The baseflow and storm flow hydrology of a precambrian shield headwater peatland

Brian A. Branfireun and Nigel T. Roulet*

The Centre for Climate and Global Change Research and Department of Geography, McGill University, Burnside Hall, 805 Sherbrooke St. W., Montreal, Quebec, H3A 2K6, Canada

Abstract:
A hydrological investigation was conducted in a small headwater peatland located in the Experimental Lakes Area, north-western Ontario, Canada, to determine the subsurface and surface flow paths within the peatland, and between the peatland and an adjacent forested upland during baseflow and storm flow conditions. Distinct zones of groundwater recharge and discharge were observed within the peatland. These zones are similar to those found in much larger flow systems even though the peatland was only influenced by local groundwater flow. Groundwater emerging in seeps and flowing beneath the peatland sustained the surface wetness of the peatland and maintained a constant baseflow. The response of the peatland stream to summer rain events was controlled by peatland water table position when the basin was dry and antecedent moisture storage on the uplands when the basin was wet. The magnitude and timing of peak runoff during wet conditions were controlled by the degree of hydrological connectivity between the surrounding upland terrain and the peatland.


KEY WORDS peatland; baseflow; storm flow; groundwater

INTRODUCTION
The hydrology of peatlands has received attention because of its importance in the initiation and maintenance of peatland ecosystems (Ingram, 1982; 1983; Siegel, 1983; Siegel and Glaser, 1987; Gafni and Brooks, 1990), and its role in the mass flux of water and chemicals within peatlands (Damman, 1978; 1986; Hemond, 1980; Verry and Timmons, 1982; Wilcox et al., 1986; Hill and Siegel, 1991). However, few studies have attempted to examine how surface and subsurface flow pathways connect within a peatland, or integrate the peatland into the catchment hydrological system. This knowledge is essential to understanding the transport and transformation of biogeochemically important elements within peatlands. In this paper we describe a hydrological investigation that was done as part of a study of the production and transport of methyl mercury in a northern peatland catchment (see Branfireun et al., 1996).

Recent work has demonstrated the importance of various scales of groundwater exchange between peatlands and their surrounding and underlying mineral terrain (e.g. Siegel and Glaser, 1987; Roulet, 1990). It had long been assumed that there is minimal exchange of water between deep peat of ombrotrophic systems and mineral substrata, but Siegel and Glaser (1987) found that a spring fen mound, water track and raised bog in the Lost River Peatland, northern Minnesota, all exchanged groundwater with the underlying mineral sediment during at least some part of the year. Head measurements and pore water chemistry indicate a significant link between the surface water and the groundwater in all three landforms (Siegel and Glaser, 1987).

* Correspondence to: Nigel T. Roulet, Department of Geography, McGill University, Burnside Hall, 805 Sherbrooke St. W., Montreal, Quebec, H3A 2K6 Canada

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Correspondence to: Nigel T. Roulet, Department of Geography, McGill University, Burnside Hall, 805 Sherbrooke St. W., Montreal, Quebec, H3A 2K6 Canada
Since flow through deeper peat (the ‘catotelm’) is considered negligible because of the low hydraulic conductivities of highly humified peat (Ingram and Bragg, 1984; Damman, 1986) research has focused on surface runoff processes over and through the more permeable surface layers of peat (the ‘acrotelm’) (e.g. Bay, 1969; Damman, 1986; Hammer and Kadlec, 1986; Verry et al., 1988). The position of the water table in the acrotelm controls the runoff response of a peatland to rainfall inputs. Specifically, the magnitude and duration of stream flow is a function of the amount and intensity of precipitation, antecedent conditions, the nature of the peat profile, the location of the wetland within the landscape and the topographic forms within the wetland (Bay, 1969; Hammer and Kadlec, 1986; Verry et al., 1988). Bay (1969) concluded that the relationship between water table position and storm discharge varied according to the initial position of the water table, and Verry et al. (1988) used this general idea to model storm runoff from peatlands.

