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Hillslope-swamp interactions and flow pathways in a hypermaritime rainforest, British Columbia

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Abstract:

The process of water delivery to a headwater stream in a hypermaritime rainforest was examined using a variety of physical techniques and tracing with dissolved organic carbon (DOC) and the stable isotopes of water. Headwater swamps, often the major discharge zones for water draining off steep forest slopes, strongly affect the physical and chemical character of streamflow in the region. The headwater swamp selected for detailed investigation was sustained by relatively constant groundwater input from the steep colluvial slopes that maintained the water table above the ground surface. During significant storm events the water table rose quickly and the swamp expanded to engulf marginal pools that developed rapidly on the adjacent ground surfaces. The corresponding release of surface water directly to the stream typically comprised up to 95% of total stream discharge. The proportion of groundwater seepage to the stream by matrix flow ($<1\%$) and via macropore-fed springs (up to 73%) increased during the recession period, but could not be sustained over the longer term. In more protracted drying periods, deep groundwater contributions to the stream were routed first to the headwater swamp.

Dissolved organic carbon (DOC) in the stream, measured daily or more frequently during storm events, was found to be directly proportional to discharge, owing to the domination of DOC-rich headwater-swamp water sources. Although $\delta^{18}O$ and $\delta^{2}H$ composition of rainwater, groundwater and stream flow were found to be similar, deuterium excess ($d \equiv \delta^{2}H - 8\delta^{18}O$) of water components was often found to be distinct, and suggested short water residence times of roughly 12 days for one event. Overall, observations of a typical headwater swamp reveal that the groundwater regime is dominated by rapid infiltration and short, emergent flow paths. With a relatively short turnover time, potential disturbances to the system by harvesting of upslope areas can be expected to occur rapidly. Forest managers can mitigate some of the harmful effects of logging operations by respecting the integrity of headwater wetland systems. The nature and magnitude of such perturbations will require further study. Copyright © 2003 John Wiley & Sons, Ltd.

KEY WORDS headwater; swamp; hillslope; flow path; hydrology; dissolved organic carbon; stable isotopes; residence time

INTRODUCTION

The British Columbia (B.C.) Ministry of Forests is exploring the idea of extending logging in the North Coast region to include old-growth conifer stands on poorly drained sites that previously have been considered inoperable owing to low timber volumes. However, potential paludification of already wet soils following harvesting (Dubé and Plamondon, 1995), and the consequent geochemical changes that are anticipated (Rosen *at al.*, 1996), could negatively affect forest regeneration in these areas. Forest types are commonly related to slope and the degree of soil development, which may differently influence water and nutrient exchanges (Emili *et al.*, 1998). One prerequisite for sustainable management of timber resources, particularly in marginal forests,

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is development of a basic understanding of hydrological and biogeochemical processes, their variability and interactions. This study focuses on complex headwater swamps, which are a common landscape feature in steeply sloping hypermaritime watersheds of the North Coast forest district.

Hydrological flow systems in steeply sloping complex terrain are characterized by a combination of surface, near-surface and deeper groundwater flow paths, which may integrate the hydrological processes from a wide range of forest types. These complex terrains control the water residence time, flow path and ultimately the discharge of water and nutrients (Gibson *et al*., 2000). Forest systems are often hydrologically and geochemically linked to landscapes that lie upslope because of their position in the watershed. For example, zero-order basins (geomorphological hollows) located in the mid- to upper sections of hillslopes, can be sites of potential runoff generation (Tsuboyama *et al*., 2000) that affect downslope systems via preferential flow pathways. These pathways include linkage of surface depressions under very wet conditions, or subsurface routes where macropore connections allow water to move quickly, bypassing matrix flow through soils with low hydraulic conductivity (Buttle *et al*., 2000).

Changes in slope or subsurface geometry that interrupt flow paths can result in the occurrence of headwater wetlands, as observed in North Coast forests. Headwater wetlands are often spring-fed (National Wetland Working Group, 1988) and water emergence and distribution over their surface affects the distribution and quality of stream flow. Roulet (1990) noted that groundwater may enter a headwater swamp at its margins through a series of springs, or through diffuse groundwater discharge. This relatively constant water supply can maintain a high level of saturation, so precipitation events are quickly transmitted by overland flow. The relatively large surface water store under such conditions results in a high proportion of pre-event water discharge following a rain input (Waddington *et al*., 1993). Consequently, headwater wetlands can control the geochemistry of streams within their catchments (Devito and Hill, 1997).

In the hypermaritime climate of the north Pacific coastal region, dissolved organic carbon (DOC) concentrations are of particular interest because of the unique climate and forest conditions. This region contributes high levels of DOC to coastal estuaries (Naiman and Sibert, 1978) owing to its high rainfall, wetlands on lesser slopes, heavy forest cover, mountainous terrain and mild climate. Flow paths, particularly storm pathways, are reflected in stream DOC (Jardine *et al*., 1990; Trumbore *et al*., 1992; Sakamoto *et al*., 1999). Although DOC is not a conservative tracer, the vertical and spatial differentiation within complex forested systems can be used to understand sources and pathways of water flow within them. For example, Hinton *et al*. (1998) noted that DOC varied as it passed along different flow paths in a forested hillslope system, DOC being higher in groundwater from shallow soil zones than from deeper groundwater. However, the complexity of sources and pathways in wetland systems sometimes produces apparently contradictory results. For example, Moore (1987) noted that DOC from a New Zealand wetland had a negative relationship with discharge, although total DOC export from forest systems encompassing wetlands can be high. In contrast, a study of seven nested headwater forested catchments in New York State found that a large portion of event water passed through the upper organic soil horizons and contributed to a delayed (highest contribution during recession limb) but positive relationship to stream DOC (Brown *et al*., 1999).

A recent study in this (north coastal B.C.) region (Gibson *et al*., 2000) found distinct DOC ranges associated with specific forest types, as well as different soil zones or depths in similar terrain. Gibson *et al*. (2000) used DOC concentrations as supporting evidence in conjunction with their isotope hydrograph separation work, to trace relative contributions of bog water, deep groundwater and shallow groundwater during a storm event. A positive relationship between DOC and stream flow was attributed to activation of shallow DOC-rich flow paths during storm events. Distinct changes in DOC patterns that were observed in a typical headwater swamp are likewise used in this study as supporting evidence for evaluating flow mechanisms and pathways to a stream regulated by a headwater wetland that collects and distributes water from upland forested hillslopes. This study builds on the work by Gibson *et al*. (2000) that explored the flow characteristics of a larger nearby catchment comprising many different landscape and forest types.

Site description

The Prince Rupert area of coastal northern British Columbia has a rugged landscape, with shallow bedrock and significant areas of wetland. Bog woodland, bog forest and fen make up approximately one-half to three-quarters of the land area in the region (National Wetland Working Group, 1988). The remaining land cover in this bog-forest complex consists of some productive forests interspersed with low-productivity, open and scrubby stands of old growth spruce, hemlock and red cedar (Kayahara and Klinka, 1997).

