bi-hourly values of precipitation, air temperature, incoming short-wave radiation, relative humidity, wind speed and wind direction. During the study period, approximately 30 site visits were conducted to collect data, download the electronic dataloggers and document the seasonal variations in the wetland.

Additional meteorological data were obtained from Environment Canada from the Waterloo-Wellington and London weather offices. The data included daily summaries of maximum and minimum temperatures, bright sunshine, relative humidity, wind speed and precipitation.

4.3.2 Rain Gauge Data

The Saugeen Valley Conservation Authority (SVCA) operates a rain gauge at the King's Highway No. 4 bridge crossing of the Teeswater River in the Greenock Township. The gauge station is located approximately 2 kilometres from the outlet of the wetland study site. Throughout the study period, precipitation data were continuously recorded at the streamflow gauge and made available for this research.

In January of 1995, precipitation data were collected at the weather tower installed near the Greenock Swamp complex. Table 4.2 provides a summary of the measured rainfall amounts during the data collection period (1994-1995) at both the SVCA gauge and the installed meteorological tower.

Table 4.2 Summary of measured precipitation volumes (mm) during study period (1994-1995)

Month	SVCA Gauge	MET Station
July 1994	84	N/A
August 1994	55	N/A
September 1994	65	N/A
October 1994	43	N/A
November 1994	74	N/A
April 1995	55	87
May 1995	45	58
June 1995	45	76
July 1995	28	32
August 1995	93	82
September 1995	50	47
October 1995	79	108

4.3.3 Radar Data

Throughout the research period, distributed rainfall data in the form of one hour rainfall accumulation (RFA) maps were available from the King City weather radar facility, currently operated by the Canadian Atmospheric Environment Service (AES). Figure 4.7 provides a RFA map for one hour of the June 25, 1995 precipitation event. The figure displays the accumulation and distribution of the rainfall, discretized in 2 km by 2 km grids. Figure 4.7 appears to indicate that a localized storm cell tracked diagonally across the wetland site.

The King City distributed rainfall estimates were used during the modelling to examine the areal distribution of the precipitation with regard to the headwater study site and to detect errors in the gauge data.

0	0	0	3	3	6	6	9	15	9	21	24
3	0	3	9	9	12	12	15	15	15	24	15
3	3	3	6	15	15	12	15	27	18	12	6
3	3	3	9	15	15	15	12	12	21	6	3
3	3	3	9	24	27	12	21	15	12	18	3
3	3	12	12	18	27	15	18	18	6	9	3
6	12	27	18	12	15	21	24	6	3	9	3
12	27	15	9	12	12	6	6	6	3	9	3
18	15	15	15	21	18	6	6	6	12	6	3
18	15	15	15	21	18	6	15	9	6	3	3

Figure 4.7 Typical 1-hour RFA CAPPI - June 25 1995 (2000 GMT)
Grids indicate elements containing a portion of the headwater swamp.
Shaded grid indicates element containing SVCA rain gauge.
Precipitation depths are in mm.

4.4 Hydrometric Data

4.4.1 Background

Streamflow records are typically obtained through the continuous operation of gauging stations. A gauging station is a field-site installation housing instrumentation capable of generating a continuous record of stage. The stage of a river or stream can be defined as the height of the free water surface above some specified datum. At any gauge site, the record of stream stage is converted into a record of stream discharge through the development of a stage-discharge relationship or rating curve. The development of a stage-discharge relationship at any particular site is made through a series of discharge measurements taken over a range in stage.

A flow meter is a device used to estimate the velocity of flowing water. The traditional approach to current metering involves discretizing the stream cross section into a series of vertical segments. The mean velocity corresponding to any particular vertical segment is obtained from a series of velocity measurements and using one of several known relationships associated with the velocity profile under open channel flow. Commonly used methods for determining the mean velocity include:

i) the one-point method.

In the one-point method, a single observation of velocity made at 0.6 of the flow depth is used to approximate the mean velocity in the vertical segment. The 0.6 depth method has been shown to provide reliable results and is suitable whenever the depth is between 0.09 and 0.46 metres. (Geological Survey Water-Supply Paper 2175, 1982)

ii) the two-point method.

The two-point method involves obtaining two velocity observations, one at 0.2 of the depth and 0.8 of the depth. The average of the two observations is taken to represent the mean velocity in the segment. The two point method is the approach generally recommended by the U.S. Geological Survey for flow depths greater than 0.76 metre (Geological Survey Water-Supply Paper 2175, 1982).

iii) the three-point method

In the three-point method, observations of velocity are taken at 0.2, 0.6 and 0.8 of the flow depth. The mean velocity for the segment is computed by averaging the 0.2 and the 0.8 depth observations and then averaging that result with the 0.6 depth measurement. The use of the three-point method is recommended whenever it appears that the vertical velocity profile is abnormally distorted through overhanging vegetation or submerged rocks.

iv) the five-point method

The five-point method involves observations made at 0.2, 0.6 and 0.8 of the depth and as close as possible to the surface and streambed as practical. The mean velocity is then calculated using the following expression:

$$v = 0.1(V_{surface} + 3V_{0.2} + 3V_{0.6} + 2V_{0.8} + V_{bed}) \qquad (4.01)$$

v) Integration method

Using the integration method, a series of velocity measurements at locations well-distributed throughout the cross section are obtained. The mean velocity associated with the section is obtained through integration of the velocity profile.

4.4.2 Methods

At the study site, a streamflow level recorder was installed at the outlet of the wetland (Figure 4.8). Continuous records of stream stage were obtained using a CP-XA Chart-Pac™ data recording module developed by Lakewood Systems Limited. The data logger was installed in a 300 mm diameter PVC tube housing along with a pulley, FS-15™ float sensor, cable and counterweight assembly. The PVC housing incorporated a galvanized steel access lid, complete with locking assembly.

A stage-discharge relationship was established at the gauge site through repeated velocity measurements. Velocity measurements were made using a Marsh-McBirney Flow-Mate™ Model 2000 flow meter. Where access to the wetland interior was possible, periodic streamflow measurements were obtained at the township culvert installations.

The majority of the stream flow measurements were obtained through wading of the stream. Under open channel flow conditions, the majority of the velocity measurements were obtained using the 2-point and 3-point methods. Where time permitted or if the stream stage was unusually high, the five point method was utilized. Flow through the culvert structures ranged from simple open channel flow conditions to full barrel flow. Under these conditions, traditional open channel flow depth-velocity relationships do not apply and as a result, the velocity measurements were made using the integration method.

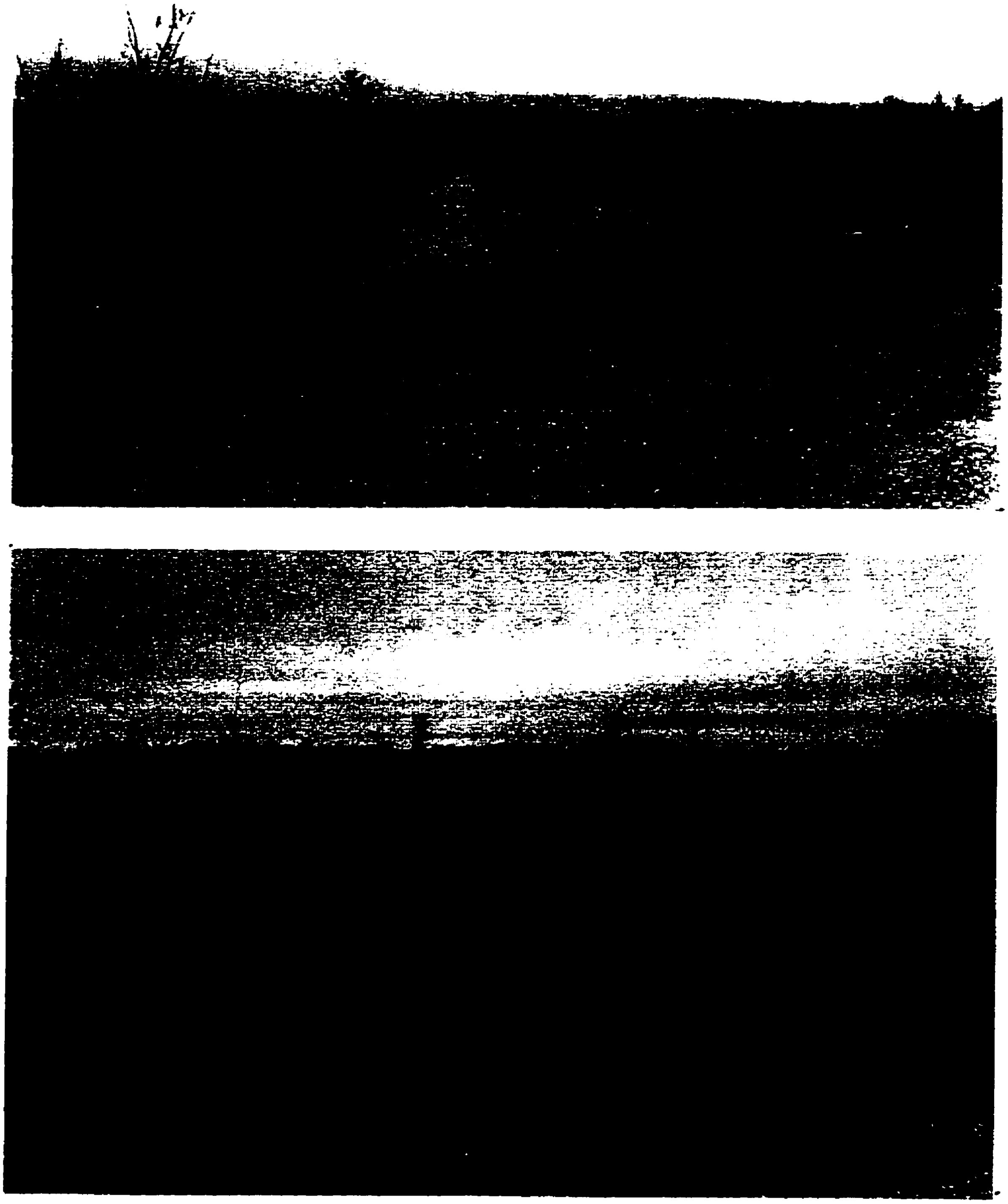


Figure 4.8 Streamflow level recording gauge site

4.4.3 Data Processing

The initial processing of the Lakewood Chart-Pac data was performed by the Lakewood LS-14™ software package. The Lakewood software provides a convenient tool for processing the logger data into a continuous record of hourly stage data in an ASCII format. As part of the data collection program, several supplemental post-processing programs were developed to aid in the handling, interpretation, plotting and storing of the streamflow data.

4.4.4 Stage-Discharge Relationship

A plot of the stage-discharge relationship developed for the outlet stream of the headwater cedar wetland is provided in Figure 4.9. The rating curve was established using velocity measurements obtained over the 1994-1995 study period with the flow depth ranging from 0.18 metre to 1.01 metre. The application of the stage-discharge relationship is illustrated in Figure 4.10, showing a plot of the record of stage and corresponding record of discharge for November 1994.

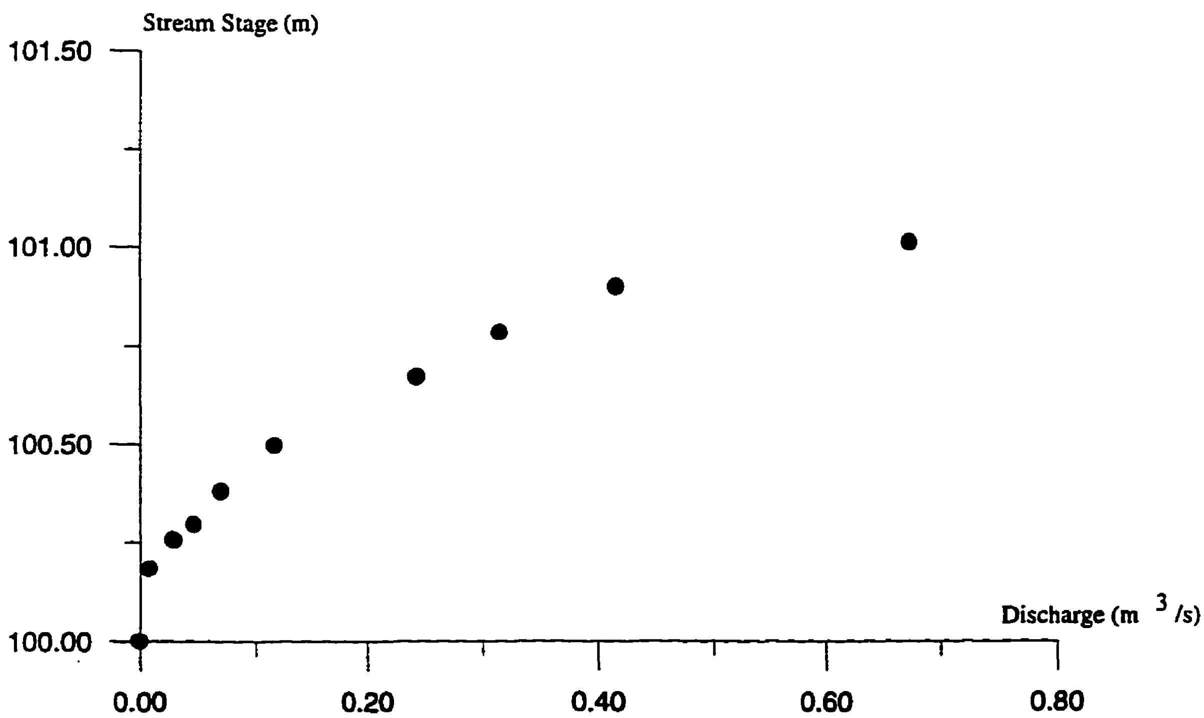


Figure 4.9 Stage-discharge relationship at gauge site

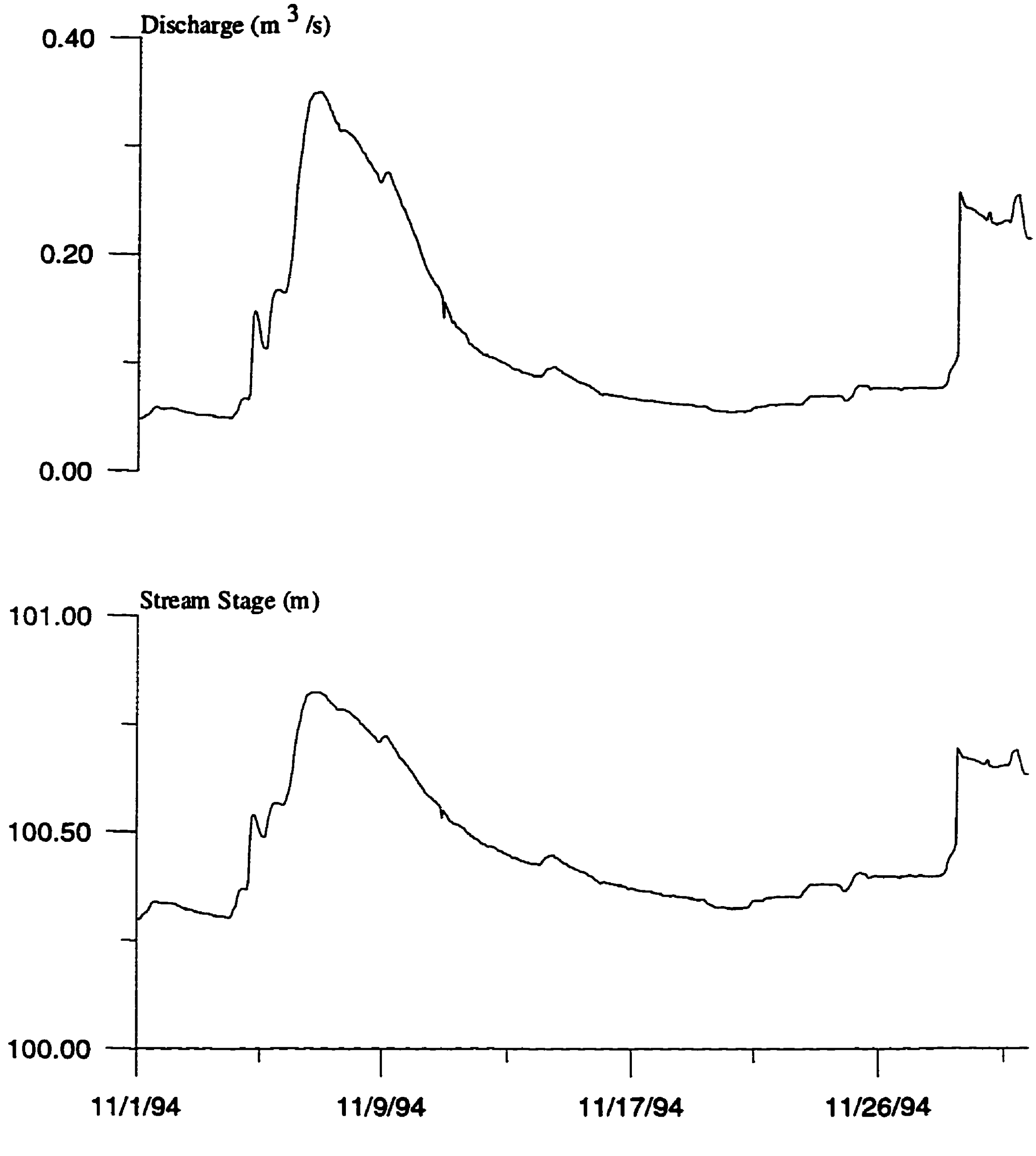


Figure 4.10 Record of stage and discharge - headwater swamp (November 1994)

4.5 Observed Hydrologic Response

4.5.1 Characteristics Of Seasonal Runoff

Drainage from the headwater wetland occurs along a primary drainage channel with lateral flows entering the channel from several natural tributaries. Within the Township road right-of-ways, additional flows are conveyed to the primary drainage channel via roadside ditches. When inundation of the wetland sediments occurs, surface flows can enter the drainage channel along numerous surface depressional channels or streamlets.

During the summer months, the water table near the wetland channel was typically located within the organic sediments and closely related to the level of flow within the drainage channel. In several locations within the wetland, surface waters were observed throughout the summer period. These surface water sites were generally located near the wetland margins where localized agricultural runoff drained into the wetland. These sites typically displayed vegetation characteristic of a marsh environment and were often poorly drained by shallow channels with low conveyance capabilities. At some surface water sites, the natural drainage pattern was disrupted by the installation of Township roads.

The character of the wetland site changed dramatically during the fall season. As the evapotranspiration demand decreased, the overall saturation state of the wetland increased significantly. Inundation of the wetland organics was observed throughout much of the fall season with standing water observed throughout most of the hummock terrain. Water levels within the drainage channels were observed to increase significantly. During the study period, several fall precipitation events produced bank-full flows along the channel network.

Throughout the winter months, streamflow was observed at the wetland outlet. When cooler temperatures prevailed, the surface water inundating the wetland sediments developed a partial ice cover although complete freezing of the surface water was seldom observed. Much of the wetland ice cover was unable to support a man's weight. However, freezing of the surface layers within the drainage channel necessitated the removal of the continuous level recorders during the cold weather months.

During any melt periods, drainage from the wetland site was similar to the conditions observed during the fall months. The majority of the wetland sediments were inundated with surface water within the hummock topography and the wetland stream regularly flowed under bank-full conditions. Inundation of the wetland sediments was gradually reduced through drainage of the wetland during the April-June period.

4.5.2 Stormflow Response

During the 1994-1995 study period, the observed streamflows associated with the wetland site displayed a significant seasonal variation. Plots providing the observed monthly streamflow hydrographs and precipitation records are provided in Appendix B. Figures 4.11 and 4.12 illustrate the observed streamflow and precipitation records observed during the study period. During the study period, measured event precipitation amounts ranged from trace amounts to 41 mm. In general, the characteristic rainfall-runoff response from the study swamp involves a relatively rapid rise in the wetland outflow hydrograph followed by a long period of recession, typically lasting 7-10 days if no additional rainfall occurs.

A summary of the observed monthly streamflows from the headwater cedar swamp is provided in Table 4.3. Examination of Table 4.3 reveals the substantial seasonal variation in the character of the wetland outflows from the headwater swamp. During September of 1995, the total observed runoff volume was calculated to be approximately 18,000 m^3. In comparison, a total runoff volume of 468,000 m^3 was discharged from the wetland in April of 1995. Year-to-year variations in the wetland discharge also appear to be significant. During July of 1994, 129,000 m^3 was discharged from the wetland. During the following year, only 20,000 m^3 of runoff was observed during the month of July.

The Saugeen Valley Conservation Authority operates a streamflow recording gauge located approximately one kilometre upstream of the confluence of the Teeswater River and the stream draining the headwater study site. For comparison, the observed wetland streamflow record was plotted with the Teeswater River streamflow record (Figures 4.13 and 4.14).

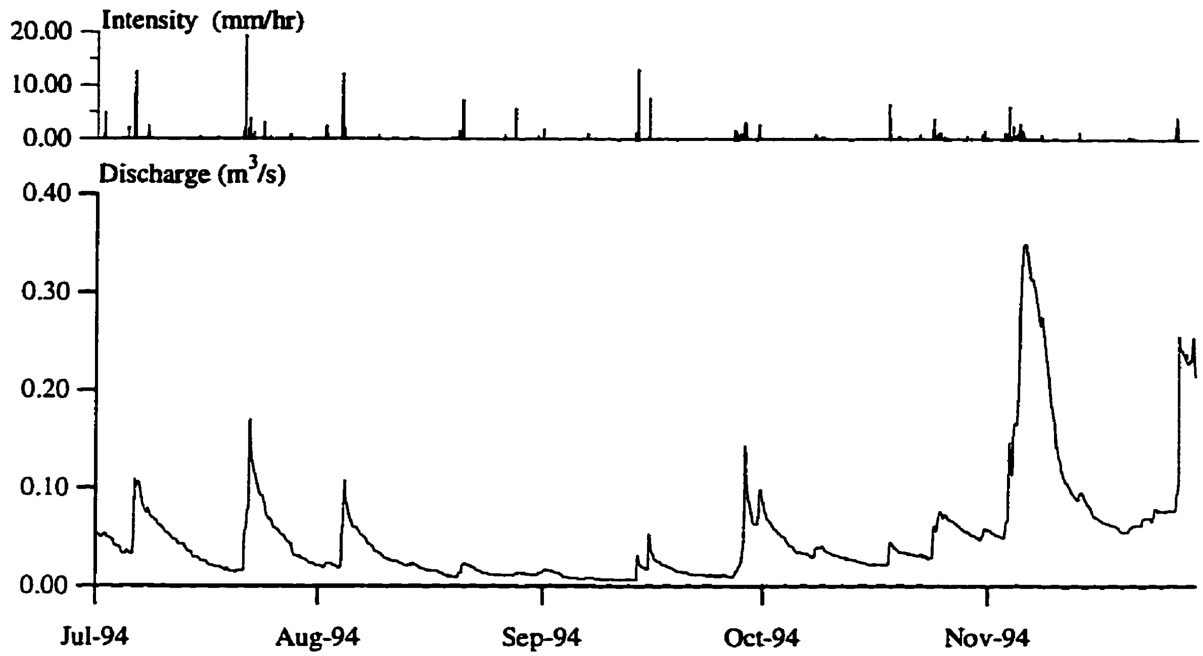


Figure 4.11 Observed rainfall-runoff response from headwater wetland (July-November 1994)

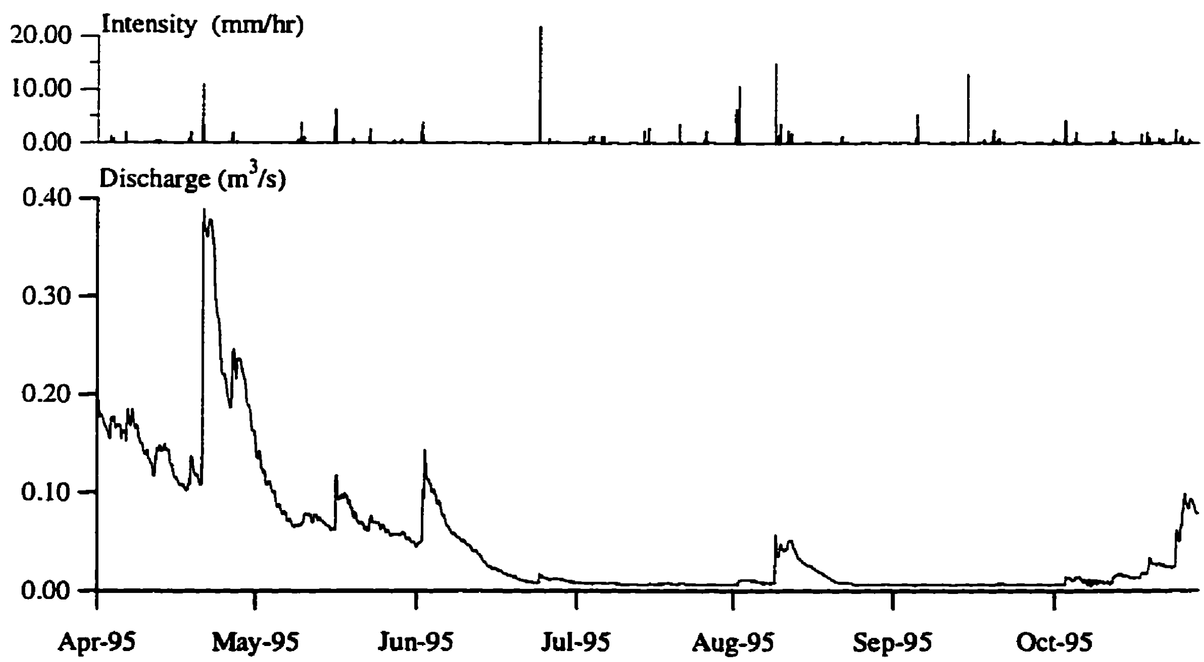


Figure 4.12 Observed rainfall-runoff response from headwater wetland (April-October 1995)

Table 4.3 Summary of observed monthly flows from headwater swamp (1994-1995)

Month	Total Runoff Volume (m^3)	Total Runoff Volume (mm)	Maximum Observed Flow (m^3/s)	Minimum Observed Flow (m^3/s)
July 1994	129000	33	0.171	0.014
August 1994	63000	16	0.108	0.008
September 1994	45000	12	0.144	0.007
October 1994	113000	29	0.099	0.021
November 1994	322000	83	0.350	0.048
April 1995	468000	120	0.390	0.102
May 1995	213000	55	0.169	0.049
June 1995	98000	25	0.143	0.008
July 1995	20000	5	0.005	0.005
August 1995	44000	11	0.058	0.005
September 1995	18000	5	0.005	0.005
October 1995	62000	16	0.099	0.005

As outlined in Chapter 2, several previous wetland studies have identified a strong seasonal variation in the stormflow response and this research reinforces those findings. Table 4.4 provides a summary of selected precipitation events and the corresponding increase in streamflow observed during the 1994-1995 collection period. During this period, there were eleven separate events where the total rainfall depths exceeded 20 mm. The largest measured precipitation event occurred on August 11, 1995 when approximately 41 mm of rain was recorded.

Table 4.4 and Figures 4.11 and 4.12 illustrate the poor correlation between the observed rainfall and the resulting stormflow response from the wetland. The ability of the wetland to depress the peak outflows during dry periods is evident from the observed data. On June 25, 1995 a 26 mm rainfall event produced only a marginal (0.008 m^3/s) increase in the peak discharge rate. Similarly, on August 03, 1995, 38 mm of precipitation produced a 0.005 m^3/s increase in the peak flow rate.

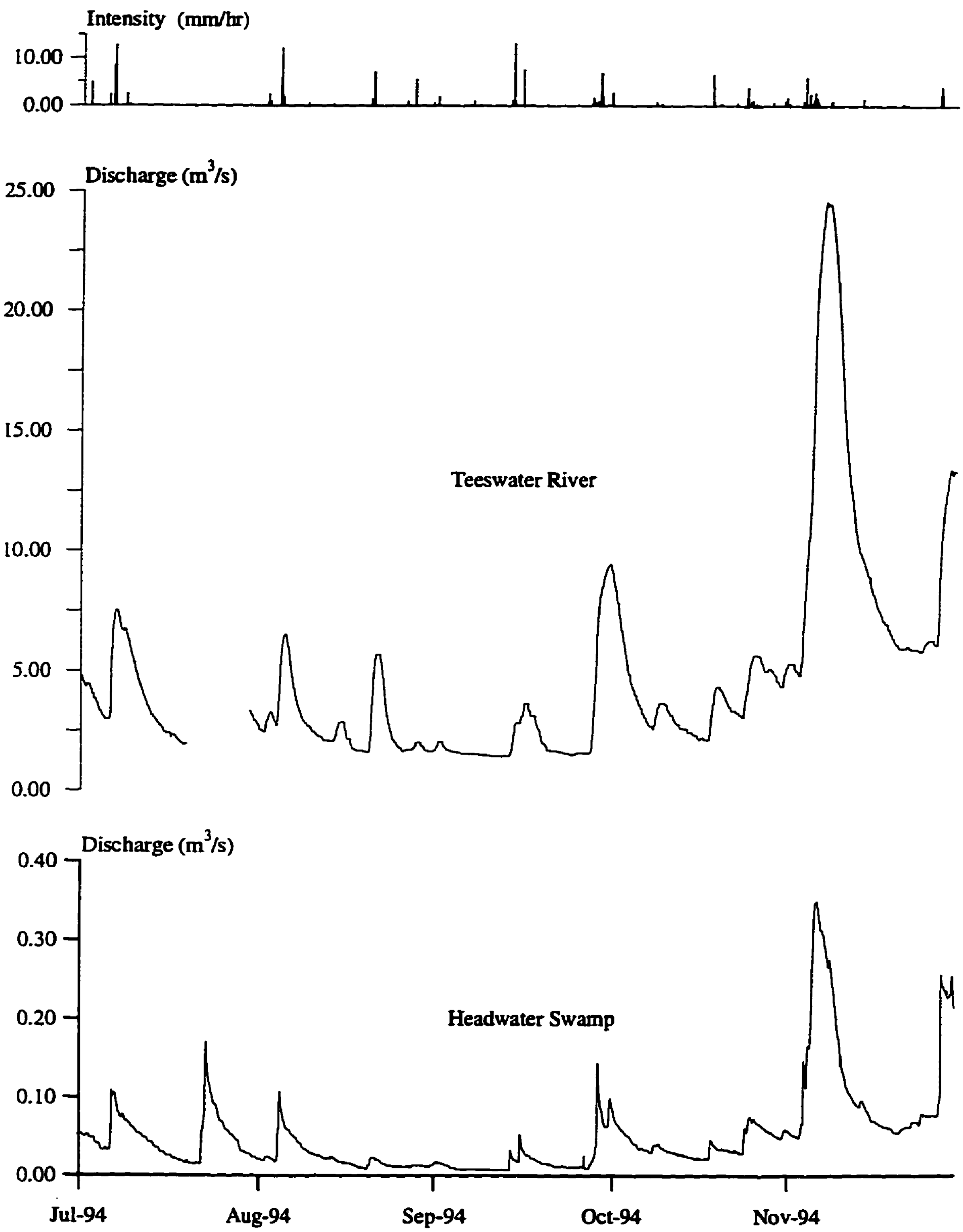


Figure 4.13 Observed streamflows for Teeswater River and headwater swamp (1994)

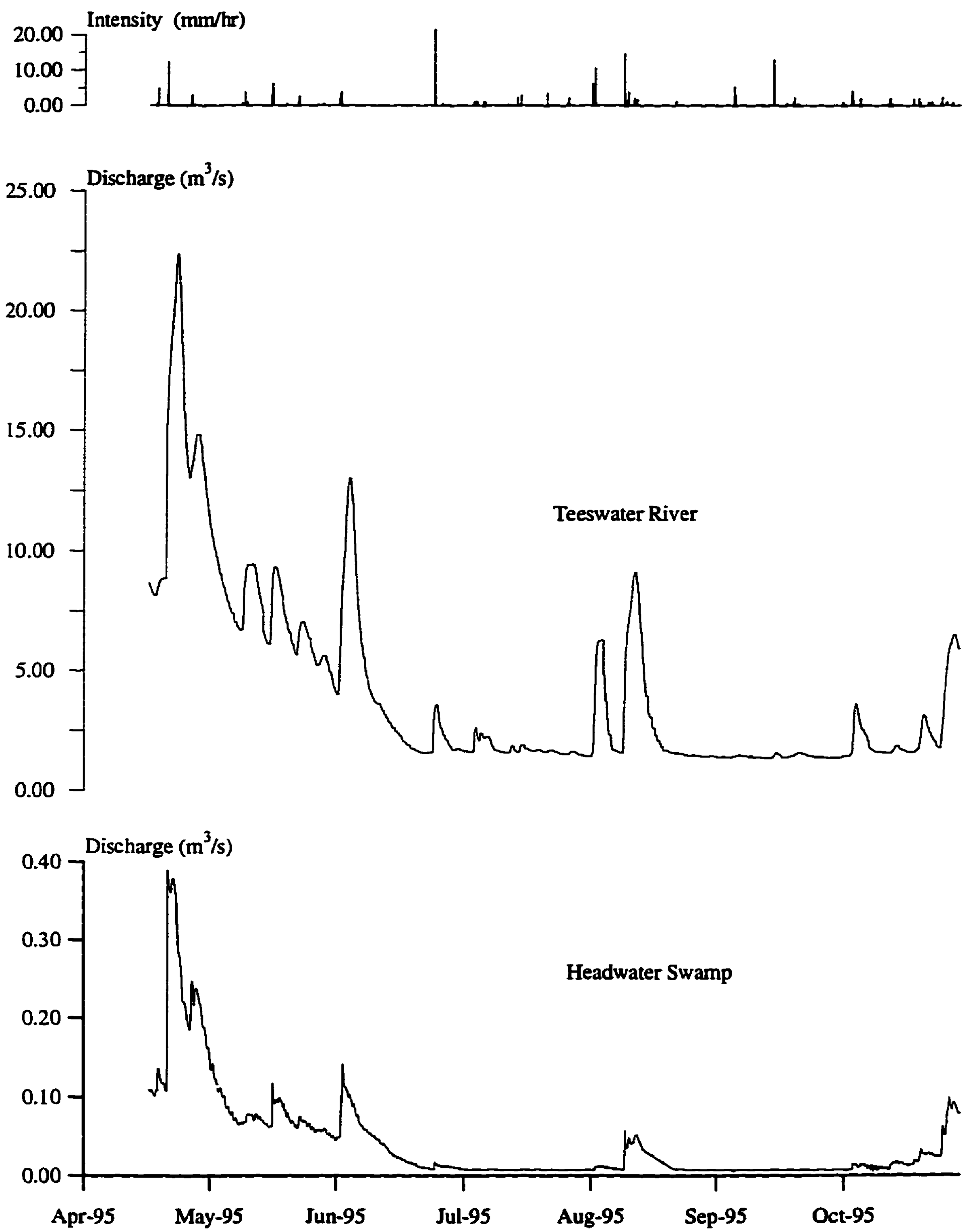


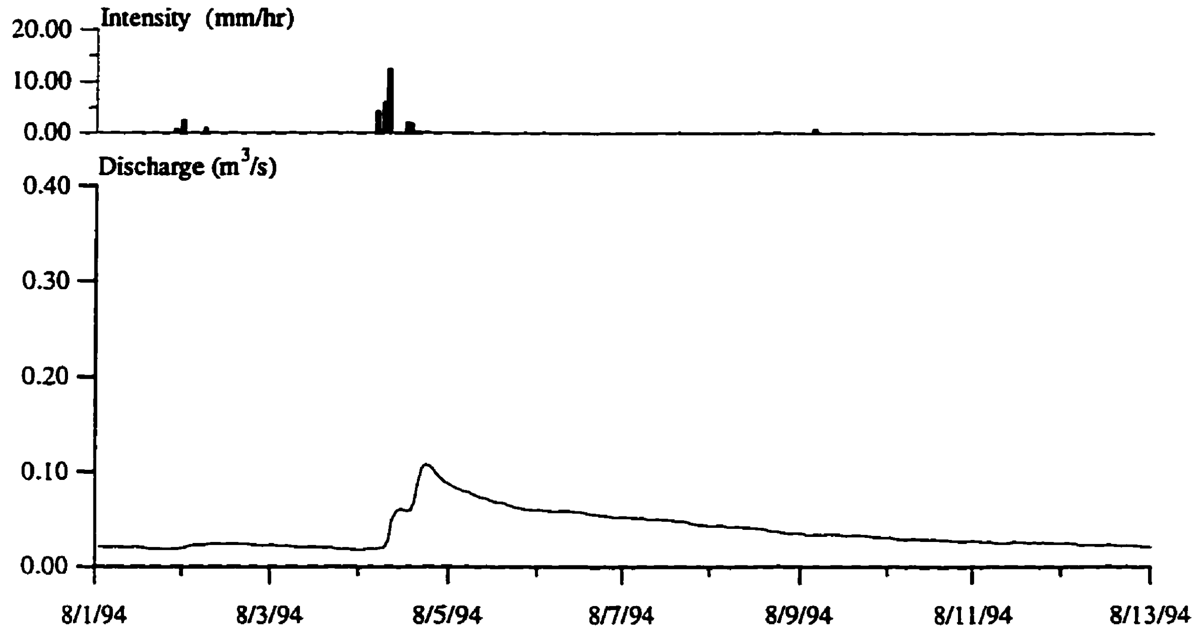
Figure 4.14 Observed streamflows for Teeswater River and headwater swamp (1995)

Table 4.4 Precipitation and corresponding peak flow rates (1994-1995)

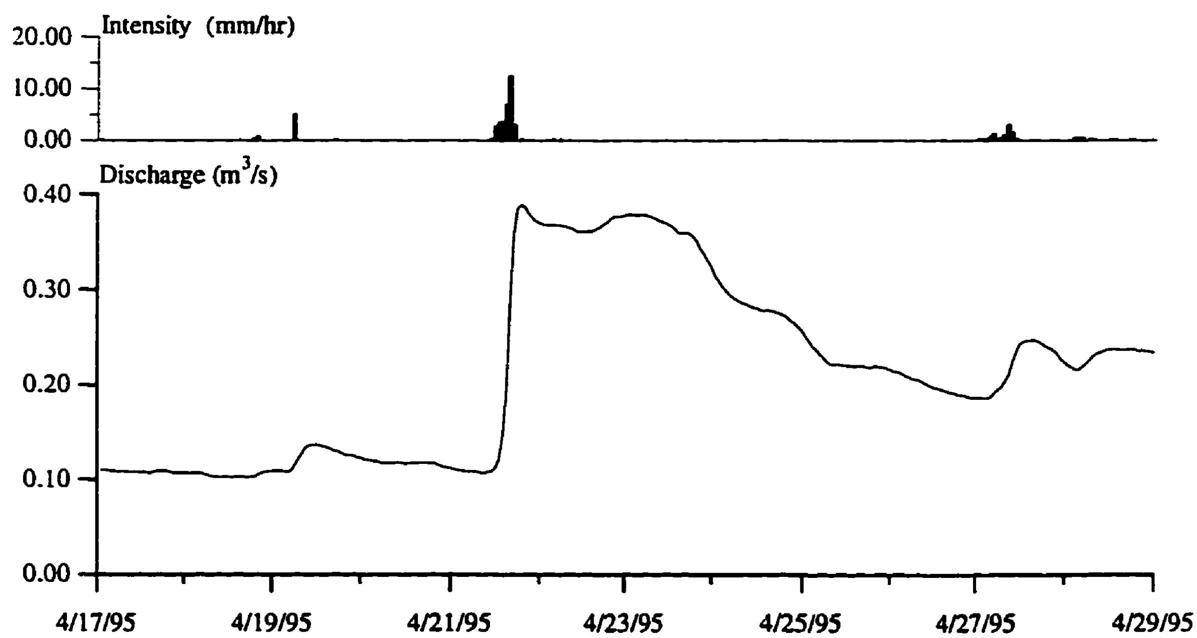
Event	Precipitation (mm)	Observed Initial Flow (m^3/s)	Observed Peak Flow (m^3/s)
1994			
July 06	24	0.033	0.109
August 04	28	0.019	0.108
August 20	11	0.009	0.023
September 13	24	0.007	0.033
September 15	12	0.017	0.053
September 28	26	0.009	0.144
October 01	5	0.063	0.099
October 19	13	0.022	0.046
October 25	18	0.029	0.076
November 01	6	0.048	0.059
November 04	40	0.049	0.350
November 28	18	0.076	0.257
1995			
April 21	32	0.109	0.390
April 27	9	0.186	0.247
May 10	12	0.068	0.079
May 17	18	0.063	0.118
May 23	10	0.062	0.076
June 03	17	0.048	0.143
June 25	26	0.008	0.017
July 16	6	0.007	0.008
July 23	10	0.008	0.008
August 03	38	0.007	0.012
August 11	41	0.007	0.058
September 7	13	0.006	0.007
September 17	21	0.007	0.008
September 21	8	0.007	0.008
October 6	24	0.007	0.015
October 15	8	0.008	0.017
October 22	9	0.017	0.034
October 27	11	0.024	0.062

During the fall and spring periods, the stormflow response from the site was significantly different. During the study period, two rainfall events measuring 26 mm were observed (940928 and 950625). The 940928 event resulted in a 0.135 m^3/s increase in the streamflow rate. In comparison, the same measured precipitation volume produced only a 0.009 m^3/s increase in the peak flow rate associated with the 950625 event.

Figure 4.15 provides a comparison of the rainfall-runoff response from the study site for two precipitation events involving roughly equal rainfall volumes. The August 04, 1994 event involved approximately 28 mm of rainfall while roughly 31 mm of rainfall was measured during the April 21, 1995 event. The resulting outflow hydrographs clearly illustrate the impact of the antecedent wetland saturation on the stormflow response.



a) August 04, 1994 Event



b) April 21, 1995 Event

Figure 4.15 Variation in stormflow response with antecedent wetland discharge

4.6 Characterization of the Stormflow Hydrographs

4.6.1 General

A stormflow hydrograph is a graphical representation of the distribution of discharge from an upstream drainage area. The stormflow hydrograph for a given precipitation event reflects the physical characteristics of the drainage basin and the precipitation event itself. The shape of the hydrograph is determined by the rate at which stormwater is transmitted from the various regions of the catchment to the outlet.

The characteristics of a stormflow hydrograph are commonly expressed in terms of time. In order to investigate the stormflow response from the wetland study site, the streamflow hydrographs observed for a selected sample of precipitation events were analyzed with respect to the following factors:

i) recession
ii) response time
iii) lag time to peak, and
iv) time of rise.

4.6.2 Recession Characteristics

In general, a stormflow hydrograph produced by an isolated period of precipitation can be segmented into three components: a rising limb, crest segment and a recession limb (Linsley *et al.*, 1982). The recession limb corresponds to the streamflow from a basin after surface inflows to the channel network have ceased. In other words, the recession period represents the withdrawal of water from storage within a drainage basin.

Figure 4.16 illustrates the observed streamflow hydrograph for the headwater wetland during August 1994. Following the precipitation event of August 4, the hydrograph displays a sharp rising limb extending to the point of peak discharge. The receding limb of the hydrograph can be subdivided into a quickflow response and the recession curve (Figure 4.17). The quickflow segment can be observed for approximately 24 hours after the cessation of rainfall. Following the quickflow, the streamflow from the wetland takes the form of a long, well-behaved recession curve lasting several weeks before the next significant precipitation event occurs. For many of the observed stormflow hydrographs

(Appendix B) the discontinuity separating the quickflow response and the groundwater recession is clearly evident.

A number of expressions have been developed to describe the recession curve characteristic of all stormflow hydrographs. One of the most commonly used equations for baseflow recession is:

$$q_2 = q_1 K_r \tag{4.02}$$

where q_1 is the observed discharge at time t_1, q_2 is the observed discharge at a later time, t_2, and K_r is the recession constant. Adopting a first-order process or depletion phenomenon, equation (4.02) can be written in the form (Dingman, 1966):

$$q_2 = q_1 \left(e^{-\frac{(t_2 - t_1)}{m}} \right) \tag{4.03}$$

where m is a recession factor. Equation (4.03) was applied to the observed streamflows from the headwater wetland for eight recession periods. The recession factor, m, was found to be approximately 8-9 days.

The recession factor, m, is influenced by the size of the drainage area and the magnitude of any groundwater inputs. In a study of a 32 hectare upland cedar swamp located within the Speed River watershed (Rai, 1962) and receiving substantial groundwater input, a recession constant of 40 days was reported. After analyzing the results presented in a study of a small groundwater recharge wetland near Peterborough (Taylor, 1982), Whiteley and Irwin (1986) calculated a recession constant of only 1 day.

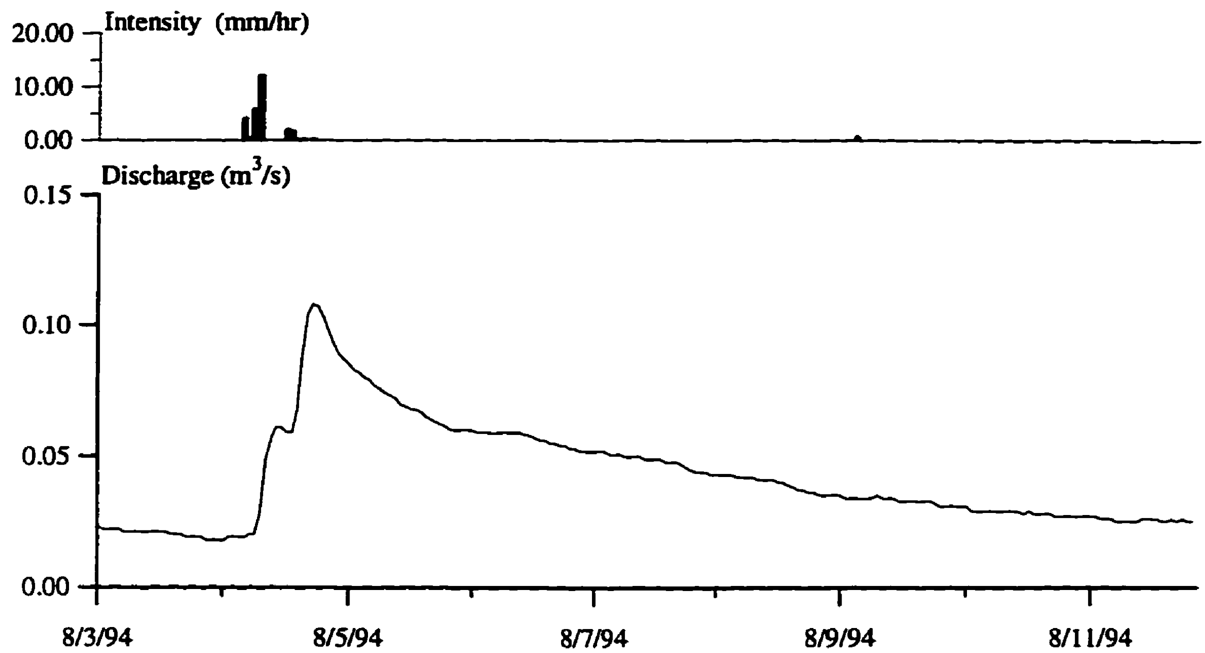


Figure 4.16 Streamflow hydrograph for August 1994

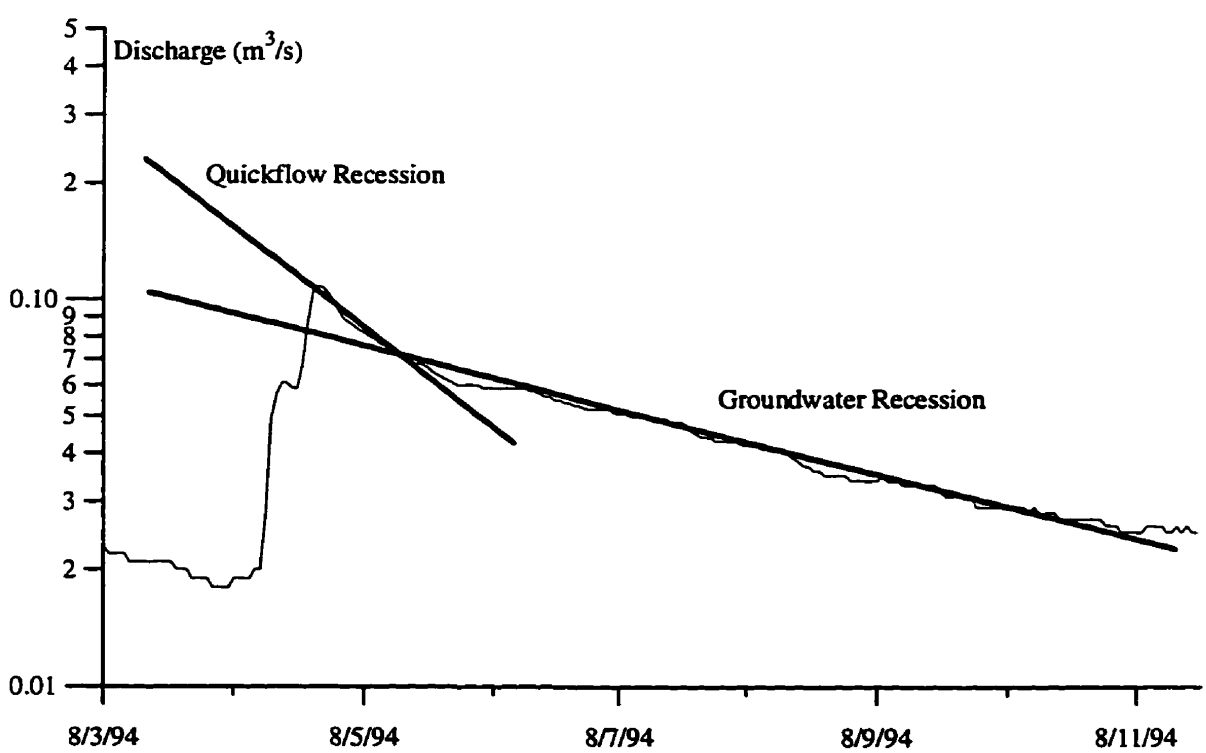


Figure 4.17 Recession curves for quickflow and groundwater discharge for August 04, 1994 precipitation event

In theory, equation (4.03) should plot as a straight line on a semilogarithmic scale. In practice, the resulting plots are seldom straight lines (Linsley et al., 1982) since discharge from the catchment reflects drainage from different storage sources: groundwater storage, storage within the surficial soils and storage within the drainage channel network. Since these storage sources often have different lag characteristics, the resulting recession plots typically do not plot as a single straight line. With respect to wetlands, the recession component of the stormflow hydrograph will reflect the rate of water depletion from the wetland sediments or acrotelm. In addition to the gravity drainage to the stream, the depletion of the water stored in the acrotelm will be influenced by the evapotranspiration demand. The curves for the eight recession periods are provided in Figure 4.18. With the exception of the period corresponding to October 11, 1994, the recession curves approximate straight lines and have reasonably similar slopes. Minor variations in the curves could be explained by the diurnal and daily variations in evapotranspiration.

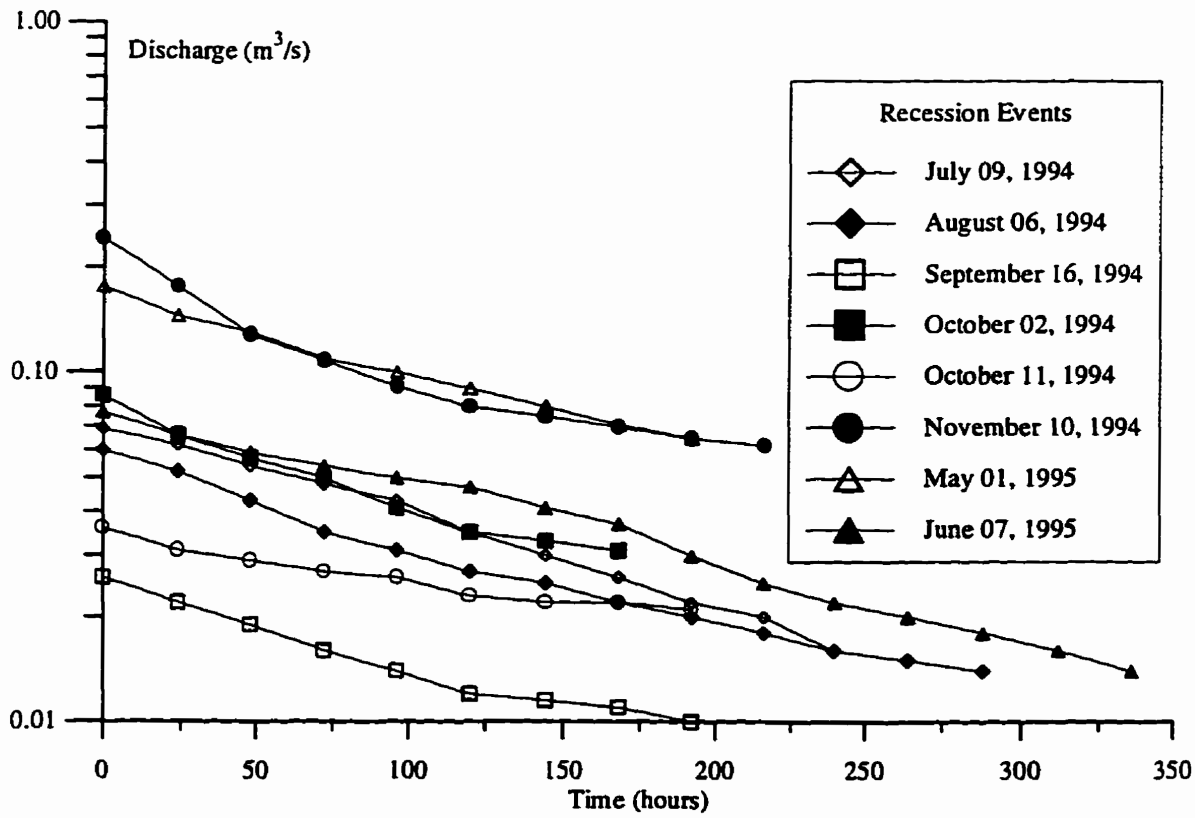


Figure 4.18 Observed discharge records for eight recession events

4.6.3 Response Time

The response time associated with a hydrograph is defined as the elapsed time between the beginning of the precipitation input and the beginning of the observed streamflow response. The response time associated with a catchment provides an indication of the influence of the areas contributing to the stormflow response. In general, when contributing areas are located near the drainage network, response times are short.

With respect to the study site, the characteristic response time was observed to be consistently less than one hour. It appears that the initial stages of the stormflow response from the headwater wetland is dominated by near-stream processes.

4.6.4 Lag Time To Peak

Lag time is defined as the time between the centre of mass of the effective rainfall and the centre of mass of the direct runoff hydrograph. In practice, determining the centre of mass of the direct runoff hydrograph is difficult, and as a result, lag time is commonly defined as the elapsed time between the centre of mass of the direct rainfall and the peak of the direct runoff hydrograph. While the lag time to peak is a characteristic time associated with a watershed, it is also dependent on the distribution of the precipitation input.

Table 4.5 summarizes the observed lag time to peak for selected discrete precipitation events. The lag time to peak observed at the study site ranged from 3.5 to 7 hours. The variation in the lag time appears to be influenced by the antecedent storage conditions and precipitation intensity. The October 6, 1995 event represented a long duration, low intensity rainfall applied to the wetland exhibiting low antecedent streamflows. The response was characterized by a 7 hour lag time to peak. The June 25, 1995 event, although it involved approximately the same volume of precipitation, occurred over a 4 hour duration with the majority of the rainfall falling in the first hour. The lag time to peak for the June 25 stormflow response was 3.5 hours, indicating a response that was twice as fast as the October 6 event.

4.6.5 Time of Rise

Time of rise is defined as the elapsed time between the observed initial streamflow response and the peak discharge. The time of rise provides an indication of the time associated with the rising limb of the stormflow hydrograph. The time of rise is influenced by the drainage characteristics of the watershed and the precipitation input.

Table 4.6 summarizes the observed time of rise for the selected precipitation events. In general, the time of rise ranged between 4 and 8 hours. Figure 4.19 and 4.20 illustrate the rainfall-runoff response for October 17, 1994 and April 21, 1995 events respectively.

Table 4.5 Observed lag time to peak for selected rainfall events (1994-1995)

Event Date	Precipitation Volume (mm)	Storm Duration (hours)	Lag Time To Peak (hours)
July 6, 1994	24	6	5.0
September 15, 1994	12	3	4.0
October 19, 1994	13	4	5.8
October 25, 1994	10	6	5.0
April 21, 1995	32	9	3.5
June 25, 1995	26	4	3.5
August 11, 1995	40	4	3.5
October 6, 1995	24	11	7.0

Table 4.6 Observed time of rise for selected rainfall events (1994-1995)

Event Date	Precipitation Volume (mm)	Storm Duration (hours)	Time of Rise (hours)
July 6, 1994	24	6	8
September 15, 1994	12	3	4
October 19, 1994	13	4	7
October 25, 1994	10	6	7
April 21, 1995	32	9	7
June 25, 1995	26	4	4
August 11, 1995	40	4	4
October 6, 1995	24	11	6

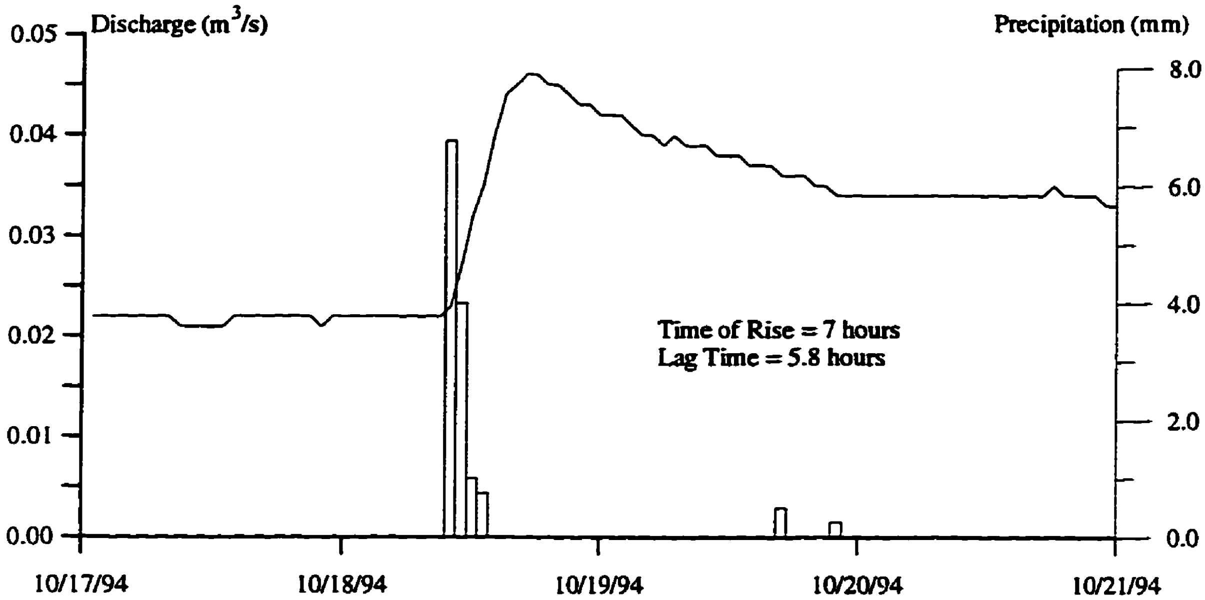


Figure 4.19 Hydrograph and hyetograph for October 17, 1994

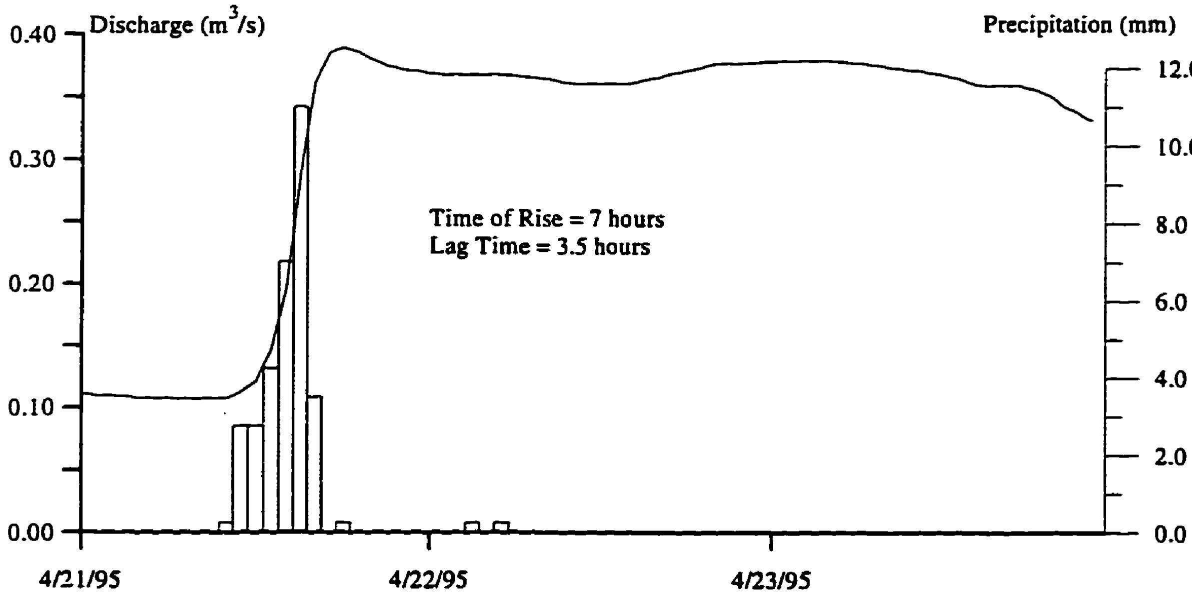


Figure 4.20 Hydrograph and hyetograph for April 21, 1995

4.7 Chapter Summary

This chapter describes the collection and analysis of the meteorologic and hydrometric data utilized in this research. A headwater wetland site located within the Teeswater River watershed was used as a study site. Data were collected over the period ranging from July 1994 to October 1995.

The hydrologic behaviour of the wetland site exhibited a strong seasonal variation. During the periods of low flow, the wetland is able to significantly depress the stormflow hydrograph peak and reduce the runoff volume discharged from the site.

Most of the wetland stormflows exhibited a distinct quickflow response followed by a long recession period lasting over a week. The characteristic lag time to peak for the wetland site was found to range from 3.5 to 7 hours. The time of rise of the stormflow hydrograph ranged from 4 to 8 hours.

CHAPTER 5

5. Application of the Wetland Model

5.1 General

For this research, a split sample approach was utilized in which the observed 1994-1995 streamflow record was divided into a calibration and validation data set. This chapter describes the application of the wetland model towards simulating the hydrologic behaviour of the headwater study site.

5.1.1 Model Efficiency Criterion

The performance of a hydrologic model should be judged on the extent to which it maintains some level of accuracy through different data sets and on the extent to which the model can sustain the level of accuracy when applied to conditions other than those used for calibrating the model (Kachroo, 1992). Model accuracy can be judged both graphically and from mathematical criteria. A visual examination of a plot comparing the observed and simulated model output enables the viewer to quickly evaluate the performance of the model. In support of any visual judgment, numerical evaluations of simulated hydrographs provide additional criteria with which to quantify model accuracy.

This research utilizes three commonly applied goodness-of-fit criterion. The Nash-Sutcliffe coefficient is defined by Nash and Sutcliffe, (1970) as:

$$R^2 = 1 - \frac{\sum_{i=1}^{n} \left(Qobs_i - Qsim_i\right)^2}{\sum_{i=1}^{n} \left(Qobs_i - \overline{Q}obs\right)^2} \tag{5.01}$$

where: n is the number of time periods in the simulation
$Qobs_i$ is the observed streamflow during time period i
$Qsim_i$ is the simulated streamflow during time period i
$\overline{Q}obs$ is the average observed flow during the simulation (n time periods)

The Nash-Sutcliffe coefficient value will equal one if a perfect fit between the observed and simulated streamflow hydrographs occurs. A coefficient value of zero indicates that the model is no better that the adopting the average observed flow for the study period.

The second criteria involves the deviation of runoff volumes, D_V, given by:

$$D_V(\%) = 100\frac{V_{sim} - V_{obs}}{V_{obs}} \tag{5.02}$$

where: V_{obs} is the observed streamflow runoff volume (m^3)
V_{sim} is the simulated streamflow runoff volume (m^3)

The deviation in runoff volumes provides a statistical comparison of the total measured and simulated runoff volumes as found by integrating the area under the streamflow hydrographs. The volume criterion provides an indication of how accurately the overall mass balance is being modelled. A large deviation between the observed and simulated runoff volumes may indicate that a significant source (ie: precipitation) or sink (ie: evapotranspiration) is not being accounted for correctly. Clearly, the volume criterion provides no information regarding the timing of the hydrographs or the corresponding distribution of the stormflow volumes.

The third criterion involves the S-criterion, the ratio of the root mean squared (RMS) error of the simulated flows to the mean observed streamflows over the simulation period and is given by:

$$S = \frac{\sqrt{\frac{1}{n}\sum_{i=1}^{n}(Qsim_i - Qobs_i)^2}}{\frac{1}{n}\sum_{i=1}^{n}Qobs_i} \qquad (5.03)$$

where: n is the number of time periods in the simulation
$Qobs_i$ is the observed streamflow during time period i
$Qsim_i$ is the simulated streamflow during time period i

The S-criterion provides an indication of the size of the estimation error relative to the mean observed flow during that simulation run.

5.2 Set-up Procedures

Prior to conducting a simulation, the set-up of the wetland model requires the preparation of a series of data files containing information regarding:

i) the idealization of the wetland basin
ii) historical streamflow data
iii) historical meteorologic data
iv) an assumed interaction between the wetland and the underlying groundwater flow system
v) the specification of the structural model components such as the number of grids and the modelling time step.

The wetland model provides a user interface to allow preprocessing of the required information. The data are stored in a series of files and accessed by the wetland program during execution of the model.

5.2.1 Idealization of Headwater Wetland Flow System

Based on examination of 1:50,000 scale topographic mapping, 1:1000 scale aerial photography and site reconnaissance, the headwater wetland was idealized into five routing reaches (Figure 5.1). A field survey was undertaken to establish the representative channel geometry along the routing reaches adopted for the wetland modelling. Vertical control was established from a traverse of the wetland via the adjacent Township roads. The survey results were used to establish channel inverts and overall wetland gradients. In conjunction with the channel survey, estimates of the thickness of the wetland sediments were obtained. Table 5.1 provides a summary of the wetland parameters established for each routing reach.

Table 5.1 Wetland modelling parameters

Parameter	Reach 1	Reach 2	Reach 3	Reach 4	Reach 5
Channel Length (m)	1500	1250	1250	1000	1000
Channel Width (m)	1.8	2.0	2.25	1.8	2.0
Channel Slope	0.001	0.001	0.001	0.001	0.001
Channel Roughness	0.055	0.055	0.055	0.055	0.055
Organic Thickness (m)	0.300	0.400	0.500	0.300	0.400
Width of Wetland Field Cell (m)	200	500	500	200	200
Slope of Wetland Field Cell	0.0005	0.0005	0.0005	0.0005	0.0005

5.2.2 Structural Components

The specification of the modelling time step and grid size can significantly affect the overall performance of the model. As with many models, it is desirable to make the time step and grid size as large as possible in order to minimize the computation costs. However, as the structural components get larger, inaccurate representations of the hydrologic processes are possible.

For this research, a one hour time step was used. A variable-size finite-difference grid consisting of 30 grid blocks was utilized for all simulations.

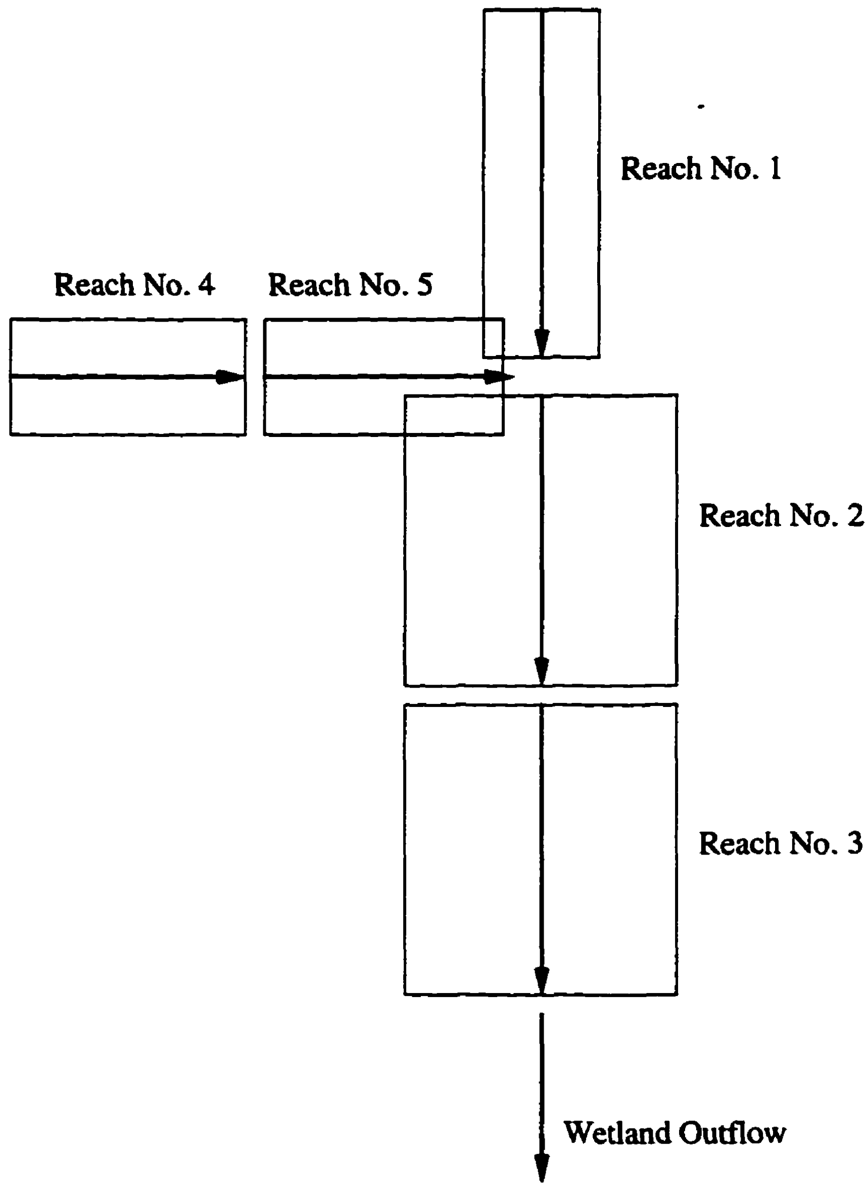


Figure 5.1 Idealized wetland reaches

5.2.3 Potential Evapotranspiration

For this analysis, estimates of monthly potential evapotranspiration were obtained using the two empirical methods incorporated into the current wetland model:

i) the Thornthwaite approach.
ii) the Turc formula

The estimation methods were selected because the empirical approaches are compatible with the limited amount of data commonly available when operating at the watershed scale. With regard to the wetland model, the significance of the evapotranspiration estimate will increase with the length of the simulation period. Table 5.2 provides a comparison of the monthly potential evapotranspiration values as found using each approach. In summary, the two approaches produced very comparable results.

Table 5.2 Monthly potential evapotranspiration demand (mm)

Month	Thornthwaite Method	Turc Formula
July 1994	127	134
August 1994	102	116
September 1994	75	83
October 1994	40	44
November 1994	15	13
April 1995	17	21
May 1995	75	87
June 1995	124	123
July 1995	136	133
August 1995	127	125
September 1995	68	80
October 1995	45	38

For the calibration and validation of the model, the Turc evapotranspiration estimates were used. The Turc approach provides potential evapotranspiration values over 10 day periods. Following the observations reported by Munro (1979, 1986), all simulations were conducted using an equilibrium evaporation regime. The sensitivity of the model outputs to changes in the evapotranspiration demand is examined in Chapter 6.

5.2.4 Estimate of Groundwater Inflow

As with evapotranspiration losses, the influence of the groundwater influx from the underlying sediments becomes more significant as the modelling duration increases. The estimation of groundwater inflows into wetland systems has proven very difficult in previous wetland studies and requires extensive field instrumentation and monitoring. In the absence of detailed hydrogeologic data, the approach used with this research relied on the development of a crude water balance and the use of several simplifying assumptions.

Two periods of study were established, August-November 1994 and May-October 1995. The groundwater contribution to the wetland site was approximated as the residual in the water budget calculations. Steady state simulations were conducted using the wetland model and estimates of the initial and final storage volumes within the site were obtained. Based on the measured streamflows, the estimated monthly evapotranspiration estimates and measured rainfall, a mean groundwater inflow of approximately 1.5 mm/day was determined. The water balance components are summarized in Table 5.3.

Table 5.3 Summary of water balance computations

Year	Precipitation (mm)	ET (mm)	Change in Wetland Storage (mm)	Total Wetland Outflow (mm)	Residual (mm)	Baseflow (m^3/s)
1994	237	184	58	139	144	0.053
1995	395	470	-8	175	242	0.056

In reality, the temporal distribution of the groundwater flux, as discharge (and possibly also as groundwater recharge), would be expected to vary with the seasonal character of the local and intermediate groundwater systems. As a result of the lack of groundwater data, for this application, the estimated groundwater flux was assumed to be constant throughout the modelling duration. It should be recognized that the estimation of the mean groundwater inflow as the residual in the wetland water balance is subject to a large potential error. The influence of the groundwater component on the resulting streamflow simulations is examined in Chapter 6.