In the previous runoff studies, there has been little concern for the processes that maintain water table position prior to a rain event, and, similarly, few of the peatland groundwater studies have examined the processes that link groundwater with surface flow. Roulet (1991) demonstrated that precipitation on saturated areas maintained by a large persistent groundwater flow (Roulet, 1990) controlled storm response in a headwater wetland in southern Ontario. Waddington et al. (1993) used hydrometric measurement and geochemical hydrograph separation techniques to determine the processes that govern storm flow production in the same wetland. While confirming the findings of Roulet (1991) they also determined that rapid groundwater–surface water mixing in the saturated areas resulted in the predominantly pre-event signature of storm flow, even though saturation overland flow was the primary flow path.

The hydrological links between external inputs of surface water and groundwater, peatland groundwater systems, peatland surface flow, water table position and peatland storm response have not been undertaken in northern peatlands. To demonstrate the relationships between these hydrological variables, and to place the peatland hydrological system in the context of a larger basin-scale system, the objectives of the present paper are: (1) to examine the nature of groundwater flow in a Precambrian Shield headwater peatland; (2) to examine the surface hydrology of the peatland by relating the water table position and stream flow during baseflow and storm events; and (3) to use the link between groundwater and surface water hydrology to explain baseflow and storm flow runoff.

SITE DESCRIPTION

The study area consisted of the inflow subcatchment (632 Inflow) of the headwater basin of Lake 632 located in the Experimental Lakes Area (ELA) in north-western Ontario (49° 40' N, 90° 43' W). The climate of the study area is classified as boreal, cold temperate. Average monthly air temperatures based on data from 1969–1989 ranged from −16.5 °C for January to 20.1 °C for July, and average total annual precipitation was 508 mm, 36% of which fell as snow (Beaty and Lyng, 1989).

The subcatchment contains a hillslope (1.2 × 10^5 m^2) and the inflow portion of a pond-side peatland that includes a mineral-poor fen and a raised peat mount (6.0 × 10^3 m^2). The peat mound rises between 0.3 and 0.4 m above the surrounding poor fen zone. A surface stream that traverses the peatland originates at a small seep at the hillslope–peatland interface (Figure 1). The bedrock geology is typical of Archean Granitic–Gneissic terrain, and is largely unfractured. Soils in the upland portion of the catchment range from silty loams of glaciolacustrine origin to patches of coarse till. Stratigraphic information from peat cores indicates that the peatland lies in a shallow bedrock basin with a deep central depression beneath the pond (see Brandfireun et al., 1996). Bedrock is overlain by well-sorted sand and gravel greater than 1 m in depth in the inflow area, and fine silts and clay in the deeper central depression. Above the inorganic sediments, cypress-aceous and detrital peat is found towards the hillslope–peatland interface, and ericaceous peat closer to the pond. Limnic peat and gyttja are found in deep cores taken near the pond margin. A surficial accumulation of dead Sphagnum spp. overlain by living Sphagnum spp. covered most of the peatland. Maximum peat depth is approximately 7 m, and average peat depth is approximately 2 m.
Upland vegetation comprises an overstorey of jackpine (Pinus banksiana) and black spruce (Picea mariana) with scattered paper birch (Betula papyrifera) (J. Bubier, personal communication, 1995). Bedrock outcrops are colonized by lichens (both foliose and fruiticose forms), juniper (Juniperus virginiana) and mosses (Racomitrium sp.).

Peatland surface vegetation is dominated by Sphagnum spp. (S. angustifolium, S. fuscum, S. magellanicum) with shrubs such as Labrador tea (Ledum groenlandicum) and leatherleaf (Chamedaphne calyculatta) in the more ombrotrophic area, and sedges (Carex spp.) in the more mineral-poor fen zones around seeps and streams (J. Bubier, personal communication, 1995). The peatland overstorey is open black spruce (Picea mariana).

METHODS

Fluxes of water to, from and within the peatland were examined from mid-May until mid-October, 1993. The locations of the sample sites referred to in the following section are shown in Figure 1.

Precipitation intensity was recorded using a tipping-bucket rain gauge. Biweekly total rainfall was measured using a standard Atmospheric Environment Service (AES) rain gauge.

