

**HYDROCHEMICAL CHARACTERISTICS OF HYPERMARITIME
FOREST-PEATLAND COMPLEXES, NORTH COAST BRITISH COLUMBIA**

by

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ABSTRACT

The landscape of north coast British Columbia (BC), Canada is a mosaic of ecosystems comprising open peatland, forested peatland, lowland and upland forest systems. The proposed harvesting of the poorly drained lowland forests of the coastal western hemlock (CWH) forest region has created the need to better understand the hydrochemical processes contributing to forest community development. There is concern that harvesting will accelerate the advance of paludification into lowland forests, decreasing productivity and forest regeneration.

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. Organic soil that accumulates in areas of concave bedrock morphology favours the invasion of hydrophytic species such as *Sphagnum* mosses. In areas where bedrock topography is not conducive to peat accumulation, hard pan formation and paludification may account for the accumulation of peat. Low horizontal hydraulic gradients (0.01-0.06) impeded drainage and maintained near surface water table in the open peatland (11.6 \pm 2.4 cm). Localized topographic highs within the peatland communities have scrubby tree stands. As horizontal hydraulic gradient increased (0.07-0.16) in the bog woodland, bog forest and swamp forest communities, the mean depth to water table increased (18.0 \pm 4.7 cm, 34.4 \pm 15.3 cm, 30.8 \pm 9.3 cm; respectively) and less productive cedar stands with shrub and moss understories transition to larger western hemlock stands with fern and moss understories. The deepest water tables (101.2 \pm 63.9 cm) occurred in the upland forest where large horizontal hydraulic gradients (0.11-0.30) increased drainage and favoured greater productivity.

The $\ln(a/\tan\beta)$ (a =upslope contributing area, $\tan\beta$ =local slope angle) topographic index of TOPMODEL 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 index was used to characterize the spatial distribution of topographically controlled groundwater flow and site conditions (as represented by water table depth and organic horizon thickness) influencing forest community type. Areas with high slope indices (topographic lows) had thicker organic soil horizons (0.3-3.2 m), water tables closer to the surface (0-0.30 m) and higher soil moisture contents (46-92%). Areas with low slope index values (topographic highs) were associated with shallower organic horizons (<0.40 m), deeper water tables (0.3- >1.5 m) and drier soil moisture (35-76%).

Interception of rain (10-41%) by the forest canopy was a significant component of the hydrologic cycle. While measured fog drip alone accounted for only 0.4% of total rainfall, the frequent but unmeasured fog drip with drizzle may be a potentially important input to the forest-peatland complexes.

Quickflow (Q_d) dominated storm hydrographs in the study drainage areas accounting for 72-91 % of peak discharge. The dominant mechanism for runoff generation was saturated shallow subsurface and overland flow. The temporal response of runoff generation to rainfall was consistent between differing drainage areas along the forest-peatland complex. Runoff increased with increasing rainfall duration and intensity. The efficiency of storm runoff (0.02-0.05) production was lowest for drainage areas with thick organic horizons. The average topographic gradient was also lowest at this site, with many surface depressions capable of retaining surface water. Runoff efficiency increased comparatively for seeps (0.06-0.40) and was greatest in the upland forest (0.33-0.69) because of the permeable soils

and steep hydraulic gradient. On an annual basis, ephemeral surface flows with small drainage areas produced large runoff depths (225-2026 mm) in comparison to perennial surface flow (141 mm). The timing of ephemeral runoff was controlled by 'threshold' water table elevations.

The $\delta^2\text{H}$ - $\delta^{18}\text{O}$ regression of precipitation yielded a slope (7.97) and intercept (5.07) below the global slope (8.03) and intercept (9.59) for continental locations. Small departures from the local meteoric water line and the narrow scatter in $\delta^2\text{H}$ - $\delta^{18}\text{O}$ plots for ground and surface waters reflected a similar source of recharge. The homogeneous composition of groundwater shows a well-mixed lateral flux from the organic soil horizon. The correlation between slope index and $\delta^{18}\text{O}$ values in groundwater suggests that the spatial pattern in the $\delta^{18}\text{O}$ composition along the forest-peatland complex is influenced by topography and provides evidence that topographic indices may be used to predict groundwater residence time. The similar isotopic composition of seep water and streamflow ($\delta^{18}\text{O} = -10.28$ to -12.84‰) was consistent with hydrometric observations that seeps were a dominant pathway of water movement.

Inorganic ion and dissolved organic carbon (DOC) concentrations in groundwater varied significantly ($p < 0.05$) along the gradient open peatland to upland forest. The pH, base cation concentration (Ca^{2+} , Mg^{2+} , Na^+ and K^+) and HCO_3^- concentration increased along this gradient as a function of increasing slope and dissolution by drainage (weathering). As hydraulic gradients decreased, poor drainage and elevated water tables slowed decomposition and contributed to the accumulation of organic matter and an increase in acidity along the gradient upland forest to open peatland. The release of cations through mineralization competes with uptake due to cation exchange, thus limiting the availability of nutrients.

Changes in water table elevation impacted redox sensitive species (Al^{3+} , Mn^{2+} , Fe^{2+} , Zn^{2+} , NO_3^- , SO_4^{2-} , PO_4^{3-}), with greater concentrations during dry periods and on better-drained slopes. A high rate of DOC production in the organic soil, coupled with high water tables, resulted in a large lateral flux of DOC ($10\text{--}48 \text{ kg ha}^{-1} \text{ y}^{-1}$) from this soil zone to the stream.

These forests are dependent on organic matter decomposition and mineral weathering for nutrient supply. Decreases in forest nutrients may occur due to 'watering up' following harvesting and will thus compromise the ability of these systems to regenerate. An increase in water table elevation may also lead to a decrease in time to peak stream flow following storms and an increase in peak flow volume with associated increases in DOC export.

This thesis has provided insight into the hydrological and biogeochemical processes that control forest community type in forest-peatland complexes in the CWH forest zone. Based on field data, a conceptual model is proposed which relates community type to soil hydrophysical characteristics and ultimately to surface topography. This model is the first step in extrapolating data from the hillslope scale to the regional (landscape) scale where forest management policies are implemented. Additionally, the results of this thesis contribute to the improvement of hydrological and hydrochemical components of numerical models used to predict the potential impacts of forest disturbance. The collection, documentation and interpretation of hydrological and hydrochemical data for the study sites represents a significant contribution as a pre-harvesting database for future reference and comparison.

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1.1 Preamble

The forest landscape of north coast British Columbia, Canada has been described as a mosaic of ecosystems comprising open peatland, forested peatland, lowland and upland forest systems (Banner *et al.*, 1986). At the hillslope scale, these communities occur in complexes along forest to peatland gradients. While the communities anchoring these gradients fit into established hydrochemical paradigms for forest (Buttle *et al.*, 2000; McDonnell and Tanaka, 2001) and peatland (Price and Waddington, 2000) systems, respectively, the transitional communities present an opportunity to establish a new model to link these paradigms. There is a paucity of information on the hydrological and biogeochemical processes that have contributed to forest community development along successional gradients. This chapter presents a synthesis of the pre-harvest pedogenic (paludification), hydrological and biogeochemical processes driving forest community type in the north coast forest region of British Columbia (BC).

