Hydrogeological influences on forest community type along forest–peatland complexes in coastal British Columbia

Lisa A. Emili, Jonathan S. Price, and Daniel F. Fitzgerald

Abstract: The prospect of harvesting forest–peatland systems in the coastal western hemlock forest region of British Columbia has created the need for an understanding of the interrelationship between topography, groundwater flow, and site productivity. Detailed topographic mapping including the use of ground-penetrating radar coupled with point measurements of specific yield, bulk density, saturated hydraulic conductivity, and groundwater level were used to determine the characteristics of groundwater flow along forest–peatland complexes. A topographic index was then used to characterize the spatial distribution of groundwater flow and site conditions (as represented by water table depth and organic horizon thickness) influencing forest community type. Forest community type mean index decreased from open peatland to upland forest. Areas with high slope indices had thicker organic horizons (0.7–1.8 m), water tables closer to the surface (0–0.2 m), and higher soil moisture contents (46–92%). These conditions affect successional dynamics and favour the invasion of hydrophytic species such as *Sphagnum* mosses. Areas with low slope index values were associated with shallower organic horizons (<0.4 m), deeper water table (0.3 to >1.6 m), and drier soil moisture (35–76%), favouring more prolific timber growth.

Résumé : L'idée de récolter du bois dans les systèmes composés de forêts et de tourbières dans la région forestière côtière occupée par la pruche occidentale en Colombie-Britannique a engendré la nécessité de comprendre les liens entre la topographie, le ruissellement souterrain et la productivité de la station. La cartographie topographique détaillée incluant l'utilisation du géoradar combinée à des mesures ponctuelles du rendement spécifique, de la densité apparente, de la conductivité hydraulique à saturation et du niveau de l'eau souterraine ont été utilisées pour déterminer les caractéristiques du ruissellement souterrain dans des complexes de forêts et de tourbières. Un indice topographique a ensuite été utilisé pour caractériser la distribution spatiale du ruissellement souterrain et les attributs de la station, tels que la profondeur de la nappe phréatique et l'épaisseur de l'horizon organique, qui ont une influence sur le type de communauté forestière. L'indice moyen du type de communauté forestière diminuait en passant de la tourbière ouverte à la forêt en milieu sec. Les zones avec un indice de pente élevé avaient un horizon organique plus épais (0,7–1,8 m), une nappe phréatique plus près de la surface (0–0,2 m) et un contenu en eau du sol plus élevé (46–92 %). Ces conditions affectent la dynamique de la succession et favorisent l'invasion d'espèces hydrophytes comme les mousses du genre *Sphagnum*. Les zones avec un indice de pente faible étaient associées à un horizon organique plus mince (< 0,4 m), une nappe phréatique plus basse (0,3–>1,6 m) et à un sol plus sec (35–76 %), favorisant une plus forte croissance des arbres.

[Traduit par la Rédaction]

Introduction

Within the coast forest region of British Columbia, old-growth upland forests have been harvested since the early 1900s (Banner et al. 2005). The poorly drained low- to middle-elevation coastal western hemlock (CWH) forests are currently being considered as a potential source of wood fibre and high-value western redcedar (*Thuja plicata* Donn.) and yellow-cedar (*Chamaecyparis nootkatensis* (D. Don) Spach.). However, there is considerable uncertainty regarding the feasibility and sustainability of harvesting these wet, slow-growing forests (Banner et al. 2006). In particular, there is concern that the removal of trees will result in an increase in the amount of water reaching the soil and a rise in water table (Emili and Price 2005) that may potentially accelerate the advance of paludification (the lateral expansion of peatlands) into lowland forests, decreasing tree productivity and forest stand regeneration.

Although the variability, magnitude, and extent of water table elevation in forested peatlands (before and after clear-cutting) has been well documented (e.g., Verry 1986; Berry and Jeglum 1988; Paavilainen and Paivanen 1995), there is a paucity of research on the hydrological processes that have contributed to forest community development in these successional ecosystems. In coastal forest systems where storm runoff response is dominated by surface and near-

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surface flow processes (Gibson et al. 2000), ground surface topography is a significant control on the spatial variability of sources, pathways, and rates of hydrologic flow (Quinn et al. 1991). Definition of the relationships between topographic characteristics and patterns of groundwater flow is needed to model hydrology and hydrochemistry (Buttle et al. 2001) and to determine the controls on site productivity and forest community type distribution (Barnes et al. 1982).

In hydrologic research, topographic indices have been widely used to represent the gravitational potential for downslope flow (e.g., Beven et al. 1984; Quinn et al. 1991; Welsch et al. 2001) and have been related to temporal and spatial patterns of solute chemistry (Robson et al. 1992; Creed et al. 1996). Topographic indices are complicated, however, by variability in soil transmissivity (Moore and Thompson 1996). The interpretation of topographically derived slope indices, particularly their implications for forest community structure, must then be accompanied with an appropriate characterization of the hydrogeological domain.

Numerous studies have been conducted to characterize the influence of topographic gradients on forest community composition and function; however, these studies have largely been restricted to well-drained hardwood forests in the continental United States (e.g., Muller 1982; McNab 1993; Iverson et al. 1997). Differences in the distribution and growth of trees in these areas have been correlated with landform indices (McNab 1993; Rubino and McCarthy 2003) and moisture indices (Allen and Peet 1990; Iverson et al. 1997). These studies have demonstrated the potential of using topographic and related indices to predict forest productivity (site index). The close spatial proximity of transitional and mature forest communities in the forest–peatland complexes of the CWH region provide an opportunity to investigate the use of topographic indices relating site characteristics to productivity in poorly drained forests, for several community types, under similar climatological conditions.

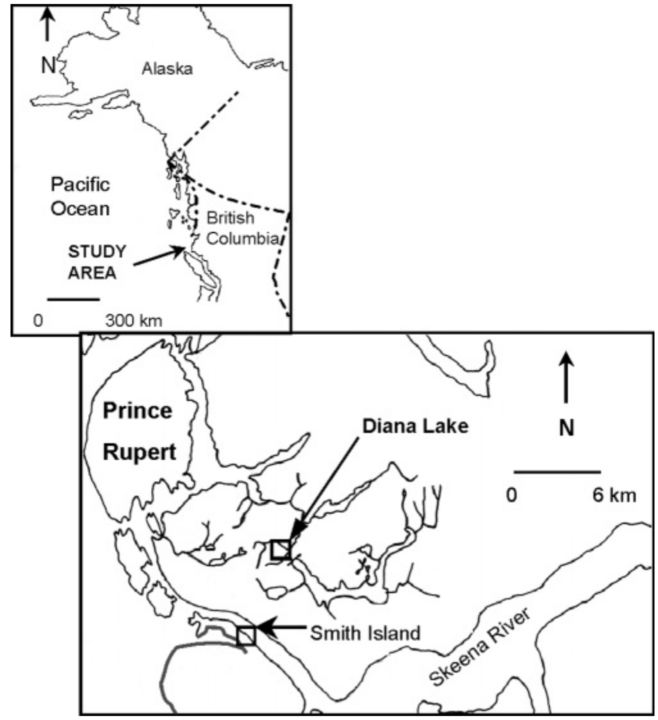
The main goal of this research was to quantify the influence of topographic gradients on hydrologic conditions controlling forest community type along forest–peatland complexes within the CWH region. To achieve this objective, two hypotheses were established: (*i*) the primary site condition controlling forest community type is substrate wetness, and (*ii*) the spatial distribution of wetness is a function of slope.

To test the hypotheses, we computed a slope index and related this index to wetness as represented by soil moisture and depth to water table.

Study area

As part of a larger multidisciplinary study (Pattern, process, and productivity in hypermaritime forests of coastal British Columbia; BC Ministry of Forests), two study sites were established within the very wet hypermaritime portion (CWHvh2) of the CWH zone. These two sites were selected based on the presence of representative examples of the full range of ecosystems from productive forests to blanket bogs (Banner et al. 2005). The first 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 (Fig. 1). This site contains a typical CWHvh2 cross-section of ecosystems, including lower-productivity forests on gentle slopes, bog forests, bog woodlands, blanket bogs, swamps, and productive forests on steeper slopes. The second study site is located within a small (0.33 km^2) watershed on Smith Island, approximately 6 km southwest of the Diana Lake site. This site is dominated by lower productivity forests on gentle slopes, productive forests on steeper slopes, bog woodlands, bog forests, and open blanket bogs.