5.3 Model Calibration

5.3.1 General

The model parameters incorporated into any process-based model have, to some degree, a physical interpretation and ideally, the parameter values could be determined through measurement in the field or laboratory. However, field scale measurements are typically point-scale measurements and not generally representative of the processes at a larger grid scale. Through calibration, effective parameter values are obtained that reflect the appropriate grid-scale processes. In a study on the application of the SHE model to catchment-scale modelling in India, Refsgaard *et al.* (1992) recognized that as a result of the 2 km. grid scale used for the modelling, the calibrated values of the overland flow parameters were compensating for the inadequate representation of the grid-scale channel routing. Our current knowledge of the relationship between effective parameter values and field measurements is presently incomplete and additional research is warranted (Beven, 1989; Bathurst *et al.*, 1995).

5.3.2 Methods

There are two alternative approaches to the estimation of model parameters, manual and automatic. Manual estimation of the model parameters typically involves adopting a trial and error approach during which parameter values are systematically altered in order to improve the outcome of the model. The manual calibration process offers the advantage of allowing the user to apply judgment and previous experience when interpreting the model outputs and adjust the parameter values accordingly.

Alternatively, automatic calibration involves the use of an automated optimization algorithm that systematically searches the parameter domain for the optimum of some estimation criterion that characterizes the agreement between the observed and the simulated observations.

5.3.2.1 Optimization Algorithm

In general, optimization algorithms can be broadly categorized into two groups: direct search and descent (gradient) methods. Direct methods start at some arbitrary location and proceed stepwise, sequentially evaluating the trial values of the coefficients in an attempt to reach an optimum. Commonly used direct search methods include the simplex method (Nelder and Mead, 1965) and the pattern search algorithm (Hooke and Jeeves, 1961). With respect to descent methods, both the function and the function gradient are evaluated at each iteration and a new search direction is determined until the strategy is unable to find a direction in which an improvement in possible.

In practice, the calibration of a hydrologic model is not a trivial task. Many model parameters involve a high degree of interaction where a change in one parameter value may be compensated by a change in another parameter. For a simple two-parameter model, long flat-bottomed valleys on the response surface occur where a large number of combinations of the parameter values produces a similar low of the objective function. In addition, it is widely recognized that local optima often exist on the response surface and may cause an optimization algorithm to terminate without locating the true optimum. In a study by Hendrickson *et al.* (1988), the results indicated that the outcome of any calibration run is highly dependent on the characteristics of the response surface in the vicinity of the initial parameter values. Using error-free synthetic data, for which the location of the true global optimum is known, a series of runs were performed during which each parameter in turn was perturbed 35% and an optimization algorithm employed to recover the true parameter value. In over half of the multi-parameter data sets, neither a direct search or gradient method were successful in determining the correct parameter values, even with ideal, error-free synthetic data. The complexities involved in finding the optimum values for parameters of an operational watershed model are clearly emphasized by an optimization study conducted by Johnston and Pilgrim (1976). Over a 2 year period, during which a full-time concentrated effort was applied to a single watershed, no true optimum set of parameter values was ever established.

Despite the apparent difficulties involved in the parameter optimization of watershed model, automatic calibration methods are routinely incorporated into almost all watershed models. Several studies related to parameter optimization of watershed models have shown favour towards the direct search methods. Hendrickson *et al.* (1988) conducted a calibration study comparing the pattern search algorithm with that of a Marquardt-Gauss-

Newton when applied to the National Weather Service River Forecasting System (NWSRFS). The results indicate that the pattern search algorithm, while incurring a greater computational expense, appears to be more robust than the Newton algorithm due to the presence of discontinuities in the response surface. Similar results were reported by Johnston and Pilgrim (1976) when the Simplex method and the Davidon descent method were applied to the Boughton model.

In this research, the model parameters were optimized using the pattern search optimization procedure presented by Hooke and Jeeves (1961) and subsequently programmed by Monro (1971). The pattern search algorithm is currently used by the WATFLOOD model and has been successfully applied for parameter determination in other hydrologic models (SWMM, MODHYDROLOG, NWSRFS, SLURP).

5.3.2.2 Selection of Objective Function

There are various criteria that can be used to measure model performance. The ordinary least squares estimator (OLS) is a commonly used objective function applied to the calibration of hydrologic models.

$$F = \sum \left(q_{sim} - q_{obs}\right)^2 \tag{5.04}$$

The OLS estimator is an index of the residual error, providing an indication on the success of the model to reproduce the observed hydrograph. The sum of squares criterion is not dimensionless and while it is well suited for comparing model outputs for a particular catchment, it is not suitable for comparing the performance of a model on different catchments or for comparing the model performance over differing periods of record.

It is generally understood that the ordinary least squares estimator will place more importance on the higher flows. An alternative function that will favour the reproduction of the low flow events involves using a square root transformation of the flow values:

$$F = \sum \left(\sqrt{q_{sim}} - \sqrt{q_{obs}}\right)^2 \tag{5.05}$$

For this research, an important goal of the wetland model was to properly simulate not only the peak discharge rates but also the long recession limbs characteristic of these wetland sites. As such, the calibration runs were performed using the square root objective function.

5.3.3 Calibrated Parameters

The focus of this calibration exercise involved the estimation of five parameters:

i) drainable porosity (hummock layer)
ii) drainable porosity (organic layer)
iii) surface flow coefficient (α)
iv) organic layer conductivity (upper boundary of organic layer)
v) organic layer conductivity (lower boundary of organic layer)

For this research, a surface flow exponent (β) value of 2.0 was adopted based on the recommendations of Kadlec and Knight (1996).

5.3.4 Calibration Procedure

A process-oriented calibration procedure was employed (Harlin, 1991). 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. Splitting the calibration period also allows for the use of different criterion for different parameter sets and is especially useful in obtaining a greater understanding of a particular process parameter when it is most active. In a study of the application of error analysis applied to a marsh hydrology model, Gardner *et al.* (1980) reported that a process-oriented calibration was necessary due to the strong seasonal behaviour of the model.

For this research effort, two subperiods were identified based on the flow processes occurring within the wetland. During the last half of August 1994 (Figure 5.2), the wetland streamflows incorporate a period of low flows associated with the recession of 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 of the model emphasized the determination of the following model parameters:

i) drainable porosity - organic layer
ii) conductivity - lower limit of organic layer

The calibration period spanning late April and early May (Figure 5.3) involves 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. Calibration of the model emphasized the estimation of the following parameters:

i) hummock flow coefficient
ii) drainable porosity - hummock layer
iii) conductivity - upper limit of organic layer

For both calibration periods, initial values for the optimization runs were determined through a manual trial and error approach until the displayed outflow hydrographs were reasonably close. Subsequent to the manually determined parameters, 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 period. This iterative procedure, alternating from the 1994 calibration period to the 1995 calibration period, was repeated until an optimal parameter set was established.

5.3.5 Calibrated Results

Figure 5.2 and 5.3 provide a comparison of the observed and calibrated model output for the 1994 and 1995 calibration periods respectively. Table 5.4 provides a summary of the efficiency criteria.

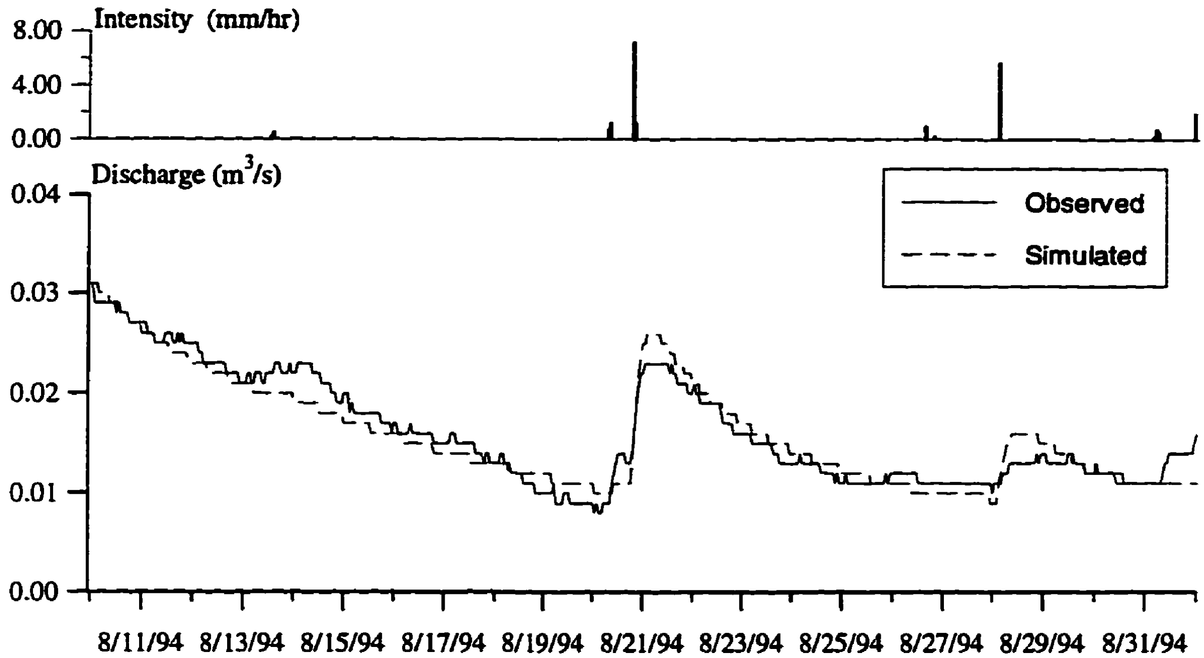


Figure 5.2 Comparison between observed and calibrated outflow hydrograph (1994 calibration period)

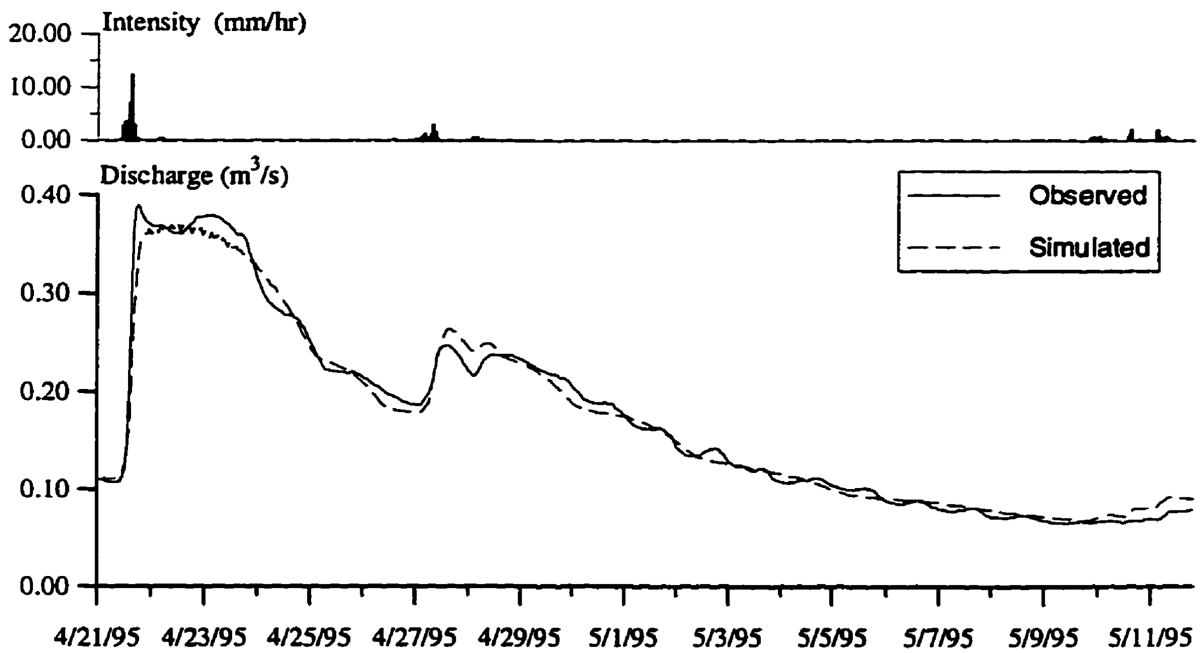


Figure 5.3 Comparison between observed and calibrated outflow hydrograph (1995 calibration period)

Table 5.4 Calibration statistics

Efficiency Criterion	1994 Period	1995 Period
Nash-Sutcliffe Coefficient	0.901	0.98
S-Criterion	0.099	0.069
Deviation in Runoff Volume (%)	0.7	-0.3

Table 5.5 provides a listing of the calibrated values resulting from this analysis of the headwater swamp. The calibrated organic layer drainable porosity value represents an average value over the range in heads encountered during the calibration period. In general, the drainable porosity value lies within the range typically reported for swamp systems in southern Ontario (for example, Woo and Valverde, 1981). The hummock storage value represents an average value reflecting the effective porosity corresponding to the vegetation and hummock/hollow topography.

Table 5.5 Summary of calibrated modelling parameters

Model Parameter	Base Case Value
drainable porosity - organic layer	0.12
drainable porosity - hummock layer	0.95
conductivity - upper limit of organic layer (m/s)	0.00510
conductivity - lower limit of organic layer (m/s)	0.00008
hummock flow coefficient (m^{-1}/s)	350

As a result of the coarse model descretization, the calibrated hydraulic conductivity values are higher than those corresponding to typical point-scale measurements of organic soils. With respect to the modelled processes, the values of the effective hydraulic conductivity parameters incorporate not only micropore flow through the soil matrix but integrate the capabilities of macropore flow and depressional streamlet flow to deliver stormflow to the channel system in excess of the amount possible by micropore flow alone. Similar results were obtained when applying a groundwater model (MODFLOW) to a raised mire in south Yorkshire in the British Isles (Bromley and Robinson, 1995). Calibration of the model was carried out using measured groundwater levels under steady-state conditions. Values of hydraulic conductivity were initially based on measured values obtained in the field by the auger hole technique. In order to match the predicted and observed levels, conductivity values had to be increased by an order of magnitude. Later examination indicated that the subsurface conductivity values represented in the model characterized a combination of flow through the peat matrix and flow through the shallow channel drainage network.

The surface flow coefficient characterizes how the surface flow is affected by the nature of the 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), representing an intermediate value between dense and sparse emergent vegetation.

5.4 Model Validation

5.4.1 Methods

The methodology employed during this study involved the evaluation of the model performance with respect to varying duration lengths. The wetland model was evaluated with regard to:

i) single event simulations
ii) monthly simulations
iii) continuous simulations

The single event simulations allowed an evaluation of the model capabilities for simulating the dominant processes governing the rainfall-runoff response from the wetland study site. The duration of the single event modelling typically ranged from 1 to 2 weeks in length. Where possible, a 1-2 day warm-up period prior to the precipitation event was utilized to help minimize the impact of the initial conditions on the simulation results.

The monthly and continuous simulations allowed an examination of the influences of the long-term hydrologic process (i.e. evapotranspiration and groundwater inflows) on the wetland behaviour. Monthly simulations were performed by initializing the wetland model to the conditions corresponding to the first day of the month and then performing a month-long simulation. The continuous simulation modelling involved initializing the wetland model at the start of the study period and conducting a simulation for the remainder of that year.

The results of the model validation exercises are presented in the following subsections.

5.4.2 Validation Results - Event Simulation

The performance of the calibrated wetland model was evaluated using 14 precipitation events. The events incorporate a wide range of precipitation volumes and antecedent wetland conditions. Plots of the observed and computed event hydrographs are provided in Appendix C. Table 5.6 provides a summary of the evaluation results corresponding to the single event simulations. With regard to the event simulations, the Nash-Sutcliffe coefficients ranged from -0.10 to 0.95. The deviation between the computed and simulated runoff volumes ranged from 0.9% to 40.1%. For many of the event simulations, it was clear that the SVCA rain gauge significantly underestimated the precipitation input to the wetland. To illustrate, the model performed poorly for the 950603 event (Appendix C, Figure C10). The Nash-Sutcliffe coefficient was computed to be -0.10 and the deviation the runoff volume was found to be -40.1%. The observed streamflow hydrograph (Figure C10) displays an initial hydrograph peak followed by a second peak approximately 9 hours later. The recorded rainfall corresponding to the second hydrograph peak measured only 0.5 mm. As shown in Figure C10, the 0.5 mm precipitation input did not produce the second hydrograph peak and the simulated recession period was significantly in error.

Table 5.6 Summary of evaluation results - single event simulations

Start of Simulation	Nash-Sutcliffe Coefficient	S-Criterion	Deviation in Runoff Volumes (D_v) (%)
July 06, 1994	0.77	0.203	-13.1
August 04, 1994	0.68	0.300	-18.7
September 13, 1994	0.89	0.173	3.8
September 28, 1994	0.24	0.429	-33.5
October 09, 1994	0.50	0.064	-3.6
October 19, 1994	0.95	0.055	-3.6
October 25, 1994	0.86	0.098	-1.5
November 04, 1994	0.89	0.188	-3.1
May 17, 1995	0.83	0.099	5.9
June 03, 1995	-0.10	0.464	-40.1
June 25, 1995	0.24	0.967	39.6
August 10, 1995	0.55	0.445	-14.2
October 15, 1995	0.81	0.113	0.9
October 20, 1995	0.87	0.085	-0.9

Figure 5.4 illustrates the variation in the computed and observed peak flow rates. Figure 5.5 shows the variation in the computed and observed stormflow runoff volumes associated with each simulation event. In summary, the modelling results could be considered satisfactory taking into account the general quality and quantity of data used in the simulations.

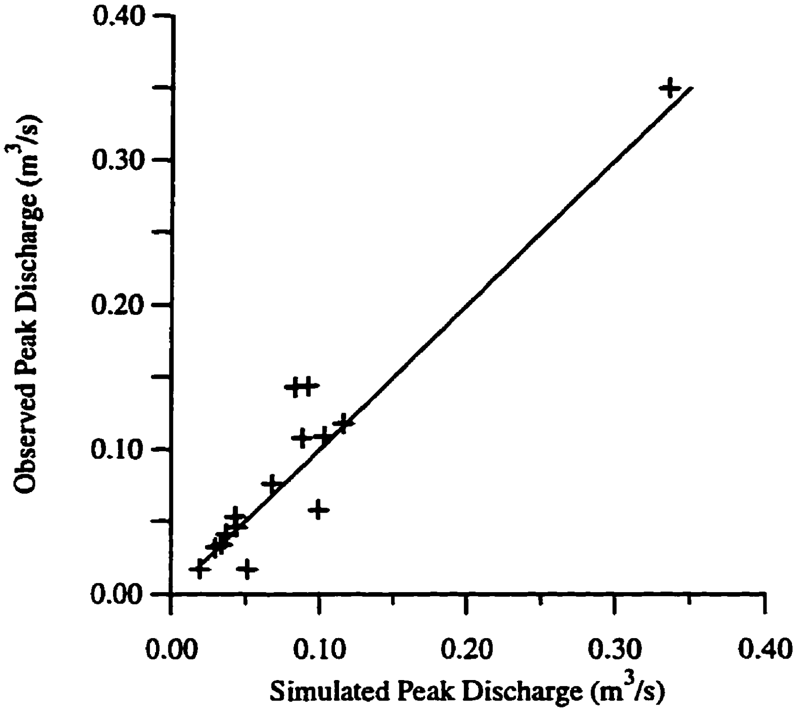


Figure 5.4 Simulated and observed peak discharge rates for event simulations (1994-1995)

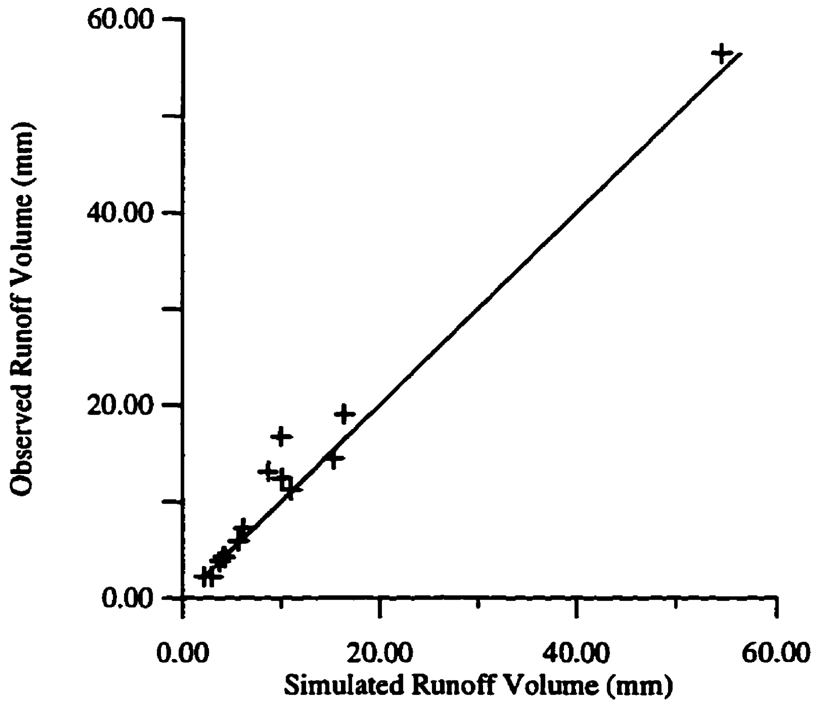


Figure 5.5 Simulated and observed runoff volumes for event simulations (1994-1995)

5.4.2.1 Application of Radar Rainfall

A primary source of uncertainty and error involves the use of a single rain gauge for the estimation of the precipitation input. It is well recognized that the measurement of precipitation from rain gauge installations is subject to large errors. Throughout the study period, this research had access to distributed radar rainfall data collected and disseminated by Environment Canada. The radar data was utilized to examine the areal distribution of the precipitation data. In several precipitation events, the radar data revealed instances where precipitation falling on the study site was not collected by the Saugeen Valley Conservation Authority gauge.

The application of the distributed radar data is demonstrated for two periods in 1994. Figure 5.6 provides a comparison between the observed streamflow hydrograph and computed streamflow hydrograph generated using the SVCA rain gauge data. Figure 5.7 illustrates the computed streamflow hydrograph using the distributed radar data. For this particular application, use of the radar data provides a significant improvement in the model performance.

Figures 5.8 and 5.9 provide a similar comparison for the month-long simulation for November 1994. The radar rainfall and rain gauge rainfall provided comparable modelling results for the 941104 event. However, the radar rainfall input resulted in a significant improvement in the 941128 precipitation event.

The behaviour of the wetland model with respect to the precipitation input is further examined in Chapter 6.

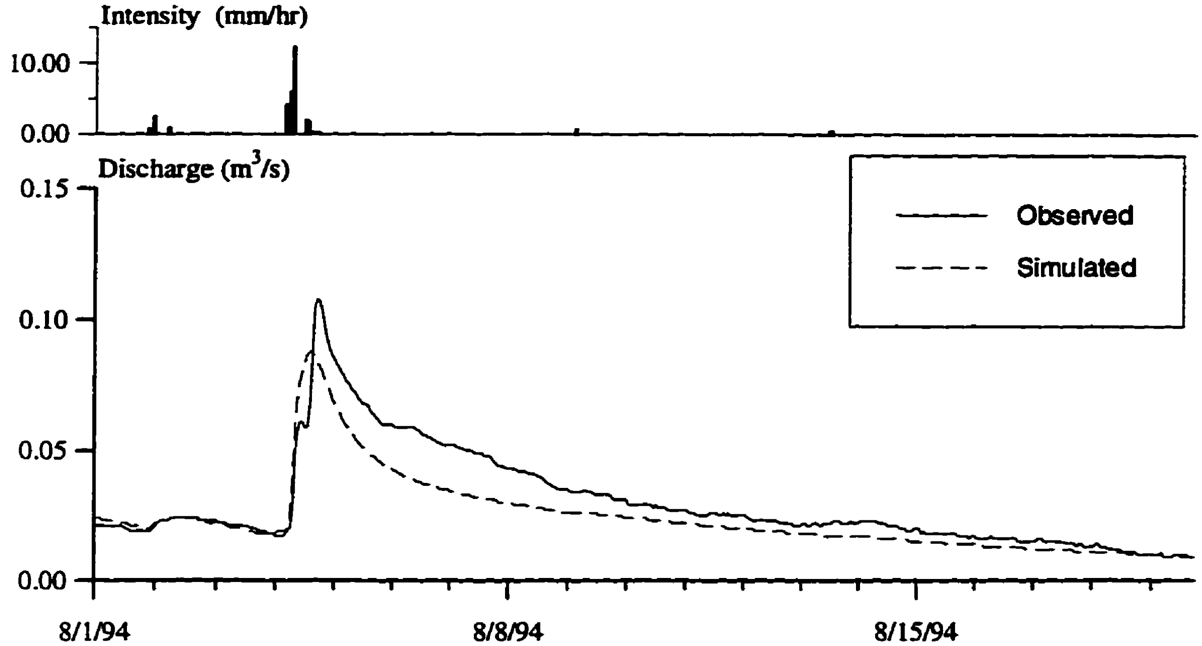


FIGURE 5.6 **Comparison of computed and simulated hydrograph utilizing rain gauge data (August 04, 1994)**

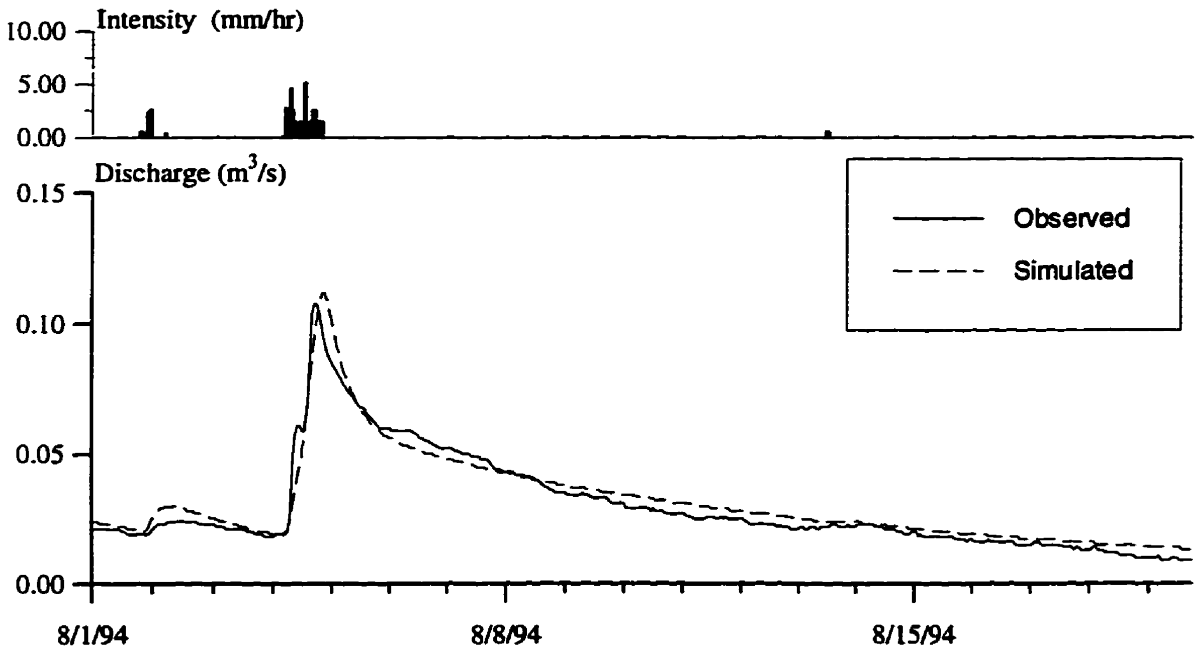


FIGURE 5.7 **Comparison of computed and simulated hydrograph utilizing weather radar data (August 04, 1994)**

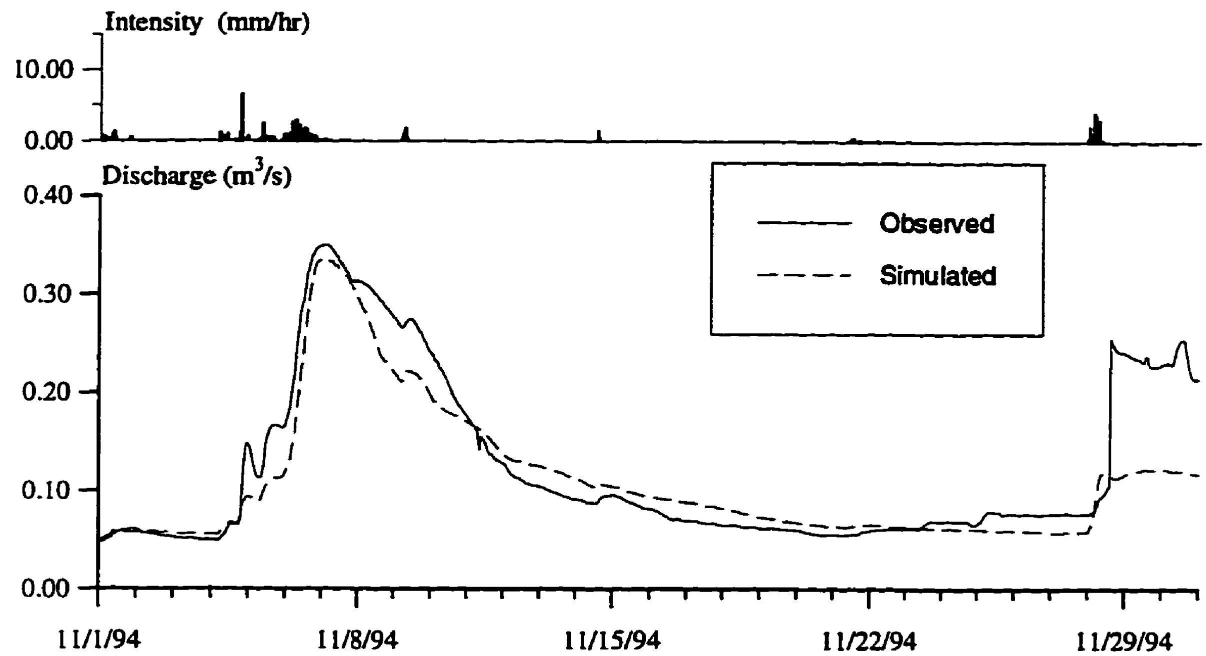


FIGURE 5.8 **Comparison of computed and simulated hydrograph utilizing rain gauge data (November, 1994)**

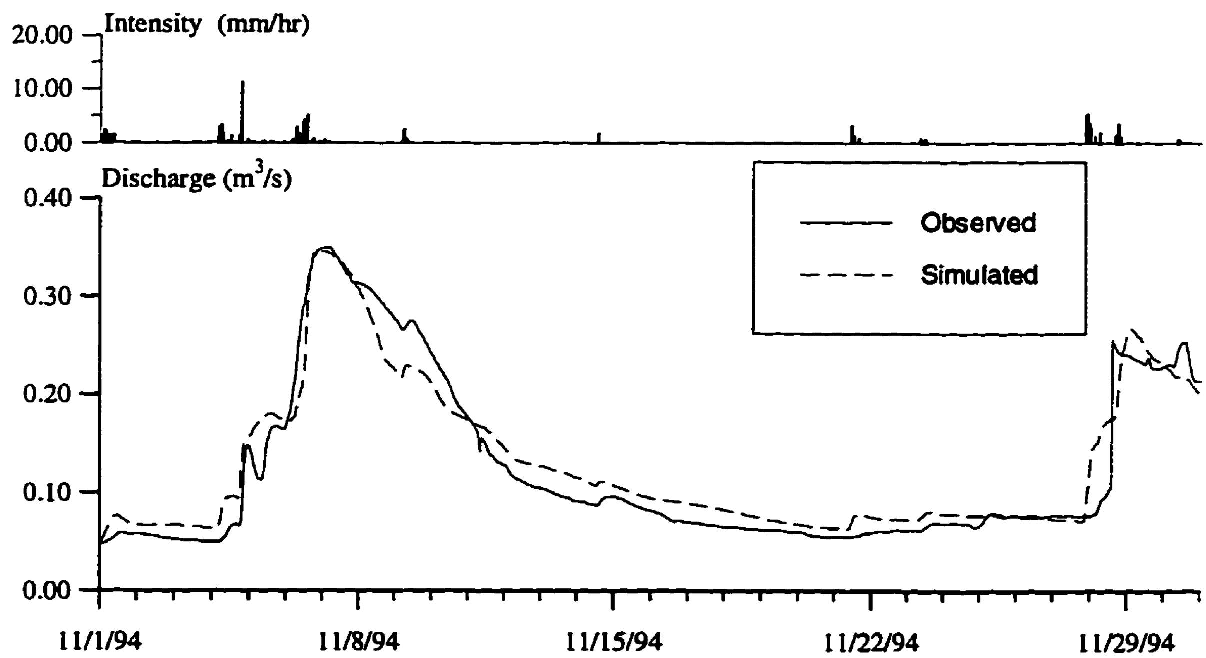


FIGURE 5.9 **Comparison of computed and simulated hydrograph utilizing weather radar data (November , 1994)**

5.4.3 Validation Results - Monthly Simulations

Plots of the simulated and observed streamflow hydrographs for the monthly simulations are provided in Appendix D. Table 5.7 provides a summary of the evaluation results with respect to the single event simulations.

Table 5.7 Summary of evaluation results - monthly simulations

Start of Simulation	Nash-Sutcliffe Coefficient	S-Criterion	Deviation in Runoff Volumes (D_v) (%)
July 1994	Missing Rainfall Data		
August 1994	0.73	0.300	-15.2
September 1994	0.85	0.347	-8.0
October 1994	0.81	0.162	9.6
November 1994	0.68	0.317	-10.6
April 1995	0.97	0.069	2.5
May 1995	0.84	0.120	4.2
June 1995	0.21	0.568	-37.8
July 1995	0.04	0.655	-64.5
August 1995	0.67	0.593	-9.5
September 1995	0.01	1.187	36.1
October 1995	-0.77	0.749	9.1

5.4.4 Validation Results - Continuous Simulations

Table 5.8 provides a listing of the efficiency criteria corresponding to the continuous simulations for the 1994 and 1995 study periods. A plot comparing the computed and observed streamflow hydrographs for the 1994 simulation period is provided in Figure 5.10. Figure 5.11 provides a similar plot for the 1995 study period.

Table 5.8 Summary of evaluation results - continuous simulations

Start of Simulation	Nash-Sutcliffe Coefficient	S-Criterion	Deviation in Runoff Volumes (D_v) (%)
August-November 1994	0.83	0.388	-12.6
April-October 1995	0.95	0.318	-3.7

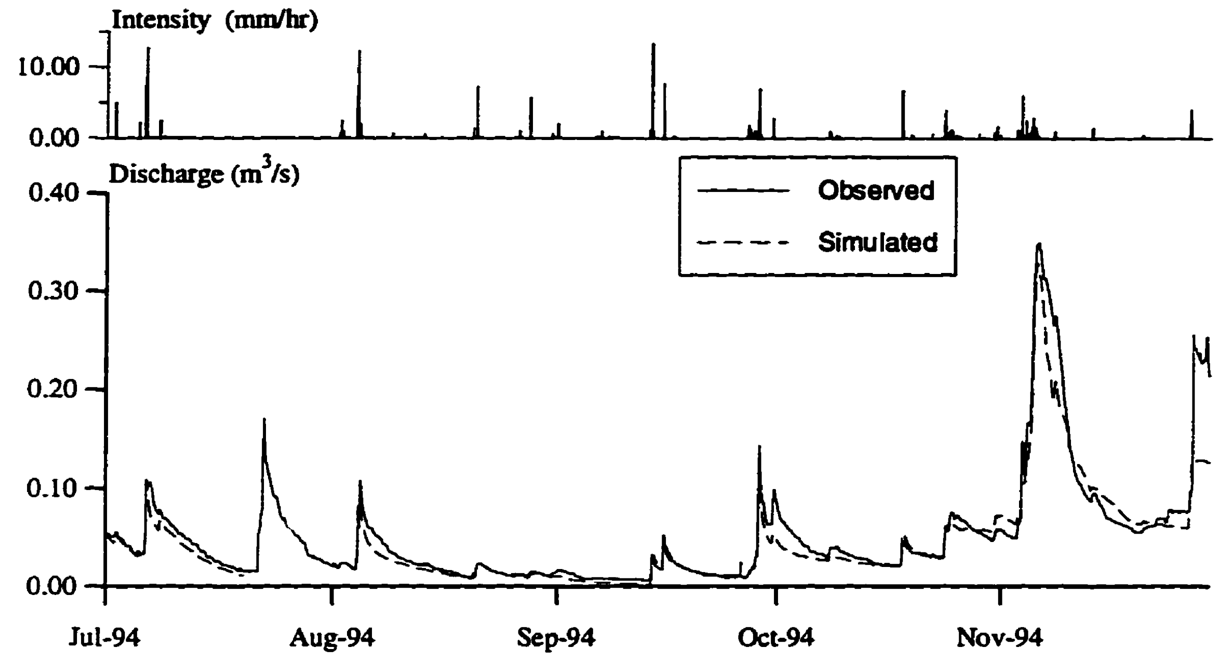


FIGURE 5.10 **Simulated and observed rainfall-runoff response from headwater wetland (1994)**

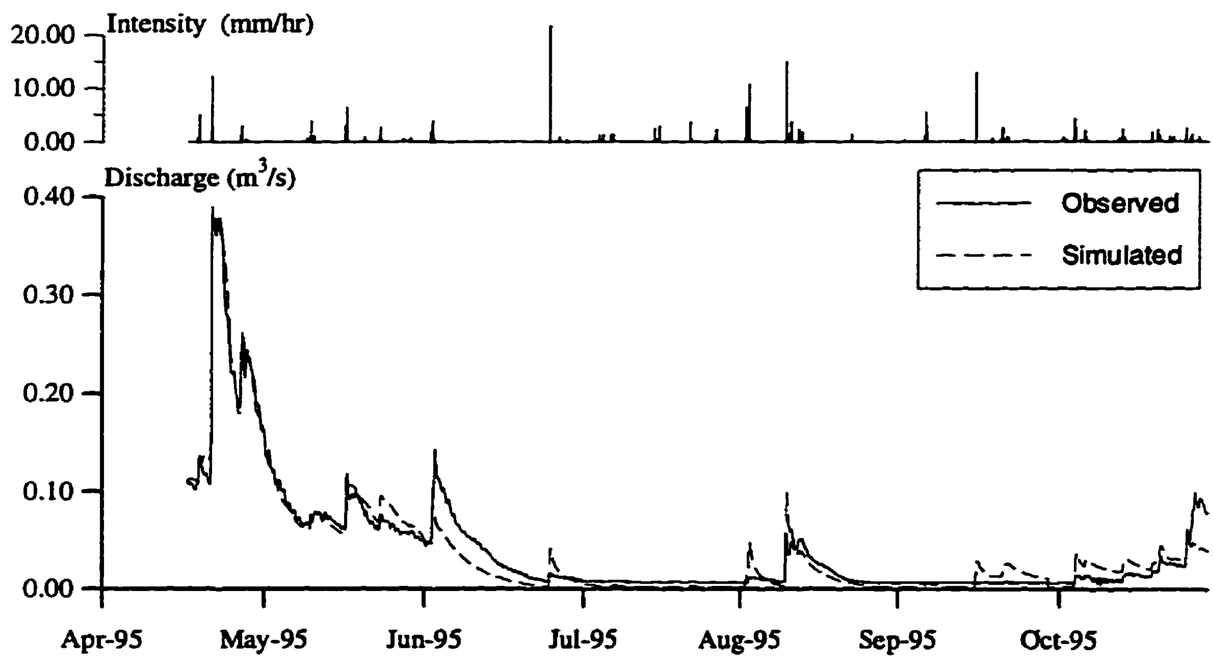


FIGURE 5.11 **Simulated and observed rainfall-runoff response from headwater wetland (1995)**

5.5 Storage-Discharge Relations

In order to gain additional understanding of the rainfall-runoff behaviour of the wetland model, the relationship between the computed discharge and the corresponding utilized storage within the wetland was examined. Two synthetic rainfall events, uniformly distributed over 10 hours were applied to the study site. The first event involved a total rainfall amount of 10 mm while the second event corresponded to a 50 mm rainfall. Figure 5.12(a) illustrates the rainfall-runoff response of the wetland site to the synthetic 10 mm precipitation event. The wetland response to the precipitation event was governed by the dynamics of the subsurface flow processes. The initial drainage, precipitation recharge and subsequent drainage of the wetland sediments are reflected in the discharge-storage relationship shown in Figure 5.12(b).

The stormflow response to a 50 mm precipitation event over 10 hours is shown in Figure 5.13(a). The discharge-storage relationship computed for the simulation is shown in Figure 5.13(b). The rainfall-runoff response from the rainfall event was influenced by a large overland flow contribution. Figure 5.13(b) displays a significant loop in the discharge-storage relationship. The relationship indicates that the simulated peak flow resulting from the 50 mm rainfall does not correspond with the maximum utilized storage within the wetland. The lag between the maximum storage of the stormflow and the maximum outflow rate from the wetland can be attributed to the development of a significant overland stormflow component from the wetland and the lag between the lateral discharge from the wetland sediments and the channel outflow at the wetland outlet.

The discharge-storage relationship for the study site was examined over two simulation periods, during late fall of 1994 and during the spring of 1995. Figure 5.14 provides the stormflow response and discharge-storage relationship computed for a 1200 hour simulation over October and November of 1994. Figure 5.15 provides similar plots for the 600 hour simulation in late April and early May of 1995. Both figures exhibit a significant hysteresis in the discharge-storage relationship.

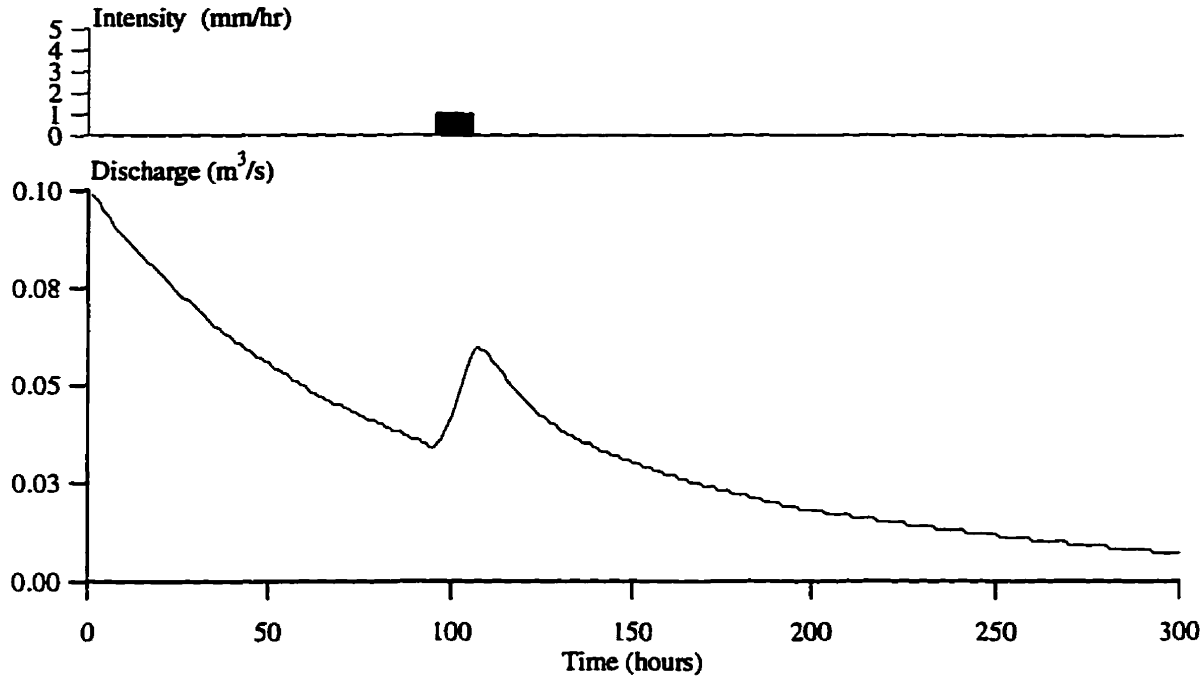


Figure 5.12(a) **Simulated streamflow hydrograph for headwater wetland synthetic 10 mm storm over 10 hours**

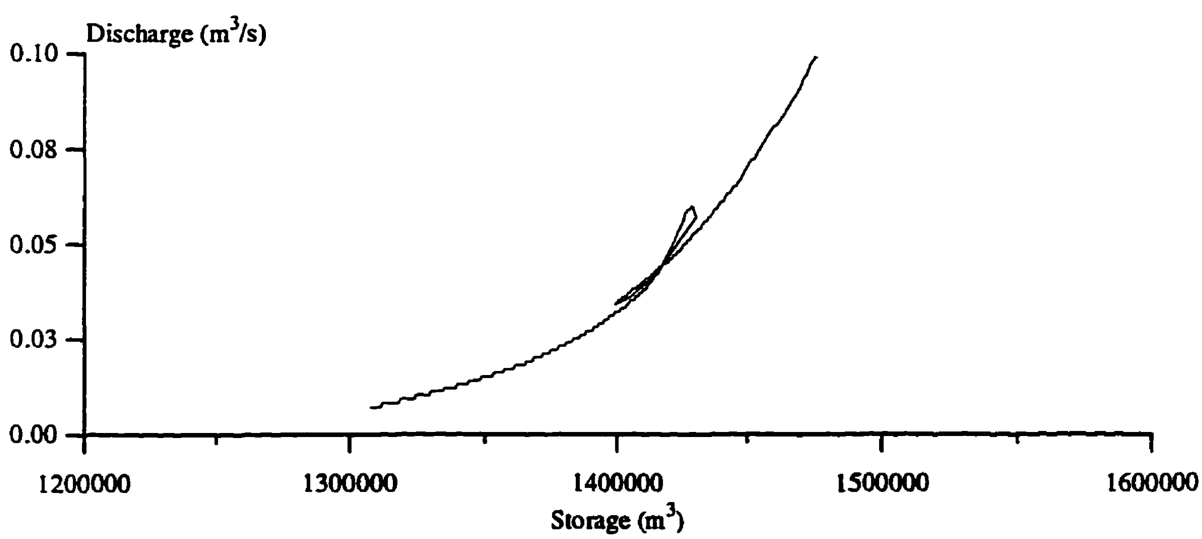


Figure 5.12(b) **Simulated storage-discharge relationship for headwater wetland, synthetic 10 mm storm over 10 hours**

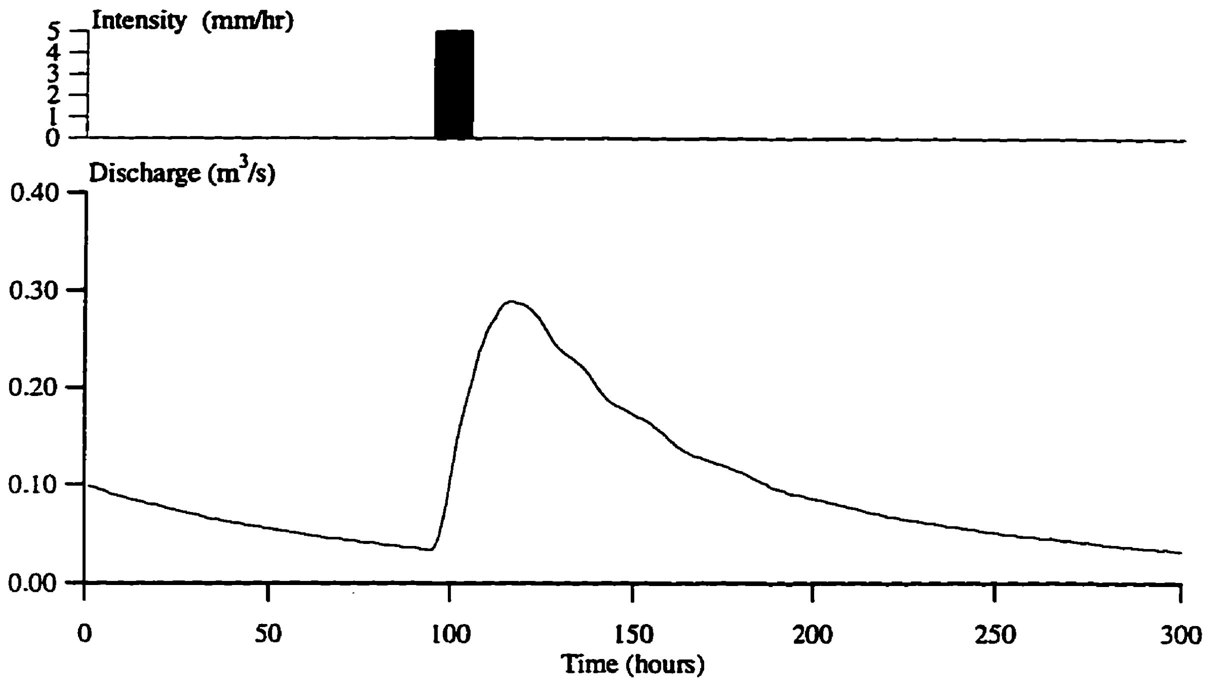


Figure 5.13(a) **Simulated streamflow hydrograph for headwater wetland synthetic 50 mm storm over 10 hours**

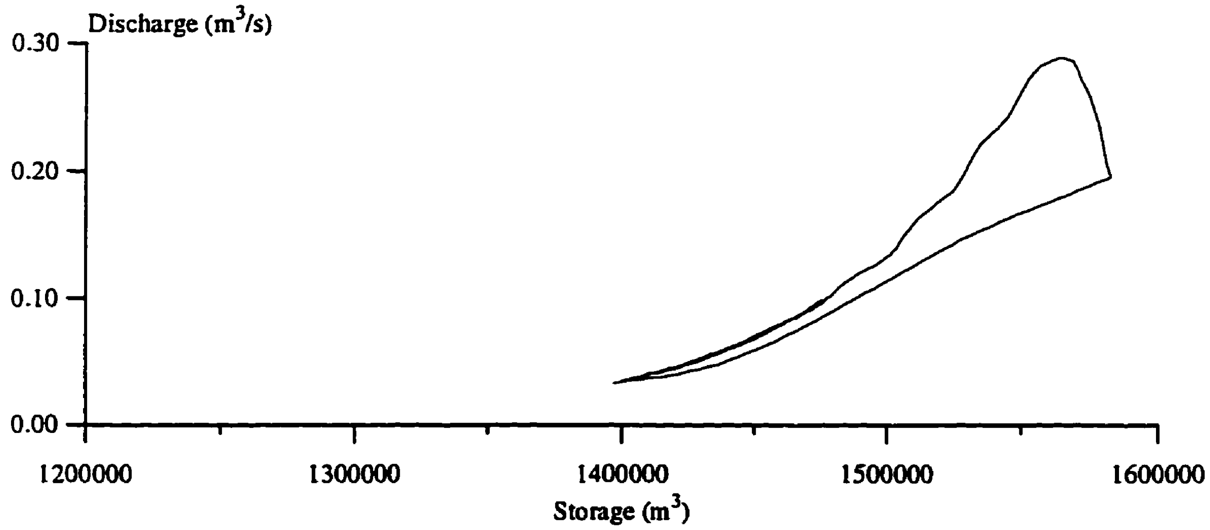


Figure 5.13(b) **Simulated storage-discharge relationship for headwater wetland, synthetic 50 mm storm over 10 hours**

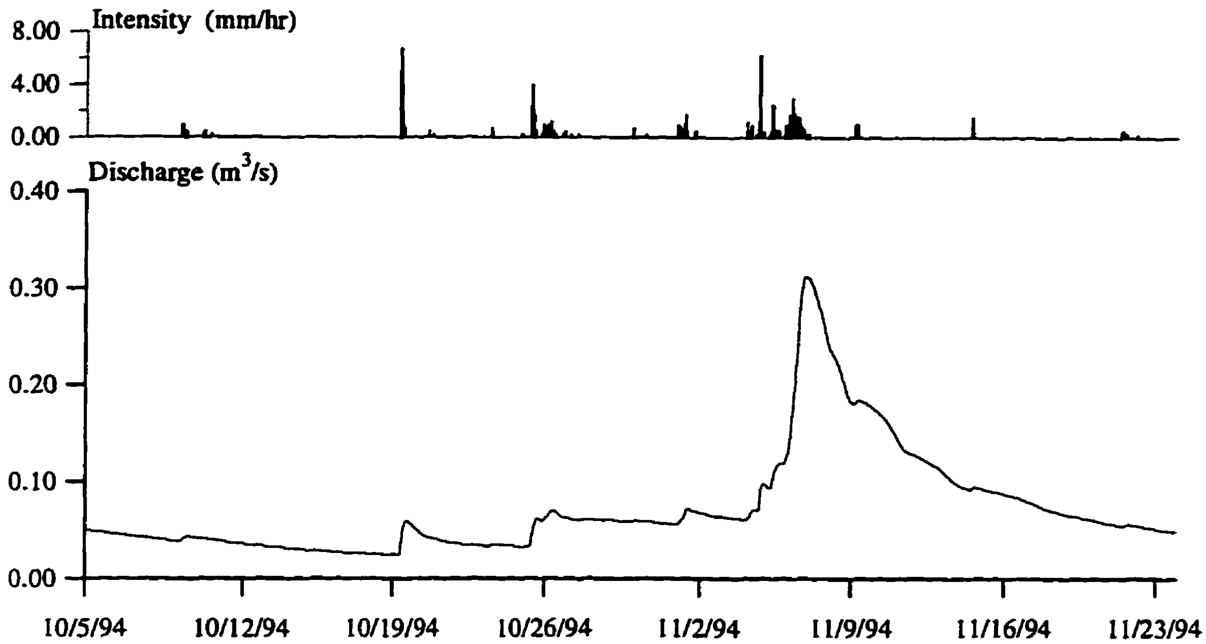


Figure 5.14(a) **Simulated streamflow hydrograph for headwater wetland October/November 1994**

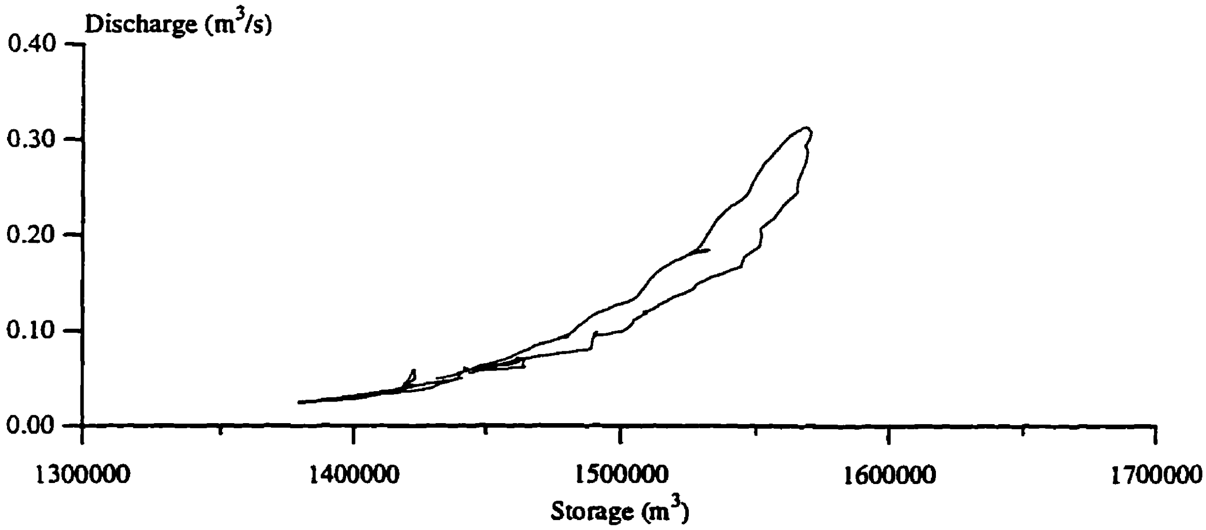


Figure 5.14(b) **Simulated storage-discharge relationship for headwater wetland, October/November 1994**

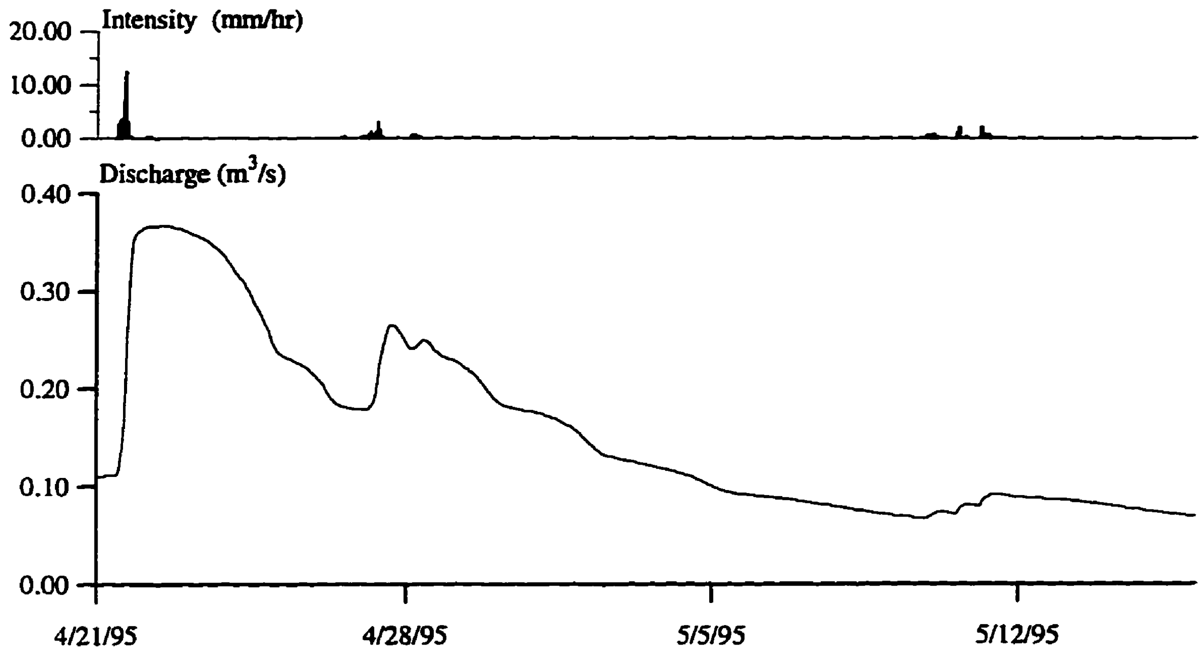


Figure 5.15(a) **Simulated streamflow hydrograph for headwater wetland April/May 1995**

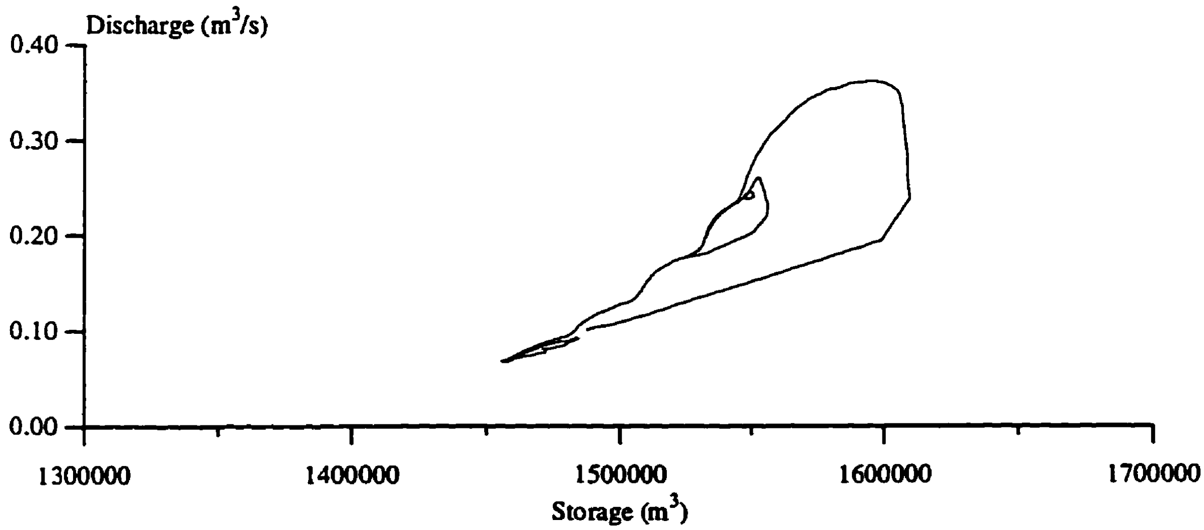


Figure 5.15(b) **Simulated storage-discharge relationship for headwater wetland, April/May 1995**

5.6 Chapter Summary

This chapter presented the application of the wetland model towards streamflow simulations at a first-order headwater swamp in the Teeswater River watershed. As with many wetland sites, access to much of the site was difficult and intensive fieldwork to obtain data was not feasible.

Precipitation inputs were obtained from data provided by the Saugeen Valley Conservation Authority. Estimates of the evapotranspiration rates were obtained using the well-known Turc formula. An estimate of the mean groundwater input was established from a simple water balance.

Even with the simplified process representations incorporated into the wetland model, the event simulations required a significant number of modelling parameters. Where possible, parameter values were found through field surveys or obtained from values reported in standard operational practice. Using a process-oriented calibration scheme, five model parameters were optimized.

The performance of the model was evaluated using three goodness-of-fit criteria, the Nash-Sutcliffe coefficient, the deviation of runoff volumes and the S-criterion. The results indicate that the wetland model is able to reproduce the rainfall-runoff response from the headwater study site with reasonable accuracy. A large source of error and uncertainty involves the use of a single rain gauge for the measurement of precipitation data. For several modelling events, the use of distributed weather radar rainfall was able to provide an improvement in the model results.

Finally, the model output indicates that the stormflow response of the wetland is not a simple function of wetland storage. The hydrologic behaviour of the wetland is dependent on the flow transport processes governing the streamflow response.

CHAPTER 6

6. Sensitivity Analysis

6.1 General

An important component of any modelling effort involves the determination of the relative sensitivity of the model outputs with respect to the model parameters. A sensitivity analysis allows examination of the model behaviour with regard to the dominant hydrologic processes. Insight into the sensitivity of the model provides valuable information regarding the effort and accuracy required for the determination of the model parameters. By revealing the indifference of the objective function to changes in the various model parameters, the results can be used to guide future model revisions or modifications. As part of this research, an analysis was performed in order to provide a better understanding of the dominant modelling parameters and to reveal how the model behaviour is influenced by the changes in the parameters.

6.2 Methods

Parameter sensitivities were evaluated by systematically varying each model parameter while maintaining all other parameter values at their original calibrated values. The sensitivity to each parameter was calculated by perturbing each parameter by 5% from its base-case value. Table 6.1 provides a listing of the calibrated model parameters evaluated during the sensitivity analysis and their associated values. In addition to the calibrated parameters, the analysis also evaluated the sensitivity of the model output to several other parameters established prior to the calibration exercise from field measurements or from current recommended practice.

Table 6.1 Calibrated modelling parameters (base case)

Model Parameter	Base Case Value
drainable porosity - organic	0.12
drainable porosity - hummock	0.95
hydraulic conductivity - upper limit of organic layer (m/s)	0.00510
hydraulic conductivity - lower limit of organic layer (m/s)	0.00008
hummock flow coefficient (m^{-1}/s)	350

6.2.1 Simulation Periods

6.2.1.1 Event Simulations

The sensitivity analysis was conducted utilizing two different modelling periods, one period where subsurface flows dominated the runoff response and another period where overland flow within the hummock layer influenced the stormflow response. A brief description of the event simulations are provided below. Table 6.2 provides a summary of the statistics corresponding to the two event periods.

Event 1 - 940929

Event 1 involves a 240 hour simulation spanning from September 26, 1994 to October 05, 1994. During the precipitation event, a 30 hour period of low intensity rainfall totalling 25 mm was followed by an eight hour storm producing 22 mm of precipitation. Approximately 48 hours later, a four hour event totalling 5 mm occurred. Water levels within the wetland were limited primarily to within the organic sediments with little overland flow within the hummock layer.

Event 2 - 941104

Event 2 involves a 300 hour simulation spanning November 02, 1994 to November 14, 1994. Approximately 40 mm of precipitation fell on the wetland over a 4 day period. Prior to the precipitation period, the wetland surface was inundated and as a result, the stormflow response was strongly influenced by overland flows within the hummock layer.

Table 6.2 Summary statistics for simulation events

	Simulation Event	
	Event 1	**Event 2**
Duration of Simulation (hours)	240	300
Total Precipitation (mm)	52	40
Total Potential Evapotranspiration (mm)	19	8
Initial Streamflow (m^3/s)	0.011	0.058
Peak Discharge Rate (m^3/s)	0.092	0.327
Final Streamflow (m^3/s)	0.041	0.106
Total Streamflow Volume (m^3)	28400	165100

6.2.1.2 Continuous Simulation

An additional analysis was performed in order to investigate the sensitivity of the model outputs with respect to a long-term simulation involving multiple precipitation events. The simulation consisted of a 1200 hour modelling period during which 98 mm of precipitation was measured. Table 6.3 summarizes the statistics characterizing the continuous simulation period.

Table 6.3 Summary statistics for continuous simulation event

	Event 3
Duration of Simulation (hours)	1200
Total Precipitation (mm)	98
Total Evapotranspiration (mm)	57
Initial Streamflow (m^3/s)	0.050
Peak Discharge Rate (m^3/s)	0.350
Final Streamflow (m^3/s)	0.069
Total Streamflow Volume (m^3)	332658

6.3 Evaluation of Model Sensitivity

6.3.1 Sensitivity Coefficient

The sensitivity of each parameter was evaluated using a normalized sensitivity coefficient (McCuen, 1973) given as:

$$R_S = \frac{\Delta F_o}{F_o} \frac{F_i}{\Delta F_i} \tag{6.01}$$

where R_S is the relative sensitivity, ΔF_o represents the change in the model output, F_o is the model output corresponding to the base case, ΔF_i is the change in the parameter value, and F_i is the base case parameter value. The sensitivity coefficient can be interpreted as the percent change in the model output that occurs as a result of a 1% change in the parameter value. Application of equation (6.01) involved the use of several criteria in order to establish the parameter sensitivity of the wetland model.

6.3.1.1 S Criteria

Employing the S criterion (equation 5.03), the relative sensitivity of the model to any changes in the parameter values is given by:

$$R_S = \frac{S_o - S_i}{S_o} \frac{X_o}{X_o - X_i} \tag{6.02}$$

where S_o is the S efficiency criteria for the base case, S_i is the efficiency criteria corresponding to the perturbed parameter value, X_o is the base case parameter value and X_i is the value of the perturbed parameter.

6.3.1.2 Peak Flow

The parameter sensitivity was also evaluated with regards to the change in predicted peak discharge as given by:

$$R_S = \frac{Qp_o - Qp_i}{Qp_o} \frac{X_o}{X_o - X_i} \tag{6.03}$$

where Qp_o is the peak discharge computed using the base case parameter set and Qp_i is the computed peak discharge rate corresponding to the perturbed parameter value.

6.3.1.3 Runoff Volume

The parameter sensitivity was also evaluated with regard to the change in the predicted total runoff volume discharging from the wetland.

$$R_S = \frac{V_o - V_i}{V_o} \frac{X_o}{X_o - X_i} \tag{6.04}$$

where V_o is the total runoff volume computed using the base case parameter set and V_i is the total runoff volume computed using the perturbed parameter value.

6.3.2 Hydrograph Plots

In many ways, the sensitivity of the wetland model can be evaluated simply by conducting a visual comparison of the model output, namely the computed wetland outflow hydrographs. In order to examine the sensitivity of the calibrated model visually, an additional series of model simulations were conducted whereby each model parameter was perturbed by ±25% and the outflow hydrographs plotted for comparison. A complete listing of the hydrograph plots is provided in Appendix E.

6.4 Sensitivity Results - Event Simulations

6.4.1 Event 1

Table 6.4 provides a summary of the calculated sensitivity terms for each parameter change associated with event 1. The relative sensitivity of the model to changes in the parameters varied for each of the sensitivity criteria. For all three sensitivity criteria, the model was most sensitive to changes in the precipitation input (e.g. as would typically be made when calibrating distributed radar data). A 1% increase in the precipitation resulted in a 1.6% decrease in the S-criterion while producing a 1.3% increase in the simulated hydrograph peak.

Table 6.4 Relative sensitivities - Event 1

Model Parameter		Relative Sensitivities*		
		S-Criterion	Runoff Volume	Peak Flow Rate
Channel network	Channel roughness	0.0823	-0.0307	-0.4348
	Channel slope	-0.0204	0.0025	0.2174
	Channel width	-0.0465	0.0250	0.2174
	Channel length	-0.7686	0.4487	0.2174
	Antecedent flow	-0.4727	-0.3824	0.2174
Wetland field cell	Wetland slope	-0.0314	0.0152	0.0000
	Wetland width	0.1809	-0.1174	0.0000
	Groundwater inflow	-0.3072	0.2019	0.0000
Organic layer	Hydraulic conductivity	-0.4555	0.2597	0.2174
	Drainable porosity	0.5511	-0.3013	-0.8696
	Depth of layer	-0.3558	-0.2111	0.0000
Hummock layer	Flow coefficient	-0.0537	0.0314	0.0000
	Drainable porosity	0.2128	-0.1286	0.0000
Climatic data	Precipitation	-1.6104	-0.9463	1.3043
	Evapotranspiration	0.1598	-0.1223	0.0000
	Canopy storage capacity	0.0519	-0.0349	0.0000

* shaded values indicate three most sensitive parameters for each evaluation criteria for a 1% parameter change

For event 1, the hydrograph peak was most influenced by the drainable porosity of the organic sediments and channel roughness. The stormflow runoff volume discharged from the wetland was most affected by the length of the drainage channel and the antecedent streamflow conditions. An increase in the channel length corresponds to a longer interface between the channel and the wetland sediments. As would be expected for an event simulation, the evapotranspiration demand and groundwater inflow had little influence on the hydrograph peak.

6.4.2 Event 2

A summary of the calculated sensitivity terms for each parameter change associated with event 2 is provided in Table 6.5. As with event 1, the simulation of event 2 was most influenced by changes in the precipitation input. The stormflow response of the wetland under event 2 is influenced by the conveyance capabilities of the drainage system with the hydrograph peak sensitive to changes in the roughness and width of the channel. With respect to the hummock layer, the hydrograph peak was found to be more sensitive to changes in the drainable porosity than to changes in the flow coefficient. As with event 1, the long-term fluxes such as evapotranspiration and groundwater inflow had little influence on the event peak. The volume of stormflow discharged during the simulation was most influenced by the length of the drainage channel and the antecedent streamflow conditions.

Further discussions regarding the model sensitivities are provided in the following subsections. Figures 6.1-6.8 are provided to allow qualitative comparisons between the resulting streamflow hydrographs and the base-case hydrograph.

Table 6.5 Relative sensitivities - Event 2

Model Parameter		Relative Sensitivities*		
		S-Criterion	Runoff Volume	Peak Flow Rate
Channel network	Channel roughness	-0.0789	-0.0182	-0.6116
	Channel slope	0.0992	0.0041	0.1835
	Channel width	0.2868	0.0185	0.6116
	Channel length	-1.1439	0.4525	0.0612
	Antecedent flow	-1.6409	0.4179	0.4281
Wetland field cell	Wetland slope	-0.2921	0.0579	0.0000
	Wetland width	-1.1823	0.0436	0.1223
	Groundwater inflow	-0.6046	0.1926	0.0612
Organic layer	Hydraulic conductivity	0.3716	-0.0309	-0.2446
	Drainable porosity	0.2474	-0.0394	-0.0612
	Depth of layer	0.9698	-0.0635	0.1835
Hummock layer	Flow coefficient	-0.4607	0.0620	0.1835
	Drainable porosity	1.9824	-0.2817	-0.6116
Climatic data	Precipitation	3.9040	0.9673	0.8563
	Evapotranspiration	0.2522	-0.0720	-0.1223
	Canopy storage capacity	0.0932	-0.0173	-0.0612

* shaded values indicate three most sensitive parameters for each evaluation criteria for a 1% parameter change

6.4.3 Sensitivity To Precipitation Input

The sensitivity analyses indicate that the wetland model output is strongly influenced by the precipitation input. The results indicate that any change in the rainfall volume will strongly affect both the peak discharge rate and the total runoff volume predicted by the wetland model.

The influence of a change in precipitation input is illustrated in Figure 6.1. For both simulation events, increasing the magnitude of the precipitation input increased the peak discharge rate while decreasing the time to peak characteristic of the simulated hydrographs. As would be expected, the total runoff volume discharged from the wetland increased as the precipitation volume was increased. A comparison of Figure 6.1(a) and Figure 6.1(b) illustrates the variability of the model behaviour with respect to a change in the precipitation input. The response of the wetland model output to a change in the precipitation is dependent on the flow processes associated with the event. With event 1, subsurface flow processes shape the wetland response and thus the simulated hydrographs retain the same general shape. With respect to event 2, an increase in the overland flow contribution resulting from a corresponding increase in the precipitation input was reflected in the predicted streamflow hydrograph.

Figure 6.1 also reveals the precipitation input significantly influences the recession limbs of the outflow hydrographs. This fact is especially significant with regard to long-term simulation modelling. Any changes in the precipitation volume influences the saturation state within the wetland and the corresponding outflow rate for many days after the rainfall event. Examination of the second hydrograph peak in Figure 6.1(a) indicates that the wetland stormflow response resulting from the 941001 precipitation event is influenced by the level of saturation resulting from the 940929 event.

6.4.4 Sensitivity To Groundwater Input

A significant input to the wetland model involves the specification of the groundwater flux associated with the wetland site. The wetland model is essentially a surface process model and requires an external estimate regarding the role of the groundwater flow with regards to the wetland hydrology. Without an expensive hydrogeologic study, the estimation of the groundwater component of a wetland water budget is difficult and subject to a large amount of uncertainty.