The study site is situated within Diana Lake Provincial Park (54°10′N, 130°15′W), located about 20 km south-east of Prince Rupert, British Columbia. The region is located in the very wet hypermaritime Coastal Western Hemlock zone characterized by high rainfall and low evapotranspiration. The climate in the area is cool (mean annual temperature of 6·9 °C) and hyperoceanic (Turunen, 1999). Over 62% of the 2551 mm annual precipitation occurs during October and March, with October being the wettest month (378 mm). Only 17% of the total precipitation falls during the summer (July–September) and July is the driest month (113 mm). Only 6% of the annual precipitation occurs as snow (Environment Canada, 1998).

The 2-ha study site subcatchment (Figure 1) comprises adjacent upland and lowland forest community types. Approximately 75% of the subcatchment is well developed old-growth productive forest occupying a steep south-facing slope. This community corresponds to the 04 site-series classification system adopted by the B.C. Ministry of Forests to describe the forest vegetation and associated topography, soil and climate (Banner *et al.*, 1993). These well-drained colluvial slopes have a depth-to-bedrock of about 0·8 m adjacent to the stream channel and 4·8 m at the top of the A–A' transect (Figure 1). A soil layer of 30 to 40 cm has developed and supports mature timber consisting primarily of sitka spruce (*Picea sitchensis*), western hemlock (*Tsuga mertensiana*) and western red cedar (*Thuja plicata*). At the lower, wetter portion of the subcatchment there is an abrupt transition to swamp forest (site-series 13) coinciding with the change in topographic gradient. This forest community consists of large mature sitka spruce and red cedar at the edge of the headwater swamp (HWS), with an understory of yellow cypress (*Chamaecyparis nootkatensis*), western red cedar, mountain hemlock, skunk cabbage (*Lysichitum americanum*) and devils club (*Oplopanax horridus*) that extends into the wetter part of the headwater swamp.

The main surface drainage originates in the headwater swamp (HWS) and begins to coalesce as a stream where the A–A' transect crosses (Figure 1). From there the stream flows between the base of the 04 site-series forested hillslope (FH) and the 13 site-series boundary forest (BF). The BF, although classified as site-series 13, is less wet than the HWS and forms a topographic boundary along the south edge of the sub-catchment. A seep, or spring, that issues from the foot of the FH slope enters the north side of the stream approximately 20 m east of the A–A' transect on the north side of the stream. Diffuse FH groundwater input also drains to the stream (GW) and was measured along the A–A' transect (see Methods).

METHODS

Field methods

Data presented in this paper were collected primarily between 30 May (day 150) and 4 July (day 185) 1999; however, installation of instrumentation began during the summer of 1997. Outflow from a groundwater seep was not measured until 22 June (day 173), so data until 22 August (day 238) have been included to characterize its response. Shallow water-table wells and piezometers were installed along a transect across the boundary forest and partially up the forested hillslope (line A–A', Figure 1). The piezometers and wells were constructed of 2·5 cm i.d. PVC pipe with the ends slotted and screened over the lower 20 cm. For installation deeper than 2 m, steel drive-point piezometers connected by teflon tubing cased in steel pipe were used. These instruments were installed in nests, and usually a well was installed with several piezometers at various depths below ground surface along the transect (Figure 2). In addition to installations along the A–A' transect, two nests of PVC piezometers were installed in the HWS, one consisting of a well and two piezometers in the

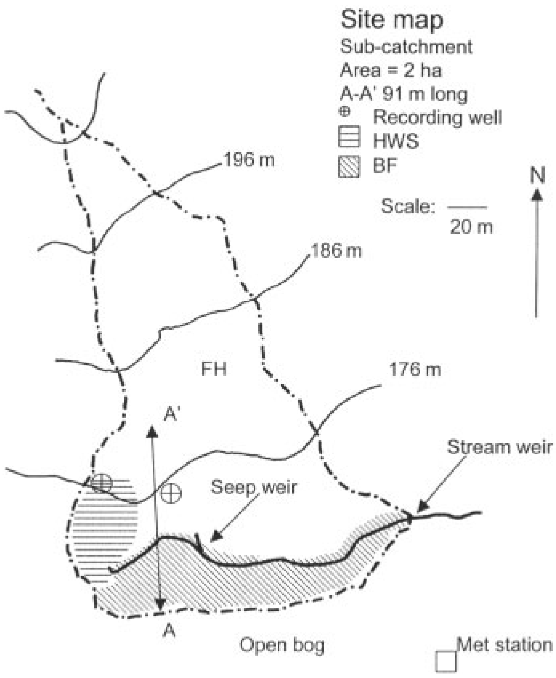

Figure 1. Study site in Diana Lake Provincial Park near Prince Rupert, British Columbia (54°10′N, 130°15′W). Most of the wells and piezometers were installed along the A–A′ transect. Discharges for the seep and stream were obtained from marked weirs. A meteorological station is located on open bog. FH (old growth productive forest) comprises approximately 75% of the subcatchment

north end of the HWS and one in south end of the HWS containing one well and piezometer. Two automatic recording wells were installed, one in FH on the A–A' transect and one in HWS. These wells recorded the water table elevation hourly between 30 May and 4 July 1999.

Groundwater discharge from the FH to the stream channel was calculated using Darcy's law

$$Q_{GW} = K_{sat} \times A_x \times i \tag{1}$$

where Q_{GW} is groundwater discharge, K_{sat} is the saturated hydraulic conductivity, A_x is the flow cross-sectional area (taken to be 0·8 m thick by the length of the stream reach above the weir, 100 m) and i is the hydraulic gradient. The values for K_{sat} were obtained from bail tests performed in piezometers installed along the A–A'

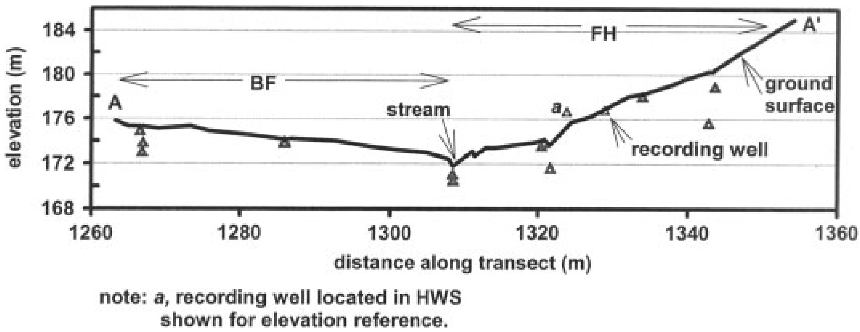

Figure 2. Profile of A–A′ transect. Wells and piezometers (indicated by triangles) were used to collect DOC and isotope samples. Forest types and stream location are also indicated

transect. The gradient (*i*) was calculated from the changing water-table elevation, automatically recorded on the FH compared with the average water surface elevation of the stream where it crosses the A–A' transect.

A 60°V-notch weir installed June 1998 was used to measure discharge (Q) from the stream. A 30°V-notch weir was installed on the seep in mid-June 1999 (Figure 1). Stage–discharge relationships for the weirs were developed through manual bucket gauging and stage records during the 1999 field season. Stage height behind each weir was recorded hourly using automatic water level recorders.

