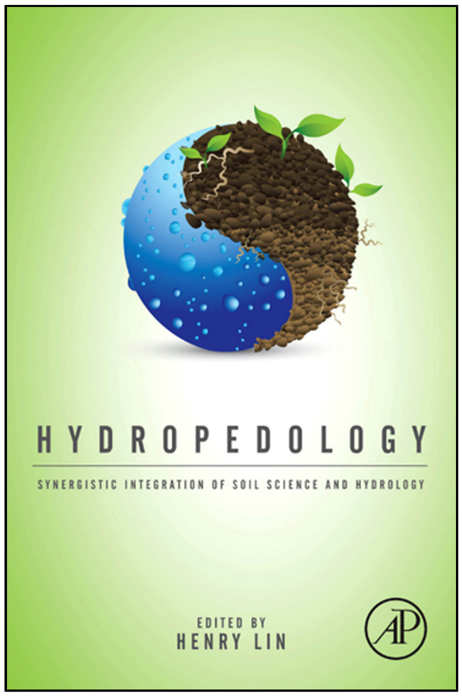

From D'Amore, D.V., Fellman, J.B., Edwards, R.T., Hood, E., Ping, C-L., 2012.
Hydropedology of the North American Coastal Temperate Rainforest. In: Lin, H. (Ed.),
Hydropedology: Synergistic Integration of Soil Science and Hydrology. Academic Press,
Elsevier B.V., pp. 351–380.
ISBN: 9780123869418

Academic Press

Chapter 11

Hydropedology of the North American Coastal Temperate Rainforest

David V. D'Amore,[1,*] Jason B. Fellman,[2] Richard T. Edwards,[1] Eran Hood[2] and Chien-Lu Ping[3]

ABSTRACT

The North American perhumid coastal temperate rainforest (NCTR), which extends along the coastal margin of British Columbia to southeast Alaska, is characterized by intense orographic precipitation caused by Pacific storm systems striking coastal mountains. This precipitation regime influences the development of soil and vegetation communities, which in turn influence the transfer of terrestrial carbon and nitrogen (primarily in dissolved forms) and other nutrients to aquatic ecosystems. These terrestrial subsidies of dissolved organic matter (DOM) are increasingly being recognized as an ecological function important to freshwater and marine ecosystems. The concentration and quality of DOM exported from the NCTR soils vary according to soil types (e.g. wetland vs. upland soils) that have formed along a topographic gradient from flat organic soils to steep mineral soils. Hydropedology provides a template to evaluate the functions associated with water movement through soils along this gradient. Five key issues of hydropedology – structure, function, scale, integration, and disturbance – were used as a framework to present the information gathered through multiyear research at the Juneau hydrologic observatory in the NCTR. We demonstrated how hydropedology can be used to elucidate mechanisms that influence DOM production and export in the NCTR. This information provides a foundation for modeling terrestrial DOM production and export under varying environmental conditions.

[1]Forest Service, U.S. Department of Agriculture, Pacific Northwest Research Station, Juneau, AK 99801, USA

[2]Environmental Science Program, University of Alaska Southeast, Juneau, AK 99801, USA

[3]School of Natural Resources and Agricultural Sciences, University of Alaska, Fairbanks, AK 99775, USA