1.2 Forest Development and the Implications of Paludification

Within the Prince Rupert Forest Region of BC, old growth upland forests have been harvested since the 1960's (Prescott and Weetman, 1994). 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*) and yellow-cedar (*Chamaecyparis nootkatensis*). There is concern that harvesting these forests will

accelerate the advance of paludification (the lateral expansion of peatlands) into lowland forests, decreasing site productivity and forest stand regeneration.

Research in BC (Banner *et al.*, 1983) and southeast Alaska (Ugolini and Mann, 1979) has shown that productive (high merchantable annual wood volume) forests, through paludification may develop into peatlands. Reconstructions of regional vegetation patterns (Hebda 1983, 1997; Warner, 1984; Banner *et al.*, 1993) and paleoclimate (Mathewes and Heusser, 1981; Hebda, 1983; Warner, 1984) demonstrate the causal role climate has played in forest succession following deglaciation (13 000 yr BP). The development of wet, minerotrophic forests coincided with the increasingly cool, oceanic climate formed following the Insolation Maximum (8 500-7 000 yr BP) (Hebda, 1997). With the establishment of the modern oceanic climate (6 000- 5 000 yr BP), paludification rather than forest encroachment has been the dominant process operating in these forests (Dyke, 2002). There is evidence (Turunen, 1999) of recent paludification (5 290 cal yr BP, 3 960 cal yr BP) within the study area (Chapter 2). While lateral expansion of peatlands at the study site has been relatively slow (3.5 cmyr^{-1} ; Turunen, 1999), harvesting of trees may accelerate this rate (Paavilainen and Päivänen, 1995).

Paludification has largely been seen as a landscape phenomenon, whereby replacement of forest plant communities by bryophytes is attributed to pedogenic processes and the concomitant variation in hydrology and biogeochemistry. The process involves a continual modification and diversification of surface topography and vegetation composition (Foster *et al.*, 1983). In the north coast of BC, cool moist conditions contribute to a slowing of litter decomposition. Consequently, infiltration rates are reduced and surface moisture content increases providing optimal growth conditions for aggressive peatland pioneers such as

Sphagnum. *Sphagnum* has a detrimental effect on the existing vegetation. These species bring about acidification of the soil solution through cation uptake and hydrogen ion (H^+) release (Clymo and Hayward, 1982). The uptake of base cations strips the soil solution of plant nutrients, particularly calcium (Ca^{2+}) and magnesium (Mg^{2+}). The loss of trees results in decreased evapotranspiration (Bosch and Hewlett, 1982), further increases in surface layer moisture (Foster and Fritz, 1987), elevation of the water table (Dubé *et al.*, 1995) and onset of self-intensification (Davis, 1984). Elevated water tables eliminate hydrologically sensitive species, placing peatland species such as *Sphagnum* at a competitive advantage (Warner *et al.*, 1989).

Paludification induced changes in plant composition result in alteration of soil structure and subsequent changes in soil moisture content and saturated hydraulic conductivity, K_{sat} (Boelter, 1965; 1972). Fibrous surface peat has a higher saturated water content and less potential to retain water than more decomposed peat at depth (Clymo, 1983). The instantaneous infiltration rate at the surface decreases as the soil moisture content of this peat increases. In addition, as plant material decomposes, pore size decreases, restricting K_{sat} (Rycroft *et al.*, 1975). Under these poor drainage conditions, the opportunity for saturation excess overland flow (SOF) increases (Church and Woo, 1990). The infiltration capacity of some organic soils is low enough to produce infiltration-excess overland flow (IEF), with faster velocities and shorter concentration times, during high intensity rainstorms (Burt *et al.*, 1990). This latter type of flow can occur on lower gradients where the water table depth is relatively shallow and in upland areas with exposed bedrock.

Flow generating processes typically occur at or near the surface with the rate of drainage and thus runoff characteristics controlled by the position of the water table (Bay, 1969). In

forest peatland systems in Minnesota, USA (Bay, 1969) and Ontario, Canada (Branfireun and Roulet, 1998), the relationship between water table position and storm flow was found to vary according to the initial position of the water table. When the water table was near the surface (in a horizon of relatively high K_{sat}), small additions of water resulted in immediate runoff. When the water table dropped below this horizon, during dry periods, increases in storage and lower K_{sat} caused a delay or prevented runoff altogether. Branfireun and Roulet (1998) also determined that antecedent moisture conditions controlled the extent of the contributing area for runoff, such that during dry conditions, flow pathways were similar to baseflow conditions with additions to runoff from subsurface storm flow (SSF) and SOF. While under wet conditions, contributing areas were much larger, with the bulk of the storm flow derived from SOF. These results are consistent with the variable source area concept (Hewlett and Hibbert, 1967).

Figure 1.1 is a conceptual diagram of the biogeochemical fluxes of interest for this study. The model is based on this author's synthesis of the current knowledge of the relevant processes in the literature. Biogeochemical cycling in CWH forests is intimately tied to the accumulation and decomposition of soil organic matter. Soil organic matter (SOM) accounts for 75-90% of the total cation exchange capacity of A horizon soils (McColl, 1994). Thus, the amount of readily available nutrient cations derived from mineral weathering is largely dependent on the amount of SOM. Soil organic matter also contains mostly all of the nitrogen (N), phosphorus (P) and sulphur (S) mineralized through microbial oxidation (McColl and Gressel, 1995). As paludification advances, anoxia induced by higher water table elevation limits the rate of organic matter decomposition and thus nutrient cycling and productivity are stagnated. As SOM accumulates, the pool of potentially labile carbon increases. Decomposition of the