A total of 13 piezometer nests and 15 wells were installed in two perpendicular transects across the peatland so that hydraulic head and water table position could be measured (Figure 1). Piezometers ranging in length from 0.5 to 3.0 m were constructed from PVC pipe (i.d. ≈ 1 cm). Each piezometer had a 20 cm slotted well point covered with a 40 μm Nitex mesh to prevent clogging. At most sites, piezometers were inserted manually by pushing them vertically into the peat to the desired depth. Where a particularly dense root mat was present, or placement of the piezometer was into the underlying sand strata, a soil auger of a diameter slightly larger than the piezometer was used to initiate a hole and the piezometer was then driven the remaining distance. All piezometers were pumped a few days after installation to remove fine materials. Initially, the depth to water measurements in piezometers were made twice weekly. Once it was established
that there was little short-term variation in hydraulic head under baseflow conditions, the measurements were made weekly with additional measurements following larger rain events. Hydraulic conductivity for selected piezometer nests was determined using Hvorslev’s method (Freeze and Cherry, 1979).

Water table wells, constructed of PVC pipe perforated along their entire length, were measured manually at some sites (IF 2, 5, 9 and 10) and continuously at the other locations using potentiometric water level recorders. Water levels were recorded every 60 seconds and 30-minute averages were stored on a data logger.

Flume boxes were installed at two locations on the inflow stream to monitor channelized surface flow (Figure 1). Both boxes were fitted with an upstream face panel that penetrated c. 50 cm into the peat below and to the sides of the box. The water level in each flume box was measured continuously in a stilling well located at the front of the box. The discharge was determined using the velocity–area method, with velocities obtained with a Pygmy current meter for a range of stage levels. A stage–discharge relationship was then developed for each box.

RESULTS

Precipitation

The period of continuous measurements began on 11 June and ended on 10 October 1993. During this period 362 mm of rain was recorded (Figure 2a). A manual AES rain gauge yielded a total rainfall input of 435 mm, or 20% more than the tipping-bucket gauge. This discrepancy is partly attributable to the coarse resolution of the tipping-bucket gauge (1 mm/tip).

Water table

Continuous well records indicate two water table regimes (Figure 2b–e). Rainfall of 25 July (Julian day 206) and 27 July (208) substantially elevated the water table in the entire peatland above the pre-July 25 ‘baseflow’ position. The water table at IF 1 (Figure 2b) was similar to the water level of the pond and was insensitive to small rainfalls. Water table position varied by only 5-4 cm and the slope of the water table recession after rain events was shallow. Water table position was not measured continuously at IF 2. The more central peatland sites, represented by IF 4 (Figure 2c), all had similar water table patterns: the range of water table positions were between 19.1 and 21.4 cm, and the water table recessions were steeper than IF 1. The water table at IF 6 (Figure 2d) was more variable, showing a greater response to rainfall and more rapid recession than the other central sites. At IF 11 (not shown) and the North Well (not shown), the ranges of water table fluctuation were similar to that of the other peatland wells (19.1 and 18.9 cm, respectively), but their response to rainfall was larger and more rapid, especially when the water table was initially lower.

The Upland Well (Figure 2e) located on the hillslope margin of a low-lying transition zone between the mineral uplands and the peatland was completely dry for much of the early part of the summer. After the rainfalls of 25 July and 27 July, the water table rose 47.4 cm, to within 5 cm of the soil surface. Recessions extended between 16 and 20 days for a single event.

Surface flow

Baseflow input to the inflow stream that flows through the peatland and into the pond comprised shallow groundwater flow emerging in a seep at the base of the hillslope at the western margin of the peatland (see Figure 1). All data presented for the inflow stream was derived from Flume Box 2 since high flows over-topped Flume Box 1, making discharge interpretation unreliable. The rating curve for Flume Box 2 had an $r^2 = 0.98$ ($n = 6$, $p = 0.001$).

Mean discharge of the inflow stream was 3·0 l s$^{-1}$, and maximum and minimum instantaneous discharge were 18·0 and 0·6 l s$^{-1}$ (Figure 2f). Total discharge from the inflow stream over the period of measurement was $2·88 \times 10^7$ l (229 mm), giving a runoff ratio (runoff ÷ precipitation) of 0·58. Stream flow persisted for the entire study period, even under very dry conditions.

