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Hydrological processes controlling ground and surface water flow from a hypermaritime forest–peatland complex, Diana Lake Provincial Park, British Columbia, Canada

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Abstract:

The proposed harvesting of previously undeveloped forests in north coastal British Columbia requires an understanding of hydrological responses. Hydrometric and isotopic techniques were used to examine the hydrological linkages between meteoric inputs to the surface-groundwater system and runoff response patterns of a forest-peatland complex. Quickflow accounted for 72–91% of peak storm discharge. The runoff ratio was lowest for open peatland areas with thick organic horizons (0·02–0·05) due to low topographic gradients and many surface depressions capable of retaining surface water. Runoff ratio increased comparatively for ephemeral surface seep flows (0·06–0·40) and was greatest in steeply sloping forest communities with more permeable soils (0·33–0·69). The dominant mechanism for runoff generation was saturated shallow subsurface flow. Groundwater fluxes from the organic horizon of seeps (1·70–1·72 m^3 day^{-1} m^{-1}) were an important component of quickflow. The homogeneous δ^2H–$\delta^{18}O$ composition of groundwater indicated attenuation of the seasonal rainfall signal by mixing during recharge. The positive correlation ($r^2 = 0{\cdot}64$ and 0·38, $\alpha = 0{\cdot}05$) between slope index and $\delta^{18}O$ values in groundwater suggests that the spatial pattern in the $\delta^{18}O$ composition along the forest-peatland complex is influenced by topography and provides evidence that topographic indices may be used to predict groundwater residence time.

KEY WORDS isotopes; topographic index; wetland; peatland; hillslope; stormflow; runoff sources; residence time

INTRODUCTION

The coastal western hemlock (CWH) forest region of north-coast British Columbia (BC) comprises transitional peatland and mature forest communities. Current proposals for harvesting western red cedar (*Thuja plicata*) and yellow cedar (*Chamaecyparis nootkatensis*) in these poorly drained systems have created the need for a better understanding of the hydrological processes contributing to forest community development (BC Ministry of Forests, 2001) and downslope water quantity and quality. There is concern that harvesting these poorly drained forests will accelerate paludification, decreasing site productivity and forest stand regeneration (Asada, 2002), and increasing peak water yields and solute export (Lortie, 2002).

Groundwater flow pathways in the CWH forest region are constrained by topography and the contrasting hydraulic characteristics of organic and mineral soil substrate (Emili, 2003). Determining how surface and subsurface flow pathways connect within forest–peatland complexes is essential to understanding runoff production and the transport and transformation of biogeochemically important elements in CWH watersheds. In the study area, Gibson *et al.* (2000) and Lortie (2002) used isotopic tracers to demonstrate that pre-event shallow groundwater is the dominant contributor to stormflow (85% and 66% at hydrograph peak respectively

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for each study). Gibson *et al.* (2000) hypothesized that, during major storms, event water contributions surpass pre-event contributions as soil matrix pathways are exceeded, and groundwater discharges to the surface (as seeps) and promotes rapid surface flow.

Although Gibson *et al.* (2000) and Lortie (2002) identified seeps as significant contributors to runoff, they did not investigate the physical mechanisms for generation, nor the temporal controls. At the study site, seep occurrence is related to changes in surface and subsurface topography that interrupt flow paths (Fitzgerald *et al.*, 2003) and where soils with higher saturated hydraulic conductivity overlie a less conductive confining layer (Emili, 2003). Seep morphology is varied, with some seeps discharging from a single point, others having the geometry of a line and still others dispersing over a broad area. There is an incomplete understanding of the integrated hydrological response of seeps and surface flows within CWH forest–peatland complexes. In this study, a combined hydrometric and isotopic approach is used to examine the hydrological linkages between meteoric inputs to surface and ground water and forest–peatland runoff response patterns. With respect to the CWH forest–peatland complex, the main objectives are to:

1. quantify hydrological inputs and canopy interception;
2. characterize the magnitude and timing of surface water runoff;
3. determine the relative contribution of hydrological inputs to groundwater recharge and streamflow;
4. define the spatial variability in groundwater isotopic composition using a slope index.

STUDY AREA

The main study site is located within Diana Lake Provincial Park (54°09′N, 130°15′W) approximately 25 km inland of the Pacific Ocean and 20 km southeast of Prince Rupert, BC (Figure 1). A second study site is located within a small (0·33 km^2) watershed on Smith Island, approximately 6 km southwest of the main study site. The Diana Lake and Smith Island watersheds are second-order watersheds with at least one tributary stream (Diana Creek and Smith Creek respectively). The two watersheds have similar elevations (Diana Creek 70–365 m a.s.l. and Smith Island 0–396 m a.s.l.), mean channel gradients (Diana Creek 32% and Smith Creek 33%) and aspect (easterly for Diana Creek and northeasterly for Smith Island). The Diana Creek and Smith Island watersheds are also located on the leeward side of a mountain barrier and an island respectively.

The climate of the study area is dominated by the prevailing westerly winds that carry cool, moisture-laden air masses to the coast, resulting in a hypermaritime climate characterized by cool (average annual temperature of 6·9 °C), with little snow (0·06% of annual precipitation) and frequent periods of fog. Mean annual rainfall at Prince Rupert is 2469 mm (Environment Canada, 2002), with summer being the driest season and autumn the wettest: 35% of rainfall occurs between September and December.

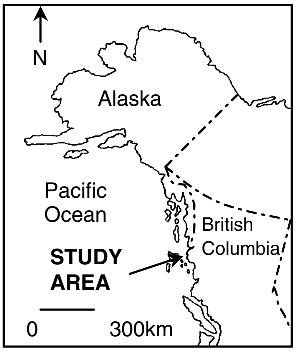

Figure 1. Study site location

At the Diana Lake site, a 500 m transect was established along a forest–peatland complex (Figures 2 and 3). The transect rises from an elevation 150–185 m a.s.l., with slopes ranging from 1% in the open peatland to 26% in the upland forest. A 170 m transect on Smith Island (35–45 m a.s.l.) was laid out through four forest community types.

The Diana Lake site comprises an assortment of landscapes characterized by distinct vegetation community types represented along the main transect, which eventually drains into Diana Creek (Figures 2 and 3). A subwatershed of the upland forest community type (see also Fitzgerald *et al.* (2003)) cuts through the main transect (upland forest stream). This stream is fed primarily by discharge from the upland forest west seep