A meteorological station was maintained on a nearby open bog (Figure 1) about 200 m from the subcatchment. Rainfall amounts were recorded using a tipping bucket rain gauge connected to a datalogger. An adjacent manual gauge was used to capture rain samples for DOC and stable isotopes. Two plastic eaves troughs were installed under the 04 forest canopy to collect throughfall water samples for isotope analysis. Troughs were rinsed with excess throughfall water after samples were collected to remove any loose debris that may have landed in the troughs.

The DOC samples were collected from the stream using an automatic sampler set to collect samples every 3 h. Manual samples were collected daily, or sometimes more frequently, from piezometers and wells. Also, daily grab samples were collected from the seep and from the stream approximately 25 m upstream of the seep where the A–A' transect crosses the stream.

Groundwater and stream-water DOC samples were field filtered into 10-mL glass vials using disposable 0·45 µm cellulose nitrate filters. The samples were preserved with dilute HCl to prevent microbial degradation. The glass vials were sealed air-tight with a rubber septum-stopper and air bubbles were removed using a syringe needle through the stopper. The samples were stored in the dark at 4 °C until they were analysed. The DOC concentration was measured by high-temperature combustion using a Dohram DC-190 total carbon analyser to an analytical uncertainty of 0·5 mg/L. Owing to logistical constraints water samples for DOC analysis were not always collected simultaneously at all sites, or with the same frequency. Therefore, linear regression was used to interpolate DOC from hourly Q values so a more complete record was available. The regression analysis was performed between Q and DOC separately for the rising and falling limb of the hydrograph for each event (see Hinton *et al*., 1997). Fits for the regression are shown in Table I.

Water samples for isotope analysis were collected in 30-mL Nalgene™ high-density polyethylene (HDPE) bottles and returned for standard determination of $^{18}O/^{16}O$ and $^{2}H/^{1}H$ ratios. Analysis was performed using mass spectrometry at the Environmental Isotope Laboratory, University of Waterloo and results are reported according to the guidelines of Coplen (1996). Analytical uncertainty is better than ±0·1‰ for ^{18}O and 2‰ for ^{2}H based on assessment of laboratory and blind repeats.

DOC mixing model calculations

The application of mixing models to characterize the magnitude of various sources of water contributing to outflow, for example, requires that 'end-members' ideally be stable and non-reactive. In this analysis DOC is used in a mixing model as a first approximation of the contribution of the HWS to stream discharge. It

Table I. Regression analysis: stream discharge (Q) versus [DOC]. The regressions were done separately for the rising or falling limbs of the hydrograph

n	Day of year	R^2	Regression formula	Rising limb or falling limb
12	152·76–154·06	0·49	[DOC] = 11·2 + 1·70Q	Rising
34	156·76–166·88	0·63	[DOC] = 10·6 + 1·60Q	Falling
3	166·88–167·13	0·92	[DOC] = 13·6 + 1·72Q	Rising
26	167·13–173·07	0·80	[DOC] = 13·0 + 1·98Q	Falling
3	173·07–173·48	0·93	[DOC] = 12·9 + 1·74Q	Rising
16	173·48–177·1	0·67	[DOC] = 12·6 + 2·17Q	Falling
8	177·10–193·52	0·65	[DOC] = 10·4 + 6·66Q	Both

cannot be considered valid if DOC changes significantly along the flow paths. The validity of this approach in the present setting for quantifying mixing proportions is discussed later.

Water at the stream weir is a mixture from two primary sources; groundwater (GW) characterized from seep discharge and matrix flow from FH, and surface water from the HWS. For the mixing model, average DOC for FH and seep were assumed to be part of a common parent groundwater reservoir (DOC was similar in both—see Results). To separate the constituent components of discharge in the stream, a mixing model approach was used where

$$Q_{\mathrm{GW}} = Q_{\mathrm{stream}}[(C_{\mathrm{stream}} - C_{\mathrm{HWS}})/(C_{\mathrm{GW}} - C_{\mathrm{HWS}})] \quad (2)$$

and Q_{GW} is the portion of stream weir discharge from FH groundwater and the seep, Q_{stream} is the total discharge at the stream weir, C_{stream} is DOC at the stream weir, C_{GW} is the DOC in FH groundwater and the seep and C_{HWS} is the DOC in the HWS.

Deuterium excess

Deuterium excess (d-excess)(Dansgaard, 1964) can be used as an index of departure of the δ^{18}O versus δ^2H plotted values from the meteoric water line (MWL, $\delta^2\mathrm{H} = 8\delta^{18}\mathrm{O} + 10$) of Craig (1961). The d-excess parameter is defined as

$$\mathrm{d} \equiv \delta^2\mathrm{H} - 8\delta^{18}\mathrm{O}(‰) \quad (3)$$

where δ^2H and δ^{18}O are the hydrogen and oxygen isotopic composition of the water respectively and 8 is the slope of the MWL (note the d-excess of the MWL is 10‰)(Gibson *et al.*, 2000). The value of the d-excess parameter is set by, or inherited from, the initial isotopic composition of the air mass as determined by the air–sea interaction (Gat, 1996). An increase in d-excess in precipitation generally reflects enhanced moisture recycling during transport, and lower d-excess reflects subdued moisture recycling (Gat *et al.*, 1994). The d-excess value of groundwater may differ from the original precipitation source if it experiences evaporation in recharge areas, which may cause evaporative enrichment of residual water (Allison *et al.*, 1983). Gibson *et al.* (2000) applied d-excess as a tracer at a nearby study site to distinguish water from different reservoirs within a single study catchment.

Gibson *et al.* (2000) argued that a shift in baseflow isotope signature before and after a distinctly labelled event could be used in catchments with limited groundwater reservoirs to estimate the effective groundwater storage volume. The effective groundwater storage before and after the event, S_{b} and S_{a}, respectively, which are a function of the fraction of event water not recovered (i.e. because it has been stored in the groundwater reservoir), can be found as

$$R + S_{\mathrm{b}} = S_{\mathrm{a}} \quad (4)$$

where R is the total depth of rainfall for the event minus total depth of discharge for the specified time period. As it is not possible to know the storage volume directly, knowledge of the d-excess, δ, for the various sources can be used in a mixing model, where

$$\delta_{\mathrm{R}}R + \delta_{\mathrm{Sb}}S_{\mathrm{b}} = \delta_{\mathrm{Sa}}S_{\mathrm{a}} \quad (5)$$

Substitution of Equation (4) into (5) and rearranging yields

$$S_{\mathrm{b}} = R(\delta_{\mathrm{R}} - \delta_{\mathrm{Sa}})/(\delta_{\mathrm{Sa}} - \delta_{\mathrm{Sb}}) \quad (6)$$

To estimate water residence times S_{b} is used in comparison with the total annual rainfall (P) to approximate the groundwater residence time before the event, such that

$$T = S_{\mathrm{b}}/P \quad (7)$$

where T is the groundwater residence time in years.