Inflow stream response to rainfall varied over the study period but the relative magnitude of response can be divided into two groups, corresponding to the periods of low and high antecedent water table (Figure 2f).
Figure 2. a) Rainfall recorded over the study period. b–e) Water table elevation recorded in wells at IF 1, IF 4, IF 6 and the Upland Well. The dashed line indicates the position of the ground surface at each site. Arrows indicate the rainfall of July 25 and the resultant change in water table regime.
Prior to 25 July, mean discharge was 1.0 l s$^{-1}$ and the hydrograph response to rainfall was subdued. After 25 July, mean discharge was 3.9 l s$^{-1}$, and peak discharges were an order of magnitude higher than those in the period prior to 25 July. The flow did not return to the pre-25 July baseflow level during the remainder of the study period.

Several storms from the ‘dry’ (≤25 July) and ‘wet’ (>25 July) stream flow periods were analysed for a number of storm flow parameters. These results are summarized in Table I.

Two storms will be discussed in detail. Both storms had large rainfalls (44 and 54 mm, respectively), but the first occurred when the peatland and hillslope were relatively ‘dry’ [25 July (206)] (Figure 3), and the other when they were relatively ‘wet’ [9 August (221)] (Figure 4). The event of 25 July began at approximately 16:00 and reached a maximum intensity of 48 mm hr$^{-1}$ at 17:30. Fifty-seven percent of the total rainfall fell within the first hour. Stream discharge and the water table in all wells responded within 30 minutes of the onset of the storm. The lag time in stream response (time of concentration), calculated as the time difference between maximum rainfall intensity and peak discharge, was 6 hours with a maximum discharge of 2.9 l s$^{-1}$ (0.09 mm hr$^{-1}$). Stream flow remained elevated until the next storm. Although total rainfall was 44 mm, total runoff was only 3.3 mm 2$^{-1}$, [volume of storm discharge from the initial rise in the hydrograph until a return to baseflow (m$^3$ t$^{-1}$)area of the subcatchment (m$^2$) resulting in a storm runoff ratio of 0.08. The lag time for the water table in the wells was between 3 and 4 hours, with the exception of IF 6, the North Well and the Upland Well, which responded slightly faster (Figure 3). The water table rose above the surface of the peatland at several of the centrally located wells to a maximum of nearly 5 cm at IF 7, and then receded gradually. IF 6 and the North Well responded sharply, but the water table did not rise to the surface, and similarly, the water table recession was more rapid.

The second storm on 9 August (Figure 4) was double peaked: 16 mm of rain fell in the first part of the storm between 00:00 and 02:30, and 38 mm fell between 03:00 and 06:30. Stream discharge and the water table at all locations responded within 30 minutes to the first input, but the bulk of the response was associated with the second storm peak (maximum intensity 32 mm hr$^{-1}$). All lag times are referenced to this second peak. The lag time of stream discharge (time of concentration) was 15.5 hours, with a maximum discharge of 18 l s$^{-1}$ (0.52 mm hr$^{-1}$). Total runoff was 32 mm 9d$^{-1}$, resulting in a runoff ratio of 0.59. The Upland and North wells responded with very short lag times of only 1.5 hours. IF 6 well exhibited two peaks in water table elevation. The first peak lagged 2 hours after peak rainfall, and the second peak lagged 6.5 hours. Lag times for IF 4 and IF 3 were 9.5 and 12.5 hours, respectively, indicating a progression in water table lag times in the downstream direction adjacent to the stream. IF 4, IF 7, IF 8 and IF 11, which are perpendicular to the stream, all had the same lag times, which may indicate that a progression of peak

<table>
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<th>Rainfall (mm)</th>
<th>Runoff (mm)</th>
<th>Runoff ratio</th>
<th>Peak runoff (mm hr$^{-1}$)</th>
<th>Peak Q (l s$^{-1}$)</th>
<th>Response time</th>
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water table elevations from the hillslope towards the pond occurred across the open fen area of the peatland, not just in the near-stream zone.

Generally, under ‘dry’ antecedent conditions, peak runoff, total runoff and runoff coefficients were low. Under ‘wet’ conditions, all the runoff characteristics were at least one order of magnitude higher for similar intensity rain under ‘dry’ conditions.