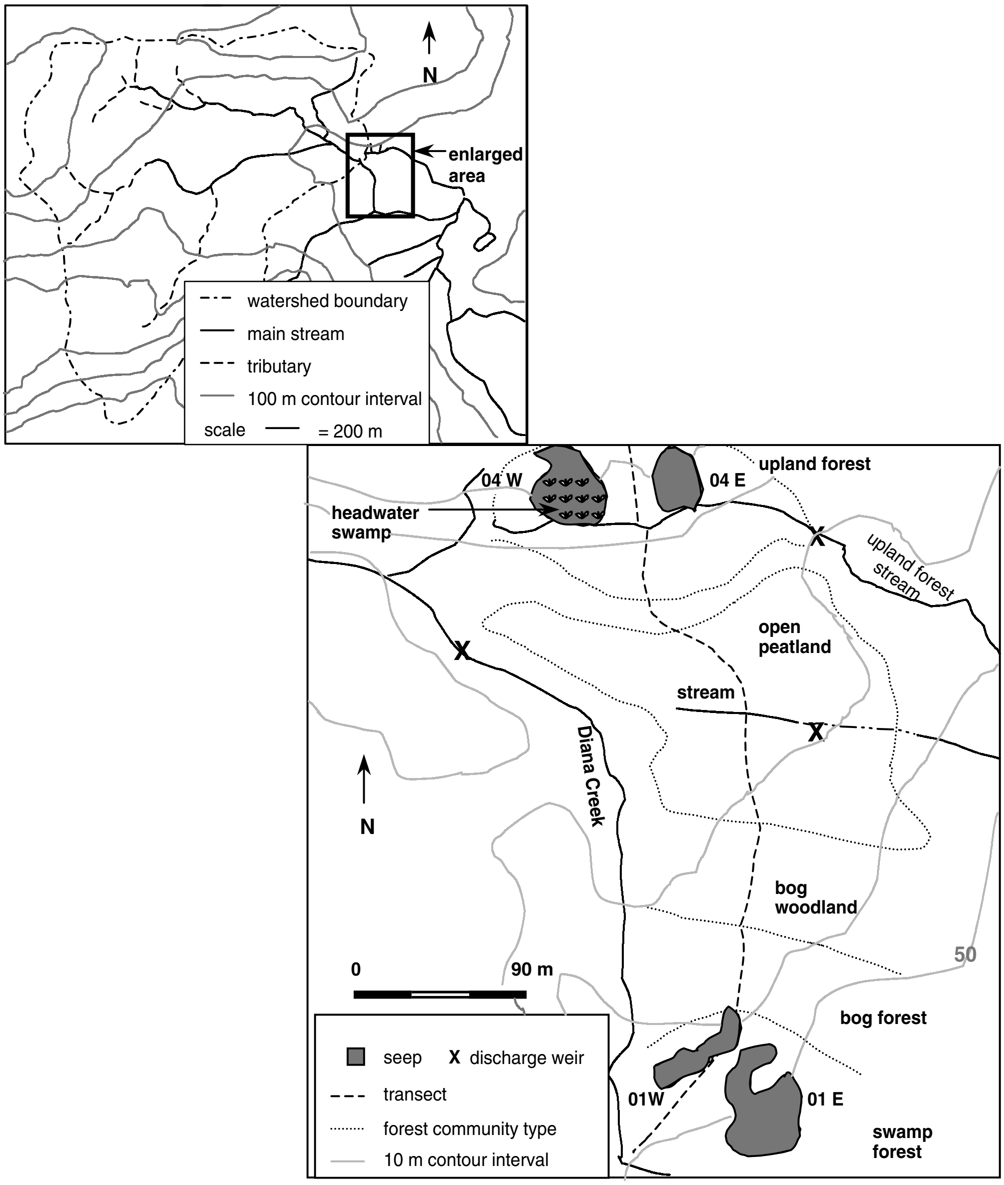

Figure 2. Diana Creek watershed and the instrumentation transect with forest community type (enlarged)

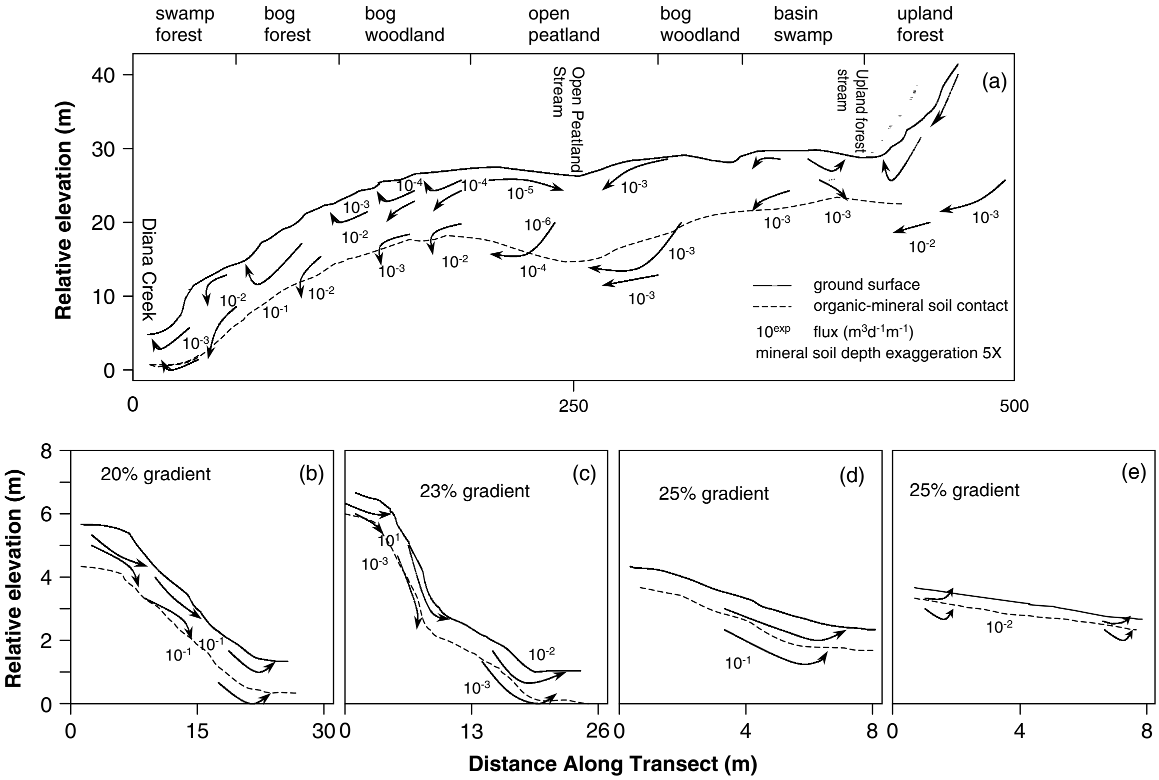

Figure 3. Groundwater flow direction and mean flux along (a) the main transect, seeps (b) west and (c) east of the main transect in the swamp forest and (d) west and (e) east of the main transect in the upland forest at Diana Lake. Groundwater discharge/recharge based on vertical hydraulic gradient is indicated by arrows

(04W) located in a small headwater swamp at the foot of the upland forest; it flows along the base of the upland forest, where additional water is contributed by another seep (04E) emerging directly from mineral soils of the upland forest and also by direct groundwater flow. Open peatland (Figure 2) also has a drainage channel that cuts across the transect to meet the upland forest stream (below the discharge weir). Open peatland grades into bog woodland, bog forest and eventually swamp forest as the slope increases. Bog woodland and bog forest have no distinct drainage channels, but swamp forest contains ephemeral seeps in hollows or gullies. Two such seeps are monitored in the swamp forest near the transect. The swamp forest west seep (01W) drains directly into Diana Creek, whereas the east seep (01E) does not.

At Diana Lake, the mean water table depth (Emili, 2003) increases along the gradient open peatland (11·6 ± 2·4 cm), bog woodland (18·0 ± 4·7 cm), swamp forest (30·8 ± 9·3 cm), bog forest (34·4 ± 15·3 cm) and upland forest (101·2 ± 63·9 cm). In each of the peatland communities (i.e. bog forest, bog woodland, open peatland), the water table was within 25 cm of the surface for 75%, 75% and 90% of the year 1998 respectively. The water table in the upland forest was below 80 cm for 75% of 1998. Mean water table depths at three stations in the swamp forest on Smith Island (Emili, 2003) were 29·2 ± 2·8, 26·9 ± 1·9 and 31·2 ± 5·1 cm. Water table depth was within 25 cm of the surface for 66% of the year 1998 at all three stations. Mean water table depths at three stations in the open peatland on Smith Island (Emili, 2003) were 12·2 ± 12·1 cm, 9·9 ± 10·8 cm and 5·5 ± 7·0 cm. Water tables were at ground surface for 50% of the year 1998 and within 25 cm of the ground surface for 70%, 80% and 90% of the year respectively for the three stations.

The bedrock geology is a complex mixture of rock types, geological structures and development sequences. The Diana Lake site is underlain by metamorphic amphibolite schist and gneiss. The Smith Island site geology is predominantly gneiss with other weakly metamorphosed coarser grained rocks, poor granite and granodiorite. Colluvial processes have resulted in rockfalls and granular disintegration in upland areas. Peat has developed on gentler slopes, ranging in thickness from approximately 40 cm on mid-forested slopes to 315 cm in open blanket bog in local depressions or benches.

In the upland forest, the forest floor horizon is shallow (<30 cm) in comparison with the mineral soil horizon (85–465 cm). In the peatland forest communities, humic folisols and mesisols (30–110 cm) overlie fine to medium sandy mineral soils less than 150 cm thick. In the open peatland, the medium to fine sand and silt of the mineral subsoil is overlain by well-decomposed *Sphagnum*–sedge peat (Turunen, 1999) of 31–315 cm thickness. Open peatland grades into bog woodland. The peat profile in these latter communities grades Fibrisol–Mesisol–Humisol with depth, and varies in thickness from 41 to 264 cm.