[*]Corresponding author: Email: ddamore@fs.fed.us

Hydropedology, Edited by H. Lin. DOI: 10.1016/B978-0-12-386941-8.00011-3

Hydropedology, First Edition, 2012, 351–380

1. THE USE OF HYDROPEDOLOGY IN THE NORTH AMERICAN TEMPERATE BIOME

1.1. The North American Coastal Temperate Rainforest Biome

The North American coastal temperate rainforest (CTR) biome extends along the coastal margin of the Pacific Northwest of the U.S.A, British Columbia, and Alaska (Fig. 1). The perhumid northern portion of the CTR, the NCTR, is composed of the southeastern Alaskan panhandle and the north coast of British Columbia and represents the largest unpopulated and unmanaged portion of the CTR. The NCTR is characterized by abundant precipitation from North Pacific storm systems that confront coastal mountains leading to intense orographic precipitation that influences terrestrial and aquatic ecosystems. Diverse terrestrial habitats and large fluxes of material to the coastal margin through plentiful surface water channels are defining attributes of the region. The NCTR has great ecological value for its abundant wildlife and diverse ecosystems that provide habitat for many endemic species of plants and animals (Cook et al., 2006). There is also an emerging appreciation for the transfer of dissolved organic matter (DOM) from terrestrial to freshwater and marine ecosystems along coastal margins such as the NCTR (Muller-Karger et al., 2005).

1.2. Applying Hydropedologic Techniques to Understand Terrestrial and Aquatic Processes in the NCTR

The flow of water is the most fundamental component in the development and maintenance of ecosystem functions in the NCTR, yet the details of water storage, transport, and delivery remain poorly understood at several spatial scales. This is despite the fact that the flux of freshwater from terrestrial systems to the Gulf of Alaska is approximately twice the annual discharge of the Mississippi River (Neal et al., 2010). The NCTR is a challenging environment for developing a spatially distributed model of hydrologic and biogeochemical function due to the close association of diverse ecosystem types (Fig. 2). The NCTR contains over 3000 watersheds $\geq$121.4 ha that drain directly into saltwater and can be delineated from the USFS level 6 hydrologic unit code (HUC) watershed boundary layer. These watersheds have formed from a variety of different combinations of geology, weather, and vegetation, creating the need for adequate replicate systems for quantifying water and nutrient fluxes and testing resulting catchment nutrient flux models.

Establishing models of how terrestrial material influences downstream aquatic ecosystems is a priority for management of terrestrial and stream resources. Hydropedology is the multiscale investigation of the source, storage, flow path, residence time, availability, and spatio-temporal distribution of water in soils that occur in the Earth's Critical Zone (Lin, 2003). Hydropedology is