Figure 6.2 illustrates the influence of the specified groundwater input on the simulation results. Increasing the groundwater inflow resulted in an increase in the total runoff volume and an increase in the hydrograph peak. For both events, a 25% change in the base-case groundwater flux is noticeable after a modelling duration of approximately 2-3 days. In the latter half of the simulations, any change in the groundwater inflow is reflected directly in the computed outflow rates with the predicted hydrograph and base-case hydrograph being essentially parallel.

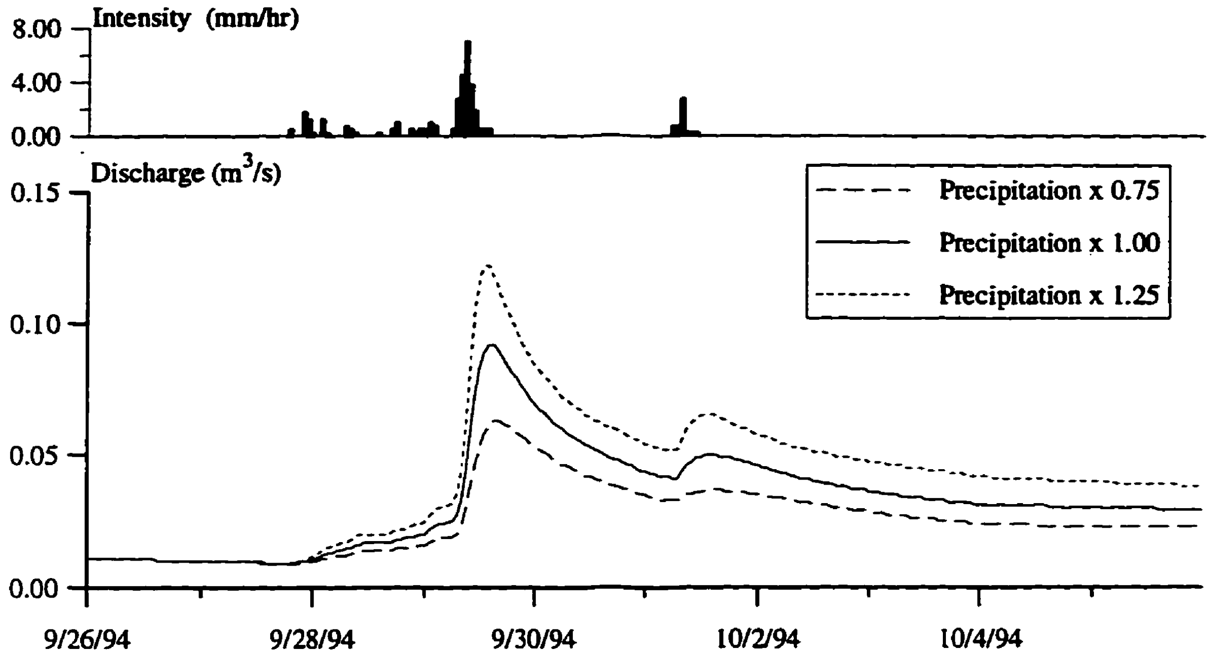


Figure 6.1(a) Sensitivity to precipitation input (Event 1)

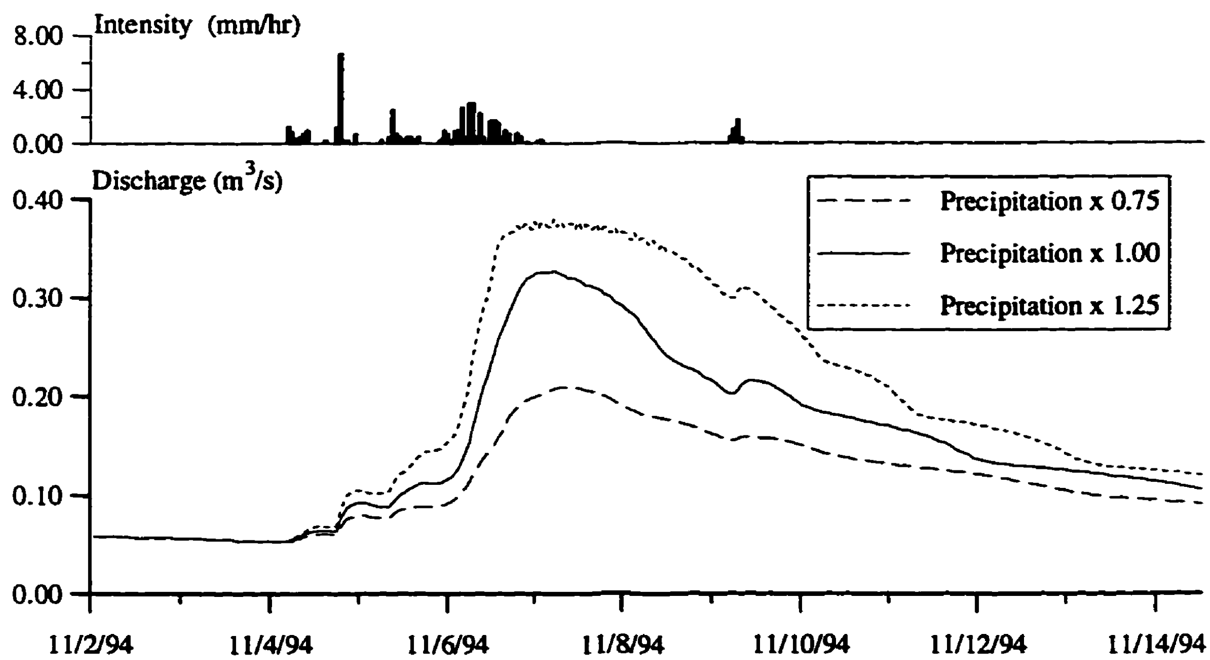


Figure 6.1(b) Sensitivity to precipitation input (Event 2)

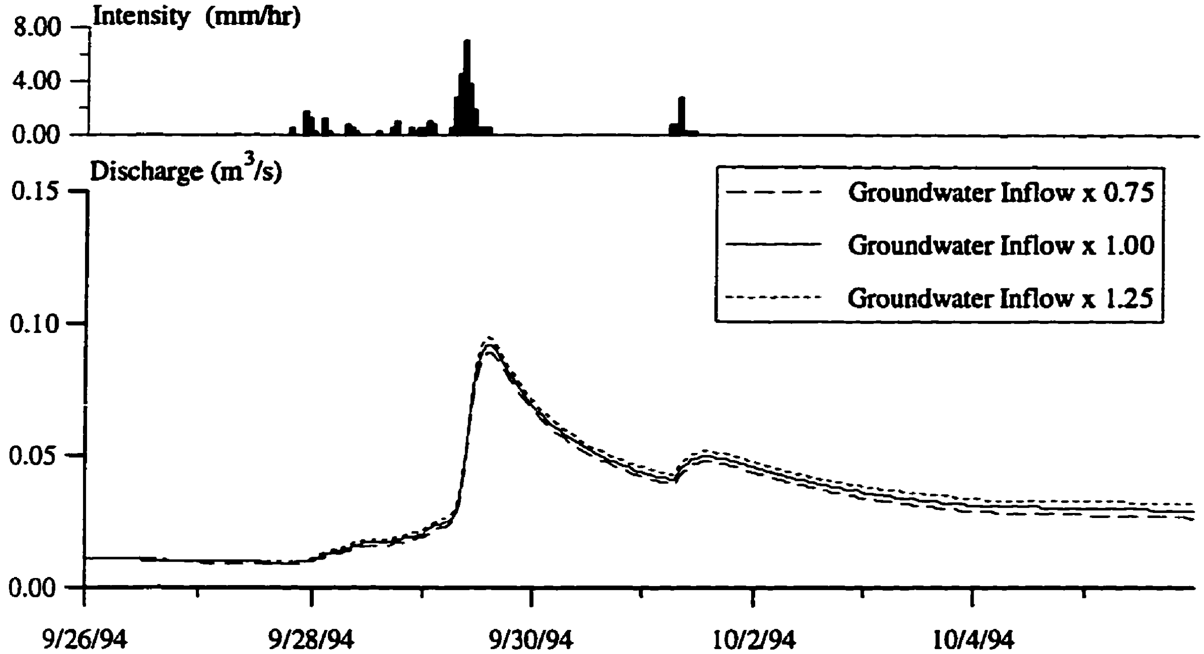


Figure 6.2(a) Sensitivity to groundwater inflow (Event 1)

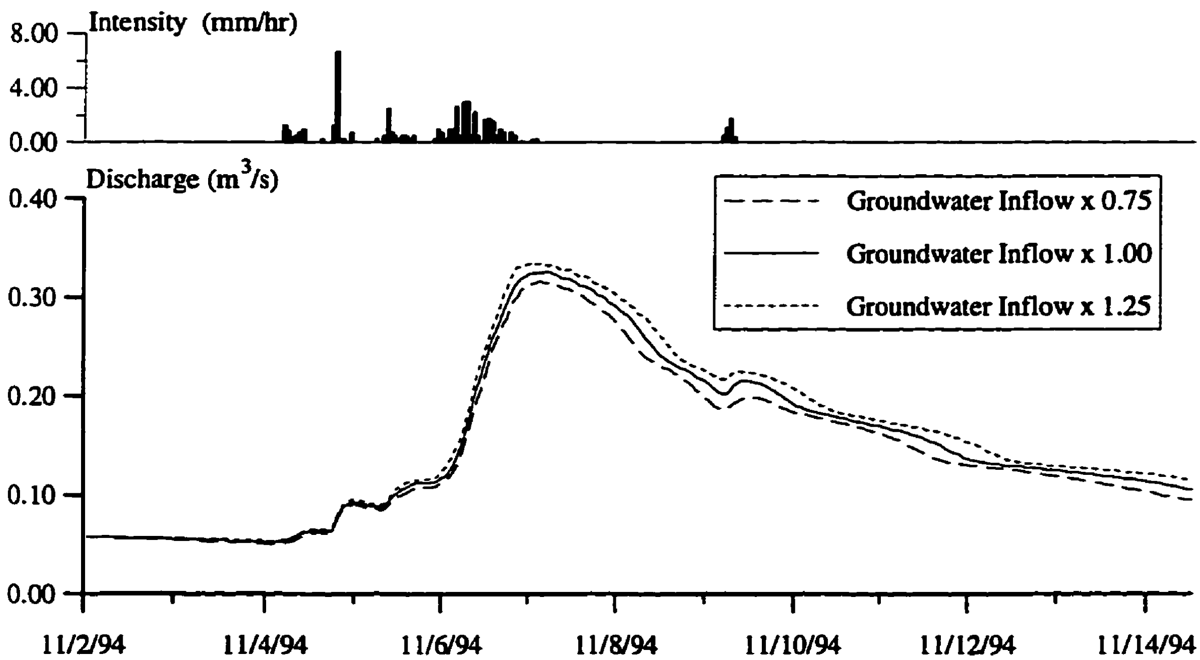


Figure 6.2(b) Sensitivity to groundwater inflow (Event 2)

6.4.5 Sensitivity To Length of Wetland Channel

The length of the wetland channel network defines the length of the interface between the wetland field hydrology model and the wetland drainage system. With respect to the wetland model, increasing the length of the routing reaches results in an increase in the total drainage area associated with the wetland. As shown in Figure 6.3, increasing the wetland channel length resulted in an increase in the runoff volume. For both the simulation events, the increase in runoff volume is reflected primarily in the recession limbs of the outflow hydrographs.

With both event 1 and event 2, increasing the channel length increased the time to peak characteristic of the outflow hydrograph. For event 1, increasing the channel length produced a corresponding increase in the peak flow rate. However, with respect to event 2, very little change in the peak flow rate resulted from a change in the channel length.

6.4.6 Sensitivity To Antecedent Streamflow

In general, the streamflow rate associated with the wetland is an indicator of the antecedent saturation conditions within the wetland system. Low streamflow rates are indicative of low water table levels within the wetland sediments. Figure 6.4 illustrates the behaviour of the wetland simulation to the antecedent streamflow rate. For both simulation events, an increase in the initial flow rate resulted in an increase in the peak flow rate and the total runoff volume. With respect to event 1, a change in the initial streamflow rate is propagated throughout the simulation with the predicted hydrograph being essentially parallel to the best-fit case.

For event 2, a change in the initial saturation level within the wetland influences the development and resulting magnitude of the overland flow contribution from the wetland. Increasing the initial streamflow rate resulted in a larger overland flow contribution as reflected in the increase in the hydrograph peak and the decrease in the time to peak. Examination of Figure 6.4(b) indicates that the hydrographs corresponding to the perturbed initial streamflow rates slowly converge towards the best-fit hydrograph along the recession limb.

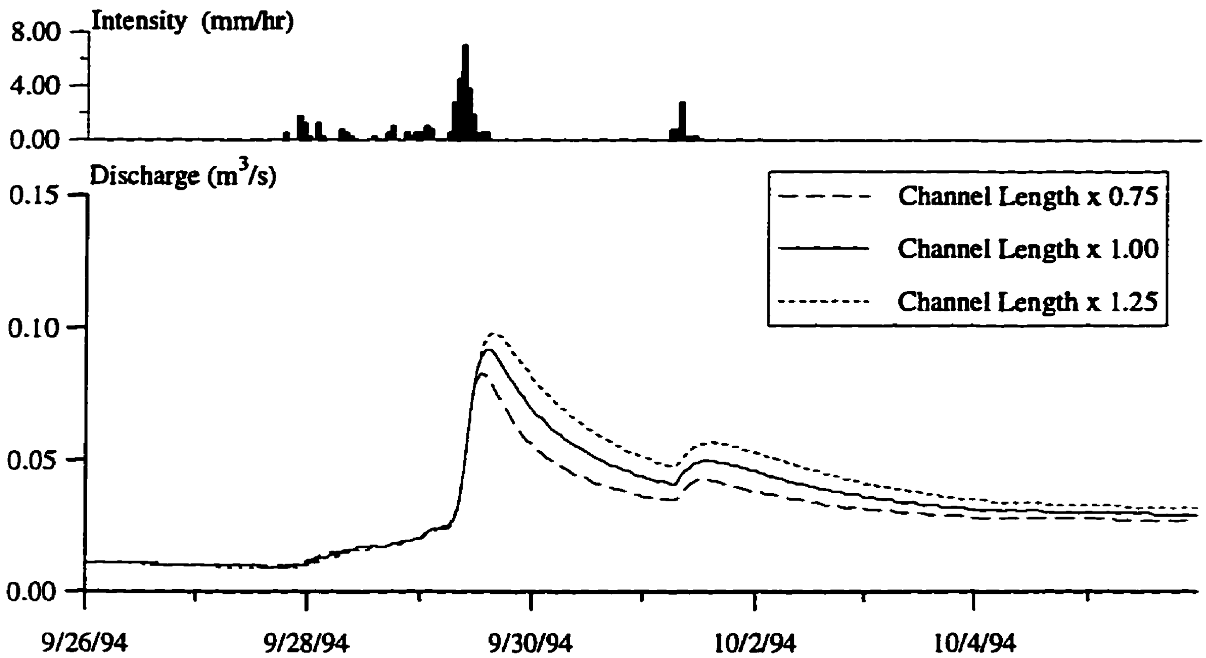


Figure 6.3(a) Sensitivity to length of wetland channel (Event 1)

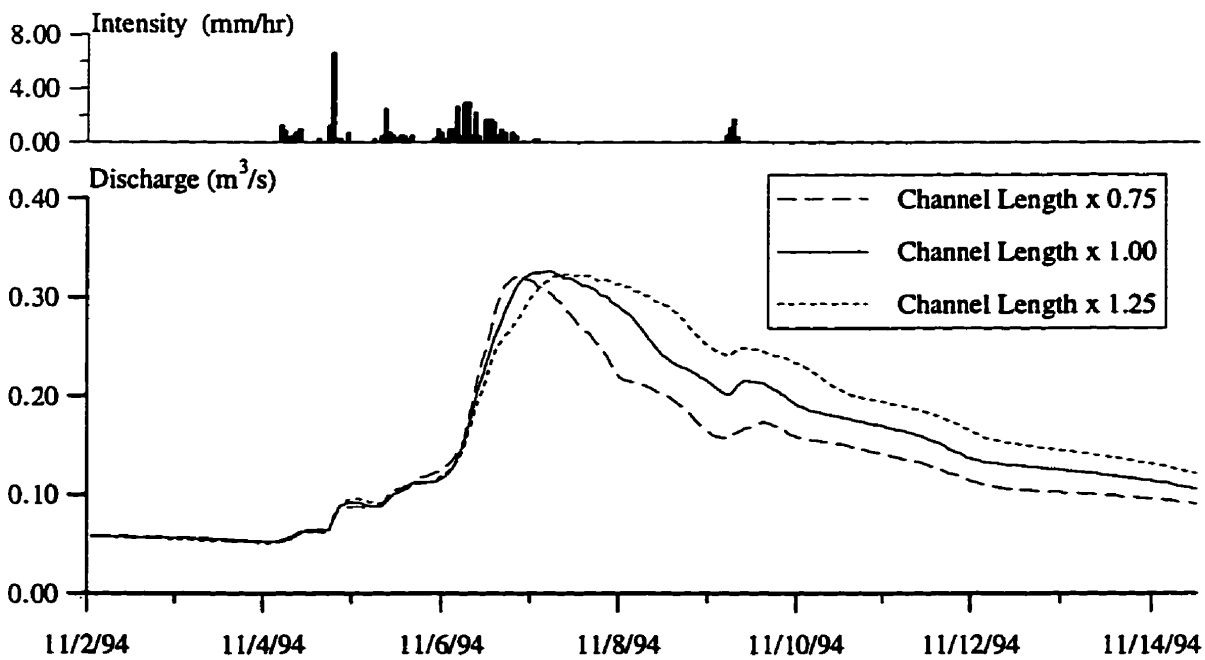


Figure 6.3(b) Sensitivity to length of wetland channel (Event 2)

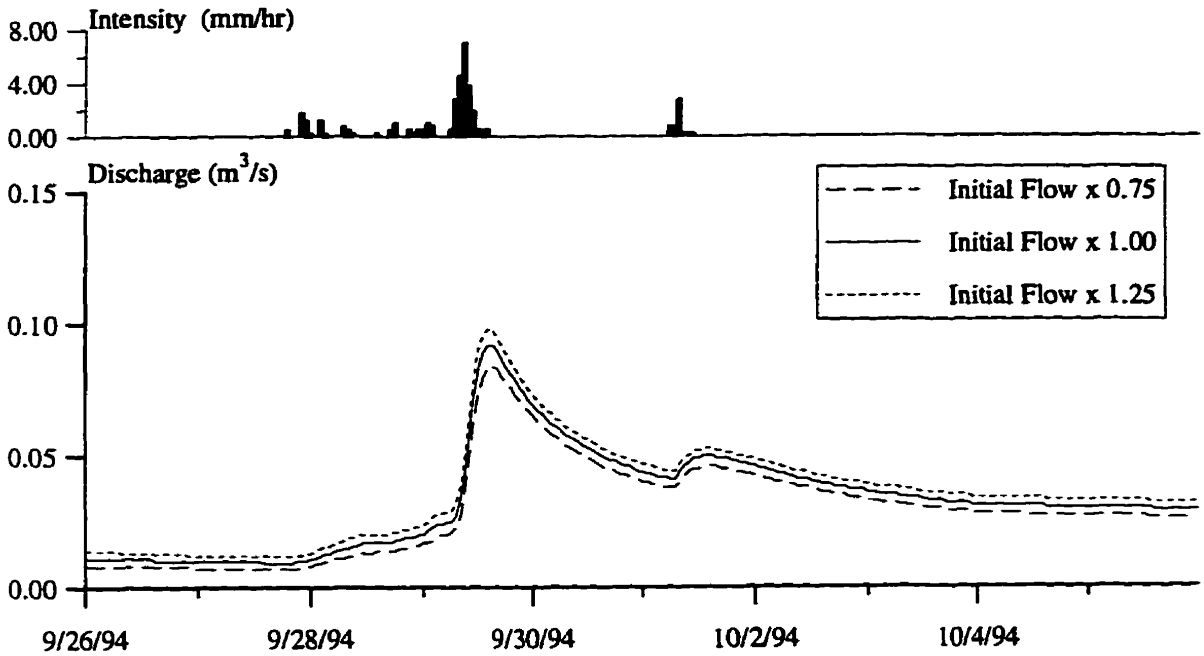


Figure 6.4(a) Sensitivity to initial streamflow (Event 1)

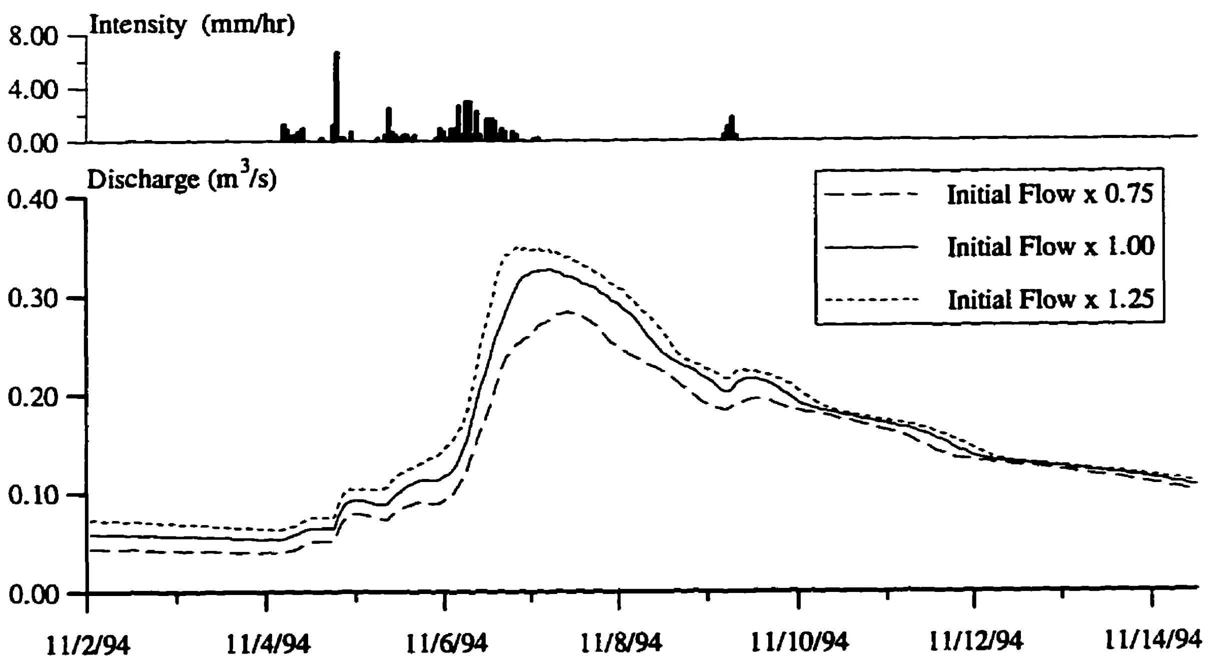


Figure 6.4(b) Sensitivity to initial streamflow (Event 2)

6.4.7 Sensitivity To Channel Roughness

The magnitude of the channel roughness, as characterized by the Manning coefficient, influences the storage-discharge relationship assigned to each routing reach. In addition, changes in the channel roughness parameter influence the channel capacity under bankfull conditions. As would be expected, the total runoff volumes associated with both event 1 and event 2 are not sensitive to the channel roughness parameter. However, for both simulation events, the predicted peak discharge rate and time to peak are influenced by the specification of the channel roughness (Figure 6.5).

With respect to event 1, the impact of the channel roughness parameter is evident along the rising limb of the hydrographs and in the vicinity of the hydrograph peak. For event 2, changes in the bankfull channel capacity influence the shape of the hydrograph under high flow conditions. Increasing the channel roughness resulted in a lower bankfull discharge capacity and as a result, the stormflow response from the inundated wetland was characterized by a lower and flatter hydrograph crest segment.

6.4.8 Sensitivity To Drainable Porosity of Organic Layer

The magnitude of the drainable porosity parameter assigned to the organic layer influences the available storage space within the sediments. When the water table is located below the wetland surface, the drainable porosity parameter affects the amount of storage space within the unsaturated zone of the organic layer. The simulated events indicate that a decrease in the drainable porosity produces a corresponding increase in the hydrograph peak and total runoff volume (Figure 6.6). In addition, decreasing the available storage space within the wetland sediments reduced the time to peak characteristic.

Event 2 corresponds to a precipitation event applied to high antecedent saturation conditions. As a result, with relatively little pore space available within the wetland sediments, the corresponding stormflow response was not sensitive to changes in the drainable porosity parameter.

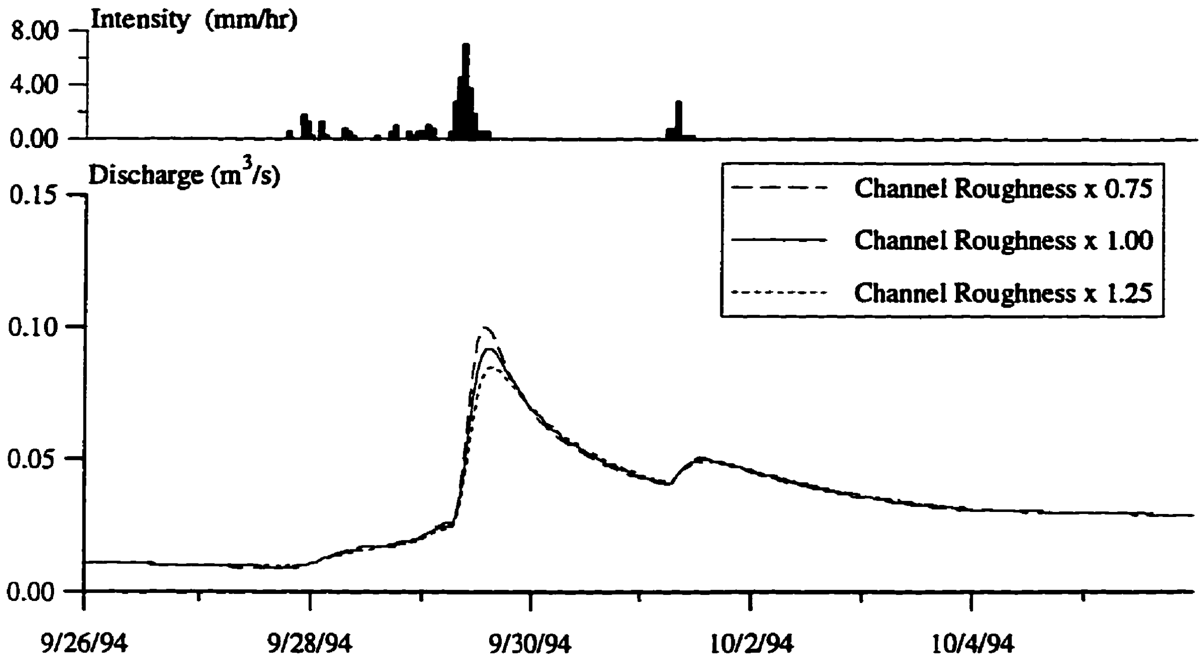


Figure 6.5(a) Sensitivity to channel roughness (Event 1)

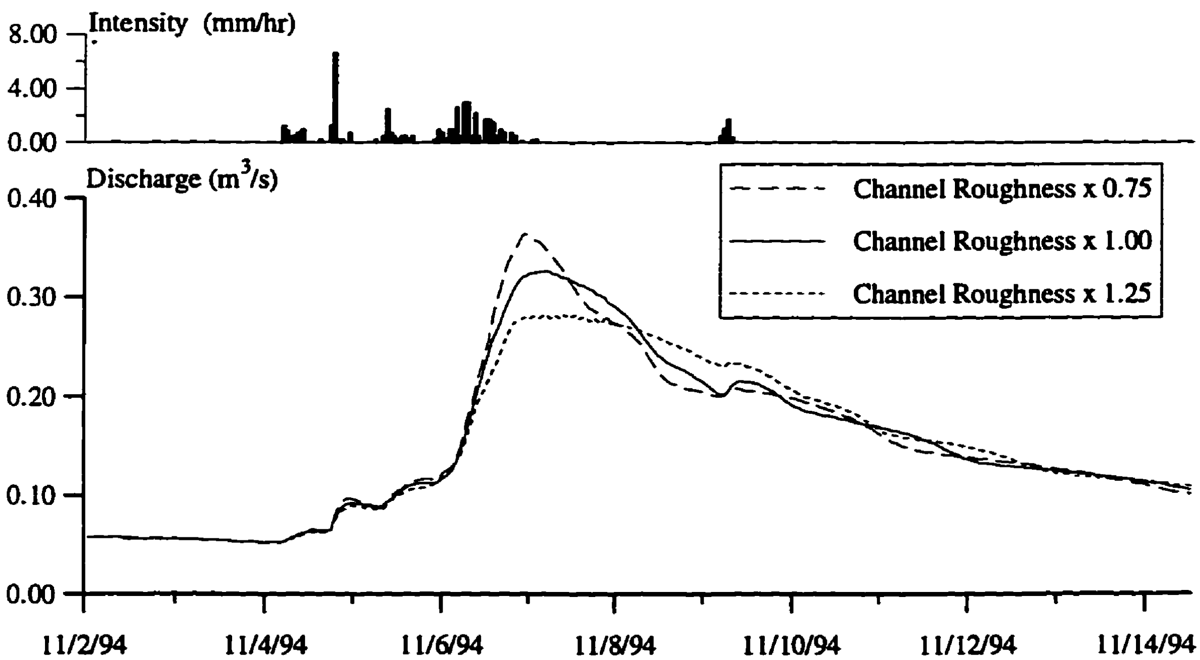


Figure 6.5(b) Sensitivity to channel roughness (Event 2)

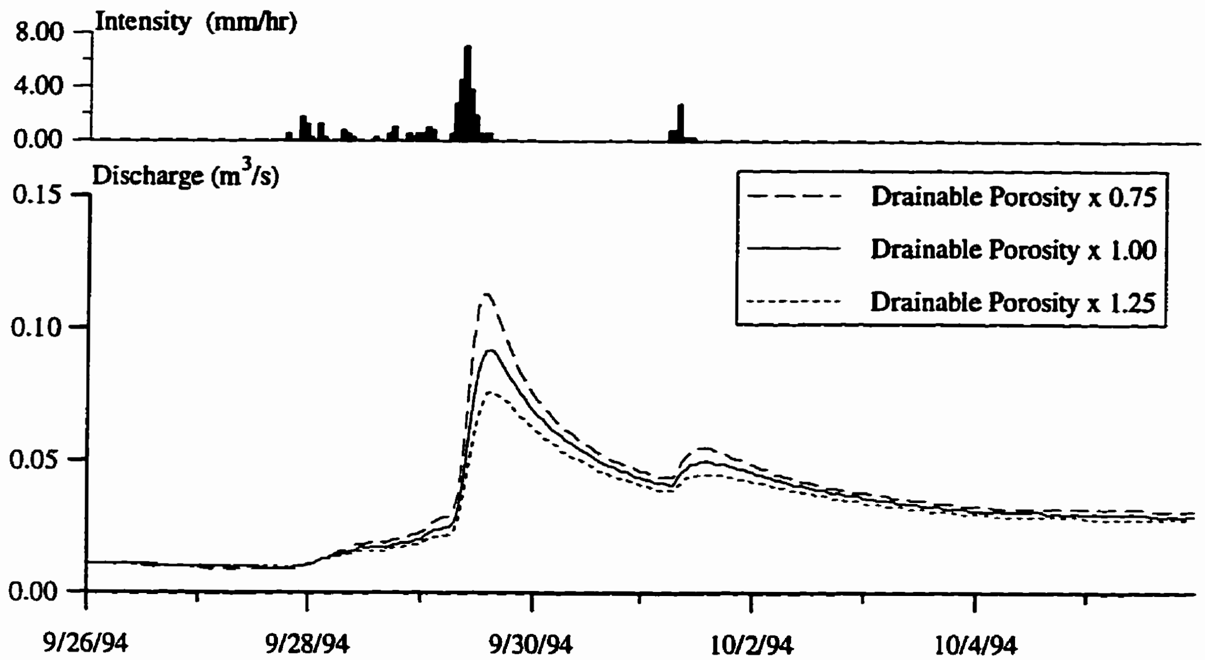


Figure 6.6(a) Sensitivity to organic layer drainable porosity (Event 1)

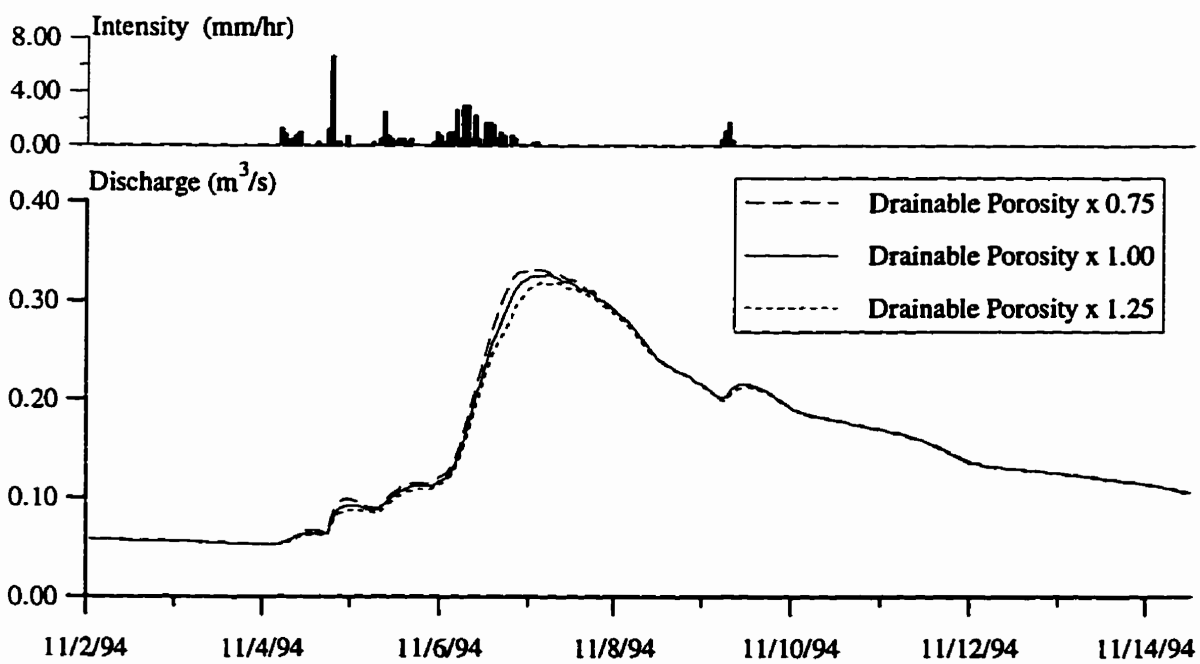


Figure 6.6(b) Sensitivity to organic layer drainable porosity (Event 2)

6.4.9 Sensitivity To Organic Layer Conductivity

The influence of the conductivity parameter on the simulated hydrograph is significantly different with respect to the two simulation scenarios. Under low flow conditions (Figure 6.7(a)), an increase in the conductivity parameter produces an increase in the peak flow rate. An increase in the conductivity reflects a greater capacity for water movement within the sediment layer. An increase in the organic conductivity produces an increase in the hydrograph peak. Increasing the conductivity parameter also results in a corresponding increase in the stormflow runoff volume discharged from the wetland.

Alternatively, for event 2 (Figure 6.7(b)) an increase in the conductivity parameter resulted in a decrease in the peak flow rate. Increasing the conductivity parameter associated with the organic layer allows more water to traverse the wetland as subsurface flow at the expense of the overland flow. As a result, increasing the value of the conductivity parameter increases the time to peak characteristic and reduces the runoff volume discharged during the event simulation.

6.4.10 Sensitivity To Width of Wetland

The response of the wetland to changes in the width of the wetland is illustrated in Figure 6.8. Under low flow conditions, the stormflow hydrograph is shaped by near-stream effects. For water stored within the sediments near the margins of the wetland, the travel time required for the water to reach the drainage network is too long to influence the stormflow hydrograph.

Under conditions where the wetland sediments become inundated, overland flow mechanisms are capable of conveying water across the wetland much quicker than subsurface flow. The influence of the increased overland flow contribution as a result of the change in the wetland width is reflected in the recession limbs of the stormflow hydrographs (Figure 6.8(b)). Increasing the width of the wetland produces a greater peak flow rate and an increase in the time to peak characteristic and an increase in the total runoff volume.

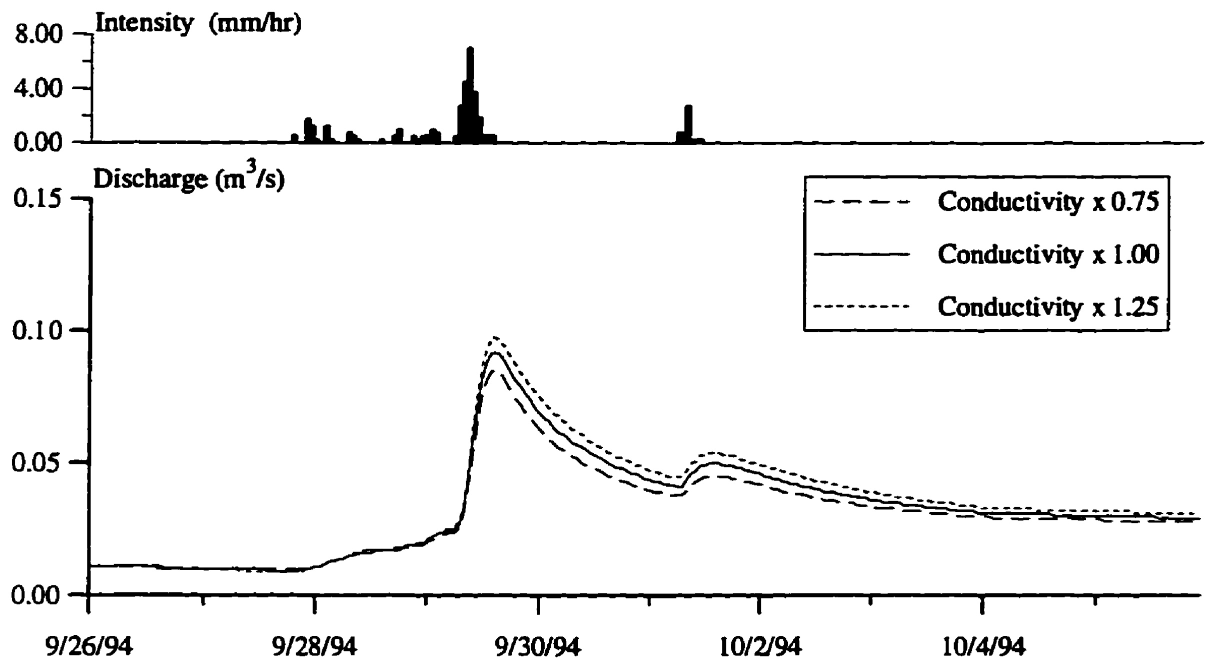


Figure 6.7(a) Sensitivity to organic layer conductivity (Event 1)

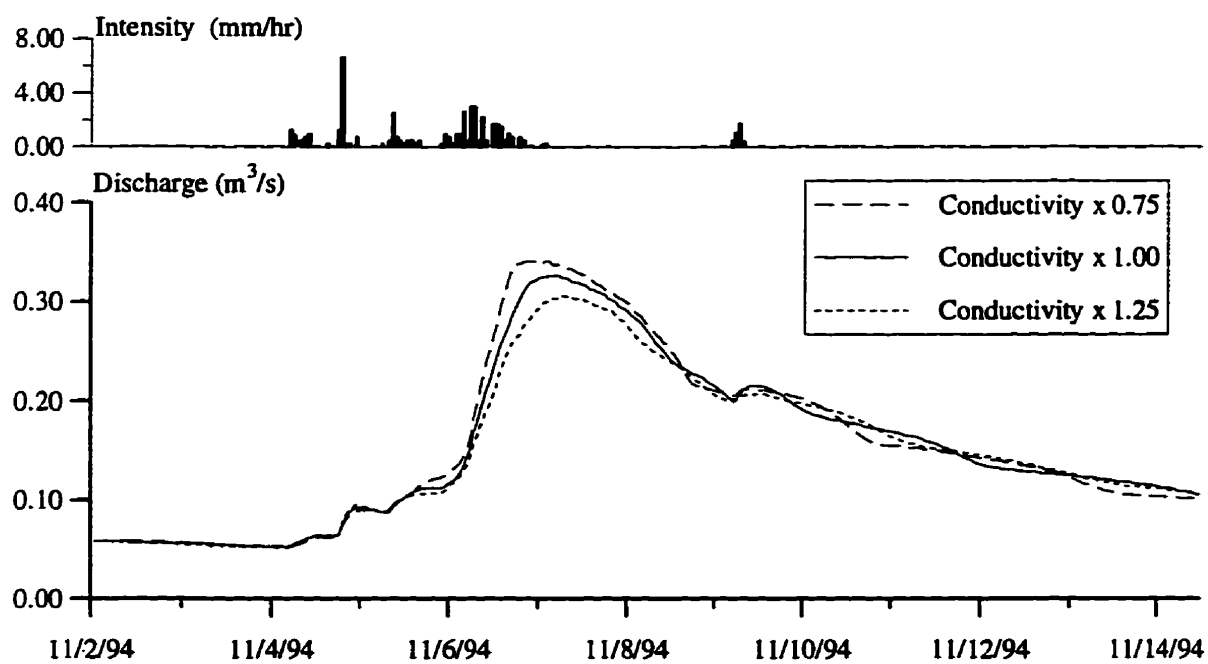


Figure 6.7(b) Sensitivity to organic layer conductivity (Event 2)

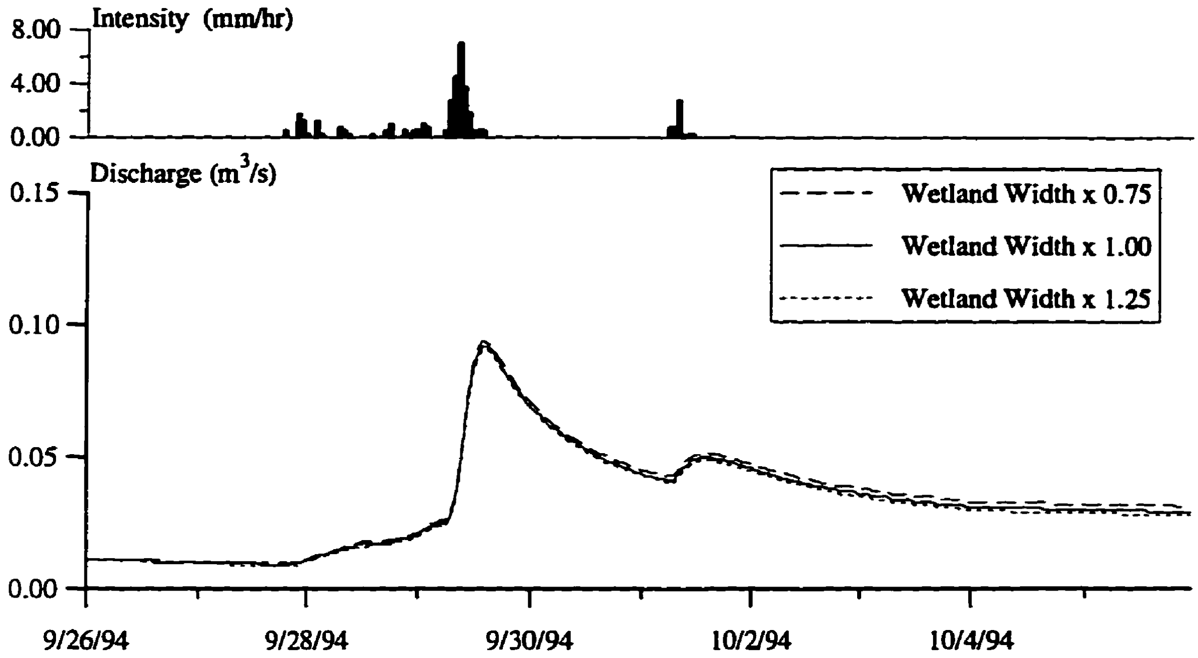


Figure 6.8(a) Sensitivity to width of wetland (Event 1)

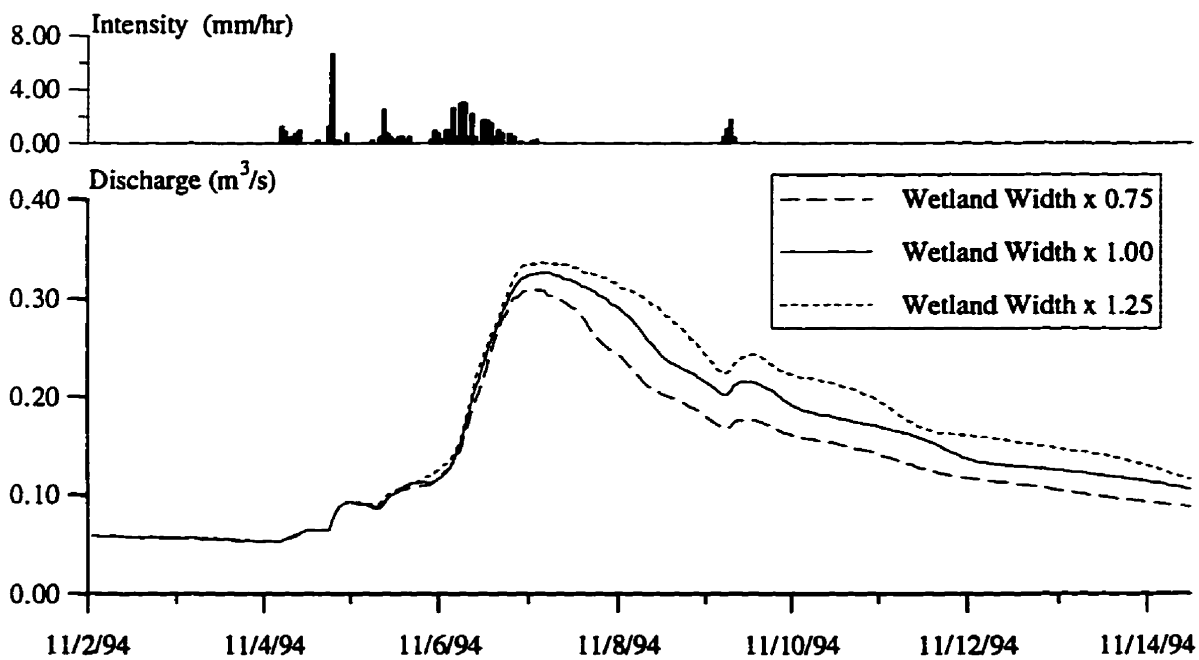


Figure 6.8(b) Sensitivity to width of wetland (Event 2)

6.4.11 Sensitivity To Modelling Time Step

In order to examine the influence of the modelling time step on the resulting simulation results, event 1 and event 2 were modelled using both a 60 minute and 5 minute time step. Figure 6.9 illustrates the resulting simulated hydrographs. The validation of the wetland model, as presented in Chapter 5, was conducted using a constant time step of 60 minutes. The simulation of both events is not significantly influenced by the selection of the time step. A slight difference between the simulated hydrographs as a result of the modelling time step is evident near the hydrograph peaks. Table 6.6 summarizes the simulated hydrograph peaks and runoff volumes.

Table 6.6 Influence of modelling time step on simulated hydrographs

	Time Step (min)	Runoff Volume (m^3)	Peak Flow Rate (m^3/s)
Event 1	5	28,383	0.093
	60	28,377	0.092
Event 2	5	165,390	0.329
	60	165,240	0.327

6.4.12 Sensitivity To Modelling Mesh

The model was also examined in order to assess the response of the wetland model with respect to the finite difference mesh used to characterize the movement of stormwater through the wetland field cells. The validation of the wetland model was conducted using a finite difference grid consisting of 30 grid blocks. Additional modelling runs were performed using 10 and 100 grid blocks. Figure 6.10 displays the resulting hydrographs for event 1 and event 2. Table 6.7 summarizes the corresponding runoff volumes and peak flow rates. For event 1, where subsurface flow was the primary stormflow mechanism, the selection of the size of the modelling mesh had little influence on the resulting streamflow hydrographs. For event 2, an event dominated by overland flow, a mesh of 30 grid blocks produced a response similar to the results obtained using 100 grid blocks. However, a mesh size of 10 grid blocks produced a somewhat irregular stormflow response with a higher hydrograph peak.

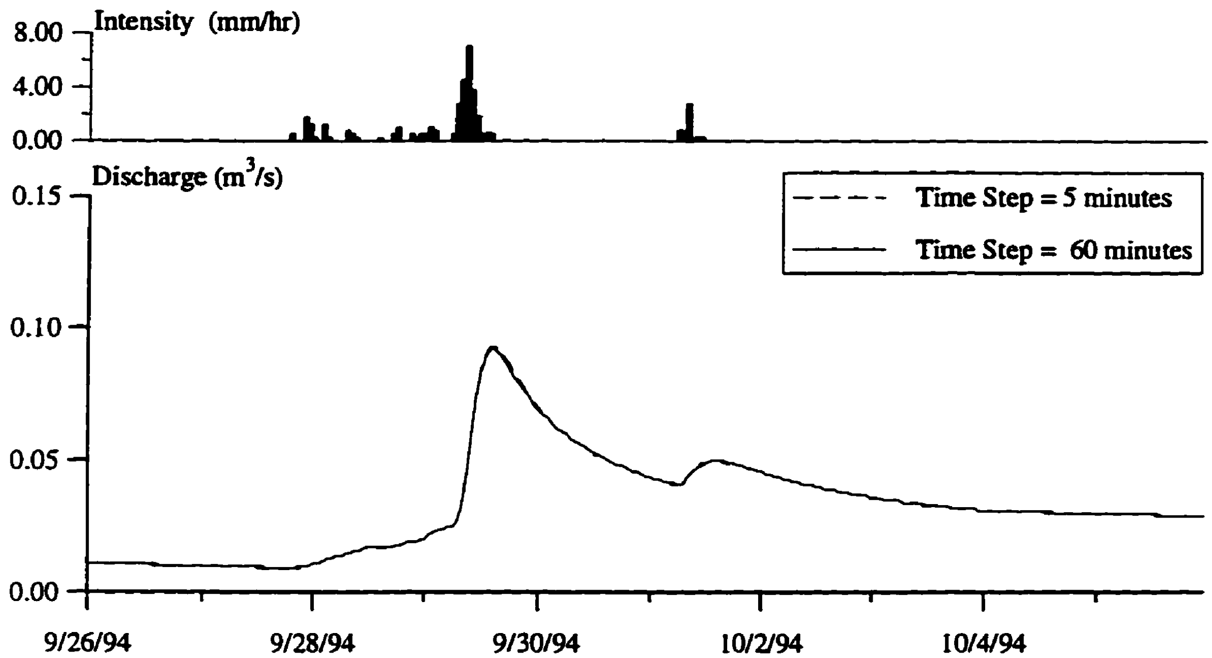


Figure 6.9(a) Sensitivity to modelling time step (Event 1)

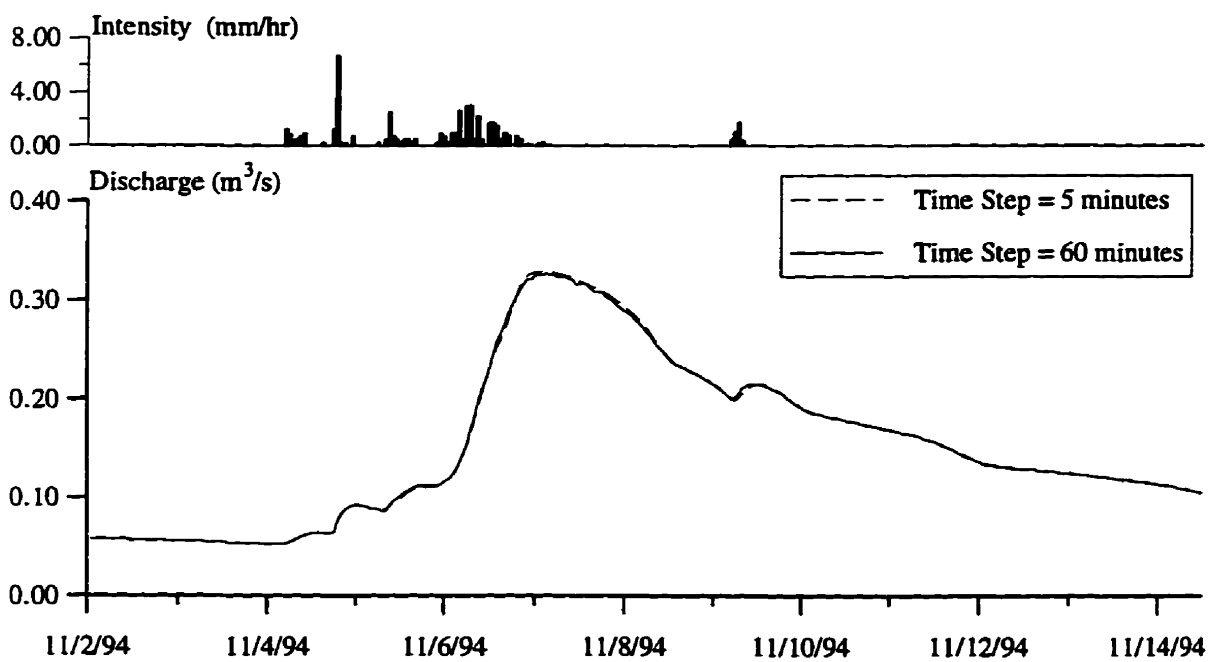


Figure 6.9(b) Sensitivity to modelling time step (Event 2)

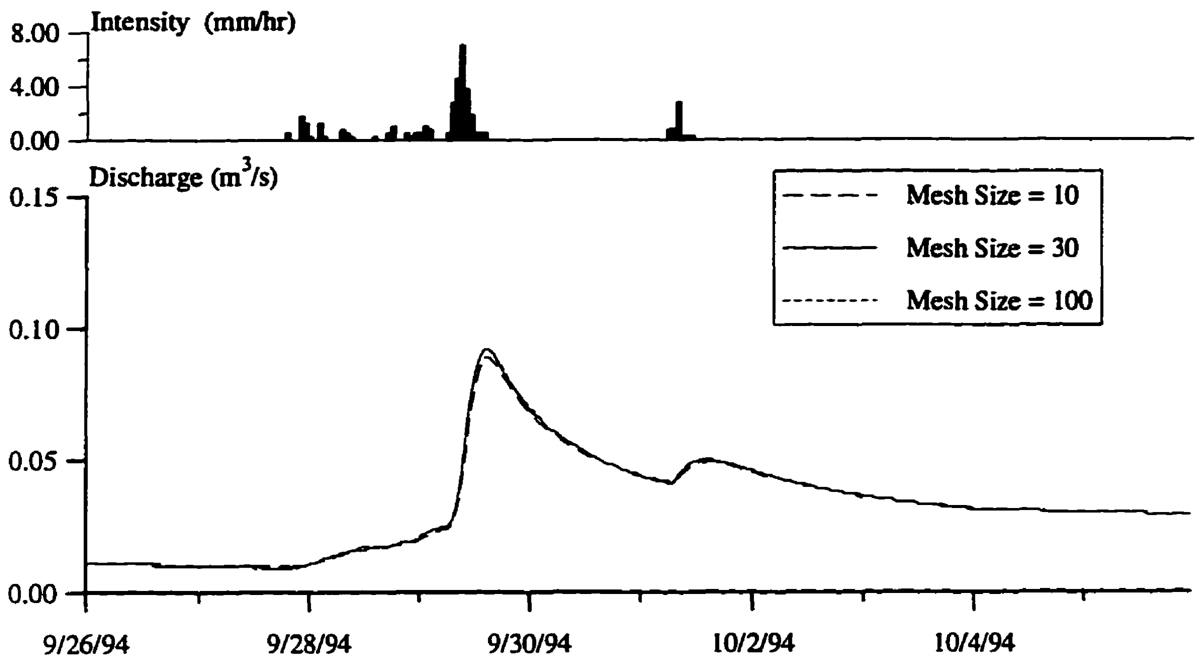


Figure 6.10(a) **Sensitivity to modelling grid (Event 1)**

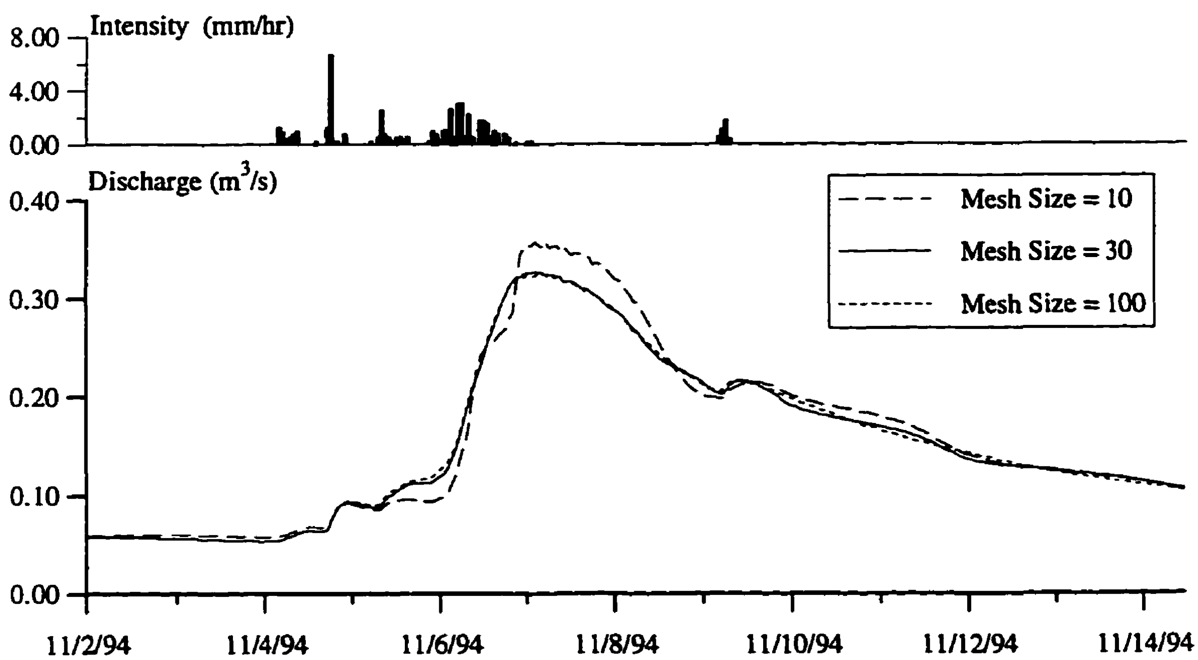


Figure 6.10(b) **Sensitivity to modelling grid (Event 2)**

Table 6.7 Influence of modelling mesh on simulated hydrograph

	Mesh Size	Runoff Volume (m^3)	Peak Flow Rate (m^3/s)
Event 1	10	28,110	0.089
	30	28,377	0.092
	100	28,415	0.092
Event 2	10	165,185	0.358
	30	165,240	0.327
	100	165,760	0.325

6.5 Systematic Errors in Precipitation Input

6.5.1 Methods

The results of the sensitivity analysis indicate that the response of the wetland model is sensitive to precipitation input. For further insight into the behaviour of the wetland model, event 1 and event 2 were modelled with the measured precipitation perturbed to reflect a systematic error. The perturbation approach is commonly used to study the effects of rainfall data uncertainties on runoff modelling (Singh, 1977; Paturel, 1995).

The approach involves the comparison of the model output from an assumed "error-free" rainfall input to that obtained from a perturbed rainfall input. For this analysis, the measured rainfall was assumed to be error free. The corresponding model output (runoff volume and hydrograph peak) was considered to be the reference output. The relative error in the rainfall input is defined by:

$$\varepsilon = \frac{P_{pert} - P_{meas}}{P_{meas}} \qquad (6.05)$$

where P_{pert} represents the perturbed rainfall amount and P_{meas} is the measured or observed precipitation amount. For this analysis, the relative rainfall input error ranged from 0 to $\pm 50\%$.

6.5.2 Evaluation of Peak Flows

Figure 6.11 illustrates a sensitivity plot showing the relative error in the hydrograph peak as a result of a relative error in the precipitation input. For event 1, the relative error in the peak flow rate is almost a linear function of the error in the rainfall. The slope of the variation in the relative hydrograph peak error is approximately 1.3, indicating that the wetland model amplifies the initial precipitation error.

For a systematic rainfall error with event 2, the relationship between the relative error in the hydrograph peak and the relative rainfall error is nonlinear, especially for a systematic overestimation of the precipitation. A large overestimation of the precipitation input results in complete inundation of the wetland site where the conveyance capabilities of the drainage network help to moderate the peak discharge rate modelled from the site.

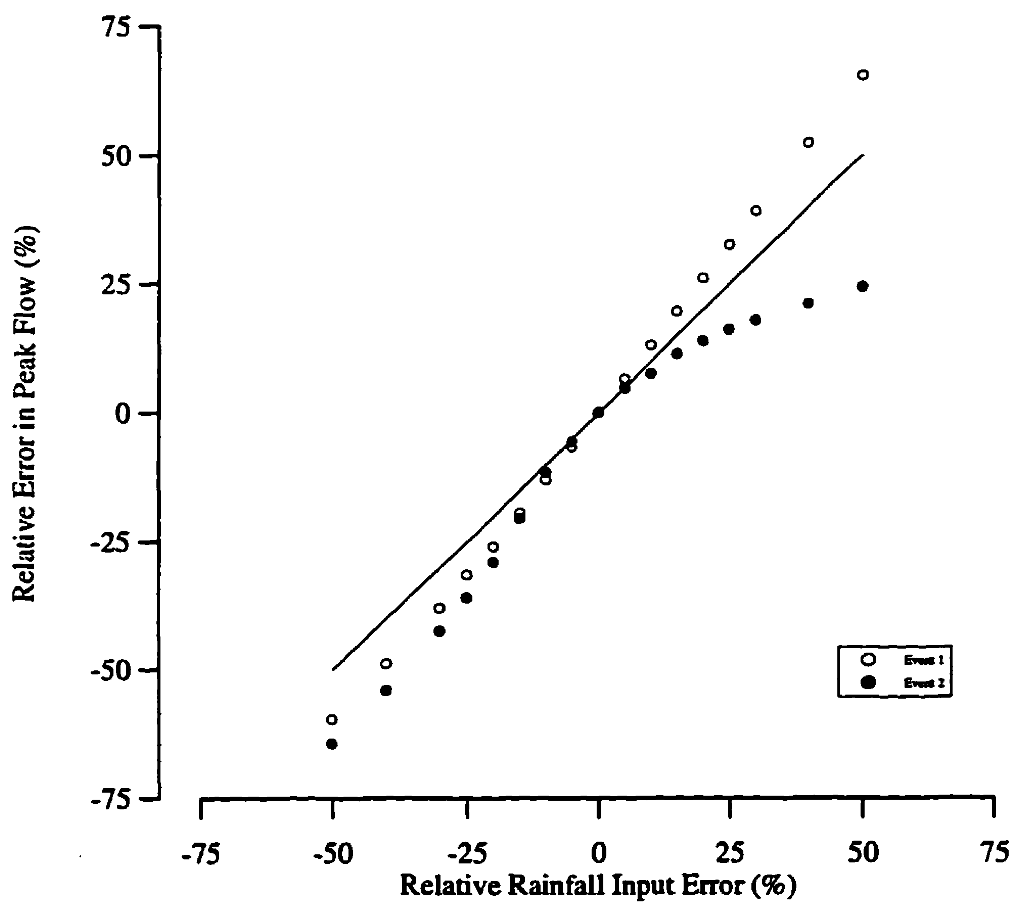


Figure 6.11 Variation in relative error in peak flow as a result of a systematic rainfall error

6.5.3 Evaluation of Runoff Volume

The relative error in the runoff volume resulting from an error in the precipitation is shown in Figure 6.12. For event 2, the relationship between the relative error in the stormflow runoff and the relative rainfall error is approximately linear with a slope slightly less than one. Any overestimation or underestimation of the precipitation amount falling on the saturated wetland directly influences the corresponding stormflow runoff volume discharged from the wetlands site. With event 1, the same linear relationship between the relative error in the runoff volume and relative rainfall error was observed, except for a high rainfall underestimation or overestimation as shown on Figure 6.12.

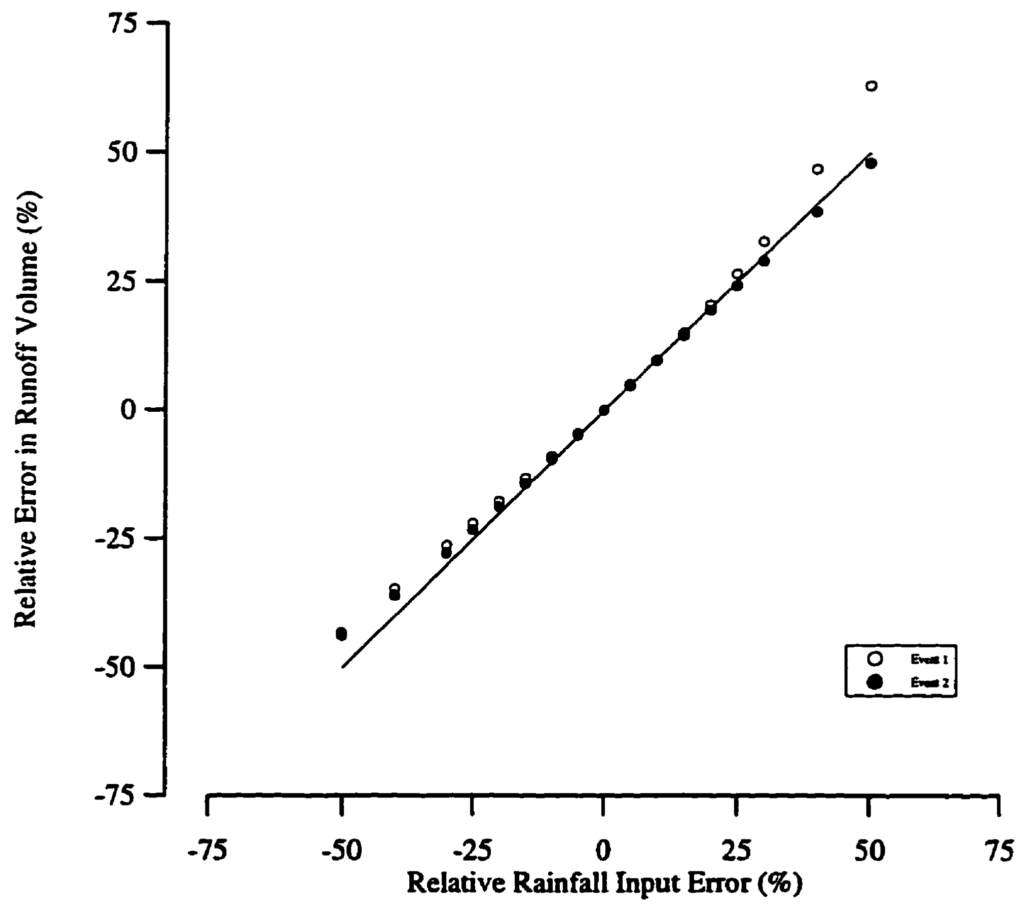


Figure 6.12 Variation in relative error in runoff volume as a result of a systematic rainfall error

6.6 Sensitivity Results - Continuous Simulation

Table 6.8 provides a summary of the calculated sensitivity terms for each parameter associated with the continuous simulation. As with the previous sensitivity results, the relative sensitivity of the wetland model to changes in the modelling parameters varied for each sensitivity criteria. The simulated runoff volume was most influenced by changes in the precipitation input, groundwater input and evapotranspiration losses. The simulated hydrograph peak associated with the complex storm occurring during the first week of November is most sensitive to the channel roughness, channel width and the depth of the organic layer.

Table 6.8 Relative sensitivities - continuous simulation

Model Parameter		Relative Sensitivities*		
		S-Criterion	Runoff Volume	Peak Flow Rate**
Channel network	Channel roughness	-0.6571	-0.0197	-0.7283
	Channel slope	0.3626	-0.0081	0.3361
	Channel width	0.9593	-0.0012	0.8964
	Channel length	-0.3029	0.3118	0.0560
	Antecedent flow	0.4715	0.1584	0.0000
Wetland field cell	Wetland slope	0.0328	0.0385	0.0000
	Wetland width	0.0031	0.2780	0.1120
	Groundwater inflow	0.9809	0.4710	0.1120
Organic layer	Hydraulic conductivity	0.2452	0.0482	-0.1120
	Drainable porosity	-0.0134	-0.0152	0.0000
	Depth of layer	1.0747	-0.0950	0.7283
Hummock layer	Flow coefficient	0.0411	0.1136	0.0560
	Drainable porosity	1.2000	-0.1171	-0.4482
Climatic data	Precipitation	1.4498	0.9654	0.5602
	Evapotranspiration	-0.6604	-0.3435	-0.1120
	Canopy storage capacity	-0.0292	-0.0265	0.0000

* shaded values indicate three most sensitive parameters for each evaluation criteria for a 1% parameter change

** maximum streamflow rate corresponding to 941104 precipitation event

6.6.1 Sensitivity To Width of Wetland Channel

Figure 6.13 illustrates the influence of the channel width on the simulated streamflow hydrographs. Changes to the channel width influenced the hydrograph during periods when the conveyance capabilities of the wetland drainage channel were important. The channel width parameter played an important role in determining the shape of the streamflow hydrograph for the 941104 storm event. For much of the continuous simulation period, altering the wetland channel width had very little impact on the computed streamflows.

6.6.2 Sensitivity To Precipitation Input

The sensitivity of the computed streamflow hydrographs to changes in the precipitation input is shown in Figure 6.14. The influence of the precipitation input varied with the antecedent streamflow and the magnitude of the precipitation depth.

6.6.3 Sensitivity To Channel Roughness

Figure 6.15 shows the influence of the channel roughness parameter on the computed stormflow hydrographs. As with the channel width parameter, the specification of the channel roughness influences the conveyance capabilities of the drainage system. The channel roughness parameter is most important under high flow conditions where the capacity of the channel controls the wetland stormflow response.

6.6.4 Sensitivity To Groundwater Input

A significant source of uncertainty with any wetland modelling effort involves identifying and quantifying the groundwater component of the wetland hydrologic budget. Figure 6.16 illustrates the simulated streamflow hydrographs associated with a ±25% change in the groundwater input.