Fig. 1. Study site and transect location at Diana Lake and Smith Island.



The study area is characterized by cool (average annual temperature of 6.9 °C), and hypermaritime conditions with little snow (0.06% of annual precipitation) and frequent periods of fog. The long-term (1971–2000) mean annual rainfall at Prince Rupert is 2469 ± 79 mm (Environment Canada 2002), with summer being the driest season and autumn the wettest; 48% of precipitation falls between September and December.

The bedrock geology is a complex mixture of rock types, geological structures, and development sequences. The study area is underlain by metamorphic amphibolite schist and gneiss. Colluvial processes have resulted in rockfalls and granular disintegration in upland areas. Peat has developed on gentler slopes, ranging from approximately 40 cm on midelevation forested slopes to 300 cm in open blanket bog in local depressions or benches. The underlying fine to medium sandy mineral soil horizon thickness is variable, ranging in thickness from 85 cm to 465 cm in the upland forest to less than 150 cm thick in swamp forest, bog forest, bog woodland, and open peatland communities.

Forest vegetation is grouped into five community types characterized by similar climax plant communities (Table 1). The forest community types in the study area consist of swamp forest, bog forest, bog woodland, open peatland, basin swamp, and upland forest. The tree canopy in the swamp

Table 1. Summary characteristics for each forest community type along the forest–peatland transects at Diana Lake and Smith Island.

Forest	Water table	Topography		Soil horizon thickness (m)		Horizon groundwater flux ($m^3 \cdot day^{-1}$)		
community	depth (m)	Surface slope	Slope index[a]	Organic	Mineral	Organic	Mineral	
Upland forest	0.31 to >1.50	0.16–0.43	1.1±1.4	0.20–0.45	0.85–4.65	nd[b]	10^{-2}	Western hemlock forests, deer fern and moss understory
Swamp forest	0.06 to 0.69	0.14–0.29	13±11	0.30–1.30	0.50–1.50	10^{-2}	10^{-1} to 10^{-2}	Western redcedar and western hemlock forests, blueberry and salal understory, *Sphagnum*
Bog forest	0.05 to 0.76	0.10–0.34	19±16	0.22–1.64	0.25–1.50	nd	10^{-1} to 10^{-2}	Scrubby western redcedar and yellow-cedar forests, salal understory, *Sphagnum*
Bog woodland	0.02 to 0.48	0.05–0.22	29±49	0.41–2.64	0.25–2.00	10^{-4} to 10^{-5}	10^{-2} to 10^{-3}	Open and very scrubby shore pine-dominated woodland, *Sphagnum*
Open peatland	0.00 to 0.34	0.002–0.18	93±149	0.31–3.15	0.50–2.00	10^{-3} to 10^{-4}	10^{-3} to 10^{-5}	Ericaceous shrubs, sedges, and *Sphagnum*

[a]Values are means ± SDs.
[b]nd, no data.

forest is not completely closed, and shrub layers are well developed. In the bog forest, the canopy is more open than the swamp forest, and tree height rarely exceeds 20 m (Asada 2002). The bog woodland is characterized by an abundance of scrubby trees. The canopy height in the upland forest is higher than 20 m (Asada 2002). The shrub layer has lower cover than the swamp and bog forests. Forest vegetation is dominated by conifer stands of western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and western redcedar; shore pine (*Pinus contorta* Dougl. ex Loud. var. *contorta*), and yellow-cedar are abundant on organic soils. The understory is composed primarily of shrubs (*Vaccinium* spp.), feathermosses (*Pleurozium* spp.) and *Sphagnum* mosses, devil's club (*Oplopanax horridus* Torr. & Gray ex Miq.), and skunk cabbage (*Lysichiton americanum* Hult. & St. John) in wetter areas. The open peatland comprises hummock, hollow, pool, and lawn communities dominated by *Sphagnum* mosses and dwarf shrubs.

Timber cruises performed by Banner et al. (2005) were used to quantify and compare the volume and quality of timber in the study area (Table 2). The upland forest trees have the highest gross and net volume, the most basal area and the largest diameter at breast height. The swamp forest and bog forest communities have progressively lower values.

Methods

Research approach

The objectives in this study were addressed by establishing transects through representative forest communities at Diana Lake and Smith Island. Ground penetrating radar (GPR) was run along these transects for the purpose of providing a spatially continuous cross-sectional profile of stratigraphy and subsurface topography. Concurrently, a network of wells and piezometers for groundwater monitoring was established along the transects and samples for the determination of soil hydrophysical properties were collected. Topographic indices were calculated at 5–10 m intervals along each of these transects and at well or piezometer locations.

Initial installation of monitoring equipment and data collection began in 1997 at Diana Lake and was expanded to Smith Island in 1998. Studies were carried out on a continuous basis at these two sites from 1997 until 2001. For the purposes of this paper, data from 1998 and 1999 are used because these are the 2 years for which there is the most complete overlap in hydrological and soil data.

Ground penetrating radar

GPR was used to derive estimates for soil depth (Greaves et al. 1996), at the Diana Lake and Smith Island sites. The Diana Lake transect (500 m) rises from an elevation of 150–185 m and passes through six forest communities (see Figs. 2 and 4). The GPR survey was divided into three lines that spanned the transect. On Smith Island, the GPR was done along three transects 170 m, 80 m, and 90 m in length, respectively. The first transect (35–45 m asl) was laid out in a northwest–southeast direction through four forest community types (see Figs. 3 and 5). The second transect (35–47 m asl), starting at the 70 m mark of transect 1, was run at a right angle to transect 1 extending northeast (Fig. 3). The third transect (47–68 m asl) was also run at a right angle to

Table 2. Summary of average stand characteristics for swamp forest, bog forest, and upland forest communities for the study area (modified from Banner et al. 2005).

Forest community	n^a	Volume/ha (m^3) Gross	Net	Basal area/ha (m^2)	Mean DBH[b] (cm)
Swamp forest	44	329.3	229.3	54.2	30.3
		298.4	202.9	50.4	37.9
Bog forest	21	188.7	133.4	38.0	28.7
		159.0	107.6	33.8	33.8
Upland forest	11	508.1	398.7	60.6	35.8
		479.0	373.2	56.6	44.7

Note: The two rows per forest community represent the lower limit of both 7.5 and 17.5 cm DBH.
[a]Number of trees.
[b]Diameter at breast height (DBH) values are the lower diameter limits.

transect 1 extending southwest and starting at the 142 m mark of transect 1 (Fig. 3).

GPR data were collected with a PulseEkko IV radar system with an antenna frequency of 100 Mhz and a depth resolution of 10 cm. A 200 Mhz frequency was used to provide better spatial resolution in the open peatland and for a common midpoint (CMP) survey within the swamp forest at Diana Lake. CMP surveys were also performed on Smith Island in the bog woodland separating open peatland along transect 1 and in the bog forest along transect 2. A station spacing of 0.25 m was used for all surveys and antenna separations were 1.0 m when using 100 Mhz antennas and 0.5 m when using 200 Mhz antennas. Spherical exponential compensation was used for gain correction of velocities to account for attenuation within the soil profile and from geometrical spreading of the GPR signal. Gain was applied to correct the signal amplitude as a function of time and depth. A velocity of 0.038 $m \cdot ns^{-1}$ and 0.060 $m \cdot ns^{-1}$ was used for organic and mineral soils, respectively.

Radar profiles were topographically corrected using surface elevation determined by a theodolite survey. The thickness of the organic soil and mineral subsoil were then estimated from radar profiles and compared to thicknesses determined by soil auger and probe measurements. A hand auger (bit width of 2.5 cm, bit length of 20 cm) was used to determine the depth to mineral soil at groundwater sampling stations at Diana Lake and Smith Island (Figs. 2 and 3). Where obstacles were encountered and depth could not be determined by the auger method, a soil pit was dug to investigate the cause of the obstruction. Three replicate measurements were taken at each station to determine the spatial variability in organic horizon thickness estimates. Probe (306 cm long, 10 mm diameter) measurements were taken at 3 m intervals along the GPR transects. Soils were differentiated as organic (O horizon) or mineral (L, F, and H horizons) according to the Canadian system of soil classification (Canadian Soil Survey Committee 1987).