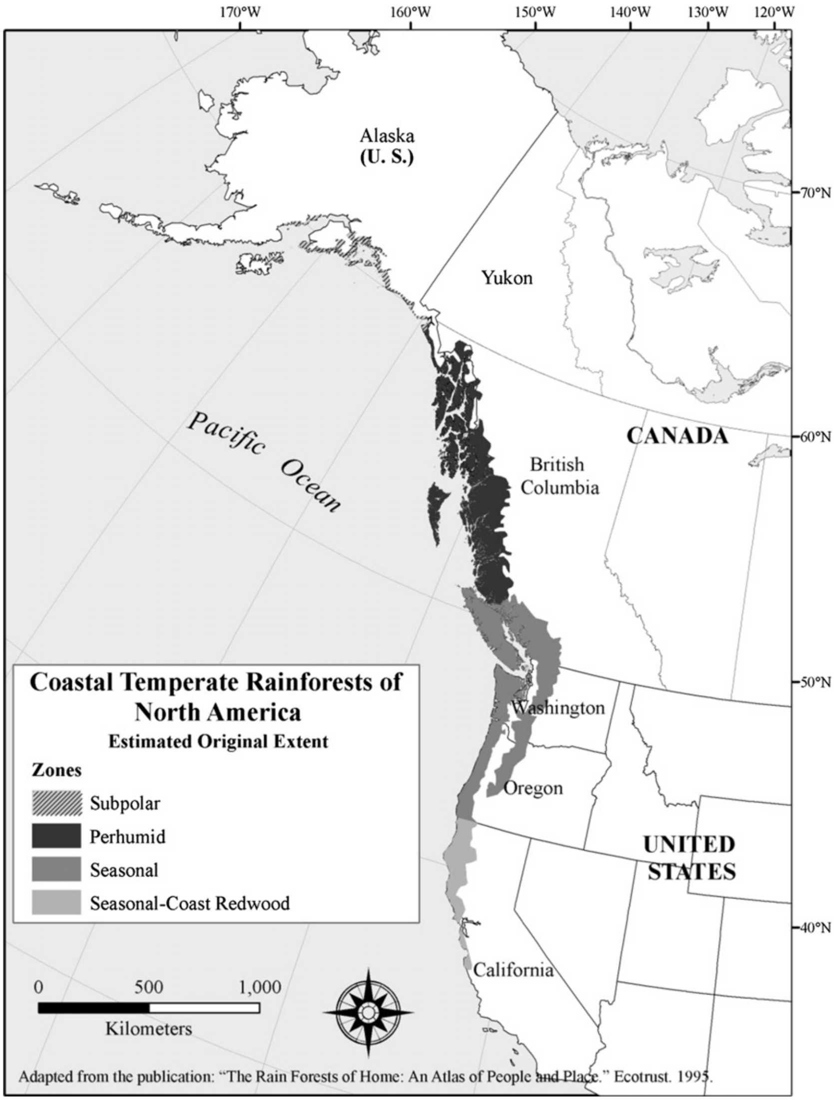

FIGURE 1 The extent and delineation of zones of the coastal temperate rainforest along the North American Pacific coast.

also the study of how the transport of materials and energy by water can be quantified and understood (Lin et al., 2006a,b). The application of hydropedology in the NCTR can increase our understanding of how the flow of material through terrestrial subsystems (i.e. different soil types) is related to biogeochemical fluxes at the watershed scale. Hydropedology can be used to

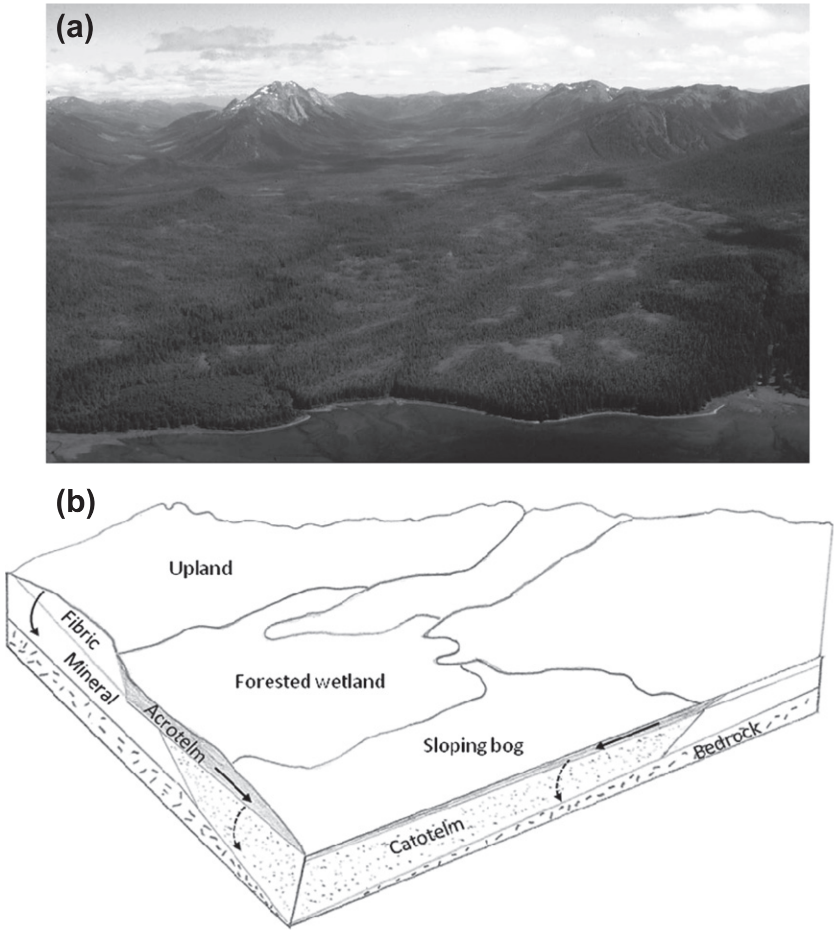

FIGURE 2 (a) The landscape mosaic of the NCTR contains many combinations of soil and vegetation woven together through the abundant flow of water. (b) Landscape relationships for three hydropedologic units are: Upland, forested wetland, and sloping bog. The drainage controls for each unit are illustrated and the dominant flow paths are indicated by arrows. Drainage controls: Upland = bedrock; Forested wetland and sloping bog = Lower organic horizon (catotelm).