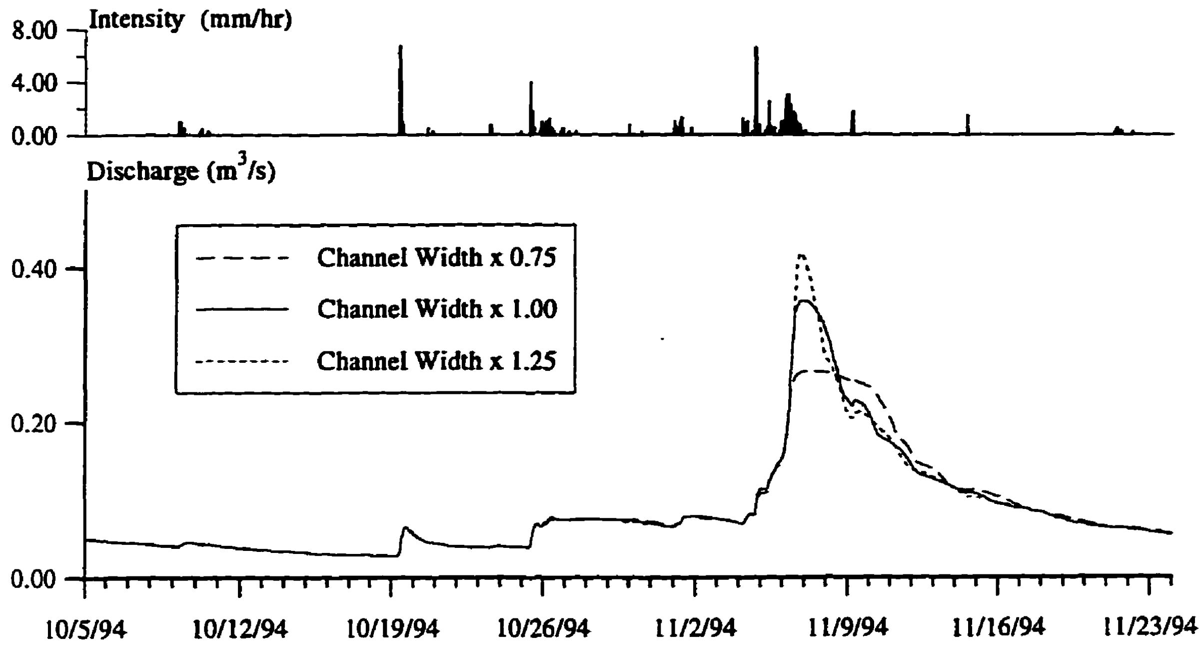


Figure 6.13 Sensitivity to channel width

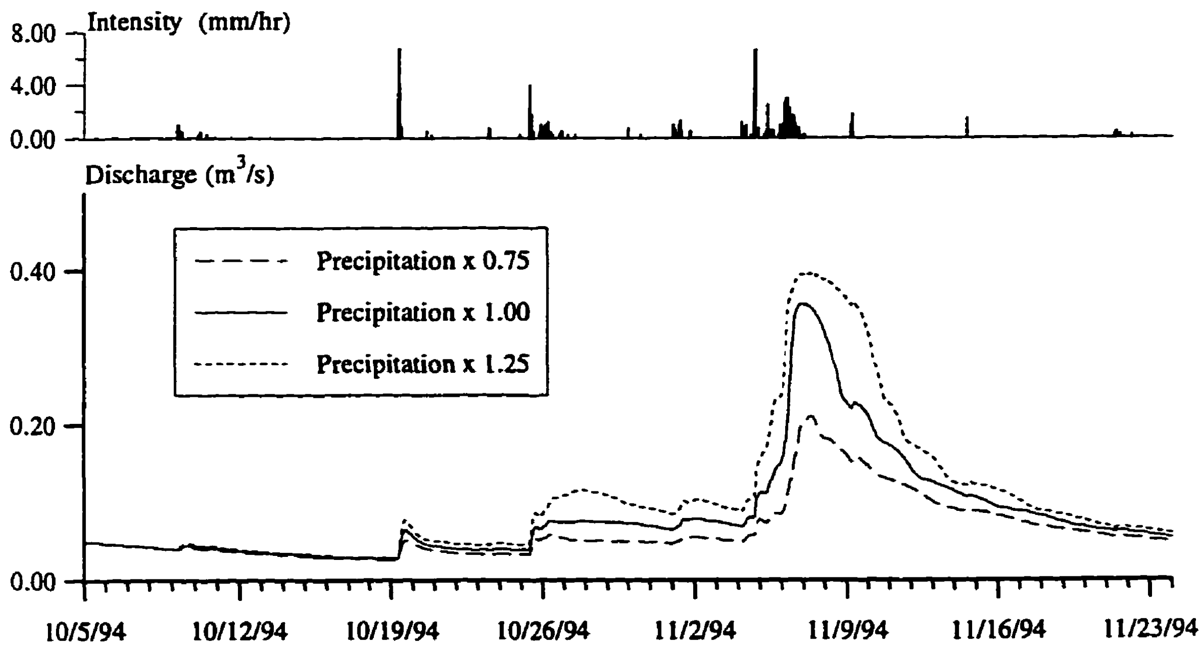


Figure 6.14 Sensitivity to precipitation input

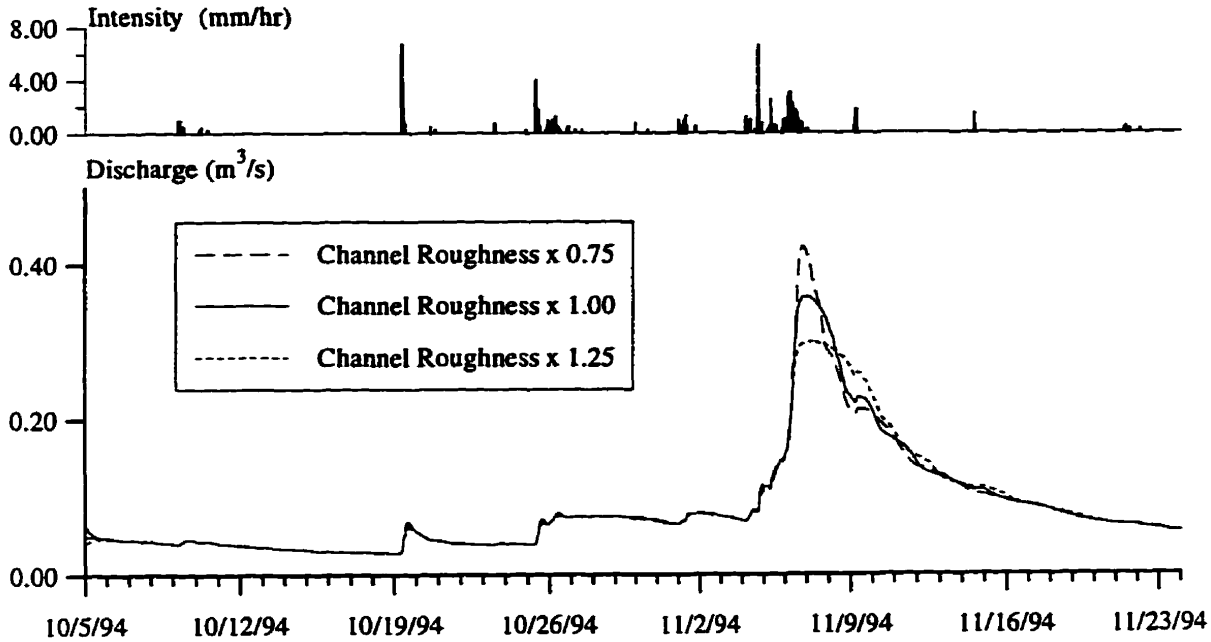


Figure 6.15 Sensitivity to channel roughness

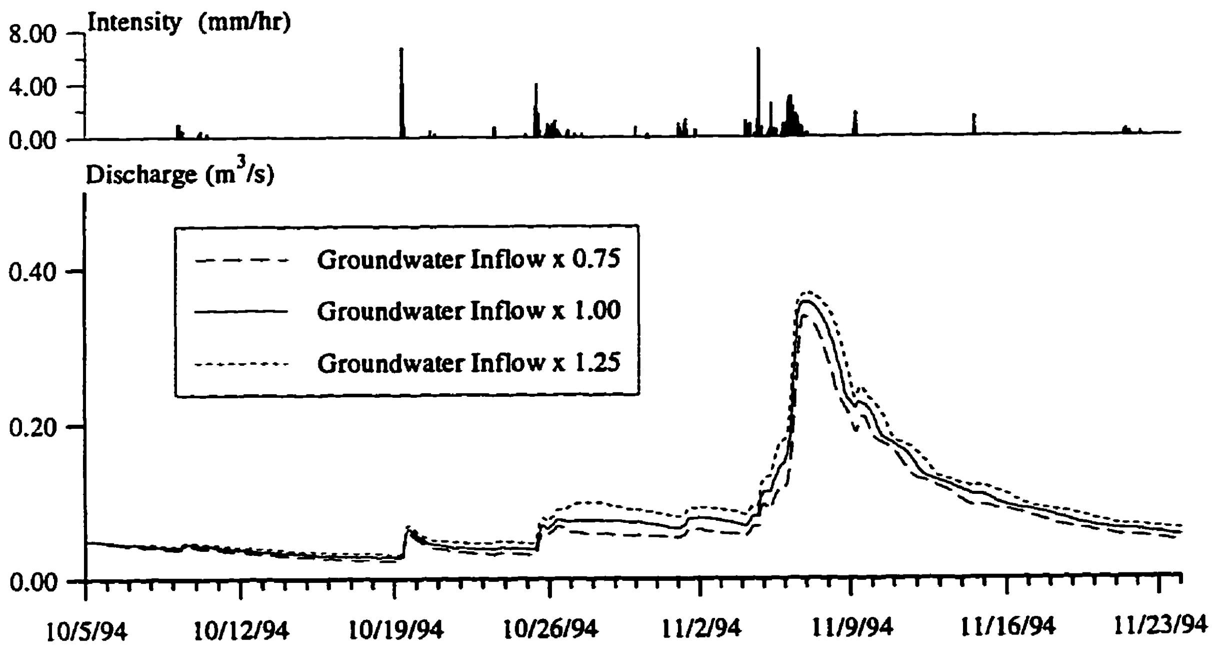


Figure 6.16 Sensitivity to groundwater input

6.7 Chapter Summary

In this chapter, the sensitivity of the wetland model to changes in the various model parameters and inputs has been examined. The sensitivity of the model was evaluated with respect to the evaluation of the model efficiency (S-criterion), hydrograph peak and total stormflow runoff volume. Two event periods, representative of low and high antecedent saturation conditions, were studied during the analysis. In addition, the model sensitivity was evaluated for a continuous simulation involving multiple precipitation events.

The sensitivity of the model to changes in the modelling parameters was found to vary significantly with regard to the antecedent saturation conditions of the wetland. The analysis revealed a complex interaction between the model parameters and their resulting influence on the simulated streamflow hydrograph. For example, under low saturation conditions, the simulated streamflows were found to be insensitive to the transverse width of the wetland field cells. However, under highly saturated conditions where surface flows mechanisms dominate the stormflow response, the simulated hydrograph peak and stormflow runoff volume are influenced by the wetland width. In addition, increasing the conductivity parameter associated with the wetland sediments was found to either increase or decrease the hydrograph peak depending on the dominant flow mechanisms associated with the event. As the length of the simulation period increases, the evapotranspiration and groundwater components take on added importance.

The model behaviour was found to be sensitive to the precipitation input. Changes to the precipitation input were observed to alter the dominant stormflow mechanisms associated with the rainfall event. For example, with events dominated by subsurface flow mechanisms, a large overestimation of the precipitation input could produce a response dominated by overland flow processes.

For both event simulation scenarios, the simulated hydrographs were not sensitive to the selection of the modelling time step. However, simulations involving overland flows through the wetland were sensitive to the size of the finite difference mesh.

CHAPTER 7

7. Conclusions and Recommendations

7.1 General

From a hydrologic modelling perspective, wetlands represent unique hydrologic systems. In the temperate regions of southern Ontario, wetlands are commonly found in the headwater regions of drainage basins. For most of these headwater sites, wetlands represent a significant link between the underlying groundwater system and the surface drainage network. The degree of saturation at these wetland sites is strongly dependent on the relationship between the precipitation input, groundwater input and the evapotranspiration demand. During the spring and fall periods, these sites commonly receive water inputs in excess of evapotranspiration demand, resulting in saturation of the wetland. Alternatively, during the summer periods when evapotranspiration demand can be in excess of the water inputs, significant available storage is made available for the temporary storage of precipitation inputs.

The stormflow response from headwater wetland systems is highly dependent on the available storage within the wetland organics, often resulting in a remarkable variability in stormflow response. The rainfall-runoff response associated with wetland sites is shaped by a complex interaction of numerous processes. Flow of water through these low gradient wetlands occurs via a unique combination of subsurface micropore and macropore flow within the organic sediments and surface flow through the hummock terrain.

In comparison to the volumes of literature produced regarding the hydrologic modelling of agricultural land uses, little attention has been focused on the development and application of operational wetland hydrologic models. If required to develop an operational flood forecast from a wetland dominated catchment, the hydrologist or engineer has few tools to use and little data available to assist him or her in predicting the stormflow response.

The goal of this research has been to develop and apply a first-generation wetland model. The numerical model was developed to provide a tool to reproduce the hydrologic behaviour of temperate region headwater wetlands. The model was developed in recognition that wetlands are difficult environments in which to work and even routine data collection is difficult. As a result, the model is based on simple representations of the dynamics of surface and subsurface flow through wetland systems.

A finite-difference model for simulating one-dimensional saturated flow in a stream-wetland system was developed in conjunction with a field data collection program to obtain precipitation and streamflow data from a headwater wetland site. The model utilizes a field hydrology model coupled to a stream routing model. The primary vertical and horizontal fluxes associated with the wetland organic layer are simulated by the field hydrology model. The horizontal movement of water within the wetland is driven by the head differential between the free surface flows in the surface drainage channels and the level of saturation within the wetland sediments. The channel routing model provides an accounting of the lateral exchange with the wetland sediments and determines the rate of outflow at the wetland outlet. The process representations incorporated into the model are consistent with the data and computational requirements appropriate to the catchment or watershed scale.

7.2 Conclusions

The wetland model was used to simulate the stormflow response from a forested headwater wetland site located within the Teeswater River watershed in southern Ontario. Based on the findings of this research:

1) the stormflow response from the study site is highly variable and exhibits a strong seasonal variation. The response of the wetland to a precipitation input is strongly dependent on the antecedent storage conditions.

2) the stormflow hydrographs characteristic of this site involve a rapid rising limb followed by a long recession limb, typically lasting 7-9 days.

3) the rainfall-runoff response from the headwater wetland site can be simulated using simplified surface and subsurface representations. The use of an idealized wetland representation involving a stream routing reach coupled to a wetland field model appears to hold promise for the simulation of the stormflow response associated with wetland-stream systems. The coupled exchange of stormwater between wetland and stream system provides a useful hydrologic tool for simulating the rainfall-runoff response from first-order wetland systems. Used in combination with a distributed hydrologic model, the coupled stream-wetland model could be utilized to evaluate the influence of streamflow routing through wetland stream reaches where the lateral exchange of streamflows with the adjacent wetland organics appears significant.

4) the quantity of precipitation data is very important for accurate simulation of the wetland response. Systematic errors in the rainfall input are magnified by the wetland model.

5) in recognition of the difficulty in obtaining accurate precipitation data, the model performs reasonably well considering the complex stormflow processes in wetlands. Properly calibrated and initialized, the wetland

model works well for predicting peak flow rates and runoff volumes for short to intermediate length simulations.

6) long term modelling of the headwater wetland site is a more challenging task. The rainfall-runoff response from these wetlands is strongly influenced by the antecedent saturation state. As a result of the long recessions associated with the wetland site, modelling errors associated with a precipitation event will impact the model prediction for any subsequent rainfall-runoff events. Continuous simulation of wooded headwater swamps requires accurate estimation of the evapotranspiration losses and groundwater fluxes.

7.3 Recommendations for Further Study

Most hydrologic models undergo a significant revision period as additional modelling experience and data are gained. It is fully hoped by the author that the current wetland model will be revised and improved through future research.

The usefulness of any hydrologic model can only be assessed through its application on numerous study sites, evaluated over a wide range of hydrologic conditions. Under this criterion, testing of the wetland model must be considered preliminary. As part of this research effort, the calibration and application of the wetland model has been limited to a relatively short period of record and a single wetland site. Testing and subsequent revision of the conceptual model will require more hydrologic data describing the stormflow response from headwater wetland sites. The resulting database would provide useful information regarding the influences of size, slope, organic depth, channel size, etc., on the stormflow response from these headwater wetland sites prevalent to southern Ontario.

The goal of the current research was the simulation of event-based and continuous modelling durations using data appropriate to the watershed scale. Long-term fluxes and storage mechanisms have been accounted for using primitive representations. In addition to modelling these headwater sites from a watershed perspective, much information could be obtained through the development and application of research-oriented applications on well-instrumented sites. Accurate long-term research-oriented modelling of wetland systems would involve more sophisticated representations of the evaporation and transpiration fluxes associated with the wetland soils and vegetation. A more rigorous representation of the unsaturated zone, infiltration mechanisms and root uptake could be included, although it would significantly increase the computational demands and data requirements necessary for operation of the wetland model.

An untouched area of research involves the simulation of snow melt events from wetland systems. Previous studies reported in the wetland literature and observations made as part of this research indicate that a significant fraction of the annual discharge from these headwater sites occurs during the spring melt period. Any study involving the application and evaluation of snow-melt simulations would provide a significant contribution to current wetland science.

With respect to this research, the impetus for the development and testing of a wetland hydrologic model came from two sources: firstly, to develop a general numerical tool for improving the predictive capability of runoff modelling from wetland ecosystems, and secondly, to incorporate a field tested wetland runoff module into an existing fully-distributed hydrologic model capable of modelling watersheds at the meso or macro scale. This research has demonstrated the utility of a coupled stream-wetland model for simulating the hydrologic behaviour of single headwater wetland site. Subsequent to this research, the next step involves the implementation of the wetland model into an existing distributed hydrologic model. Utilizing the concept of a Grouped Response Unit (GRU), the WATFLOOD program (Kouwen, 1996) is well suited for meso and macro scale hydrologic simulations. The next task involves the implementation of a coupled stream-wetland model into a GRU context. Application of the wetland model in a GRU approach will require additional research in order to evaluate the most important meso-scale model features (i.e. length of wetland channel system, % wetland landcover, representative size of wetland cell, etc.). Since wetland-groundwater interactions play a dominant role in shaping the hydrologic behaviour of wetland systems, GRU representations of regional-scale groundwater flow systems must be developed and evaluated.

REFERENCES

Abbott, M.B., J.C. Bathurst, J.A. Cunge, P.E. Connell and J. Rasmussen (1986). An introduction to the European Hydrological System - Systeme Hydrologique Europeen, "SHE", 1: history and philosophy of a physically-based distributed modelling system. *Journal of Hydrology*, 87:45-59.

Abdul, A.S. and R.W. Gillham (1989). Field studies of the effects of the capillary fringe on streamflow generation, *Journal of Hydrology*, 112:1-18.

Baker, J.A. (1986), Wetland Hydrology, In: *Mitigating freshwater wetland alterations in the glaciated northeastern United States*, Proceedings of a workshop held at the University of Massachusetts, 66-88.

Bardecki, M. (1981), The role of agriculture in declining wetlands, In: *Proceedings, Ontario Wetland Conference*, A. Champagne editor. Federation of Ontario Naturalists, Toronto, Ontario, Sept. 18/19.

Barten P.K. and K.N. Brooks (1988), Modelling streamflow from headwater areas in the northern lake states, Modelling Agricultural, Forest and Rangeland Hydrology, *Proceedings of the 1988 International Symposium*, p. 347-356.

Bathurst, J.C., J.M. Wicks and P.E. O'Connell (1995), The SHE/SHESED basin scale water flow and sediment transport modelling system, In: Computer Models of Watershed Hydrology, Water Resources Publications, (ed. Vijay P. Singh), p.563-594.

Bay, R.R. (1969), Runoff from small peatland watersheds, *Journal of Hydrology*, 9:90-102.

Bear J. (1979), Hydraulics of Groundwater, McGraw-Hill Inc., New York, 569 p.

Beven, K. (1989), Changing ideas in hydrology - the case of physically based models, *Journal of Hydrology*, 105:157-172.

Blaney, H.F. and W.D. Criddle (1945), A method of estimating water requirements in irrigated areas from climatological data, U.S. Soil Conservation Service, 23 pp.

Boelter, D.H. (1969), Physical properties of peats related to degree of decomposition, *Soil Sci. Soc. Am. Proc.*, 33:606-609

Bottomley, D.J., D. Craig and L.M. Johnson (1986), Oxygen-18 studies of snowmelt runoff in a small precambrian shield watershed: implications for streamwater acidification in acid-sensitive terrain, *Journal of Hydrology*, 88:212-234.

Bouten, W., M.G. Schaap, D.J. Bakker and J.M. Verstraten (1992), Modelling soil water dynamics in a forested ecosystem. I: a site specific evaluation, *Hydrological Processes*, 6:435-444.

Bradley. C., (1996), Transient modelling of water table variation in a floodplain wetland, Narborough Bog, Leicestershire, *Journal of Hydrology*, 185:87-114.

Bromley, J. and M. Robinson (1995), Groundwater in raised mire systems: models, mounds and myths, *In: Hydrology and Hydrochemistry of British Wetlands*. Edited by J.M.R. Hughes and A.L. Heathwaite, John Wiley and Sons Ltd., 486 p.

Brown, R.G., J.R. Stark and G.L. Patterson (1987), Groundwater and surface water interactions in Minnesota and Wisconsin wetlands, In: *Proceedings of International Symposium on Ecology and Management of Wetlands*, Chapter 12, p.146-160.

Buttle, J.M. and K. Sami (1992), Testing the groundwater ridging hypothesis of streamflow generation during snowmelt in a forested catchment, *Journal of Hydrology*, 135:53-72.

Burt T.P. and A.T. Gardiner (1984), Runoff and sediment production in a small peat-covered catchment: some preliminary results. In Burt, T.P. and Walling D.E. (eds), Catchment Experiments in Fluvial Geomorphology, Geobooks, Norwich, p.133-152.

Burt T.P., A.L. Heathwaite and J.C. Labadz (1990), Runoff production in peat-covered catchments, (Chapter 14), In Process Studies in Hillslope Hydrology, M.G. Anderson and T.P. Burt (eds). John Wiley and Sons, 539 p.

Carter, V. (1986), An overview of hydrologic concerns related to wetlands in the United States, *Canadian Journal of Botany*, 64(2):364-374.

Carter, V. and R.P. Novitzki (1987), Some comments on the relationship between groundwater and wetlands, In: *Proceedings of International Symposium on Ecology and Management of Wetlands*, Chapter 7, p.69-86.

Carter, V., M.S. Bedinger, R.P. Novitzki and W.O. Wilken (1979), Water Resources and Wetlands, *In Wetland Functions and Values: The State of Our Understanding* (ed. P.E Greeson, J.R. Clark and J.E. Clark) American Water Resources Association, pp.344-376.

Cunge J.A., F.M. Holly and A. Verwey (1980), Practical Aspects of Computational River Hydraulics, Pitman Publishing, Inc., Boston, Mass.

Davies, J.A. and C.D. Allen, (1972), Equilibrium, potential and actual evaporation from cropped surfaces in southern Ontario, *Journal of Applied Meteorology*, 12:649-657.

Dingman, S.L. (1966), Characteristics of summer runoff from a small watershed in central Alaska, *Water Resources Research*, 2(4):751-754.

Dunne, T. and R.D. Black (1970), Partial area contribution to storm runoff in a small New England watershed, *Water Resources Research*, 6:1296-1311.

Freeze, R.A. (1972), Role of subsurface flow in generating surface runoff 1. baseflow contributions to channel flow, *Water Resources Research*, 8(3):609-623.

Freeze R.A. (1974), Streamflow generation, *Rev. of Geophysics and Space Physics*, 12(4):627-647.

Gardner, R.H., D.D. Huff, R.V. O'Neill, J.B. Mankin, J. Carney and J. Jones (1980), Application of error analysis to a marsh hydrology model, *Water Resources Research*, 16(4):659-664.

Gash, J.H. (1979), An analytical model of rainfall interception in forests, *Quarterly Journal of the Royal Meteorological Society*, 105(1):43-55.

Gerla, P.J. (1992), The relationship of watertable changes to the capillary fringe, evapotranspiration and precipitation in intermittent wetlands, *Wetlands: The Journal of the Society of Wetland Scientists* 12(2):91-98.

Gilvear, D.J., R. Andrews, J.H. Tellam, J.W. Lloyd and D.N. Lerner (1993), Quantification of the water balance and hydrogeological processes in the vicinity of a small groundwater-fed wetland, East Anglia, UK. *Journal of Hydrology* 144:311-334.

Gosselink, J.G., W.H. Conner, J.W. Day Jr. and R.E. Turner (1981), Classification of wetland resources: land, timber and ecology, in *Timber Harvesting of Wetlands*, B.D. Jackson and J.L. Chambers, eds., Div. of Cont. Ed., Louisiana State University, Baton Rouge. pp.28-48.

Guertin, D.P., P.K. Barten and K.N. Brooks (1987), The peatland hydrologic impact model: development and testing, *Nordic Hydrology*, 18(2):79-100.

Hammer, D.E. and R.H. Kadlec (1986), A model for wetland surface water dynamics, *Water Resources Research*, 22(13):1951-1958.

Hargreaves, G.H. (1966), Consumptive use computations from evaporation pan data, Methods for estimating evapotranspiration, Irrigation and Drainage Specialty Conference, Las Vegas Nevada, p. 35-64.

Harlin, J. (1991), Development of a process oriented calibration scheme for the HBV hydrological model, *Nordic Hydrology* 22:15-36.

Harvey, J.W., P.F. Germann and W.E. Odum (1987), Geomorphological control of subsurface hydrology in the creekbank zone of tidal marshes, *Estuarine, Coastal and Shelf Science*, 25:677-691.

Hendrickson J.D., S. Sorooshian and L. Brazil (1988), Comparison of Newton-type and direct search algorithms for calibration of conceptual rain-fall runoff models, *Water Resources Research*, 24(5):691-700.

Hewlett J.D. and W.L. Nuttle (1970), The varying source area of stormflow from upland basins, *Proceedings of the Symposium on Watershed Management, Am. Soc. Civ. Eng.*, New York, pp.21-46.

Hollands, G.G., G.E. Hollis and J.S. Larson (1986), Science base for freshwater wetland mitigation in the glaciated northeastern United States: hydrology, In: *Mitigating freshwater wetland alterations in the glaciated northeastern United States*, Proceedings of a workshop held at the University of Massachusetts, 131-143.

Holzer, T.L. (1986), Inland wetlands and groundwater in eastern Connecticut, In: *Mitigating freshwater wetland alterations in the glaciated northeastern United States*, Proceedings of a workshop held at the University of Massachusetts, 66-88.

Hooke, R. and T.A. Jeeves (1961), Direct search solution of numerical and statistical problems, *J. Assoc, Comput. Mach.*, 8(2):212-229.

Horton, R.E. (1933), The role of infiltration in the hydrologic cycle, *Transactions of the American Geophysical Union*, 14:446-460.

Huff, D.D. and H.L. Young (1980), The effect of a marsh on runoff: I. A water budget model, *J. Environmental Qual.*, 9(4):633-64.

Hunt, R.J., D.P. Krabbenhoft and M.P. Anderson (1996), Groundwater inflow measurements in wetland systems, *Water Resources Research*, 32(3):495-507.

Ingram H.A.P. (1983), Ecosystems of the World (4b) - Mires: Swamp, Bog, Fen and Moor, (ed. A.J.P. Gore) Elsevier Scientific Publishing Company, Amsterdam, Chapter 4

Ivanov, K.E. (1981), Water Movement in Mirelands, Academic Press, London. 276 p.

Jensen, M.E., R.D. Burman, and R.G. Allen. (1990), Evapotranspiration and Irrigation Water Requirements: a manual prepared by the Committee on Irrigation Water Requirements of the Irrigation and Drainage Division of the American Society of Civil Engineers.

Johnston P.R. and D.H. Pilgram (1976), Parameter optimization for watershed models, *Water Resources Research*, 12(3):477-486.

Kachroo, R.K. (1992), River flow forecasting. Part 1. A discussion of principles, *Journal of Hydrology*, 133:1-15.

Kadlec, R.H., D.E. Hammer, I. Nam and J.O. Wilks (1981), The hydrology of overland flow in wetlands, *Chem. Eng. Commun.*, Vol 9, pp.331-344.

Kadlec R.H., R.B. Williams and R.D. Scheffe (1987), Wetland evapotranspiration in temperate and arid climates, In: *Proceedings of International Symposium on Ecology and Management of Wetlands*, Chapter 12, p.146-160.

Kadlec, R.H. (1990), Overland flow in wetlands: vegetation resistance, *Journal of Hydrology*, 116(5):691-706.

Kadlec, R.H. and R.L.Knight (1996), Treatment Wetlands, Lewis Publishers, 893 p.

Kittelson, J.M. (1988), Analysis of Flood Peak Moderation By Depressional Wetland Sites, In: *The Ecology and Management of Wetlands, Vol 1*, pp. 98-111.

Konyha, K.D., D.D. Robbins and R.W. Skaggs (1988), Evaluating peat-mining hydrology using DRAINMOD, *Journal of Irrigation and Drainage Engineering*, 114(3):490-504.

Kouwen, N. (1988), WATFLOOD: a microcomputer-based flood forecasting system based on real-time weather data, *Canadian Water Resources Journal*, 13(1):62-77.

Kouwen, N. (1996), WATFLOOD Users Manual, Water Resources Group, University of Waterloo.

LaBaugh, J.W. (1986), Wetland ecosystem studies from a hydrologic perspective, *Water Resources Bulletin*, 22(1):1-10.

Lloyd, J.W. and J.H. Tellam (1995), Groundwater-fed wetlands in the U.K., In: Hydrology and Hydrochemistry of British Wetlands, Edited by J.M.R. Hughes and A.L. Heathwaite, John Wiley and Sons Limited, 486 p.

Linsley, R.K., M.A. Kohler and J.L.H. Paulhus (1982), Hydrology for Engineers, McGraw-Hill Book Company, New York, 508 p.

McCarthy, E.J., J.W. Flewelling and R.W. Skaggs (1992), Hydrological model for drained forest management, *Journal of Irrigation and Drainage Engineering*, 118(2):242-255.

McCuen, R.H. (1973), The role of sensitivity analysis in hydrologic modelling, *Journal of Hydrology*, (18):37-53.

McNaughton, K.G. and T.A. Black (1973), A study of evapotranspiration from a douglas-fir forest using the energy balance approach, *Water Resources Research*, 9:1579-1590.

Ministry of Natural Resources (1992). *Manual of Implementation Guidelines for the Wetlands Policy Statement*, Queen's Printer of Ontario, 116 p.

Mitsch, W.J. and J.G. Gosselink (1986), Wetlands, Van Nostrand Reinhold Company, New York. 537 p.

Monro J.C. (1971), Direct search optimization in mathematical modelling and a watershed model application, NOAA Technical Memorandum NWS HYDRO-12, U.S. Dept. of Commerce, 52 p.

Moore, R.J. (1989), Tracing runoff sources with deuterium and oxygen-18 during spring melt in a headwater catchment, *Journal of Hydrology*, 12:135-143.

Munro, D.S. (1979), Daytime energy exchange and evaporation from a wooded swamp, *Water Resources Research*, 15(5):1259-1265.

Munro, D.S. (1981), Hydroclimatologic investigation in the Beverly Swamp, *In Conf. Proc. Ontario Wetlands*, Toronto, Ontario, Sept. 18/19.

Munro, D.S. (1984), Summer soil moisture content and the water table in a forested wetland peat, *Can. J. For. Res.*, 14:331-335.

Munro, D.S. (1986), On forested wetlands as evaporators, *Canadian Water Resources Journal*, 11(1):89-99.

Mustonen, S.E. and J.L. McGuinness (1968), Estimating evapotranspiration in a humid region, Technical Bulletin No. 1389, U.S. Department of Agriculture, 123 pp.

Nash J.E. and J.V. Sutcliffe (1970), River flow forecasting through conceptual models: Part I - a discussion of principles, *Journal of Hydrology*, 10(3):282-290.

National Wetlands Working Group (1986), Canada's Wetlands, Map Folio, Energy, Mines and Resources Canada and Environment Canada, Ottawa Ontario.

National Wetlands Working Group (1988), Wetlands of Canada, Ecological Land Classification Series, No. 24. Sustainable Development Branch, Environment Canada, 452 p.

Neff, T (1996), Mesoscale water balance of the boreal forest using operational evapotranspiration approaches in a distributed hydrologic model, M.A.Sc. Thesis, University of Waterloo, 233 p.

Neiber J.L. and G.S. Warner (1991), Soil pipe contribution to steady subsurface stormflow, *Hydrological Processes*, 5:329-344.

Nelder, J.A. and R. Mead (1965), A simplex method for function minimization, *Comput. J.*, 7:308-313.

Novitzki R.P. (1979), Hydrologic characteristics of Wisconsin's wetlands and their influence on floods, streamflow and sediment, *In Wetland Functions and Values: The State of Our Understanding* (ed. P.E Greeson, J.R. Clark and J.E. Clark) American Water Resources Association, pp. 377-388

Nuttle W.K. and J.W. Harvey (1995), Fluxes of water and solute in a coastal wetland sediment. 1. The contribution of regional groundwater discharge, *Journal of Hydrology*, 164:89-107.

Nuttle, W.K. (1988), The extent of lateral water movement in the sediments of a New England salt marsh, *Water Resources Research*, 24(12):2077-2084.

O'Brien, A.L. (1986), Hydrology and the construction of a mitigating wetland, In: *Mitigating freshwater wetland alterations in the glaciated northeastern United States*, Proceedings of a workshop held at the University of Massachusetts, 82-100.

O'Brien, A.L. (1980), The role of groundwater in stream discharges from two small wetland controlled basins in Eastern Massachusetts, *Groundwater*, 4:350-365.

O'Brien, A.L. (1977), Hydrology of two small wetland basins in eastern Massachusetts, *Water Resources Bulletin*, 13:325-340.

Paturel, J.E., E. Servat and A. Vassiliadis (1995), Sensitivity of conceptual rainfall-runoff algorithms to errors in input data - case of the GR2M model, *Journal of Hydrology*, 168:111-125.

Penman, H.L. (1948), Natural evaporation from open water, bare soil and grass, *Proceedings of the Royal Society of London*, A193:120-145.

Pinder, G.F. and S.R. Sauer (1971), Numerical simulation of flood wave modification due to bank storage effects, *Water Resources Research*, 7(1):63-70.

Price, J.S. and M.K. Woo (1988), Studies of a sub-arctic coastal marsh: 1. Hydrology, *Journal of Hydrology*, 103:275-292.

Priestley, C.H.B. and R.J. Taylor (1972), On the assessment of surface heat flux and evaporation using large-scale parameters. *Monthly Weather Review*, 100:81-92.

Rai, R.K. (1962), Relationship of groundwater levels to streamflow from a swamp, M.Sc. Thesis, University of Toronto, Toronto, Ontario.

Refsgaard J.C., S.M. Seth, J.C. Bathurst, M. Erlich, B. Storm, G.H. Jorgensen and S. Chandra (1992), Application of the SHE to catchments in India part 1. General Results, *Journal of Hydrology*, 140:1-23.

Romanov, V.V., K.K Pavlova, I.L. Kalyuzhnuu and P.K. Vorbiev (1975), Hydrophysical investigations of bogs in the USSR. In *Hydrology of Marsh-ridden Areas*, The Unesco Press, IAHS, p. 77-84.

Roulet, N.T. (1990), Hydrology of a headwater basin wetland: groundwater discharge and wetland maintenance, *Hydrological Processes*, 4:387-400.

Roulet, N.T. (1991), Stormflow production in a headwater basin swamp, *Nordic Hydrology*, 22:161-174.

Rutter, A.J., A.J. Morton and P.C. Robins (1971), A predictive model of rainfall interception in forests II. Generalization of the model and comparison with observations in some coniferous and hardwood stands, *J. Appl. Ecol.*, 12:367-80.

Saugeen Valley Conservation Authority (1979), Greenock Swamp Study. 186 p.

Siegel, D.I. (1987), A review of the recharge-discharge functions of wetlands. In: *Proceedings of International Symposium on Ecology and Management of Wetlands*, Chapter 6, p. 59-67.

Siegel D.I., (1988), The recharge-discharge function of wetlands near Juneau Alaska: Part I. Hydrogeological investigations, *Groundwater*, 26(4):427-434.

Singh, V.P. (1977), Sensitivity of some runoff models to errors in rainfall excess, *Journal of Hydrology*, 33:301-318.

Skaggs, R.W. (1982), Field evaluation of a water management simulation model, *Transactions of the American Society of Agricultural Engineers*, 25:666-674.

Skaggs ,R.W., J.W. Gilliam and R.O. Evans (1991), A computer simulation study of pocosin hydrology, *Wetlands: The Journal of the Society of Wetland Scientists*, 11:399-416.

Sklash, M.G. and R.N. Farvolden (1979), The role of groundwater in storm runoff, *Journal of Hydrology*, 43:45-65.

Sklash, M.G., M.K. Stewart and A.J. Pearce (1986), Storm runoff generation in humid headwater catchments 2. a case study of hillslope and low-order stream response, *Water Resources Research, Vol.22, No. 8*, pp.1273-1282.

Stewart, R.B. and W.R. Rouse (1976), Simple models for calculating evaporation from dry and wet tundra surfaces, *Arctic Alpine Res.*, 8(3):263-274.

Taylor, C.H. (1982), The effect on storm response of seasonal variations in contributing zones in small watersheds, *Nordic Hydrology*, 13:165-182.

Thomas, D.L. and D.B. Beasley (1986), A physically-based forest hydrology model I. Development and sensitivity of components, *Transactions of the ASAE*, pp. 962-972.

Thornthwaite C.W. and J.R. Mather, (1957), Instructions and tables for computing potential evapotranspiration and the water balance, *Publ. in Climatol.*, 10:185-311.

Turc L. (1961), Estimation of irrigation water requirements, potential evapotranspiration: a simple climatic formula evolved up to date, *Annuls of Agronomy*, 12:13-14.

U.S. Army Corps of Engineers (1972), *Charles River Watershed*, Massachusetts, New England Division, Waltham, Massachusetts 65 pp.

Verry, E.S. and D.H. Boelter (1979), Peatland hydrology, *In Wetland Functions and Values: The State of Our Understanding* (ed. P.E Greeson, J.R. Clark and J.E. Clark) American Water Resources Association, pp. 389-402.

Verseghy, D.L., N.A. McFarlane and M. Lazare (1993), CLASS - A Canadian land surface scheme for GCMS, II. Vegetation model and coupled runs. *International Journal of Climatology*, 13:347-370.

Von Post, L. and E. Granlund (1926), Sodra sveriges toruillgangar I., *Sven. Geol. Unders.*, C:335

Waddington, J.M., N.T. Roulet and A.R. Hill (1993), Runoff mechanisms in a forested groundwater discharge swamp, *Journal of Hydrology*, 146:37-60.

Walton R., R.S. Chapman and J.E. Lewis (1996), Development and application of the wetlands dynamic water budget model, *Wetlands: The Journal of the Society of Wetland Scientists*, 16(3):347-357.

Walton, W.C. (1995), Designing Groundwater Models with WINDOWS™, Lewis Publishers, 196 p.

Ward, R.C. (1984), On the response to precipitation of headwater streams in humid areas, *Journal of Hydrology*, 74:171-189.

Weyman, D.R. (1970), Throughflow on hillslopes and its relation to the stream hydrograph, *Bull. Int. Assn. Sci. Hydrology*, 15(3):25-33.

Whiteley, H.R. and R.W. Irwin (1986), The hydrological response of wetlands in southern Ontario, *Canadian Water Resources Journal*, 11(1):100-110.

Woo, M.K. and J. Valverde (1981), Summer streamflow and water levels in a mid-latitude swamp, *Forest Science*, 27:177-189.

Zoltai, S.C. and F.C. Pollett (1983), *Ecosystems of the World (4b) - Mires: Swamp, Bog, Fen and Moor*, (ed. A.J.P. Gore) Elsevier Scientific Publishing Company, Amsterdam, Chapter 8.

APPENDIX A

Visual Basic Display Screens

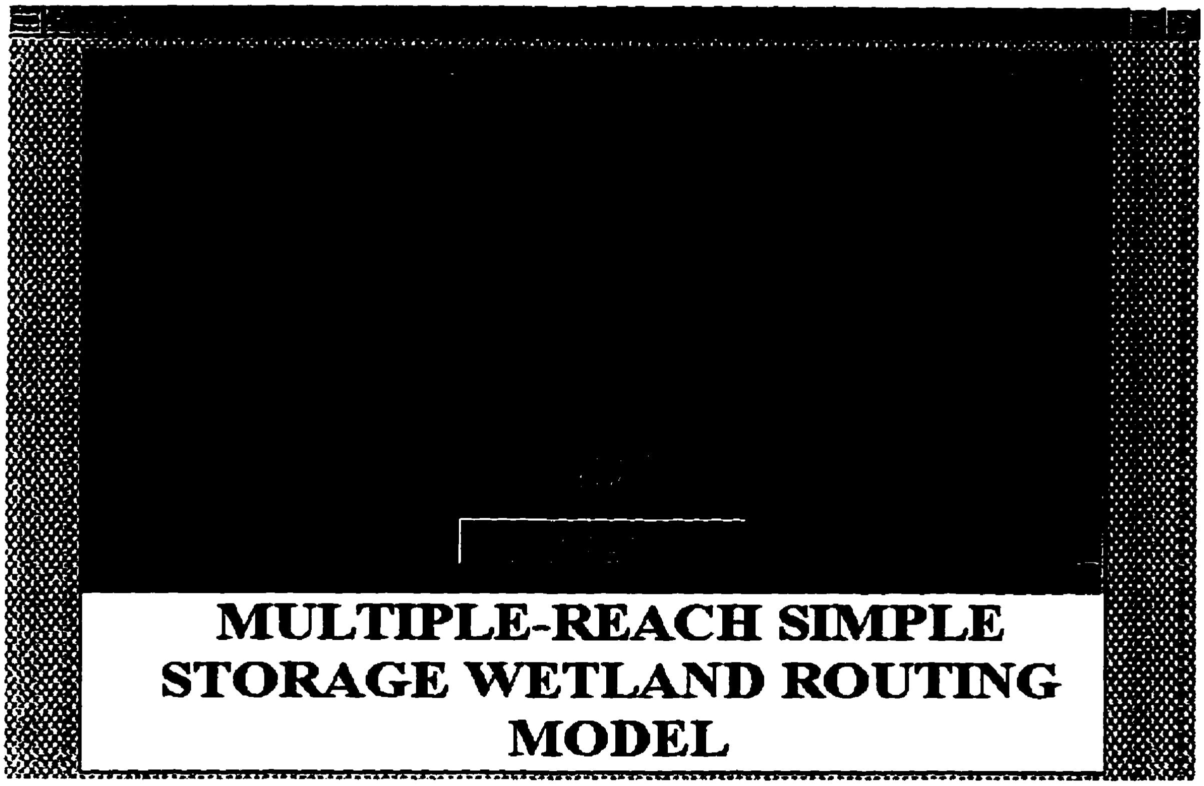


Figure A1 Program Title Screen

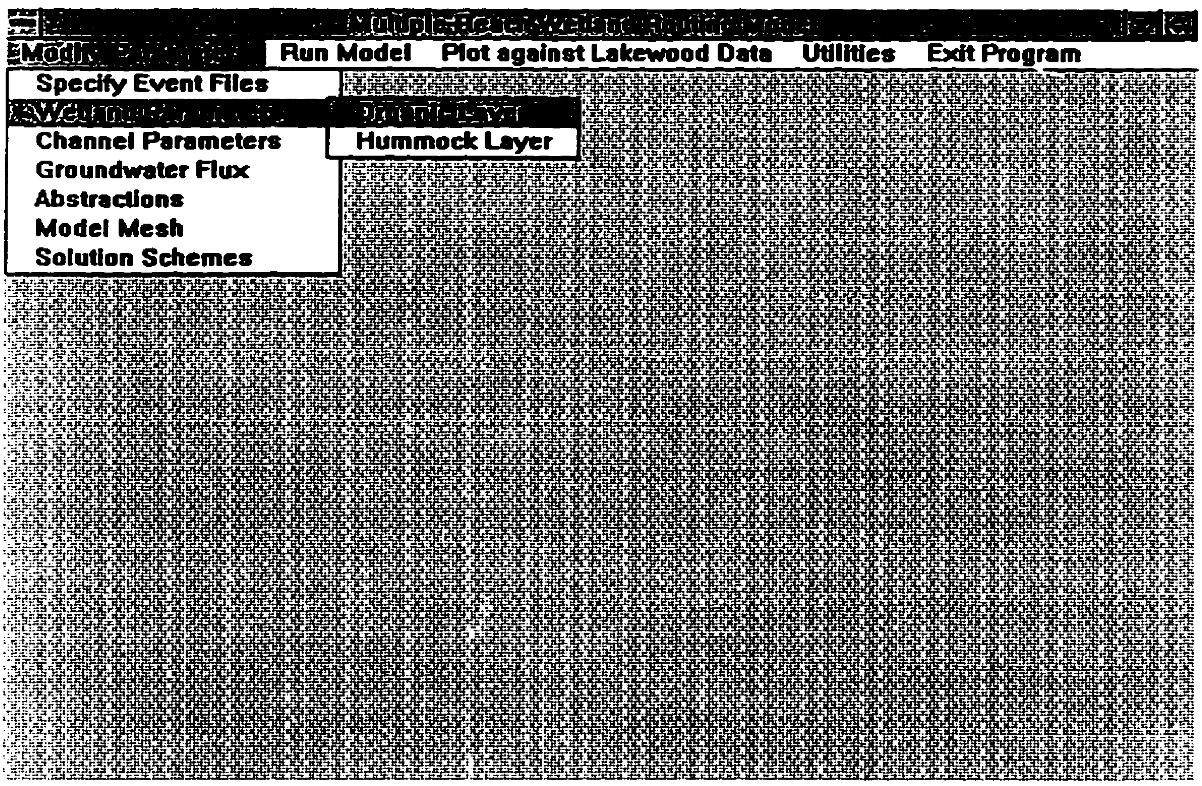


Figure A2 Program Pull-Down Menu - Parameter Input

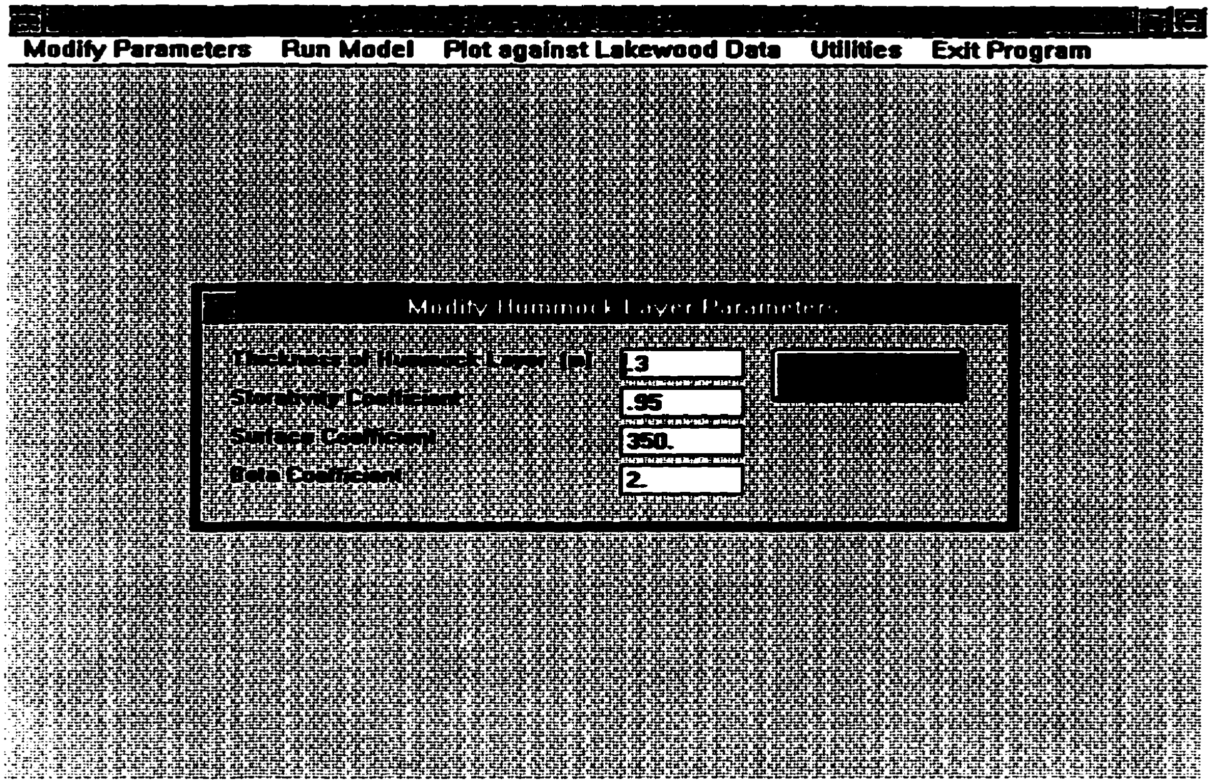


Figure A3 Program Input Screen - Hummock Parameters

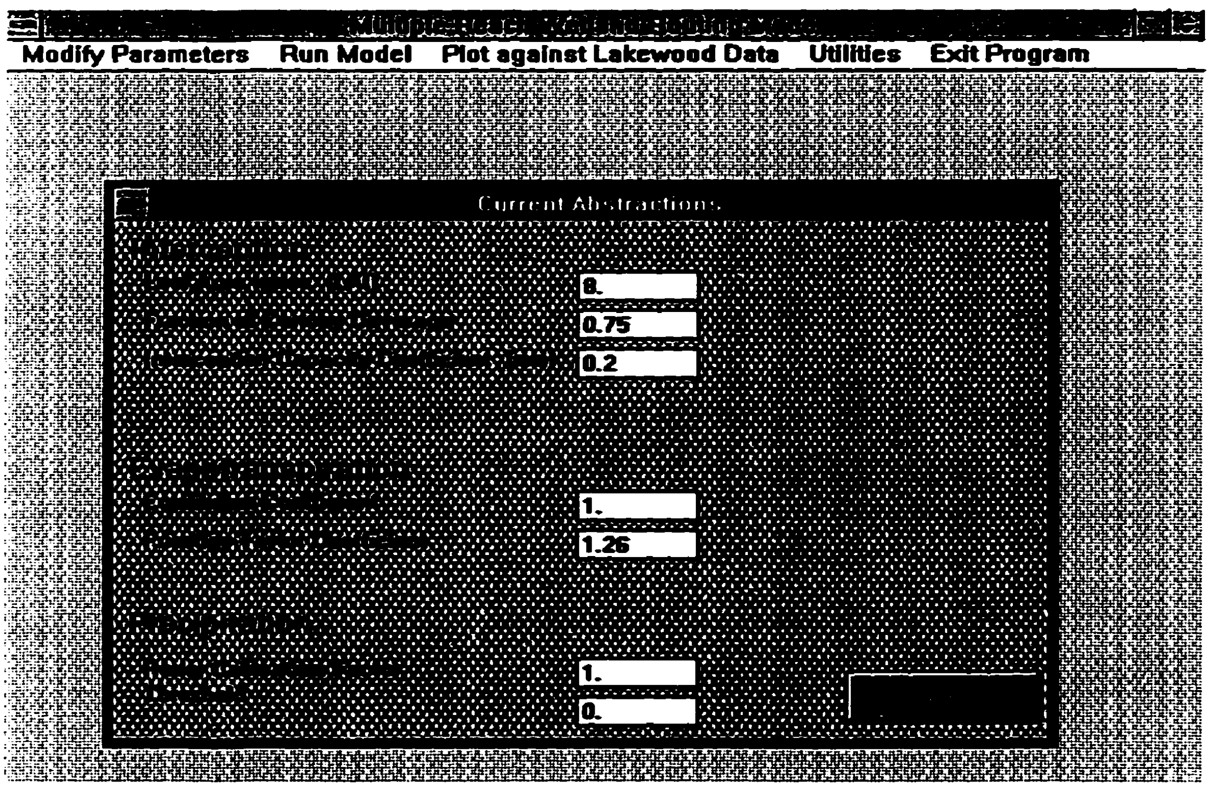


Figure A4 Program Input Screen - Hydrologic Abstractions

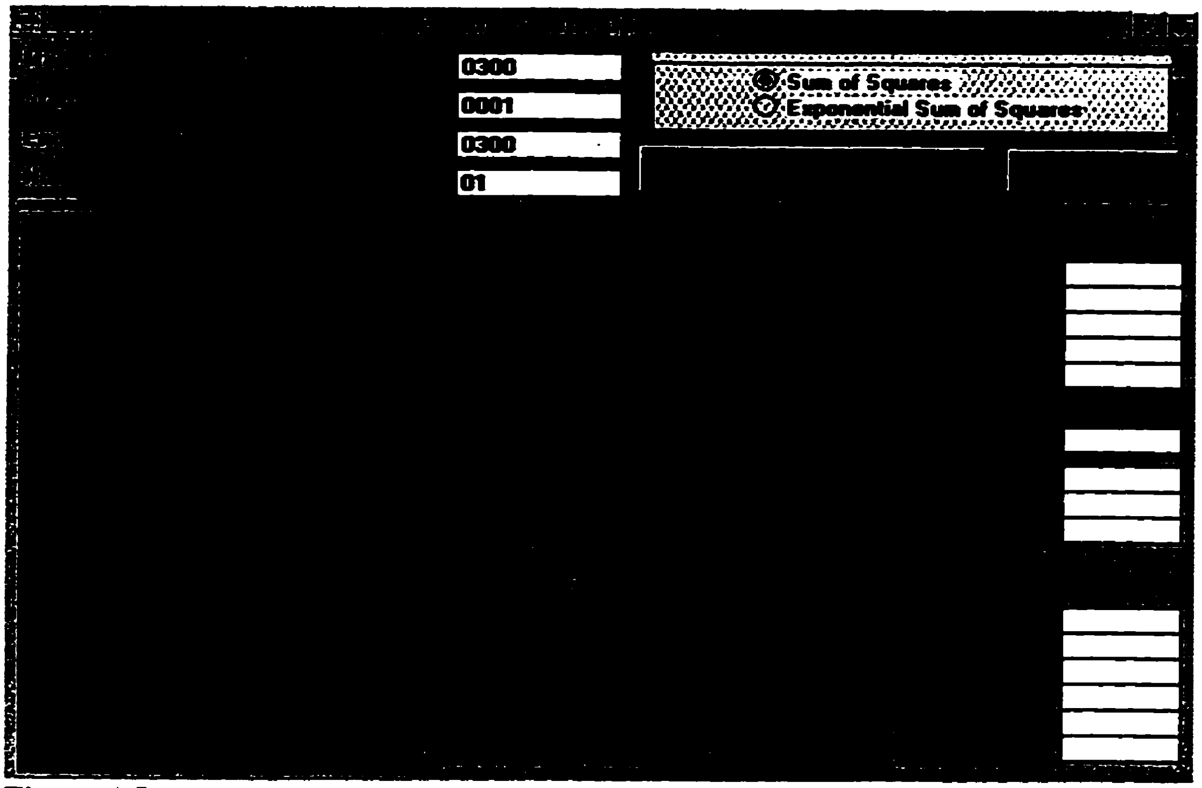


Figure A5 Program Input Screen - Model Calibration

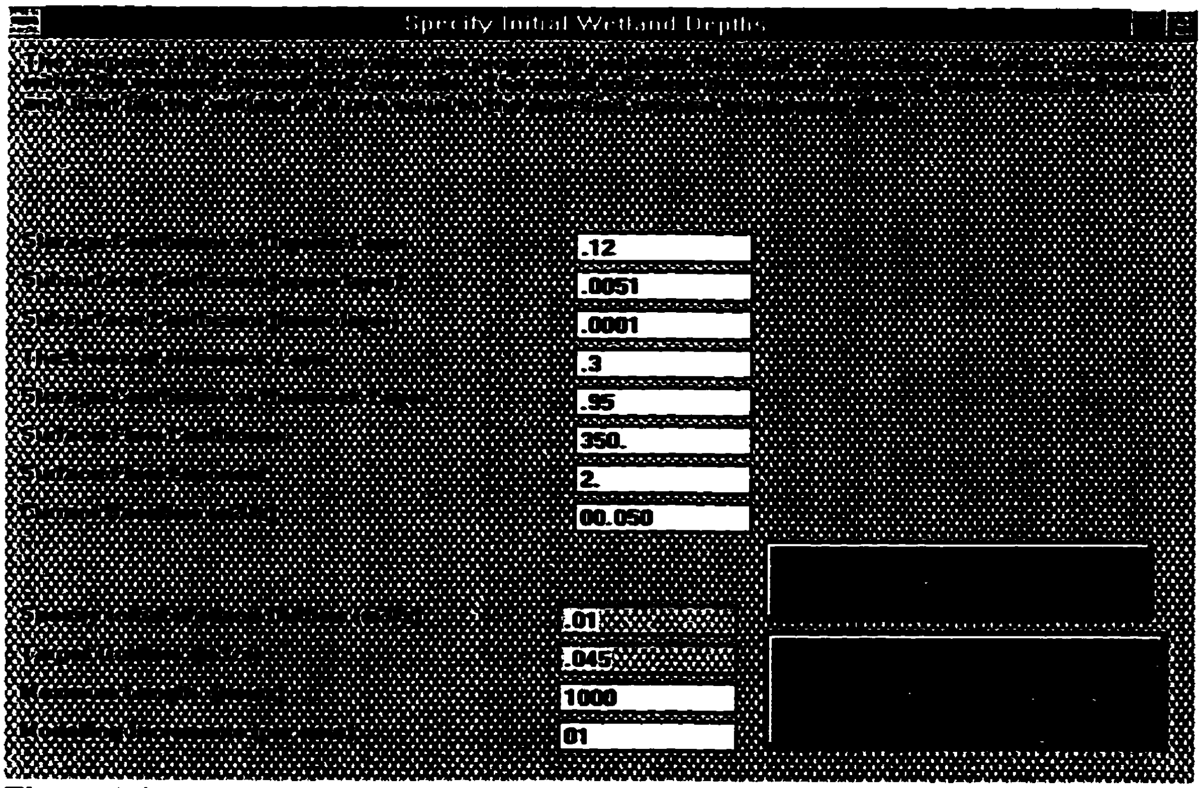


Figure A6 Program Input Screen - Model Initialization

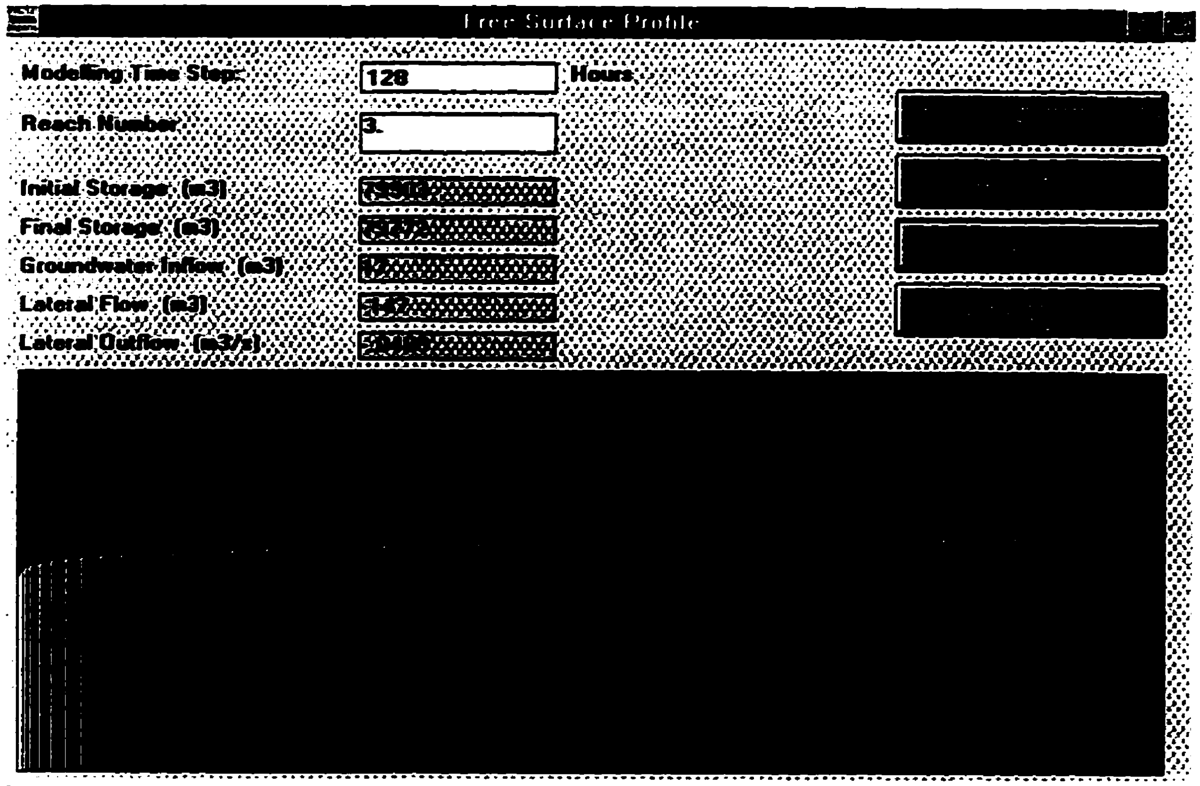


Figure A7 Program Display Screen - Profile of Phreatic Surface

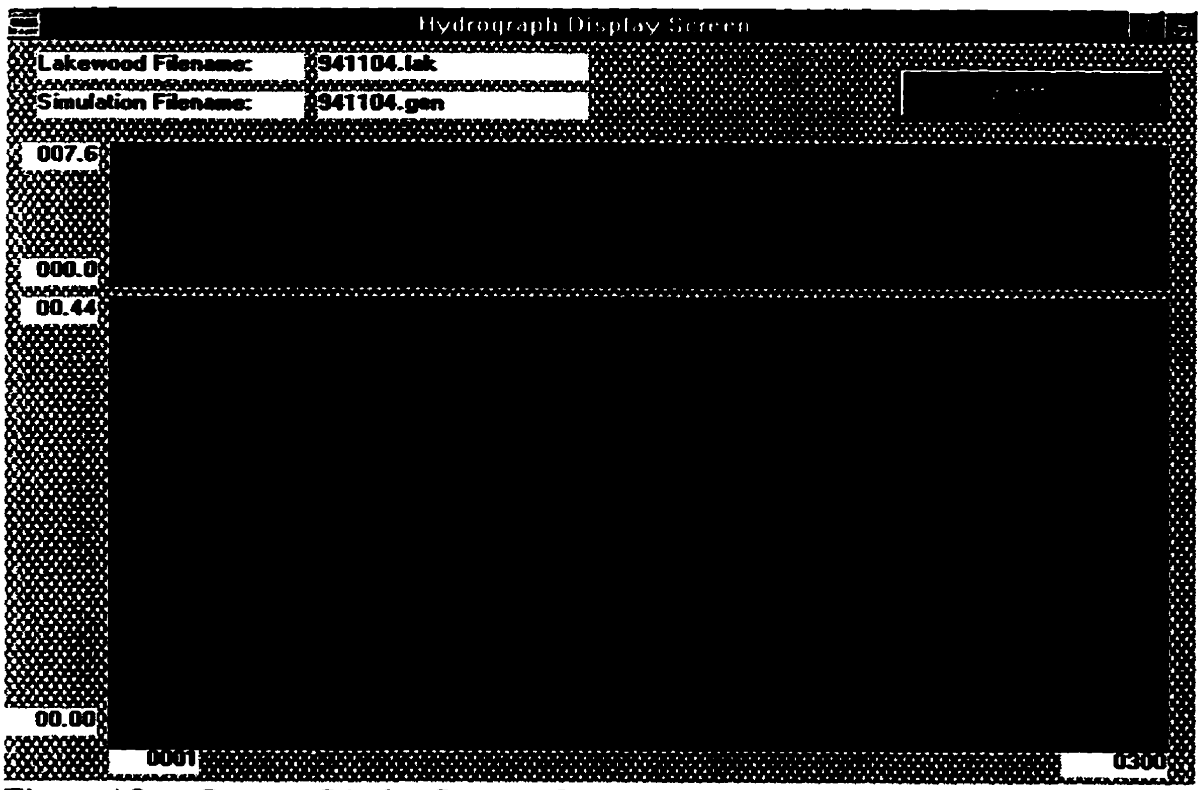


Figure A8 Program Display Screen - Computed and Observed Streamflow Hydrographs

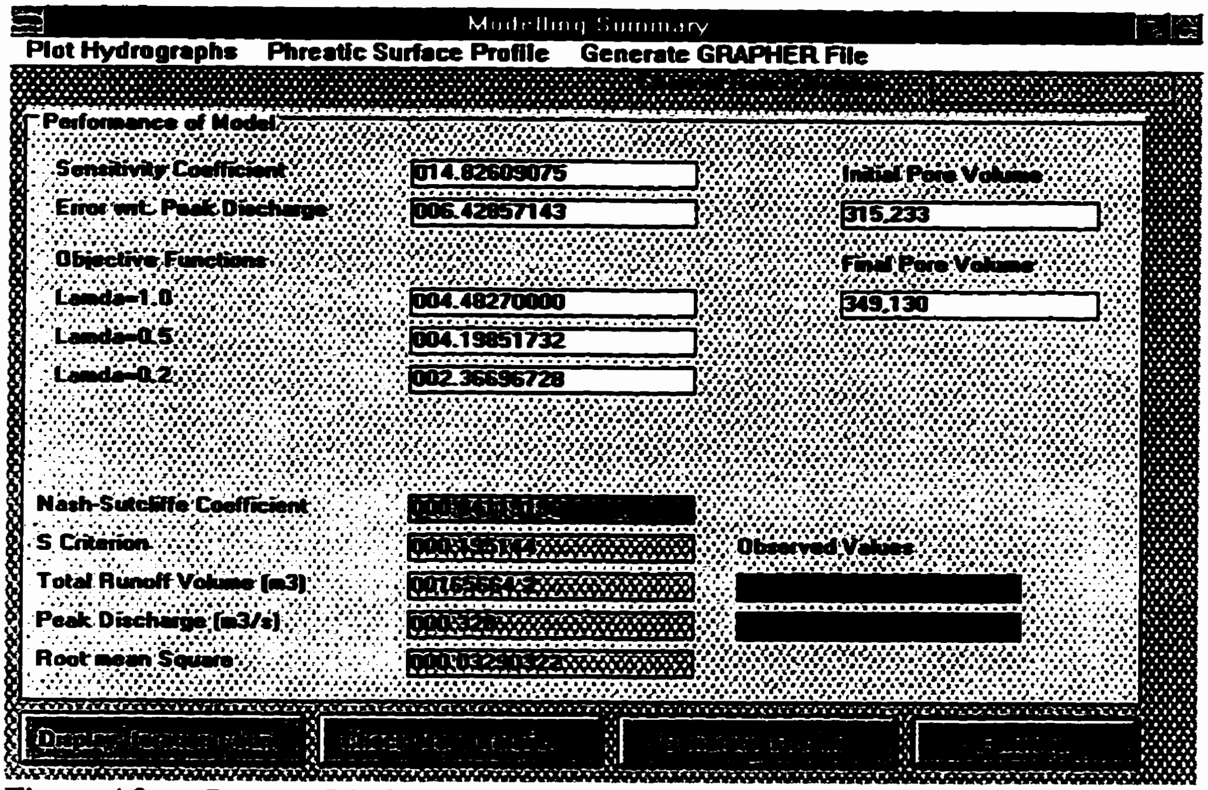


Figure A9 Program Display Screen - Summary Statistics

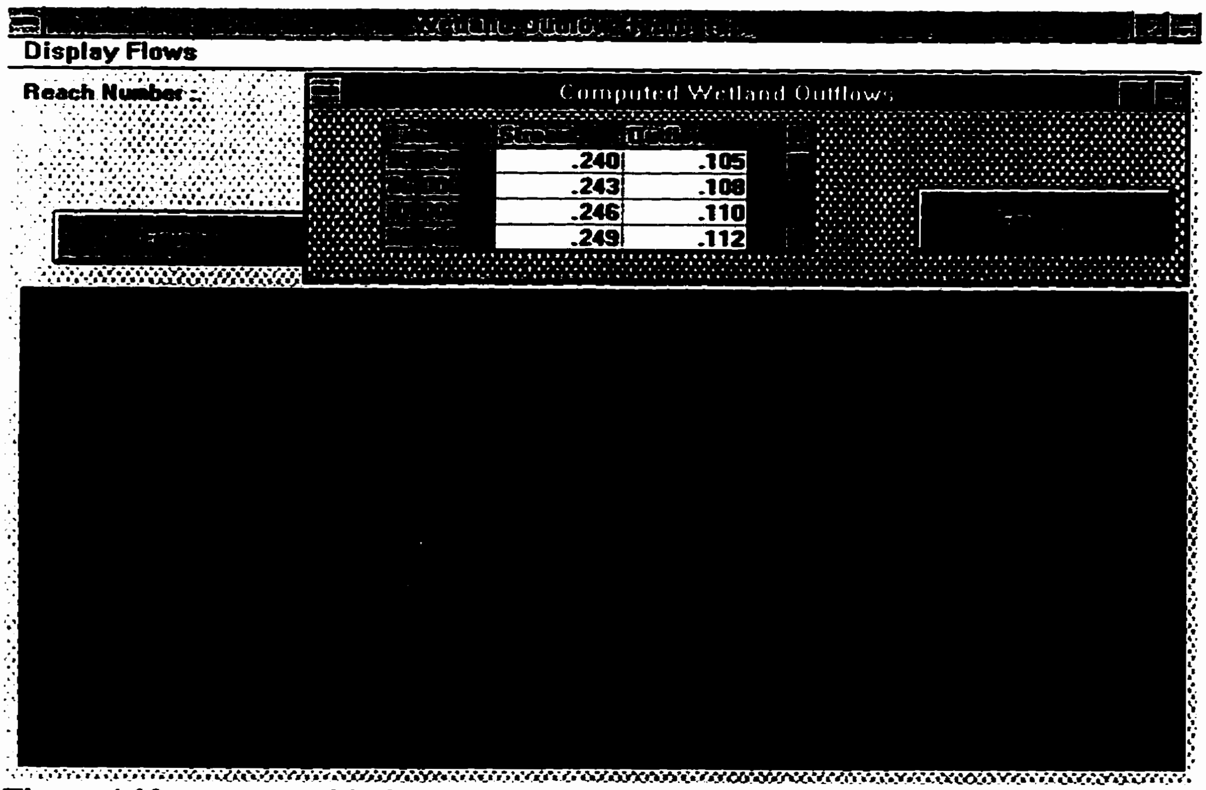


Figure A10 Program Display Screen - Computed Reach Outflow Hydrographs

APPENDIX B

Observed Streamflow Hydrographs (1994-1995)

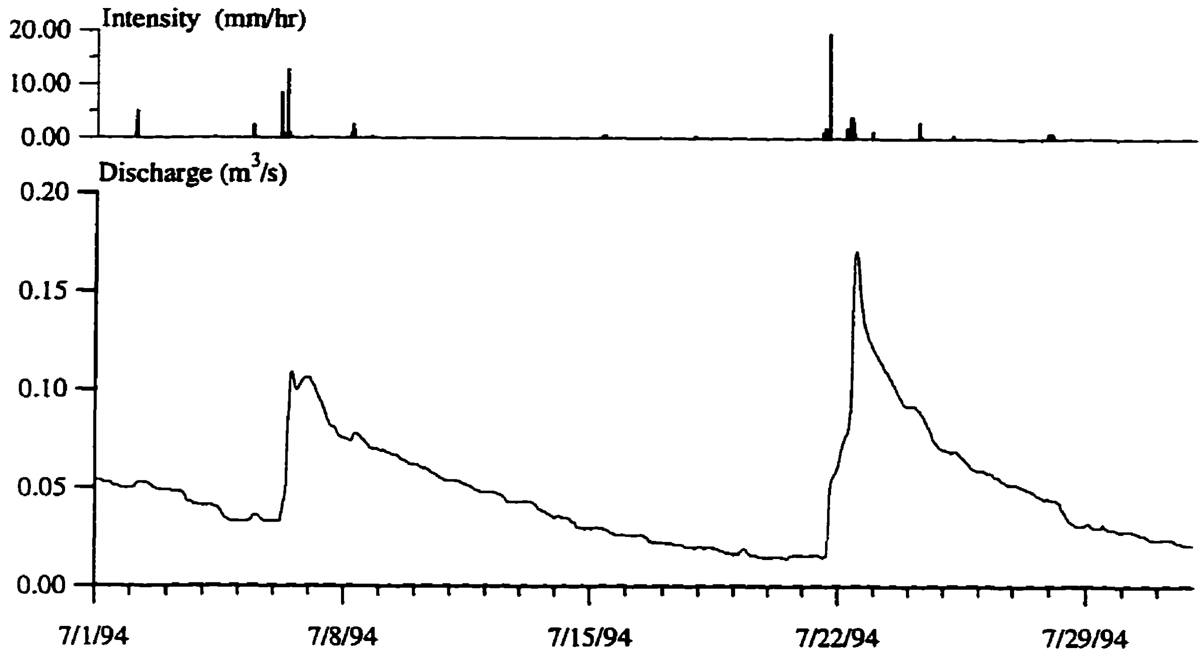


Figure A1 Rainfall-runoff response from headwater wetland (July 1994)

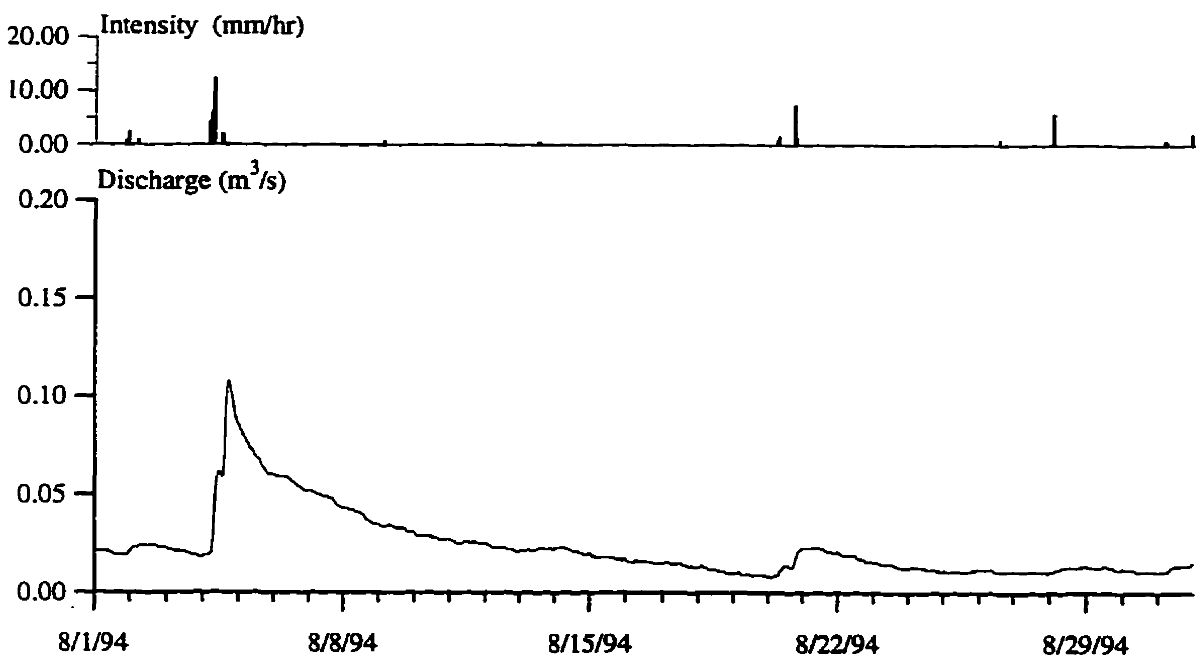


Figure A2 Rainfall-runoff response from headwater wetland (August 1994)