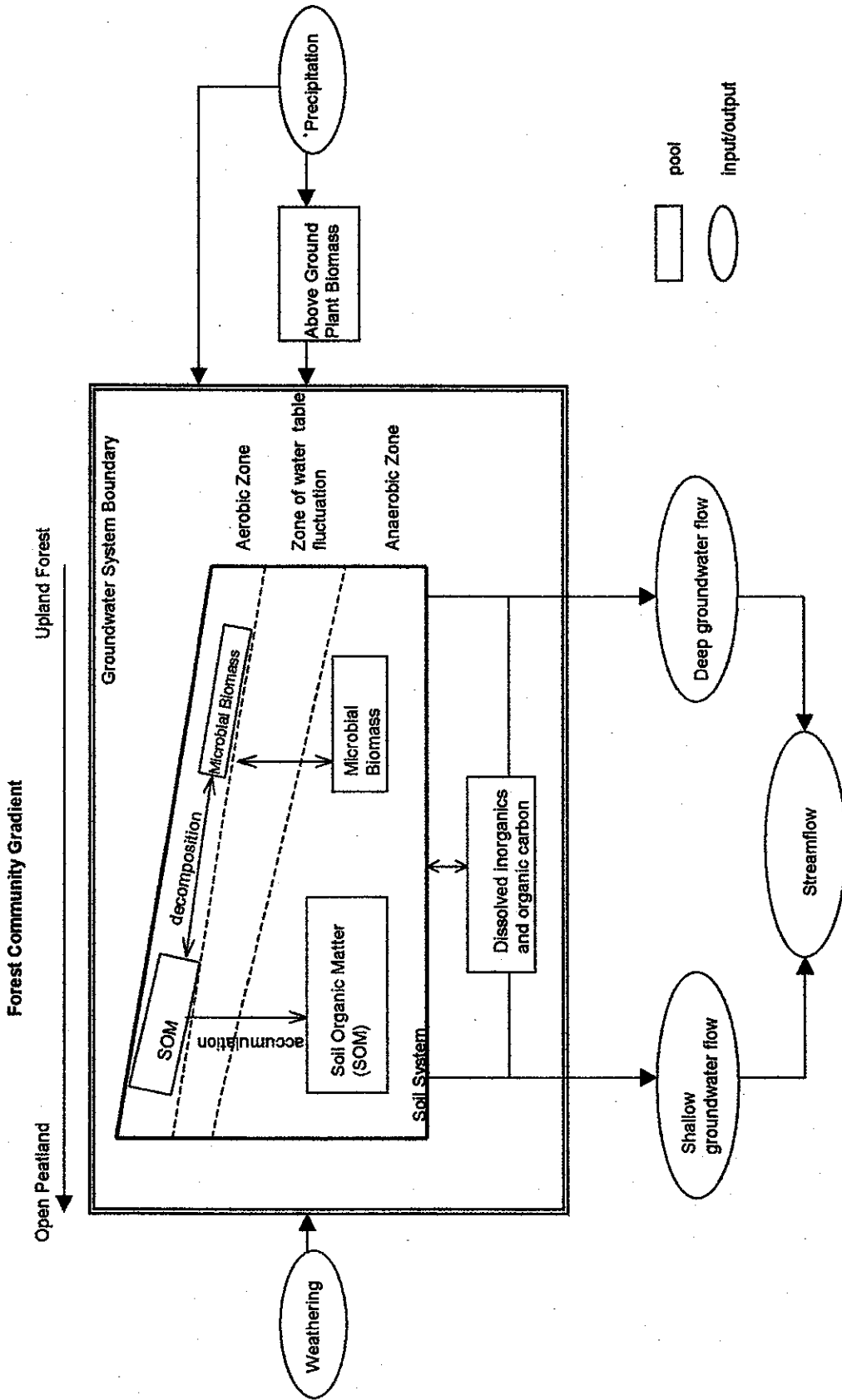


Figure 1.1: Schematic presentation of biogeochemical cycling in Coastal Western Hemlock forests of northern British Columbia.

organic carbon is largely confined to the surface soil horizons where there are higher temperatures and oxygen content (Clymo, 1984). Where hydrogen ions (H^+) and organic acid by-products of decomposition exceed the rate of neutralization by weathering, soil water pH decreases to levels detrimental to tree growth (Jalal and Read, 1983).

The role of peatlands as important sources and sinks in the global carbon cycle has been widely discussed (e.g. Gorham, 1991). In order to evaluate the efficiency of CWH systems as organic carbon reservoirs, in particular in regard to the fraction of organic matter delivered via lateral transport from forest-peatland complexes to streams, characterization and quantification of suspended organic carbon is important. This suspended load is partitioned into dissolved organic carbon (DOC) and particulate organic carbon (POC). Carbon stored in the dissolved fraction will remain in suspension and available for microbial breakdown to CO_2 under oxic conditions (Hansell *et al.*, 1997) and the production of CH_4 by anaerobic bacteria (Shotyk, 1989). The availability of POC as a potential source of CO_2 is dependent on particle settling velocities, biological oxidation and the flux of POC to DOC (Degens and Mopper, 1976).

Decomposition and leaching of soil organic matter provide a comparatively (cf. POC) large amount of reduced, reactive dissolved organic carbon (DOC) to the soil-groundwater system (Hedges *et al.*, 1997). Dissolved organic carbon mediates the transport of metals such as aluminum (Al^{3+}) and iron (Fe^{2+}) and is important in the translocation of oxides, humus and silicate clays in soils (Krug and Isaacson, 1984; Dawson *et al.*, 1981). Dissolved organic carbon exports are an important pathway for carbon loss in harvested systems (Moore, 1989) and impact stream water quality (Driscoll *et al.*, 1980; Effler *et al.*, 1985).

1.3 Hydrochemical Flow and Cycling in CWH Ecosystems

The author's conceptualization of the set of processes operating to maintain and characterize forest community type in CWH forests is represented in Figure 1.2. Meteorologic (rainfall, fog drip, throughfall), geologic (ground and surface water) and biologic (leachate) vectors of water and chemical flow are considered to be inputs and outputs to the ecosystem. The subsystems are defined as hydrological, biogeochemical and physico-chemical. The latter two subsystems not only provide the physical substrate through which water and chemicals flow, but are also the primary sources of chemicals. The hydrological subsystem controls the rate of flow and impacts biogeochemical processes such as redox potential and decomposition and physico-chemical processes such as weathering.

The organic compartment includes all nutrients incorporated in the living and dead biomass. The decomposition of litter and SOM constitutes a dynamic transition between the biotic component (living biomass) and the abiotic (soil). Nutrients are made available by the decomposition and leaching of litter and SOM. Primary and secondary minerals contain nutrients that comprise the inorganic soil and rock portion of the physico-chemical subsystem. Minerals are converted to available nutrients through weathering.

Cycling between these subsystems is mediated by environmental constraints imposed by state variables. The hydrochemical flow, and ultimately the evolution and productivity of forest community type, is controlled by the key state variables of topography and soil type. The entire ecosystem, including inputs and outputs, is constrained by climate.