Plots of water table elevation versus inflow stream discharge were constructed using water table position data from a peatland well (IF 4) and the Upland Well (Figure 5). On the peatland (IF 4) (Figure 5a), under ‘dry’ antecedent conditions when the water table was deep in the peat profile (e.g. 25 July), increases in water table elevation were significant (8–10 cm), but increases in discharge were small. Under ‘wet’ antecedent conditions when the water table was already at, or near, the ground surface (e.g. 9 August), stream flow increased rapidly, from around 2 to 18 l s$^{-1}$, with a water table increase of around 12 cm. These findings are presumably the result of increasing hydraulic conductivity towards the ground surface. A slight clockwise hysteresis is apparent near the end of the recession.
Figure 4. Changes in inflow stream discharge and water table elevation in response to the storm of July 25, 1994 (Day 206)

When the water table was deep in the soil profile at the Upland Well (Figure 5b) a slight increase in stream discharge (~ 0.5–3.0 l s⁻¹) was associated with a moderate increase in water table elevation (~10 cm) under both ‘dry’ and ‘wet’ antecedent conditions. An increase in water table elevation of over 30 cm was associated with a significant increase in stream discharge. Under ‘dry’ antecedent conditions (25 July) a slight increase in discharge is associated with the water table rising to within 20 cm of the ground surface followed by a drop in water table without any decrease (and even a slight increase) in discharge. Under ‘wet’ antecedent conditions a rise in the water table elevation in the hillslope to within ~10 cm of the ground surface was associated with a large increase in discharge with a strong clockwise hysteresis apparent on the recession limb of the storm. The Upland Well was located on the margin of the transition zone between the mineral upland and the peatland. Water table elevations measured at this site, which were within 15 cm of the ground surface, correspond with observed saturation overland flow from the mineral uplands, through the transition zone, directly into the inflow stream.
Groundwater flow

Measured values of hydraulic conductivity are presented in Figures 6a and 7a. The range of hydraulic conductivities \( (K) \) was in excess of four orders of magnitude \((1.1 \times 10^{-5} \text{ to } 4.6 \times 10^{-9} \text{ m s}^{-1})\). The highest value of \( K \) was found in the shallowest piezometers located in the peat (0.5 m) and at depth in the sand underlying IF 4, IF 7 and IF 11. The lowest \( K \) value was in the deeper peat at IF 1, IF 2 and IF 6. The \( K \) values at IF 1 (1.0 m) and IF 4 (1.25 m) were too large to measure. Hydraulic conductivity of the near-surface peat (0–50 cm) was not determined.

Hydraulic head varied, both seasonally and over shorter time periods, in response to rainfall. Flow nets for the two piezometer transects are shown for three dates during the study period, illustrating ‘dry’ (21 June), ‘wet’ (10 August) and early autumn (19 September) patterns of hydraulic heads and groundwater flow (Figures 6b–d and 7b–d, respectively). Flow nets from the IF 1–6 transects (east to west, parallel to the inflow stream, along the long axis of the peatland) illustrate the presence of two groundwater flow systems under all moisture conditions (Figure 6b–d). Hillslope water was transmitted through the sand substrate and deeper peat to discharge areas in the open fen zone and to the littoral zone of the pond.

During the summer, the raised bog located between 2 and 30 m from the pond was a relatively stable zone of local recharge (Figure 6b–d). Precipitation was the sole input at this site because of the surface topography and water table configuration. Water moved down from the peat mound and diverted towards discharge points in the littoral zone of the pond and the open fen behind the bog. Under storm flow conditions, this pattern intensified (Figure 6b). The maximum downward hydraulic gradient in the peatland, measured under the bog mound, was 0.153. However, during the autumn recession, hydraulic gradients reversed (Figure 6c).

The discharge area located in the open fen persisted for the entire study period. The upward gradient in this zone is evident both in the IF 7–11 (Figure 7) and in the IF 1–6 (Figure 6) piezometer transects. The maximum gradient here was 0.176.
A zone of high hydraulic head which varied seasonally and during storm events existed beneath the inflow stream (Figure 7). The upward gradient beneath the stream at the IF 7–11 transect indicates that groundwater discharged through the stream bed over the entire study period.

Using a mean value of hydraulic conductivity for each site and Darcy’s equation, maximum downward and upward flow for the study period at the inflow site were 0.11 m d$^{-1}$ and 0.29 m d$^{-1}$, respectively.