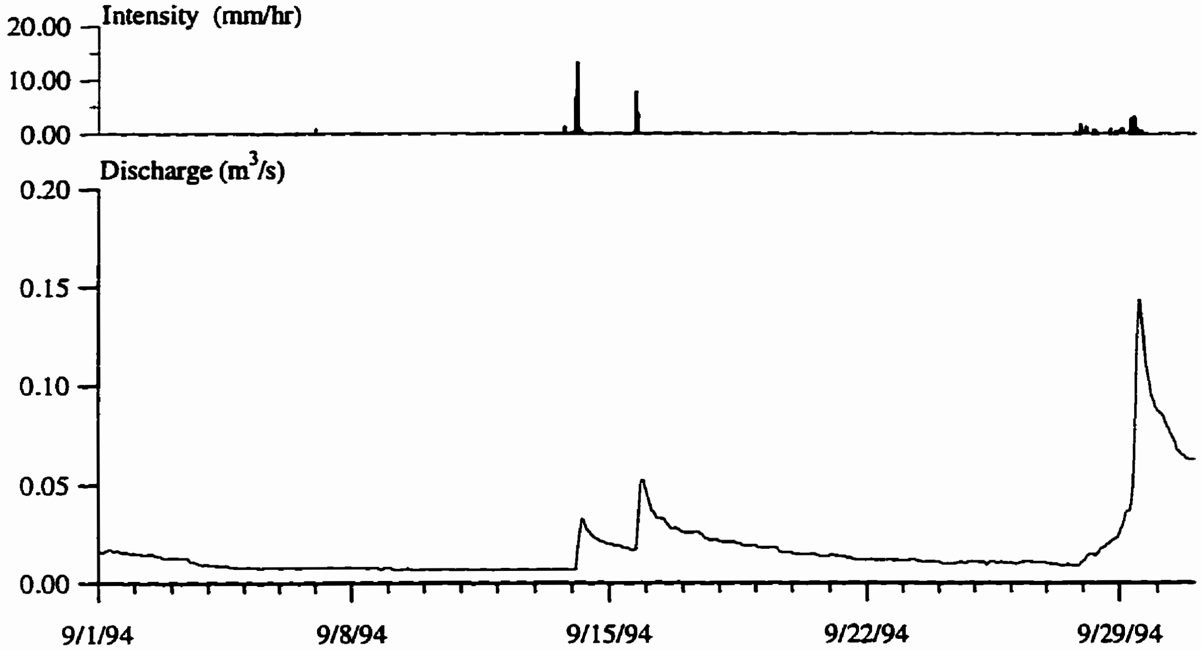


Figure A3 Rainfall-runoff response from headwater wetland (September 1994)

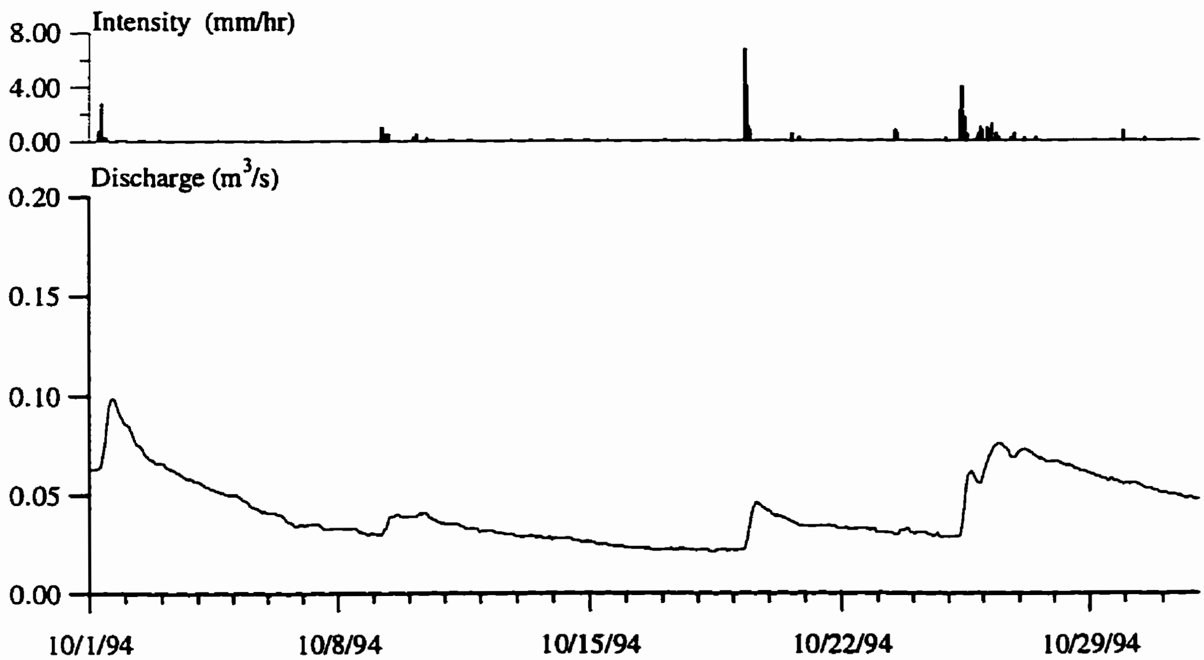


Figure A4 Rainfall-runoff response from headwater wetland (October 1994)

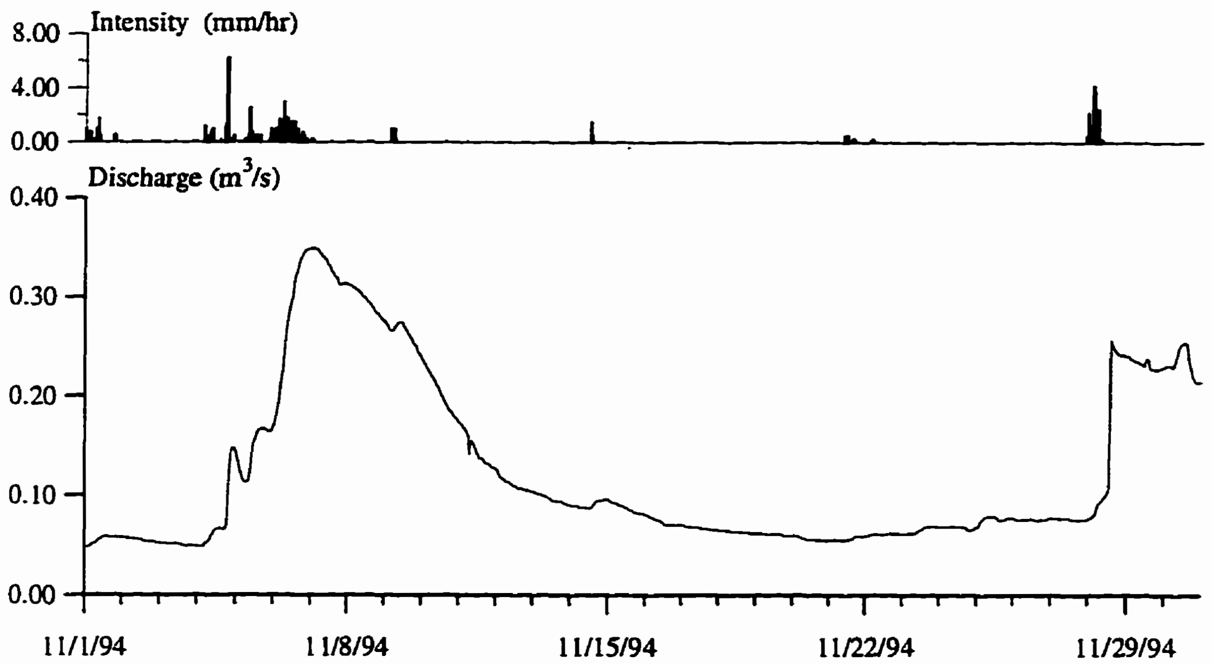


Figure A5 Rainfall-runoff response from headwater wetland (November 1994)

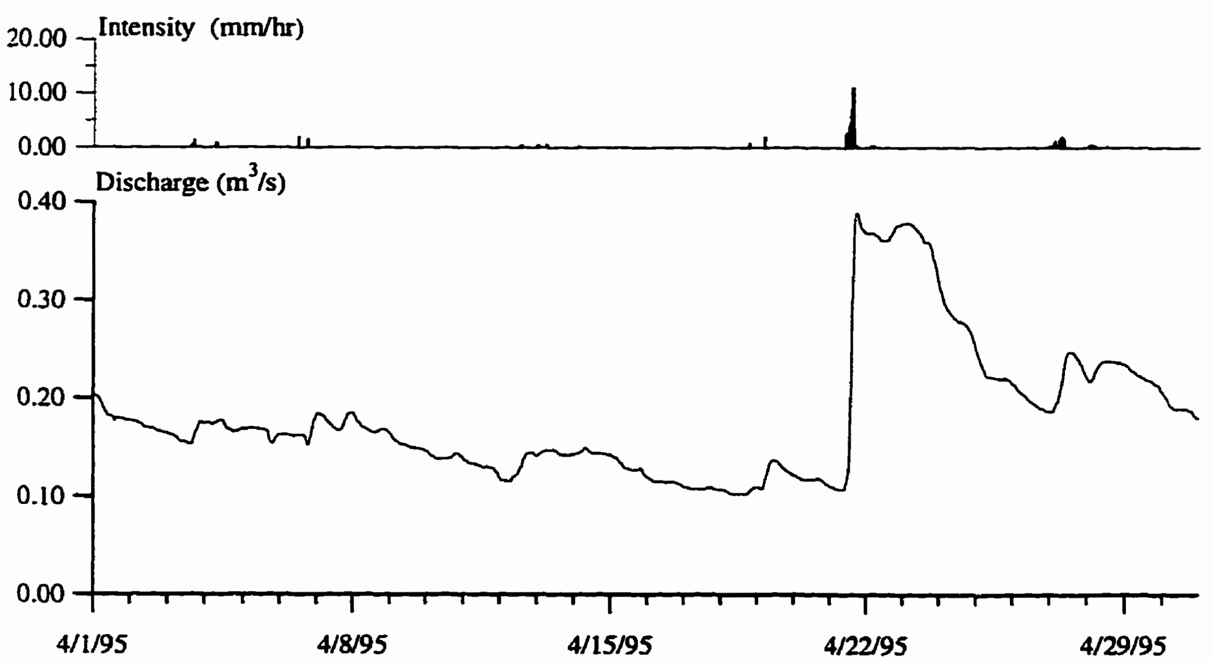


Figure A6 Rainfall-runoff response from headwater wetland (April 1995)

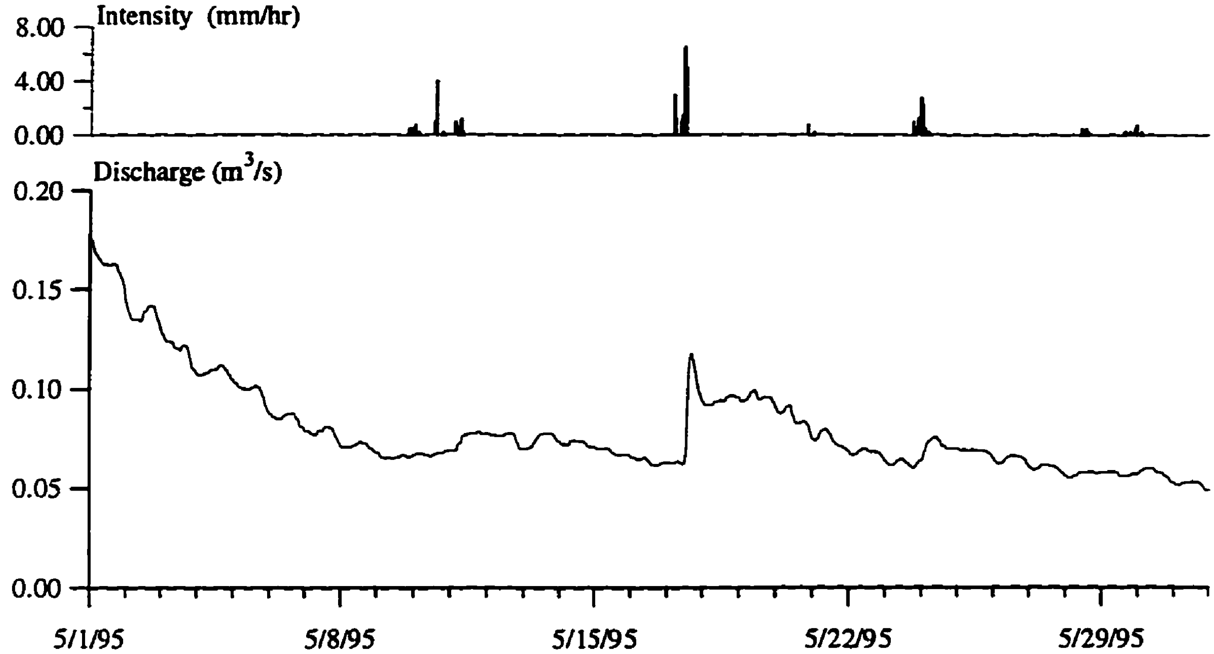


Figure A7 Rainfall-runoff response from headwater wetland (May 1995)

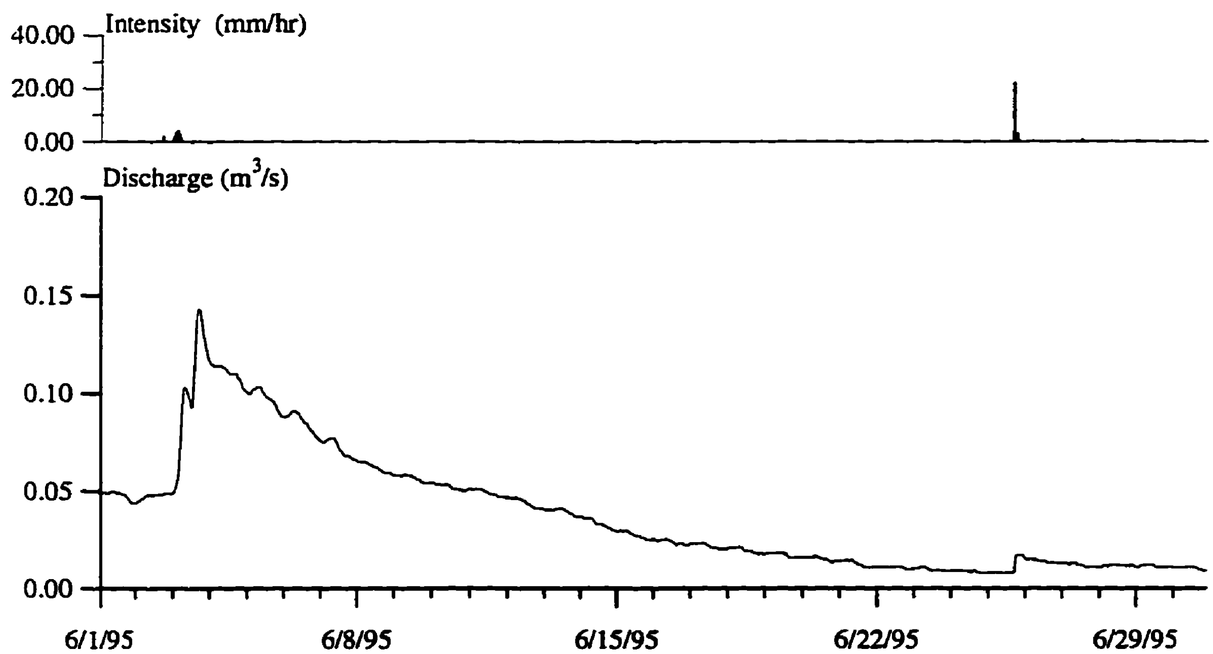


Figure A8 Rainfall-runoff response from headwater wetland (June 1995)

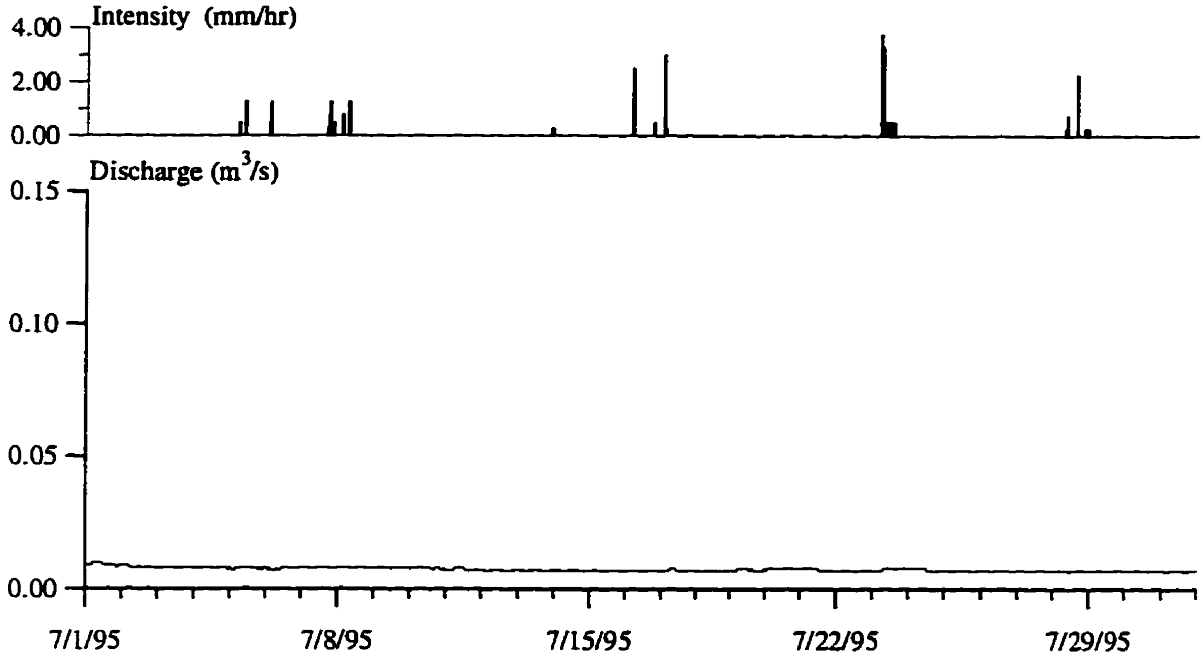


Figure A9 Rainfall-runoff response from headwater wetland (July 1995)

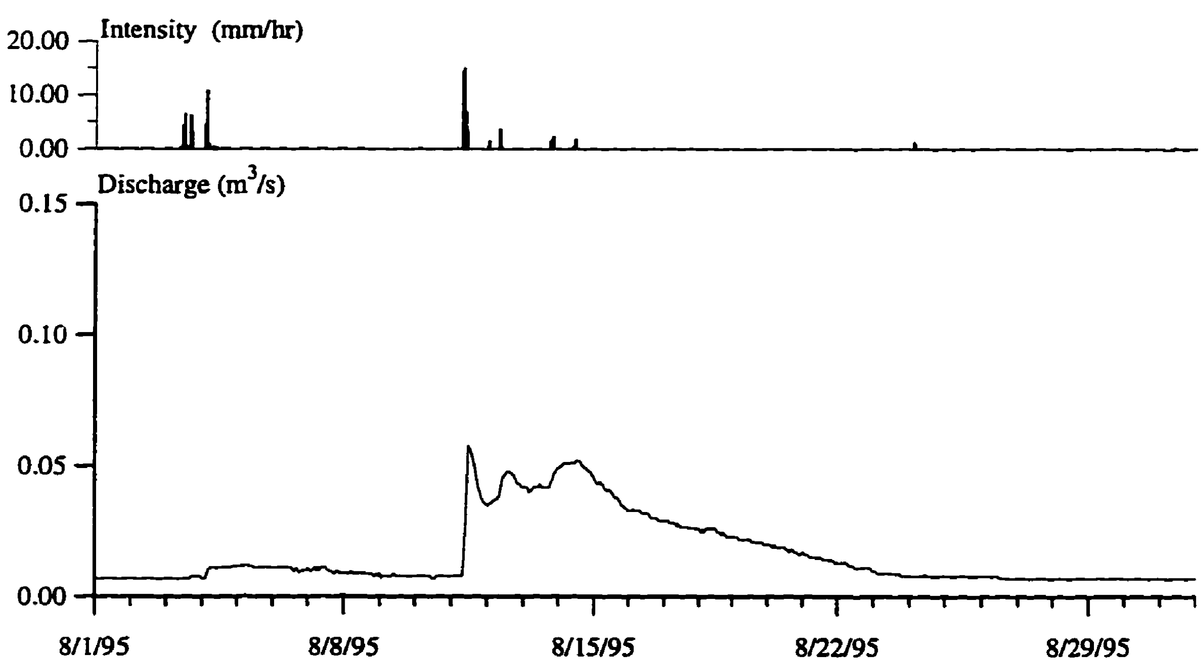


Figure A10 Rainfall-runoff response from headwater wetland (August 1995)

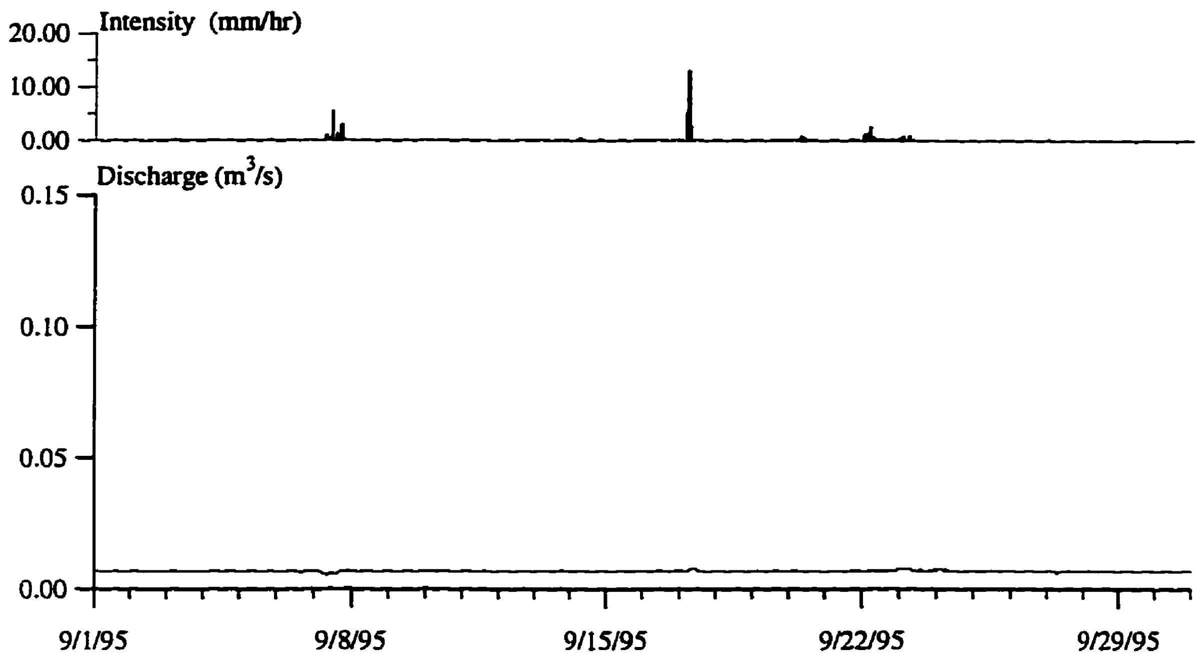


Figure A11 Rainfall-runoff response from headwater wetland (September 1995)

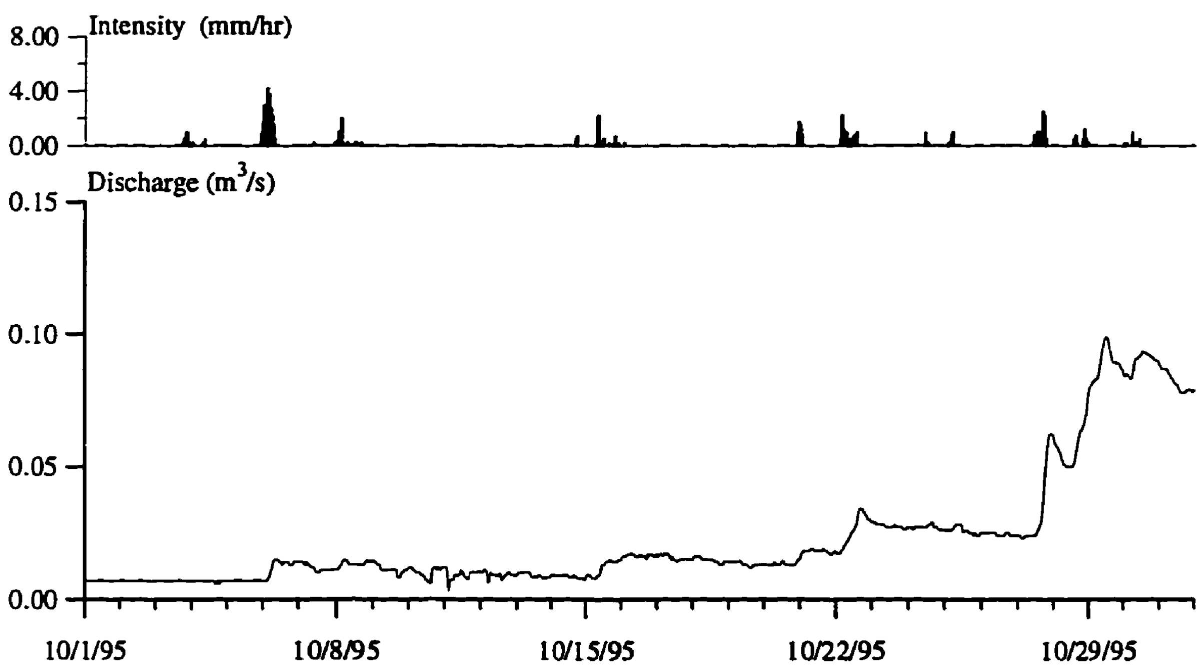


Figure A12 Rainfall-runoff response from headwater wetland (October 1995)

APPENDIX C

Event Validation of Wetland Model

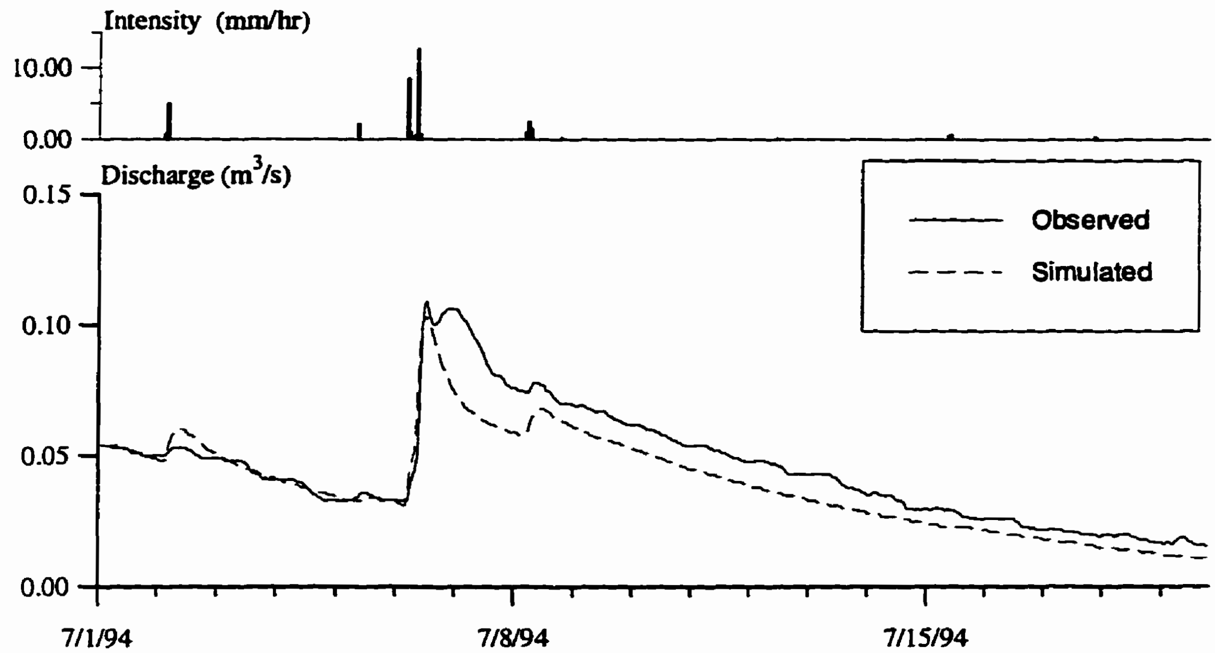


Figure C1 **Simulated and observed rainfall-runoff response from headwater wetland (July 06, 1994)**

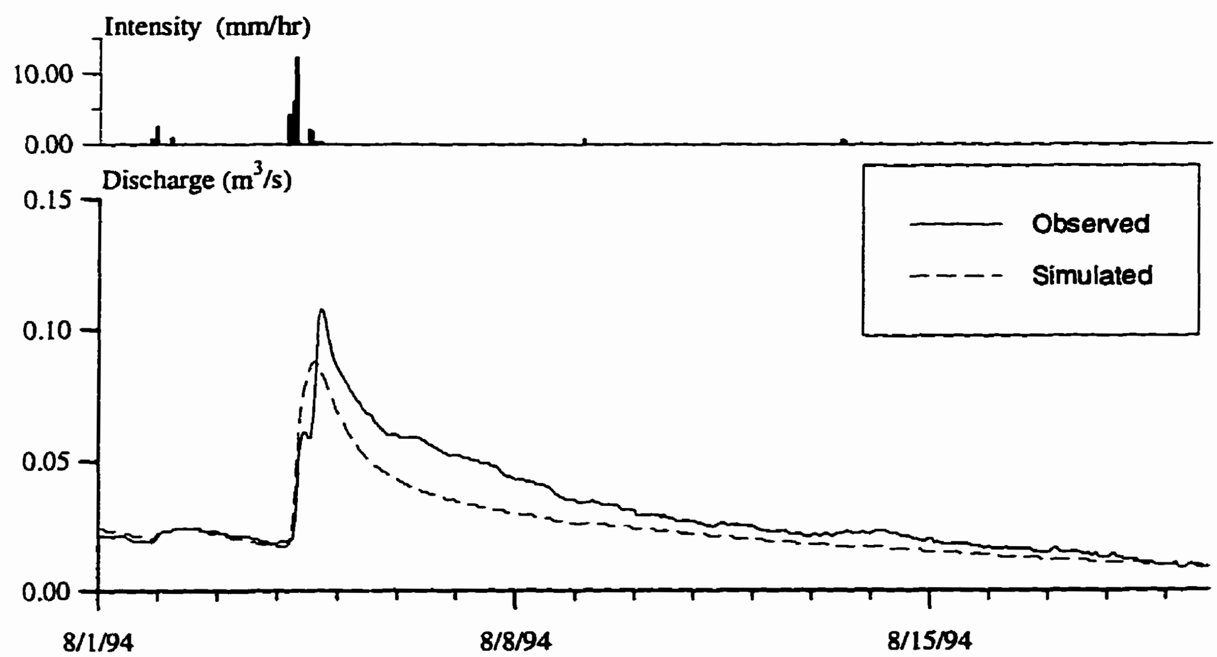


Figure C2 **Simulated and observed rainfall-runoff response from headwater wetland (August 04, 1994)**

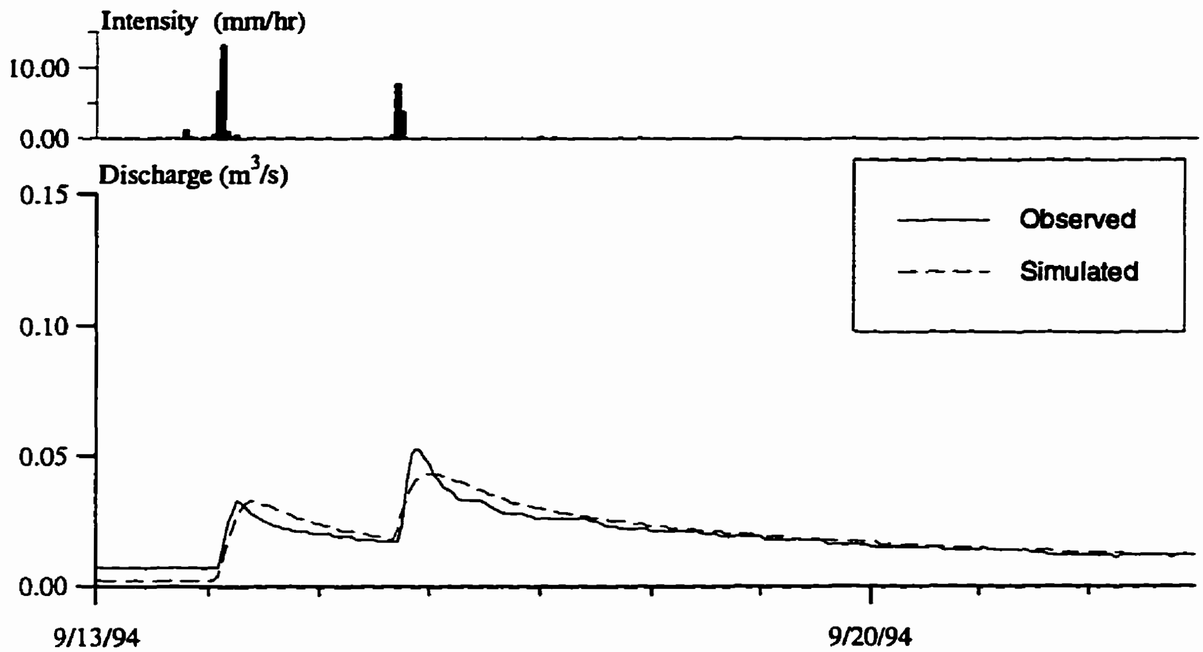


Figure C3 **Simulated and observed rainfall-runoff response from headwater wetland (September 13, 1994)**

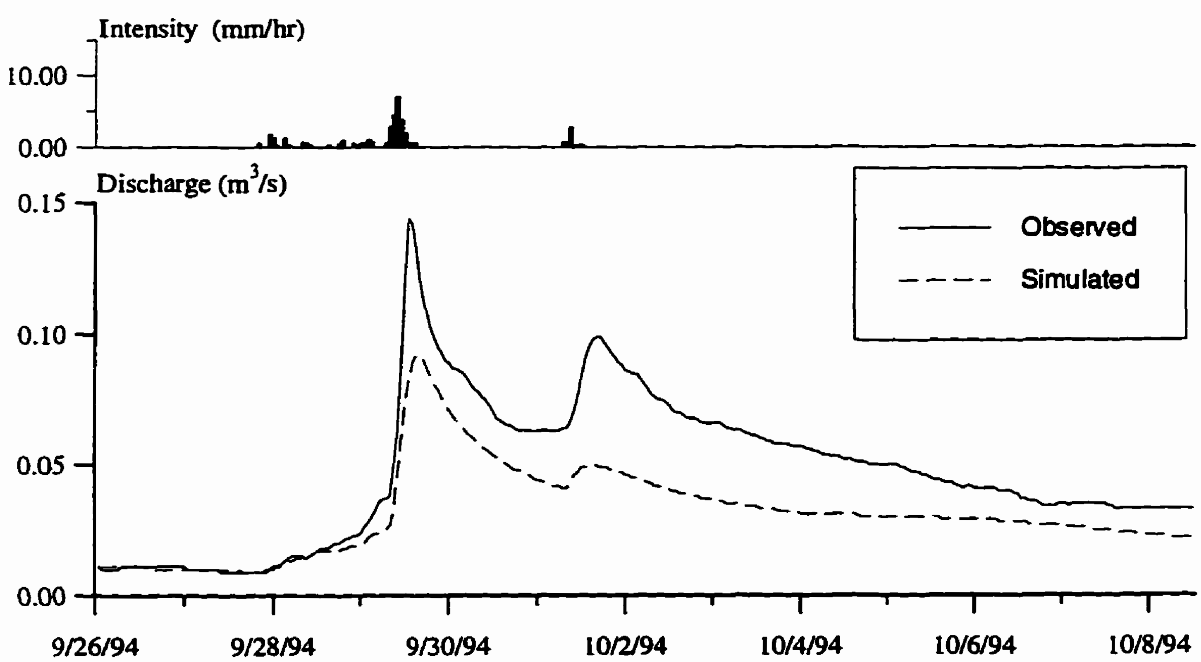


Figure C4 **Simulated and observed rainfall-runoff response from headwater wetland (September 28, 1994)**

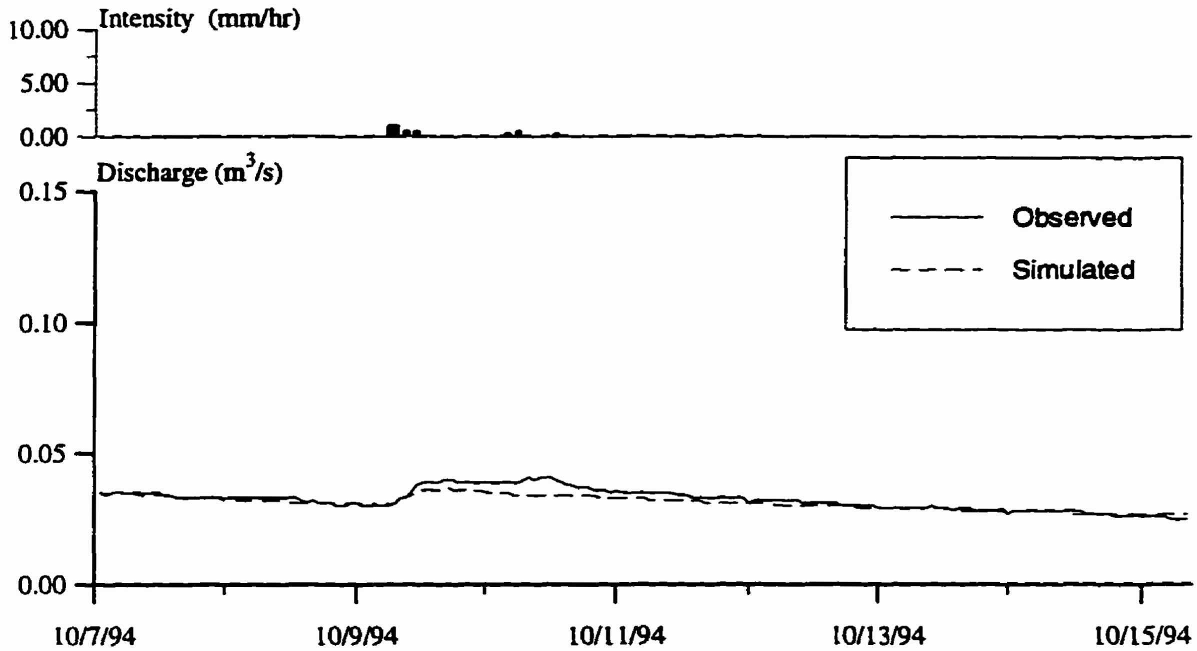


Figure C5 **Simulated and observed rainfall-runoff response from headwater wetland (October 09, 1994)**

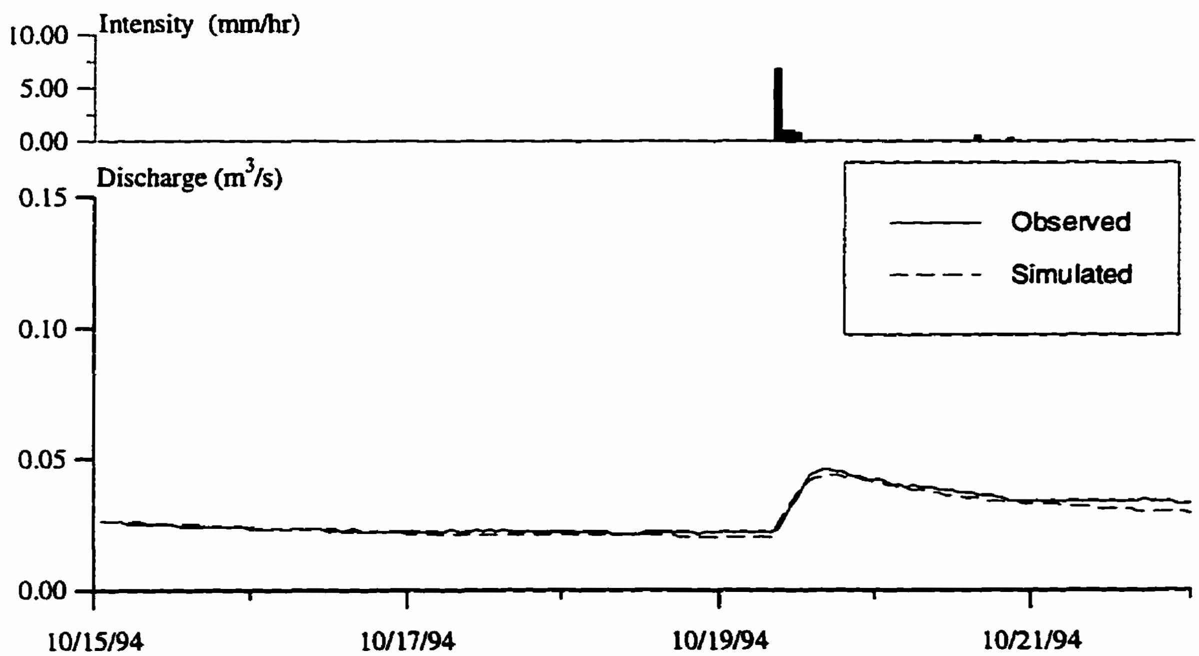


Figure C6 **Simulated and observed rainfall-runoff response from headwater wetland (October 19, 1994)**

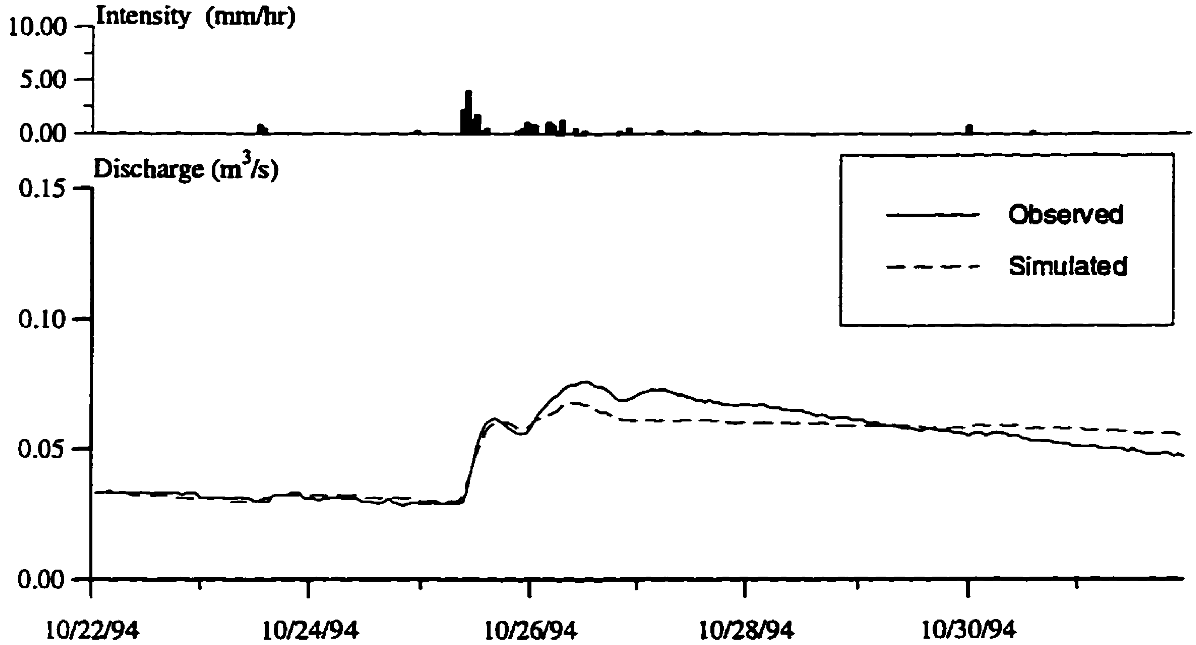


Figure C7 **Simulated and observed rainfall-runoff response from headwater wetland (October 25, 1994)**

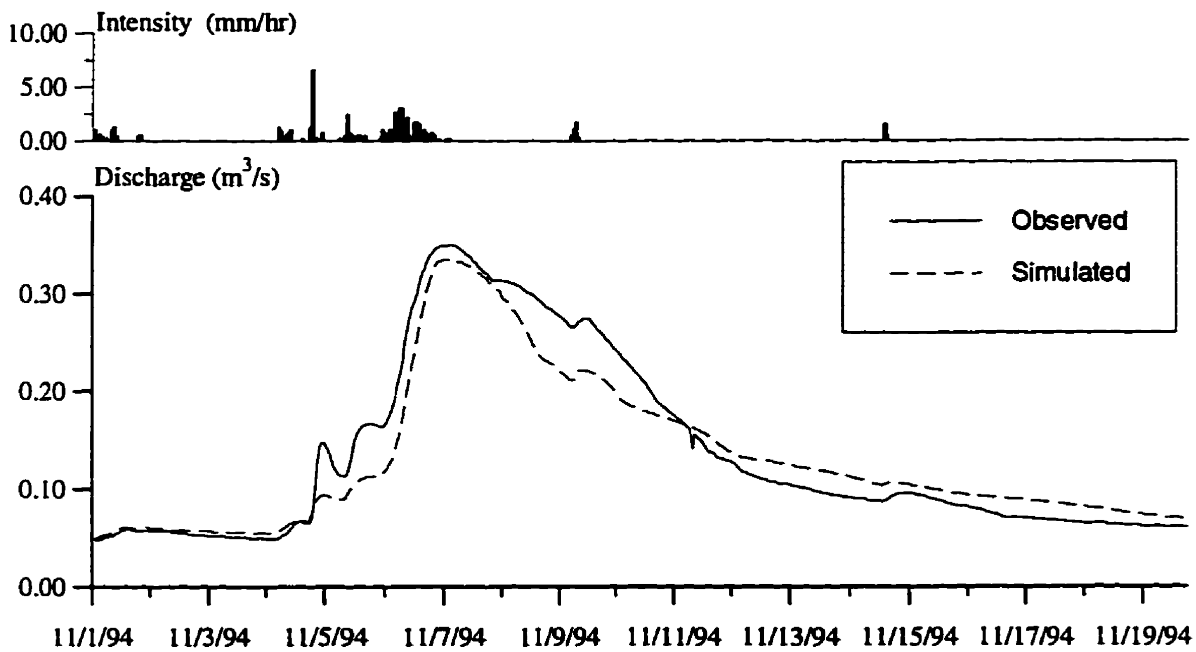


Figure C8 **Simulated and observed rainfall-runoff response from headwater wetland (November 04, 1994)**

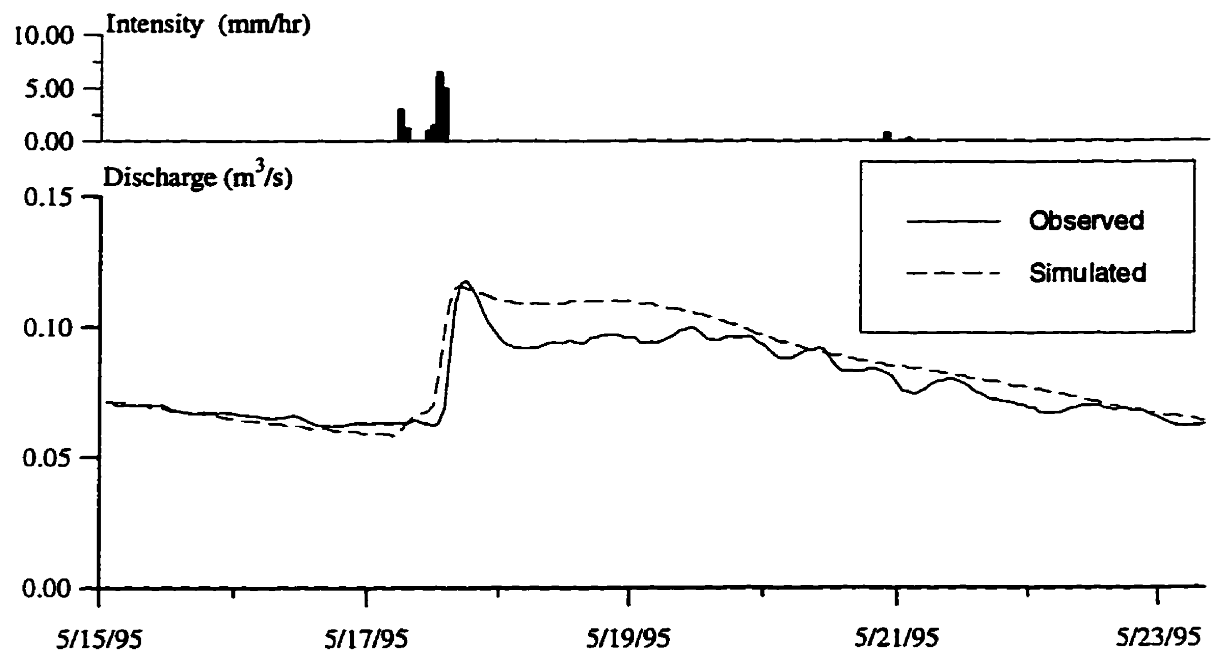


Figure C9 **Simulated and observed rainfall-runoff response from headwater wetland (May 17, 1995)**

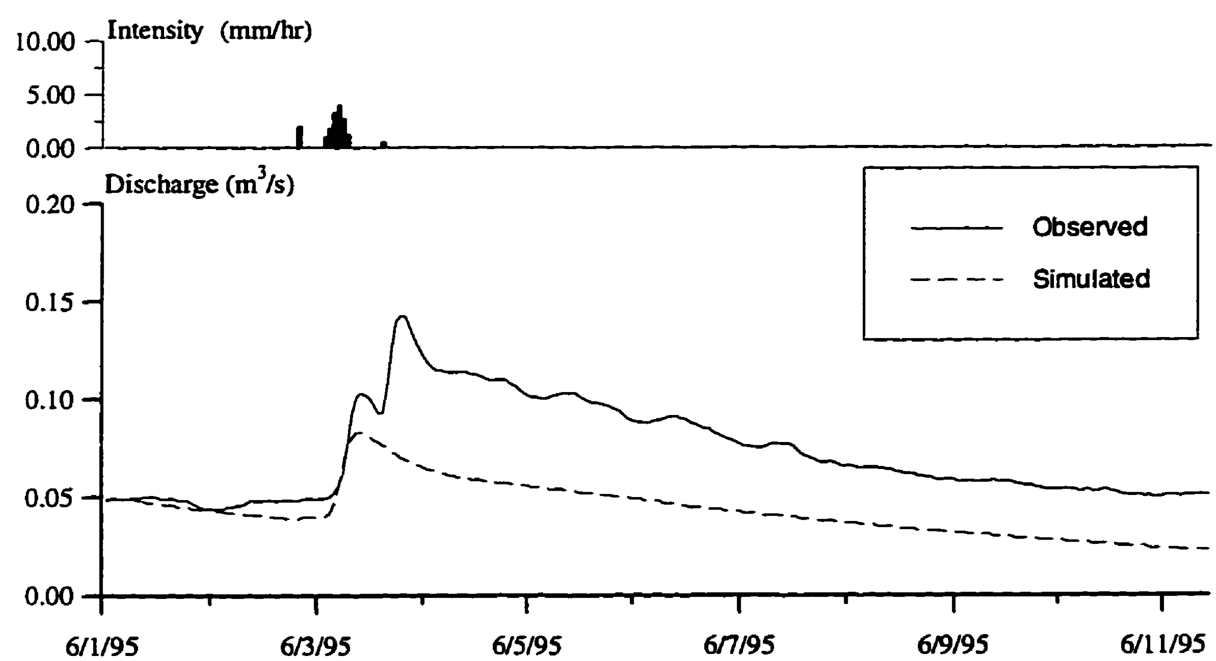


Figure C10 **Simulated and observed rainfall-runoff response from headwater wetland (June 03, 1995)**

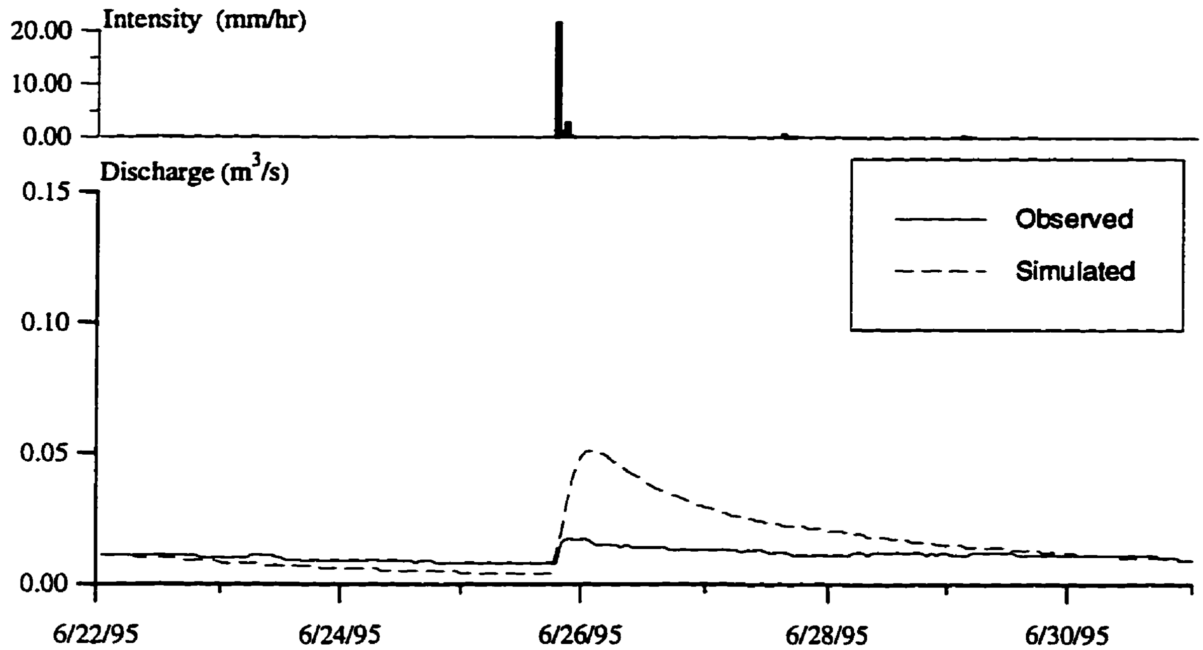


Figure C11 Simulated and observed rainfall-runoff response from headwater wetland (June 25, 1995)

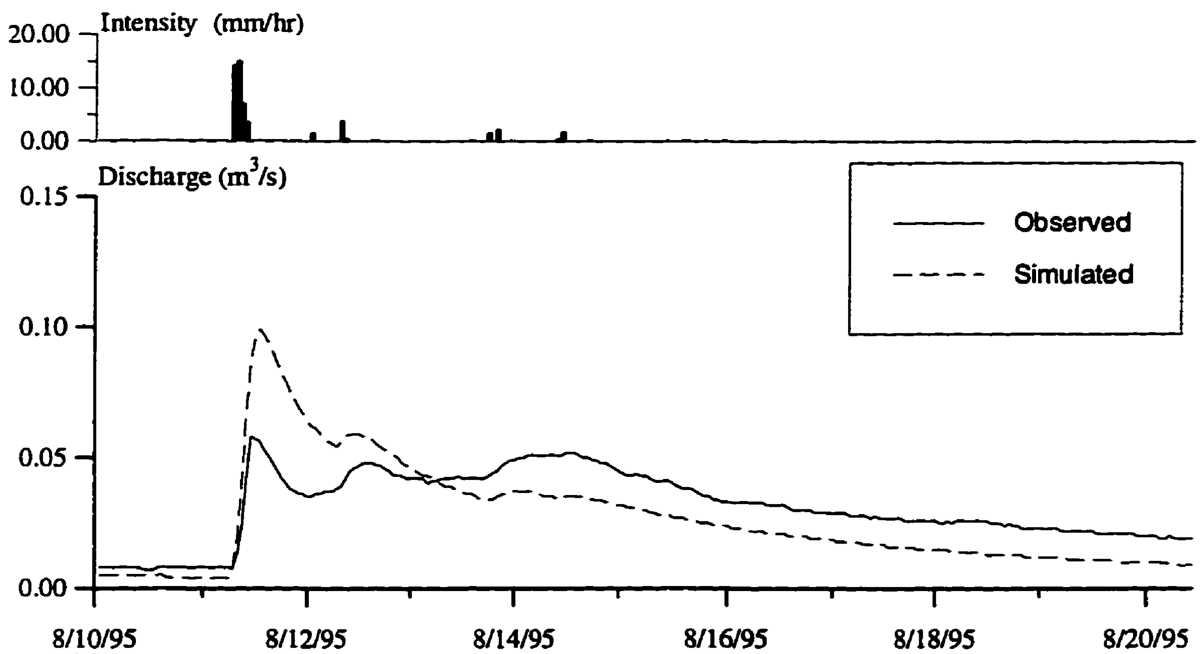


Figure C12 Simulated and observed rainfall-runoff response from headwater wetland (August 10, 1995)

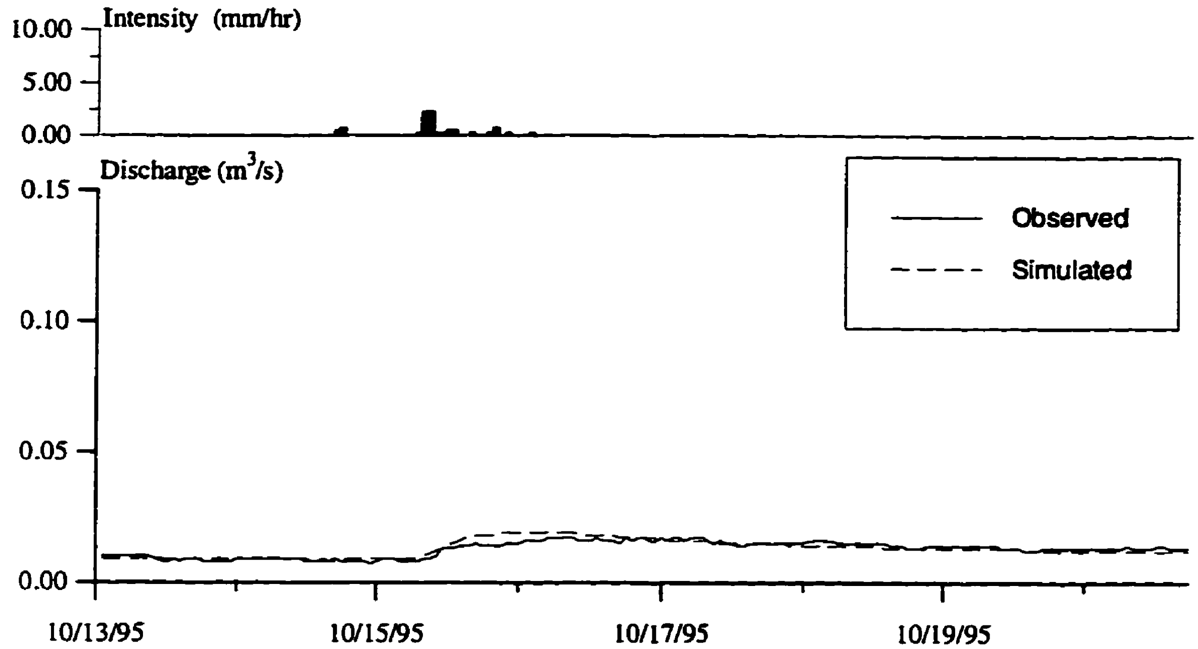


Figure C13 Simulated and observed rainfall-runoff response from headwater wetland (October 13, 1995)

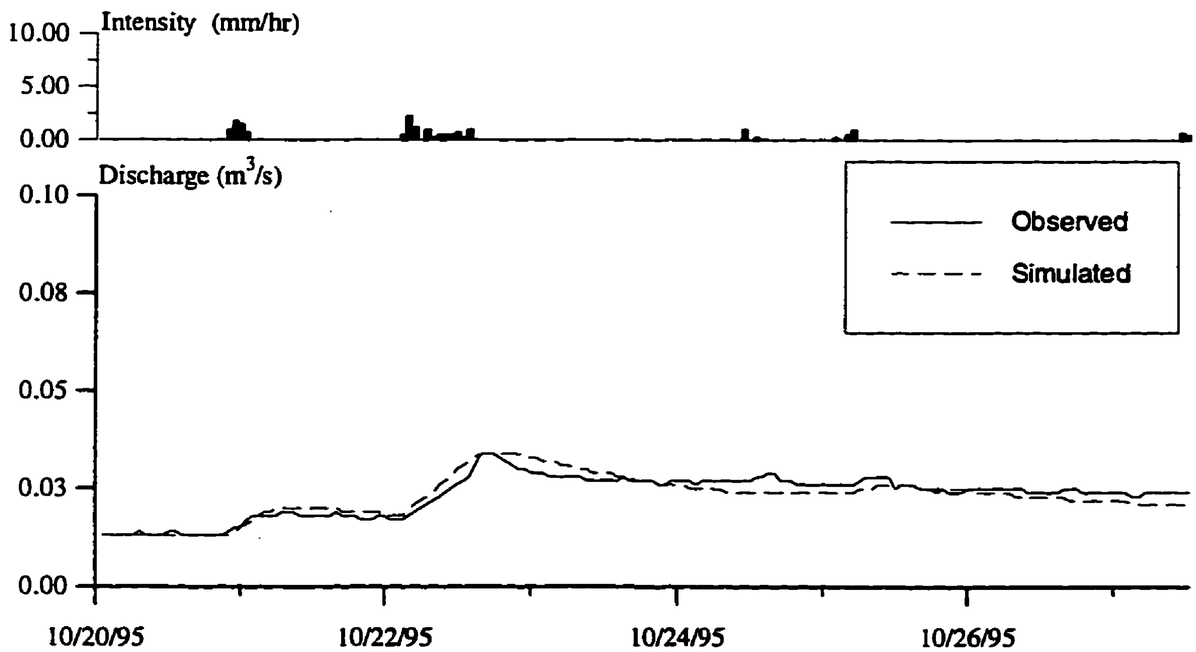


Figure C14 Simulated and observed rainfall-runoff response from headwater wetland (October 20, 1995)

APPENDIX D

Monthly Simulations

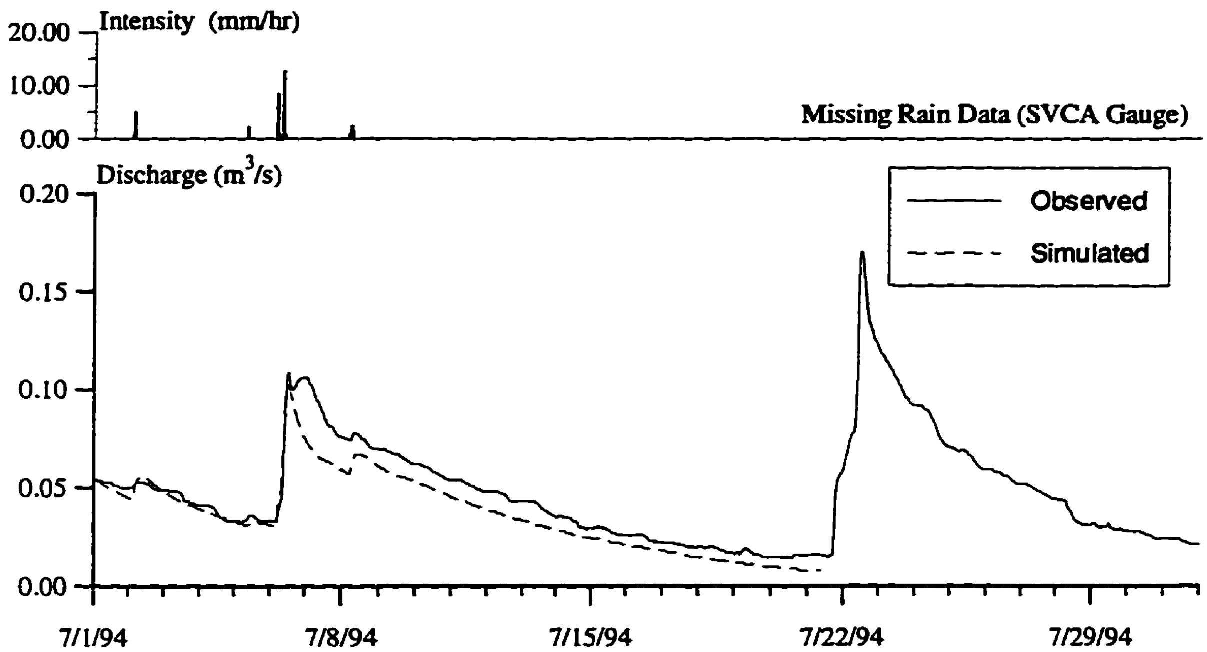


Figure D1 **Simulated and observed rainfall-runoff response from headwater wetland (July, 1994)**

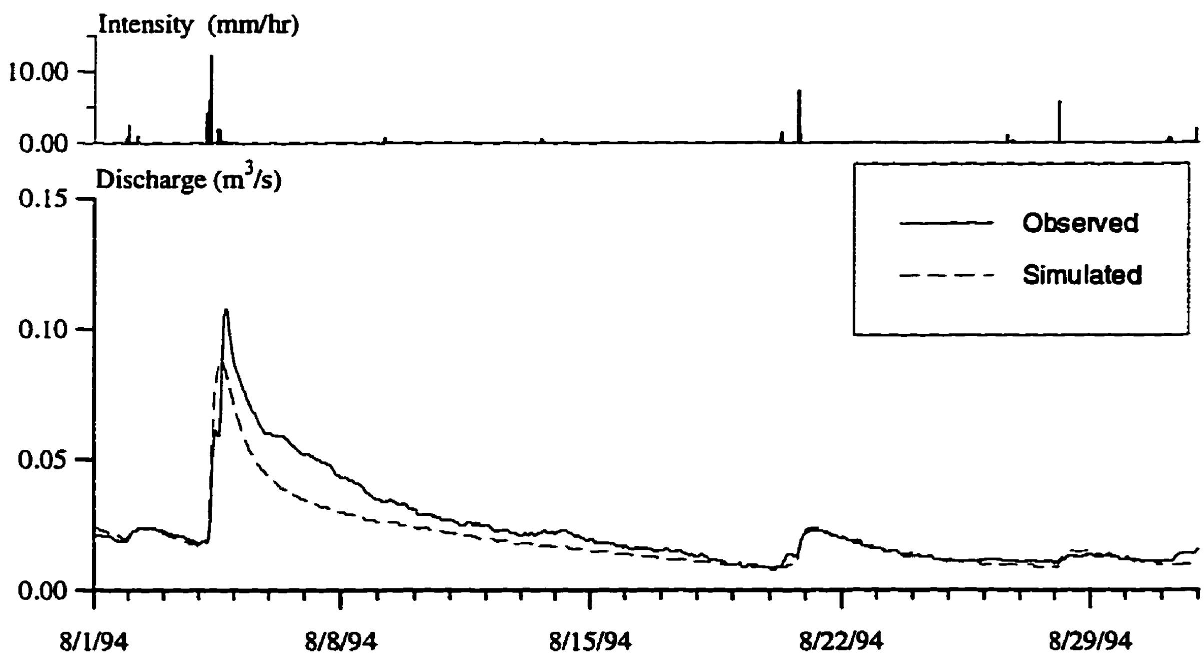


Figure D2 **Simulated and observed rainfall-runoff response from headwater wetland (August, 1994)**

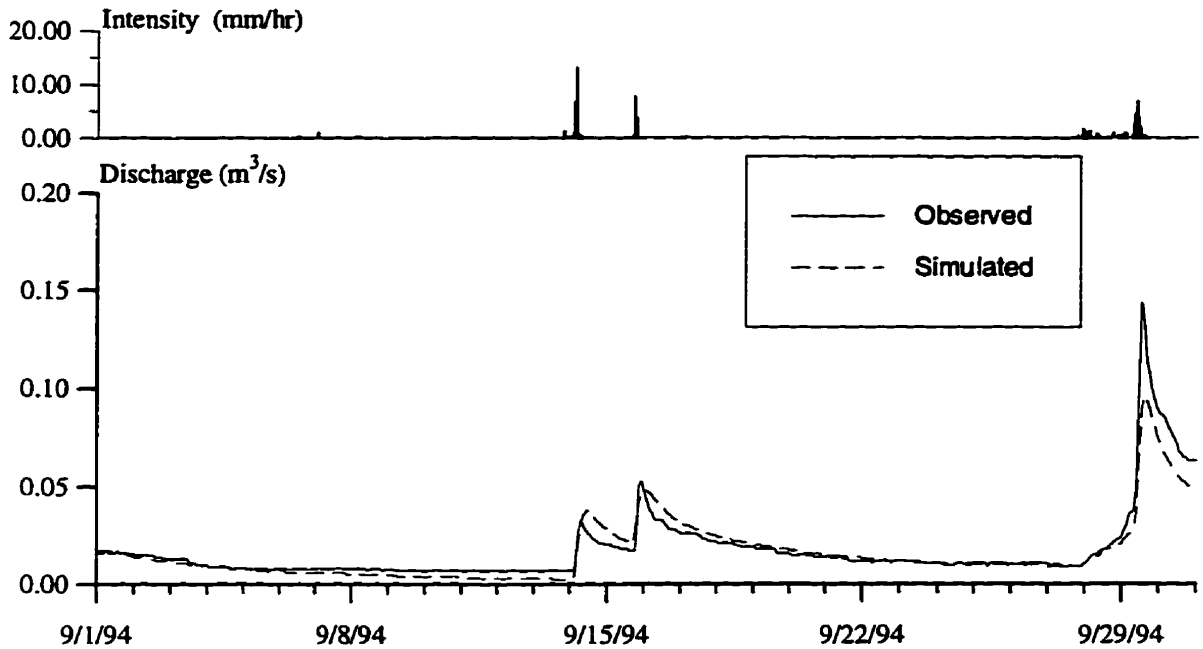


Figure D3 **Simulated and observed rainfall-runoff response from headwater wetland (September, 1994)**

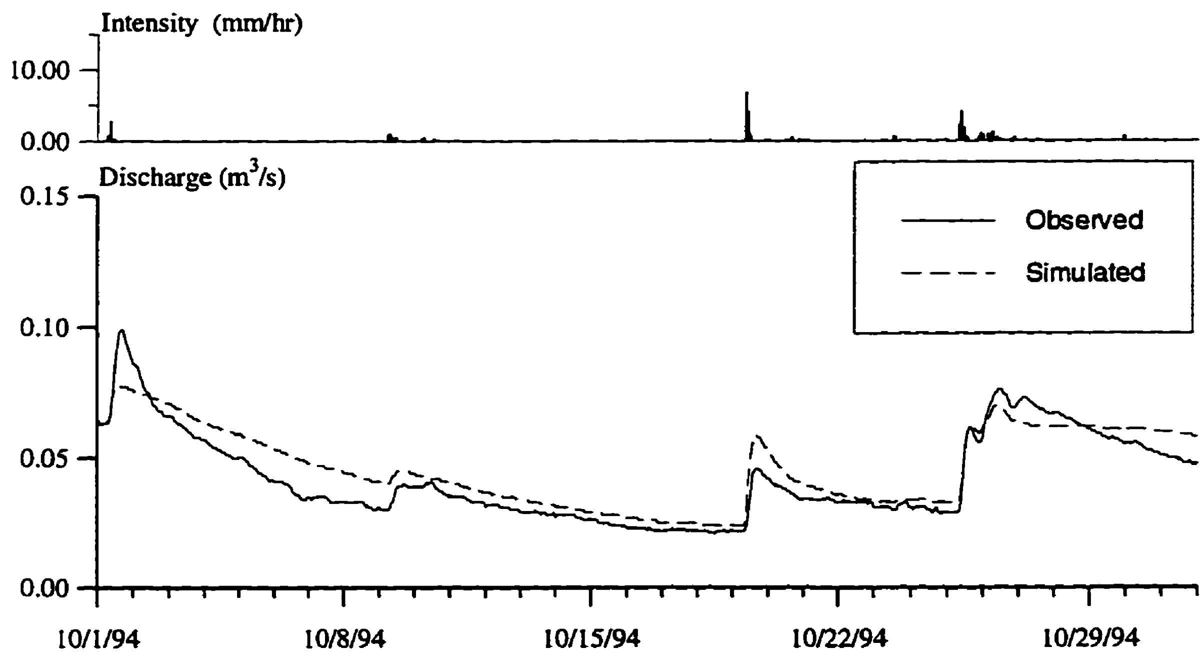


Figure D4 **Simulated and observed rainfall-runoff response from headwater wetland (October, 1994)**