create a conceptual framework to link soils with watershed biogeochemical function. There are two essential components of the hydropedologic approach that can be applied to the NCTR to address the challenge imposed by the diverse landscape. The first is landscape stratification using soil pedological mapping techniques. The second is the determination of hydrologic functions associated with these pedological units. With proper delineation, the variability in underlying biogeochemical processes can be minimized to capture the overall landscape response among units for development of robust watershed biogeochemical models. Testing models that describe terrestrial-aquatic biogeochemical linkages is very important given the increasing need to identify and predict the effects of changes in climate and land use on watershed nutrient cycles.

In this chapter, we present a framework for understanding terrestrial and aquatic interactions based on the hydropedologic research vision (Lin et al., 2006a). The framework is derived from data gathered at a soil hydrologic observatory in the NCTR that relies on the extensive soil ecosystem classification available through the Tongass National Forest (Tongass) soil resource inventory (USDA Forest Service, 1996). Our design for the hydrologic observatory uses mapped geomorphic and vegetative patterns present on the landscape as a first approximation of functional units. We define similar soil geomorphic and vegetative functional units as hydropedologic units, which are similar, but not necessarily the same as soil map units. Hydropedologic units are a key to adequately attributing the influence of terrestrial hydrologic and biogeochemical functions on watershed outputs from specific areas of the landscape. We use these hydropedologic units to test the relationship between the distinct functional responses in hydrodynamics and associated biogeochemical transport and transformation. We then examine whether these landscape units provide adequate resolution of cumulative biogeochemical and hydrologic changes to extrapolate and aggregate these functions throughout the entire watershed. Finally, we present some tools for refining landscape stratification using topographic models for soil moisture.

2. SETTING AND DETAILS OF THE NCTR HYDROLOGIC OBSERVATORY

2.1. Geology and Climate

The accretion of terranes through the subduction of the Pacific plate under the North American continent combined with geologic faulting, deposition, and intrusion has formed a diverse assemblage of physiographic divisions along the extended island archipelago of the NCTR (Gehrels and Berg, 1994). Climate shifts and glaciation through several glacial epochs (Mann and Hamilton, 1995) left a pattern of mountain summits, fjordlands, wide glacial valleys, widespread deposits of glacial drift, and varying stream dissection along hillslopes. These postglacial physiographic landscape features established the structural foundation for development of stream and vegetation patterns. The slope and parent material imposed by the geologic and geomorphic history in a watershed influence the trajectory of soil hydrologic patterns and the associated development of soils and plant communities.

The rainforest climate of the NCTR is cool and wet across a wide range of latitude. Rainforests have at least 1400 mm of annual precipitation and cool annual temperatures (<5 °C) (Alaback, 1996). The CTR contains four rain-forest subzones: warm temperate, seasonal, perhumid, and subpolar (Alaback, 1991; Fig. 1). The warm temperate and seasonal subzones have fire as a source of stand replacement while fire is very infrequent in the perhumid and subpolar zones. Annual precipitation increases and potential evapotranspiration decreases from the south to north along the coast. As a result, the interaction between moisture and temperature shifts from limiting growth in the south to limiting decomposition in the north. Lower decomposition has resulted in enhanced organic matter accumulation at these northern latitudes (Alaback and McClellan, 1992).

2.2. Soils and Vegetation

Landform and climate are the principal components that determine soil geomorphic associations and plant distribution in the NCTR. Groundbreaking studies of landscape evolution and vegetation community development were undertaken in postglacial landscapes of the NCTR (Chandler, 1942; Crocker and Major, 1955; Ugolini, 1968; Chapin et al., 1994). These early models of ecosystem development used the glacial chronosequence as a template for studying the dynamics of vegetation feedbacks to soils and the initiation of peatland as a climax state due to the development of impermeable spodic horizons in the absence of disturbance (Ugolini and Mann, 1979). Implicit in these models is the accumulation of water leading to waterlogging of soils and subsequent development of deep organic accumulations. However, these models did not address seasonal cycles of water flow and accumulation in the soils and consequent changes in soils and vegetation that impacted the entire watershed.