Forest vegetation is dominated by conifer stands of western hemlock (*Tsuga heterophylla*) and western red cedar (*T. plicata)*; shore pine (*Pinus contorta* var. *contorta*) and yellow cedar (*C. nootkatensis*) are abundant on organic soils. The understorey is composed primarily of shrubs (*Vaccinium* spp.), feather mosses (*Pleurozium* sp.) and *Sphagnum* mosses, devil's club (*Oplopanax horridus*) and skunk cabbage (*Lysichiton americanum*) in wetter areas. The open peatland comprises hummock, hollow, pool and lawn communities dominated by *Sphagnum* mosses and dwarf shrubs.

METHODS

Sample collection and analysis

The Diana Lake study site (hereafter referred to as Diana Lake) served as the primary comprehensive site for the collection of topographic, hydrometric and isotopic data. The secondary site (Smith Island) was used to supplement the isotopic sampling at Diana Lake.

Rainfall was recorded (May 1997–December 2000) using a tipping-bucket rain gauge positioned 50 cm above the ground surface in the open peatland at Diana Lake (170 m a.s.l.) and Smith Island (52 m a.s.l.). Samples for isotope analysis were collected (1997–2000) into 30 ml Nalgene™ acid-rinsed bottles from a polyethlyene storage rain gauge with an aperture of 41·5 cm^2, placed 45 cm above the ground surface in the open peatland at both sites. The storage rain gauges were emptied daily and rinsed with distilled water.

Throughfall was measured (July–December 1998, May–December 1999) using 5 m long, 0·1 m wide, 0·1 m deep stainless steel troughs angled at 10° from the horizontal, and set 1·5 m above the ground surface. A total of five troughs were used at Diana Lake. Each of the troughs drained into tipping-bucket rain gauges. As stemflow was negligible (<1% of total rainfall; Emili, 2003), canopy interception (millimetres) was calculated as the difference between incident rainfall and the amount reaching the forest floor as throughfall (millimetres).

Throughfall was collected (August 1998, June 1999) for isotope analysis in three plastic troughs in the upland forest. Troughs were scrubbed and flushed with distilled water on a weekly basis to remove leaf debris. Troughs emptied through a screened polyethylene funnel, into a 4 l polyethylene collection bottle. Samples were decanted from the collection bottle into 30 ml Nalgene™ acid-washed bottles.

Two rectangular 'harps' (1·2 m × 0·9 m) with a frame constructed of 3·8 cm (o.d.) ABS pipe strung with vertically oriented 0·2 mm diameter monofilament nylon line spaced 0·5 cm apart (Price, 1992) were used to measure the timing and relative magnitude of fog drip (January–August 1998) and to collect fog drip for isotopic analysis. These harps were located in open peatland at Diana Lake (177 and 212 m a.s.l.). One harp was positioned over a funnel that was directed into a tipping-bucket rain gauge. The other harp was positioned over a funnel that was directed into a 4 l polyethylene storage container from which samples for isotopic analysis were decanted into 30 ml Nalgene™ acid-washed bottles. Samples were collected for one event in August and October 1997 and May 1998.

Water table level and hydraulic head were measured weekly (May–September 1997 and 1998) from a network of wells and piezometers along the Diana Lake transect (Figure 2). Wells of 2·5 cm (i.d.) PVC pipe, slotted along the entire length and covered with 250 μm Nitex™ mesh were pushed into pre-bored, pilot holes. Wells were generally 1·2 m long, although 0·6 m wells were installed to determine whether perched water tables were present at one station each in the swamp forest, bog forest and upland forest. Drive point piezometers were installed at the latter stations to bedrock depth. Piezometers of 2·5 cm (i.d.) PVC, slotted along the bottom 20 cm and screened with 250 μm Nitex™ mesh, were nested at depths determined by the depth of the organic soil, to the organic–mineral soil transition and to mineral soil. Two such stations were instrumented within each forest community. Three piezometer nests were installed in each of the seeps in the swamp forest and two piezometer nests were installed in each of the seeps in the upland forest.

Vertical hydraulic gradients dh/dz were expressed as a ratio of the change in piezometric head between two piezometers to the distance between these piezometers. Hydraulic conductivity K_{sat} was determined for each manual well and piezometer in seeps and along the Diana Lake transect in August 1997 and 1998 using the Hvorslev water-level recovery method (Freeze and Cherry, 1979).

Groundwater samples for isotope analysis were collected in 30 ml Nalgene™ acid-washed bottles from the network of wells and piezometers at Diana Lake and Smith Island using an Easy-Load® hand pump with 0·63 cm (o.d.) Masterflex® tubing. Piezometers were purged 24 h in advance of sampling.

Surface flow was monitored at spatial scales ranging from Diana Creek, which drains a 579·2 ha watershed, to a 0·03 ha hillslope seep (Figure 2). Seeps were instrumented in the swamp forest and upland forest with 15 cm (o.d.), 120 cm length open-ended PVC pipe, laid downslope and partially embedded lengthwise into the organic soil so as to capture shallow subsurface and overland flow. A pipe was similarly installed in the rivulet draining the open peatland by laying it in the small, incised channel and backfilling around the pipe so that water was directed through it. Flow from each of these pipes was manually gauged using a calibrated bucket and stopwatch. Stage height was recorded using an automatic water-level recorder and converted to discharge by establishing a stage–discharge relationship. Samples for isotope analysis were collected during rain events in 30 ml Nalgene™ acid-washed bottles.

Stage height was recorded hourly (January 1998–December 1999) at Diana Creek and Smith Creek with a Unidata Hydrostatic water depth probe (Model 6508B). To test probe accuracy, stream depth was recorded using a staff gauge at the time of data download from a data logger. Staff gauge measurements were well correlated to probe measurements ($r^2 = 0{\cdot}98$, $\alpha = 0{\cdot}05$). Stream discharge (obtained using an OSS stream gauging meter) and stage heights were correlated to produce a stage–discharge curve. The equation for this curve was used to calculate total hourly discharge from stage height data (Maloney *et al.*, 1999). Streamflow in the upland forest stream was measured (January–December 1998) using a 60°V notch weir. Discharge was manually gauged using a calibrated bucket and stopwatch. Stage height was recorded using an automatic water-level recorder and converted to discharge by using the stage–discharge relationship. Streamflow samples for isotope analysis were grab sampled in 500 ml Nalgene™ acid-washed bottles from Diana Creek, the upland forest stream (May–June 2000) and a creek on Smith Island (July 1998–June 2000). These samples were then decanted into 30 ml Nalgene™ acid-washed bottles for isotope analysis.

The determination of $^{18}O/^{16}O$ and $^{2}H/^{1}H$ isotope ratios was performed by mass spectrometry at the Environmental Isotope Laboratory, University of Waterloo. The results are reported according to the guidelines of Coplen (1996). Assessment of laboratory and blind repeats determined analytical uncertainty to be better than ±0·1‰ for ^{18}O and 2‰ for ^{2}H (Gibson *et al.*, 2000).

Deuterium excess d (Dansgaard, 1964) was defined as

$$d\ (‰) = \delta^{2}H - 8\delta^{18}O \tag{1}$$

where 8 is the slope of the global meteoric water line and $\delta^{2}H$ and $\delta^{18}O$ are respectively the hydrogen and oxygen isotopic compositions of water. d is a function of the air mass origin and secondary processes of re-evaporation and mixing (Clark and Fritz, 1997). Groundwater d may differ from that of precipitation due to evaporation in recharge areas, causing enrichment of residual groundwater (Allison *et al.*, 1983).

Topographic analysis

The topographic index used in the TOPMODEL approach (Quinn *et al.*, 1995) was modified to represent the downslope movement of water along the forest–peatland complex. The slope index SI is expressed as

$$\mathrm{SI} = \frac{L}{\tan\beta} \tag{2}$$

where L (m) represents the slope length contributing to downslope flow and $\tan\beta$ is the lateral hydraulic gradient as approximated by local ground-surface slope. With L having dimensions of length, the index thus depends on the length unit selected, i.e. for similar values of $\tan\beta$, a longer L would give a higher SI value.