Figure 6. Water table position versus inflow stream discharge for a) a well located in the peatland (IF 4) and b) a well located in the mineral soil upland adjacent to the peatland (Upland Well). Arrows indicate the direction of hysteresis.
From the flow nets of the IF 1–6 and IF 7–11 transects, calculations for mass flux of water show that 501 m$^3$ d$^{-1}$ per linear metre of shoreline discharges from groundwater to the littoral zone of the pond under dry conditions. Under wet conditions the hydraulic gradient steepens and this value increases to 0.02 m$^3$ m$^{-1}$ d$^{-1}$. If it is estimated that 50 m of shoreline is receiving groundwater discharge then this

Figure 7. IF 1–6 Transect (east to west parallel to the stream along the long axis of the peatland). a) Hydraulic conductivity. Representative groundwater flow nets for b) June, 1993 (dry), c) August, 1993 (wet) and d) September, 1993 (Autumn reversal). Units of equipotentials are in meters of head above an arbitrary datum. Arrows indicate direction of flow. Vertical exaggeration is 13x

translates to 0.75 m$^3$ d$^{-1}$, or 84 m$^3$ over the 112-day period of stream discharge measurement. This value represents a minuscule contribution of water to the pond when compared with inflow stream discharge (0.67 mm vs. 229 mm). The downward mass flux of water beneath the peat mound at IF 2 is approximately 0.20 m$^3$ d$^{-1}$ under wet and dry conditions. During the autumn reversal of hydraulic gradient measured at this site, approximately 0.07 m$^3$ d$^{-1}$ is discharged to the peat surface. Discharge of groundwater at IF 4 is greater during dry conditions (0.18 m$^3$ d$^{-1}$) than during wet (0.09 m$^3$ d$^{-1}$). At IF 7, groundwater discharges at a rate of 0.11 m$^3$ d$^{-1}$ under both wet and dry conditions, whereas discharge to the stream bed varies from 0.01 m$^3$ d$^{-1}$ to 0.04 m$^3$ d$^{-1}$ per metre of stream.

**DISCUSSION**

During baseflow conditions hillslope seepage coupled to the peatland groundwater system supplied a small amount of water to the pond and sustained baseflow in the inflow stream. During storm flow conditions, additional pathways of water flow were introduced and, depending on the antecedent moisture on the hillslope, the discharge pattern of the inflow stream could be characterized into a ‘dry’ [$\leq 25$ July (206)] or a ‘wet’ [$> 25$ July (206)] response. The two flow regimes had distinct baseflow and storm flow responses.

Antecedent moisture conditions in the subcatchment controlled the extent of the contributing area of runoff. For storm events on a dry basin the flow pathways were similar to those observed under baseflow conditions with the addition of runoff from the near-stream zone in the form of subsurface storm flow and saturation overland flow. For very large rain events (e.g. 25 July, 27 July, 9 August), or smaller rainfalls on a wet basin, saturation overland flow over a larger area of the peatland, and observed saturation overland flow and return flow on the hillslope, connected the inflow stream to a much larger contributing area, influencing both the magnitude and timing of the stream flow response.

The existence of different responses in peatland storm flow has been previously explained by the antecedent moisture conditions in the peatland itself (Bay, 1969; Verry et al., 1988). The ‘dry’ response pattern observed in this study is analogous to the low water table response observed by Bay (1969), but in this study the source of storm flow was the peatland area directly adjacent to the stream. The ‘wet’ response is again similar to the high water table response observed by Bay (1969), but the bulk of the storm flow is derived from the hillslope as saturation overland flow and is transported across the peatland. Therefore, the controls on large storm response are extra-wetland processes.

During baseflow, groundwater discharge at the hillslope–peatland interface was the sole input of water to the peatland. This flow probably took one of two pathways along the bedrock–soil interface (Renzetti, et al., 1992), which discharged into the mineral soil beneath the peat, or into and on the peat to become shallow subsurface flow and surface flow (Roulet, 1990). The contribution by these flow paths was not measured. However, on average of 3.0 $1$ s$^{-1}$ was discharged from the inflow stream to the pond. Assuming that the wetland and hillslope contributed runoff in proportion to their surface area (i.e. runoff contributions are a result of precipitation only), the seepage input to the wetland from the upland portion (which constitutes 95% of the area) of the subcatchment was 218 mm (out of 229 mm) for the study period. This indicates that the external sources of water to this peatland were approximately 55% of that of direct precipitation (396 mm). Although the hillslope and the peatland contributed water to the catchment via very different mechanisms and at different rates, this assumption may not be unreasonable over the time period of the study since hillslope water most likely has a residence time of weeks to months, rater than years, given the very shallow/non-existent soils that are present. This conservative estimate indicates that ‘upland’ water inputs were probably significant components of the annual water budget of this peatland, which could appear ‘ombrotrophic’ rather than ‘oligotrophic’ if a detailed hydrological study were not undertaken.