Slope index

The TOPMODEL slope index represents a theoretical estimation of the accumulation of flow at any point in a watershed and the downslope movement of water from that point by gravitational forces (Quinn et al. 1995). The topographic effects of the cumulative upslope contributing area drained through a point per unit contour length (a) and the slope angle (β) at that point are represented by the topographic index (TI), such that

$$[1] \qquad \mathrm{TI} = \ln\left(\frac{a}{\tan\beta}\right)$$

TOPMODEL relies on the processing of digital terrain data to calculate the watershed distribution of TI. The calculated values of a and $\tan\beta$ are, therefore, dependent on the grid resolution used and the flow-path algorithms (Quinn et al. 1991). Areas of the landscape most likely to become saturated during rain events are those with large contributing areas or low slope gradients, for example, and are characterized by a high topographic index.

For this study, the index was modified to represent the downslope movement of water at the hillslope scale, i.e., along the forest–peatland transects for which concurrent stratigraphic and hydrologic data were measured. The slope index (SI) is expressed as

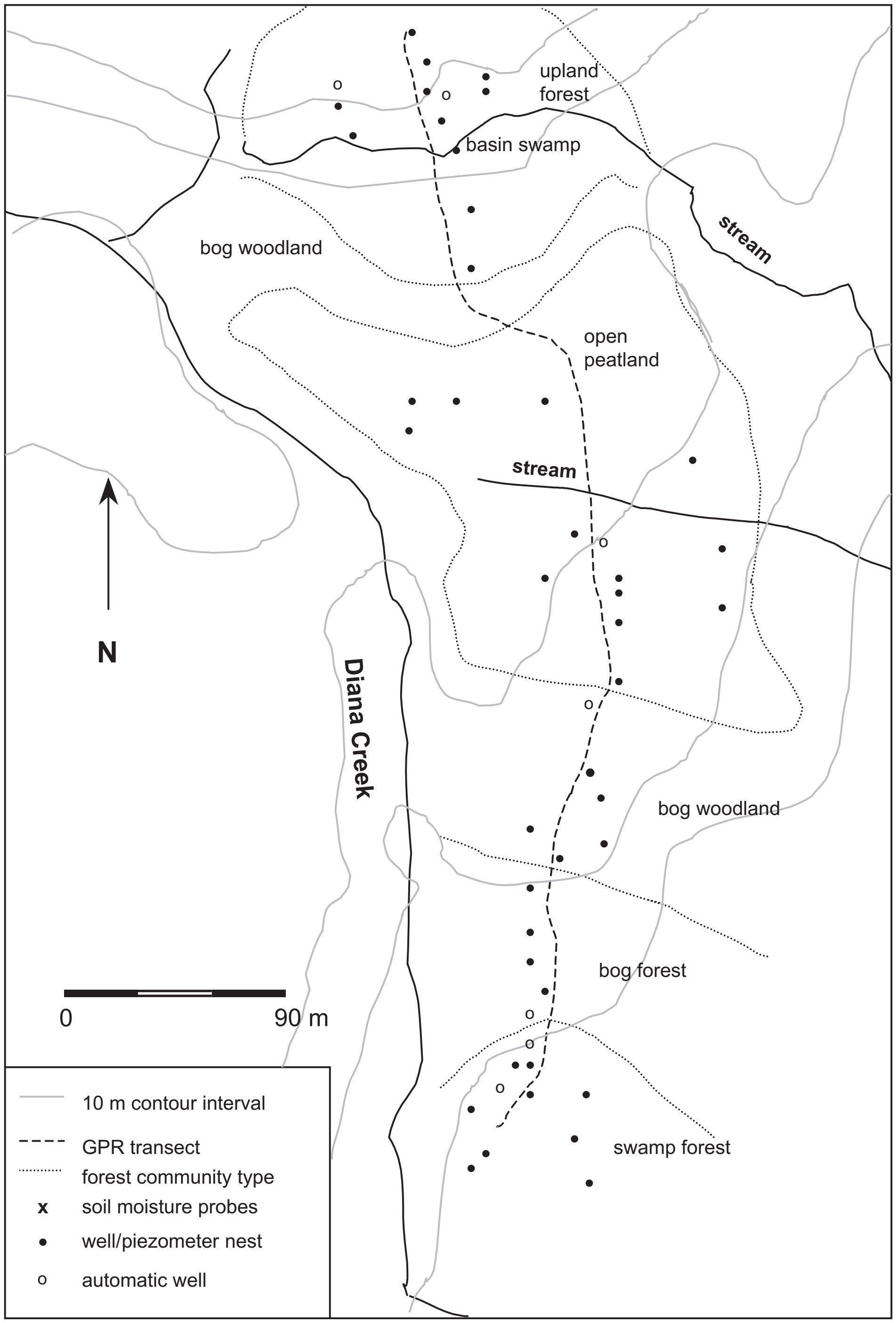
$$[2] \qquad \mathrm{SI} = \frac{L}{\tan\beta}$$

where the portion of the transect contributing to groundwater flow at points along the transect is represented by slope length, L. The upslope contributing length originates at a topographic high and terminates at the point of observation. The local ground surface slope is $\tan\beta$. It should be noted the L has the dimension of length, and thus, the value of the index depends on the selected length unit, i.e., for similar values of $\tan\beta$. This approach assumes that subsurface flow at any point along the hillslope is Darcian and that the local lateral hydraulic gradient is approximated by the local ground surface slope ($\tan\beta$).

Water table, piezometric head, and vertical gradients

Remote Data System™ WL40 automatic recording wells were used to monitor water table fluctuation at 12-hour intervals in 1998 at one station per forest community type at Diana Lake and three stations in the swamp forest on Smith Island in 1999. Wells with a potentiometric encoder attached to a float were recorded with a datalogger that collected hourly water level response at three locations in the open peatland on Smith Island in 1999. Manual wells of 2.5 cm (i.d.) PVC pipe, slotted along the entire length and covered with 250 mm Nitex™ mesh were pushed into prebored pilot

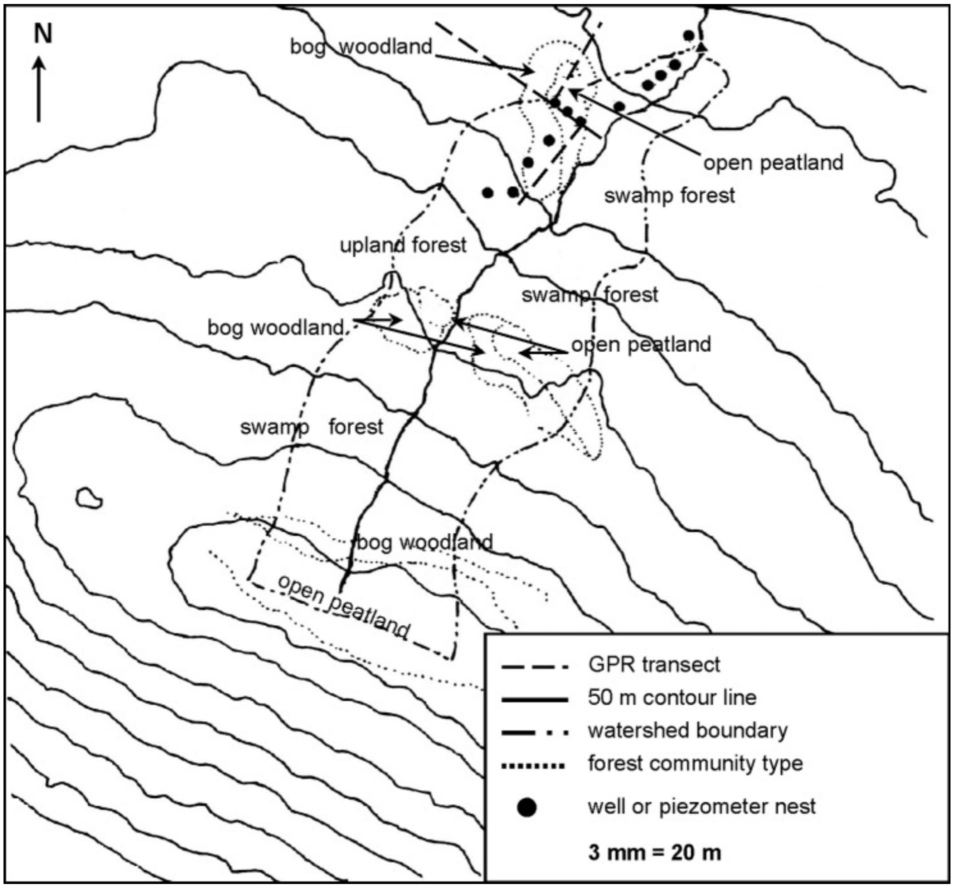
Fig. 2. Network of wells, piezometers, and soil moisture probes along the ground penetrating radar (GPR) transect at Diana Lake.



holes. At Diana Lake, manual wells were generally 1.2 m deep, although 0.6 m wells were installed to establish if 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, to measure hydraulic head in the mineral soil layer. On Smith Island, two manual wells (0.70–1.25 m long) were installed in each of the bog forest, bog woodland, open peatland and upland forest communities. Four manual wells (0.80–1.00 m deep) were installed in the swamp forest on Smith Island.