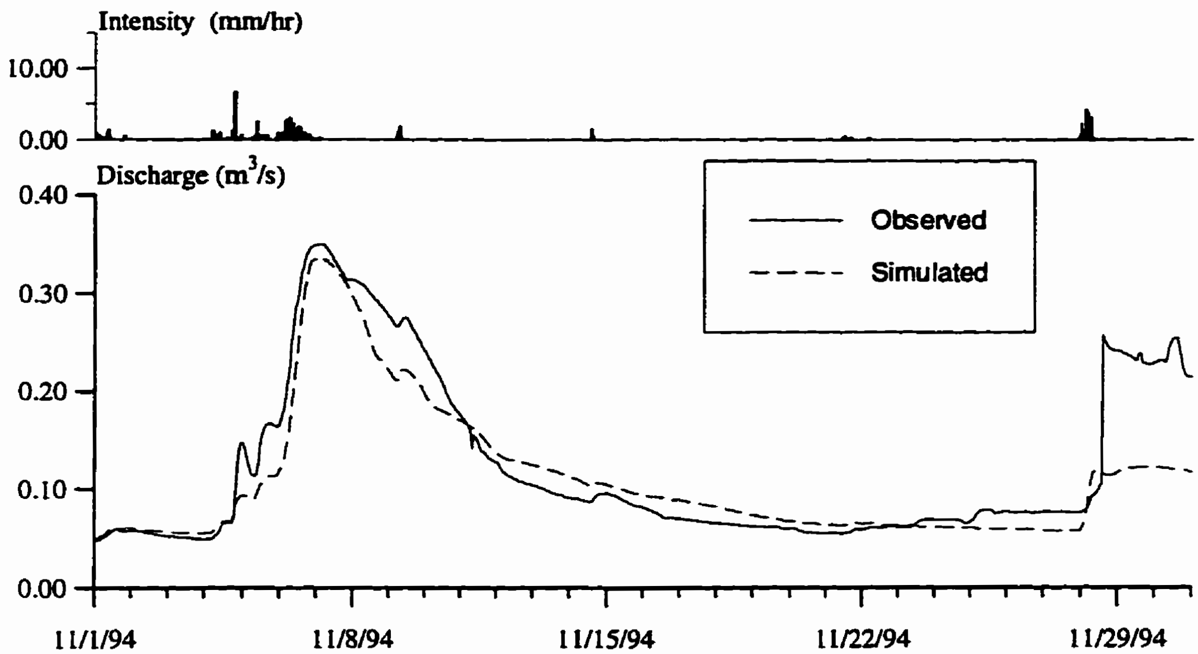


Figure D5 Simulated and observed rainfall-runoff response from headwater wetland (November, 1994)

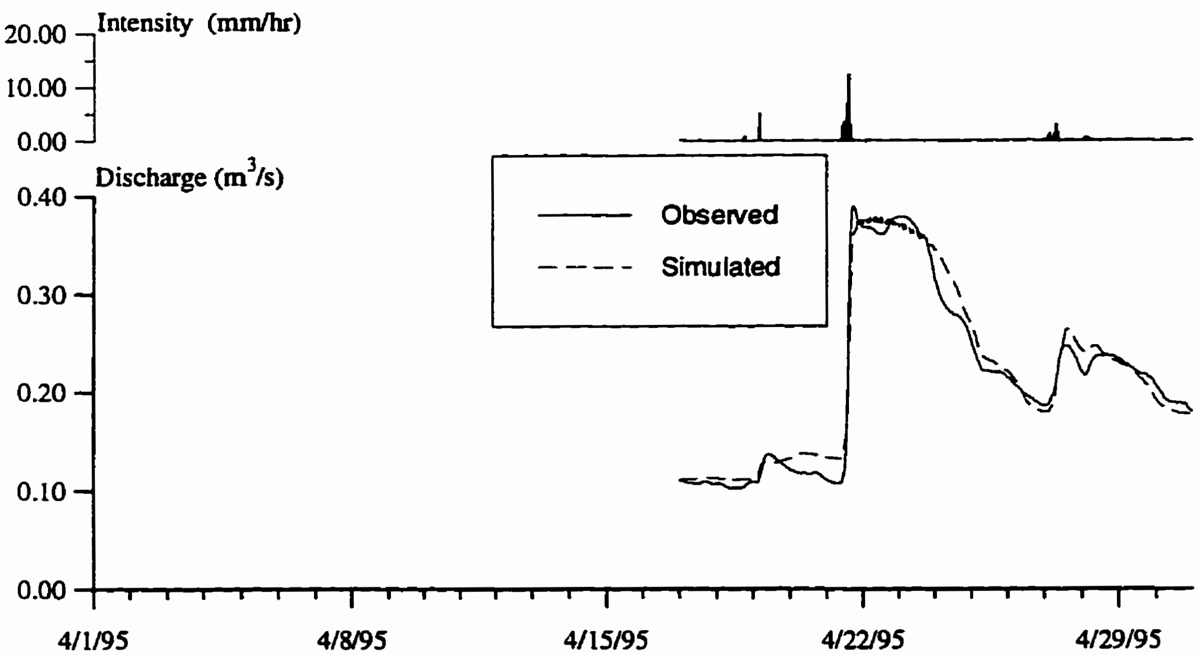


Figure D6 Simulated and observed rainfall-runoff response from headwater wetland (April, 1995)

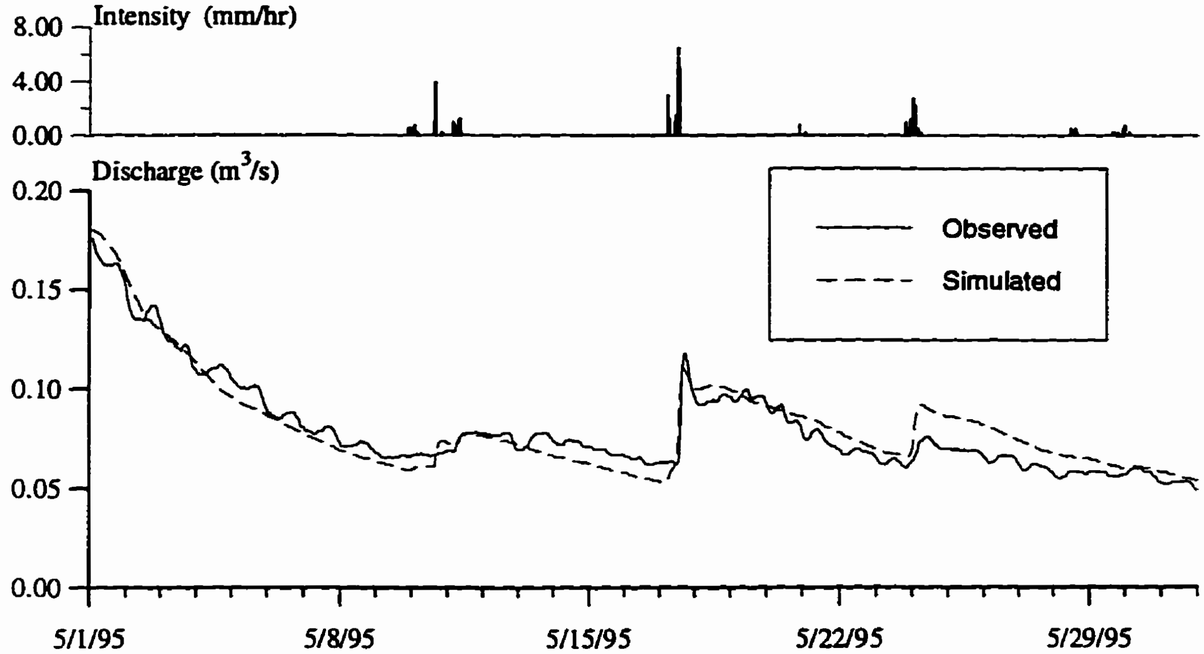


Figure D7 **Simulated and observed rainfall-runoff response from headwater wetland (May, 1995)**

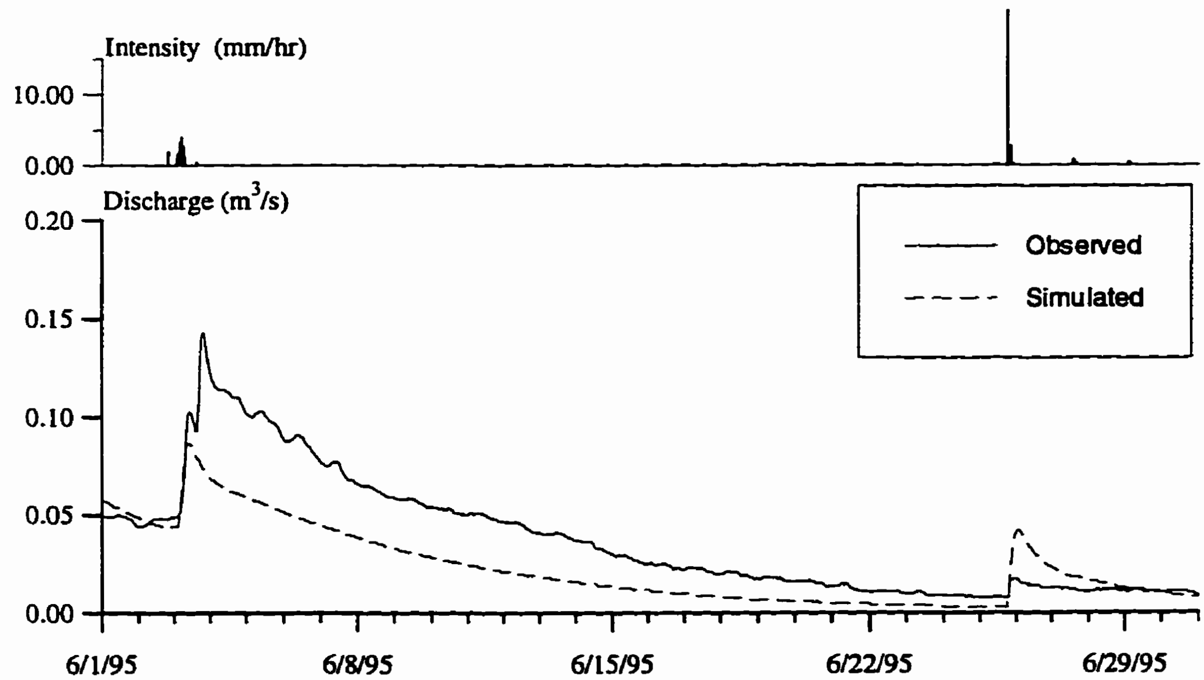


Figure D8 **Simulated and observed rainfall-runoff response from headwater wetland (June, 1995)**

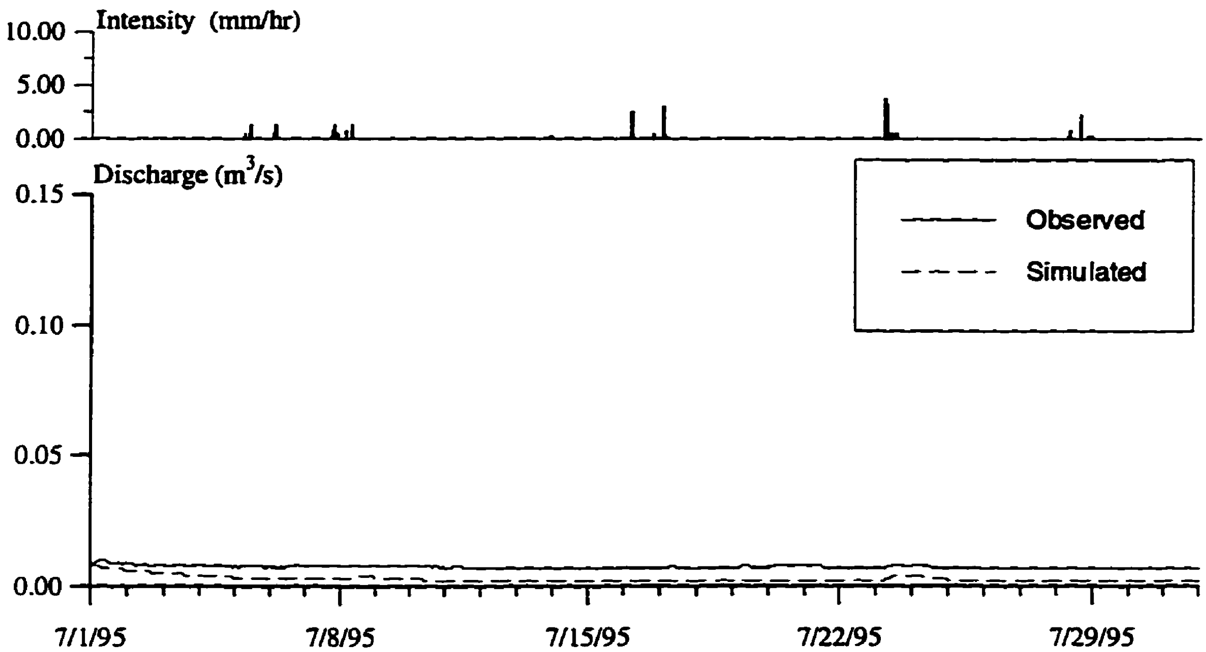


Figure D9 **Simulated and observed rainfall-runoff response from headwater wetland (July, 1995)**

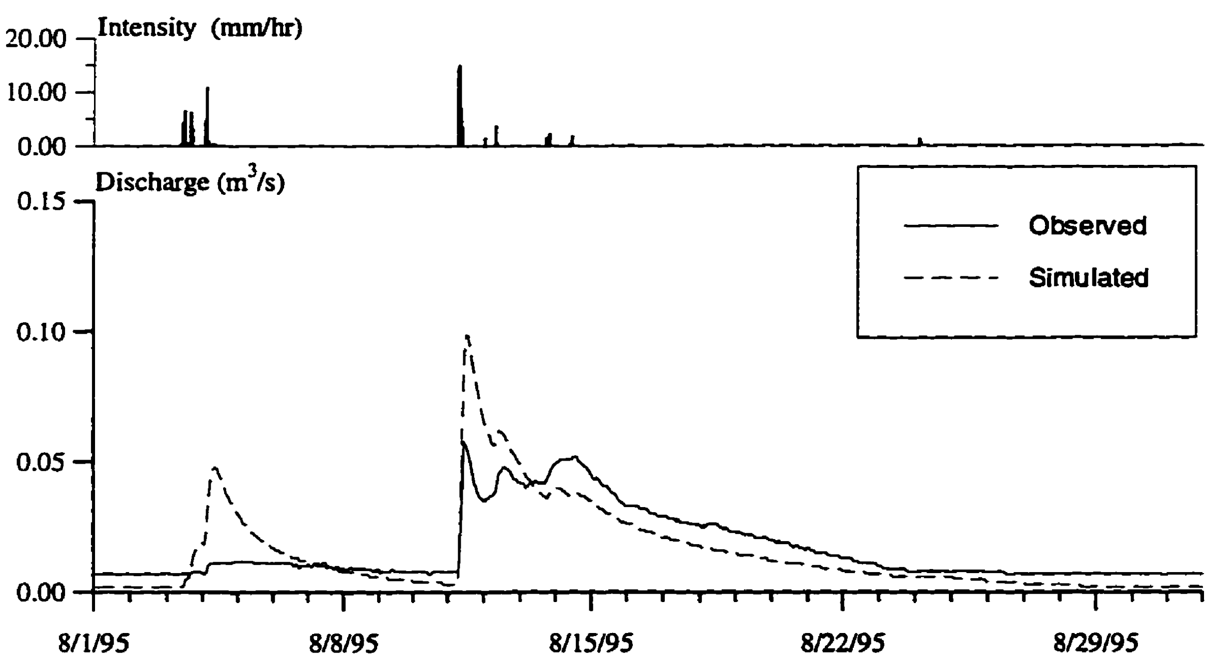


Figure D10 **Simulated and observed rainfall-runoff response from headwater wetland (August, 1995)**

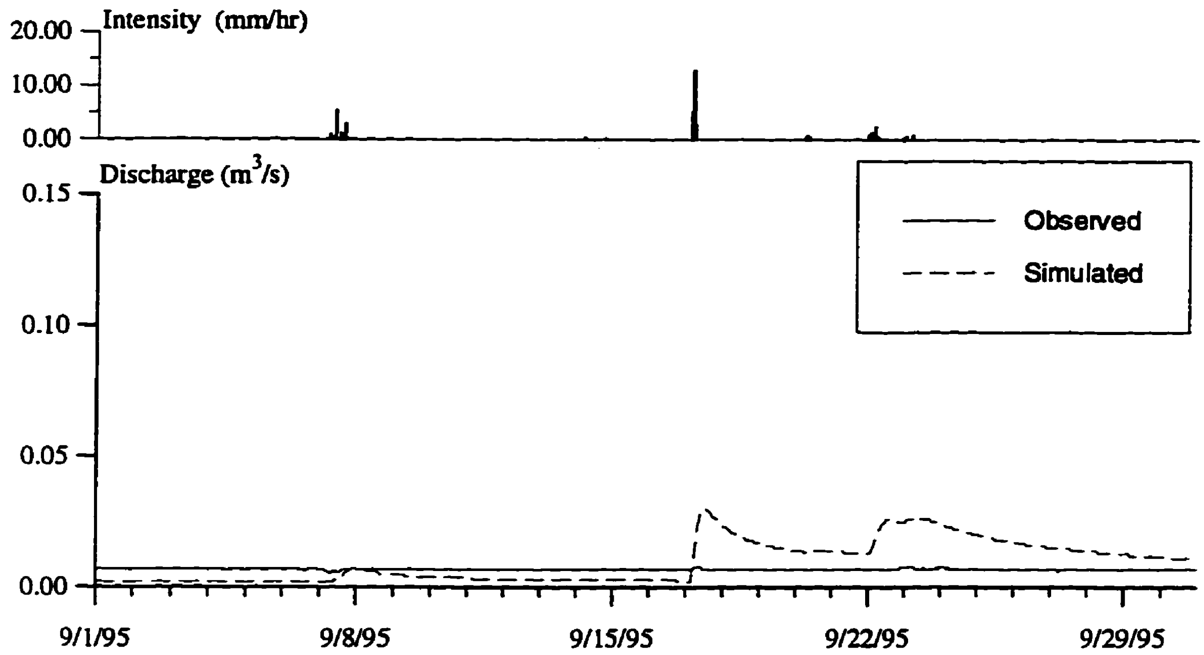


Figure D11 Simulated and observed rainfall-runoff response from headwater wetland (September, 1995)

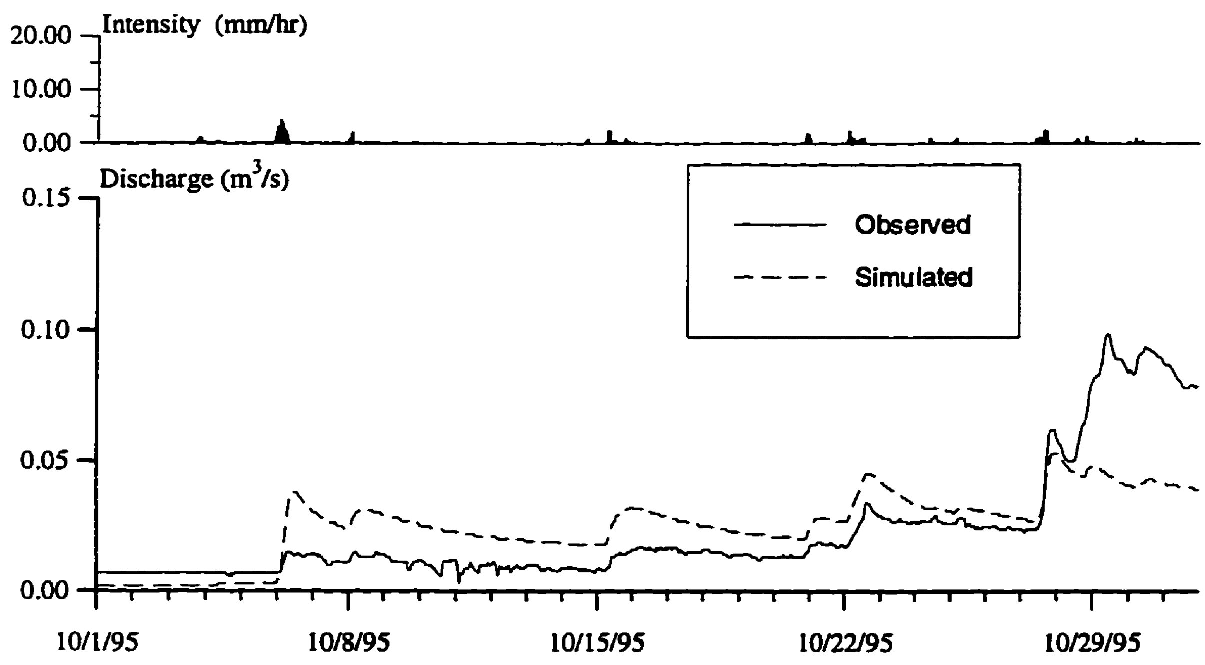


Figure D12 Simulated and observed rainfall-runoff response from headwater wetland (October, 1995)

APPENDIX E

Sensitivity Analysis of Wetland Model

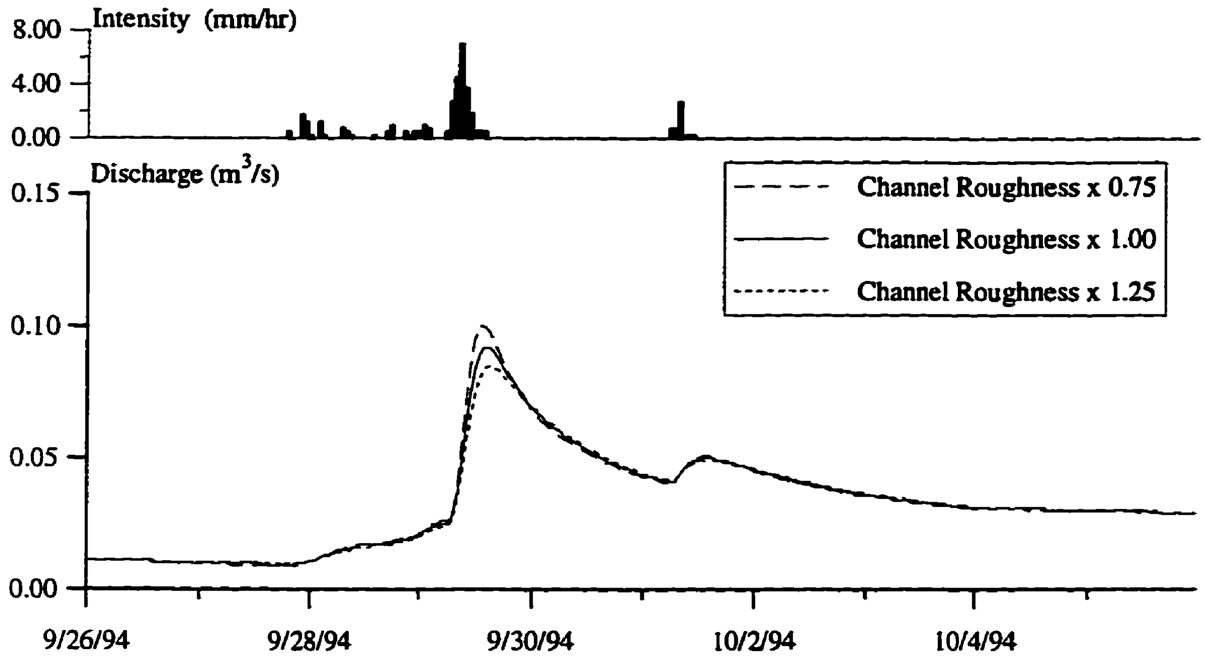


Figure E1(a) Sensitivity to channel roughness (Event 1)

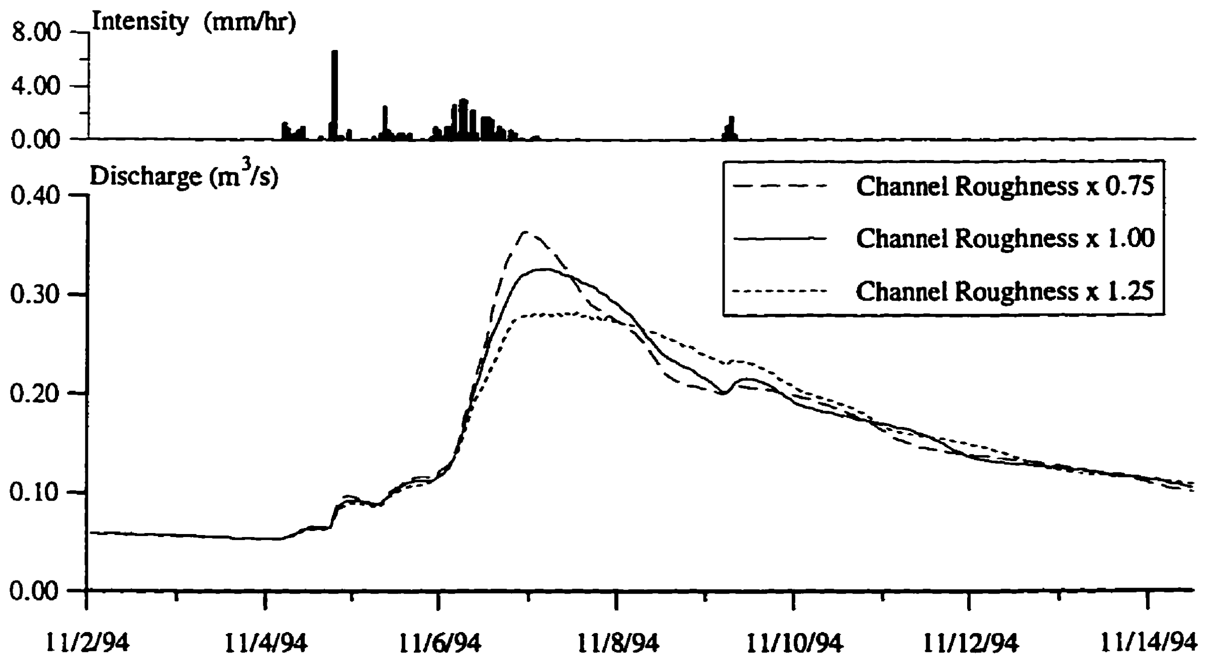


Figure E1(b) Sensitivity to channel roughness (Event 2)

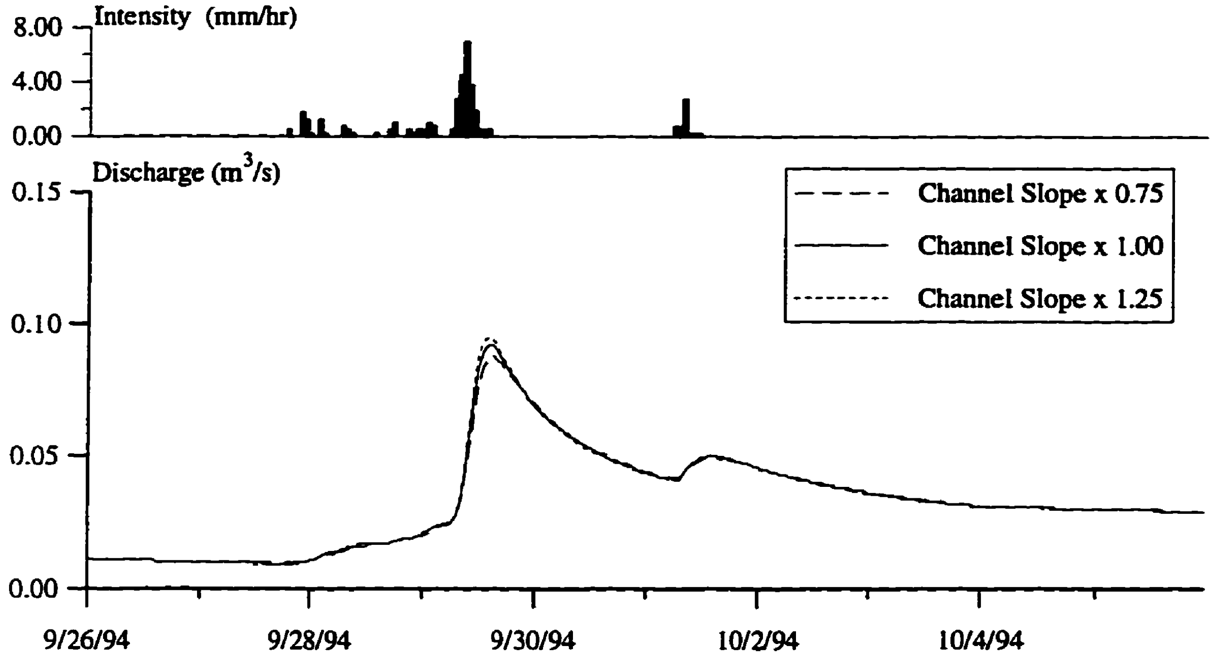


Figure E2(a) Sensitivity to channel slope (Event 1)

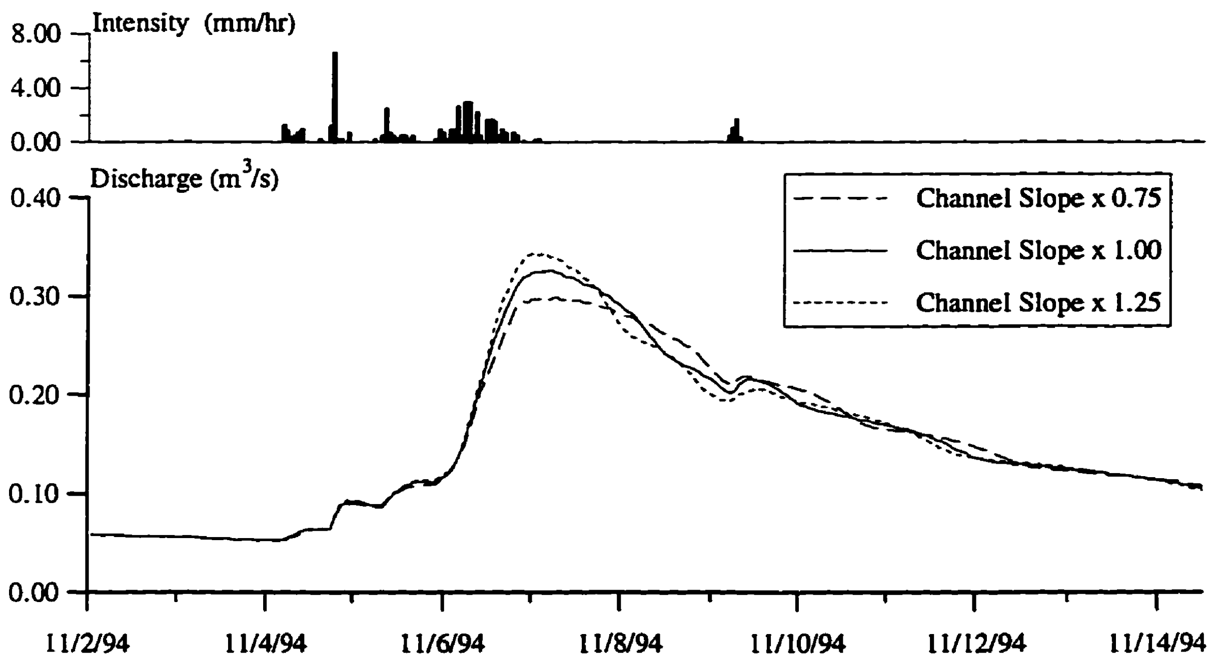


Figure E2(b) Sensitivity to channel slope (Event 2)

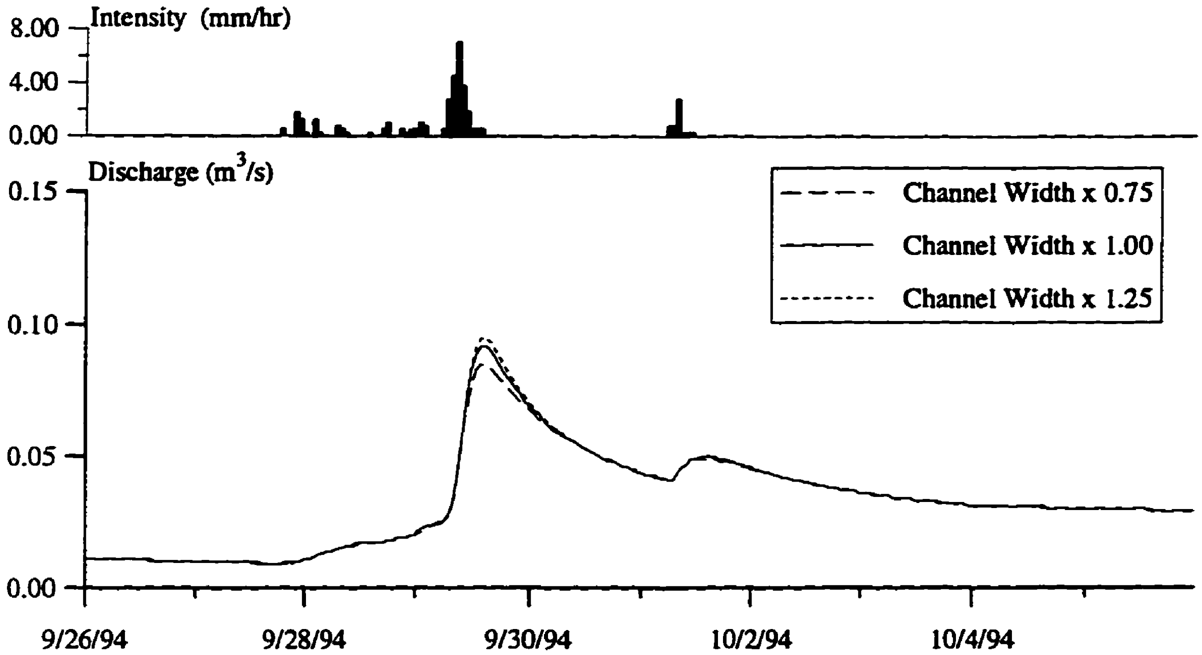


Figure E3(a) Sensitivity to channel width (Event 1)

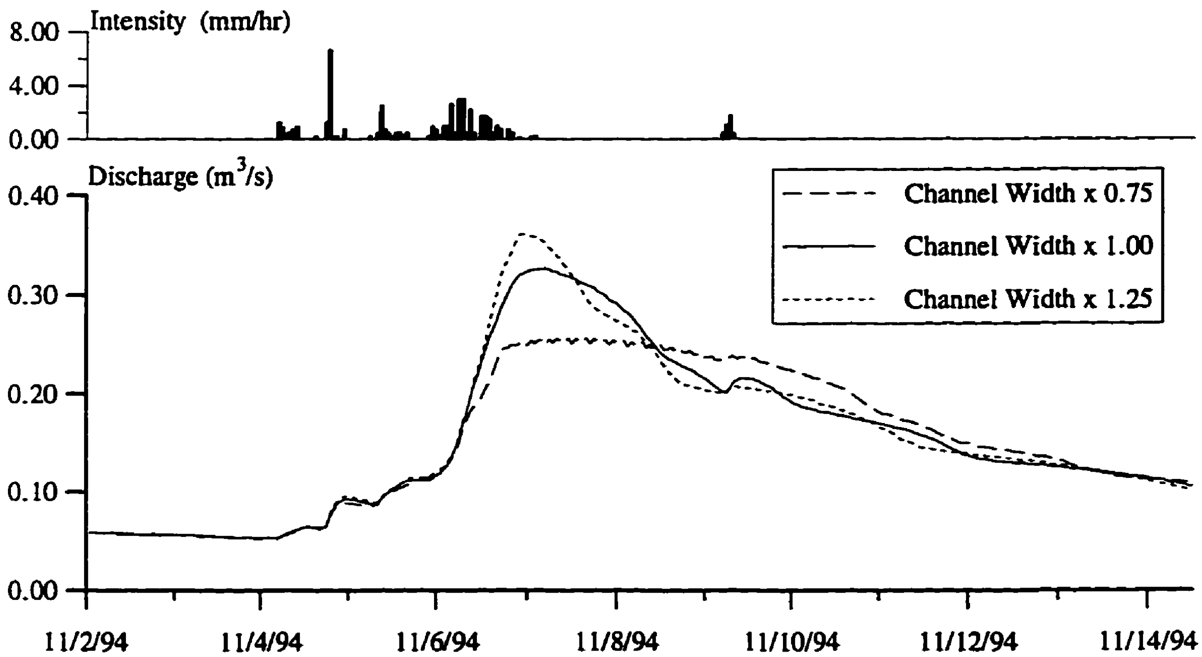


Figure E3(b) Sensitivity to channel width (Event 2)

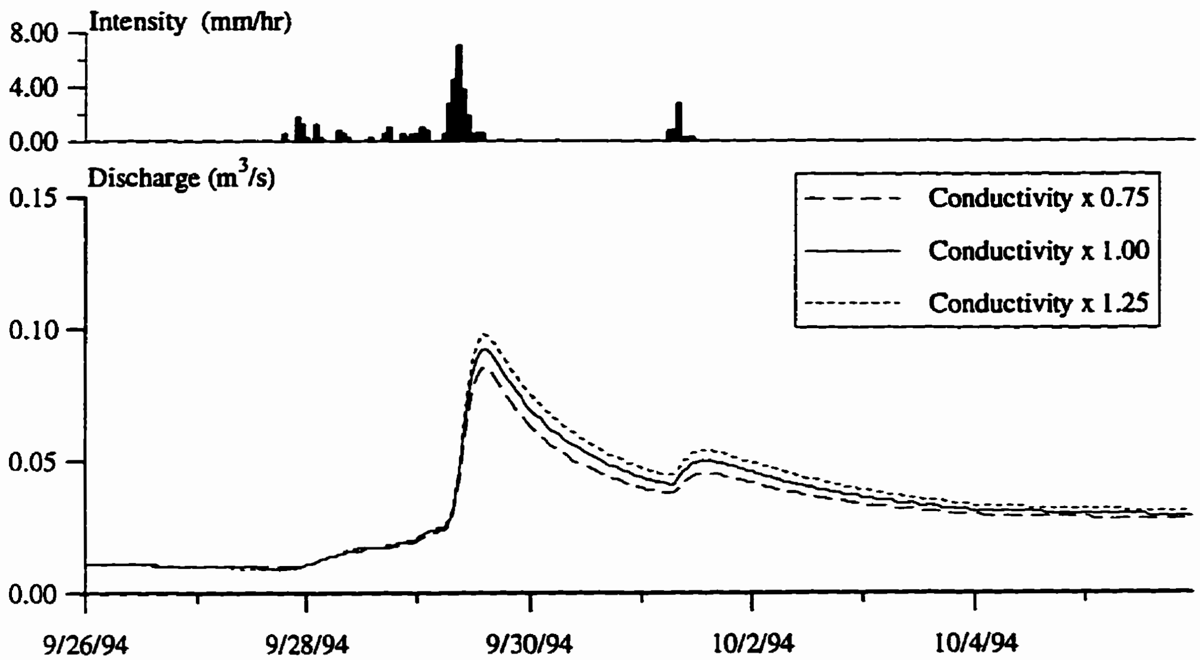


Figure E4(a) Sensitivity to organic layer conductivity (Event 1)

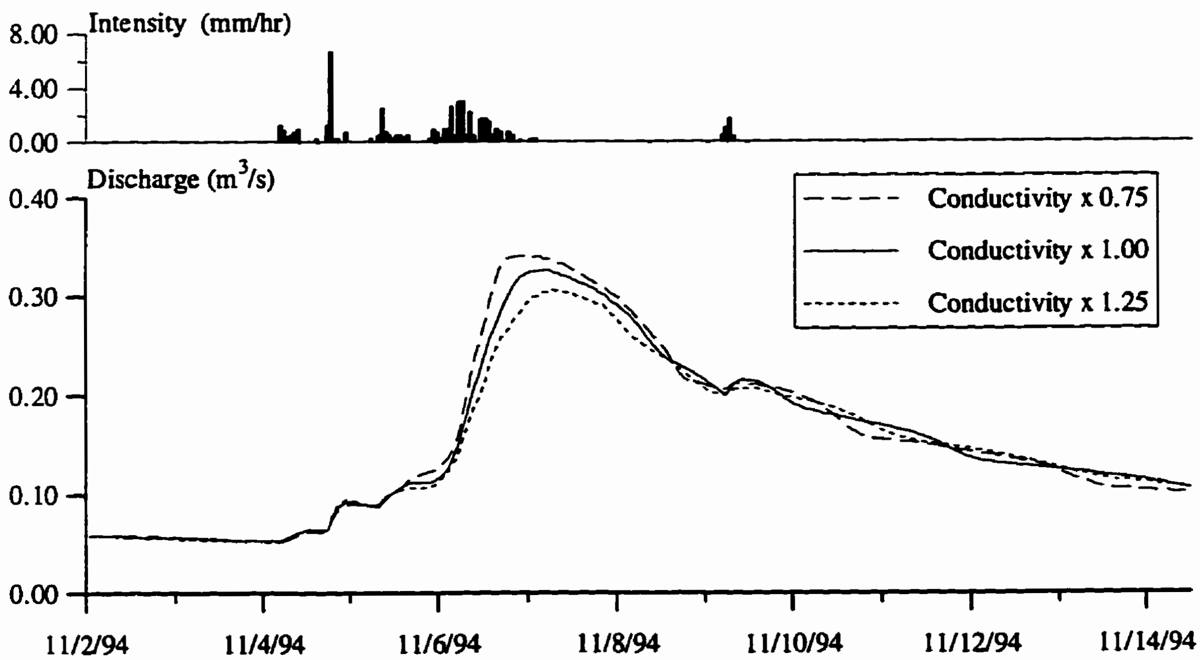


Figure E4(b) Sensitivity to organic layer conductivity (Event 2)

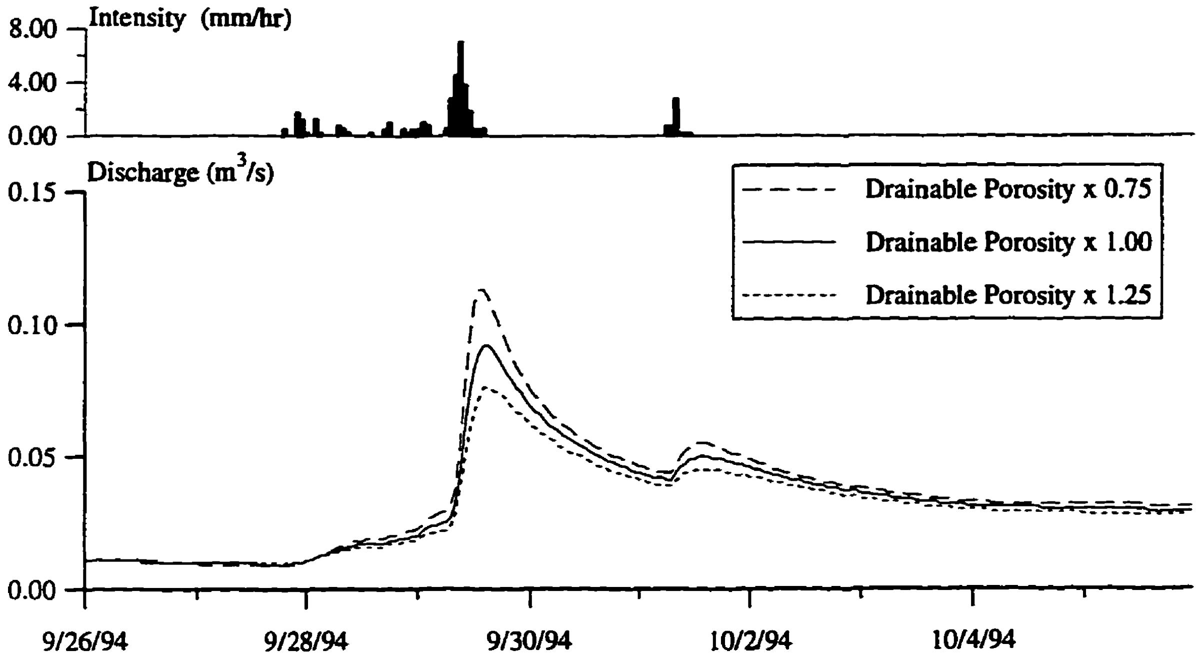


Figure E5(a) Sensitivity to organic layer drainable porosity (Event 1)

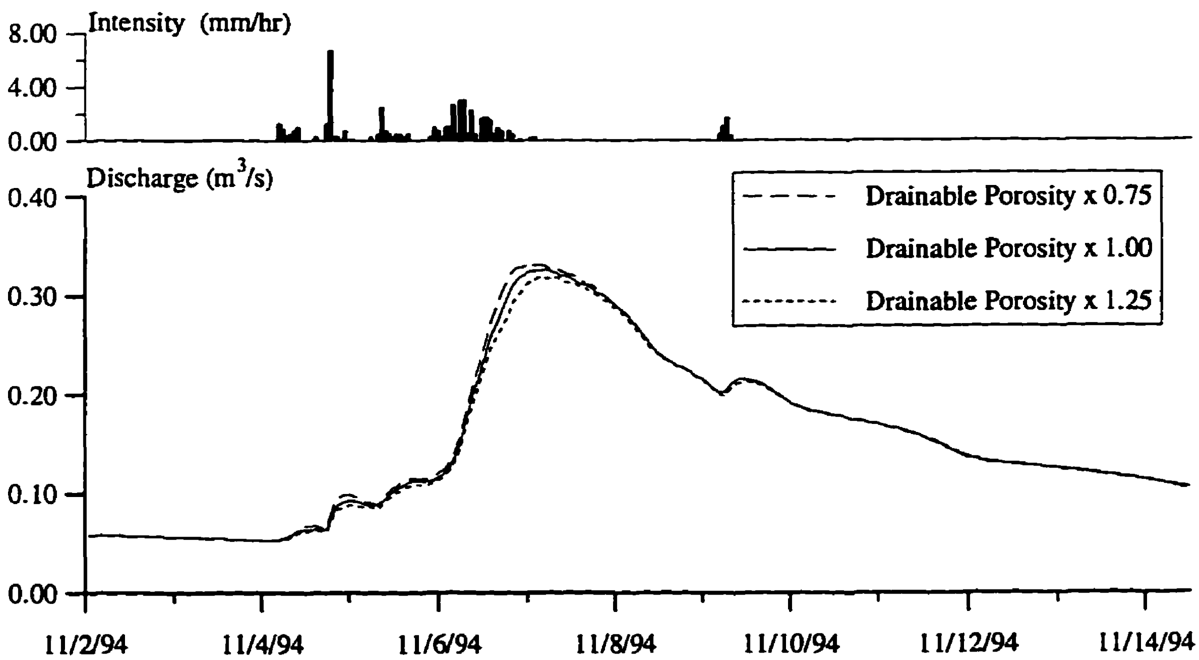


Figure E5(b) Sensitivity to organic layer drainable porosity (Event 2)

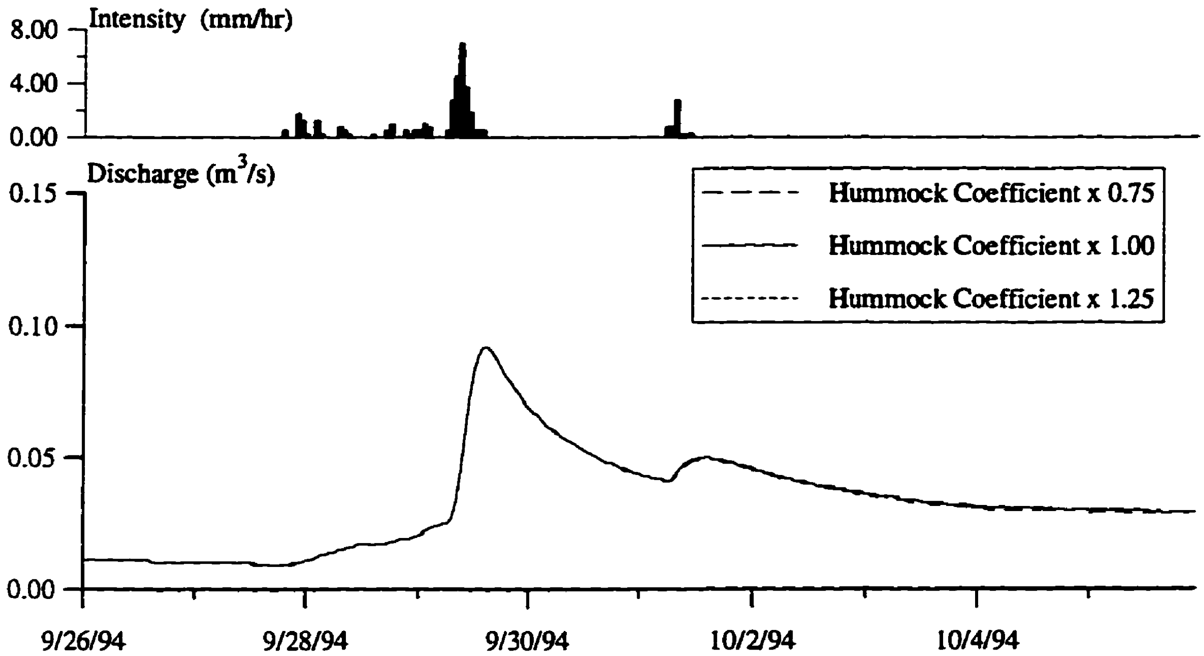


Figure E6(a) Sensitivity to hummock layer flow coefficient (Event 1)

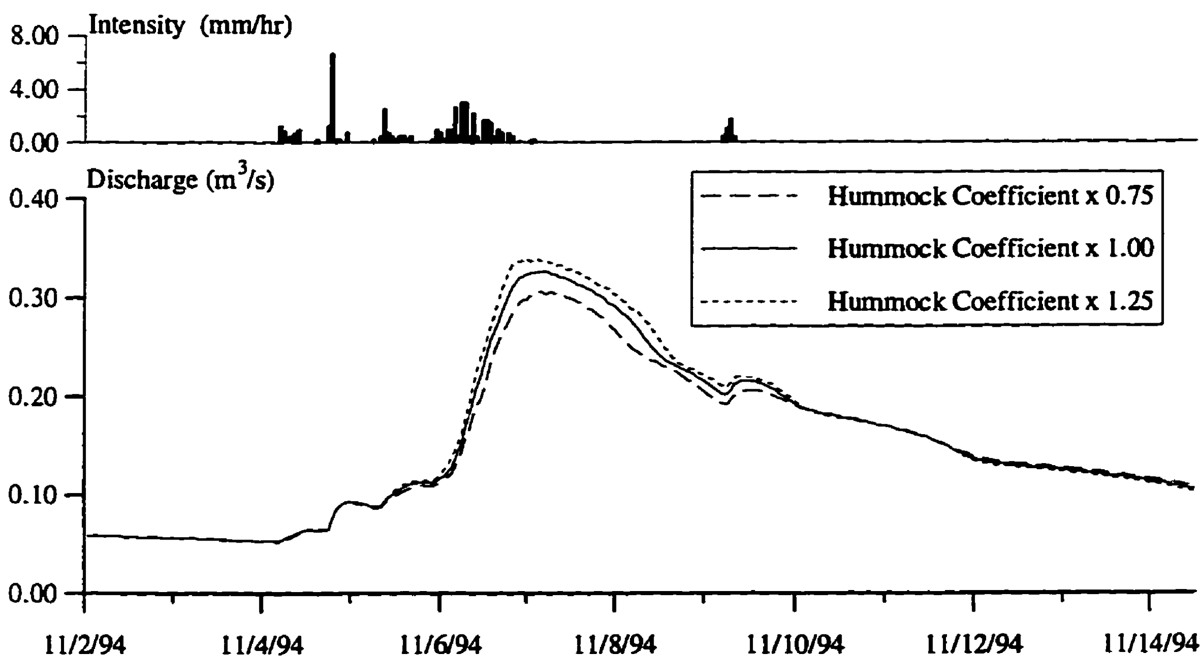


Figure E6(b) Sensitivity to hummock layer flow coefficient(Event 2)

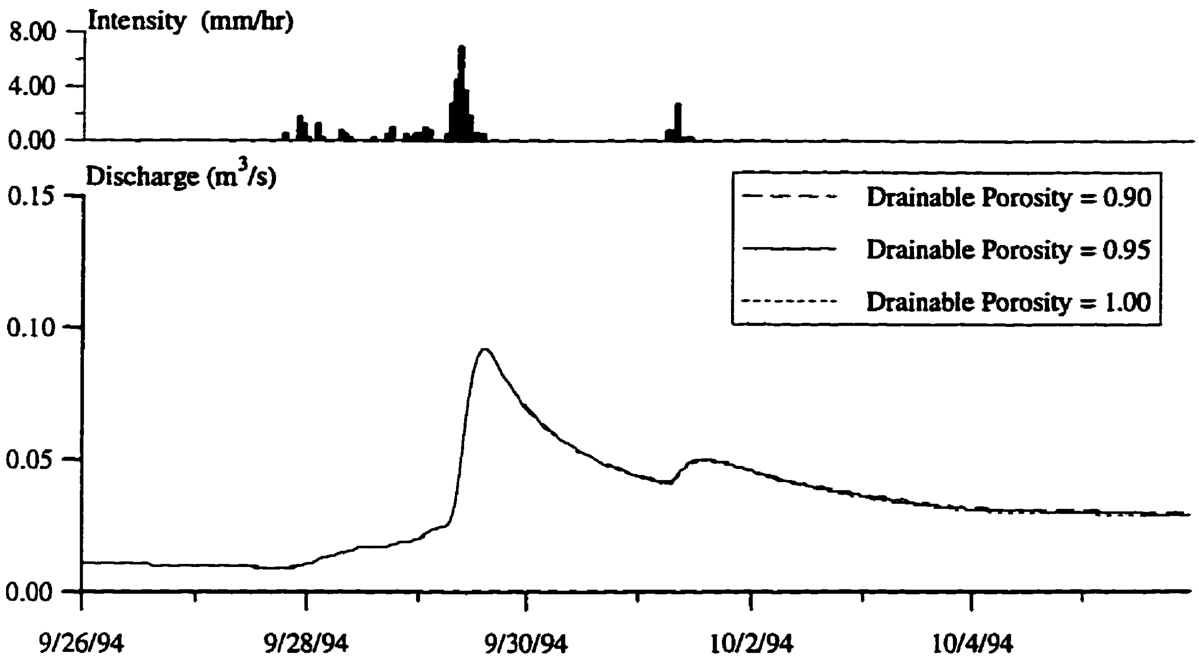


Figure E7(a) Sensitivity to hummock layer drainable porosity (Event 1)

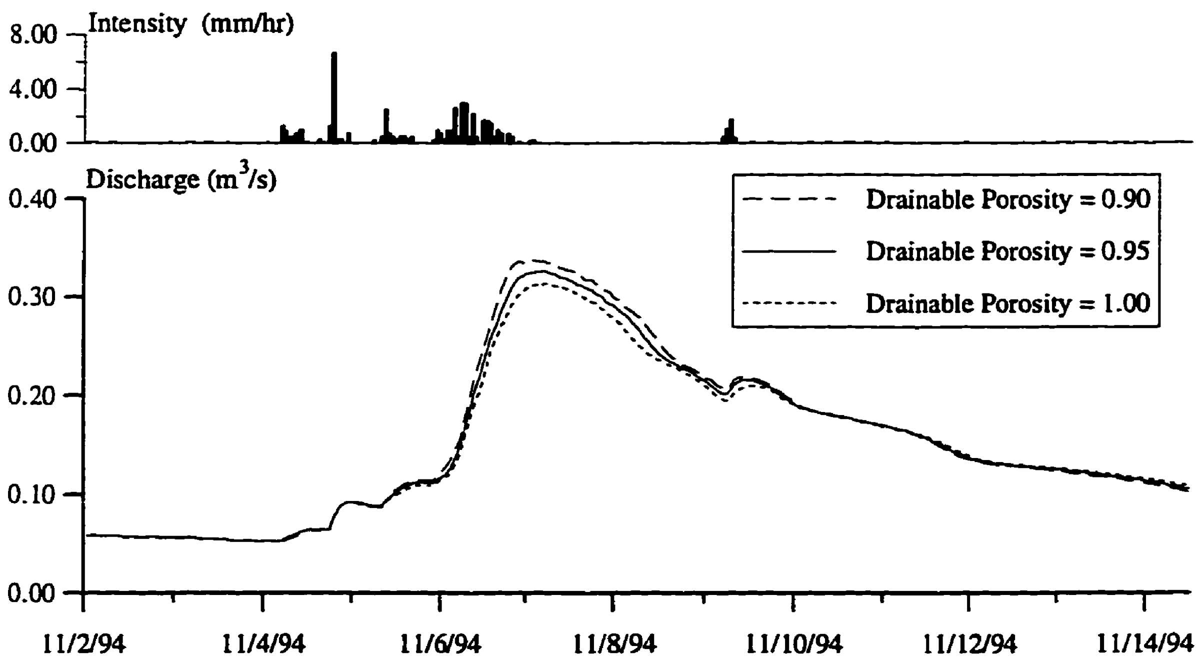


Figure E7(b) Sensitivity to hummock layer drainable porosity (Event 2)

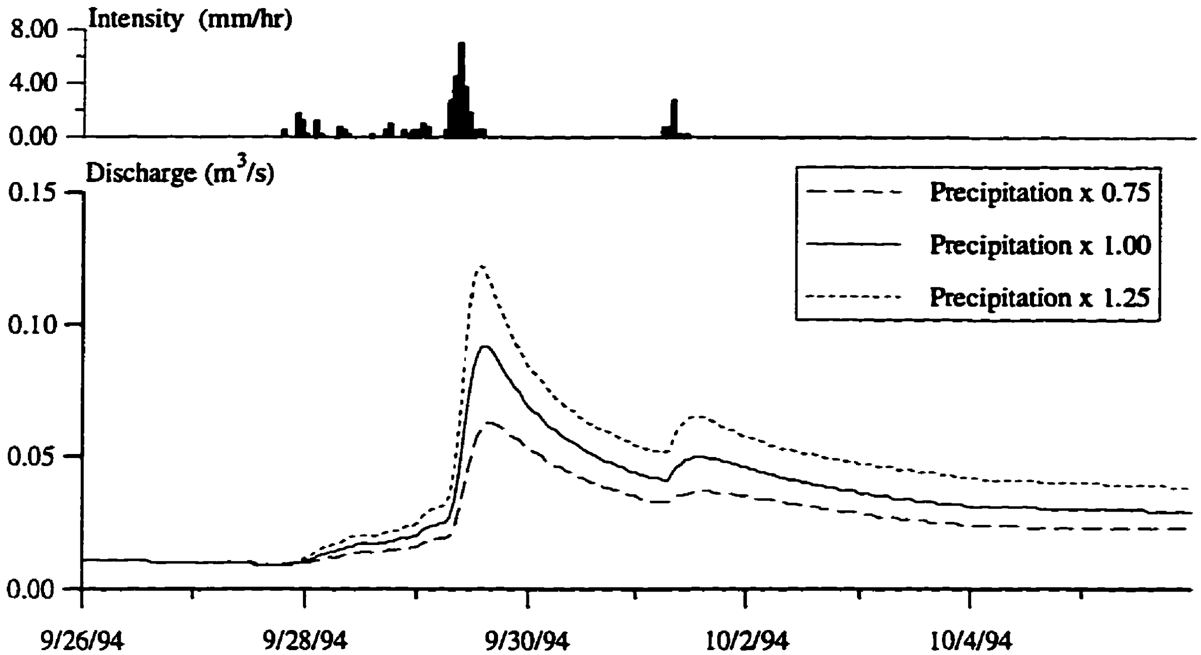


Figure E8(a) Sensitivity to precipitation input (Event 1)

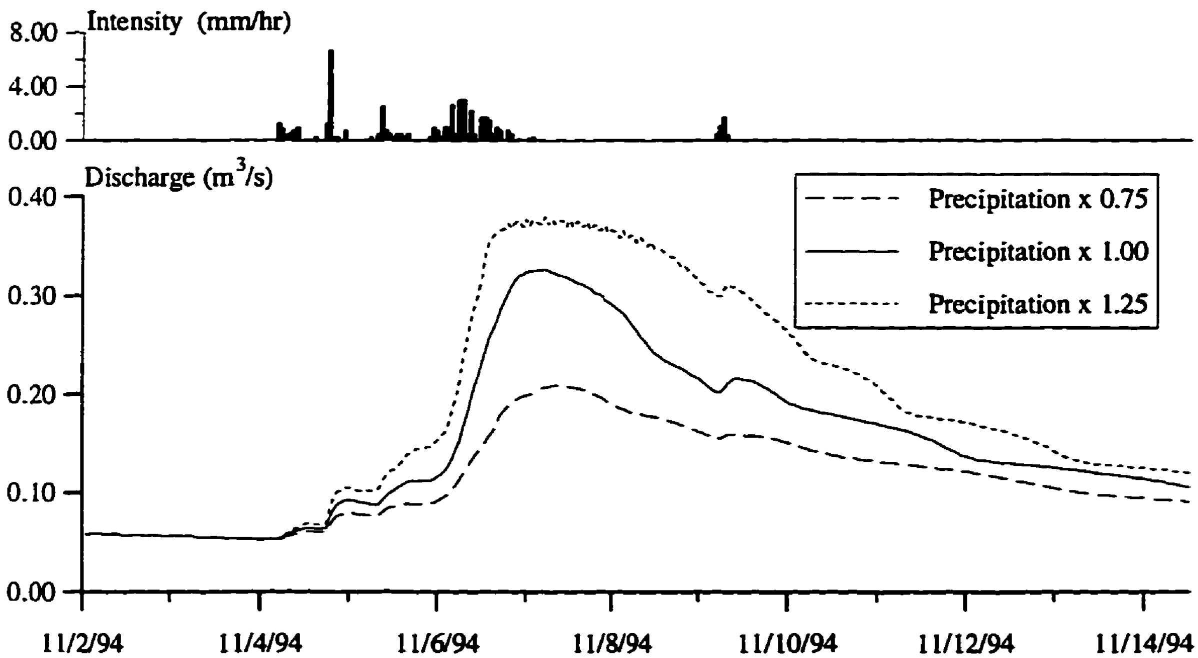


Figure E8(b) Sensitivity to precipitation input (Event 2)

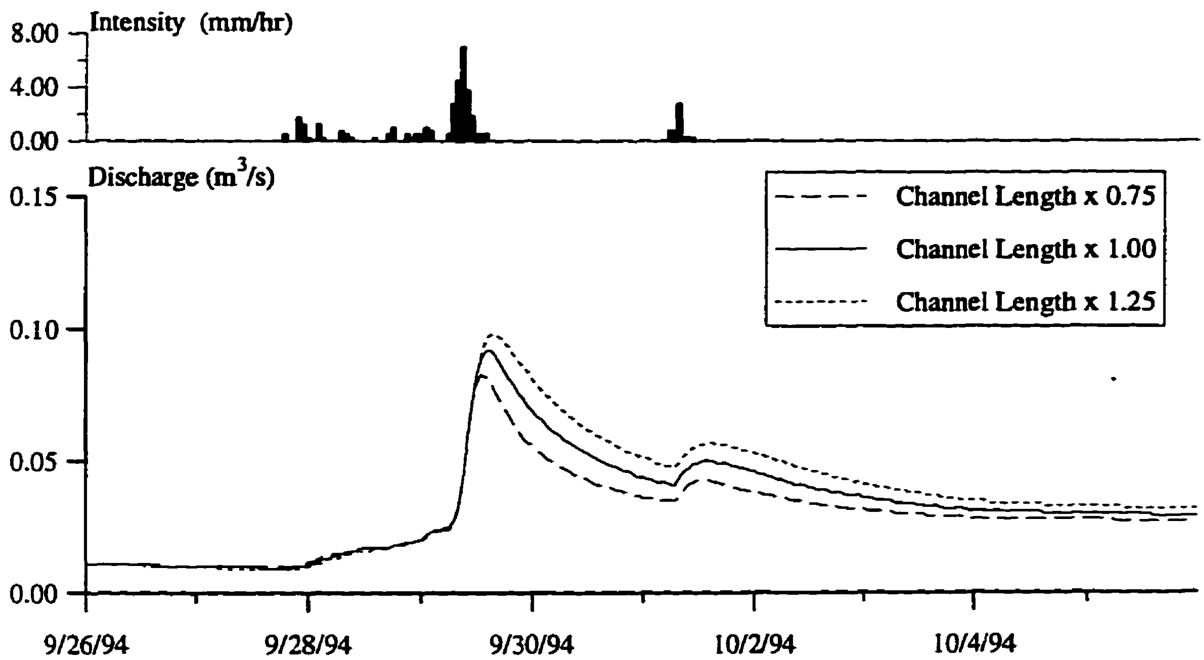


Figure E9(a) Sensitivity to length of wetland channel (Event 1)

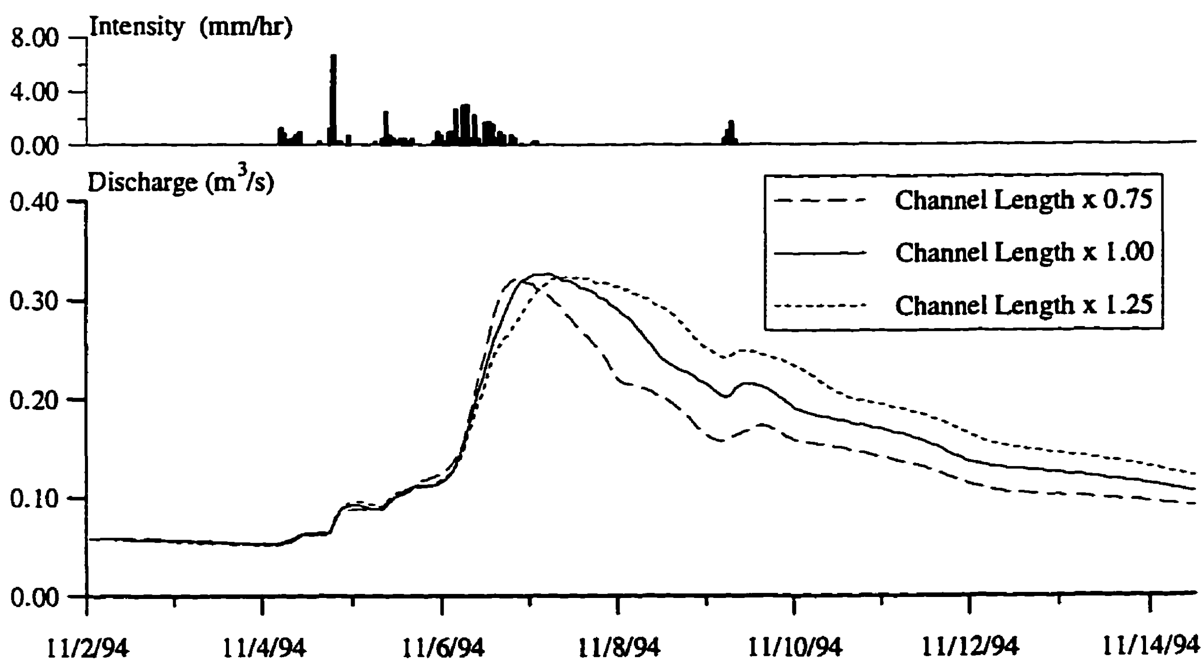


Figure E9(b) Sensitivity to length of wetland channel (Event 2)

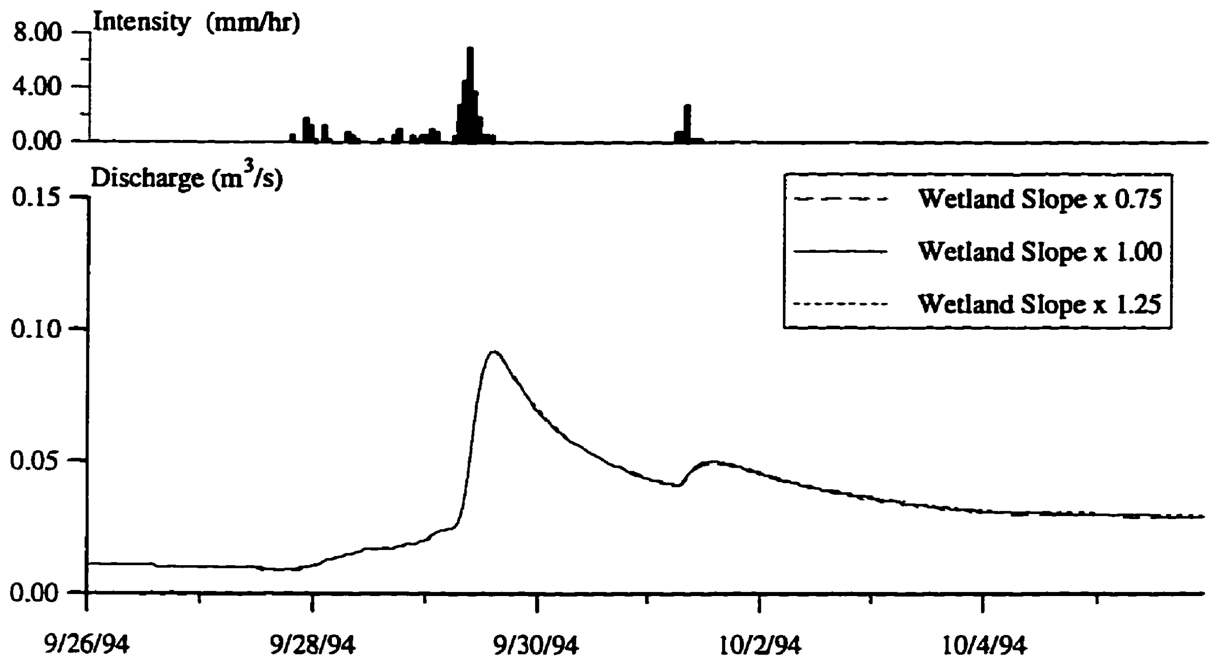


Figure E10(a) Sensitivity to slope of wetland (Event 1)

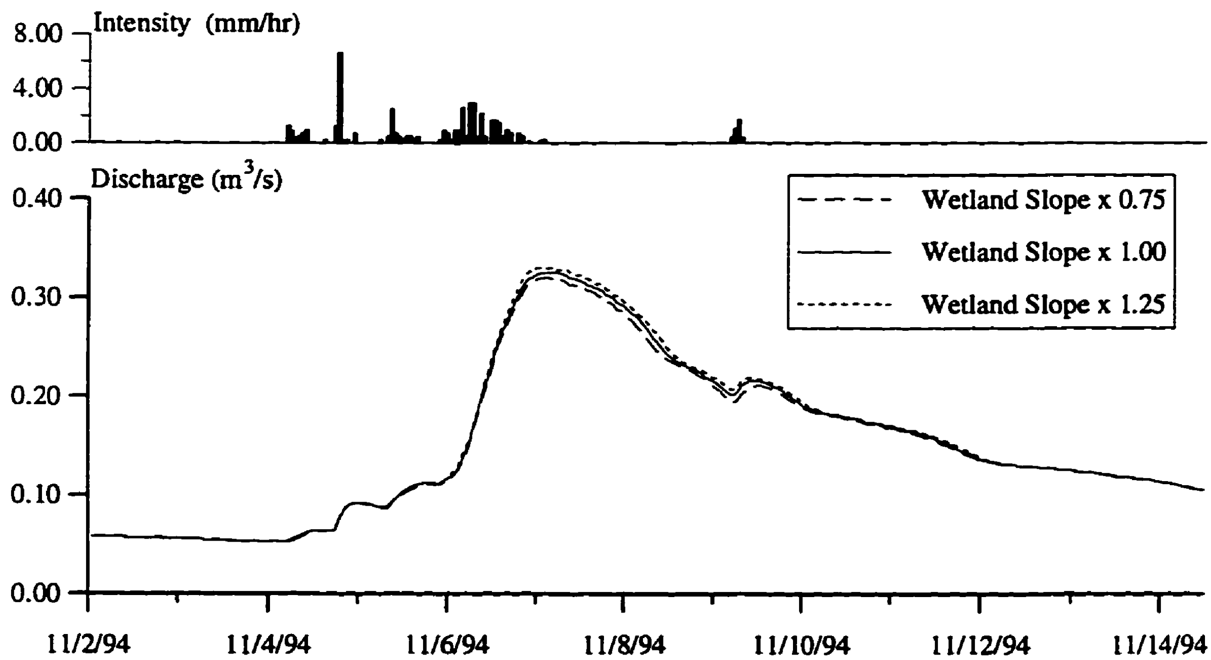


Figure E10(b) Sensitivity to slope of wetland (Event 2)

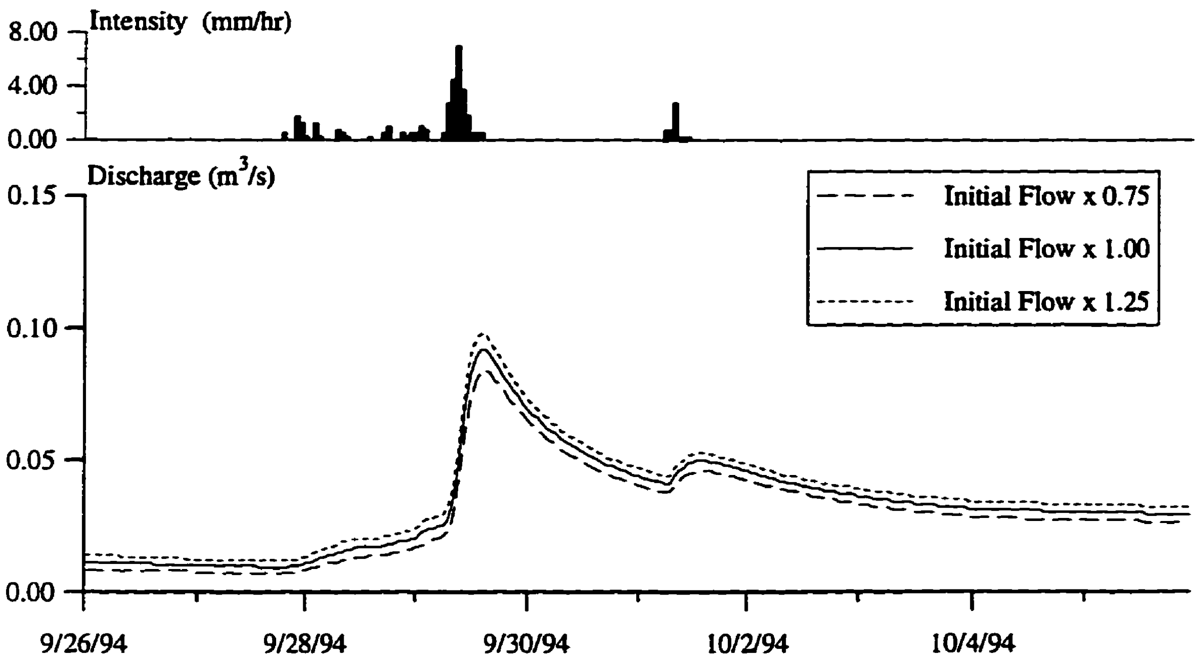


Figure E11(a) Sensitivity to initial streamflow (Event 1)