Hydraulic heads indicate that subsurface inputs to the peatland were relatively constant under baseflow conditions. Stable upward and downward gradients indicate that groundwater input is spatially diverse, but that the flow paths are consistent. The pattern of smaller scale flow systems between the hillslope and the peatland landforms is in keeping with the patterns of groundwater recharge and discharge measured and
modelled by Siegel (1983) for the regional-scale flow paths in the Glacial Lake Agassiz Peatland in northern Minnesota. The scale of the landforms in this investigation is much smaller than those of the Glacial Lake Agassiz Peatlands but the flow paths found here are consistent with those modelled by Siegel (1983), suggesting that the pattern of flow is not scale dependent. The water table beneath the bog mound showed the most variation; it was a recharge zone with precipitation as the sole input. A reversal of hydraulic gradient was found to occur at this site during the autumn recession, most likely as a result of low autumn precipitation which weakened the downward hydraulic gradient in the bog mound (see Devito et al., 1996). Siegel and Glaser (1987) suggest that these seasonal changes may be a result of seasonal variations in water table along the groundwater flow paths affecting the peatland.

Rainfall on the ‘dry’ subcatchment increased inflow stream discharge marginally. The rainfall input via direct precipitation raised the peatland water table, but not generally above the ground surface except immediately beside the stream. Surface depression storage on the majority of the peatland was not exceeded and no overland flow was observed except in the near-stream zone (e.g. IF 3, IF 4, IF 11), where increased water table elevations resulted in the transmission of water from this zone to the stream via subsurface flow and saturation overland flow. Bay (1969) also attributed low peak discharges when the water table was low to a relatively large detention storage in the bogs as a result of peatland microtopography. Verry et al. (1988) found that the water table had to rise to within 7 cm of the bottoms of the hollows before stream flow response was evident, and that the water table had to rise above the bottom of the hollows before a significant increase occurred.

In the upland source area, no subsurface storm flow or overland flow to the peatland was generated under dry conditions as indicated by the dry status of the Upland Well. It would appear that the dry soil-filled depressions in the upland, and the saturated zone between the upland and the peatland have large storage capacities that detain upland runoff during dry conditions (Allan and Roulet, 1994).

In dry antecedent conditions the small increase in stream discharge was synchronous with an increase in water table position in the surrounding peatland but there was little relation between upland water table and storm discharge. Thus, the peatland and hillslope hydrological systems are decoupled when the subcatchment is ‘dry’. The short response times, and short water table and discharge recessions were the result of a small contributing area adjacent to the stream. A stronger positive relationship between water table elevation and discharge at IF 4 (on the peatland) than at the Upland Well site also supports this conjecture.

During ‘wet’ antecedent conditions there was a more direct hydrological coupling of the upland to the inflow stream. During larger rainfalls, water was translated downslope to the interface zone causing the water table to rise and creating a zone of saturation on the hillslope above the hillslope–peatland interface. This zone varied in areal extent. During the largest summer storms the entire interface zone was saturated. When additional rainfall occurred on this ‘wet’ antecedent condition (e.g. 27 July, 9 August) the stream response was much larger than under ‘dry’ conditions (see Figures 2f; 3 and 4). This finding is consistent with the ‘variable source area concept’ (Dunne, 1978, 1983).