Piezometers of 2.5 cm (i.d.) PVC, slotted along the bottom 20 cm and screened with 250 mm Nitex™ mesh, were nested at depths determined by the depth of the organic soil, depth to the organic–mineral soil transition, and depth to mineral soil. At Diana Lake, two such stations were instrumented within each forest community along the main transect. On Smith Island, piezometers were nested at depths determined by the depth of the organic soil and depth to mineral subsoil. Two stations were installed in each of the bog forest, bog woodland, and open peatland communities. Four stations were located in the swamp forest. All piezo-

Fig. 3. Network of wells and piezometers along the GPR transects on Smith Island.



meter nests were in locations representative of the physiognomy ascribed by Banner et al. (1993) to that particular forest community.

Manual wells (n = 45) and piezometers (n = 66) at Diana Lake were measured weekly from May September 1998. Levels in manual wells (n = 16) and piezometers (n = 32) on Smith Island were monitored every 7–10 days in June and July 1998.

Vertical hydraulic gradients (dh/dz) were expressed as a ratio of the change in piezometric head (dh) between two piezometers to the distance between these piezometers (dz).

Volumetric moisture content

Campbell Scientific soil water content reflectometers (CS 615) attached to Campbell Scientific CR 10 and 21X data-loggers were used to monitor volumetric moisture content (VMC) in the swamp forest (10, 20 and 35 cm depth) and upland (10, 17 and 24 cm depth) forests at Diana Lake from January–September 1998 (Fig. 2). The difference between the respective reflectometer output at saturation (i.e., when the probe was below the water table) and the total soil porosity (as determined according to eq. 3) was used as an offset to correct all reflectometer values.

Soil properties and ground water flux

In the laboratory, samples for specific yield (S_y) were saturated for 24 h and weighed (M_{sat}) and then drained by gravity for 24 h and weighed ($M_{drained}$). The yield of water removed from the soil (g·cm^{-3}/g·cm^{-3}) was expressed as

$$[3] \qquad S_y = \frac{(M_{sat} - M_{drained}/\rho w}{M_{sat}/\rho w}$$

where ρw is the density of water (1000 kg·m^{-3} at 25 °C).

Porosity (ϕ) was determined according to the equation:

$$[4] \qquad \phi = 1 - \frac{\rho b}{\rho s}$$

where ρb is bulk density and ρs is particle mass density. Bulk density was expressed as the oven-dry mass (95–105 °C for 48 h) of sample divided by the saturated volume of sample. Particle mass density was assumed to be 1.4 g·cm^{-3} for organic soil (Pyatt and John 1989) and 2.65 g·cm^{-3} for mineral soil (Freeze and Cherry 1979).

Hydraulic conductivity was determined in the field for each manual well and piezometer along the Diana Lake transect in August 1998 and one piezometer per nest in the swamp forest on Smith Island in May–July 1999 using a bail test and interpretation of water level recovery by the Hvorslev method (Freeze and Cherry 1979). Recovery was 90% for wells and 80% for piezometers.

Groundwater flux (m^3·day^{-1}·m^{-1}) was determined between successively downslope pairs of piezometers as

$$[5] \qquad Q = K_{sat} \frac{dh}{dl} bw$$

where K_{sat} is the mean value for saturated hydraulic conductivity of the two piezometers and dh/dl is the change in hy-

Fig. 4. Stratigraphic profile of the forest–peatland complex at Diana Lake based on GPR profiles.

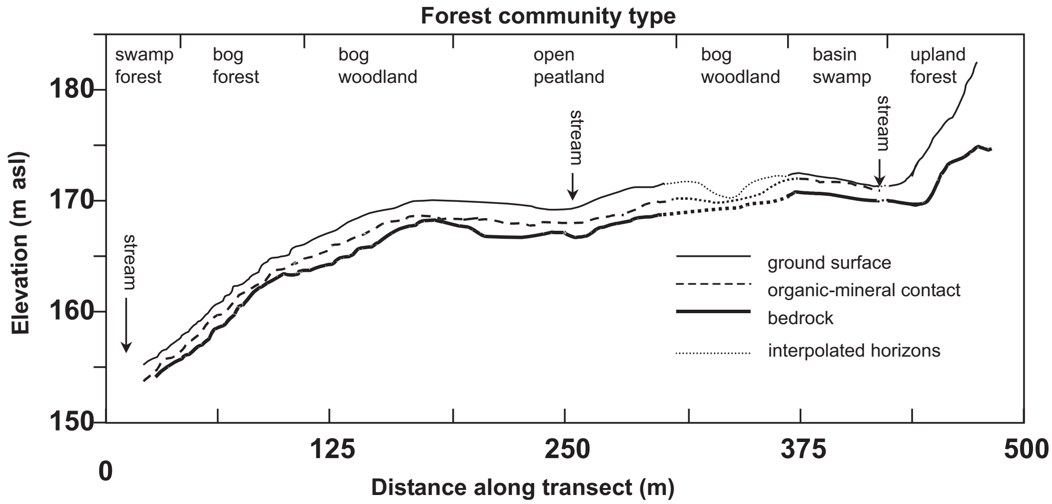
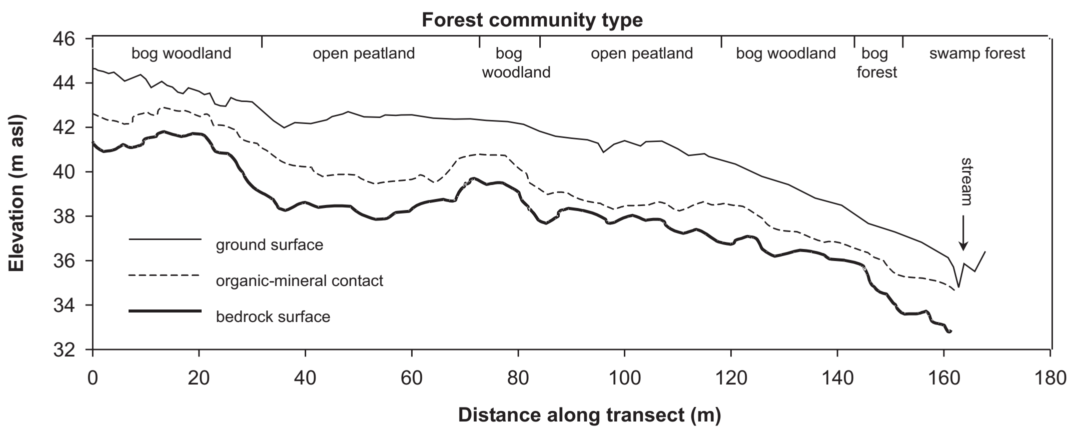


Fig. 5. Stratigraphic profile along transect 1 on Smith Island based on the GPR profile.



draulic 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.

Statistical analyses

Pearson correlation analysis was used to investigate the relationship between organic and mineral soil depth as estimated by GPR and that estimated by manual probing, between bedrock morphology and ground surface slope and between slope index and several factors (water table depth, organic horizon thickness, and site index). The correlation coefficient (r) was used as a measure of the strength of the relationship. The test statistic (t) was used to determine whether there was a significant correlation between the two variables. The significance level was set at $\alpha = 0.05$.

A one-factor between-subjects univariate analysis of variance (ANOVA) of unbalanced design was used to test the equality of forest community type slope index means. The nonparametric Kolmogorov–Smirnov test was used to determine if the frequency distributions of slope index differed between the Diana Lake and Smith Island study sites (Kirkman 2002).