Young, recently deglaciated areas developed soil after initial plant colonization and the accumulation of large amounts of organic matter. Organic acid leaching can develop incipient spodic horizons in soils after 200 years, but mature Spodosols take 500–1000 years to form well-developed spodic horizons (Chandler, 1942). The Spodosols are common on moderately- to well-drained soils and dominate upland landforms (Fig. 2). Histosols are common in areas of low slope that form the NCTR's abundant wetlands. The original glacial chronosequence studies established idealized principles for landscape evolution, but there is much parent material variability across the extended island archipelago. Soils of the region formed in the postglacial Holocene deposits composed of glacial drift, colluvium, alluvium, and bedrock. In addition, soils were periodically disturbed by windthrow, which provides a new mix of parent material for subsequent soil formation (Bormann et al., 1995). Often modal concepts of the mapped soil series are not expressed throughout the mapping unit and a broad range of characteristics exists. Therefore, rather than relying on ideal expressions of soil type, we rely on general soil geomorphic relationships at higher orders in taxonomic groups to identify soil types across broad landscapes.

Forbs and alders initially colonized postglacial soils and were followed by conifers during the first half of the Holocene. Organic accumulations enabled the spread of Sitka spruce (*Picea sitchensis* (Bong.) Carr) and western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) across the landscape from various glacial refugia (Carrara et al., 2007). A climate shift to colder, wetter conditions approximately 4000 years ago promoted the development of extensive peatlands and the increase in redcedar (*Thuja plicata* (Donn ex D.Don)) and yellow-cedar (*Callitropsis nootkatensis* (d. Spach)) (Heusser, 1960). The current distribution of vegetation communities among different soil types is a response to varying seasonal soil saturation that led to well-drained or waterlogged soils (Neiland, 1971).

Plant distribution patterns and ecology were strong influences in establishing landscape classification guides in the NCTR (Viereck et al., 1992; Meidinger and MacKinnon, 1989). The latest landscape stratification established subsection boundaries for the entire NCTR and neighboring parts of Canada using the National Hierarchical Framework of Ecological Units (ECOMAP; Cleland et al., 1997; Nowacki et al., 2001). The ECOMAP delineation was guided by physiography, lithology, and surficial geology which are all factors related to the land's ability to process water. ECOMAP is much more detailed than the major land resource area (MLRA) map that has two delineations in the U.S. NCTR, the Alexander Archipelago-Gulf of Alaska Coast and the Southern Alaska Coastal Mountains (USDA, 2004).

2.3. Establishing a Hydropedologic Observatory in the NCTR

We established a hydrologic observatory to implement a working model consistent with the research vision for hydropedology (Lin et al., 2006a). We chose watersheds in three different ecological subsections as delineated by ECOMAP as our core sites to address the higher-order hydrogeomorphic control (Fig. 3). Peterson watershed, which is drained by Peterson Creek, is in the Stephens Passage glaciomarine terrace subsection and is composed primarily of slowly permeable glaciomarine sediments (Miller, 1973) along with bedrock outcrops that occur on moderate to low slopes (Fig. 3). Peterson represents watershed types dominated by wetlands (53% of watershed area). In contrast, McGinnis watershed, which is drained by McGinnis Creek, is primarily composed of recently deglaciated areas within the Boundary Ranges Icefield subsection and has low wetland coverage (<5% of watershed area). Eaglecrest watershed, which is drained by Fish Creek, is composed of intrusive volcanic and sedimentary rock in the Stephens Passage volcanic subsection and represents a mix of physiographic features from alpine to lowland wetlands.