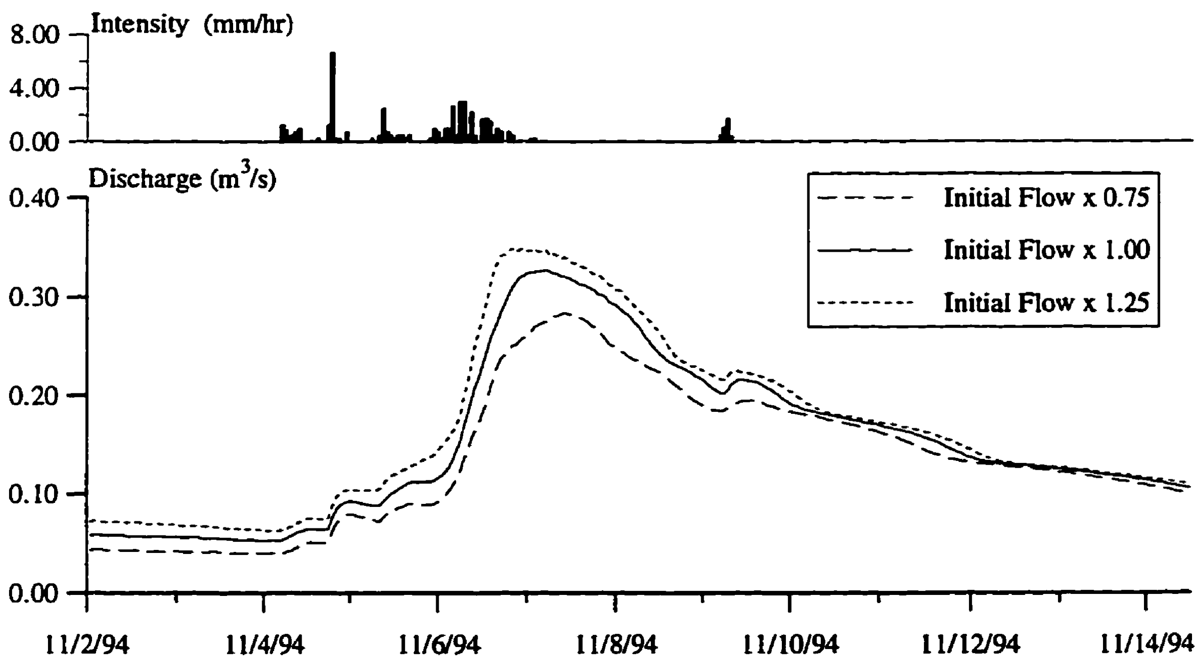


Figure E11(b) Sensitivity to initial streamflow (Event 2)

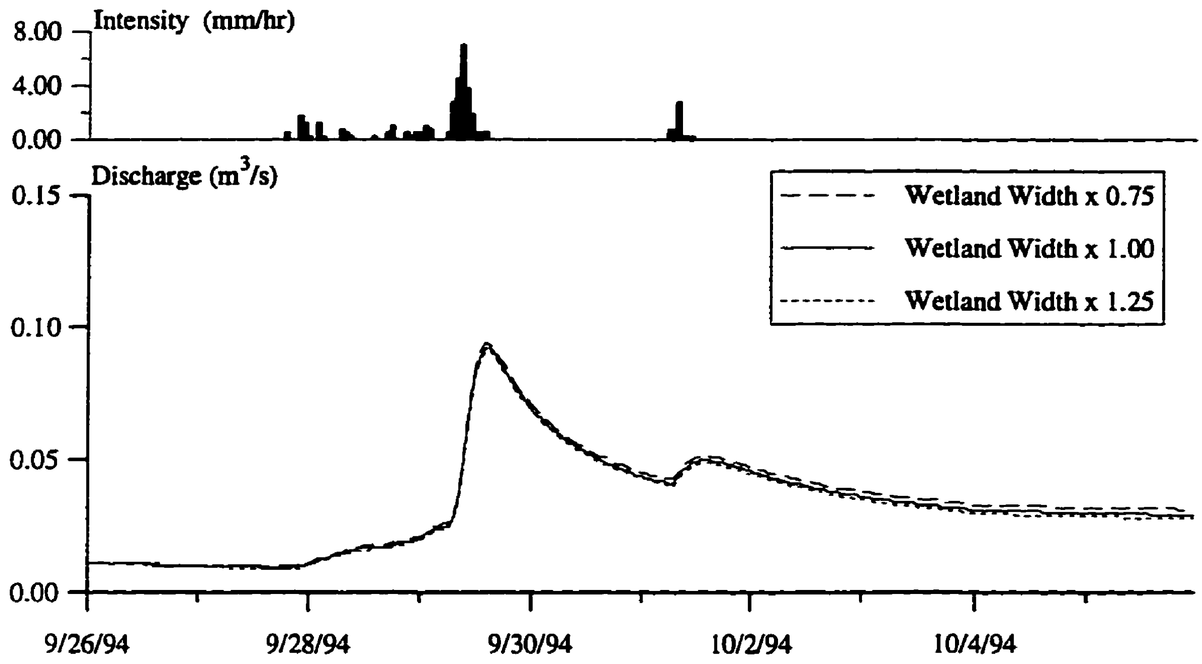


Figure E12(a) Sensitivity to width of wetland (Event 1)

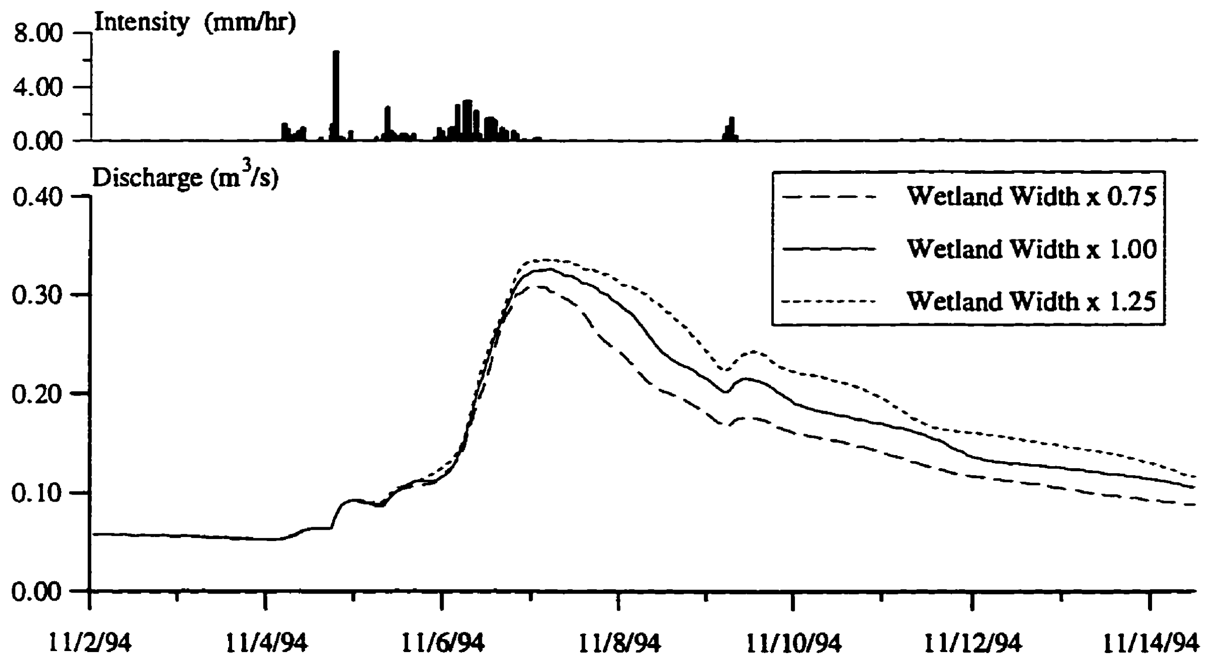


Figure E12(b) Sensitivity to width of wetland (Event 2)

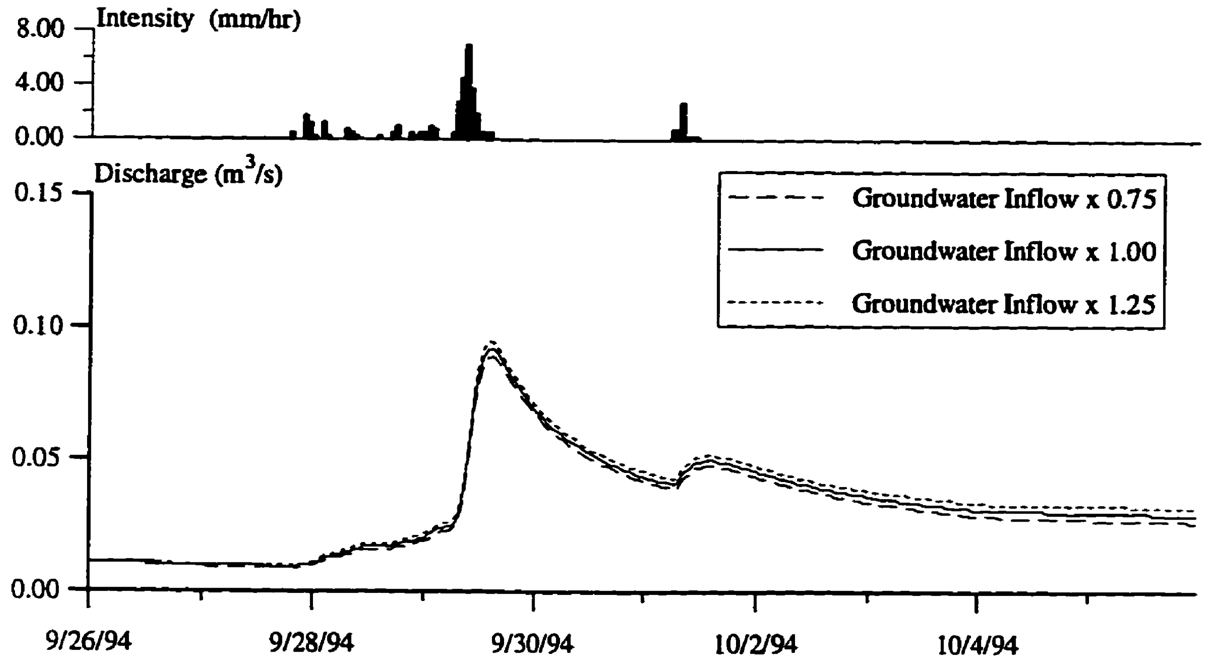


Figure E13(a) Sensitivity to groundwater inflow (Event 1)

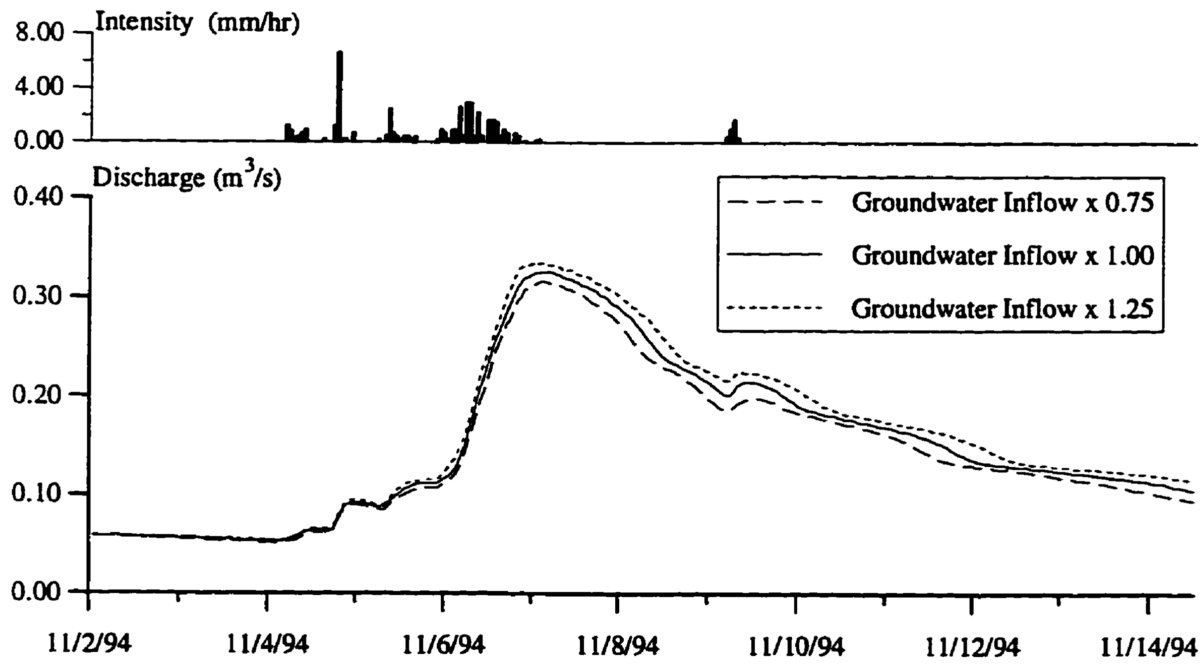


Figure E13(b) Sensitivity to groundwater inflow (Event 2)

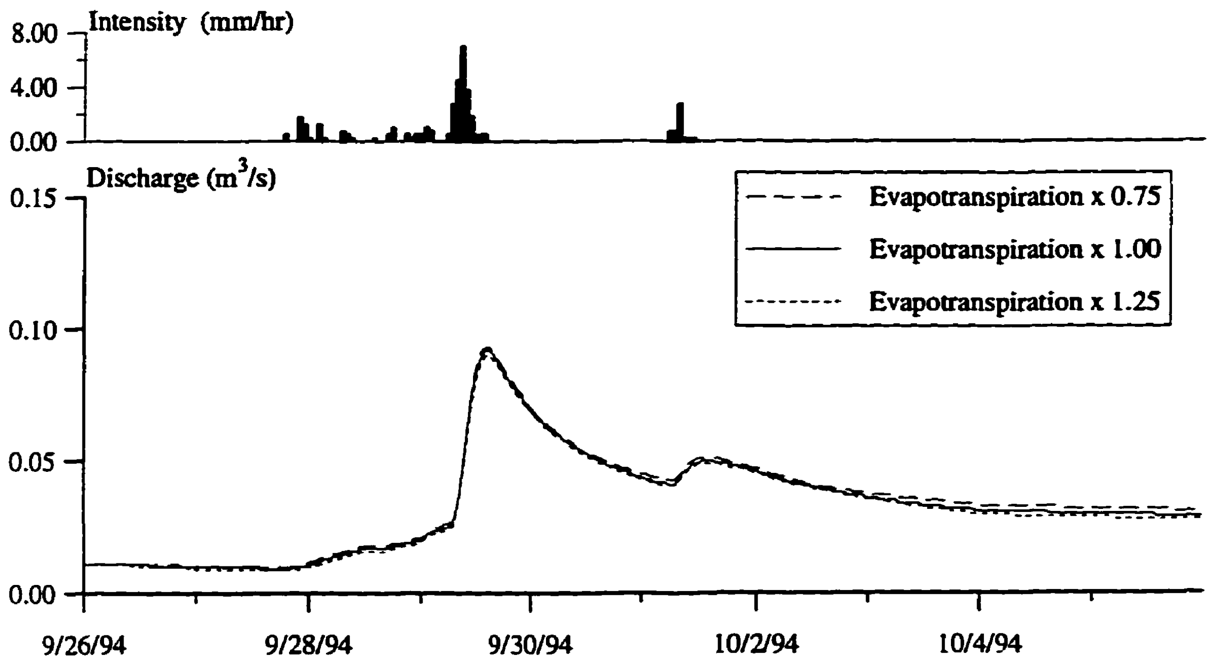


Figure E14(a) Sensitivity to evapotranspiration demand (Event 1)

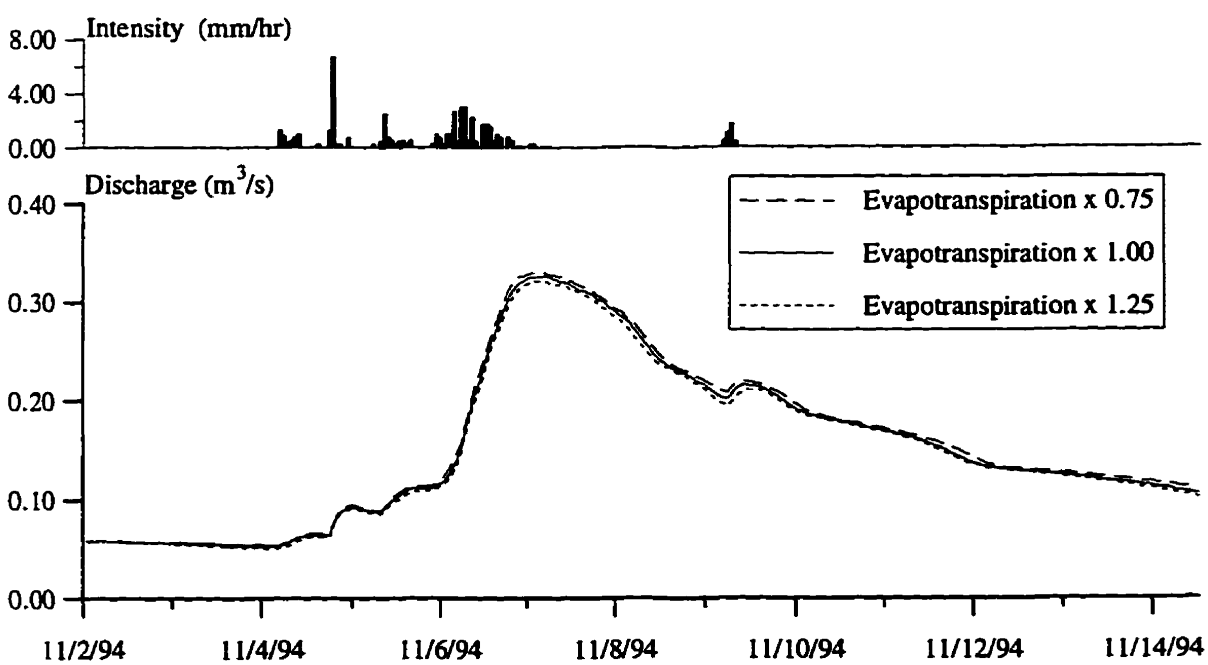


Figure E14(b) Sensitivity to evapotranspiration demand (Event 2)

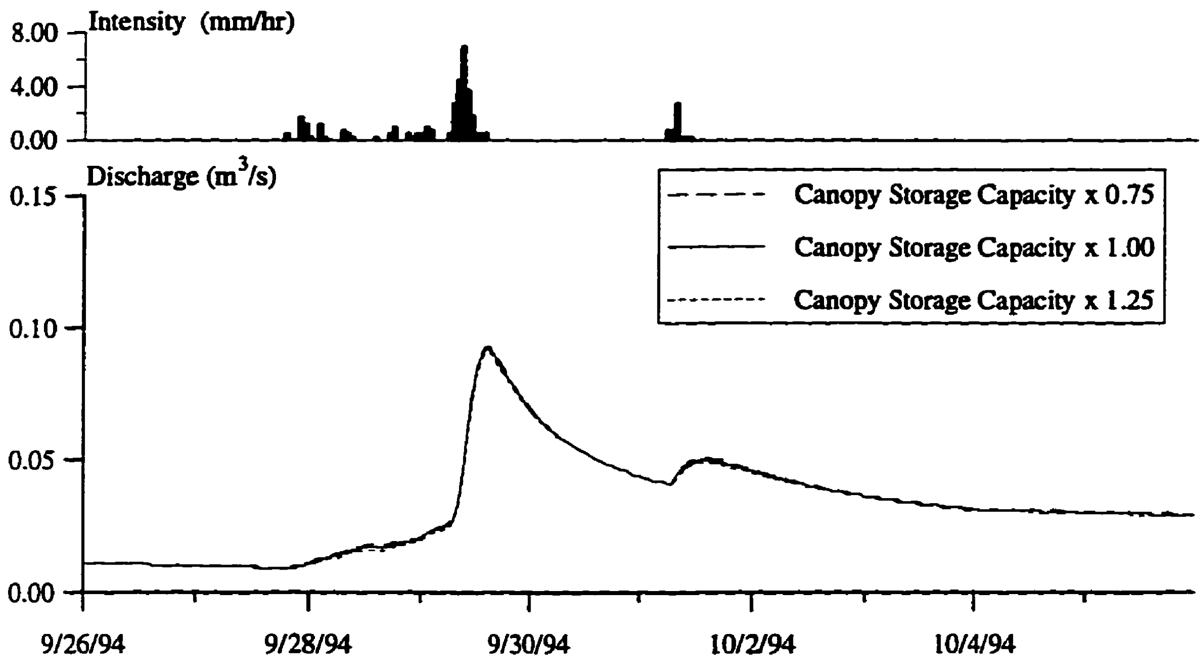


Figure E15(a) Sensitivity to canopy storage capacity (Event 1)

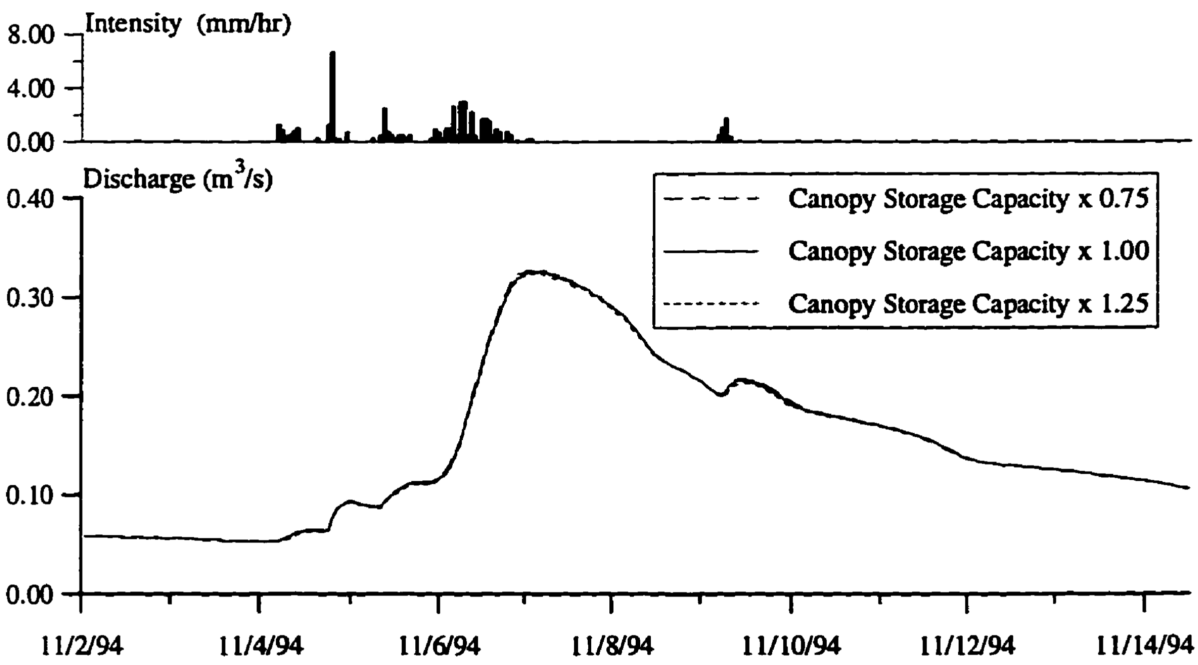


Figure E15(b) Sensitivity to canopy storage capacity (Event 2)

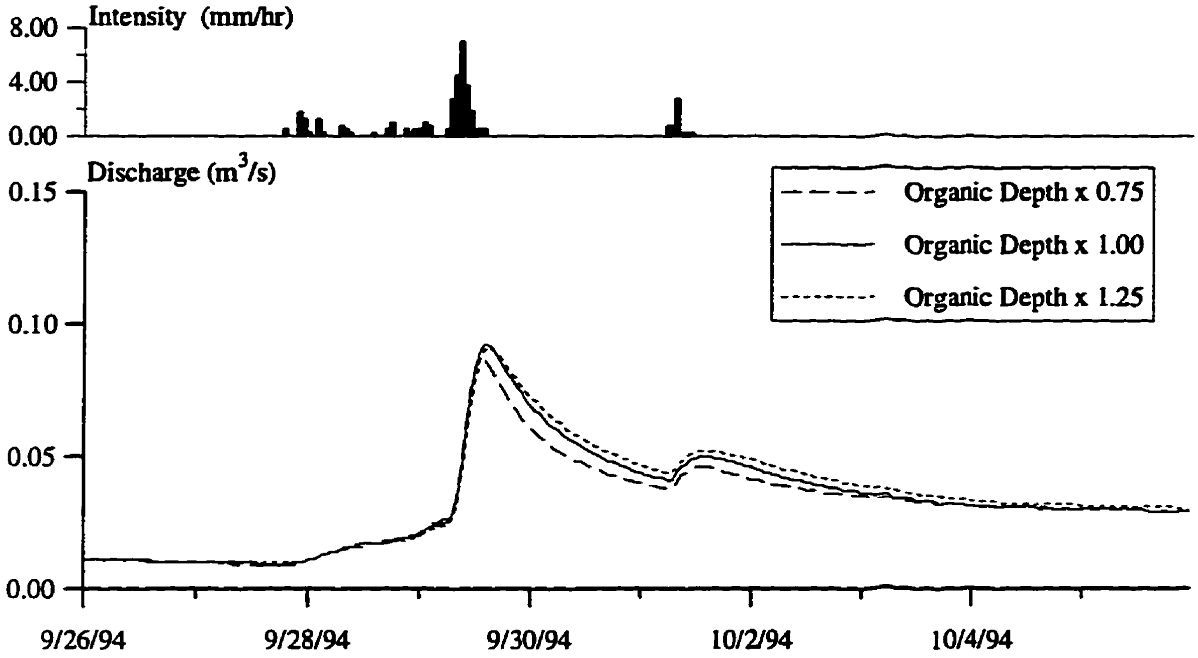


Figure E16(a) Sensitivity to depth of organic layer (Event 1)

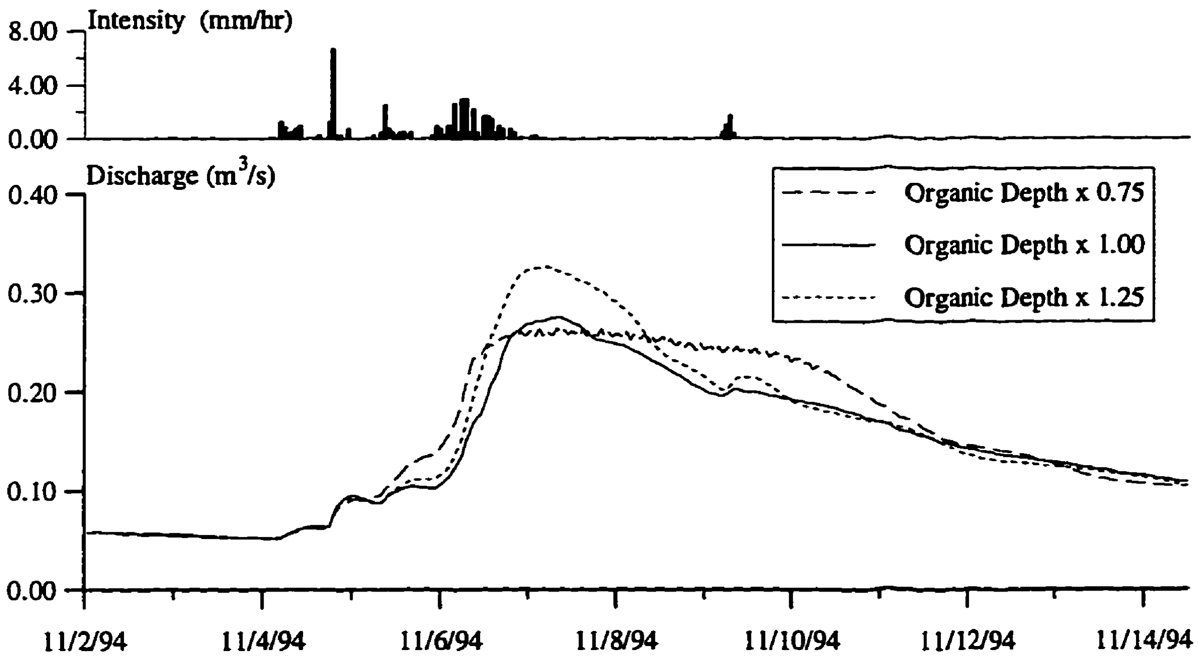


Figure E16(b) Sensitivity to depth of organic layer (Event 2)