Results

Evaluation of the GPR technique

The major boundary identified by GPR was the interface between the organic soil and the mineral subsoil (Figs. 4 and 5); this represents the organic layer thickness. At Diana Lake, the organic soil depth estimated with GPR was well correlated with that determined by manual probing ($r = 0.91$, $t = 18.22$, $P < 0.05$) for transect 1 (swamp forest, bog forest, bog woodland, open peatland). The correlation, although weaker, was significant for the transects on Smith Island ($r = 0.58$, $t = 8.18$, $P < 0.05$). Regarding the mineral soil depth, i.e., to bedrock, there was a poor relationship ($r = 0.73$, $t = 2.12$, $P < 0.05$). The limited number of probe measurements (one per forest community) in the mineral subsoil at Diana Lake likely accounted for the poor correlation to GPR estimates. Organic soil depths determined by manual probing at Diana Lake were about 90% of GPR measurements. For Smith Island transects 1, 2, and 3 the depth to mineral soil determined by manual probing was 61%, 69%, and 61%, respectively, of depths determined by GPR (Graham 2000).

Characterization of the flow domain

Based on an analysis of the GPR profiles, a detailed picture of the flow domain could be established. The ground surface slope within forest communities at Diana Lake increased along the gradient open peatland < bog woodland < bog forest < swamp forest < upland forest (Fig. 4). Surface slopes ranged from 1% in the open peatland to 16% in the swamp forest and 26% in the upland forest. A similar pattern in forest community surface slope was found at Smith Island, with the exception of the bog forest community along transect 1. This community had a comparable surface slope (7%) to the bog woodland communities (5–9%). Ground surface slope increased at Smith Island from transect 1 to transect 3. There was a significant positive correlation between bedrock morphology and ground surface slope (r = 0.76, t = –0.25, P < 0.05). Steeper surface versus bedrock slopes occurred in the open peatland and in the upland forest at Diana Lake (Fig. 4). In contrast, steeper bedrock versus surface slope occurred in the bog forest on transect 1 at Smith Island (Fig. 5).

At Diana Lake and Smith Island, bog woodland communities overlie the margins of the bedrock basins in which the open peatlands formed (Figs. 4 and 5). The organic horizon is deepest in the centre of each peatland (1.60–3.15 m) and is thinner in the bog woodland communities (0.40–0.63 m). Soil cores at Diana Lake showed that well-decomposed *Sphagnum*–sedge peat of the open peatland overlays a fine sand and silt mineral subsoil less than 2.00 m thick (Turunen 1999). In the swamp forest and bog forests at Diana Lake and Smith Island, humic folisols (0.20–1.75 m) overlie fine to medium sandy mineral soil (<1.50 m), which have localized ortstein horizons. Mineral subsoil at Diana Lake was greatest in the upland forest (0.85–4.65 m). Mineral subsoil was variable across the three transects on Smith Island and ranged in thickness from 0.50 m to 2.25 m.

Water table and volumetric moisture content

Mean water table depths (Table 3) as determined by automatic wells at Diana Lake were progressively deeper along the gradient open peatland (7.9 ± 6.9 cm; mean ± SD), bog forest (14.3 ± 6.5 cm), bog woodland (15.3 ± 5.0 cm), swamp forest (22.2 ± 7.6 cm) and upland forest (93.0 ± 7.1 cm). Manually measured water table depth (Table 3) increased 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). Since there were more manual wells per community type, they may be more representative of the spatial variability of water table depth.

In each of the peatland communities (bog forest, bog woodland, and open peatland), water table (determined by automatic wells) was within 25 cm of the surface for 75%, 75%, and 90% of the study period, respectively. Water table in the upland forest was below 80 cm for 75% of the season. Mean water table depths at three stations in the swamp forest on Smith Island were 29.2 ± 2.8 cm, 26.9 ± 1.9 cm, and 31.2 ± 5.1 cm. Water table depth was within 25 cm of the surface for 66% of the sampling season at all three stations. Mean water table depths at three stations in the open peatland on Smith Island 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 sampling season and within 25 cm of the ground surface for 70%, 80%, and 90% of the season for the three stations, respectively. The flooding at this site was caused by an upslope landslide area that diverted streamflow during high flow periods (Lortie 2002).

Table 3. Water table depths (cm) for forest community types at Diana Lake and Smith Island.

Study site	Forest community	Type of well	Depth (cm)[a]
Diana Lake	Swamp forest	Manual	30.8±9.3
		Automatic	22.2±7.6
	Bog forest	Manual	34.4±15.3
		Automatic	14.3±6.5
	Bog woodland	Manual	18.0±4.7
		Automatic	15.3±5.0
	Open peatland	Manual	11.6±2.4
		Automatic	7.9±6.9
	Upland forest	Manual	101.2±3.9
		Automatic	93.0±7.1
Smith Island	Swamp forest	Automatic	29.2±2.8
		Automatic	26.9±1.9
		Automatic	31.2±5.1
	Open peatland	Automatic	12.2±12.1
		Automatic	9.9±10.8
		Automatic	5.5±7.0

[a]Values are means ± SDs.

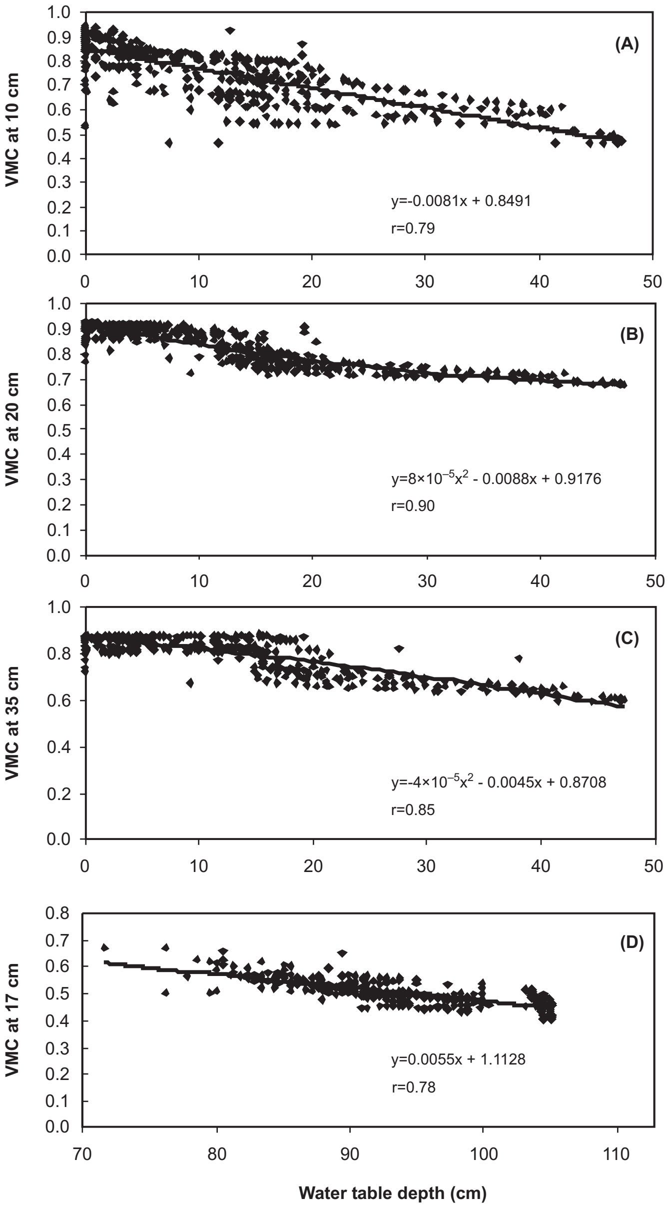
VMC in the swamp forest and upland forest was correlated to water table position (Fig. 6). The strength of this relationship in the swamp forest was lower in the surface layer from which evaporative losses occur, than deeper in the soil profile.

Slope index

The spatial distribution of topographically controlled site conditions (i.e., water table depth, soil moisture content, and organic horizon thickness) influencing forest community type at Diana Lake and Smith Island was characterized using slope index (SI = L/tan β). Mean SI decreased from open peatland (83 ± 124) to upland forest (1.1 ± 1.4). Slope index values were significantly different between forest communities for the Diana Lake (ANOVA, P << 0.0001) and Smith Island (ANOVA, P = 0.003) transects. The lower SI values in the swamp forest, bog forest and bog woodland communities on Smith Island as compared with Diana Lake (Fig. 7) result from the greater surface slopes (tan β) and shorter slope lengths (L) at Smith Island. Comparison of the frequency distributions of SI values for the two study sites (Kolmogorov–Smirnov test; Kirkman 2002) revealed similar frequency distributions (D = 0.300, P = 0.675) for all forest communities. The similarity in the frequency distributions shows that SI may be used to predict the areal pattern of site conditions within forest–peatland complexes in the study area.