Statistical analyses

A one-way analysis of covariance (ANCOVA) with a single fixed covariate (SPSS v.11·5, SAS Institute, Inc. Cary, NC) was used to test the statistical significance of the regression coefficients for the δ^2H versus δ^{18}O relationship for meteoric, ground and surface waters at Diana Lake and Smith Island. A general linear model was used to adjust for interaction effects. *Post hoc* pairwise comparisons were performed to compare the adjusted means for meteoric water, groundwater and surface water regression data. The Bonferroni procedure ($\alpha = 0{\cdot}05/3 = 0{\cdot}0167$) was used to control for Type I error across the three comparisons.

RESULTS

Hydrological inputs

Annual rainfall in 1997 (2525 mm) and 1998 (2218 mm) was comparable to long-term climate normals (2469 mm; Environment Canada, 2002); 1999 was a relatively wet year, with a rainfall total of 3887 mm. Fall rainfall accounted for the greatest fraction of the annual total except for 1997, when winter rainfall accounted for a greater fraction of the annual total. During 1997, 1998 and 1999, rainfall occurred on 71%, 62% and 77% of the days respectively. A rainfall event was defined as a minimum 1 h period of rain (>0·03 mm) separated by at least four rain-free hours from the next event. During 1998 and 1999, greater than 50% of the events were less than 50 mm (event data for 1997 were only recorded for the latter half of the year). Events greater than 50 mm accounted for 84% and 92% of annual rainfall in 1998 and 1999 respectively. Annual snowfall in 1997 (95·4 cm) and 1998 (85·0 cm) was lower than long-term snowfall for Prince Rupert (126·3 cm). The greatest snowfall occurred in January in these two years, with snowfall extending into April in 1997. Snowfall was not recorded in 1999.

Total throughfall from July to November in 1998 and 1999 was 1200 mm and 1265 mm respectively. Throughfall varied with the canopy condition preceding the event, with greater mean throughfall when the canopy was wet (17 ± 28 mm) compared with dry (14 ± 25 mm). For small (<2 mm), short-duration (1–8 h), low-intensity (0·1–0·6 mm $\mathrm{h^{-1}}$) rain events, 59% of rainfall was intercepted. Interception as a percentage of rainfall (Table I) was 17·3% and 22·4% in 1998 and 1999 respectively. On a monthly basis, interception ranged from 10·1 to 29·4% of rainfall.

Fog drip or drizzle not recorded by the rain gauge occurred on 125 out of 126 of the days that rainfall occurred during January to July 1998. Fog drip alone (as indicated by throughfall without rainfall) was measured on 12 days (5·3 mm) and accounted for 0·4% of total throughfall. The majority of fog events (58%) and fog mixed with rain (39%) were 4–12 h in duration.

Streamflow and surface flows

Total annual depth of streamflow for Diana Creek was 1820 mm and 3457 mm in 1998 and 1999 respectively when applied to the watershed. In general, streamflow was greatest in the fall months and lowest in the summer. In 1998, the maximum discharge of Diana Creek reached 15·6 $\mathrm{m^3\ s^{-1}}$ during a 102·5 mm

Table I. Rainfall, throughfall and interception

	Rainfall (mm)	Throughfall (mm)	Interception	
			(mm)	(%)
1998[a]	1451·5	1199·7	251·8	17·3
1999[a]	1630·0	1265·0	365·0	22·4
2000[b]	1800·0	1429·0	371·0	20·6
2001[b]	1873·0	1446·0	427·0	22·8

[a] Data collected July–November.

[b] Data collected May–November (Maloney *et al.*, 2002).

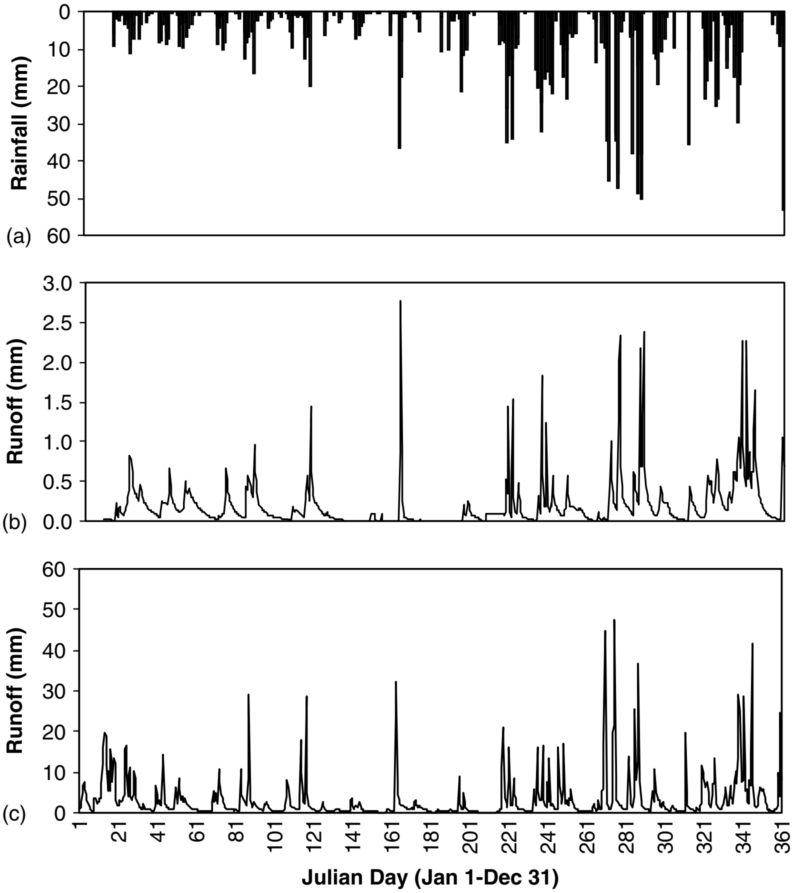

Figure 4. (a) Daily rainfall and runoff for (b) the upland forest stream and (c) Diana Creek

event of 2·1 mm h^{-1} intensity. The annual hydrograph for Diana Creek illustrates the rapid response to rainfall events (Figure 4). Diana Creek total discharge was well correlated ($r^2 = 0{\cdot}71$, $\alpha = 0{\cdot}05$) to storm size, with total discharge and peak discharge increasing with the intensity and duration of storm events.

Streamflow response to rainfall was examined for six storm events (Tables II and III). The first three events are representative of the dry-period summer storm events and the remaining three were the largest storm events

Table II. Storm response analysis for Diana Creek and the upland forest stream for three storm events in each of the summer and fall 1998 sampling periods

Location	Julian day	Rainfall (mm)	Intensity (mm h^{-1})	Runoff[b] (mm)	Runoff ratio	Peak Q (m^3 s^{-1})	L_p[c] (h)	T_c[d] (h)
Diana Creek	164–166	102·2[a]	—	47·5	0·46	7·20	10	10
Upland forest stream				70·2	0·69	0·03	11	9
Diana Creek	197–199	33·4	2·6	10·4	0·31	1·45	9	8
Upland forest stream				11·1	0·33	0·006	9	7
Diana Creek	220–222	86·1	2·3	41·3	0·48	3·27	26	18
Upland forest stream				43·5	0·51	0·01	25	17
Diana Creek	272–274	102·5	2·1	53·7	0·52	15·62	12	1
Upland forest stream				58·3	0·57	0·05	11	1
Diana Creek	277–279	158·3	3·5	75·5	0·48	9·78	9	1
Upland forest stream				73·5	0·46	0·04	9	1
Diana Creek	290–292	108·9	2·9	50·3	0·46	5·24	14	2
Upland forest stream				57·4	0·53	0·02	14	1

[a] Collected in storage rain gauge.

[b] Runoff (mm) = [discharge (m^3 s^{-1})/drainage area (m^2)] × 1000.

[c] Lag to peak calculated as the time from initial storm response in discharge to peak discharge.

[d] Time of concentration calculated as the time between the centre of mass of rainfall excess and the inflection point on the recession of the direct runoff hydrograph.

during the wettest part of the year (fall). A fixed time of 48 h (beginning at the time of the lowest discharge rate prior to flood runoff) was chosen to avoid biases in runoff volume caused by event duration, and in all cases discharge returned to baseflow. Stormflow runoff from these six events accounted for 14% and 11% of annual runoff for Diana Creek and the upland forest stream respectively. The increase in upland forest stream discharge in response to rainfall events was smaller with a longer return to baseflow relative to Diana Creek (Figure 4). The lag time in stream response (lag to peak and time of concentration) was similar for Diana Creek and the upland forest stream (Table II). The lag to peak for five of the six events was 9–14 h (Table II). The time of concentration was much lower during the wet (∼1 h) compared with the dry-period (∼7–18 h) events (Table II).