APPENDIX F

Visual Basic Source Code

```
' ---------------------------------------------------------------------------
'   Program Name:    MULTI.BAS
'
'   Purpose:         To simulate the rainfall-runoff response from
'                    swamp environments.
'
'   Programmer:      Robert McKillop
'                    University of Waterloo
'
'   First Revision: June 23, 1994
'   Final Version:  January 19, 1997
' ---------------------------------------------------------------------------
'   Variable Documentation
' ---------------------------------------------------------------------------
'   nx               number of grid blocks defining finite-difference mesh
'   nxm1             number of grid blocks minus one
'   nxm2             number of grid blocks minus two
'   nxm3             number of grid blocks minus three
'   nsteps           number of modelling increments per hour
'   rn               number of routing reaches
'   nend             number of hours in modelling simulation
'   n                hourly counter
'   dt               modelling time increment
'   ob               overbank identifier
'   yhour(2000)      hourly simulation counter
'   zhour(2000)      hourly GMT counter
'   initstor         utilized storage volume within wetland at start of
'                    modelling simulation
'   finalstor        utilized storage volume within wetland at end of
'                    modelling simulation
'   begstor          utilized storage volume at start of time step
'   endstor          utilized storage volume at end of time step
'   fluxtotal        net inflow volume to wetland over the time step
'   tstarthours      starting hour of simulation
'   tstophours       terminating hour of simulation
'   numrain          number of hours in precipitation data
'   numhoursmonth    number of hours in month
' ---------------------------------------------------------------------------
'   wetland field hydrology model
' ---------------------------------------------------------------------------
'   a) structural parameters
'
'   dx(15,2,152)             size of finite-difference grid block
'       | | |------------------> number of grid blocks in mesh
'       | |--------------------> number of overbanks
'       |----------------------> number of routing reaches
'
'   hwet(15,2,152)           hydraulic head in finite-difference grid block
'   hold(15,2,152)           hydraulic head in grid block corresponding to
'                            previous time step
'   topsedelev(15,2,152)     elevation corresponding to the top of the
'                            mineral sediments underlying the wetland
'                            organics
'   toporgelev(15,2,152)     elevation corresponding to the top of the
'                            wetland organic layer
'   tophumelev(15,2,152)     elevation defining the upper limit of the
'                            wetland hummock layer
'   wetwid(15)               width of wetland field cell
'   wetlen(15,2)             length of wetland field cell
'   wetslp(15)               transverse slope of wetland field cell
'   surfarea                 total areal extend of wetland sediments
'   kequiv(152)              depth-average hydraulic conductivity
'                            associated with the grid block
'   sequiv(152)              appropriate drainable porosity value for
'                            grid block
'   bsat(152)                total depth of saturated flow within both
'                            organic and hummock layer
'   b)  organic layer
'
'   orgdep(15)               thickness of organic layer
'   orgcontop                hydraulic conductivity corresponding to
'                            organic sediments at upper limit of layer
'   orgconbot                hydraulic conductivity corresponding to
'                            organic sediments at lower limit of layer
'   orgstofc                 drainable porosity of organic layer
'   b(152)                   thickness of saturated flow within organic layer
'   korg                     organic conductivity associated with organic
'                            sediments
```

```
'   c)  hummock layer
'
'   humdep                  thickness of hummock layer
'   surfcoeff               pre-multiplier of overland flow equation
'   beta                    depth exponent of overland flow equation
'   humsto                  drainable porosity of hummock layer
'   d(152)                  depth of flow within the hummock layer
'   khumm                   depth-averaged conductivity associated with
'                           hummock layer
'   d)  hydrologic processes
'
'   rainmm(2000)            hourly precipitation volume (mm)
'   raininter(2000)         hourly intercepted precipitation (mm)
'   prechan                 precipitation falling on channel
'   qr(152)                 rate of precipitation input to grid block
'   qs(152)                 rate of groundwater input to grid block
'   qe(152)                 rate of evapotranspirational loss to grid block
'   qnet(152)               net source/sink rate to grid block
'   ptcoeff                 Priestley-Taylor coefficient (1.26)
'   eqcoeff                 Equilibrium coefficient (1.00)
'   petday                  potential evapotranspiration demand (mm/day)
'   pethour                 potential evapotranspiration demand (mm/hour)
'   canstor                 maximum canopy storage depth (mm)
'   canstorutil             utilized canopy storage (mm)
'   cancover                canopy coverage fraction
'   lai                     leaf area index
'   ------------------------------------------------------------------------
'   wetland channel routing model
'   ------------------------------------------------------------------------
'   nrchmain                number of routing reaches defining the main
'                           channel
'   numlat                  number of lateral drainage channels
'   lchannel                total length of the wetland drainage system (m)
'   lflux                   net linear flux along the wetland drainage
'                           channel (m3/s/m)
'   nrchlat(5)              number of routing reaches defining the lateral
'   reachno(15)             reach number identifier
'   latid(5)                lateral channel identifier
'   termreach(5)            reach number associated with terminal channel
'                           section
'   confreach(5)            reach number associated with confluence channel
'                           section
'   tbelev(15)              top of bank elevation (m)
'   bedinv(15)              bed invert elevation (m)
'   bedslp(15)              slope of channel slope
'   cwid(15)                width of channel
'   crough(15)              Manning's n associated with routing reach
'   cdep(15)                depth of channel along routing reach
'   ireach1                 inflow rate to reach at start of time step
'   ireach2                 inflow rate to reach at end of time step
'   oreach1                 outflow rate to reach at start of time step
'   oreach2                 outflow rate to reach at end of time step
'   ireach(15)              inflow rate associated with routing  reach
'   areach(15)              area of flow associated with routing reach
'   hreach(15)              elevation of free surface along routing reach
'   oreach(15)              outflow rate associated with routing reach
'   sreach(15)              storage associated with routing reach
'   yreach(15)              flow depth along routing reach
'   qlat(15)                lateral inflow to routing reach
'   qlat1reach              lateral inflow to reach at start of time step
'   qlat2reach              lateral inflow to reach at end of time step
'   qlake(2000)             observed wetland outflow (m3/s)
'   qwet(15,2000)           computed wetland outflow (m3/s)
'   ovolume                 total outflow volume discharged from wetland
'   tpchan                  time to wetland outflow hydrograph peak (hours)
'   qpchan                  maximum hydrograph peak (m3/s)
'   qplat                   maximum lateral hydrograph peak (m3/s)
'   tplat                   time to maximum lateral hydrograph peak (hours)
'   routeiter               iteration counter
' --------------------------------------------------------------------------
'   model evaluation criteria
' --------------------------------------------------------------------------
'   nashcoeff          Nash-Sutcliffe coefficient
'   rmscoeff           root mean square (RMS)
'   scriter            S-criterion
'   eecoef             error in peak flow rate
'
```

```
' -------------------------------------------------------------------
'   flags
' -------------------------------------------------------------------
'   runflag             flag identifying type of simulation
'                           1 = optimization run
'                           2 = initialization run
'                           3 = historical simulation
'
'   statusflag(152)     flag identifying saturation state of grid block
'                           1 = unsaturated
'                           2 = saturated
'                           3 = saturation of grid block occurs during
'                               time step
'                           4 = desaturation of grid block occurs
'                               during time step
'   currsatflag(152)    flag identifying saturation state at beginning of
'                       time step
'                           1 = unsaturated
'                          -1 = saturated
'   satflag(152)        flag identifying saturation state at start of a
'                       new iteration loop
'                           1 = unsaturated
'                          -1 = saturated
'
'   revsatflag(152)     flag identifying saturation state at end of a
'                       new iteration loop
'                          -1 = unsaturated
'                           1 = saturated
'
' -------------------------------------------------------------------
'   solution schemes
' -------------------------------------------------------------------
'   c(152)  ----------------|
'   g(152)                  |       matrix coefficients for solution
'   e(152)                  |       of groundwater model
'   f(152)  ----------------|
'   aa(152) ----------------|
'   ab(152)                 |       coefficients for solution of
'   ac(152)                 |       tridiagonal matrices using Thomas
'   bb(152)                 |       solver
'   xx(152) ----------------|
'   qstart                          starting wetland outflow, prior to
'                                   initialization of wetland model
'   qtarget                         target wetland outflow used to terminate
'                                   the initialization routine
'   errval                          tolerance for Newton-Raphson routine
'
' -------------------------------------------------------------------
'   optimization module
' -------------------------------------------------------------------
'   optim1                          optimization using RMS objective function
'   optim2                          optimization using square root obj. funct.
'   opta(18)                        optimization parameters
'   ddelta(18)                      size of step used by search algorithm
'   checkl(18)                      lower bound of parameter value
'   checkh(18)                      upper bound of parameter value
'
' -------------------------------------------------------------------
'   program file structure
' -------------------------------------------------------------------
'       direct$                     name of working directory
'       multi.wfc                   file containing parameter data defining
'                                   channel and wetland structure
'       event$                      event identifier
'       event$.lak                  historical streamflow data
'       event$.gen                  generated streamflow data
'       event$.clm                  climate data
'       event$.rai                  precipitation data
'       event$.met                  evapotranspiration data
'       event$.prm                  event parameters
'       event$.beg                  initial wetland streamflows and levels
'       event$.fin                  final wetland streamflows and levels
```

```
' ----------------------------------------------------------------------
'   Model Revisions
' ----------------------------------------------------------------------
'   Date            Update
'   ====            ======
'
'   Aug 18, 1995    converted bank storage program into SIMPLE, a
'                   single reach wetland module using storage routing
'   Aug 21, 1995    program capable of multiple time steps
'                   with data recorded on hourly intervals
'   Aug 23, 1995    incorporated coupled iterative procedure
'                   for lateral exchanges between channel
'                   and wetland field cells
'   Dec 15, 1995    modified form to allow specification of
'                   program output structure
'   Jan 04, 1996    finalized relaxation scheme to assist with
'                   convergence of channel surcharging solution
'   Jan 10 1996     modified program to generate summary output file
'   Jan 12 1996     program is now compatible with revised
'                   [.lak] and [.rai] output
'   Jan 15,1996     program generates a default file if a full month
'                   has been simulated
'                   program now adopts an interception storage value for
'                   the month and allows depletion of the interception
'                   storage volume at PET rates
'   Jan 20, 1996    modified program to account for precipitation
'                   falling directly on stream
'   Jan 29, 1996    corrected wetland slope parameter
'                   added monthly climate parameters
'   Feb 05, 1996    allowed saturated thickness to extend below the stream invert
'   Feb 21, 1996    program now allows multiple channels
'   Mar 04, 1996    added direct search optimization package  (Munro 1971)
'   Mar 13, 1996    program now reads in entire precip file at once and
'                   writes .gen file at end of execution
'   Apr 04, 1996    DISPHEAD form now displays performance criterion
'                       Nash-Sutcliffe coefficient
'                       root mean square error
'                       percentage error wrt. peak flow
'   Apr 06, 1996    program now reads PET from a .met data file
'   Apr 06, 1996    optimization is performed on a separate data series
'                   that can be longer than one month  (for now: 2000 hours)
'   Oct 03, 1996    modified canopy interception to be a function of
'                   leaf area index (LAI)
'   Oct 16, 1996    modified model to incorporate multiple routing reaches
'   Nov 05, 1996    revised mass balance calculations for GW model
'   Jan 16, 1997    program can now generate a storage-discharge relationship
'   Jan 19, 1997    program can now generate a lateral dicharge file
' ----------------------------------------------------------------------
'   variable declarations
' ----------------------------------------------------------------------
Global hold(15, 2, 152) As Double, rn, ob, nend, n, dt, nn
Global hstor(152, 2000), rntrack, obb, nextgrid
Global sflag(152)
Global hwet(15, 2, 152) As Double
Global nxm1, nxm2, nxm3, nx
Global dx(15, 2, 152)
Global surfcoeff, surfaceflag, beta, deltas(152), availstor(152)
Global b(152) As Double, bsat(152) As Double, bsed(152)
Global c(152) As Double, d(152) As Double, e(152) As Double
Global gg(152) As Double, f(152) As Double
Global qs(152) As Double
Global qr(152) As Double
Global qe(152)   As Double
Global qnet(152) As Double
Global qinf(152) As Double
Global aa(152) As Double, ab(152) As Double, ac(152) As Double
Global bb(152) As Double, xx(152) As Double
Global kequiv(152) As Double, humsto, depmin
Global yhour(2000), zhour(2000), precip(2000), zstring$(2000)
Global rainmm(2000), raininter(2000), raingross(2000), htime(2000)
Global numlat, latid(5), nrchlat(5), termreach(5), confreach(5)
Global combreach(5), nrchmain, rchcounter, reachno(15)
Global qlat(15), ireach1, ireach2, oreach1, oreach2, differ
Global hreach1prev, sreach1prev, oreach1prev, ireach1prev, qbf
Global deltastortstep(15), massbalerr(15), discreptstep(15)
Global maxmberr, timemberr, rnmberr
Global discreptotal, inflowtotal, outflowtotal
Global deficit, rzdep, rzeffpor, evapuzs, fraction
Global sequiv(152) As Double, sorg(152) As Double, shum(152) As Double
Global evapgrid(152) As Double, raingrid(152) As Double, evapunsat(152) As Double
Global orgstofc As Double, orgstowp As Double
```

```
Global unsatdep As Double
Global unsatstorutil(152) As Double
Global unsatstorwp(152) As Double
Global unsatstorfc(152) As Double
Global unsatstordef(152) As Double
Global unsatstorpet(152) As Double
Global initstorcoeff As Double
Global qeu(152)
Global evapweight, thresh
Global tophumelev(15, 2, 152) As Double, toporgelev(15, 2, 152) As Double
Global topsedelev(15, 2, 152) As Double, baseelev(15) As Double
Global monthstart, monthend, initvol, finalvol
Global tbelev(15) As Double, flowmax, flowmin, maxflow, minflow
Global wetwid(15), wetlen(15, 2), wetslp(15) As Double
Global humdep, orgdep(15), orgcontop, orgconbot, sedcon, sedsto
Global initstor, finalstor, lattotal, begstor, endstor
Global deltastor, fluxtotal
Global tptotal, evtotal, gwtotal, bslat, blat, bflux, latstor
Global intertotal As Double, tpgross
Global mass(152), qlsub(152), qlsur(152), qrsub(152), qrsur(152)
Global qsource(152), qmass(152), initsatflag(152), currsatflag(152)
Global hprev(15, 2, 152) As Double
Global satflag(152), revsatflag(152), blocksatflag, ddsat
Global a(20, 20) As Double, eqn(20, 20) As Double, statusflag(152), rerun
Global hsprev(15, 2, 152) As Double, depthmin, solverflag, coupleflag
Global khum(152) As Double, g(152) As Double
Global opta(19), ddelta(18), checkl(18), checkh(18), optba(18), optb(18), delta(18)
Global nsign(18), les(18), optc(18), iclosl(18), iclosh(18)
Global nstart, optstop, optstart, optnper, maxn, kc, optnn, numa
Global flag$, optcc, optcd, it, izy, NCOUN, ICOUN, ifirs
Global LDELT, nsave, optys, optyx, optyy, ll, lc, senscoeff
Global qlake(2000), optim, optiml, optim2, optflag
Global lamdal, lamda2, lamda3, bedslpmult, cwidmult, croughmult
Global massbalflag, gridflag, rainstart, rainstop
Global rain As Double, gw As Double, smethod
Global bedinv(15), cwid(15), bedslp(15), crough(15), cdep(15)
Global nlfrate(2000), bstor(2000), estor(2000)
Global gwstor(2000), nlstor(2000), nlflux(2000), plotflow(2000)
Global direct$, event$, chandata$, numplot, hh, block$
Global plotevent$, plotlakefile$, plotgenfile$
Global genfile$, lakefile$, rainfile$, grffile$, metfile$, begfile$
Global plotvar(22), dummy1$, dummy2$, dummy3$
Global nxnsz, lennsz, tstarthours, tstophours
Global numzonel, numzone2, numzone3
Global lenzonel, lenzone2, lenzone3
Global runflag, nsteps, numiter, numstoriter
Global fcomml$, fcomm2$, fcomm3$
Global qwet(15, 2000), yreach(15), numchan
Global interstormax, interstorutil, raincalib, baseflow As Double, surfarea As Double
Global evap As Double, pethourly(2000) As Double
Global pethour As Double, petday As Double, petsec As Double
Global evaputil As Double, evapavail As Double, evapleft As Double
Global ptcoeff As Double, eqcoeff As Double
Global canstor As Double, cancover As Double, canstorutil As Double
Global canstorfract As Double, evapinter As Double, evaptran As Double
Global lai, cancoeff
Global qtarget As Double, gradflux As Double
Global latflux As Double, qlat1reach As Double
Global qlat2reach As Double, hhstart As Double
Global oreach(15) As Double, ireach(15) As Double, sreach(15) As Double
Global preach As Double, hreach(15) As Double, areach(15) As Double
Global ytrial As Double, otrial As Double, strial As Double, lamda
Global outopt(10)
Global qpchan, qplat, qmlat
Global tpchan, tplat, tmlat, endstortrial
Global sreachinit, sreachfinal
Global oreachinit, oreachfinal
Global olatinit, olatfinal, latstorflux
Global nxmid, oreachprev, ovolume, lvolume, dstor, deltachanstor, massball
Global newevent$, numhoursmonth, numrain, rainchan, chansurfarea, iprecip
Global qstart, lchannel, lflux, bff, initflag
Global dispflag
```

```
Sub applevap ()
' -----------------------------------------------------------------------
'
'       Subroutine: applevap
'       Purpose:    to apply evapotranspiration demand towards canopy
'                   evaporation and uptake from wetland organics
'
' -----------------------------------------------------------------------
'   weight interception evaporation based on percentage of canopy storage
'   utilized
    canstorfract = canstorutil / canstor
    If canstorutil > 0 Then
'       canopy is currently wet
'       ...utilize potential rates  (mm)
        evapavail = evap * 3600 * 1000
        evapequil = evap * 3600 * 1000 / ptcoeff
'       assign evaporation weighting to canopy evaporation and transpiration
'       as functions of the potential rate
        evapinter = canstorfract * evapavail
        evaptran = (1 - canstorfract) * evapavail
        If evaptran > evapequil Then evaptran = evapequil
'       reduce interception storage
        If evapinter < canstorutil Then
'           can't evaporate all canopy storage
'           reduce interception volume through potential ET (mm)
            canstorutil = canstorutil - evapinter
'           assign ET available to groundwater model (m/s)
            evap = evaptran / 3600 / 1000
            etcanopy = etcanopy + evapinter
        Else
'           all canopy storage removed with available ET for
'           transpiration
            evaputil = canstorutil
            canstorutil = 0
            etcanopy = etcanopy + evaputil
            evapleft = evapinter - evaputil
'           ET available to GW model for current time step
            evap = (evapleft + evaptran) / 3600 / 1000
        End If
    Else
'       canopy is currently dry
'       ...utilize equilibrium rates for transpiration (m/s)
        evap = evap / ptcoeff
    End If

End Sub
```

```
Sub applflux (ob)
' -----------------------------------------------------------------------
'
'       Subroutine: applflux
'       Purpose:    to apply sources/sinks to wetland organics
'
' -----------------------------------------------------------------------
'   compute fluxes to field hydrology model for specified overbank (ob)
    fluxtotal = 0
    For i = 1 To nxml
'       identify fluxes to groundwater model
'       precipitation (m3/s)
        qr(i) = -(rain * dx(rn, ob, i) * wetwid(rn))
'       evapotranspiration  (m3/s)
        qe(i) = (evap * (dx(rn, ob, i) * wetwid(rn)))
'       regional groundwater inflow (m3/s)
        qs(i) = -(gw * (dx(rn, ob, i) * wetwid(rn)))
        qnet(i) = qs(i) + qr(i) + qe(i)
'       compute total flux (m3/s) for the time step
        fluxtotal = fluxtotal - (qs(i) + qr(i) + qe(i))
    Next
End Sub
```

```
Sub applyprecip ()
' ----------------------------------------------------------------------------
'       Subroutine: applyprecip
'       Purpose:    to apply precipitation to wetland field hydrology
'                   model and partition into interception and
'                   throughfall components
' ----------------------------------------------------------------------------
'       apply precipitation if start of new hour
        rainmm(n) = precip(n)
'       compute gross rainfall depth for time step (mm)
        raingross(n) = rainmm(n) * raincalib
'       sum gross precipitation volume
        tpgross = tpgross + ((rainmm(n) * raincalib) * surfarea)
'       assign appropriate rainfall to interception storage (mm)
        canstorutil = canstorutil + (cancover * rainmm(n) * raincalib)
        intertotal = intertotal + (cancover * rainmm(n) * raincalib)
'       compute net precipitation
        If canstorutil > canstor Then
'           available interception storage is exceeded
'           allow excess to spill (mm)
            surplus = canstorutil - canstor
'           adjust cumulative depth of interception storage (mm)
            intertotal = intertotal - surplus
'           set utilized storage to maximum (mm)
            canstorutil = canstor
'           allow excess to fall as precipitation (mm)
            rainmm(n) = surplus + (1 - cancover) * rainmm(n) * raincalib
'           define fraction of precip that held in interception storage (mm)
            raininter(n) = raingross(n) - rainmm(n)
        Else
'           all rainfall coincident with canopy is
'           is lost to interception storage
            rainmm(n) = (1 - cancover) * rainmm(n) * raincalib
            raininter(n) = raingross(n) - rainmm(n)
        End If
'       convert rainfall to a flux (m/s)
        If rainmm(n) < 0 Then rainmm(n) = 0
        rain = rainmm(n) / 1000 / 3600
'       compute total volume falling on channel (mm)
        rainchan = rainmm(n) * raincalib
'       compute total volume falling on channel (m3)
        precchan = precchan + (rainchan * chansurfarea)
'       compute throughfall
        tpthrough = tpthrough + (rain * 1000 * 3600)

End Sub
```

```
Sub bankfull (i, qbf, bff)
' --------------------------------------------------------------------------
'       Subroutine: bankfull
'       Purpose:    to compute bankfull discharge along stream reach
' --------------------------------------------------------------------------
    chanarea = cwid(i) * cdep(i) * bff
    chanperim = cwid(i) + 2 * cdep(i) * bff
    chanhr = chanarea / chanperim
    qbf = 1 / crough(i) * chanarea * (chanhr ^ 2 / 3) * (bedslp(i) ^ .5)

End Sub
```

```
Sub cmpflux (endstortrial, begstor, latflux)
' ---------------------------------------------------------------------------
'       Subroutine: cmpflux
'       Purpose:    to compute flux across wetland-stream interface (m3/s)
' ---------------------------------------------------------------------------
'   change in storage in single field cell (m3)
    deltastor = endstortrial - begstor
'   account for vertical moisture inputs   (m3)
    latstor = deltastor - (fluxtotal * dt)
'   net lateral flow to/from stream (m3/s) based on change in wetland storage
    latstorflux = latstor / dt
'
'   compute lateral flux based on head gradient at interface
'
    numer = 2 * kequiv(1) * kequiv(2) * bsat(1) * bsat(2) * wetwid(rn)
    denom = kequiv(1) * bsat(1) * dx(rn, ob, 2) + kequiv(2) * bsat(2) * dx(rn, ob, 1)
    gradflux = numer / denom * (hwet(rn, ob, 1) - hwet(rn, ob, 2))
'
'   assign lateral flux value
'
    latflux = gradflux
End Sub
```

```
Sub cmpgridsize ()
' -----------------------------------------------------------------
'
'       Subroutine: cmpgridsize
'       Purpose:    to construct a variable-size finite-difference
'                   modelling mesh
'
' -----------------------------------------------------------------
        nx = 32
        nxm1 = nx - 1
        nxm2 = nx - 2
        nxm3 = nx - 3
        For i = 1 To nrchmain
            For j = 1 To 2
              If wetlen(i, j) > 0 Then
                For k = 1 To nxm2
                    distle = wetlen(i, j) * ((k - 1) / nxm2) ^ 2
                    distre = wetlen(i, j) * ((k) / nxm2) ^ 2
                    dx(i, j, k + 1) = distre - distle
                Next k
                dx(i, j, 1) = dx(i, j, 2)
                dx(i, j, nx) = dx(i, j, nxm1)
                Else
'               no field cell
                    For k = 1 To nx
                        dx(i, j, k) = 0
                    Next
                End If
            Next
        Next
'       do the same for any laterals
        If numlat > 0 Then
            For ii = 1 To numlat
                For i = Val(termreach(ii)) To Val(confreach(ii))
                    For j = 1 To 2
                      If wetlen(i, j) > 0 Then
                        For k = 1 To nxm1
                            distle = wetlen(i, j) * ((k - 1) / nxm2) ^ 2
                            distre = wetlen(i, j) * ((k) / nxm2) ^ 2
                            dx(i, j, k + 1) = distre - distle
                        Next k
                        dx(i, j, 1) = dx(i, j, 2)
                        dx(i, j, nx) = dx(i, j, nxm1)
                    Else
'                       no field cell
                        For k = 1 To nx
                            dx(i, j, k) = 0
                        Next
                    End If
                    Next j
                Next i
            Next ii
        End If
End Sub
```

```
Sub cmpgridsize2 ()
' -----------------------------------------------------------------------
'       Subroutine: cmpgridsize2
'       Purpose:    to establish a uniform grid mesh
' -----------------------------------------------------------------------
'
        nx = 32
        nxm1 = nx - 1
        nxm2 = nx - 2
        nxm3 = nx - 3
        For i = 1 To nrchmain
            For j = 1 To 2
              If wetlen(i, j) > 0 Then
                    For k = 1 To nx
                        dx(i, j, k) = wetlen(i, j) / nxm2
                    Next
                Else
'               no field cell
                    For k = 1 To nx
                        dx(i, j, k) = 0
                    Next
                End If
            Next
        Next
'       do the same for any laterals
        If numlat > 0 Then
            For ii = 1 To numlat
                For i = Val(termreach(ii)) To Val(confreach(ii))
                    For j = 1 To 2
                        If wetlen(i, j) > 0 Then
                            For k = 1 To nx
                                dx(i, j, k) = wetlen(i, j) / nxm2
                            Next
                        Else
'                           no field cell
                            For k = 1 To nx
                                dx(i, j, k) = 0
                            Next
                        End If
                    Next
                Next
            Next
        End If

End Sub
```

```
Sub cmpgwinflow ()
' -------------------------------------------------------------------------
'
'       Subroutine: cmpgwinflow
'       Purpose:    to convert specified baseflow (m3/s) to a
'                   mean areal groundwater flux (m/s)
' -------------------------------------------------------------------------
    gw = baseflow / surfarea

End Sub
```

```
Sub cmphydcon (ob)
' -------------------------------------------------------------------------
'
'       Subroutine: cmphydcon
'       Purpose:    to compute the depth-averaged hydraulic conductivity
'                   associated with the saturation state in each grid block
' -------------------------------------------------------------------------
'
    For i = 1 To nxm1
        If hwet(rn, ob, i) > topsedelev(rn, ob, i) And hwet(rn, ob, i) <= toporgelev(rn,
ob, i) Then
'           phreatic surface in organic layer
            dd2 = hwet(rn, ob, i) - topsedelev(rn, ob, i)
            zz3 = hwet(rn, ob, i)
            zz1 = topsedelev(rn, ob, i)
            zz2 = toporgelev(rn, ob, i)
            aa1 = orgconbot
            aa2 = orgcontop
            Call interp(zz3, zz1, zz2, aa1, aa2, aa3)
            ksed = sedcon
            korg = (aa3 + aa1) / 2
            kequiv(i) = korg
        End If
        If hwet(rn, ob, i) > toporgelev(rn, ob, i) Then
'           apply laminar flow equation to determine surface conductivity
            ksed = sedcon
            korg = (orgcontop + orgconbot) / 2
            khumm = surfcoeff * (d(i) ^ beta)
            If khumm < orgcontop Then khumm = orgcontop
'           compute arithmetic mean of the hyd. conductivities
            kequiv(i) = ((korg * b(i)) + khumm * d(i)) / (b(i) + d(i))
        End If
    Next i

End Sub
```

```
Sub cmpsatdep (ob)
' -------------------------------------------------------------------------
'       Subroutine: cmpsatdep
'       Purpose:    to compute the saturated depths within each layer
' -------------------------------------------------------------------------
    For i = 1 To nx
        bsat(i) = hwet(rn, ob, i) - topsedelev(rn, ob, i)
        If hwet(rn, ob, i) <= toporgelev(rn, ob, i) And hwet(rn, ob, i) > topsedelev(rn,
ob, i) Then
'           block is unsaturated
            b(i) = hwet(rn, ob, i) - topsedelev(rn, ob, i)
            d(i) = 0
        End If
        If hwet(rn, ob, i) > toporgelev(rn, ob, i) Then
'           block is ponded
            b(i) = orgdep(rn)
            d(i) = hwet(rn, ob, i) - toporgelev(rn, ob, i)
        End If
    Next

End Sub
```

```
Sub cmpsatstatus (rn, ob)
' ----------------------------------------------------------------------------
'
'        Subroutine: cmpsatstatus
'        Purpose:    to identify the saturation state within each grid block
' ----------------------------------------------------------------------------
    For k = 2 To nx
            If hwet(rn, ob, k) > toporgelev(rn, ob, k) Then
'            block is saturated at beginning of time step
            satflag(i) = -1
        Else
'            block is unsaturated at beginning of time step
            satflag(i) = 1
        End If
    Next k

End Sub
```

```
Sub cmpstor (storage, ob)
' ------------------------------------------------------------------------
'
'       Subroutine: cmpstor
'       Purpose:    to compute total stored water within wetland field cells
' ------------------------------------------------------------------------
    orgporosity = .8
    humporosity = 1
    storage = 0
    For i = 2 To nxml
        If hwet(rn, ob, i) > topsedelev(rn, ob, i) And hwet(rn, ob, i) <= toporgelev(rn,
ob, i) Then
'           phreatic surface located within the organic layer
            storl = wetwid(rn) * dx(rn, ob, i) * b(i) * (orgporosity)
            stor00 = wetwid(rn) * dx(rn, ob, i) * (toporgelev(rn, ob, i) - hwet(rn, ob,
i)) * (orgporosity - orgstofc)
            stor2 = wetwid(rn) * dx(rn, ob, i) * humdep * (humporosity - humsto)
            storage = storage + stor00 + storl + stor2
        End If
        If hwet(rn, ob, i) > toporgelev(rn, ob, i) And hwet(rn, ob, i) <= tophumelev(rn,
ob, i) Then
'           phreatic surface located within the hummock layer
            storl = wetwid(rn) * dx(rn, ob, i) * orgdep(rn) * orgporosity
            stor2 = wetwid(rn) * dx(rn, ob, i) * d(i) * humporosity
            stor3 = wetwid(rn) * dx(rn, ob, i) * (humdep - d(i)) * (humporosity - humsto)
            storage = storage + storl + stor2 + stor3
        End If
        If hwet(rn, ob, i) > tophumelev(rn, ob, i) Then
'           free surface flows within block
            storl = wetwid(rn) * dx(rn, ob, i) * orgdep(rn) * orgporosity
            stor2 = wetwid(rn) * dx(rn, ob, i) * humdep * humporosity
            stor3 = wetwid(rn) * dx(rn, ob, i) * (d(i) - (humdep))
            storage = storage + storl + stor2 + stor3
        End If
    Next
'
End Sub
```

```
Sub cmpstor2 (storage, ob)
' ---------------------------------------------------------------------------
'
'       Subroutine: cmpstor2
'       Purpose:    to compute total utilized pore space within wetland
' ---------------------------------------------------------------------------
    storage = 0
    For i = 2 To nxml
        If hwet(rn, ob, i) > topsedelev(rn, ob, i) And hwet(rn, ob, i) <= toporgelev(rn,
ob, i) Then
'           phreatic surface located within the organic layer
            stor1 = wetwid(rn) * dx(rn, ob, i) * b(i) * orgstofc
            storage = storage + stor1
        End If
        If hwet(rn, ob, i) > toporgelev(rn, ob, i) And hwet(rn, ob, i) <= tophumelev(rn,
ob, i) Then
'           phreatic surface located within the hummock layer
            stor1 = wetwid(rn) * dx(rn, ob, i) * orgdep(rn) * orgstofc
            stor2 = wetwid(rn) * dx(rn, ob, i) * d(i) * humsto
            storage = storage + stor1 + stor2
        End If
        If hwet(rn, ob, i) > tophumelev(rn, ob, i) Then
'           free surface flows within block
            stor1 = wetwid(rn) * dx(rn, ob, i) * orgdep(rn) * orgstofc
            stor2 = wetwid(rn) * dx(rn, ob, i) * humdep * humsto
            stor3 = wetwid(rn) * dx(rn, ob, i) * (d(i) - (humdep))
            storage = storage + stor1 + stor2 + stor3
        End If
    Next
End Sub
```

```
Sub cmpstorcoeff (ob)
' -------------------------------------------------------------------------
'
'       Subroutine: cmpstorcoeff
'       Purpose:    to assign an appropriate storage coefficient
'
' -------------------------------------------------------------------------
    For i = 1 To nxml
        If hwet(rn, ob, i) > topsedelev(rn, ob, i) And hwet(rn, ob, i) <= toporgelev(rn,
ob, i) Then
'           phreatic surface in organic layer
            sorg(i) = orgstofc
            shum(i) = humsto
        End If
        If hwet(rn, ob, i) > toporgelev(rn, ob, i) And hwet(rn, ob, i) <= tophumelev(rn,
ob, i) Then
'           phreatic surface in hummock layer
            sorg(i) = orgstofc
            shum(i) = humsto
        End If
        If hwet(rn, ob, i) > tophumelev(rn, ob, i) Then
'           phreatic surface above the hummock layer
            sorg(i) = orgstofc
            shum(i) = 1
        End If
    Next i
End Sub
```

```
Sub cmpsurfarea ()
' -------------------------------------------------------------------------
'
'       Subroutine: cmpsurfarea
'       Purpose:    to compute total surface area of wetland sediments
' -------------------------------------------------------------------------
    surfarea = 0
    For i = 1 To nrchmain
        For j = 1 To 2
            surfarea = surfarea + (wetwid(i) * wetlen(i, j))
        Next
    Next
    If numlat > 0 Then
        For ii = 1 To numlat
            For i = Val(termreach(ii)) To Val(confreach(ii))
                For j = 1 To 2
                    surfarea = surfarea + (wetwid(i) * wetlen(i, j))
                Next
            Next
        Next
    End If
End Sub
```

```
Sub display ()
' -----------------------------------------------------------------------------
'
'       Subroutine: display
'       Purpose:    to display appropriate message to user
' -----------------------------------------------------------------------------
    If runflag = 2 Or runflag = 3 Then
        progstring$ = Format$(htime(n), "0000") + "/" + Format$(tstophours, "0000")
        runmess.zululbl.Caption = Format$(zhour(n), "0000")
        runmess.zulustringlbl.Caption = Format$(zstring$(n))
        iper = htime(n) / tstophours * 100
        updateprogress runmess.Picture2, iper, progstring$
        runmess.zululbl.Refresh
    End If
    If runflag = 1 Then
        optimout.hourlbl = Format$(htime(n), "0000")
        optimout.hourlbl.Refresh
    End If
End Sub

Sub distevap ()
' -----------------------------------------------------------------------------
'       Subroutine: distevap
'       Purpose:    to distribute evapotranpirational demand over 24 hour day
' -----------------------------------------------------------------------------
If zhour(n) = 5 Then evap = 1 * pethourly(n) / 3600000
If zhour(n) = 6 Then evap = 1 * pethourly(n) / 3600000
If zhour(n) = 7 Then evap = 1 * pethourly(n) / 3600000
If zhour(n) = 8 Then evap = 1 * pethourly(n) / 3600000

If zhour(n) = 9 Then evap = 1 * pethourly(n) / 3600000
If zhour(n) = 10 Then evap = 1 * pethourly(n) / 3600000
If zhour(n) = 11 Then evap = 1 * pethourly(n) / 3600000
If zhour(n) = 12 Then evap = 1 * pethourly(n) / 3600000
If zhour(n) = 13 Then evap = 1 * pethourly(n) / 3600000
If zhour(n) = 14 Then evap = 1 * pethourly(n) / 3600000
If zhour(n) = 15 Then evap = 1 * pethourly(n) / 3600000
If zhour(n) = 16 Then evap = 1 * pethourly(n) / 3600000
If zhour(n) = 17 Then evap = 1 * pethourly(n) / 3600000

If zhour(n) = 18 Then evap = 1 * pethourly(n) / 3600000
If zhour(n) = 19 Then evap = 1 * pethourly(n) / 3600000
If zhour(n) = 20 Then evap = 1 * pethourly(n) / 3600000
If zhour(n) = 21 Then evap = 1 * pethourly(n) / 3600000

If zhour(n) = 22 Then evap = 1 * pethourly(n) / 3600000
If zhour(n) = 23 Then evap = 1 * pethourly(n) / 3600000
If zhour(n) = 0 Then evap = 1 * pethourly(n) / 3600000

If zhour(n) = 1 Then evap = 1 * pethourly(n) / 3600000
If zhour(n) = 2 Then evap = 1 * pethourly(n) / 3600000
If zhour(n) = 3 Then evap = 1 * pethourly(n) / 3600000
If zhour(n) = 4 Then evap = 1 * pethourly(n) / 3600000

End Sub
```

```
Sub evaluate ()
' ------------------------------------------------------------------------
'
'       Subroutine: evaluate
'       Purpose:    to compute evaluation statistics
' ------------------------------------------------------------------------
'
'   sum of squares criteria
'
    optim1 = 0
    For i = 1 To tstophours
'       only evaluate optimization within specified limits
        If i >= optstart And i <= optstop Then
            optim1 = optim1 + (qwet(nrchmain, i) - qlake(i)) ^ 2
        End If
    Next
'
'   square root criteria
'
    optim2 = 0
    For i = 1 To tstophours
        If i >= optstart And i <= optstop Then
            optim2 = optim2 + (qwet(nrchmain, i) ^ .5 - qlake(i) ^ .5) ^ 2
        End If
    Next
    If optflag = 1 Then
        optim = optim1
    ElseIf optflag = 2 Then
        optim = optim2
    End If
End Sub
```

```
Sub fillwet ()
' -----------------------------------------------------------------------
'
'       Subroutine: fillwet
'       Purpose:    to initialize stream levels and establish
'                   initial heads in wetland finite-difference mesh
'       Procedure:
'
'       1)  prorate channel flow along all channel sections
'       2)  compute normal depth at outlet reach
'       3)  generate water surface profiles along main channel
'           and all laterals
'       4)  establish initial saturation levels in all wetland field cells
'
' -----------------------------------------------------------------------
'       define runflag =2 as initialization mode for implicit routine
        runflag = 2
        fill.MousePointer = 11
'       define a marginal headwater discharge
        qupstream = .001
        hinc = .01
        lchannel = 0
'       establish total channel length by summing over all reaches
        For i = 1 To nrchmain
            If wetlen(i, 1) > 0 Or wetlen(i, 2) > 0 Then
'               wetland field cell lies along reach
                lchannel = lchannel + wetwid(i)
            End If
        Next i
        If numlat > 0 Then
            For ii = 1 To numlat
                For i = termreach(ii) To confreach(ii)
                    If wetlen(i, 1) > 0 Or wetlen(i, 2) > 0 Then
'                       wetland field cell lies along reach
                        lchannel = lchannel + wetwid(i)
                    End If
                Next i
            Next
        End If
'
'       establish linear flux along channel (m3/s/m)
        lflux = qstart / lchannel
'
'       assign discharge in main channel
'       and assign initial lateral flow for reach
'
        ireach(1) = qupstream
        For i = 1 To nrchmain
            If wetlen(i, 1) > 0 Or wetlen(i, 2) > 0 Then
                oreach(i) = ireach(i) + wetwid(i) * lflux
                qlat(i) = wetwid(i) ** lflux
            Else
                oreach(i) = ireach(i)
                qlat(i) = 0
            End If
        ireach(i + 1) = oreach(i)
        Next i
'       assign discharge along laterals if any exist
        If numlat > 0 Then
            For ii = 1 To numlat
                ireach(termreach(ii)) = qupstream / 2
                For i = termreach(ii) To confreach(ii)
                    If wetlen(i, 1) > 0 Or wetlen(i, 2) > 0 Then
                        oreach(i) = ireach(i) + wetwid(i) * lflux
                        qlat(i) = wetwid(i) * lflux
                    Else
                        oreach(i) = ireach(i)
                        qlat(i) = 0
                    End If
                    ireach(i + 1) = oreach(i)
                Next i
            Next ii
        End If
'
'       include lateral channel flows to all downstream sections
'
        If numlat > 0 Then
            For ii = 1 To numlat
                For i = 1 To nrchmain
                    If Val(combreach(ii)) = Val(i) Then
                        For j = combreach(ii) To nrchmain
```

```
                    ireach(j) = ireach(j) + oreach(confreach(ii))
                    oreach(j) = oreach(j) + oreach(confreach(ii))
                Next
            End If
        Next
    Next
End If
'
'   establish a water levels along main channel
'
For i = 1 To nrchmain
    Call normal(i, oreach(i), bedslp(i), yy)
    yreach(i) = yy
    hreach(i) = yreach(i) + bedinv(i)
    areach(i) = yreach(i) * cwid(i)
    sreach(i) = areach(i) * wetwid(i)
Next i
'   set water level in laterals if any exist
If numlat > 0 Then
    For ii = 1 To numlat
        For i = termreach(ii) To confreach(ii)
            Call normal(i, oreach(i), bedslp(i), yy)
            yreach(i) = yy
            hreach(i) = yreach(i) + bedinv(i)
            areach(i) = yreach(i) * cwid(i)
            sreach(i) = areach(i) * wetwid(i)
        Next i
    Next
End If
'
'   compute grid mesh
'
Call cmpgridsize
'
'   Compute elevations for each soil interface
'
For i = 1 To nrchmain
    For j = 1 To 2
        dist = 0
        For k = 2 To nxm1
            dist = dist + dx(i, j, k - 1)
            toporgelev(i, j, k) = dist * wetslp(i) + tbelev(i)
            topsedelev(i, j, k) = toporgelev(i, j, k) - orgdep(i)
            tophumelev(i, j, k) = toporgelev(i, j, k) + humdep
        Next
        toporgelev(i, j, 1) = toporgelev(i, j, 2)
        topsedelev(i, j, 1) = topsedelev(i, j, 2)
        tophumelev(i, j, 1) = tophumelev(i, j, 2)
        toporgelev(i, j, nx) = toporgelev(i, j, nxm1)
        topsedelev(i, j, nx) = topsedelev(i, j, nxm1)
        tophumelev(i, j, nx) = tophumelev(i, j, nxm1)
'       compute thickness of saturated flow at stream
        ddsat = hreach(i) - topsedelev(i, j, 1)
        For k = 2 To nx
            hwet(i, j, k) = topsedelev(i, j, k) + ddsat + hinc
        Next
    Next j
Next i
'
'   Compute elevations for each soil interface
'
If numlat > 0 Then
    For ii = 1 To numlat
        For i = Val(termreach(ii)) To Val(confreach(ii))
            For j = 1 To 2
                dist = 0
                For k = 2 To nxm1
                    dist = dist + dx(i, j, k - 1)
                    toporgelev(i, j, k) = dist * wetslp(i) + tbelev(i)
                    topsedelev(i, j, k) = toporgelev(i, j, k) - orgdep(i)
                    tophumelev(i, j, k) = toporgelev(i, j, k) + humdep
                Next
                toporgelev(i, j, 1) = toporgelev(i, j, 2)
                topsedelev(i, j, 1) = topsedelev(i, j, 2)
                tophumelev(i, j, 1) = tophumelev(i, j, 2)
                toporgelev(i, j, nx) = toporgelev(i, j, nxm1)
                topsedelev(i, j, nx) = topsedelev(i, j, nxm1)
                tophumelev(i, j, nx) = tophumelev(i, j, nxm1)
'               compute thickness of saturated flow at stream
                ddsat = hreach(i) - topsedelev(i, j, 1)
                For k = 2 To nx
```

```
                    hwet(i, j, k) = topsedelev(i, j, k) + ddsat + hinc
                Next
            Next j
        Next i
    Next ii
End If
'
'       write initialized data to file
'
        Call writebeg
        fill.MousePointer = 0
End Sub
```

```
Sub implicit ()
' -----------------------------------------------------------------------
'
'       Subroutine: implicit
'       Purpose:    This subroutine begins wetland model and calls all
'                   appropriate subroutines to solve wetland field hydrology
'                   model and channel routing procedure for the specified
'                   duration of the simulation.
' -----------------------------------------------------------------------
'   read in current channel and field cell parameters
    Open direct$ + "multi.wfc" For Input As #88
    Line Input #88, comment1$
    Line Input #88, comment2$
    Line Input #88, comment3$
    Line Input #88, comment4$
    Line Input #88, comment5$
    Line Input #88, dummy$
    Input #88, nrchmain
    rchcounter = nrchmain
    Line Input #88, dummy$
    Line Input #88, dummy$
    For i = 1 To nrchmain
        Input #88, reachno(i), wetwid(i), wetlen(i, 1), wetlen(i, 2), cwid(i), cdep(i),
orgdep(i), crough(i), bedslp(i), wetslp(i)
    Next i
'
'   read in laterals
'
    Line Input #88, dummy$
    Line Input #88, dummy$
    numlat = RTrim$(LTrim$(Left$(dummy$, 20)))
    If numlat > 0 Then
        For i = 1 To numlat
'           read in lateral id number
            Line Input #88, dummy$
            latid(i) = RTrim$(LTrim$(Left$(dummy$, 20)))
'           read in number of reaches defining the lateral
            Line Input #88, dummy$
            nrchlat(i) = RTrim$(LTrim$(Left$(dummy$, 20)))
'           read in most upstream reach number
            Line Input #88, dummy$
            termreach(i) = RTrim$(LTrim$(Left$(dummy$, 20)))
'           read in most downstream reach number
            Line Input #88, dummy$
            confreach(i) = RTrim$(LTrim$(Left$(dummy$, 20)))
'           read in main channel reach to be combined with lateral
            Line Input #88, dummy$
            combreach(i) = RTrim$(LTrim$(Left$(dummy$, 20)))
            For ii = termreach(i) To confreach(i)
                Input #88, reachno(ii), wetwid(ii), wetlen(ii, 1), wetlen(ii, 2),
cwid(ii), cdep(ii), orgdep(ii), crough(ii), bedslp(ii), wetslp(ii)
            Next ii
        Next
    End If
    Close #88
    If runflag = 2 Then
'       display current program revision during initialization
        rev$ = "Oct 26, 1996"
        runmess.revlbl.Caption = rev$
        runmess.titlelbl.Caption = "Initializing Wetland Model"
    End If
    If runflag = 3 Then
'       display current program revision during simulation
        rev$ = "Oct 26, 1996"
        runmess.revlbl.Caption = rev$
        runmess.titlelbl.Caption = "Multiple-Reach Wetland Model"
'       adjust channel parameters if required
        For i = 1 To nrchmain
'               modify channel property
                bedslp(i) = bedslp(i) * bedslpmult
                cwid(i) = cwid(i) * cwidmult
                crough(i) = crough(i) * croughmult
        Next i
        If numlat > 0 Then
            For ii = 1 To numlat
                For i = termreach(ii) To confreach(ii)
                    bedslp(i) = bedslp(i) * bedslpmult
                    cwid(i) = cwid(i) * cwidmult
                    crough(i) = crough(i) * croughmult
                Next i
            Next ii
```

```
        End If
    End If
'
'   clear monitor screen and change mouse pointer to an hourglass
    main.Cls
    main.MousePointer = 11
    blocksatflag = 1
    lamda = 1
    routetol = .0001
    If runflag = 1 Then
'       under optimization runs, do not print .gen file
        outopt(1) = 0
'       read in channel parameter data
        For i = 1 To nrchmain
'               modify channel property
                bedslp(i) = bedslp(i) * bedslpmult
                cwid(i) = cwid(i) * cwidmult
                crough(i) = crough(i) * croughmult
        Next i
        If numlat > 0 Then
            For ii = 1 To numlat
                For i = termreach(ii) To confreach(ii)
                    bedslp(i) = bedslp(i) * bedslpmult
                    cwid(i) = cwid(i) * cwidmult
                    crough(i) = crough(i) * croughmult
                Next i
            Next ii
        End If

    End If
'   open all specified output files
        If outopt(1) = 1 Then
            Open direct$ + event$ + ".gen" For Output As #81
        End If
        If outopt(2) = 1 Then
            Open direct$ + event$ + ".lat" For Output As #18
        End If
        If outopt(3) = 1 Then
            Open direct$ + event$ + ".dbg" For Output As #15
        End If
        If outopt(4) = 1 Then
            Open direct$ + event$ + ".itt" For Output As #16
        End If
        If outopt(5) = 1 Then
            Open direct$ + event$ + ".rit" For Output As #17
        End If
        If outopt(6) = 1 Then
            Open direct$ + event$ + ".pl1" For Output As #55
        End If
        If outopt(7) = 1 Then
            Open direct$ + event$ + ".pl2" For Output As #56
        End If
        If outopt(8) = 1 Then
            Open direct$ + event$ + ".pl3" For Output As #57
        End If
'
'   initialize mass balance counters
'
    plotstor = 0
    maxmberr = 0
    discreptotal = 0
    inflowtotal = 0
    outflowtotal = 0
    initstor = 0
    finalstor = 0
    lattotal = 0
    gwtotal = 0
    evap = 0
    evtotal = 0
    etunsat = 0
    etsat = 0
    etcanopy = 0
    precusz = 0
    precsz = 0
    tptotal = 0
    tpgross = 0
    tpthrough = 0
    precchan = 0
    canstorutil = 0
    intertotal = 0
    blat = 0
```

```
    dslat = 0
    bslat = 0
    ireachtotal = 0
    tstarthours = 1
    ivolume = 0
'   maximum channel flow
    qpchan = 0
'   maximum lateral outflow (from channel)
    qplat = 0
'   maximum lateral inflow (to channel)
    qmlat = 0
    tpchan = 0
    tplat = 0
    tmlat = 0
'   outflow volume from wetland
    ovolume = 0
'   lateral flow volume from wetland field cells
    lvolume = 0
'   define initial channel parameters
    If runflag = 2 Then
'       establish all parameters under initialization mode
        rain = 0
        petsec = 0
        petday = 0
        canstorutil = 0
        evap = 0
    End If
'
'   determine time parameters
    dt = 3600 / nsteps
'
    If runflag = 1 Or runflag = 3 Then
'       open all required data files if required for simulation
        Open direct$ + rainfile$ For Input As #80
'       read over comment lines in precip file
        For i = 1 To 6
            Line Input #80, dummy7$
        Next
        Input #80, numrain
'       numrain is equivalent to the number of hours in month
        numhoursmonth = numrain
        If tstophours > numrain Then
            tstophours = numrain
        End If
'       read all precipitation for month
        For i = 1 To tstophours
            Input #80, yhour(i), zhour(i), precip(i), zstring$(i)
'           apply thresholding if required
            If precip(i) > thresh Then
                precip(i) = precip(i) - thresh
            Else
                precip(i) = 0
            End If
        Next i
        Close #80
'       open MET file
        Open direct$ + metfile$ For Input As #80
        Input #80, numrain
'       numrain is equivalent to the number of hours in month
        numhoursmonth = numrain
        If tstophours > numrain Then
            tstophours = numrain
        End If
'       read all evap data for month
        For i = 1 To tstophours
            Input #80, yhour(i), zhour(i), pethourly(i), zstring$(i)
        Next i
        Close #80
'       compute appropriate canopy interception (mm)
        canstor = .2 * lai
    End If
    If outopt(1) = 1 Then
        Print #81, "Generated hydrograph file"
        Print #81, tstarthours
        Print #81, tstophours
        Print #81, dt / 3600
    End If
    If outopt(2) = 1 Then
        Print #18, "Generated lateral discharge hydrograph file"
        Print #18, tstarthours
        Print #18, tstophours
```

```
        Print #18, dt / 3600
    End If
    If runflag = 1 Or runflag = 3 Then
'       read in default settings
        Call readbeg
    End If
'   specify vertical fluxes
    fluxtotal = 0
    fluxstor = 0
'
'   set initial and boundary conditions
'
'   initialization mode
    Call init2
    Call cmpsurfarea
    Call cmpgwinflow
'   define approximate midpoint in wetland field
    nxmid = Int(nx / 2)
'   define boundary block properties at margin
'
    sequiv(nx) = 1E+20
    kequiv(nx) = 1E-20
'
' -------------------------------------------------------------------------
'   begin computational loop
' -------------------------------------------------------------------------
    If runflag = 2 Or runflag = 3 Then
        runmess.Show
        runmess.MousePointer = 11
    End If
    n = 0
    hourcounter = 0
'
'   estimate initial storage for entire wetland
'
        initvol = 0
        initvoltot = 0
        For rn = 1 To nrchmain
            For ob = 1 To 2
                If wetlen(rn, ob) > 0 Then
                    Call cmpsatdep(ob)
                    Call cmpstor2(begstor, ob)
                    Call cmpstor(begstortot, ob)
                    initvol = initvol + begstor
                    initvoltot = initvoltot + begstortot
                End If
            Next ob
        Next rn
        If numlat > 0 Then
            For ii = 1 To numlat
                For rn = termreach(ii) To confreach(ii)
                    For ob = 1 To 2
                        If wetlen(rn, ob) > 0 Then
                            Call cmpsatdep(ob)
                            Call cmpstor2(begstor, ob)
                            Call cmpstor(begstortot, ob)
                            initvol = initvol + begstor
                            initvoltot = initvoltot + begstortot
                        End If
                    Next ob
                Next rn
            Next ii
        End If
        disphead.Label14.Caption = Format$(initvol, "##,###,###")
'
'       ++++++++++++++++++++++++++++++++++++++
'       +   start main computational loop    +
'       ++++++++++++++++++++++++++++++++++++++
'
'   begin at first hour
    ttime = 0
'   htime = ttime / 3600
    Do While htime(n) < tstophours
        If runflag = 2 Then
'           test for convergence (to within 1%) during initialization
            If initflag = 1 And oreach(nrchmain) > qtarget Then GoTo finishup:
            If initflag = -1 And oreach(nrchmain) < qtarget Then GoTo finishup:
        End If
'       increment the hourly counter
        n = n + 1
        hourcounter = hourcounter + 1
```

```
        If hourcounter = 25 Then hourcounter = 1
        For iii = 1 To nsteps
'           increment time counter
            ttime = ttime + dt
            htime(n) = ttime / 3600
            If Val(iii) = 1 Then
'               beginning of a new hourly time interval
                If runflag <> 2 Then
'                   apply precipitation to historical simulation
                    Call applyprecip
                Else
'                   initialization mode (no meteorologic inputs)
                    rain = 0
                    tpthrough = 0
                End If
'               display  appropriate message to user
                Call display
                If runflag <> 2 Then
'                   distribute evapotranspiration losses based on hour
                    Call distevap
'                   apply evapotranspiration demand
                    Call applevap
                End If
            End If
'           Begin computational loop
'           - starting with all lateral tributaries and then
'             computing streamflow along main channel
            If numlat > 0 Then
                For ii = 1 To numlat
                    For rn = termreach(ii) To confreach(ii)
'                       store current parameter values for reach
                        ireach1prev = ireach(rn)
                        oreach1prev = oreach(rn)
                        sreach1prev = sreach(rn)
                        hreach1prev = hreach(rn)
'                       identify current stream flows in reach
                        ireach1 = ireach(rn)
                        oreach1 = oreach(rn)
'                       update reach inflow based on upstream outflow
                        If Val(rn) = Val(termreach(ii)) Then
'                           headwater reach
                            ireach2 = ireach1
                        Else
                            ireach2 = oreach(rn - 1)
                        End If
'                       apply field hydrology model and solve for
'                       reach storage and outflow
                        Call reach
'                       solution is complete for the reach
'                       establish reach inflow for next time step
                        ireach(rn) = ireach2
                    Next rn
                Next ii
            End If
'           now repeat routing procedure for main channel
            For rn = 1 To nrchmain
'               store current parameter values for reach
                ireach1prev = ireach(rn)
                oreach1prev = oreach(rn)
                sreach1prev = sreach(rn)
                hreach1prev = hreach(rn)
'               identify stream flows in reach at start of time step
                ireach1 = ireach(rn)
                oreach1 = oreach(rn)
'               update reach inflow based on upstream outflow
                If Val(rn) = 1 Then
'                   headwater reach
                    ireach2 = ireach1
                Else
'                   for interior reach, assign outflow at end of time
'                   step from upstream reach as the inflow
                    ireach2 = oreach(rn - 1)
'                   include any lateral inflow if appropriate
                    If numlat > 0 Then
                        For ii = 1 To numlat
                            If Val(rn) = Val(combreach(ii)) Then
                                ireach2 = ireach2 + oreach(confreach(ii))
                            End If
                        Next ii
                    End If
                End If
```

```
'               apply field hydrology model and solve for
'               reach storage and outflow
                Call reach
'               solution is complete for the reach
'               establish reach inflow for next time step
                ireach(rn) = ireach2
            Next rn
'           solution is complete for the time increment and we can
'           proceed with mass balance calculations associated
'           with the end of the time step
'
'
'           compute volume of lateral flow over time step
            lvolume = lvolume + (qlat1reach + qlat2reach) / 2 * dt
            qlat1reach = qlat2reach
'           update maximum channel peak
            If oreach(nrchmain) > qpchan Then
                qpchan = oreach(nrchmain)
                tpchan = htime(n)
            End If
'           update maximum lateral outflow from channel
            If qlat2reach > qplat Then
                qplat = qlat2reach
                tplat = htime(n)
            End If
'           update maximum lateral inflow to channel
            If qlat2reach < qmlat Then
                qmlat = qlat2reach
                tmlat = htime(n)
            End If
'           sum the total outflow volume from the wetland
            ovolume = ovolume + (oreachprev + oreach(rn)) / 2 * dt
            oreachprev = oreach(rn)
            ireachtotal = ireachtotal + ireach(rn) * dt
            If runflag = 3 Then
'               write to mass balance grid
                Rrow = Rrow + 1
                timeh = ttime / 3600
                massbal.Grid.Col = 0
                massbal.Grid.Row = Rrow
                massbal.Grid.Text = Format$(timeh, "####.0000")
                For i = 1 To nrchmain
                    massbal.Grid.Col = Val(i)
                    massbal.Grid.Text = Format$(massbalerr(i) * 100, "##.0000")
                    If Abs(massbalerr(i)) > Abs(maxmberr) Then
                        maxmberr = Abs(massbalerr(i))
                        timemberr = timeh
                        rnmberr = Val(i)
                        verror = discreptstep(i)
                    End If
                Next i
                If numlat > 0 Then
                    For ii = 1 To numlat
                        For iiii = termreach(ii) To confreach(ii)
                            massbal.Grid.Col = Val(iiii)
                            massbal.Grid.Text = Format$(massbalerr(iiii) * 100, "##.0000")
                            If Abs(massbalerr(iiii)) > Abs(maxmberr) Then
                                maxmberr = Abs(massbalerr(iiii))
                                timemberr = timeh
                                rnmberr = Val(iiii)
                                verror = discreptstep(iiii)
                            End If
                        Next iiii
                    Next ii
                End If
            End If
        Next iii
'       record wetland outflows for each reach at end of hourly time increment
'
        For rn = 1 To nrchmain
            qwet(rn, n) = oreach(rn)
        Next rn
        If numlat > 0 Then
            For ii = 1 To numlat
                For rn = termreach(ii) To confreach(ii)
                    qwet(rn, n) = oreach(rn)
                Next rn
            Next ii
        End If
        bstor(n) = begstor
        estor(n) = endstor
        gwstor(n) = fluxtotal * dt
```

```
        nlstor(n) = latstor
        nlfrate(n) = latflux
        nlflux(n) = subflux
'       store wetland heads for plotting tracked field cell
        Call storeheads
        If runflag <> 1 Then
'           write to disphead.grid except under optimization mode
            Row = Row + 1
            timeh = ttime / 3600
            iter.Grid.Col = 0
            iter.Grid.Row = Row
            iter.Grid.Text = Format$(timeh, "###.###")
            iter.Grid.Col = 1
            iter.Grid.Text = Format$(numiter, "###")
            iter.Grid.Col = 2
            iter.Grid.Text = Format$(numstoriter, "###")
            iter.Grid.Col = 3
            iter.Grid.Text = Format$(routeiter, "###")
'
            flows.Grid.Col = 0
            flows.Grid.Row = Row
            flows.Grid.Text = Format$(timeh, "###.000")
            flows.Grid.Col = 1
            flows.Grid.Text = Format$(yreach(nrchmain), "###.000")
            flows.Grid.Col = 2
            flows.Grid.Text = Format$(oreach(nrchmain), "###.000")

            plotstor = 0
            For rn = 1 To nrchmain
                For ob = 1 To 2
                    If wetlen(rn, ob) > 0 Then
                        Call cmpsatdep(ob)
                        Call cmpstor(begstor, ob)
                        plotstor = plotstor + begstor
                    End If
                Next ob
            Next rn
            If numlat > 0 Then
                For ii = 1 To numlat
                    For rn = termreach(ii) To confreach(ii)
                        For ob = 1 To 2
                            If wetlen(rn, ob) > 0 Then
                                Call cmpsatdep(ob)
                                Call cmpstor(begstor, ob)
                                plotstor = plotstor + begstor
                            End If
                        Next ob
                    Next rn
                Next ii
            End If
        End If
    Loop
'
'   end of primary computational loop
'
finishup:
    nend = n
    If outopt(1) = 1 Then
        For i = 1 To tstophours
            Print #81, Format$(yhour(i), "0000"); Spc(5); Format$(zhour(i), "0000");
Spc(5); Format$(htime(i), "0000"); Spc(5); Format$(qwet(nrchmain, i), "000.000"); Spc(5);
Format$(raingross(i), "00.00"); Spc(5); Format$(raininter(i), "00.00"); Spc(5);
Format$(rainmm(i), "00.00"); Spc(5); zstring$(i)
        Next
    End If
'   compute final storage in wetland cell
'
    finalvol = 0
    For rn = 1 To nrchmain
        For ob = 1 To 2
            If wetlen(rn, ob) > 0 Then
                Call cmpsatdep(ob)
                Call cmpstor2(begstor, ob)
                finalvol = finalvol + begstor
            End If
        Next ob
    Next rn
    If numlat > 0 Then
        For ii = 1 To numlat
            For rn = termreach(ii) To confreach(ii)
                For ob = 1 To 2
```

```
                    If wetlen(rn, ob) > 0 Then
                        Call cmpsatdep(ob)
                        Call cmpstor2(begstor, ob)
                        finalvol = finalvol + begstor
                    End If
                Next ob
            Next rn
        Next ii
    End If
    disphead.Label16.Caption = Format$(finalvol, "##,###,###")
'
'   write data to default file
'
    If runflag = 2 Then
'       initialization run
'       write to beg file
        Call writebeg
'       write optimized parameters to file
        Open direct$ + event$ + ".prm" For Output As #88
'           wetland parameters
'           organic layer
            Print #88, Tab(5); Format$(orgcontop, "0.00000"); Tab(40); " Upper
Conductivity of Organic Layer"
            Print #88, Tab(5); Format$(orgconbot, "0.00000"); Tab(40); " Lower
Conductivity of Organic Layer"
            Print #88, Tab(5); Format$(orgstofc, "0.000"); Tab(40); "Storage Coefficient -
organic layer at field capacity"
'           hummock layer
            Print #88, Tab(5); Format$(humdep, "0.000"); Tab(40); "Depth of Hummock Layer"
            Print #88, Tab(5); Format$(humsto, "0.000"); Tab(40); "Storage Coefficient -
hummock layer"
            Print #88, Tab(5); Format$(surfcoeff, "000000.0"); Tab(40); "Surface friction
law coefficient"
            Print #88, Tab(5); Format$(beta, "0.00"); Tab(40); "Surface friction law
exponent"
        Close #88
        Open direct$ + event$ + ".clm" For Output As #88
'           abstractions
            Print #88, Tab(5); Format$(lai, "00.00"); Tab(40); "Leaf Area Index"
            Print #88, Tab(5); Format$(cancover, "00.00"); Tab(40); "Canopy coverage"
            Print #88, Tab(5); Format$(eqcoeff, "0.00"); Tab(40); "Equilibrium
coefficient"
            Print #88, Tab(5); Format$(ptcoeff, "0.00"); Tab(40); "Priestley-Taylor
coefficient"
            Print #88, Tab(5); Format$(baseflow, "0.000"); Tab(40); "Baseflow "
            Print #88, Tab(5); Format$(raincalib, "0.00"); Tab(40); "RFA coefficient"
        Close 88
    End If
'
'   Generate a month-end default file if appropriate
'
    If tstophours = numhoursmonth Then
    If runflag = 3 Then
        eventval = Val(event$)
        neweventval = eventval + 100
        newevent$ = LTrim$(Str$(neweventval))
'       initialization run .
'       write to structural default file
        Call writenextbeg
        Open direct$ + newevent$ + ".def" For Output As #88
'           wetland parameters
        Close 88
'       write optimized parameters to file
        Open direct$ + newevent$ + ".prm" For Output As #88
'           wetland parameters
'           organic layer
            Print #88, Tab(5); Format$(orgcontop, "0.00000"); Tab(40); " Upper
Conductivity of Organic Layer"
            Print #88, Tab(5); Format$(orgconbot, "0.00000"); Tab(40); " Lower
Conductivity of Organic Layer"
            Print #88, Tab(5); Format$(orgstofc, "0.000"); Tab(40); "Storage Coefficient -
organic layer at field capacity"
            Print #88, Tab(5); Format$(orgstowp, "0.000"); Tab(40); "Storage Coefficient -
organic layer at lower limit"
'           hummock layer
            Print #88, Tab(5); Format$(humdep, "0.000"); Tab(40); "Depth of Hummock Layer"
            Print #88, Tab(5); Format$(humsto, "0.000"); Tab(40); "Storage Coefficient -
hummock layer"
            Print #88, Tab(5); Format$(surfcoeff, "000000.0"); Tab(40); "Surface friction
law coefficient"
```

```
            Print #88, Tab(5); Format$(beta, "0.00"); Tab(40); "Surface friction law
exponent"
'           stream
            Print #88, Tab(5); Format$(bedslp(rn), "0.00000"); Tab(40); "Channel Bed
Slope"
            Print #88, Tab(5); Format$(cwid(rn), "00.0"); Tab(40); "Channel Width"
            Print #88, Tab(5); Format$(cdep(rn), "0.000"); Tab(40); "Channel depth"
            Print #88, Tab(5); Format$(crough(rn), "0.0000"); Tab(40); "Channel Roughness"
        Close #88
    End If
    End If
'
'--------------------Close output file and terminate program
'
'
'   assign appropriate values to summpage.frm
'
    summpage.Label14.Caption = Format$(wetwid(rn), "####.0")
    summpage.Label28.Caption = Format$(wetlen(rn, 1), "####.0")
    summpage.Label30.Caption = Format$(wetslp(rn), "0.00000")

'    summpage.Label31.Caption = Format$(orgdep, "#0.000")
    summpage.Label32.Caption = Format$(orgcontop, "##.0000000")
    summpage.Label33.Caption = Format$(orgsto, "0.000")

    summpage.Label44.Caption = Format$(humdep, "0.000")
    summpage.Label45.Caption = Format$(surfcoeff, "######.0")
    summpage.Label46.Caption = Format$(beta, "0.000")
    summpage.Label47.Caption = Format$(humsto, "0.0000")

    summpage.Label34.Caption = Format$(bedslp(rn), "0.00000")
    summpage.Label35.Caption = Format$(cwid(rn), "####.000")
    summpage.Label36.Caption = Format$(crough(rn), "0.0000")

    dthours = 1 / nsteps
    summpage.Label37.Caption = Format$(dthours, "0.000")
    summpage.Label38.Caption = Format$(nx, "####")
    summpage.Label39.Caption = block$
    tdur = tstophours - tstarthours + 1
    summpage.Label40.Caption = Format$(tdur, "####.00")
    summpage.Label41.Caption = Format$(petday, "##.0")
    summpage.Label42.Caption = Format$(baseflow, "##.000")
    summpage.Label43.Caption = Format$(raincalib, "#.0")
    summpage.Label81.Caption = Format$(hwet(rn, 1, nxmid), "###.000")
    summpage.Label82.Caption = Format$(hwet(rn, 1, nx - 1), "###.000")
    summpage.Label79.Caption = Format$(oreach(nrchmain), "###.000")
    summpage.Label80.Caption = Format$(hreach(nrchmain), "###.000")
    summpage.Label86.Caption = Format$(sreachfinal, "###.000")
    summpage.Label84.Caption = Format$(2 * initstor, "#########.0")
    summpage.Label83.Caption = Format$(2 * finalstor, "#########.0")
    summpage.Label71.Caption = Format$(qpchan, "###.000")
    summpage.Label72.Caption = Format$(tpchan, "###.000")
    summpage.Label91.Caption = Format$(precchan / 1000, "#####.0")
    summpage.Label90.Caption = Format$(2 * precusz / 1000, "########.0")
    summpage.Label89.Caption = Format$(2 * etusz / 1000, "########.0")
    summpage.Label96.Caption = Format$(intertotal * surfarea / 1000, "##########.0")
    summpage.Label97.Caption = Format$(tpgross / 1000, "##########.0")
    summpage.Label75.Caption = Format$(tpthrough * surfarea / 1000, "########.0")
    summpage.Label77.Caption = Format$(2 * etsz / 1000, "########.0")
    summpage.Label69.Caption = Format$(2 * precsz / 1000, "########.0")
'   compute net change in channel storage
    deltachanstor = sreachfinal - sreachinit
    summpage.Label73.Caption = Format$(deltachanstor, "###.000")
'   compute lateral outflow volume (m3)
    summpage.Label76.Caption = Format$(-2 * gwtotal, "######.0")
    dstor = 2 * (finalstor - initstor)
    summpage.Label78.Caption = Format$(dstor, "######.0")
    summpage.Label94.Caption = Format$(ovolume - ireachtotal, "######.0")
'   compute net mass balance
'       I-O=delta S
    tinf = (-2 * gwtotal + tpgross / 1000 + precchan / 1000) + ireachtotal
    tout = ovolume + intertotal * surfarea / 1000 + 2 * etsz / 1000 + 2 * etusz / 1000
    tdeltastor = deltachanstor + dstor
    massball = (tinf - tout) - tdeltastor
    summpage.Label74.Caption = Format$(massball, "########.0")
'   return mouse pointer to default
    main.MousePointer = 0
    If outopt(1) = 1 Then
        Close #81
    End If
    If outopt(2) = 1 Then
```

```
        Close #18
    End If
    If outopt(3) = 1 Then
        Close #15
    End If
    If outopt(4) = 1 Then
        Close #16
    End If
    If outopt(5) = 1 Then
        Close #17
    End If
    If outopt(6) = 1 Then
        Close #55
    End If
    If outopt(7) = 1 Then
        Close #56
    End If
    If outopt(8) = 1 Then
        Close #57
    End If
    If runflag <> 1 Then
        Open "simpstor.def" For Output As #82
            Print #82, direct$
            Print #82, event$
        Close 82
    End If
'
'   display program output
'
    If runflag = 2 Or runflag = 3 Then
        Unload runmess
    End If

    If runflag = 2 Then
        If n <> tstophours Then
            aa1 = MsgBox("Wetland levels initialized to equilibrium conditions", 64,
"Multi")
        Else
            aa1 = MsgBox("Wetland levels not initialized to equilibrium conditions", 16,
"Multi")
        End If
    End If
    If runflag = 3 Then
'       display main output form
'       evaluate performance criterion
        Call nash
        disphead.Show
    End If
    If runflag = 2 Then
'       display main output form under initialization run
        disphead.Show
    End If
    If runflag = 3 Then
'       display mass balance summaries
        massbal.Label4.Caption = Format$(maxmberr * 100, "####.000")
        massbal.Label6.Caption = Format$(timemberr, "####.0000")
        massbal.Label5.Caption = Format$(rnmberr, "####")
        massbal.Label7.Caption = Format$(discreptotal, "#############.00")
        massbal.Label8.Caption = Format$(inflowtotal, "#############.00")
        massbal.Label9.Caption = Format$(outflowtotal, "#############.00")
        totmberr = discreptotal / inflowtotal
        massbal.Label10.Caption = Format$(totmberr * 100, "####.000")
        massbal.Label30.Caption = Format$(verror, "#############.00")
    End If

End Sub
```

```
Sub init2 ()
' ----------------------------------------------------------------------
'
'       Subroutine: init2
'       Purpose:    to initialize wetland heads
' ----------------------------------------------------------------------
        nxm1 = nx - 1
        nxm2 = nx - 2
        nxm3 = nx - 3
        For i = 1 To nrchmain
            For j = 1 To 2
                hwet(i, j, 1) = hreach(i)
                hold(i, j, 1) = hreach(i)
                hprev(i, j, 1) = hreach(i)
            Next j
        Next i
        For i = 1 To nrchmain
            For j = 1 To 2
                For k = 2 To nx
                    hold(i, j, k) = hwet(i, j, k)
                    hprev(i, j, k) = hold(i, j, k)
                Next k
            Next j
        Next i
        If numlat > 0 Then
            For ii = 1 To numlat
                For i = termreach(ii) To confreach(ii)
                    For j = 1 To 2
                        hwet(i, j, 1) = hreach(i)
                        hold(i, j, 1) = hreach(i)
                        hprev(i, j, 1) = hreach(i)
                    Next j
                Next
                For i = termreach(ii) To confreach(ii)
                    For j = 1 To 2
                        For k = 2 To nx
                            hold(i, j, k) = hwet(i, j, k)
                            hprev(i, j, k) = hold(i, j, k)
                        Next k
                    Next j
                Next
            Next
        End If
'       compute channel surface area
'
        chansurfarea = 0
        For i = 1 To nrchmain
            chansurfarea = chansurfarea + cwid(i) * wetwid(i)
        Next i
        If numlat > 0 Then
            For ii = 1 To numlat
                For i = termreach(ii) To confreach(ii)
                    chansurfarea = chansurfarea + cwid(i) * wetwid(i)
                Next
            Next
        End If
End Sub
```

```
Sub interp (zz3, zz1, zz2, aa1, aa2, aa3)
' --------------------------------------------------------------------------
'
'       Subroutine: interp
'       Purpose:    to perform linear interpolation
' --------------------------------------------------------------------------
    schor = aa2 - aa1
    scver = zz2 - zz1
    dver = zz3 - zz1
    dhor = dver * (schor / scver)
    aa3 = aa1 + dhor
End Sub
```

```
Sub nash ()
' ------------------------------------------------------------------------
'
'       Subroutine: nash
'       Purpose:    to evaluate goodness of fit criteria
'                   1) Nash-Sutcliffe coefficient
'                   2) S-Criterion
'                   3) RMS
'                   4) error in peak flow rate
' ------------------------------------------------------------------------
'   read in lakewood data
    plotlakefile$ = event$ + ".lak"
    Open direct$ + plotlakefile$ For Input As #7
    For i = 1 To 11
        Line Input #7, dummy$
    Next
    For i = 1 To tstophours
        Input #7, yhour(i), stage, qlake(i), zhour(i), zstring$(i)
    Next
    Close #7
'   compute average observed hourly flow over the observation period
    qtotal = 0
    ncount = 0
    For i = 1 To tstophours
        ncount = ncount + 1
        qtotal = qtotal + qlake(i)
    Next
    qbar = qtotal / ncount
'   compute nash-sutcliffe coeff.
    numer = 0
    denom = 0
    For i = 1 To tstophours
            numer = numer + (qwet(nrchmain, i) - qlake(i)) ^ 2
            denom = denom + (qwet(nrchmain, i) - qbar) ^ 2
    Next
    nashcoeff = 1 - (numer / denom)
'
'   compute S criterion  (WMO)
'
    scriter = (Sqr(numer / ncount)) / qbar
'
'   compute root mean square value
'
    numer = 0
    denom = 0
    For i = 1 To tstophours
            numer = numer + ((qwet(nrchmain, i) - qlake(i)) ^ 2) / ncount
    Next
    rmscoeff = numer ^ .5
'
'   compute error in peak discharge
'
            peaklake = 0
            peakwet = 0
            For i = 1 To tstophours
                If qwet(nrchmain, i) > peakwet Then peakwet = qwet(nrchmain, i)
                If qlake(i) > peaklake Then peaklake = qlake(i)
            Next
            eecoeff = (peaklake - peakwet) / peaklake * 100
'
'   compute total runoff volume from hourly flows
'
    rvol = 0
    lvol = 0
    For i = 1 To (tstophours - 1)
            qaver = (qwet(nrchmain, i) + qwet(nrchmain, (i + 1))) / 2
            rvol = rvol + qaver * 3600
            qaver = (qlake(i) + qlake(i + 1)) / 2
            lvol = lvol + qaver * 3600
    Next

End Sub
```

```
Sub normal (nn, qq, s0, yy)
' -----------------------------------------------------------------------
'
'       Subroutine: normal
'       Purpose:    to compute normal depth for rectangular
'                   channel using Newton-Raphson routine
' -----------------------------------------------------------------------
    cc1 = crough(nn) * qq / Sqr(s0)
    cc2 = 2
    errval = 1000000#
    yest = .4
    tol = .001
    Do While errval > tol
        chanarea = cwid(nn) * yest
        chantopw = cwid(nn)
        chanperim = cwid(nn) + 2 + yest
        chanhr = chanarea / chanperim
        fy = chanarea * chanhr ^ .6667 - cc1
        dfdy = 1.6667 * chantopw * chanhr ^ .6667 - .66667 * chanhr ^ 1.66667 * cc2
        yrev = yest - fy / dfdy
        errval = Abs((yrev - yest) / yrev)
        yest = yrev
    Loop
    yy = yest

End Sub
```

```
Sub nraphson (cc1, cc2, cc3, yguess, ynrtol, yest)
' ---------------------------------------------------------------------------
'
'       Subroutine: nraphson
'       Purpose:    to root solve using Newton Raphson routine
' ---------------------------------------------------------------------------
        errval = 100000
        yest = yguess
        Do While errval > .001
            arevised = cwid(rn) * yest
            prevised = cwid(rn) + 2 * yest
            hrevised = arevised / prevised
            fy = cc2 - cc3 * yest - cc1 * arevised * hrevised ^ (2 / 3)
            dfdy = -cc3 - cc1 * (5 / 3) * cwid(rn) * hrevised ^ (2 / 3) + cc1 * (2 / 3) *
2 * hrevised ^ (5 / 3)
            yrev = yest - fy / dfdy
            If yrev < 0 Then yrev = .001
            errval = Abs(yrev - yest)
            yest = yrev
        Loop

End Sub
```

```
Sub optimiz ()
' -------------------------------------------------------------------------
'
'       Subroutine: optimiz
'       Purpose:    to perform a complete optimization of the model parameters
'                   using Hooke and Jeeves (1971) routine as modified by Nick Kouwen
'                   of the University of Waterloo
'
' -------------------------------------------------------------------------
'
'   optimization subroutine
'
2000 ' ..... SUBROUTINE OPT
2010 If nstart > 0 Then 2200
2020 ' ..... INITIALIZATION ROUTINE
2030 For i = 1 To numa
2040    les(i) = 0
2050    optba(i) = opta(i): optb(i) = opta(i)
2060    iclosl(i) = 0
2070    iclosh(i) = 0
2080    If optnper > 0 Then 2110
2090    delta(i) = ddelta(i)
2100    GoTo 2120
2110    delta(i) = Abs(ddelta(i) * opta(i))
2120    optcc = opta(i) - 1.01 * delta(i)
2130    If optcc <= checkl(i) Then 4000
2140    optcc = opta(i) + 1.01 * delta(i)
2150    If optcc >= checkh(i) Then 4000
2160 Next i
2170 lc = 0
    it = 1
    izy = 0
    optnn = 0
    NCOUN = 1
    ICOUN = 0
    ifirs = 0
    LDELT = 0
    nstart = 1
    nsave = 0

2180 Print #40, "INITIAL VALUES OF THE COEFFICIENTS:"
2190 Print #40, "TRIAL RUN CRITERIA"
2200 optys = optim
2210 optnn = optnn + 1
2220 If optnn > maxn Then
'          Print "ALLOWABLE # ITERATIONS EXCEEDED"
         flag$ = "T"
         GoTo 4000
     End If
2230 If ifirs = 1 Then 2250
2240 optyx = optim
     optyy = optyx
     ifirs = 1
2250 Print #40, NCOUN; optnn; optys;
    For i = 1 To numa
        Print #40, Format$(opta(i), "####.####");
    Next i
    Print #40,
2260 If les(it) = 1 Then 2590
2270 If izy > 0 Then 2420
2280 If optys > optyy Then 2300
2290 nsave = 1
     optyx = optys
     optyy = optys
2300 Print #40, "TRIAL RUN CRITERIA"
2310 izy = izy + 1
     it = izy
2320 If les(izy) = 1 Then 2640
2330 ll = 0
2340 '
2350 ' ..... LOCAL EXCURSION ROUTINE
2360 ' ..... LOCAL EXCURSION WITH +VE DELTA(I) FIRST
2370 opta(izy) = opta(izy) + delta(izy)
2380 nsign(izy) = 0
2390 If iclosh(izy) = 0 Then 2410
2400 ll = ll + 1: GoTo 2430
2410 ll = ll + 1: GoTo 4000
2420 If optyx > optys Then 2510
2430 On ll GoTo 2440, 2480, 2520
2440 opta(izy) = opta(izy) - 2 * delta(izy)
2450 nsign(izy) = 1
```

```
2460 If iclosh(izy) = 1 Then 2480
2470 GoTo 2410
2480 opta(izy) = opta(izy) + delta(izy)
2490 nsign(izy) = 0
2500 GoTo 2520
2510 optyx = optys
2520 If izy < numa Then 2310
2530 it = 1
     izy = 0
2540 If optyy = optyx Then 3060
2550 optyy = optyx: GoTo 2830
2560 '
2570 ' ..... LOCAL EXCURSION WITH -VE DELTA(I) FIRST
2580 '
2590 If izy > 0 Then 2700
2600 If optys > optyy Then 2620
2610 nsave = 1
     optyx = optys
     optyy = optys
2620 izy = izy + 1
     it = izy
2630 If les(izy) = 0 Then 2330
2640 ll = 0
2650 opta(izy) = opta(izy) - delta(izy)
2660 nsign(izy) = 1
2670 If iclosl(izy) = 0 Then 2690
2680 ll = ll + 1: GoTo 2710
2690 ll = ll + 1: GoTo 4000
2700 If optyx > optys Then 2780
2710 On ll GoTo 2720, 2760, 2790
2720 opta(izy) = opta(izy) + 2 * delta(izy)
2730 nsign(izy) = 0
2740 If iclosh(izy) = 1 Then 2760
2750 GoTo 2690
2760 opta(izy) = opta(izy) - delta(izy)
2770 nsign(izy) = 1: GoTo 2790
2780 optyx = optys
2790 If izy < numa Then 2620
2800 it = 1
     izy = 0
2810 If optyy = optyx Then 3060
2820 optyy = optyx
2830 If optnper = 0 Then 2870
2840 For i = 1 To numa
2850    delta(i) = Abs(ddelta(i) * opta(i))
2860 Next i
2870 lc = 0
     nsave = 0
2880 Print #40, NCOUN; optnn; optyy;
   For i = 1 To numa
       Print #40, Format$(opta(i), "####.####");
   Next i
   Print #40,
2890 Print #40, "     PATTERN MOVE"
2900 NCOUN = NCOUN + 1
2910 ' ..... PATTERN MOVE ROUTINE
2920 For i = 1 To numa
2930    les(i) = nsign(i)
        optba(i) = opta(i)
        opta(i) = 2 * opta(i) - optb(i)
2940    ' .... CHECH UPPER AND LOWER CONSTRAINTS
2950    optcc = opta(i) - 1.01 * delta(i)
2960    optcd = opta(i) + 1.01 * delta(i)
2970    If optcc > checkl(i) Then 2990
2980    iclosl(i) = 1
        opta(i) = optba(i)
        GoTo 3000
2990    iclosl(i) = 0
3000    If optcd < checkh(i) Then 3020
3010    iclosh(i) = 1
        opta(i) = optba(i)
        GoTo 3030
3020    iclosh(i) = 0
3030    optb(i) = optba(i)
3040 Next i
3050 GoTo 4000
3060 lc = lc + 1
3070 '
3080 ' ..... DESTROY PRESENT PATTERN
3090 If lc <= 0 Then
'        Print "STOPPED LINE 3010"
```

```
        End
     End If
3100 If lc = 1 Then 3120
3110 If lc >= 2 Then 3170
3120 If nsave = 1 Then 3200
3130 For i = 1 To numa
3140    opta(i) = optba(i)
3150 Next i
3160 ICOUN = ICOUN + 1
     GoTo 3260
3170 If LDELT >= kc Then
'         Print "SMALLEST RESOLUTION REACHED"
        flag$ = "T"
        GoTo 4000
     End If
3180 '
3190 ' ..... HALVE DELTA(I) (RESOLUTION)
3200 nsave = 0
3210 For i = 1 To numa
3220    ddelta(i) = ddelta(i) / 2
3230    delta(i) = delta(i) / 2
3240 Next i
3250 LDELT = LDELT + 1
3260 Print #40, "PATTERN= "; ICOUN; " RESOLUTION= "; LDELT
3270 Print #40, NCOUN; optnn; optyy;
    For i = 1 To numa
        Print #40, Format$(opta(i), "####.####");
    Next i
    Print #40,
3280 GoTo 2260
4000    'exit subroutine
End Sub
```

```
Sub reach ()
' -------------------------------------------------------------------------
'
'       Subroutine: reach
'       Purpose:    to solve the wetland model for a given reach
' -------------------------------------------------------------------------
    weight = .95
    qlat1reach = qlat(rn)
    ob = 1
    If wetlen(rn, ob) > 0 Then
'       reach has wetland interface
'       assign prescribed head boundary to wetland flow model
        hwet(rn, ob, 1) = hreach1prev
        hold(rn, ob, 1) = hwet(rn, ob, 1)
        Call applflux(ob)
'       compute mass balance (m3)
        gwtstep = 0
        tptstep = 0
        evtstep = 0
        For i = 2 To nxm1
            gwtstep = gwtstep + qs(i) * dt
            tptstep = tptstep + qr(i) * dt
            evtstep = evtstep + qe(i) * dt
        Next
        gwtotaltstep = gwtotaltstep + gwtstep
        tptotaltstep = tptotaltstep + tptstep
        evtotaltstep = evtotaltstep + evtstep
'       compute cumulative inflow (m3)
        fluxstor = fluxstor + fluxtotal * dt
        Call cmpsatdep(ob)
        Call cmpstor2(begstor, ob)
        begstortstep = begstor
        Call satstatus(ob)
        Call wetmodel(rn, ob)
'       compute lateral flux rate based on revised hwet values
        Call cmpsatdep(ob)
        Call cmpstor2(endstortrial, ob)
        endstortrialtstep = endstortrial
        Call cmpflux(endstortrial, begstor, latflux)
        qlat2reach = latflux
    Else
        qlat2reach = 0
    End If
    ob = 2
    If wetlen(rn, ob) > 0 Then
        If wetlen(rn, ob) = wetlen(rn, 1) Then
'           wetland is symmetrical about stream
            qlat2reach = qlat2reach * 2
            gwtotaltstep = gwtotaltstep + gwtstep
            tptotaltstep = tptotaltstep + tptstep
            evtotaltstep = evtotaltstep + evtstep
            begstortstep = begstortstep + begstor
            endstortrialtstep = endstortrialtstep + endstortrial
            fluxstor = fluxstor * 2
        Else
'           right overbank is a different size
'           reach has wetland interface
'           assign prescribed head boundary to wetland flow model
            hwet(rn, ob, 1) = hreach1prev
            hold(rn, ob, 1) = hwet(rn, ob, 1)
            Call applflux(ob)
'           compute mass balance (m3)
            gwtstep = 0
            tptstep = 0
            evtstep = 0
            For i = 2 To nxm1
                gwtstep = gwtstep + qs(i) * dt
                tptstep = tptstep + qr(i) * dt
                evtstep = evtstep + qe(i) * dt
            Next
            gwtotaltstep = gwtotaltstep + gwtstep
            tptotaltstep = tptotaltstep + tptstep
            evtotaltstep = evtotaltstep + evtstep
'           compute cumulative inflow (m3)
            fluxstor = fluxstor + fluxtotal * dt
            Call cmpsatdep(ob)
            Call cmpstor2(begstor, ob)
            begstortstep = begstortstep + begstor
            Call satstatus(ob)
            Call wetmodel(rn, ob)
'           compute lateral flux rate based on revised hwet values
```

```
            Call cmpsatdep(ob)
            Call cmpstor2(endstortrial, ob)
            endstortrialtstep = endstortrialtstep + endstortrial
            Call cmpflux(endstortrial, begstor, latflux)
            qlat2reach = qlat2reach + latflux
        End If
    Else
        qlat2reach = qlat2reach + 0
    End If
'
'   solve storage routing procedure
    routeiter = 0
    Call route(ytrial, otrial, strial)
'   update channel flow parameters
    htrial = ytrial + bedinv(rn)
    hcomp = hreach1prev
    hrevised = htrial
    htrial = hrevised * (1 - weight) + (hcomp * (weight))
reroute1:
'   re-solve the wetland flow model
'
'   solve left bank first (ob=1)
    ob = 1
    If wetlen(rn, ob) > 0 Then
'       reach has wetland interface
'       assign prescribed head boundary to wetland flow model
        hwet(rn, ob, 1) = htrial
        hold(rn, ob, 1) = hwet(rn, ob, 1)
        For i = 2 To nx
            hwet(rn, ob, i) = hold(rn, ob, i)
            hprev(rn, ob, i) = hwet(rn, ob, i)
        Next
        Call applflux(ob)
        Call cmpsatdep(ob)
        Call satstatus(ob)
        Call wetmodel(rn, ob)
'       compute lateral flux rate based on revised hwet values
        Call cmpsatdep(ob)
        Call cmpstor2(endstortrial, ob)
        endstortrialtstep = endstortrial

        Call cmpflux(endstortrial, begstor, latflux)
        qlat2reach = latflux
    Else
        qlat2reach = 0
    End If
    ob = 2
    If wetlen(rn, ob) > 0 Then
        If wetlen(rn, ob) = wetlen(rn, 1) Then
'           wetland is symmetrical about stream
            qlat2reach = qlat2reach * 2
            endstortrialtstep = endstortrialtstep + endstortrial
        Else
'           right overbank is a different size
'           reach has wetland interface
'           assign prescribed head boundary to wetland flow model
            hwet(rn, ob, 1) = htrial
            hold(rn, ob, 1) = hwet(rn, ob, 1)
            For i = 2 To nx
                hwet(rn, ob, i) = hold(rn, ob, i)
                hprev(rn, ob, i) = hwet(rn, ob, i)
            Next
            Call applflux(ob)
            Call cmpsatdep(ob)
            Call satstatus(ob)
            Call wetmodel(rn, ob)
'           compute lateral flux rate based on revised hwet values
            Call cmpsatdep(ob)
            Call cmpstor2(endstortrial, ob)
            endstortrialtstep = endstortrialtstep + endstortrial
            Call cmpflux(endstortrial, begstor, latflux)
            qlat2reach = qlat2reach + latflux
        End If
    Else
        qlat2reach = qlat2reach + 0
    End If
'
'   solve routing model to establish a new stream level
    Call route(ytrial, otrial, strial)
'   update channel flow parameters
    hrevised = ytrial + bedinv(rn)
```

```
    If (Abs(hrevised - htrial)) > .001 Then
        routeiter = routeiter + 1
        hcomp = htrial
'       new trial value for the stream head
        htrial = hrevised * (1 - weight) + hcomp * (weight)
        If routeiter <= 100 Then
            weight = .95
        End If
'       if iteration count exceeds 100 then apply relaxation
        If routeiter > 100 Then
             weight = weight - .01
             htrial = hrevised * (1 - weight) + hcomp * (weight)
        End If
        If routeiter > 150 Then
            Stop
        End If
        GoTo reroute1:
    End If
'   after completion of the solution:
'   establish parameters for next time step
    ob = 1
    For i = 2 To nx
        hold(rn, ob, i) = hwet(rn, ob, i)
        hprev(rn, ob, i) = hwet(rn, ob, i)
    Next
    ob = 2
    If wetlen(rn, ob) = wetlen(rn, 1) Then
'   symmetrical overbanks
        For i = 2 To nx
            hwet(rn, ob, i) = hwet(rn, 1, i)
            hold(rn, ob, i) = hwet(rn, 1, i)
            hprev(rn, ob, i) = hwet(rn, 1, i)
        Next
    Else
        For i = 2 To nx
            hold(rn, ob, i) = hwet(rn, ob, i)
            hprev(rn, ob, i) = hwet(rn, ob, i)
        Next
    End If
    yreach(rn) = ytrial
    hreach(rn) = yreach(rn) + bedinv(rn)
    areach(rn) = cwid(rn) * yreach(rn)
    preach = cwid(rn) + 2 * yreach(rn)
    rreach = areach(rn) / preach
    oreach(rn) = 1 / crough(rn) * areach(rn) * rreach ^ (2 / 3) * bedslp(rn) ^ (.5)
    sreach(rn) = wetwid(rn) * areach(rn)
    qlat(rn) = qlat2reach
    deltastortstep(rn) = endstortrialtstep - begstortstep
    oaverage = (-(qlat1reach + qlat2reach) / 2) * dt + evtotaltstep
    iaverage = -(gwtotaltstep + tptotaltstep)
'   compute error in volume for time step (m3)
    discrep = ((iaverage - oaverage) - deltastortstep(rn))
    discreptotal = discreptotal + Abs(discrep)
    inflowtotal = inflowtotal + iaverage
    outflowtotal = outflowtotal + oaverage
    massbalerr(rn) = ((iaverage - oaverage) - deltastortstep(rn)) / iaverage
    discreptstep(rn) = ((iaverage - oaverage) - deltastortstep(rn))
End Sub
```

```
Sub readbeg ()
' ----------------------------------------------------------------------
'       Subroutine: readbeg
'       Purpose:    to read in primary input data [filename.beg]
' ----------------------------------------------------------------------
    Open direct$ + begfile$ For Input As #22
'
        Input #22, nrchmain
        Input #22, nx
        For i = 1 To nrchmain
            Input #22, ireach(i), oreach(i), yreach(i)
        Next
        For i = 1 To nrchmain
            Input #22, i, wetwid(i), hreach(i), bedinv(i), tbelev(i)
            For k = 1 To nx
                For j = 1 To 2
                    Input #22, hwet(i, j, k), dx(i, j, k), toporgelev(i, j, k),
topsedelev(i, j, k), tophumelev(i, j, k)
                Next j
            Next k
        Next i
        For i = 1 To nrchmain
            Input #22, i, qlat(i)
        Next i
        Input #22, numlat
'
'       read data for laterals
'
        If numlat > 0 Then
            For ii = 1 To numlat
                For i = termreach(ii) To confreach(ii)
                    Input #22, ireach(i), oreach(i), yreach(i)
                Next
                For i = termreach(ii) To confreach(ii)
                    Input #22, i, wetwid(i), hreach(i), bedinv(i), tbelev(i)
                    For k = 1 To nx
                        For j = 1 To 2
                            Input #22, hwet(i, j, k), dx(i, j, k), toporgelev(i, j, k),
topsedelev(i, j, k), tophumelev(i, j, k)
                        Next j
                    Next k
                Next
                For i = termreach(ii) To confreach(ii)
                    Input #22, i, qlat(i)
                Next i
            Next
        End If
    Close #22

End Sub
```

```
Sub readparam ()
' -----------------------------------------------------------------------
'
'       Subroutine: readparam
'       Purpose:    to read in wetland modelling parameters
' -----------------------------------------------------------------------
        Open direct$ + "sunnside.prm" For Input As #88
'           wetland parameters
'           organic layer
            Line Input #88, dumm$
            orgcontop = Val(RTrim$(LTrim$(Left$(dumm$, 20))))
            Line Input #88, dumm$
            orgconbot = Val(RTrim$(LTrim$(Left$(dumm$, 20))))
            Line Input #88, dumm$
            orgstofc = Val(RTrim$(LTrim$(Left$(dumm$, 20))))
'           hummock layer
            Line Input #88, dumm$
            humdep = Val(RTrim$(LTrim$(Left$(dumm$, 20))))
            Line Input #88, dumm$
            humsto = Val(RTrim$(LTrim$(Left$(dumm$, 20))))
            Line Input #88, dumm$
            surfcoeff = Val(RTrim$(LTrim$(Left$(dumm$, 20))))
            Line Input #88, dumm$
            beta = Val(RTrim$(LTrim$(Left$(dumm$, 20))))
        Close 88
        Open direct$ + event$ + ".clm" For Input As #88
'           read in monthly climate/abstraction data
'           abstractions
            Line Input #88, dumm$
            lai = Val(RTrim$(LTrim$(Left$(dumm$, 20))))
            Line Input #88, dumm$
            cancover = Val(RTrim$(LTrim$(Left$(dumm$, 20))))
            Line Input #88, dumm$
            eqcoeff = Val(RTrim$(LTrim$(Left$(dumm$, 20))))
            Line Input #88, dumm$
            ptcoeff = Val(RTrim$(LTrim$(Left$(dumm$, 20))))
            Line Input #88, dumm$
            baseflow = Val(RTrim$(LTrim$(Left$(dumm$, 20))))
            Line Input #88, dumm$
            raincalib = Val(RTrim$(LTrim$(Left$(dumm$, 20))))
        Close 88
'
'   read in reach parameters
'
    Open direct$ + "multi.wfc" For Input As #88
        Line Input #88, comment1$
        Line Input #88, comment2$
        Line Input #88, comment3$
        Line Input #88, comment4$
        Line Input #88, comment5$
        Line Input #88, dummy$
        Input #88, nrchmain
        rchcounter = nrchmain
        Line Input #88, dummy$
        Line Input #88, dummy$
        For i = 1 To nrchmain
            Input #88, reachno(i), wetwid(i), wetlen(i, 1), wetlen(i, 2), cwid(i),
cdep(i), orgdep(i), crough(i), bedslp(i), wetslp(i)
            bedinv(i) = 99
            tbelev(i) = bedinv(i) + cdep(i)
            baseelev(i) = tbelev(i) - orgdep(i)
        Next i
'
'       read in laterals
'
        Line Input #88, dummy$
        Line Input #88, dummy$
        numlat = RTrim$(LTrim$(Left$(dummy$, 20)))
        If numlat > 0 Then
            For i = 1 To numlat
'               read in lateral id number
                Line Input #88, dummy$
                latid(i) = RTrim$(LTrim$(Left$(dummy$, 20)))
'               read in number of reaches defining the lateral
                Line Input #88, dummy$
                nrchlat(i) = RTrim$(LTrim$(Left$(dummy$, 20)))
'               read in most upstream reach number
                Line Input #88, dummy$
                termreach(i) = RTrim$(LTrim$(Left$(dummy$, 20)))
'               read in most downstream reach number
                Line Input #88, dummy$
```

```
                confreach(i) = RTrim$(LTrim$(Left$(dummy$, 20)))
'               read in main channel reach to be combined with lateral
                Line Input #88, dummy$
                combreach(i) = RTrim$(LTrim$(Left$(dummy$, 20)))
                For ii = termreach(i) To confreach(i)
                    Input #88, reachno(ii), wetwid(ii), wetlen(ii, 1), wetlen(ii, 2),
cwid(ii), cdep(ii), orgdep(ii), crough(ii), bedslp(ii), wetslp(ii)
                    bedinv(ii) = 99
                    tbelev(ii) = bedinv(ii) + cdep(ii)
                    baseelev(ii) = tbelev(ii) - orgdep(ii)
                Next ii
            Next
        End If
    Close #88
End Sub
```

```
Sub route (yrevised, orevised, srevised)
' ----------------------------------------------------------------------
'
'       Subroutine: route
'       Purpose:    to perform channel routing of wetland stormflows
'                   using a storage routing approach
' ----------------------------------------------------------------------
'
        ytol = .001
        ynrtol = .001
        yiter = 0
        ilat = -1 * (qlat1reach + qlat2reach)
        irch = ireach1 + ireach2
        orch = oreach1
'       include precipitation falling directly on channel (m3/s)
        iprecip = wetwid(rn) * cwid(rn) * rainchan / 3600000
        sreach(rn) = wetwid(rn) * yreach(rn) * cwid(rn)
        yguess = yreach(rn)
'       compute normal depth using Newton-Raphson Solver
        cc1 = Sqr(bedslp(rn)) / crough(rn)
        cc2 = (2 * iprecip) + irch + ilat - orch + (2 / dt * sreach(rn))
        cc3 = 2 * cwid(rn) * wetwid(rn) / dt
        Call nraphson(cc1, cc2, cc3, yguess, ynrtol, yest)
        yrevised = yest
        hrevised = yrevised + bedinv(rn)
        arevised = cwid(rn) * yrevised
        previsED = cwid(rn) + 2 * yrevised
        rrevised = arevised / prevised
        orevised = 1 / crough(rn) * arevised * rrevised ^ (2 / 3) * bedslp(rn) ^ (.5)
        srevised = wetwid(rn) * arevised

End Sub
```

```
Sub satstatus (ob)
' -------------------------------------------------------------------------
'
'       Subroutine: satstatus
'       Purpose:    to assign saturation status flag to each grid block
' -------------------------------------------------------------------------
    For i = 1 To nx
'       identify saturation state of each grid block
        If hwet(rn, ob, i) > toporgelev(rn, ob, i) Then
'           block is saturated at beginning of time step
            statusflag(i) = 2
        Else
'           block is unsaturated at beginning of time step
            statusflag(i) = 1
        End If
    Next i
End Sub
```

```
Sub storeheads ()
' ---------------------------------------------------------------------------
'
'       Subroutine: storeheads
'       Purpose:    to store wetland heads for plotting
' ---------------------------------------------------------------------------
            For k = 1 To nx
                hstor(k, n) = hwet(rntrack, 1, k)
            Next k
End Sub
```

```
Sub thomas ()
' -------------------------------------------------------------------------
'
'       Subroutine: thomas
'       Purpose:    to solve tri-diagonal matrix using Thomas solver
' -------------------------------------------------------------------------
    For i = 2 To nxm2
        dd = aa(i) / ab(i - 1)
        ab(i) = ab(i) - ac(i - 1) * dd
        bb(i) = bb(i) - bb(i - 1) * dd
    Next
'   back substitution
    xx(nxm2) = bb(nxm2) / ab(nxm2)
    For i = 1 To nxm3
        j = nxm2 - i
        xx(j) = (bb(j) - ac(j) * xx(j + 1)) / ab(j)
    Next
'   corrected heads
    For i = 1 To nxm2
        hwet(rn, ob, i + 1) = xx(i)
    Next
    hwet(rn, ob, nx) = hwet(rn, ob, nxm1)
End Sub
```

```
Sub updateprogress (pb As Control, ByVal percent, progstring$)
' ---------------------------------------------------------------------------
'
'       Subroutine: updateprogress
'       Purpose:    to udate the screen progress bar
' ---------------------------------------------------------------------------
Dim numm$
If Not pb.AutoRedraw Then
    pb.AutoRedraw = -1
End If
pb.Cls
pb.ScaleWidth = 100
pb.DrawMode = 10

numm$ = Format$(percent, "##0") + "%"
pb.CurrentX = 50 - pb.TextWidth(progstring$) / 2
pb.CurrentY = (pb.ScaleHeight - pb.TextHeight(progstring$)) / 2
pb.Print progstring$

pb.Line (0, 0)-(percent, pb.ScaleHeight), , BF
' pb.Refresh
End Sub
```

```
Sub wetmodel (rn, ob)
' -------------------------------------------------------------------------
'
'       Subroutine: wetmodel
'       Purpose:    primary subroutine to solve wetland field hydrology
'                   model
'       Procedure:  this module performs the following:
'                   1) establishes currsatflag in each grid block
'                   2) establishes satflag in each grid block
'                   3) computes saturated depths in each grid block
'                   4) computes depth average hyd. cond.
'                   5) computes appropriate storativity
'                   6) generates coefficient matrix and solves groundwater
'                      flow model to obtain new wetland heads
' -------------------------------------------------------------------------
    blocksatflag = 1
    numiter = 0
    numstoriter = 0
    For i = 1 To nx
        If hold(rn, ob, i) > toporgelev(rn, ob, i) Then
'           block is saturated at beginning of next time step
            currsatflag(i) = -1
        Else
'           block is unsaturated at beginning of next time step
            currsatflag(i) = 1
        End If
    Next
iternewsolutiondahc:
'   set saturation flag for current time step
    For i = 1 To nx
        If hold(rn, ob, i) > toporgelev(rn, ob, i) Then
'           block is saturated at beginning of next time step
            satflag(i) = -1
            If massbalflag = 1 Then
                Print #15, "satflag", i, satflag(i)
            End If
        Else
'           block is unsaturated at beginning of next time step
            satflag(i) = 1
        End If
    Next
'   establish saturation depths at start of iteration
    Call cmpsatdep(ob)
'   compute equivalent hydraulic conductivity as a weighted arithmetic mean
    Call cmphydcon(ob)
'   compute appropriate storativity value
    Call cmpstorcoeff(ob)
onemoretime:
'
'   generate coefficients
'
    For i = 2 To nxm1
'       uses harmonic mean of transmissivities
'       compute C coefficient
            term1 = dx(rn, ob, i) / (2 * wetwid(rn) * bsat(i) * kequiv(i))
            term2 = dx(rn, ob, i - 1) / (2 * wetwid(rn) * bsat(i - 1) * kequiv(i - 1))
            c(i) = 1 / (term1 + term2)
'       compute g coefficient
            term1 = dx(rn, ob, i) / (2 * wetwid(rn) * bsat(i) * kequiv(i))
            term2 = dx(rn, ob, i + 1) / (2 * wetwid(rn) * bsat(i + 1) * kequiv(i + 1))
            g(i) = 1 / (term1 + term2)
'
'       compute E coefficient
'       based on current layer
            If statusflag(i) = 1 Then
                e(i) = sorg(i) * dx(rn, ob, i) * wetwid(rn) / dt
            End If
            If statusflag(i) = 2 Then
                e(i) = shum(i) * dx(rn, ob, i) * wetwid(rn) / dt
            End If
            If statusflag(i) = 3 Then
'           saturation has occurred in grid block
                e(i) = sorg(i) * dx(rn, ob, i) * wetwid(rn) / dt
                f(i) = shum(i) * dx(rn, ob, i) * wetwid(rn) / dt
            End If
            If statusflag(i) = 4 Then
'           desaturation has occurred in grid block
                e(i) = shum(i) * dx(rn, ob, i) * wetwid(rn) / dt
                f(i) = sorg(i) * dx(rn, ob, i) * wetwid(rn) / dt
            End If
    Next i
```

```
'    block adjacent to stream cell
        If statusflag(2) = 1 Or statusflag(2) = 2 Then
            ab(1) = -(c(2) + g(2) + e(2))
            ac(1) = g(2)
            bb(1) = qnet(2) + qinf(2) - e(2) * hold(rn, ob, 2) - c(2) * hold(rn, ob, 1)
        End If
        If statusflag(2) = 3 Then
            ab(1) = -(c(2) + g(2) + f(2))
            ac(1) = g(2)
            bb(1) = qnet(2) + qinf(2) - e(2) * hold(rn, ob, 2) - c(2) * hold(rn, ob, 1) +
toporgelev(rn, ob, 2) * (e(2) - f(2))
        End If
        If statusflag(2) = 4 Then
            ab(1) = -(c(2) + g(2) + f(2))
            ac(1) = g(2)
            bb(1) = qnet(2) + qinf(2) - e(2) * hold(rn, ob, 2) - c(2) * hold(rn, ob, 1) +
toporgelev(rn, ob, 2) * (e(2) - f(2))
        End If
'    block adjacent to wetland margin (considered impermeable)
        If statusflag(nxm1) = 1 Or statusflag(nxm1) = 2 Then
            ab(nxm2) = -(c(nxm1) + g(nxm1) + e(nxm1))
            aa(nxm2) = c(nxm1)
            bb(nxm2) = qnet(nxm1) + qinf(nxm1) - e(nxm1) * hold(rn, ob, nxm1)
        End If
        If statusflag(nxm1) = 3 Then
            ab(nxm2) = -(c(nxm1) + g(nxm1) + f(nxm1))
            aa(nxm2) = c(nxm1)
            bb(nxm2) = qnet(nxm1) + qinf(nxm1) - e(nxm1) * hold(rn, ob, nxm1) +
toporgelev(rn, ob, nxm1) * (e(nxm1) - f(nxm1))
        End If
        If statusflag(nxm1) = 4 Then
            ab(nxm2) = -(c(nxm1) + g(nxm1) + f(nxm1))
            aa(nxm2) = c(nxm1)
            bb(nxm2) = qnet(nxm1) + qinf(nxm1) - e(nxm1) * hold(rn, ob, nxm1) +
toporgelev(rn, ob, nxm1) * (e(nxm1) - f(nxm1))
        End If
'    interior blocks
    For nr = 2 To nxm3
        If statusflag(nr + 1) = 1 Or statusflag(nr + 1) = 2 Then
            aa(nr) = c(nr + 1)
            ab(nr) = -(c(nr + 1) + g(nr + 1) + e(nr + 1))
            ac(nr) = g(nr + 1)
            bb(nr) = qnet(nr + 1) + qinf(nr + 1) - e(nr + 1) * hold(rn, ob, nr + 1)
        End If
        If statusflag(nr + 1) = 3 Then
            aa(nr) = c(nr + 1)
            ab(nr) = -(c(nr + 1) + g(nr + 1) + f(nr + 1))
            ac(nr) = g(nr + 1)
            bb(nr) = qnet(nr + 1) + qinf(nr + 1) - e(nr + 1) * hold(rn, ob, nr + 1) +
toporgelev(rn, ob, nr + 1) * (e(nr + 1) - f(nr + 1))
        End If
        If statusflag(nr + 1) = 4 Then
            aa(nr) = c(nr + 1)
            ab(nr) = -(c(nr + 1) + g(nr + 1) + f(nr + 1))
            ac(nr) = g(nr + 1)
            bb(nr) = qnet(nr + 1) + qinf(nr + 1) - e(nr + 1) * hold(rn, ob, nr + 1) +
toporgelev(rn, ob, nr + 1) * (e(nr + 1) - f(nr + 1))
        End If
    Next
'
'    Thomas subroutine for tri-diagonal matrices
'
    For i = 2 To nxm2
        dd = aa(i) / ab(i - 1)
        ab(i) = ab(i) - ac(i - 1) * dd
        bb(i) = bb(i) - bb(i - 1) * dd
    Next
'    back substitution
    xx(nxm2) = bb(nxm2) / ab(nxm2)
    For i = 1 To nxm3
        j = nxm2 - i
        xx(j) = (bb(j) - ac(j) * xx(j + 1)) / ab(j)
    Next
'    corrected heads
    For i = 1 To nxm2
        hwet(rn, ob, i + 1) = xx(i)
    Next
    hwet(rn, ob, nx) = hwet(rn, ob, nxm1)
'
'    check to see if saturation state of grid blocks has changed
'
```

```
    For i = 2 To nxml
        If hwet(rn, ob, i) > toporgelev(rn, ob, i) Then
'           block is currently saturated
            revsatflag(i) = -1
        Else
'           block is currently unsaturated
            revsatflag(i) = 1
        End If
    Next
'
'   determine any changes in the saturation of grid blocks
'
    For i = 2 To nxml
        If revsatflag(i) = 1 And satflag(i) = 1 Then
'           saturation state remains unsaturated
            statusflag(i) = 1
        End If
        If revsatflag(i) = -1 And satflag(i) = -1 Then
'           saturation state remains saturated
            statusflag(i) = 2
        End If
        If revsatflag(i) = -1 And satflag(i) = 1 Then
'           saturation has occurred in grid block
            statusflag(i) = 3
        End If
        If revsatflag(i) = 1 And satflag(i) = -1 Then
'           de-saturation has occurred in grid block
            statusflag(i) = 4
        End If
    Next
    rerun = 0
    For i = 2 To nxml
'       if saturation state has changed in any grid block
'       rerun variable is set at -1
        If Val(revsatflag(i) * currsatflag(i)) = -1 Then rerun = -1
    Next
    If rerun = -1 Then
'       saturation state has changed in at least one grid block.  As
'       such:
'
'           1)  assign head values back to those at beginning of time step
'           2)  solve again using appropriate statusflag
'
        numstoriter = numstoriter + 1
'       if solution does not converge, terminate the program
        If numstoriter = 100 Then Stop
        For i = 1 To nx
            hwet(rn, ob, i) = hold(rn, ob, i)
        Next
        For i = 2 To nxml
            currsatflag(i) = revsatflag(i)
        Next
        GoTo onemoretime:
    End If
'
'   establish maximum difference in change of head
'
    maxdiffhead = 0
    For i = 2 To nxml
        headdiff = Abs(hwet(rn, ob, i) - hprev(rn, ob, i))
        If headdiff > maxdiffhead Then maxdiffhead = headdiff
    Next
'
'   if maximum head difference is greater than 0.5 mm, then repeat iteration
'
    If maxdiffhead > .0005 Then
        numiter = numiter + 1
'       if solution cannot converge, terminate program
        If numiter > 50 Then Stop
        For i = 2 To nxml
            hprev(rn, ob, i) = hwet(rn, ob, i)
        Next
        GoTo iternewsolutiondahc:
    End If
'   compute revised saturation depths and thicknesses
    For i = 2 To nx
'       identify saturation state of each grid block
        If hwet(rn, ob, i) > toporgelev(rn, ob, i) Then
'           block is saturated at beginning of time step
            satflag(i) = -1
        Else
```

```
'           block is unsaturated at beginning of time step
            satflag(i) = 1
        End If
    Next i
End Sub
```

```
Sub writebeg ()
' -------------------------------------------------------------------------
'       Subroutine: writebeg
'       Purpose:    to write primary input data to file [filename.beg]
' -------------------------------------------------------------------------
    Open direct$ + begfile$ For Output As #22
'
        Print #22, nrchmain
        Print #22, nx
        For i = 1 To nrchmain
            Print #22, Format$(ireach(i), "000.000"), Format$(oreach(i), "000.000"),
Format$(yreach(i), "0.000")
        Next
        For i = 1 To nrchmain
            Print #22, Format$(i, "000"), Format$(wetwid(i), "0000.0"), Format$(hreach(i),
"000.000"), Format$(bedinv(i), "000.000"), Format$(tbelev(i), "000.000")
            For k = 1 To nx
                For j = 1 To 2
                    Print #22, Format$(hwet(i, j, k), "000.000"), Format$(dx(i, j, k),
"000.000"), Format$(toporgelev(i, j, k), "000.000"), Format$(topsedelev(i, j, k),
"000.000"), Format$(tophumelev(i, j, k), "000.000")
                Next j
            Next k
        Next i
        For i = 1 To nrchmain
            Print #22, Format$(i, "000"), Format$(qlat(i), "0000.000000000")
        Next i
        Print #22, numlat
'
'       write data for laterals
'
        If numlat > 0 Then
            For ii = 1 To numlat
                For i = termreach(ii) To confreach(ii)
                    Print #22, Format$(ireach(i), "000.000"), Format$(oreach(i),
"000.000"), Format$(yreach(i), "000.000")
                Next
                For i = termreach(ii) To confreach(ii)
                    Print #22, Format$(i, "000"), Format$(wetwid(i), "0000"),
Format$(hreach(i), "000.0000"), Format$(bedinv(i), "000.0000"), Format$(tbelev(i),
"000.000")
                    For k = 1 To nx
                        For j = 1 To 2
                            Print #22, Format$(hwet(i, j, k), "000.000"), Format$(dx(i, j,
k), "000.000"), Format$(toporgelev(i, j, k), "000.000"), Format$(topsedelev(i, j, k),
"000.000"), Format$(tophumelev(i, j, k), "000.000")
                        Next j
                    Next k
                Next
                For i = termreach(ii) To confreach(ii)
                    Print #22, Format$(i, "000"), Format$(qlat(i), "0000.000000000")
                Next i
            Next
        End If
    Close #22

End Sub
```

```
Sub writenextbeg ()
' --------------------------------------------------------------------------
'       Subroutine: writenextbeg
'       Purpose:    to write wetland data to file for use
'                   with modelling next simulation period [filename.fin]
' --------------------------------------------------------------------------
    Open direct$ + event$ + ".fin" For Output As #22
'
        Print #22, nrchmain
        Print #22, nx
        For i = 1 To nrchmain
            Print #22, Format$(ireach(i), "000.000"), Format$(oreach(i), "000.000"),
Format$(yreach(i), "0.000")
        Next
        For i = 1 To nrchmain
            Print #22, Format$(i, "000"), Format$(wetwid(i), "0000.0"), Format$(hreach(i),
"000.000"), Format$(bedinv(i), "000.000"), Format$(tbelev(i), "000.000")
            For k = 1 To nx
                For j = 1 To 2
                    Print #22, Format$(hwet(i, j, k), "000.000"), Format$(dx(i, j, k),
"000.000"), Format$(toporgelev(i, j, k), "000.000"), Format$(topsedelev(i, j, k),
"000.000"), Format$(tophumelev(i, j, k), "000.000")
                Next j
            Next k
        Next i
        For i = 1 To nrchmain
            Print #22, Format$(i, "000"), Format$(qlat(i), "0000.000000000")
        Next i
        Print #22, numlat
'
'       write data for laterals
'
        If numlat > 0 Then
            For ii = 1 To numlat
                For i = termreach(ii) To confreach(ii)
                    Print #22, Format$(ireach(i), "000.000"), Format$(oreach(i),
"000.000"), Format$(yreach(i), "000.000")
                Next
                For i = termreach(ii) To confreach(ii)
                    Print #22, Format$(i, "000"), Format$(wetwid(i), "0000"),
Format$(hreach(i), "000.0000"), Format$(bedinv(i), "000.0000"), Format$(tbelev(i),
"000.000")
                    For k = 1 To nx
                        For j = 1 To 2
                            Print #22, Format$(hwet(i, j, k), "000.000"), Format$(dx(i, j,
k), "000.000"), Format$(toporgelev(i, j, k), "000.000"), Format$(topsedelev(i, j, k),
"000.000"), Format$(tophumelev(i, j, k), "000.000")
                        Next j
                    Next k
                Next
                For i = termreach(ii) To confreach(ii)
                    Print #22, Format$(i, "000"), Format$(qlat(i), "0000.000000000")
                Next i
            Next
        End If
    Close #22

End Sub
```