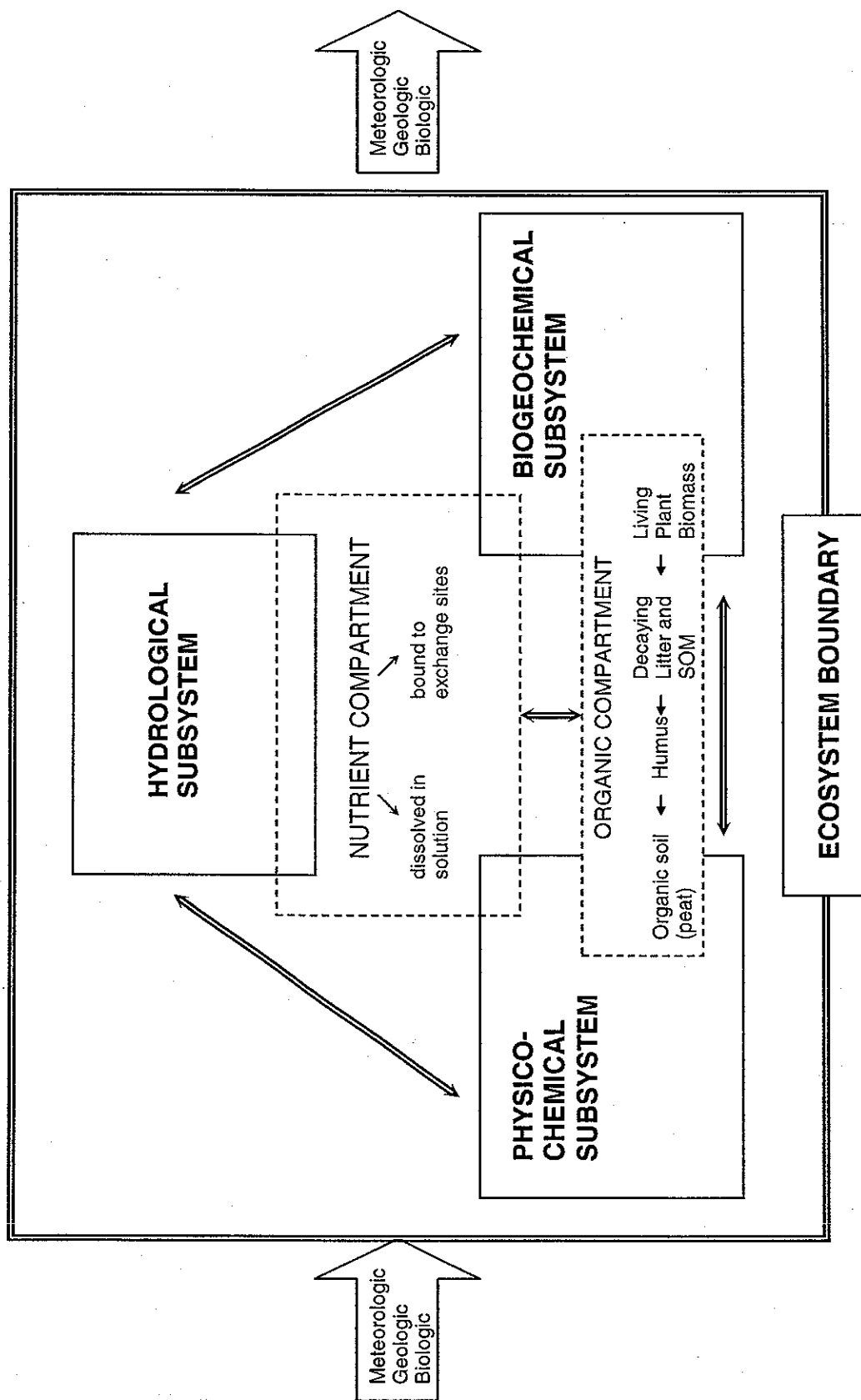


Figure 1.2: The inter-relationship of hydrological, biogeochemical and physico-chemical processes in Coastal Western Hemlock forests of northern British Columbia.

1.4 Forest-Peatland Complexes as Linked Landscapes

Hydrological, biogeochemical and physico-chemical processes combine in space and time in the forest-peatland complexes of the CWH forest region. The close spatial proximity of transitional and mature forest communities provide an opportunity to study several forest community types under similar climatological conditions, thus providing a way to relate site characteristics with their susceptibility to hydrochemical changes following harvesting.

Successional processes link forest communities in the north coast landscape. Each forest-peatland complex represents a contemporaneous view of historical succession from upland forest to open peatland. It has been argued that paludification induced succession from forest to peatland is not secondary succession, but rather retrogressive (Iversen, 1964) or reverse succession (Lugo, 1990). Although the resultant open peatlands possess communities physiognomically similar to early primary succession, they are dissimilar with respect to biophysical and hydrochemical characteristics. Defining open peatlands, however, as climax communities is subject to debate. Clymo's (1984, 1991) decay model predicted that open peatlands eventually attain a steady state when the input of detritus at the surface is balanced by the loss of organic matter decomposition throughout the profile. In contrast, Winston (1994) found that the thickness of the active peat layer (acrotelm) was reduced when the maximum height of the peat body was reached as lateral expansion (paludification) continued after this maximum height was attained. The age/depth curve determined for the study site (Turnen, 1999) did not fit Clymo's model for a steady state peatland.

1.5 Research Context

As market pressure for wood products and international scrutiny of forest practices intensifies, the need for scientific studies that support operational decision-making has increased (BC Ministry of Forests, 2002). A review of Canadian forestry development identified hydrological factors as key indicators of sustainable forest management and called for increased research aimed at understanding hydrological processes in a greater range of forested landscapes (Canadian Council of Forest Ministers, 1997).

Currently, the Forest Practices Code of BC requires a watershed assessment procedure (WAP) to be completed for watersheds where harvesting is to occur (BC Ministry of Forests, 1999). The guidelines for completing the WAP are largely qualitative in nature, reflecting the significant gaps in knowledge of forest hydrologic processes and development effects (Alila and Beckers, 2001). This framework has been based on mass balance, paired-watershed studies (e.g. Carnation Creek Study, Penticton Creek Watershed Study) that have assessed the impact of forest harvesting on the timing and magnitude of streamflow, sediment movement and fish habitat. Comparatively few process-oriented studies have examined hydrologic controls on water flowpath, biogeochemistry and stream quality (eg. Hudson, 1995). These studies have been concentrated in the southern and interior portions of the province (BC Ministry of Forests, 2000a).

As forest harvesting extends into previously undeveloped north coast systems, locally relevant hydrological information is needed (BC Ministry of Forests, 2001). In response to the Chief Forester's request for research in these areas (Pederson, 1995), a multi-disciplinary collaborative study: Pattern, Process and Productivity in Hypermaritime forests of coastal British Columbia (HyP³) was initiated in 1997. This project is organized into five study

components, each involving a specific aspect of the functioning, management and inventory of the CWH forests of north coast BC (Table 1.1). This thesis contributes to the Hydrology, Geochemistry and Peat Development component of HyP³.

This thesis provides insight into hydrologic and hydrochemical processes that control forest community type in CWH forests as they relate to soil physical origin and topography. Water table elevation, hydraulic gradient and water retention capacity of the substrate largely control the magnitude, rate and type of flow path and soil anoxia and thus patterns of chemical transport and transformation within these ecosystems. To scale these findings from the hillslope to the regional scale where forest management policies are implemented, a conceptual model of the complex interaction of abiotic and biotic factors influencing the hydrological dynamics in these forests is essential.

1.6 Research Objectives

The overall goal of this thesis was to characterize hydrological and biogeochemical fluxes within and between forest communities along forest-peatland complexes in the CWH region in order to determine the relationship of these fluxes to forest community type. To achieve this research goal, three working hypotheses were established:

Hypothesis 1: Forest communities occupy distinct hydrogeologic settings with characteristic hydrophysical and hydrologic properties. The spatial variation in these properties is a function of topographic heterogeneity.

PATTERN, PROCESS AND PRODUCTIVITY IN HYPERMARITIME FORESTS OF COASTAL BRITISH COLUMBIA (HyP³)

Regeneration, growth and productivity

- Develop baseline information on the mechanisms and patterns of regeneration
- Assess regeneration success on high and low productivity sites
- Estimate growth and productivity across the spectrum of forest community types

Hydrology, geochemistry and peat development

- Document watershed and soil hydrology of the forest-peatland complexes
- Predict how forest harvesting can affect soil and watershed hydrology, forest succession and regeneration
- Document past and present ecological succession in relation to peat development and how this is linked to site hydrology and geochemistry

Soil Ecology

- Document the relationship among soil chemical, biological and physical characteristics and forest community type
- Examine soil respiration, litter decomposition and organic matter dynamics in relation to forest productivity and bedrock type
- Examine the potential for manipulating soil characteristics through logging and site treatments and improving second growth tree productivity

Operational Research Trials

- Develop a strategy for testing a variety of harvesting and silvicultural approaches in target forest types
- Assessment of mounding trials
- Establish additional operational trials

Classification and Inventory

- Describe the range of ecological site characteristics associated with target forest types and their operational significance
- Examine the potential of using Terrestrial Ecosystem Mapping and Predictive Ecosystem Mapping to identify stands with the highest potential for timber management
- Identify rare/sensitive components of biodiversity that could be at risk under forest management
- Examine the wood quality and end product recovery of timber harvested from poor and low site cedar hemlock stands

Table 1.1: HyP³ study components and respective research objectives (Banner and Shaw, 1999).