Higher SI values (>100), indicating greater local slope length and (or) lower slope, were wetter areas such as bog woodland and open peatland communities (both study sites) and basin swamp (Diana Lake). Lower SI values (<25) were associated with recharge areas in the open peatland and bog woodland communities (see next section) and greater mean slope (26% ± 18%) in the bog forest, swamp forest and up-

Fig. 6. Relationship between fractional volumetric moisture content (VMC) and water table depth in the swamp forest (A–C) and upland forest (D) at Diana Lake, January–August 1998.



land forest communities (both study sites). Slope indices between 0 and 10 were associated with ranges in organic soil horizons of 0–0.96 m, water table depth of 0.26–1.57 m, and VMCs of 35–76%. For SI in the range 11–30, the corresponding ranges were 0.30–1.18 m, 0.19–0.42 m, and 46–87%, respectively. Slope indices between 51 and 200 had mean organic soil horizon thickness of 0.67–1.82 m, water table depths of 0.09–0.24 m and VMCs of 46–92%. For SI ≥ 201, thickness of the organic soil horizon ranged from 1.27 to 2.18 m. Corresponding water table depth and VMC were not available for slope indices ≥201.

Water table depth and soil moisture content were used as wetness indicators. Slope index was well correlated (r = 0.88, t = 17.65, $P < 0.05$) with water table depth, decreasing with increasing depth to water table (Fig. 8). The thickness of the organic horizon (peat layer) is a measure of the relative wetness of the site. Slope index was positively correlated (r = 0.75, t = 10.88, $P < 0.05$) with the organic horizon thickness (Fig. 8).

To determine the relationship between slope index and forest productivity, slope indices for the Diana Lake and Smith Island transects were compared with site index values from several CWHvh2 plots (Banner et al. 2005). Mean slope index values for each community type were compared with mean site index values for western redcedar, western hemlock, mountain hemlock, shore pine, and yellow-cedar (Table 4). With the exception of mountain hemlock, slope index and site index exhibited a negative linear relationship; however, only shore pine site index was significantly correlated to slope index (r = 0.99, t = 7.0, α = 0.05). The low correlation between slope index and site index for western redcedar, western hemlock, mountain hemlock, and yellow-cedar might be explained by variations in site index attributed to sources other than slope (McNab 1993) but is more likely due to the use of site index values determined for plots that were not coincident with the transects used to determine slope index.

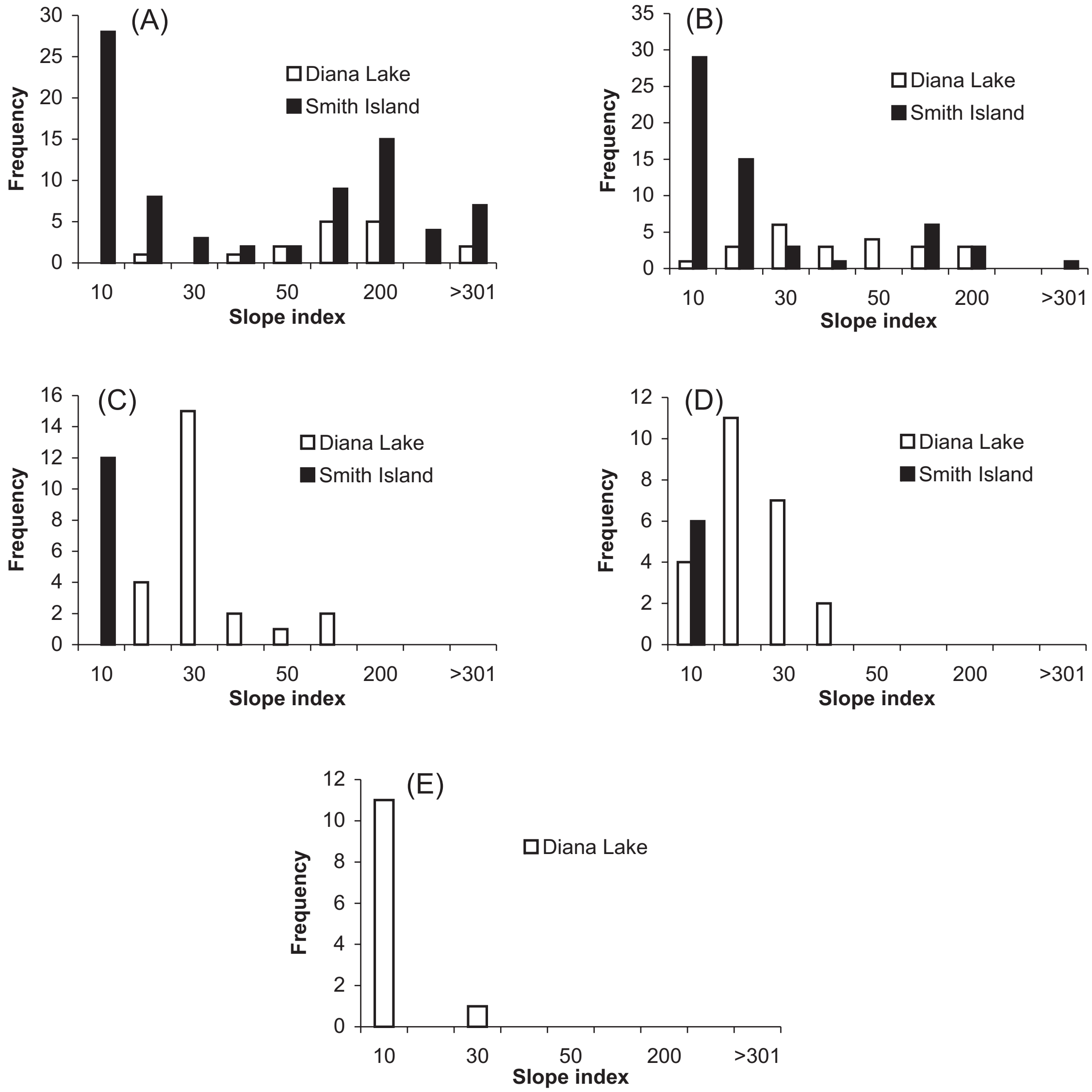
Hydraulic gradients, groundwater recharge or discharge, and groundwater flux

Vertical hydraulic gradients at Diana Lake were both spatially and temporally diverse. Vertical hydraulic gradients were greatest in the open peatland (–0.76 to 0.04). Negative piezometric head relative to water table depth in the open peatland on the main transect and west of the main transect indicated that these areas were consistent regions of recharge. East of the main transect, organic soil was discharging groundwater. Vertical hydraulic gradients in the swamp forest, bog forest, and bog woodland were in the range of –0.35 to 0.01. In these three communities, piezometric head was greater than the local water table depth; thus, the organic soil horizon was discharging groundwater. Except at the base of steep slopes (zones of discharge), the mineral subsoil in the swamp forest and bog forest were zones of recharge. In the bog woodland, flow direction was downward during rain events and upward during dry periods. The range in vertical hydraulic gradient was lowest in the upland forest (0.02–0.15), where recharge occurred for the entire sampling period.

Groundwater flux per unit slope width of transect (1 m) was determined in each forest community along the transect from 1 June to 31 August 1998 at Diana Lake (Fig. 9). Groundwater flux varied spatially from organic to mineral soil horizons and was a function of variations in K_{sat}. In general, K_{sat} was lower in the organic horizon (10^{-6} to 10^{-7} $cm{\cdot}s^{-1}$) compared with the mineral horizon (10^{-4} to 10^{-5} $cm{\cdot}s^{-1}$). Exceptions to this trend occurred in the open peatland, where K_{sat} was comparable in the organic and mineral soil horizons (10^{-6} to 10^{-7} $cm{\cdot}s^{-1}$) and in zones of discharge located at the base of steep slopes in the swamp and upland forests. In these discharge zones, K_{sat} decreased with depth from organic soil (10^{-4} to 10^{-5} $cm{\cdot}s^{-1}$) to mineral soil (10^{-6} to 10^{-8} $cm{\cdot}s^{-1}$).

The groundwater flux for the organic soil was determined for the zone below the water table (20–170 cm) for at least three stations in each of the swamp forest, bog woodland, and open peatland communities. The mean groundwater flux

Fig. 7. The distribution of slope index values for (A) open peatland, (B) bog woodland, (C) bog forest, (D) swamp forest, and (E) upland forest communities at Diana Lake and Smith Island.



along the transect was 0.005 ± 0.006 $m^3 \cdot day^{-1} \cdot m^{-1}$ and 0.032 ± 0.072 $m^3 \cdot day^{-1} \cdot m^{-1}$ in the organic horizon and mineral subsoil, respectively.