The greatest runoff occurred during the Julian day (JD) 277–279 event for all streams and seeps (except 01W seep). The lowest runoff for these events occurred during the JD 197–198 event for all locations (Tables II and III). Runoff ratios for Diana Creek and the upland forest stream (0·46–0·69) were higher than the open peatland stream and seeps (0·02–0·40) during the JD 164–166 event (Tables II and III). On an annual (1998) basis, runoff from the upland forest (141·2 mm) and open peatland streams (225·3 mm) was much lower than Diana Creek (1819·9 mm). Annual seep flow runoff varied greatly, with only 8·0 mm from the 01E seep to 2026·0 mm from the 04W seep (Table IV). Flow persisted for Diana Creek, the upland forest stream and the 04E seep for the entire study period, but ceased in the open peatland, 01W seep and 04W seep when water tables were below 'threshold' levels (Figure 5). Threshold levels are defined as the water table depth below which there is no runoff and were determined by zero discharge.

Groundwater flow

The water discharged from groundwater was determined by constant slope baseflow separation of the total runoff hydrograph for Diana Creek. This method separates direct runoff (rapid throughflow) and baseflow (delayed throughflow and groundwater flow) by connecting a straight line extending from the point of the lowest discharge rate on the hydrograph prior to storm runoff to the inflection point (when the slope of the recession curve changes from >1 to <1) on the recession limb (McCuen, 1998). Baseflow Q_b during the six

Table III. Storm response analysis for the stream draining the open peatland and seeps in the swamp forest and upland forest for three storm events in each of the summer and fall sampling periods

Location	Julian day	Rainfall (mm)	Intensity (mm h^{-1})	Runoff[d] (mm)	Runoff ratio	Maximum WT rise (cm)	WT[e] response
Open peatland stream	164–166	102·2[c]	—	1·8	0·02	3·4	0·3
01W seep[a]				41·2	0·40	4·1	0·4
04W seep[b]				22·7	0·22	4·9	0·5
Open peatland stream	197–199	33·4	2·6	1·8	0·05	6·9	2·1
01W seep				4·0	0·12	3·6	1·1
04W seep				5·6	0·17	13·0	3·9
Open peatland stream	220–222	86·1	2·3	3·2	0·04	11·2	1·3
01W seep				15·4	0·18	2·8	0·3
04W seep				17·0	0·20	3·1	0·4
Open peatland stream	272–274	102·5	2·1	2·8	0·03	5·3	0·5
01W seep				11·6	0·11	2·0	0·2
04W seep				5·7	0·06	6·1	0·6
Open peatland stream	277–279	158·3	3·5	7·3	0·05	10·2	0·6
01W seep				36·5	0·23	3·3	0·2
04W seep				28·4	0·18	0·6	0·04
Open peatland stream	290–292	108·9	2·9	3·6	0·03	8·4	0·8
01W seep				17·3	0·16	1·3	0·1
04W seep				17·1	0·16	0·8	0·07

[a] West seep in the swamp forest.
[b] West seep in the upland forest.
[c] Collected in storage rain gauge.
[d] Runoff (mm) = [discharge (m^3 s^{-1})/drainage area (m^2)] × 1000.
[e] Water table (WT) response was determined by dividing the rainfall depth (mm) by the water table rise (mm).

Table IV. Seasonal distribution of runoff for streams and seeps (January–December 1998)

	Runoff (mm)							Seasonal rainfall (mm)
	Diana Creek	Open peatland stream	Upland forest stream	04W seep	04E seep	01W seep	01E seep	
Winter	719·2	50·2	50·1	721·4	317·1	221·6	1·7	404·4
Spring	277·5	59·3	23·9	453·6	160·8	149·9	2·5	261·4
Summer	275·3	44·2	20·6	175·2	177·0	129·5	0·7	517·8
Fall	547·9	71·5	46·6	675·8	320·6	153·0	3·1	1034·4
Annual	1819·9	225·2	141·2	2026·0	975·5	654·0	8·0	2218·0
Drainage area (ha)	579·2	0·7	2·0	0·06	0·05	0·03	0·05	—

events studied accounted for 9–28% of peak discharge for Diana Creek and 12–18% of peak discharge for the upland forest stream.

To determine the potential subsurface contribution of organic horizon groundwater versus mineral horizon groundwater to streamflow, the groundwater flux along the forest–peatland transect and within seeps was calculated for each horizon. Groundwater flux (m^3 day^{-1} m^{-1}) was determined between successively

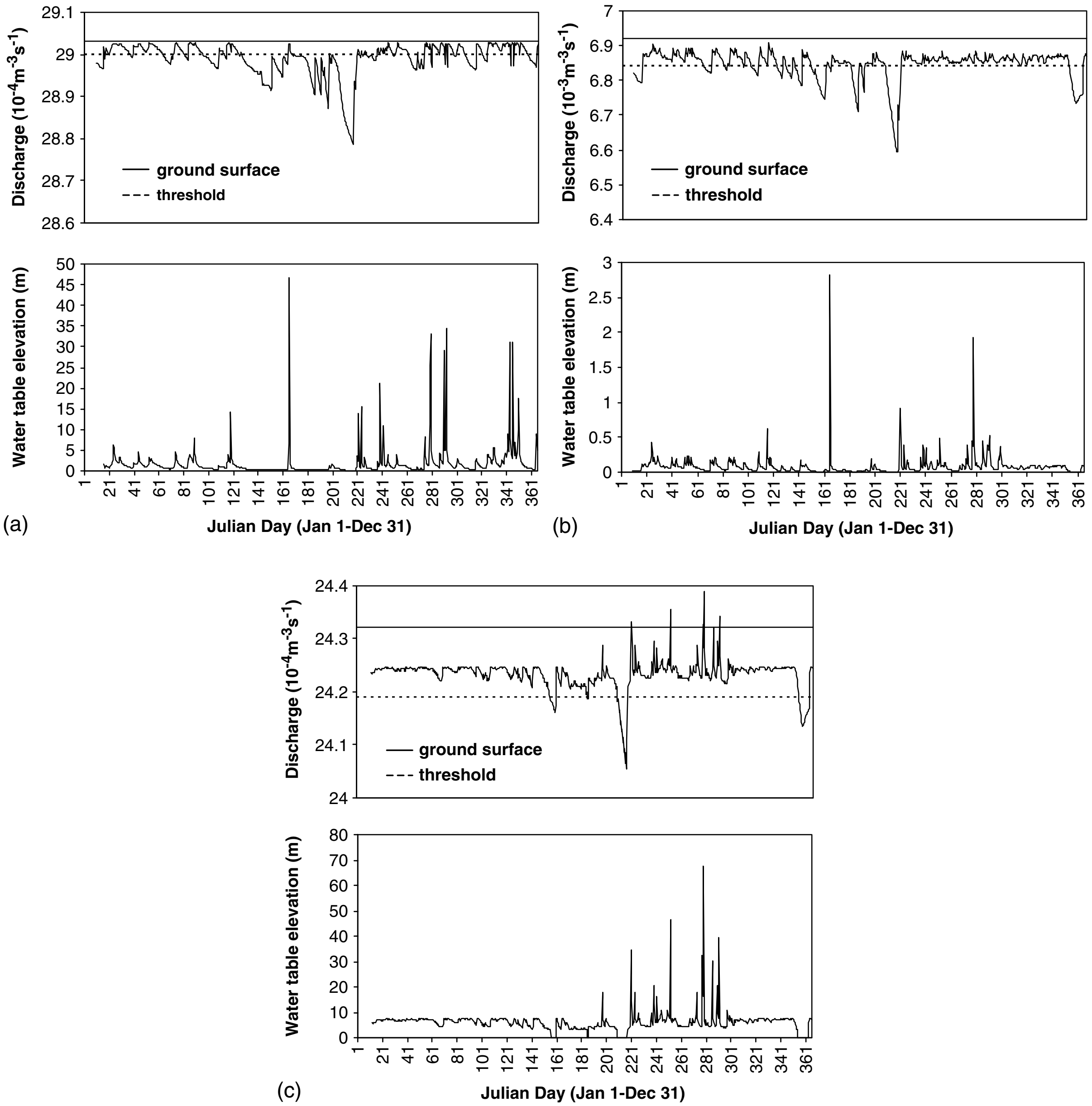

Figure 5. Daily water table elevation with respect to flow threshold and discharge for (a) the upland forest west seep, (b) swamp forest west seep and (c) the open peatland stream

downslope pairs of piezometers according to

$$Q = K_{\mathrm{sat}} \frac{\mathrm{d}h}{\mathrm{d}l} bw \tag{3}$$

where K_{sat} is the mean value for saturated hydraulic conductivity of the two piezometers and $\mathrm{d}h/\mathrm{d}l$ is the change in hydraulic head over the distance between the piezometers. The flux through a cross-section of slope was defined for the organic soil horizon and the mineral soil horizon, where b represents the saturated thickness of the particular soil horizon and w is the width of the cross-section. Fluxes from each soil horizon were summed to determine total flux and expressed per unit slope width.