RESULTS

Precipitation

Total precipitation recorded in May 1999 on the open bog near the study site (330 mm at 160 m a.s.l.) exceeded the May climate normals (1960 to 1991) for four recording stations in the Prince Rupert area (142 to 169 mm, at 34 to 91 m a.s.l, respectively). The monthly totals for June and July were 181 and 106 mm, compared with an average of the normals reported for the four Prince Rupert stations of 134 mm (range 120 to 142 mm) and 113 mm (range 113 to 137 mm), respectively (Environment Canada, 1998). Rainfall during the study period, 30 May to 4 July 1999, fell mainly in six storm events (Table II and Figure 3). The largest event, occurring on May 31 (day 150), was prior to the start of the sampling program for isotopes and DOC, but is included because of its magnitude and the anticipated influence that it likely had on 'flushing' of the system.

Groundwater response

Monitoring at the A-A' transect (Figure 2) revealed continuous groundwater recharge to the stream, with piezometric heads ranging from 0·23 m to 0·35 m and averaging 0·28 m above the stream bed. The water table, expressed relative to the surface within FH ranged from −0·96 m to −0·75 m (average of −0·88 m) indicating groundwater recharge. Within the BF, along the A–A' transect, the water table ranged between −0·45 m and −0·10 m (average of −0·28 m) again indicating groundwater recharge. Within the zone defined as the HWS the water table ranged between about −0·092 m and +0·017 m (average of −0·023 m) varying between recharge and discharge. The vertical hydraulic gradients at the well/piezometer nest in the stream (Figure 2), ranged between +0·016 and +0·11 (discharging) with an average of +0·067. In the FH at the piezometer nest nearest the stream the vertical hydraulic gradient averaged −0·25 with a range of −0·34 and −0·22. The gradients at the north end of the HWS were between −0·11 and +0·22 (average of +0·023), indicating a discharge zone, but at the south end of the HWS ranged between −0·01 and −0·053 with an average of −0·027 m indicating recharge. The vertical gradients in the BF ranged between −0·20 and −0·14 (average of −0·16) (1998 manual data).

The system responded rapidly to rainfall events (Figure 3). At the beginning of this study the water table in the HWS was already above the surface, so additional rain, surface water and groundwater inflow immediately increased the depth of ponded water and drained to the stream. Events following drier periods (e.g. day 167) caused a steep rise in water table to produce the ponded condition (Figure 3). Discharge in the stream began to peak after the water table in HWS intersected the ground surface. The influence of the HWS on the discharge at the stream weir is shown in Figure 4. In first 5 h of the event on day 167 there was a sharp response in the HWS but, no corresponding increase in stream discharge or rise in the water table in the FH. At the beginning of the day 167 event the water table in the FH did not begin to rise for 5 or 6 h after the rise in the HWS. However, when the HWS water table intersected the ground surface, flow rapidly increased in the stream, and the water table elevation in the FH began to rise. Both the day 150 and 167 events had similar trends despite different antecedent conditions.

Table II. Subcatchment rain and runoff estimates by event

Duration of storm (time in days)	Rainfall amount per event (mm)	Total discharge stream (mm)	ΔS subcatchment (mm)	Stream runoff (%)
149–152	62·7	69·1	−6·4	110
154–160	48·2	40·9	7·3	85
166–167	32·7	20·0	12·7	61
173–174	26·5	20·0	6·5	75
178–182	42·7	35·4	7·3	83
Total	212·8	185·4	27·4	87

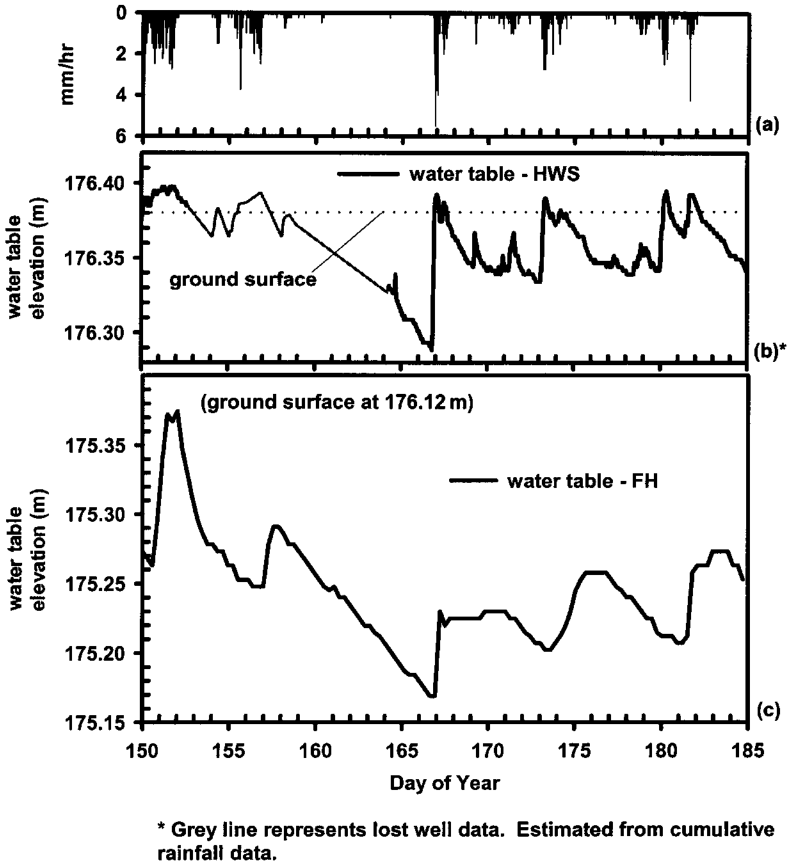

Figure 3. Precipitation and water table data. (a) Precipitation amounts in mm/h collected on a nearby open bog (see Figure 1). (b) Hourly water table elevation for the HWS. Dotted line indicates the elevation of the ground surface at the recording well. (c) Water table elevations recorded in the FH. The ground surface at the recording well is 176·12 m

The contribution to stream flow calculated from groundwater matrix flow was small and never exceeded 0·6% of the total flow. However, groundwater discharge at the seep averaged 14% of stream flow, based on seep and stream Q data collected between 22 June (day 173) and 26 August (day 238) 1999. Although the range of seep input varied from <1 to 73% of stream flow, the proportion was mostly below 30% (Table III). A slight depression in the proportion of seep flow occurred during rain events (Figure 5), but the highest proportion occurred during very small rain events near the end of hydrograph recession periods, where the response from the seep, in stream flow, was greater than from HWS surface runoff. However, during the longer drying periods, seep discharge decreased to its smallest proportion of stream flow as its flow almost ceased. During the same time period (day 173–238) a strong relationship was also found between water table position in the FH and the seep Q. When the FH water table elevation was above 175·28 m (0·84 m below local ground surface) the seep Q increased significantly and showed a very strong relationship ($r^2 = 0{\cdot}93$) to FH water table fluctuations (Figure 6). However, seep Q was much less sensitive to changes in the water table when the FH water table was below the 175·28 m threshold.