Hypothesis 2: Saturated shallow subsurface flow and overland flow are parts of a continuum of hydrologic response that are controlled by soil hydraulic properties and rainfall patterns. The spatial variability in the relative magnitude of response and runoff efficiency can be predicted based on topography, e.g., topographic lows prone to saturation with groundwater reservoirs within close proximity of the soil surface would rapidly generate runoff.

Hypothesis 3: Forest community biogeochemistry is linked to its hydrologic regime by the interaction between soil aeration and drainage and the availability of major ions and dissolved organic carbon (DOC) within the soil-groundwater system.

1.7 Thesis Organization

The overall research objective is addressed in chapters 3-5; however, each of these chapters focuses on a separate aspect of the conceptual framework shown in Figure 1.2. Chapter 3 examines the influence of topography on soil hydrophysical properties, pedogenesis and resultant forest community type. Chapter 4 quantifies meteoric inputs, characterizes runoff-generating mechanisms and determines the relative contribution of hydrologic inputs to groundwater recharge and streamflow. Chapter 5 discusses the dependency of the system on organic matter decomposition and mineral weathering for nutrient supply. Chapter 6 addresses the implications of this research for forest harvesting and numerical modelling. The final chapter integrates the processes discussed in chapters 3-5 and presents a conceptual model of the system.

2.1 Location of Study Sites

The main study site is located within the Diana Lake Provincial Park (54° 09' 45" N, 130° 15' 15" W) approximately 25 km inland of the Pacific Ocean and 20 km southeast of the town of Prince Rupert, BC (Figure 2.1). The secondary study site is located within a small watershed (0.33 km²) on Smith Island, approximately 6 km southwest of the main study site (Figure 2.1).

2.2 Climate

Climate in this maritime area is characterized by cool, hyperoceanic conditions. Long-term climate data (Table 2.1) for Prince Rupert show relatively little snow (<6% of annual precipitation) and frequent periods of fog from July to September, averaging 7 days per month (Environment Canada, 2002). Temperature averages 6.9 °C annually, with the coldest month (January) averaging 0.8 °C and the warmest month (August) averaging 13.3 °C. Mean annual rainfall at Prince Rupert is 2552 mm, with summer being the driest season and autumn the wettest, 35% of precipitation falling between September and December.

2.3 Physiography

The study area is in the Western System physiographic region. This region includes the mountains of Vancouver Island, the Queen Charlotte Islands and the west-most reaches of the Coast Mountains subsystem and adjacent islands. The Insular and Coast ranges are separated by the Coastal Trough. The Insular Mountain ranges are largely made up of granites and various metamorphosed sedimentary and volcanic rocks and the Coast

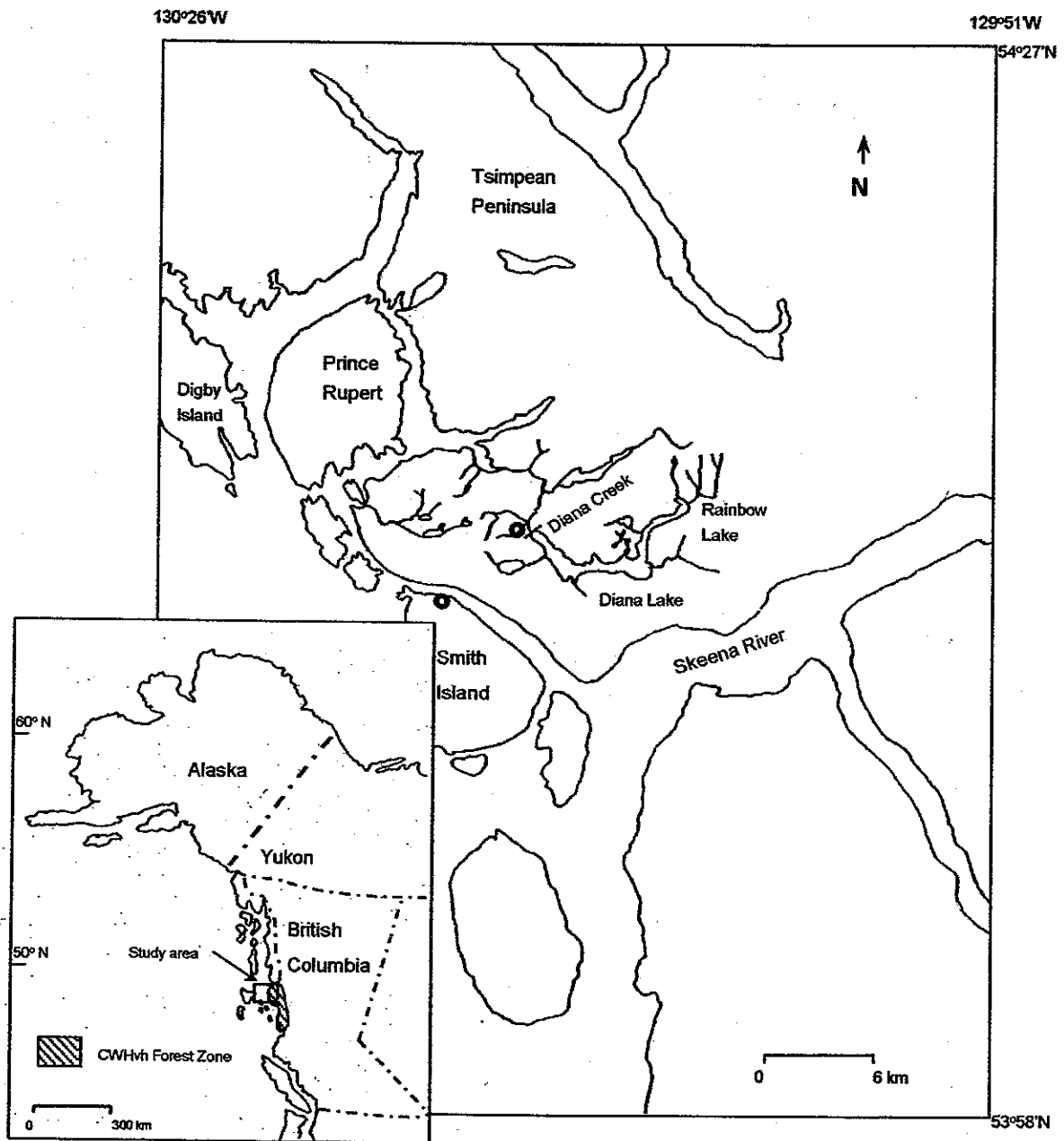


Figure 2.1: Location of the Diana Lake and Smith Island study sites.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Yr
Temperature													
Daily max (°C)	4.1	5.9	7.2	9.4	12.0	14.1	15.9	16.5	15.0	11.3	7.0	4.8	10.3
Daily min (°C)	-2.5	-1.0	0	1.6	4.6	7.6	9.8	10.0	7.7	4.7	0.6	-1.5	3.5
Daily mean (°C)	0.8	2.5	3.7	5.5	8.4	10.9	12.9	13.3	11.3	8.0	3.8	1.7	6.9
Rainfall (mm)	205.6	189.1	168.3	174.3	142.0	119.5	112.9	162.8	244.7	378.6	272.2	239.2	2409.1
Snowfall (mm)	46.9	28.4	19.1	6.4	0	0	0	0	0	0.4	10.9	30.4	142.6
Precipitation (mm)	250.8	216.5	188.2	181.0	142.0	119.5	112.9	162.8	244.7	378.9	284.4	269.8	2551.6
Number of days with fog	2	1	1	0	1	3	5	8	7	2	1	2	34

Table 2.1: Long-term climate normal (1961-1990) data for Prince Rupert (54° 18' N, 130° 26' W, 34 masl). Abstracted from Environment Canada (2002).