With the exception of the open peatland and seeps in the swamp forest, saturated hydraulic conductivity K_{sat} increased with depth from organic soil (10^{-6}–10^{-7} cm s^{-1}) to mineral soil (10^{-4}–10^{-5} cm s^{-1}) at Diana Lake. In the open peatland, K_{sat} in both the organic and mineral soil horizons was in the range 10^{-6} to 10^{-7} cm s^{-1}. In the seeps located in the swamp forest, K_{sat} decreased with depth from the organic (10^{-4}–10^{-5} cm s^{-1}) to the mineral (10^{-6}–10^{-8} cm s^{-1}) horizon.

The groundwater flux during three of the six storm events (JD 164–166, JD 197–199, JD 220–222) was compared with the groundwater flux during the longest dry period (JD 201–216) of the summer 1998 sampling period. During storm events, the greatest groundwater flux was from the swamp forest seeps (2·39–2·41 m^3 day^{-1} m^{-1}) in comparison with the forest–peatland transect (0·29–0·33 m^3 day^{-1} m^{-1}) and upland forest seeps (0·12–0·14 m^3 day^{-1} m^{-1}). During these events, the organic horizon flux (1·70–1·72 m^3 day^{-1} m^{-1}) in the swamp forest seeps was much greater than the transect organic horizon flux (0·16–0·17 m^3 day^{-1} m^{-1}). The mineral horizon flux (0·69–0·70 m^3 day^{-1} m^{-1}) from the swamp forest seeps was also large compared with the transect flux for the same events (0·13–0·16 m^3 day^{-1} m^{-1}). During the dry period, the greatest flux was from the swamp forest seeps, with a greater flux from the mineral horizon (0·70 m^3 day^{-1} m^{-1}) than the organic horizon (0·59 m^3 day^{-1} m^{-1}). The total flux from the forest–peatland transect for the dry period was comparatively low (0·34 m^3 day^{-1} m^{-1}), with comparable fluxes from the mineral and organic horizons (0·17 m^3 day^{-1} m^{-1}). For all conditions, the lowest flux (0·12–0·13 m^3 day^{-1} m^{-1}) was from the upland forest seeps. The order of magnitude of groundwater fluxes is shown in Figure 3.

Isotopic distribution

The physical influences controlling isotopic composition of water at Diana Lake and Smith Island are similar. The two watersheds have similar physical characteristics and similar locales; thus, the prevailing weather influences are the same and ultimately the source of rainfall is the same. The δ^2H and δ^{18}O contents of rainfall do, however, vary with differences in elevation and related temperature differences (Gat, 1980). Rainfall was collected at 170 m a.s.l. and 52 m a.s.l. at Diana Lake and Smith Island respectively. Owing to the limited number of data available for overlapping rainfall events at Diana Lake and Smith Island ($n = 5$), it is not possible to make a statistical inference as to the similarity of isotopic composition on an event-by-event basis. However, the similarity in δ^{18}O composition and d for ground (z-score $\delta^{18}\text{O} = -0{\cdot}49$, z-score $d = 1{\cdot}60$, $\alpha = 0{\cdot}05$) and surface waters (z-score $\delta^{18}\text{O} = -0{\cdot}05$, z-score $d = -0{\cdot}01$, $\alpha = 0{\cdot}05$) from Diana Lake and Smith Island indicate the same origin (Clark and Fritz, 1997).

The local meteoric water line (LMWL) was determined from the δ^{18}O and δ^2H in precipitation samples from Diana Lake and Smith Island, yielding a slope and intercept of $7{\cdot}97 \pm 0{\cdot}29$ ($\alpha = 0{\cdot}05$) and $5{\cdot}07 \pm 3{\cdot}53$ ($\alpha = 0{\cdot}05$) respectively (Figure 6). Although there was relatively little scatter in the precipitation and throughfall δ^{18}O and δ^2H values for the study area, there was a significant ($z = 1{\cdot}99$, $\alpha = 0{\cdot}01$) difference between fall (wet) and summer (dry) seasonal compositions. The mean isotopic composition of rainfall was greater during the wet season ($\delta^{18}\text{O} = -10{\cdot}48 \pm 2{\cdot}93$‰) than the dry season ($\delta^{18}\text{O} = -12{\cdot}56 \pm 5{\cdot}91$‰). Throughfall isotopic composition exhibited a similar trend ($\delta^{18}\text{O} = -10{\cdot}84 \pm 1{\cdot}86$‰ and $-12{\cdot}18 \pm 6{\cdot}12$‰ respectively).

With the exception of the open peatland stream, the range in δ^{18}O values for surface waters ranged from $-10{\cdot}28$ to $-12{\cdot}84$‰ (Figure 6). The only two samples taken from the open peatland stream (during a summer storm event) had δ^{18}O values of $-7{\cdot}12$ and $-8{\cdot}18$‰. The slope ($6{\cdot}63 \pm 0{\cdot}77$, $\alpha = 0{\cdot}05$) and intercept ($-6{\cdot}91 \pm 8{\cdot}65$, $\alpha = 0{\cdot}05$) of the δ^2H–δ^{18}O regression line for surface waters fell between the LMWL and the regression line for groundwater (slope of $5{\cdot}56 \pm 1{\cdot}21$, $\alpha = 0{\cdot}05$ and intercept $-19{\cdot}21 \pm 13{\cdot}3$, $\alpha = 0{\cdot}05$) (Figure 6). The δ values for groundwater clustered around the LMWL. The seasonal isotopic composition of groundwater tended toward the composition of mean annual rainfall (Figure 7).

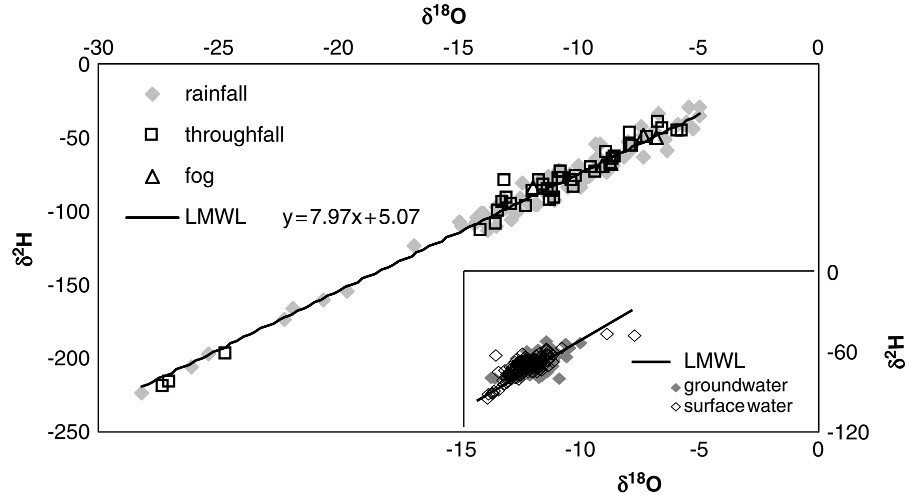

Figure 6. δ^2H and δ^{18}O plots for meteoric and throughfall inputs. Groundwater ($y = 5{\cdot}56x - 19{\cdot}21$) and surface waters ($y = 6{\cdot}63x - 6{\cdot}91$) inset