Discussion

Topographic controls on forest community type

Ground surface slope, depth to water table, and organic soil horizon thickness significantly influence the distribution of forest community type at Diana Lake and Smith Island. Asada (2002), using ecological gradient analysis (a plot of plant responses to changes along a particular environmental gradient), also found the primary factors controlling vegetation community distribution at Diana Lake to be minimum water table depth and slope. However, he did not investigate the physical controls on these two factors. In this study, the slope index was used to quantify the effect of local hydraulic gradients on groundwater flow and the primary site conditions influencing productivity (organic matter accumulation and water table depth).

Not only was the range in slope index values significant in determining the spatial distribution of drainage and hence forest community type, but the frequency of occurrence of high slope index values was important. Although frequency of occurrence of slope indices less than 50 is more than double that of indices greater than 50, it is this latter set representing topographic lows (with thicker organic soil horizons, water tables near the surface, and higher soil moisture contents) that have the potential to contribute strongly to surface runoff generation and solute transport (Salvucci and Entekhabi 1995). Exceptions to this trend, i.e., greater organic soil depth where slope index is low, occurred in the swamp forest and bog forest at Diana Lake where hard-pan formation increased organic thickness regardless of topographic position and on Smith Island because of paludification.

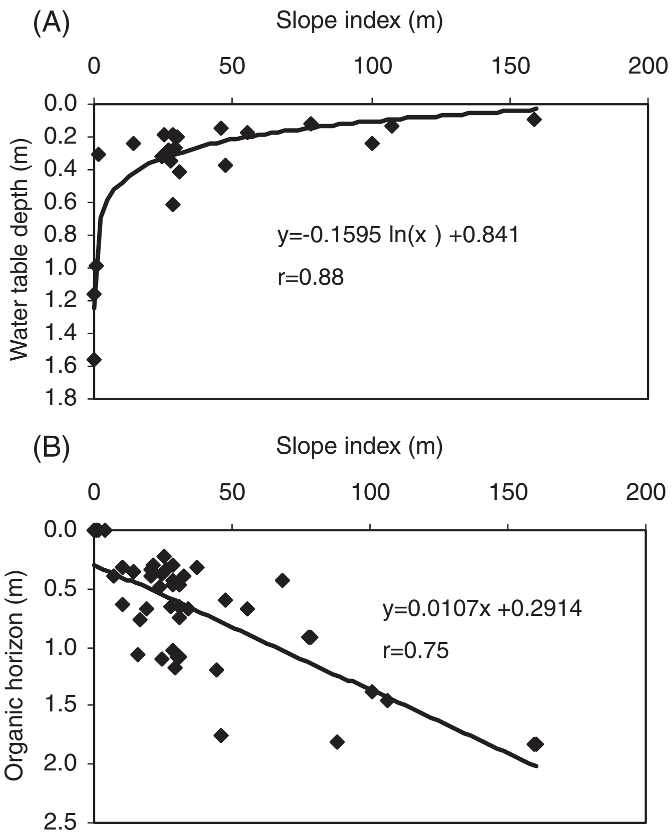
Topographic highs, i.e., areas with low slope index values, were associated with deeper water tables and lower soil moisture. These areas have lower accumulations of peat and in the upland forest, an absence of peat that contributed to

Table 4. Site index values for the tree species of the forest community types in the CWHvh2 forest zone (modified from Banner et al. 2005) and their correlations with slope index.

Forest community	Western redcedar	Mountain hemlock	Western hemlock	Shore pine	Yellow-cedar
Swamp forest	3.9 (1.9–10.5)	3.0 (2.0–7.7)	2.7 (1.3–6.2)	4.8 (2.3–9.5)	4.0 (1.7–9.8)
Bog forest	2.9 (2.0–4.5)	3.1 (2.3–3.9)	3.1 (1.4–5.3)	3.8 (1.8–7.1)	2.9 (1.7–5.5)
Bog woodland	3.3 (2.5–4.5)	3.0 (2.2–5.5)	2.0 (1.9–2.1)	2.8 (1.8–3.7)	2.4 (1.7–3.5)
Upland forest	5.2 (2.8–7.4)		3.2 (1.7–5.3)		
Correlation coefficient (*r*)[a]	0.87	0.79	0.14	0.99	0.94

Note: Site index is defined as total tree height (m) at a breast height age of 50 years. Values are means with ranges given in parentheses.
[c]Coefficient for the correlation of site index to slope index.

Fig. 8. Correlation between slope index and (A) mean water table depth (m) and (B) organic horizon thickness (m).



enhanced infiltration and groundwater recharge that is responsible for sustained baseflow in local discharge zones and streams (Fitzgerald et al. 2003).

Freer et al. (1997) questioned the validity of using surface topography to determine hillslope groundwater characteristics and suggested that it may be more appropriate to use subsurface gradients relating to the soil–bedrock interface. Their investigation relates to steeply sloping well-drained forest systems where rapid flow occurs in the mineral subsoil horizons. In these environments, bedrock surface has a considerable influence on hydrological gradients and dominant flow-path directions. In peatland communities (bog forest, bog woodland, and open peatland) such as in the study area, where the hydrophysical properties of the organic soil horizon result in predominantly lateral shallow subsurface groundwater flow, surface topography is a valid means of estimating downslope hydraulic gradients. However, in the upland forest and swamp forest communities, this estimation may be confounded by surface irregularities, namely bedrock outcrops and gullies, affecting groundwater flow.

System structure

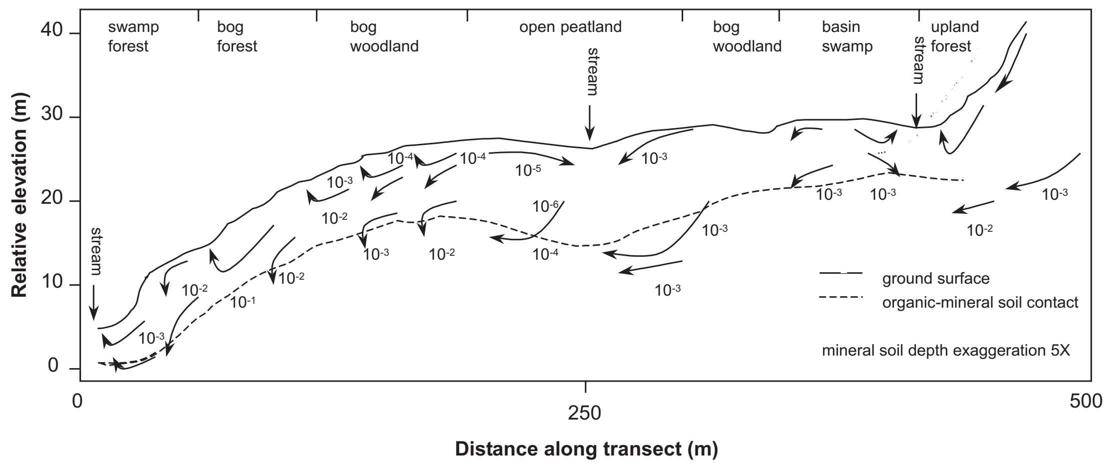
There was a systematic underestimation of organic soil depth using manual probing as compared with GPR, which increased with the thickness of the organic material; thus, greater differences were apparent at the Smith Island site. The cause of the error is uncertain, but soil pits indicated that subsurface obstacles (such as roots, logs, and rocks), particularly in the bog forest and upland forest at Diana Lake, resulted in underestimation of depth to mineral subsoil by manual probing.

However, GPR proved to be a valuable tool in distinguishing the interface between organic and mineral soil horizons and in delineating bedrock topography. The major reflector identified along the profiles was the contact between the organic soil and mineral subsoil. The interface between mineral soil and bedrock was less clear because of scattering by cobbles and boulders, particularly in the upland forest at Diana Lake.

The heterogeneity of the mineral soil – bedrock interface causes chaotic scattering of the GPR signal; this noise is difficult to interpret. Similar results have been found in other environments with colluvial blanketed slopes (Olson and Doolittle 1985). Additional test holes and drill cores are necessary for a complete delineation of the hydrogeology at Diana Lake and Smith Island. Although hydrometric and isotopic data indicate shallow subsurface flow predominates (Emili 2003), the complexity of the mineral soil – bedrock interface suggests that flow in this layer could be profound. However, the resolution of the GPR for the organic horizon fairly represents the depth and extent of peat accumulation at the study sites.