Mountains are composed of middle Jurassic igneous intrusive quartz diorite and granodiorite bedrock (Holland, 1976). The Coastal Trough, a depression of rocky coastal islands and submerged areas extending from southeastern Alaska to northern Washington, includes the Hecate Depression west of Prince Rupert. The non-submerged section, known as the Hecate Lowland, extends to the east past Prince Rupert. Bedrock geology is Paleozoic metamorphic rock, primarily schist and gneiss (Holland, 1976). The Diana Lake study site is underlain by metamorphic amphibolite schist and gneiss. The Smith Island study site geology is predominantly gneiss with other weakly metamorphosed coarser grained rocks, poor granite and granodiorite.

2.4 Quaternary History

The north coast of BC was covered by the Cordilleran ice sheet during the Fraser glaciation (30 000-10 500 yr BP) (Clague, 1989). Several confluent ice tongues extending into the Hecate Strait west of the main ice sheet covered the Prince Rupert area (Clague, 1989). Along the north coast, eustatic sea levels dropped 140-200 m. Downwasting, frontal retreat and eustatically rising sea levels were the mechanisms for deglaciation which began $12\ 700 \pm 120$ yr BP in the Prince Rupert area (Clague, 1985; 1989).

Deglaciation was not uniform throughout the north coast. Evidence of the extent of marine inundation in the Prince Rupert area is contradictory. While Heusser (1960) suggests that marine limits were between 40 and 135 m, Clague *et al.* (1982) estimate a much lower limit at 13 m. With the elevation of the Diana Lake study site between 145 and 200 m, it is not likely that the area was inundated. Isostatic rebound, the consequent emergence of the

Prince Rupert area and stabilization of sea levels near present levels occurred between 8 700-8 000 yr BP (Clague, 1985).

Colluvial processes have resulted in rockfalls and granular disintegration in upland areas along the coast. These scree slopes are characterized by an accumulation of coarse rock debris and crudely stratified material.

2.5 Vegetation

The BC Ministry of Forests uses a biogeoclimatic scheme for forest identification (Banner *et al.*, 1993). This system provides common terminology for researchers and resource managers. Zone identification is based on the dominant tree species, while subzone reflects climate. The CWH zone is located on the mainland and coastal islands between the Hecate Lowland and the Coast Mountains with an elevational range of 0-1 000 m above sea level. The study site is located within the Coastal Western Hemlock (CWH) very wet (v) hypermaritime (h) subzone (Figure 2.1). Within this subzone, there are site series (forest communities). Site series reflect variations in soil and physiographic properties and soil and nutrient regimes and are characterized by similar climax plant communities. The nomenclature of the BC Ministry of Forests system was modified for this study according to Table 2.2.

The forest community types in the study area comprise swamp forest, bog forest, bog woodland, open peatland, basin swamp and upland forest (Figures 2.2-2.5). The tree canopy in the swamp 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

Site Series (Banner <i>et al.</i> , 1993)		Forest Community Type (This thesis)	
Site Series	Numerical Designation	Forest Community Type	Numerical Designation
Zonal Forest-Salal	01	Swamp Forest	01
Bog Forest-Goldthread	11	Bog Forest	11
Bog Woodland-Sphagnum	12	Bog Woodland	12
Non-forested slope/blanket bog	32	Open Peatland	32
Swamp Forest-Skunk Cabbage	13	Basin Swamp	13
Productive Forest-Lanky Moss	04	Upland Forest	04

Table 2.2: Modification of the BC Ministry of Forests forest community type nomenclature as used in this thesis.

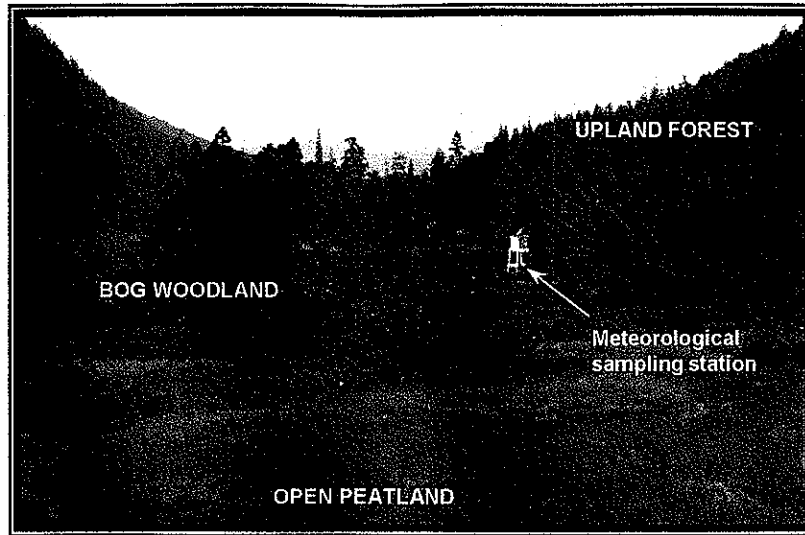


Photo by J.S. Price

Figure 2.2: Open peatland, bog woodland and upland forest communities at Diana Lake.



Photo by L.A. Emili

Figure 2.3: Basin swamp and bog forest communities at Diana Lake.



Photo by J.S. Price

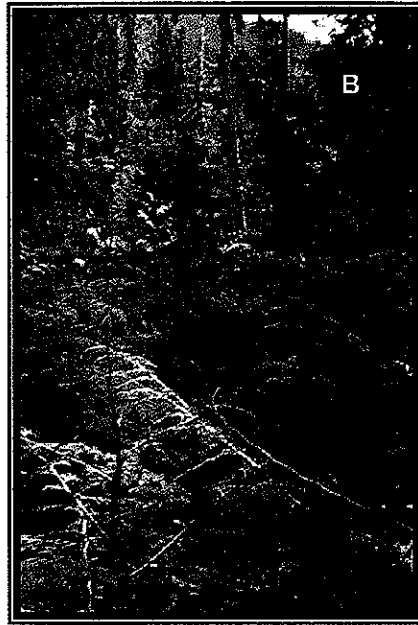


Photo by J.S. Price

Figure 2.4: Bog forest (A) and swamp forest (B) communities at Diana Lake.



Photo by L.A. Emili

Figure 2.5: Upland forest community at Diana Lake.

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*) and western redcedar (*Thuja plicata*); shore pine (*Pinus contorta* var. *contorta*) and yellow-cedar (*Chamaecyparis nootkatensis*) are abundant on organic soils. The understory 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. A more detailed listing of dominant species in each forest community is provided in Table 2.3.