DOC distribution

The DOC was collected from the HWS, FH, the stream before the seep, the seep and the stream at the weir. The DOC concentrations at the stream weir were closely correlated to water discharge (Table I),

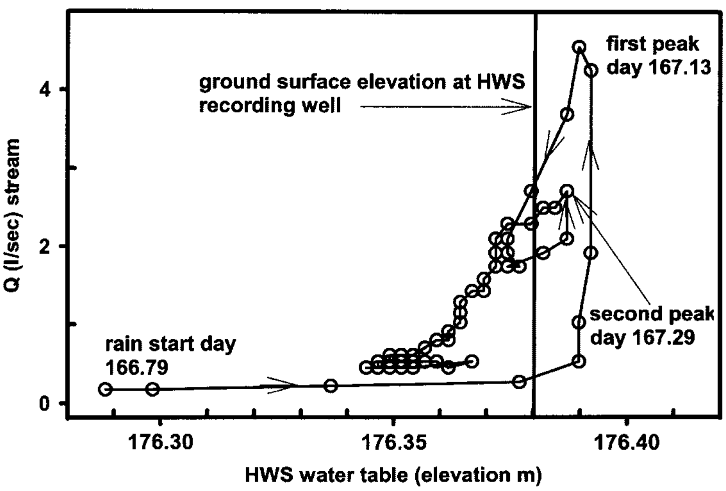

Figure 4. Stream Q response to change in HWS water table. 15 June (day 166) event is shown. Circles mark hourly change from start of rainfall. Vertical line at 176·38 m corresponds to ground surface elevation at the HWS recording well. Note that during the first 5 h of the event the water table rose nearly 10 cm, at which point the water table intersected ground surface. Before that time there was little change in stream discharge

Table III. Percentage contribution of seep discharge to the total stream discharge in rising and falling limbs of the hydrograph, from 22 June to 26 August (day 173–238) 1999

	Physical measurement				
	Rising and falling limbs (seep $Q \leq 0{\cdot}5$ L/s)	Rising and falling limbs (seep $Q \geq 0.5$ L/s)	Baseflow recession (longer drying periods)		DOC mixing model (rising and falling limbs)
Time period (Julian Day)	173–186	227–238	188–209	215–226	152–181
Average (14%)[a]	24	17	10	7	42
Maximum (73%)[a]	58	35	73	28	73
Minimum (0·03%)[a]	5	4	0·05	0·03	4

[a] Percentage of seep Q as a fraction of stream Q for entire period, day 173–238.

a result also reported for another local stream (Gibson *et al.*, 2000). The average DOC concentration (± standard deviation) for the HWS, FH, the stream before the seep, the seep and the stream were: 18·80 ± 3·57, 6·45 ± 2·05, 12·81 ± 2·55, 5·86 ± 1·4, and 13·37 ± 2·37 mg/L, respectively, for the 35-day sampling period. The stream DOC concentration was found most frequently to be intermediate between groundwater (both FH and seep) and the HWS (Figure 7). However, after the day 167 event the DOC in stream baseflow shifted to higher concentrations (Figure 7), as it did in the HWS and to a lesser extent at FH (Table IV). This step-shift is attributed to a 'turn over' in the groundwater system within the subcatchment (see Discussion section).

DOC mixing model—a first-approximation

The DOC shifts were applied semi-quantitatively to characterize robust short-term shifts in contributions of surface water (HWS) and groundwater (seep/FH) to total streamflow (Q_{total}) (Figure 8). The results, based on Equation 2, are consistent with groundwater contributions to Q_{total} ranging between about 4%

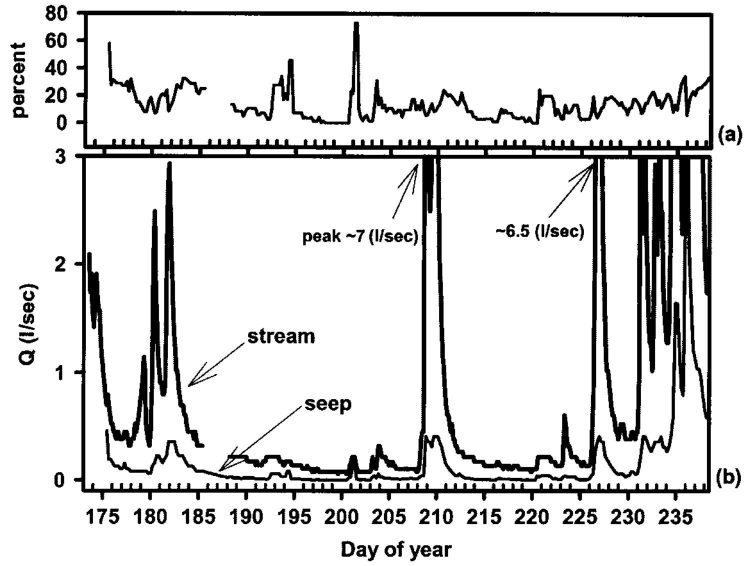

Figure 5. (a) Percentage of discharge in stream originating from the seep. (b) Seep and stream discharges. Times are for days 173 (install date for seep weir) through to 238

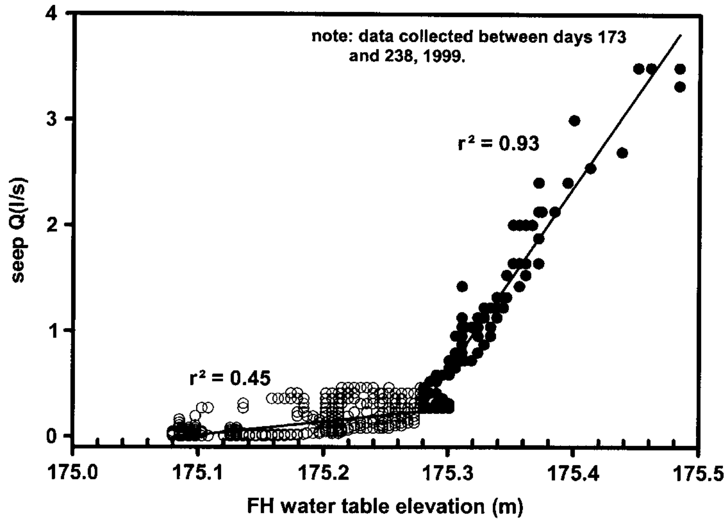

Figure 6. FH water table elevation versus seep discharge. Seep discharge was less sensitive to FH water table fluctuations when water table was below 175·28 m

and 73% (averaging 42%) (Table III). Contributions from groundwater sources were calculated to be at a maximum during baseflow conditions in response to a small rain event (e.g. 73 and 66% at time of lowest stream discharge on days 165–166) and at a minimum during peak discharge (e.g. 4% and 10% on day 156 and 167, respectively). These extreme values are similar to those obtained by comparing the physical discharge measurements for seep and stream weirs (Table III and Figure 5). However, the average value of seep contributions determined by the mixing model (42%) exceeded the physically measured seep contribution (13%), which may in part be a result of the difference in the sampling periods or non-conservative behaviour of DOC (evolution) as it moves and interacts in the hydrological system. An uncertainty analysis