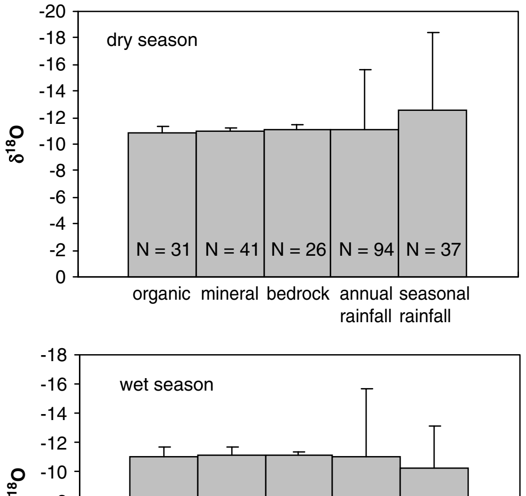

Figure 7. Mean seasonal δ^{18}O values (standard deviation as error bar) of organic, mineral and bedrock horizon groundwater compared with mean annual rainfall at Diana Lake and Smith Island (1997–2000)

There were significant differences (ANCOVA, $F = 16{\cdot}022$, $p < 0{\cdot}001$) among the three adjusted means for groundwater, surface water and meteoric water (LMWL). *Post hoc* pairwise comparisons showed that the δ^2H versus δ^{18}O linear regression relationships for both groundwater ($F = 15{\cdot}080$, $p < 0{\cdot}001$) and surface water ($F = 32{\cdot}038$, $p < 0{\cdot}001$) were significantly different from the LMWL.

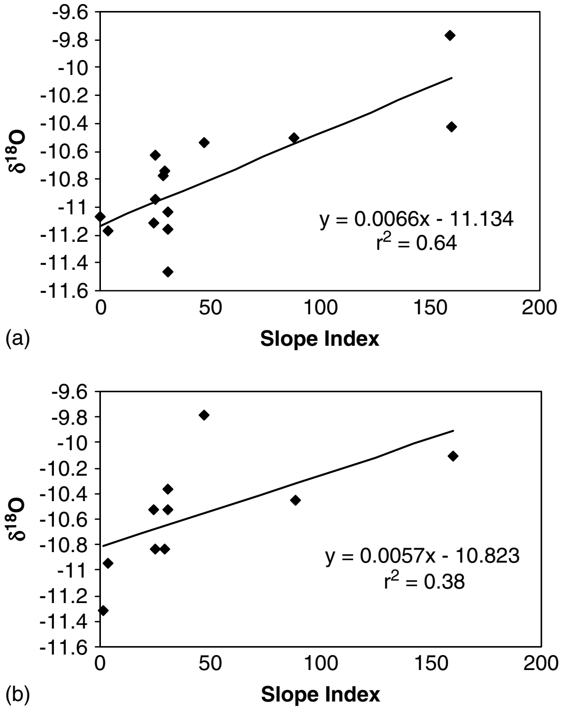

Figure 8. Regression between δ^{18}O and slope indices along the forest–peatland complex for (a) August 1997 and (b) October 1997

Groundwater δ^{18}O did not differ significantly between forest community type (ANOVA $F = 1{\cdot}73$, $p = 0{\cdot}16$, $\alpha = 0{\cdot}05$). Within forest communities, there was a significant positive correlation between δ^{18}O values and slope indices along the Diana Lake transect for both summer ($r^2 = 0{\cdot}64$, $t = 4{\cdot}619$, $\alpha = 0{\cdot}05$) and fall ($r^2 = 0{\cdot}38$, $t = 2{\cdot}228$, $\alpha = 0{\cdot}05$) seasons in 1997 (Figure 8), with δ^{18}O values being more enriched (higher) with greater slope index (flatter, poorer drainage).

The average residence time of groundwater in the organic horizon of the swamp forest and open peatland at Diana Lake was estimated according to

$$\text{residence time (days)} = \frac{\text{groundwater storage (m}^3)}{\text{groundwater flux (m}^3\ \text{day}^{-1})} \tag{4}$$

where groundwater storage is the product of soil depth (m), the hillslope area (m^2) and soil porosity (0·83–0·93). The average residence time for the swamp forest organic horizon at Diana Lake was estimated at 3–5 months, but the average residence time for the much deeper organic horizon of the open peatland was an estimated 65 years.

DISCUSSION

The primary meteoric input to the groundwater–surface water system was direct rainfall. Interception at Diana Lake (17·3–22·4%) was a function of rainfall amount, intensity and duration and was comparable to other CWH forests in southwestern BC (30%; Spittlehouse, 1996) and a site 38 km northwest of Diana Lake (21%; Beaudry and Sagar, 1995). If forest harvesting occurs at Diana Lake, then decreased interception losses and evapotranspiration may increase soil moisture, decrease available soil matrix storage capacity and translate into greater outflow from the forest–peatland complex, thus increasing the potential for hillslope and channel erosion (Harr, 1986).

Fog drip occurred on 59% of days during the sampling season and 99% was coincident with rainfall. It is difficult, however, to separate out the magnitude of fog drip from that of drizzle or rain given the type of collector used. An automatic fog-sampling unit with a shielded fog collector, activated by an optical sensor, would ensure that fog-only events are sampled (e.g. Fuzzi *et al.*, 1996). Nevertheless, the amount of fog drip, as indicated by throughfall in the absence of rainfall (5·3 mm), was lower than expected in comparison with other coastal forests (Azevedo and Morgan, 1974; Harr, 1982).

The upland forest provided an important surface input to Diana Creek (i.e. through the upland forest stream), particularly during the summer periods when flow from the open peatland and seeps was low and intermittent. During storm events, the rise in water table above threshold values and subsequent surface flow in the 04W seep contributed to the rapid connection of surface pools and the release of surface water from the headwater swamp to the upland forest stream. During large summer-storm events, surface water inputs from the headwater swamp contributed up to 95% of total stream discharge (Fitzgerald *et al.*, 2003). During dry periods and between storm events, baseflow in the upland forest stream was sustained by deep groundwater contributions from the headwater swamp and contributions (up to 73% of streamflow) from the 04E seep (Fitzgerald *et al.*, 2003). The open peatland and swamp forest behaved differently. During dry conditions, the open peatland and seeps in the swamp forest experienced relatively low water tables with respect to flow thresholds (Figure 5), and thus had high potential water storage capacity. In the spring, when water tables were high and storage capacity was low, the 01W seep in the swamp forest and open peatland stream contributed more significantly to runoff.

The stream subsystems at Diana Lake exhibit distinct regimes in response to seasonal and event inputs. The rapid response of storm flow and the comparatively small amount of baseflow (Figure 4) is characteristic of watersheds extensively covered in organic soil (Burt *et al.*, 1990). The efficiency of storm runoff production varied temporally, with increased runoff and shorter concentration times during wet-season storm events compared with dry-season events (Tables II and III).

The efficiency of storm runoff production was related to the relative depth of organic soil. The open peatland had the thickest organic horizon, the lowest average topographic gradient and many surface depressions capable of retaining surface water, and thus had the lowest runoff ratios (Table III). In contrast, runoff ratios for seeps were much larger and had a more rapid runoff response. When soil moisture and water table elevation were high, the efficiency of runoff production was increased by a wet transition layer between the saturated zone and the ground surface. During storm events, the water table rose quickly into this wet soil zone, initiating runoff at 'threshold' water table elevations within 5–15 cm of the ground surface (Figure 5). In the upland forest outside of seep areas, with a shallow organic horizon the rainfall infiltrated more rapidly to mineral and bedrock groundwater stores. This water re-emerges in the 04W seep and headwater swamp, contributing rapidly to event flow in the upland forest stream (Fitzgerald *et al.*, 2003). The high runoff ratio for Diana Creek (0·31–0·52) reflected the high proportion of the watershed contributing to storm runoff in rapid response to rainfall (Mulholland *et al.*, 1990).

In general, direct runoff Q_d dominated storm hydrographs accounting for 72–91% of peak discharge for Diana Creek and the upland forest stream. The greater relative contribution of Q_d to storm discharge in the upland forest stream compared with Diana Creek was a function of the quick runoff response of the seeps and the headwater swamp. The two seeps with the lowest frequency of surface flow (01E and 04 W) exhibited a greater proportion of Q_b during storm runoff.