During ‘wet’ periods the stream hydrograph tracks changes in upland water table elevation during very high flow events (observed saturation overland flow) suggesting that runoff from the upland subcatchment controls the magnitude and timing of peak discharge (Figure 5b). However, the clockwise hysteresis during the hydrograph recession suggests that once the primary ‘pulse’ of upland runoff had moved through the system the contributing area shrunk and the shape of the recession limb is controlled by intra-peatland runoff processes (i.e. the upland–peatland system switches from being hydrologically connected to being disconnected). The relationship between discharge is similar on both the rising limb and the falling limb for the well in the stream-side area of the peatland (IF 4) suggests that the runoff from this zone controls the magnitude of stream discharge on the recession limb. This hysteresis loop is generally opposite to that found by Verry et al. (1988). The storm water table in the present study was direct influenced by extra-wetland runoff, whereas Verry et al. (1988) documented only intra-wetland runoff, specifically from a raised bog mound.

Normally, under ‘wet’ antecedent conditions, one would expect a shorter lag time associated with larger runoff ratios. However, since the major source of water is extra-wetland it has a longer path length and transit
time. The peak water table elevations occur sequentially from the hillslope across the peatland suggesting a ‘wave’ of water translated from the hillslope through the open poor fen zone. Verry et al. (1988) suggested that a large increase in peatland stream discharge associated with upland runoff contributions under high flow conditions, and the hysteresis noted in the stage–discharge relationship, was caused by wedge storage when the channel-like lagg developed a moving wedge of water, presumably derived from the hillslope. The ‘wave’ of water observed in this study may be likened to the moving wedge noted by Verry et al. (1988), but in this investigation the ‘wave’ progressed from the hillslope across the open fen, as well as in the channel.

The pattern of hydraulic head was also affected by large rainfalls under ‘wet’ conditions. The groundwater system, which was presumably recharged at the hillslope–peatland interface and discharges into the open fen and littoral zone, strengthens after major rainfalls. This finding suggests that groundwater flow systems through deeper peat with lower hydraulic conductivity may respond within days of a major rainfall. Discharge from the sand substrate into the peat in the open fen zone demonstrates that there is significant hydrological interaction between the highly humified peat and the underlying mineral soil. This stable volume of water, supplied to the open fen zone via groundwater flow paths, magnified and maintained elevated water tables, enhancing the conditions for saturation overland flow and subsurface storm flow to occur. This finding is in agreement with the findings of Siegel (1983) and Siegel and Glaser (1987) regarding the importance of the groundwater interaction between deep peat and underlying mineral sediments. Increases in groundwater discharge to the inflow stream and to the littoral zone of the pond after a large rainfall suggest that increases in water table elevation in the hillslope profile serve to increase the long-axis hydraulic gradient in the peatland. Strengthened groundwater recharge at the raised peat mount also serves to provide additional discharge at the littoral zone. Although the volumes of water are relatively small compared with the discharge of the inflow stream under storm flow conditions, this increase may be significant with respect to biogeochemical processes that are active at the sediment–water interface.

In summary, there are two runoff regimes whose occurrence depends on the antecedent moisture conditions in the subcatchment, which are superimposed on the baseflow flow paths. The various flow paths under baseflow and storm flow conditions are presented schematically in Figure 8. Baseflow flow pathways comprise: hillslope seepage into the mineral substrata underlying the peat; peat subsurface flow supplied by hillslope subsurface flow and by groundwater discharge from the underlying mineral sediments; and peat

Figure 8. IF 7–11 Transect (perpendicular to the long axis of the peatland at the inflow stream mid-point). a) Hydraulic conductivity. Representative groundwater flow nets for b) June, 1993 (dry), c) August, 1993 (wet) and d) September, 1993 (Autumn reversal). Units of equipotentials are in meters of head above an arbitrary datum. Arrows indicate direction of flow. Vertical exaggeration is 7x
surface flow supplied by hillslope groundwater emerging at the seep and downstream groundwater discharge from the peat into the bed of the inflow stream.

Storm flow is produced in two areas depending upon antecedent moisture conditions. Storms in ‘dry’ antecedent conditions produce a rapid, low-magnitude response, with runoff being generated in the peatland from the area adjacent to the stream. Storms in ‘wet’ antecedent conditions produce a slower, higher magnitude response, with runoff being generated on the hillslopes and peatland. The key difference between small and large magnitude storm flow response is the degree of surface coupling between the hillslope and peatland. Not only do the baseflow and storm flow pathways maintain saturation in the peatland and determine storm hydrological response, but they are also the principal controllers of the transport of biogeochemically important chemical species such as methyl mercury (Branfireun et al., 1996).

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