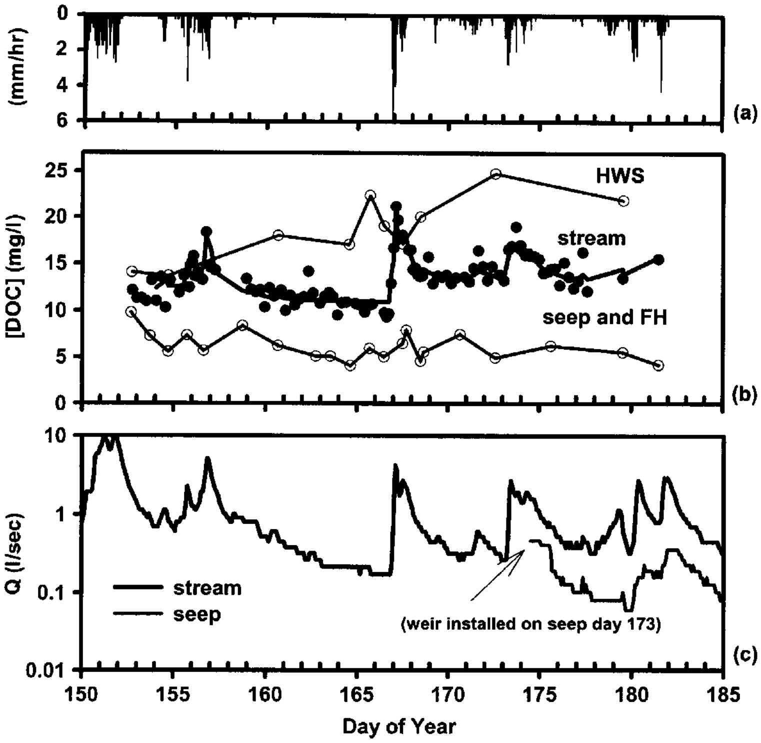

Figure 7. (a) Precipitation. (b) [DOC] for HWS, stream and seep/FH. Note: solid line for stream values is based on regressions (stream Q versus [DOC]) done separately for each rising and falling limb (see Methods and Table I). (c) Stream and seep Q. Note: weir used to record seep Q was not installed until day 173

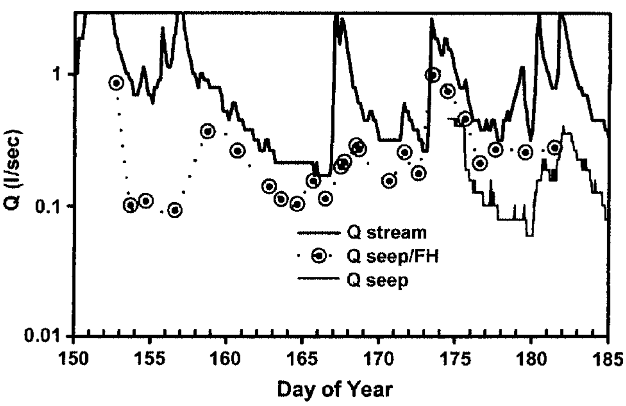

Figure 8. Stream Q (Q_{total}, solid line) measured at the stream weir. Values obtained from two component mixing model Q_{GW} (GW = seep/FH) estimated from two component mixing model represented by open circles with dotted line (see Methods section). Lowest per cent Q_{GW} contribution to stream flow occurs on day 156, 4% of total. Highest percentages on days 165–6 (72 and 66%)

(Genereux, 1998) designed for tracer-based hydrograph separation concentrations was applied to the DOC data. The uncertainty was found to be between 0·13 and 0·75 mg/l, and averaged 0·25 mg/l. The highest uncertainty occurred at the beginning of the DOC time-series when the end members were close together (Figure 7).

Table IV. Average ± SD of DOC concentrations, isotope and d-excess distribution (number of samples in parentheses)

	Average DOC concentration		Average isotope values[a], day 150 to 167.7			Average isotope values[a], day 167.8 to 185		
	Day 150 to 167.7	Day 167.8 to 185						
	(mg/L)	(mg/L)	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	d-excess	$\delta^{18}O$ (‰)	$\delta^{2}H$ (‰)	d-excess
Throughfall	n/a	n/a	−11·25 (6[b])	−83·73 (6[b])	6.30 (6[b])	−10·31 (5[c])	−73·46 (5[c])	9·05 (5[c])
Rain	3·71 ± 1·33 (5)	3·76 ± 1·59 (4)	−11·40 (6[b])	−87·52 (6[b])	3·72 (6[b])	−10·56 (5[c])	−87·21 (5[c])	−2·76 (5[c])
HWS	17·33 ± 2·97 (7)	22·23 ± 2·39 (3)	−11·14 ± 0·21 (7)	−83·42 ± 2·66 (7)	5·72 ± 3·31 (7)	−11·38 ± 0·14 (4)	−81·30 ± 2·24 (4)	9·70 ± 1·79 (4)
Stream above seep	11·94 ± 3·24 (9)	13·07 ± 1·24 (9)	−11·46 ± 0·42 (9)	−79·30 ± 2·03 (9)	12·36 ± 5·10 (9)	−11·25 ± 0·11 (7)	−79·39 ± 1·58 (7)	10·61 ± 2·26 (7)
Seep	6·00 ± 1·50 (14)	5·60 ± 1·30 (8)	−11·51 ± 0·38 (13)	−80·63 ± 2·33 (13)	11·43 ± 1·22 (13)	−11·55 ± 0·12 (7)	−80·56 ± 1·27 (7)	2·03 (7)
FH	6·54 ± 2·35 (8)	6·34 ± 1·78 (6)	−11·17 ± 0·62 (13)	−78·13 ± 3·82 (13)	11·22 ± 2·11 (13)	−11·07 ± 0·13 (3)	−80·67 ± 2·08 (3)	7·87 ± 3·04 (3)
Stream	12·46 ± 2·55 (54)	14·53 ± 1·49 (44)	−11·18 ± 0·13 (8)	−80·08 ± 1·23 (8)	9·39 ± 1·61 (8)	−10·99 ± 0·10 (10)	−81·73 ± 2·46 (10)	6·21 ± 2·74 (10)

[a] Rain and throughfall ($\delta^{18}O$, $\delta^{2}H$ and d-excess) are amount-weighted averages based on storm amount.
[b] Rain and throughfall samples collected concurrently.
[c] Collected concurrently except for 21 June (no throughfall sample) and 28 June (rain sample lost).

Isotope distribution

The $\delta^{18}O$ composition of streamwater ranged from −11·35‰ to −10·78‰ (average −11·08‰), which was close to that of mean rainfall for the study period. Groundwater sampled in shallow wells and piezometers in the FH, and seep water fed by deep FH sources, was also relatively constant in $\delta^{18}O$, ranging from −11·85‰ to −10·92‰ (average −11·36‰). Rain $\delta^{18}O$ values varied between −13·5‰ and −5·3‰ with an amount-weighted average of −11·1‰. Throughfall values for the same time period ranged from −13·3‰ to −5·7‰ with an amount-weighted average −10·9‰. Comparable results were obtained for δ^2H. No significant rain event monitored during this study had $\delta^{18}O$ or δ^2H signatures that were sufficiently distinct from groundwater to permit a quantitative hydrograph separation using a single tracer. A plot of $\delta^{18}O$ versus δ^2H (Figure 9) shows that most samples collected from the subcatchment clustered along the global meteoric water line (MWL). Rain during the study was, however, distinguished by its lower deuterium excess, falling on a linear trend subparallel and below the MWL. The enlarged portion of the graph (Figure 9) illustrates that groundwater (seep/FH water) tended to cluster above the MWL as opposed to HWS water and stream water, which plotted below the MWL and closer to the rain trend line (dotted line, Figure 9).