Peat accumulation occurred in topographic sites favouring wet conditions, i.e., concave bedrock morphology. In areas where bedrock topography cannot explain peat accumulation, such as in the swamp and bog forest communities at Diana Lake, core data indicated that localized hard-pan formation constrained drainage, causing peat accumulation. The poor correlation between bedrock slope and ground surface slope was related to the infilling of depressions and the lateral advancement (paludification) of peat over bedrock irregularities (Turunen 1999). For example, steeper bedrock versus surface slope in the bog forest on transect 1 at Smith Island (Fig. 5) was due to peat accumulation and downslope paludification. In contrast, steeper surface versus bedrock

Fig. 9. Groundwater flow direction and mean flux ($m^3 \cdot day^{-1} \cdot m^{-1}$) along the transect at Diana Lake. Small-scale groundwater recharge or discharge based on vertical hydraulic gradient as indicated by arrows.



slopes occur in the open peatland at Diana Lake, where incised streambanks of an erosional channel lower the peat surface, and in the upland forest, where colluvium overlies bedrock (Fig. 4).

Wetness indicators

Soil moisture was largely controlled by the water table depth (Fig. 6), with moisture content in the rooting zone (10–35 cm) decreasing with increasing water table depth. Low horizontal hydraulic gradients (0.01–0.06) impeded drainage and maintained the water table near the surface (11.6 ± 2.4 cm) in the open peatland. Higher horizontal hydraulic gradients in the bog woodland, bog forest, and swamp forest (0.07 to 0.16) resulted in a deeper water table (18.0 ± 4.7 cm, 34.4 ± 15.3 cm, 30.8 ± 9.3) because of improved drainage. The deepest water tables (101.2 ± 63.9 cm) occurred in the upland forest where an absence of peat and increased horizontal hydraulic gradient (0.11–0.30) and higher specific yield (0.16–0.25) increased drainage and favoured greater forest productivity.

The influence of water table on soil moisture and aeration is also related to soil properties that affect infiltration and water retention (Boelter 1965). In peat, groundwater flux is largely dependent on hydraulic conductivity that varies with soil water content, soil matric potential, and gravity potential. Hydraulic conductivity to a certain extent controls infiltration and regulates the rate at which water stored at depth is supplied to surface layers. The release of water from storage is characterized by the specific yield, which is a function of porosity and is, in turn, controlled by the degree of decomposition and compaction of the soil (Boelter 1965).

At Diana Lake, the less decomposed peat of near-surface (0–20 cm) organic soil horizons (0.04–0.10 $g \cdot cm^{-3}$) had higher porosity (93–94%) and was characterized by soil moisture contents of 46–92% by volume. The more moderately decomposed peat (0.14–0.20 $g \cdot cm^{-3}$) at greater depth was characterized by porosity of 91–92% and soil moisture content of 60–88%. This more decomposed peat with smaller pores retained water and slowed the rate of groundwater flow ($K_{sat} = 10^{-6}$ to 10^{-7} $cm \cdot s^{-1}$).

As a result of the larger saturated water capacity of the near-surface soil layer and the lower conductivity of the layers at greater depth, rainfall input will enter the near-surface layer faster than it is infiltrating the deeper layers, resulting in a higher VMC than lower in the soil profile. The decrease in VMC with depth is indicative of a wet transition layer between the saturated zone and the ground surface. When soil moisture and water table elevation are high, this wet layer increases the efficiency of runoff production, i.e., increased ratio to precipitation (Emili and Price 2006).

In the mineral soil horizon, K_{sat} was several orders of magnitude greater (10^{-4} to 10^{-5} $cm \cdot s^{-1}$). The exceptions to this trend occurred in the open peatland. The comparatively low K_{sat} in the mineral subsoil of the open peatland (10^{-6} to 10^{-7} $cm \cdot s^{-1}$) was a function of finer soil texture (silt to fine sand) as compared with subsoil (fine to medium sand) in the other forest communities. The spatial variation in groundwater flux (Fig. 9) was consistent with the variation in K_{sat}.

Groundwater flow patterns

The variation in vertical hydraulic gradient among and between forest community types reflected the temporal and spatial diversity in groundwater input. With the exception of the open peatland, horizontal hydraulic gradients were greater than vertical gradients indicating that flow paths were consistently downslope. In the open peatland, lower horizontal hydraulic gradients increased groundwater residence time and, hence, the interaction between organic and mineral soil horizons. In the other forest communities, the hydrological interaction between the organic horizon and mineral subsoil was limited to localized areas of groundwater discharge.

In general, low slope indices were associated with groundwater recharge in topographically higher areas and high slope indices were related to groundwater discharge in topographically lower areas. Although this is true for the slope length scale, the superimposition of smaller scale flow (Fig. 9) illustrated a more complex interaction between surface water and groundwater. At this scale, discharge occurred where net saturated flow (groundwater) was directed upwards towards the water table. Recharge then occurred where groundwater flow was directed away from the water table.

The recharge or discharge function of the soil profile in peatland systems can affect vegetation community type (Glaser et al. 1981) and groundwater chemistry (Devito 1994). Changes in flow direction and, particularly, discharge from the organic soil horizon at Diana Lake were important for the transport and flushing of carbon from this horizon during storm events (Fig. 9; Emili 2003). Discharge from the mineral subsoil in discharge zones at the base of local slopes in the upland and swamp forests (Fig. 9) was responsible for the upward distribution of inorganic ions (Emili 2003). The discharge of ion-rich groundwater can potentially buffer acidification in discharge areas and increase nutrient availability and may produce and maintain unique site conditions (Klijn and Witte 1999).

Management implications

The examination of forest community type in the context of hydrogeological setting allows for the development of generalizations of forest–peatland complex functioning that can be transferred from the studied sites to other forest–peatland systems. Understanding how topographic gradients create spatially diverse site conditions and the correlation to a simply derived slope index is an important first step in predicting and mapping site productivity across landscapes. This information will aid forest managers in predicting how forest communities will respond to various harvesting activities.

The slope index used in this study is simple in concept, easily defined, and provides a quantitative descriptor of slope. Simple linear regressions between slope index and shore pine site index values for the CWHvh2 region demonstrate the potential of using slope index to predict site index. The results suggest that productivity is related to slope index, decreasing as the slope index increases, i.e., with increasing soil moisture and water table elevation associated with topographic lows. Further study is needed to test this relationship; this would entail the collection of data on plot characteristics (e.g., tree height, age, and canopy cover) and distribution characteristics (e.g., diameter at breast height) along the transects at Diana Lake and Smith Island. The quantitative slope index (cumulative downslope flow of water), soil moisture, and forest plot data generated from such study can be used to develop multivariate models to predict site index in CWH forests or may be used to calibrate existing models for use in CWH forests. An example of the latter is the integrated moisture index – site index multiple linear regression model developed by Iverson et al. (1997, 2004) for use in hardwood forests in the Midwest and eastern United States.

Conclusions

The analysis of topography, hydrophysical properties of the soil substrate, and groundwater flow for the forest–peatland complexes demonstrated a systematic linkage between forest productivity and local hydrogeologic gradients. Although the communities anchoring each end of the successional gradient at Diana Lake and Smith Island occupy distinct hydrogeologic settings, the transitional communities (swamp forest, bog forest, and bog woodland) are characterized by a range of hydrogeologic characteristics and hydrological variables (Table 1).

Forest community type was a function of the extent of organic matter accumulation and water table depth as constrained by topography. The accumulation of organic matter decreased infiltration and drainage resulting in higher soil moisture and water tables. These conditions alter successional dynamics and favour the invasion of hydrophytic species such as *Sphagnum* mosses. Localized topographic highs within the peatland communities have scrubby stands of shore pine and ericaceous shrubs. As slopes increase and the relative thickness of the organic soil horizon decreases along the forest–peatland complex, less productive western redcedar and yellow-cedar stands with blueberry, salal, and moss understories give way to larger western hemlock stands with fern and moss understories.

The potential of using a slope index derived from easily obtainable survey data as a surrogate for pedogenic variability and site-specific hydrology has been demonstrated. This index can be used to better manage forest resources where poor drainage and high soil moisture limit productivity.

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