Forest Community Type	Trees	Shrubs	Herbs	Mosses
Swamp Forest	<i>Tsuga heterophylla</i> <i>Thuja plicata</i> <i>Chamaecyparis nootkatensis</i> <i>Picea sitchensis</i> <i>Tsuga mertensiana</i>	<i>Vaccinium alaskanse</i> <i>Vaccinium ovalifolium</i> <i>Menziesia ferruginea</i> <i>Gaultheria shallon</i>	<i>Cornus Canadensis</i> <i>Rubus pedatus</i> <i>Blechnum spicant</i> <i>Linnaea borealis</i> <i>Listera cordata</i>	<i>Rhytidiadelphus loreus</i> <i>Hylocomium splendens</i> <i>Sphagnum rubiginosum</i> <i>Sphagnum pacificum</i>
Bog Forest	<i>Pinus contorta</i> var. <i>contorta</i> <i>Chamaecyparis nootkatensis</i> <i>Thuja plicata</i> <i>Tsuga heterophylla</i>	<i>Chamaecyparis nootkatensis</i> <i>Gaultheria shallon</i> <i>Ledum groenlandicum</i>	<i>Fauria crista-galli</i> <i>Cornus Canadensis</i>	<i>Sphagnum pacificum</i> <i>Sphagnum capillifolium</i> <i>Pleurozium schreberi</i> <i>Hylocomium splendens</i> <i>Rhytidiadelphus loreus</i>
Bog Woodland	<i>Pinus contorta</i> var. <i>contorta</i> <i>Thuja plicata</i> <i>Chamaecyparis nootkatensis</i>	<i>Chamaecyparis nootkatensis</i> <i>Pinus contorta</i> var. <i>contorta</i>	<i>Fauria crista-galli</i> <i>Sanguisorba officinalis</i> ssp. <i>microcephala</i> <i>Drosera rotundifolia</i>	<i>Shagnum fuscum</i> <i>Sphagnum rubellum</i> <i>Cladina portentosa</i> sp. <i>pacifica</i>
Open Peatland		<i>Juniperus communis</i> <i>Ledum groenlandicum</i>	<i>Drosera rotundifolia</i> <i>Kalmia microphylla</i> ssp. <i>occidentalis</i> <i>Menyanthes trifoliata</i> <i>Rhynchospora alba</i>	<i>Sphagnum austinii</i> <i>Sphagnum tenellum</i> <i>Rhacomitrium lanuginosum</i> <i>Cladina portentosa</i> sp. <i>Pacifica</i>
Basin Swamp	<i>Thuja plicata</i> <i>Chamaecyparis nootkatensis</i> <i>Tsuga heterophylla</i> <i>Picea sitchensis</i>	<i>Tsuga heterophylla</i> <i>Vaccinium parvifolium</i>	<i>Lysichiton americanum</i>	<i>Rhizomnium glabrescens</i> <i>Pleurozium schreberi</i>
Upland Forest	<i>Abies amabilis</i> <i>Tsuga heterophylla</i> <i>Picea sitchensis</i> <i>Thuja plicata</i>	<i>Menziesia ferruginea</i> <i>Vaccinium parvifolium</i> <i>Oplopanax horridus</i>	<i>Blechnum spicant</i> <i>Gymnocarpium dryopteris</i> <i>Polystichum munitum</i> <i>Tarella trifoliata</i>	<i>Rhytidiadelphus loreus</i> <i>Hylocomium splendens</i>

Table 2.3: Dominant species in each forest community type at the Diana Lake and Smith Island study sites.

CHAPTER 3

Hydrogeological Influences on Forest Community Type along the Forest-Peatland Complexes at Diana Lake and Smith Island

3.1 Introduction

The prospect of harvesting in low to middle elevation forests of the cedar-cypress-western hemlock (CWH) forest region, north coast British Columbia (BC Ministry of Forests, 2000b) has created the need for the prediction of hydrological responses to such activities (Pearse, 2001). These predictions rely on a coherent understanding of the hydrogeologic setting and its control of hydrologic phenomena. In hillslope environments, the primary hydrogeologic influence on the occurrence and movement of groundwater is topography. Definition of the relationships between topographic characteristics and patterns of groundwater flow are 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).

Surface topography and vegetation composition in CWH forests have been altered by paludification (Banner *et al.*, 1986). Previously moderately drained surficial systems have slowly been replaced by poorly drained conditions conducive to the invasion of hydrophytic species such as *Sphagnum* mosses. Prescott and Weetman (1994) hypothesize that the distribution of the forest-peatland communities in the CWH region is determined by topography, specifically the slope. Depressional and flat bogs are widespread over gently sloping portions of the lowlands. Slope bogs and forested bog systems commonly occur on gentle to steep (10-60%) slopes (Banner *et al.*, 1988).

In coastal forest systems where storm runoff response is dominated by surface and near 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). 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). The most commonly used index (Beven and Kirkby, 1979) is a ratio of the local hydraulic gradient (approximated by surface topography) to the upslope area contributing lateral flow to a point in a watershed. An increase in index value with decreased slope angle indicates a greater probability for soil saturation at that point (Buttle *et al.*, 2001). The spatial variability of topographic indices has been related to temporal and spatial patterns of solute chemistry (Robson *et al.*, 1992; Creed *et al.*, 1996). Areas of greater index value have a high potential for surface saturation and thus may export relatively large concentrations of solutes to streams (Creed *et al.*, 1996).

In peatland forests, runoff is controlled more by water table variability than by the extension of saturated areas (Branfireun and Roulet, 1998). Water table variability is also an important site factor influencing plant occurrence and distribution, i.e., hydrophytic species are associated with high groundwater levels (De Becker *et al.*, 1999). Additionally, topographic variation in groundwater flow influences the distribution of plant nutrients (Klijn and Witte, 1999). The results of studies investigating topographic controls on the spatial distribution of groundwater level have been conflicting (Moore and Thompson, 1996; Seibert *et al.*, 1997; Buttle *et al.*, 2001). Moore and Thompson (1996) suggest that varying results may be due to the significant spatial variability in soil transmissivity that is inherently a function of soil hydrophysical properties. The interaction between groundwater depth and soil hydrophysical properties largely determines soil moisture conditions and the amount of oxygen in the rooting zone at a particular site (Klijn and Witte, 1999).

In peat, groundwater flux is largely dependent on hydraulic conductivity that varies with soil water content, matric 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, a function of porosity, pore size distribution and pore architecture (Ingram, 1983) which are, in turn, controlled by the degree of decomposition and compaction of the soil (Boelter, 1970).

The overall objective of this chapter was to characterize the relationship between hydrogeologic setting and forest community type along forest-peatland complexes at Diana Lake and Smith Island. This chapter evaluates how detailed mapping of surface and subsurface topography, coupled with point measurements of substrate hydrophysical properties (specific yield, bulk density, saturated hydraulic conductivity) and groundwater level, can be used to determine the direction and rate of groundwater flow and its effect on forest community type.

The specific objectives, therefore, were to:

- (i) provide a spatially continuous cross-sectional profile of stratigraphy and subsurface topography to define the hydrogeological structure
- (ii) define a slope index that can be related to spatial variation in organic matter accumulation, water table depth and forest community type
- (iii) characterize the hydrophysical properties of organic and mineral soil horizons within the existing hydrogeological structure and define their influence on groundwater flow paths and rates

3.2 Study Area

A general description of the Diana Lake and Smith Island study sites is provided in Chapter 2.

A detailed description follows based on the evaluation of ground penetrating radar (GPR) data.

3.3 Methods

3.3.1 Ground Penetrating Radar

GPR is an imaging technique that can provide a continuous cross-sectional profile of shallow (0.25-10 m) subsurface features. Using numerical modelling and signal processing of components of the return signal, it is possible to derive estimates for soil depth (Greaves *et al.*, 1996). GPR transects were established at the Diana Lake (Figure 3.1) and Smith Island (Figure 3.2) sites. The Diana Lake transect (500 m) rises 35 m from an elevation of 150 m to 185 m and passes through six forest communities. The GPR survey was divided into three lines that spanned the length of the transect. Line 1 ran from 0 m on the transect to 305 m (the northern boundary of the open peatland). Line 2 encompasses the basin swamp and line 3, the upland forest.