In the present setting, d-excess in seep water was found to be relatively constant (typical values ranging from 8·9‰ to 15·6‰, averaging 11·6‰) during a 35 day period in May–June of 1999 (Figure 10). Wider variations in d-excess values were observed for rainfall, ranging from −8·1‰ to 4·8‰ and averaging (amount-weighted) 1·6‰ and throughfall values ranging from 0·4‰ to 8·0‰, averaging (amount-weighted) 7·2‰. Note that d-excess of the MWL is 10‰. Some notable shifts in the d-excess values were observed before and after the day 167 event (Figure 10 and Table III). The amount-weighted average d-excess for rainfall before the event was 3·7‰ compared with −2·8‰ after the event. The d-excess values for the stream appear to have shifted in response to increased rainfall contributions to stream flow, which averaged 9·5‰ and 6·2‰ before and after the event, respectively. The d-excess values for the seep remained relatively stable

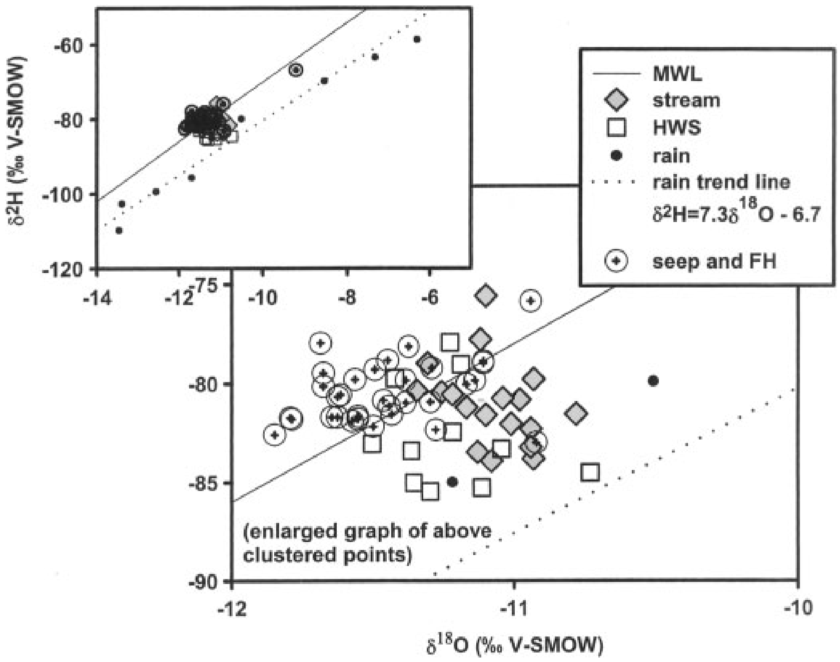

Figure 9. $\delta^{18}O$ versus δ^2H. Upper left (large scale) shows full distribution of rain collected during the study period. Lower right is smaller scale so that differences in collected samples can be seen more clearly. MWL (meteoric water line, $\delta^2H = 8\delta^{18}O + 10$) solid line and local rain water line shown as dotted line from samples collected during the study period ($\delta^2H = 7{\cdot}3\delta^{18}O - 6{\cdot}7$)

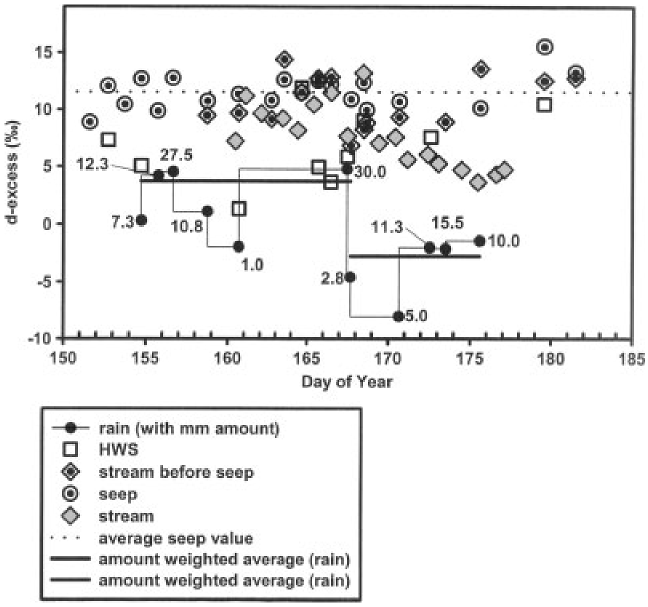

Figure 10. Plot of d-excess values against time. Dotted line is the average of d-excess values for the seep. Before event on day 167 the d-excess in the stream is similar to the seep but after day 167 the stream values drifted towards the local rain values (see Table IV)

across the event, in the range of 11·4‰ to 11·9‰, indicating a deep groundwater source, and d-excess from the HWS also increased significantly from 5·7 to 9·7‰. The d-excess values (Table IV) and the cumulative runoff and rainfall data (Table II) were used as a semiquantitative indicator to estimate effective groundwater storage within the subcatchment from Equation. (6). The fraction of unrecovered event water (presumed to be recharged) was examined for the three rain events occurring between days 166 and 182 (75·4 mm). The amount weighted d-excess value for rain for the three events was used as a reference along with the FH d-excess values before and after day 167 for groundwater. Based on Equation. (6), the estimated effective groundwater storage before the day 167 event was about 260 mm. Residence time calculation (Equation 7) for the subcatchment was approximately 12 days.

DISCUSSION

A conceptual model of the subcatchment's hydrology is shown in Figure 11. Precipitation water falling on the catchment is received by both the headwater swamp (HWS) and forested hillslope (FH). From physical monitoring and tracer studies it is found that infiltration and downslope movement of precipitation recharged within FH contributes flow either directly to the stream by diffuse groundwater flow (<1%), via groundwater emerging in seeps (*c*. 14%), or discharges and is routed to the stream via the HWS (>85%). As a result, the HWS is a primary regulator of discharge in the stream, accounting typically for 30 to 99% of the stream discharge, depending on flow conditions.