The groundwater flux in the organic and mineral horizons was calculated to determine the potential subsurface discharge contribution from these horizons to Q_d. The variation in groundwater flux was a function of the complex topography and differences in K_{sat}, affecting both the pattern of discharge/recharge areas and the quantity of flow along the main transect and in seeps (Figure 3). In the organic horizon along the main transect, more decomposed peat with smaller pores (Emili, 2003) retained water and slowed K_{sat} (10^{-6}–10^{-7} cm s^{-1}) and event groundwater flux (0·16–0·17 m^3 day^{-1} m^{-1}). The greater

K_{sat} (10^{-4}–10^{-5} cm s^{-1}) and groundwater flux (1·70–1·72 m^3 day^{-1} m^{-1}) in the organic horizon of swamp forest seeps may be due to differences in peat type. Despite lower mineral soil K_{sat} (10^{-6}–10^{-7} cm s^{-1}) in the swamp forest seeps, the flux of groundwater (0·69–0·70 m^3 day^{-1} m^{-1}) was greater than the main transect mineral horizon flux (0·13–0·16 m^3 day^{-1} m^{-1}). This disparity is likely due to increased vertical hydraulic gradients and perhaps also to differences in the mineral subsoil texture of seeps. The organic and mineral horizons in seeps discharged groundwater, whereas the discharge/recharge function of horizons along the main transect varied with topography and antecedent moisture conditions (Emili, 2003). During dry periods, the flux from the mineral subsoil of seeps (0·70 m^3 day^{-1} m^{-1}) was the greatest contributor to Q_b, with smaller contributions from seep organic horizons (0·59 m^3 day^{-1} m^{-1}) and the forest–peatland transect (0·12–0·17 m^3 day^{-1} m^{-1}).

The δ^2H and δ^{18}O in precipitation yielded an LMWL slope (7·97) and intercept (5·07) lower than the global slope (8·03) and intercept (9·59) for continental locations (Yurtsever and Gat, 1981). The narrow variation in δ^2H and δ^{18}O in ground and surface waters indicated similar recharge sources and attenuation of the rainfall signal. The homogeneous isotopic composition of groundwater (Figure 7) is a result of mixing during recharge (e.g. see Gat (1981)). The mechanism for this mixing is the upward and downward movement of water in response to rainfall events.

The slope (5·56) of the groundwater δ^2H–δ^{18}O regression line was less than the LMWL (7·97) and suggests evaporative enrichment of surface water prior to infiltration (Lee *et al*., 1999). The enrichment of δ^{18}O in groundwater is a function of residence time (Clark and Fritz, 1997). The estimated residence time of groundwater in the organic horizon along the forest–peatland hillslope (3–5 months) was similar to estimates of 2–4 months for a hillslope on Smith Island (Gibson *et al*., 2000). The longer groundwater residence time for the open peatland at Diana Lake, in addition to shallow water tables, would allow for evaporative enrichment of near-surface groundwater and may explain the more enriched isotopic composition (δ^{18}O values of −7·12 and −8·18‰) of runoff from this community.

The correlation between slope index and δ^{18}O values in groundwater at Diana Lake (Figure 8) suggests that the spatial pattern in the δ^{18}O of groundwater along the forest–peatland complex is influenced by topography. Topographic variability at Diana Lake and Smith Island creates spatially diverse site hydrological conditions (organic soil horizon thickness and water table depth) that influence groundwater flow and ultimately the isotopic composition of groundwater (Emili, 2003). These site conditions can be predicted using slope indices.

In general, forest community types had characteristic slope indices, with mean slope index decreasing from open peatland (83 ± 124) to upland forest (1·1 ± 1·4). Topographic highs, i.e. areas with low slope index values, were associated with deeper water tables and lower soil moisture. These areas have lower accumulations of peat, and in the upland forest an absence of peat, that contributed to enhanced infiltration and groundwater recharge. As the topographic gradient decreases (and slope index increases), the organic horizon thickness increases and the organic matter accumulation slows infiltration, resulting in shallow water tables. Areas with higher slope index values (>100) were wetter areas, such as bog woodland and open peatland communities.

At Diana Lake, the trend is towards higher δ^{18}O and, therefore, isotopically heavier groundwater values in areas of high topographic index, such as the open peatland. The lower hydraulic gradients and slower groundwater velocity in these areas contribute to slower infiltration and a longer groundwater residence time. These latter two factors increase the potential for the evaporative enrichment of δ^{18}O in groundwater (Fitzgerald *et al*., 2002).

These results suggest that slope index may be used as a surrogate variable for relative groundwater age, i.e. the oldest water (represented by more enriched δ^{18}O values) would be exported from locations with a large water store per unit area as indicated by high slope indices. Rodhe *et al*. (1996) also found a positive, albeit weak, relationship between the age of groundwater and the topographic index in a small watershed in southwest Sweden. The positive relationship reported here demonstrates the possibility of linking groundwater age estimates and ultimately hydrochemical models to topographically based models (Buttle *et al*., 2001).

For the smallest event of the sampling period, the pre-event isotopic signature of stormflow for the creek on Smith Island indicated that near-surface and surface flow accounted for only a small portion of runoff at peak flow (Gibson *et al*., 2000). During this period, the hillslope contributed more to stream water runoff than seeps and open peatland (Tables II and III).

During larger events, the importance of runoff from seeps and the open peatland increased (Table III). Increases in mean vertical hydraulic gradient (0·06–0·24) indicated stronger discharge from seeps and topographic lows along the hillslope. The poor drainage properties of the organic soil contribute to higher water tables. The dominant mechanism for runoff generation under these conditions is saturated shallow subsurface and overland flow.

High slope indices in the open peatland community indicate the potential for large stormflow generation from this community. High slope indices indicate shallow water tables, and thus flow-generating processes at or near the surface. Small additions of water should result in immediate runoff. However, the open peatland exhibited a smaller response to storm events than seeps. Similarly, Lortie (2002) found a comparatively small runoff response (generally $<1{\cdot}1\%$ of stormflow) from an open peatland on Smith Island in comparison with the forested hillslope. At Diana Lake, the water table depth was lower, and hence the storage capacity to be overcome prior to runoff in the open peatland was larger in comparison with the seeps. Fitzgerald *et al*. (2002) determined that large rain events (56 mm) and pre-event water table close to the ground surface (10 cm depth) were needed to exceed the open peatland groundwater storage capacity and generate runoff.

CONCLUSIONS

The prospect of harvesting in previously undeveloped forests in the north-coast forest region of BC has created the need for the prediction of hydrological responses to such activities. An understanding of the hydrological processes affecting groundwater recharge and streamflow is necessary for operational decision-making that will support long-term productivity and preserve forest sustainability.

The results of this study indicate that removal of trees will result in an increase in the amount of water reaching the soil and a rise in water table. In other forested wetland environments, 'watering up' has been related to a decrease in interception following harvesting (Dubé *et al*., 1995). In addition to an increase in water table elevation, increased water inputs may lead to a decrease in time to peak streamflow following storms and an increase in peak flow volume (Jones and Grant, 1996), thus increasing the potential for downslope impacts resulting from increased erosion and sedimentation. Additionally, the rise in water table produces site conditions conducive to peatland expansion.

Combined hydrometric and isotopic analyses demonstrated that (1) the dominant mechanism for runoff generation was saturated shallow subsurface flow and (2) the organic horizon groundwater flux in seeps was an important contributor to stormflow. Since storm runoff response is dominated by near-surface flow processes, ground surface topography is a significant control on the spatial variability of sources, pathways and rates of groundwater flow (Emili *et al*., 2005). The use of slope index as a surrogate variable for groundwater age demonstrated the potential of linking hydrochemical models to topographically based models, thus improving the ability of forest managers to predict potential hydrological impacts of forest harvesting. Post-harvesting increases in water table elevation may increase the number and discharge volume of seeps, potentially causing severe erosion and increased sediment loading to streams (Lortie, 2002). Furthermore, mechanical disturbance of the ground surface and substrate during harvesting or reforestation site-preparation treatments (LePage *et al*., 2002) will interrupt seep drainage pathways.

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