On Smith Island (Figure 3.2), the GPR was done along three transects 170 m, 80 m and 90 m in length, respectively. The first transect (35-45 masl) was laid out in a northwest-southeast direction through four forest community types. The second transect (35-47 masl), starting at the 70 m mark of transect 1, was run at a right angle to transect 1 extending northeast. The third transect (47-68 masl) was also run at a right angle to transect 1 extending southwest and starting at the 142 m mark of transect 1.

To conduct the GPR surveys, two antennae were moved along a survey line: one to transmit high frequency electromagnetic energy and the other to receive the energy that was reflected

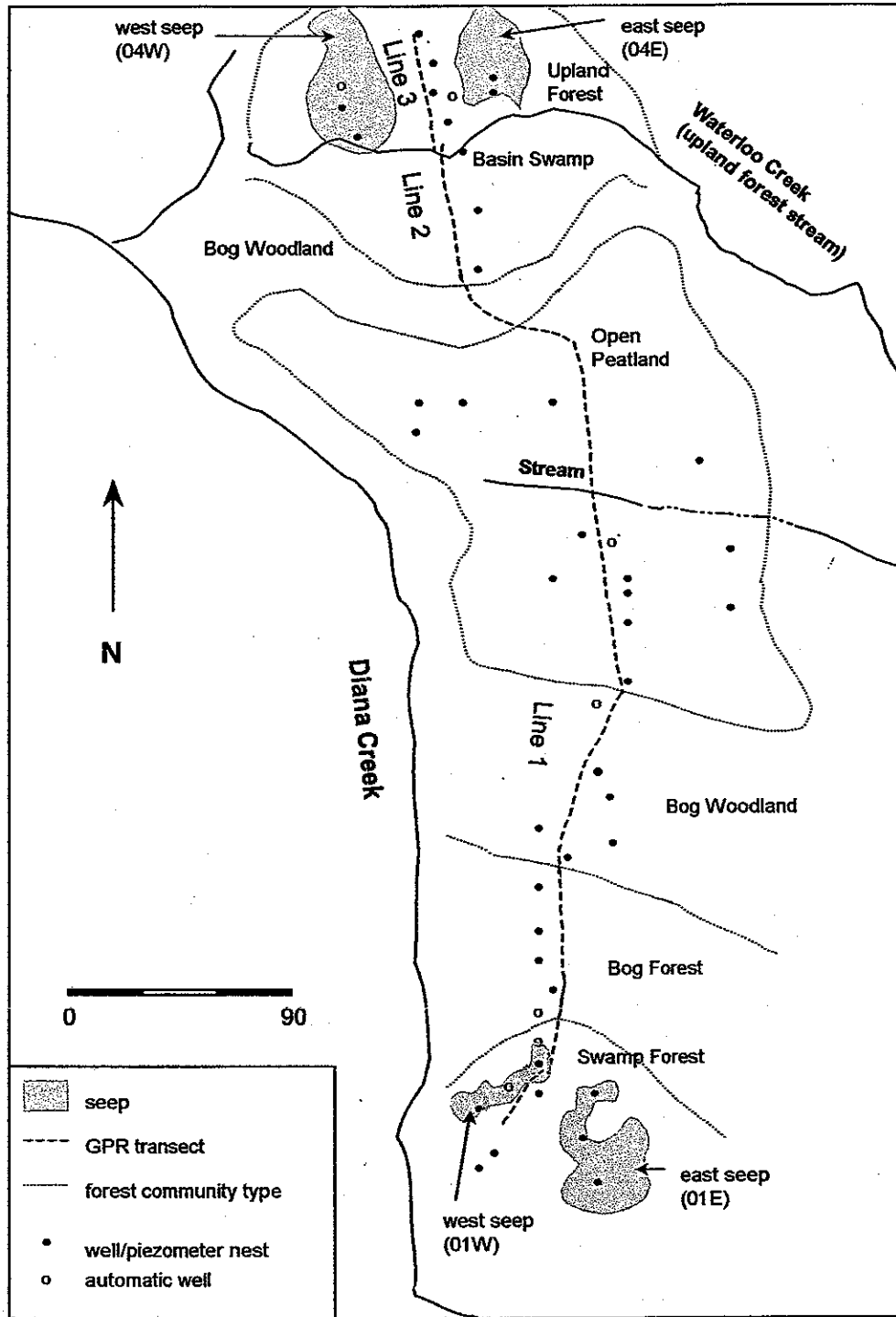


Figure 3.1: Network of wells and piezometers along GPR transects at Diana Lake.

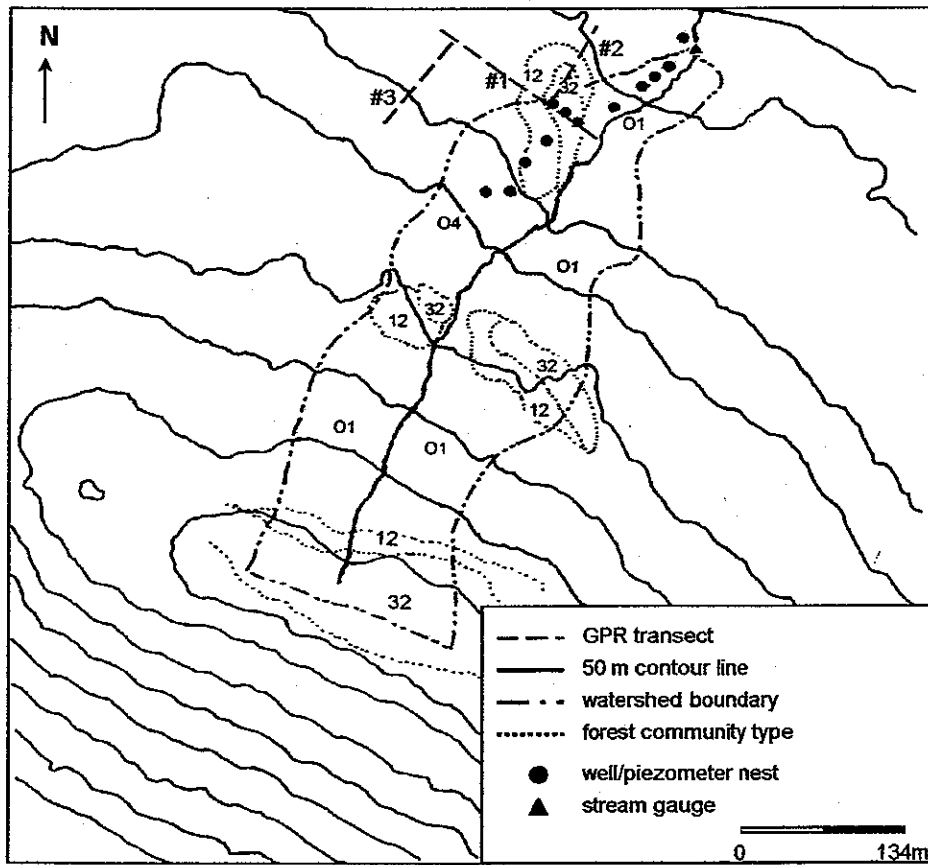


Figure 3.2: GPR transects relative to well and piezometer network on Smith Island (after Gibson *et al.*, 2000).