Physical hydrology evidence alone demonstrates the importance of the HWS on runoff production. The water table in HWS was highly responsive (Figure 3), owing to upward hydraulic gradients and an ephemeral spring at the upper (north) end which maintained the water table close to the ground surface. Major rain events raised the water table above the surface within 7 h, and surface ponding was observed during the onset of stormflow (Figure 4). Runoff recession occurred quickly when the HWS surface water elevation began to decline. The similarity between the HWS water table and stream runoff during wet and dry periods is consistent with the HWS as a primary runoff source. The water table in FH was also much more variable than

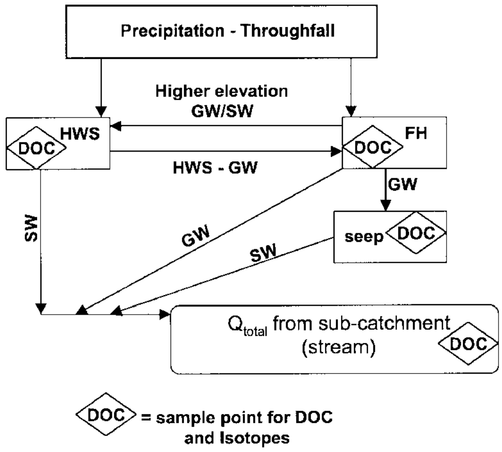

Figure 11. Conceptual flow model for the subcatchment. GW = groundwater; SW = surface water

that of the HWS. A relatively rapid decline observed in water storage (notably following the major storm on day 152) can be attributed to the steep hydraulic gradients on the FH slope (16 to 18%). Water table recessions showed no signs of flattening out even during the longest dry period (days 158–166), evidence of continued drainage toward the seep and the stream that suggests it was a source of baseflow. Seep discharge responded slowly to changes in FH water table below 175·28 m (Figure 6), but did become negligible during the longer dry periods. On these occasions baseflow was apparently sustained by drainage of deeper groundwater through HWS.

The HWS was a major source of DOC in this system, consistently having higher concentrations than the other source area, FH. This reflects the large pool of carbon associated with the peat soils in HWS. [DOC] was fairly constant in the seep and FH, although it was significantly diluted by the heavy rain following the day 150–152 storm (Figure 7); evidence that the system was flushed. During the dry period (days 158–166) [DOC] in HWS increased as pore-water residence time increased in that location. Subsequent storms caused partial flushing, but pore-water concentrations remained relatively high.

The distinct [DOC] in HWS and FH were used to assess the relative importance of drainage from HWS. In this small catchment, where flow paths and residence times were short, DOC provided a first approximation for hydrograph separation through the mixing model approach (Equation 2). The short flow paths and residence times, especially for HWS, and the short channel segment over which sampling occurred, minimize the bias that occurs in larger systems. Moreover, the three component parts of the mixing model were distinct from one another over the 35 day collection period. Although DOC cannot be counted on to provide absolute discretization of source waters, it does offer potential as a semiquantitative hydrological tracer (Gibson *et al.*, 2000), particularly when supported by direct physical measurements and other tracers (e.g. d-excess). The DOC mixing model indicated that HWS supplied between 90 and 95% of flow (Figure 8, Table III) during the highest stream flows (day 156 and 167). During this time the HWS experienced a prolonged period of inundation (Figure 3), acting as a source area for saturation overland flow. During recession periods, the DOC mixing model indicates that seep/FH water contributed 40–70% of stream discharge. This corresponds fairly well with the higher end of the physical measurements, 35–58%, but not the lower range of 4·0–5·4% (Table III).

The timing of collection of DOC samples from later events did not coincide well with peak runoff times, and thus they were not suitable to characterize the later contributions of HWS. Consequently, the correspondence between measured seep discharge and that estimated from DOC mixing model (Figure 8, Table IV) was poor. When the two methods did overlap later in the study, the measured flow was less. This may have been because interception increased significantly in HWS over the course of the study, as skunk cabbage (very large leaves and a closed funnel-like structure) covered much of the HWS, thus partially diminishing its role as a source of runoff.

Isotope data plotted in $\delta^{18}0$ versus. δ^2H space indicate that seep/FH waters were slightly above the MWL whereas HWS and stream waters were below, closer to rainfall values. This suggests that the HWS and stream discharges comprised waters from rain events occurring during the study period. Deuterium-excess results convey a similar picture. During the low rainfall period (e.g. days 155–166) characterized by a pronounced streamflow recession, d-excess values tended toward the signature of seep (Figure 10), suggesting that this was a primary source of water at low flow. Following a 32·7 mm rain event on day 167, there was a progressive reduction in d-excess owing to higher contributions of rain and throughfall, and standing surface water in the HWS, which is a mixture of groundwater, rain and throughfall. Prior to the day 167 rain event d-excess in the stream drifted towards those of the seep. However, after the rain event the stream d-excess tended towards the d-excess values of rain. The small rainfall component in peak discharge in these systems (Gibson *et al.*, 2000) attests to the importance of infiltration and short flow paths. In this system, Darcian water input to the channel from FH was small ($<1\%$). The vertical hydraulic gradient at the stream where it crosses the transect was strongly upward (0·067), but K was low (10^{-5} cm/s). However, it is evident from d-excess at the stream before the seep (Figure 10) that water input to the stream between the HWS and the seep had a significant FH signal. The relatively large FH signal implies there were zones of much higher hyporheic exchange along the channel reach that were not measured. No other seeps were observed.

In this study three distinct methods were used to quantify flow paths (physical techniques, DOC and d-excess mixing approaches), each with strengths and weaknesses. Physical measurement has simplicity and provides a better understanding of the processes based on well-founded theory but can be subject to error caused by spatial under- or misrepresentation. In this study, for example, our d-excess analysis suggests that additional FH/seep water sources enter the stream than could be accounted for by physical measurements made at the groundwater transect. Thus it is a strength of the mixing-model approach that spatial integration can be captured (when sampled adequately), although details of the processes cannot always be demonstrated. Using DOC in a mixing model takes advantage of the clearly distinct naturally occurring signatures that water acquires when resident in peaty soil, versus deeper groundwater sources. Rigorous accounting in the mixing model, however, cannot be assured because of transformations that can occur along its flow path. When flow paths are short, and when reservoirs are clearly distinct, DOC analysis can be constructive in understanding the physical linkages of the system. Finally, isotopes ^{18}O and ^{2}H are valued because of their non-reactive properties and similarity to (common isotope) water. However, as seen in this study, they are often not distinct from rainfall, so cannot be used in the traditional manner. Yet when expressed as d-excess, a clear signature may be evident, that permits flow paths and residence times to be illustrated.

CONCLUSIONS

The HWS occupies about one-quarter of the study subcatchment area but it strongly affected water storage and runoff from the larger watershed. Because of its position in the subcatchment it received relatively constant groundwater input from the steep colluvial slopes that kept its water table relatively high. During significant storm events, therefore, its water table rose quickly and pools developed on the surface, coinciding with a release of water to the stream. During these storms over 95% of stream discharge had its source from overland flow in HWS. Between storms, the proportion of groundwater seepage from FH to the stream increased over time. Diffuse groundwater flow to the stream was minor ($<1\%$), but groundwater discharge to one major seep (spring) that emerged near the stream contributed up to 73% between storms. The sensitivity of discharge to relatively small areas in the watershed during high flow (HWS) and low flow (seep) has implications for harvesting activities. Logging on HWS areas leading to a rise in water table (e.g. Dubé and Plamondon, 1995) will exacerbate flood translation. The lack of sensitivity of seep discharge to variations in FH water table suggests that these sites (FH slopes) will be affected to a lesser extent by forestry activity.

The DOC was useful to characterize source areas, particularly during events, but could not be used to determine residence time. However, examination of residence time based on d-excess, indicated a 12 day residence period. With this relatively short turnover period, disturbances to the system can be expected to establish themselves rather quickly, both in terms of water relations and nutrient redistribution. Forest managers can mitigate some of the harmful effects of logging operations by respecting the integrity of headwater wetland systems.

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