The highly resolved ECOMAP landtype-phase classification (Cleland et al., 1997), which provides information on the distribution of fine-scale hydrologic classes, is not available in the NCTR. The best-available information on soil hydrology is the drainage class assignment of Tongass soil map units based on soil morphology (Fig. 4). The Tongass soil resource inventory provides

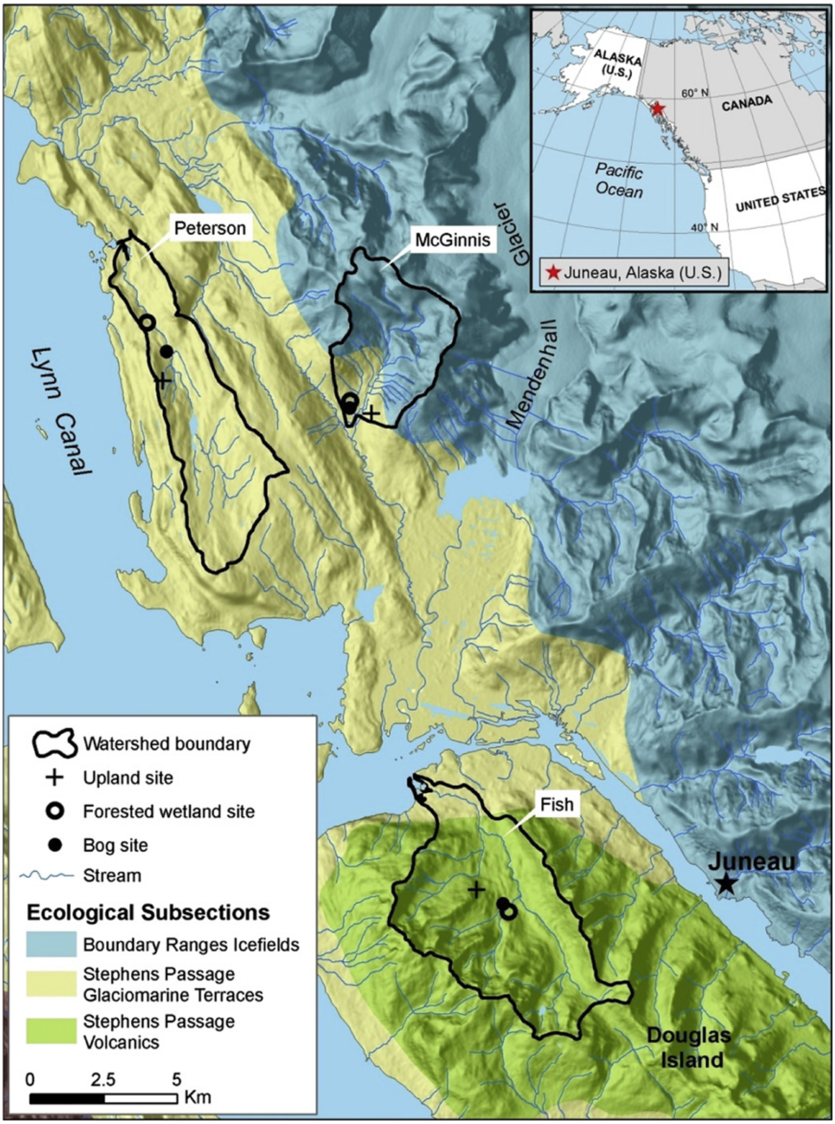

FIGURE 3 Ecological subsections and watersheds of the Juneau hydrologic observatory. Peterson Creek and McGinnis Creek watersheds include the uplifted marine terraces and boundary ranges Icefields, which are located on the mainland. The Eaglecrest (Fish Creek) watershed is located on the Stephens passage volcanics located on Douglas Island. *(Color version online and in color plate)*

a discrete approach (see Park and van de Geisen, 2004) to subdivide the coarse subsection structure available in the ECOMAP (Nowacki et al., 2001; Fig. 3) into units that capture small-scale spatial variability within homogeneous geological formations. The discrete mapping approach recognizes the presence

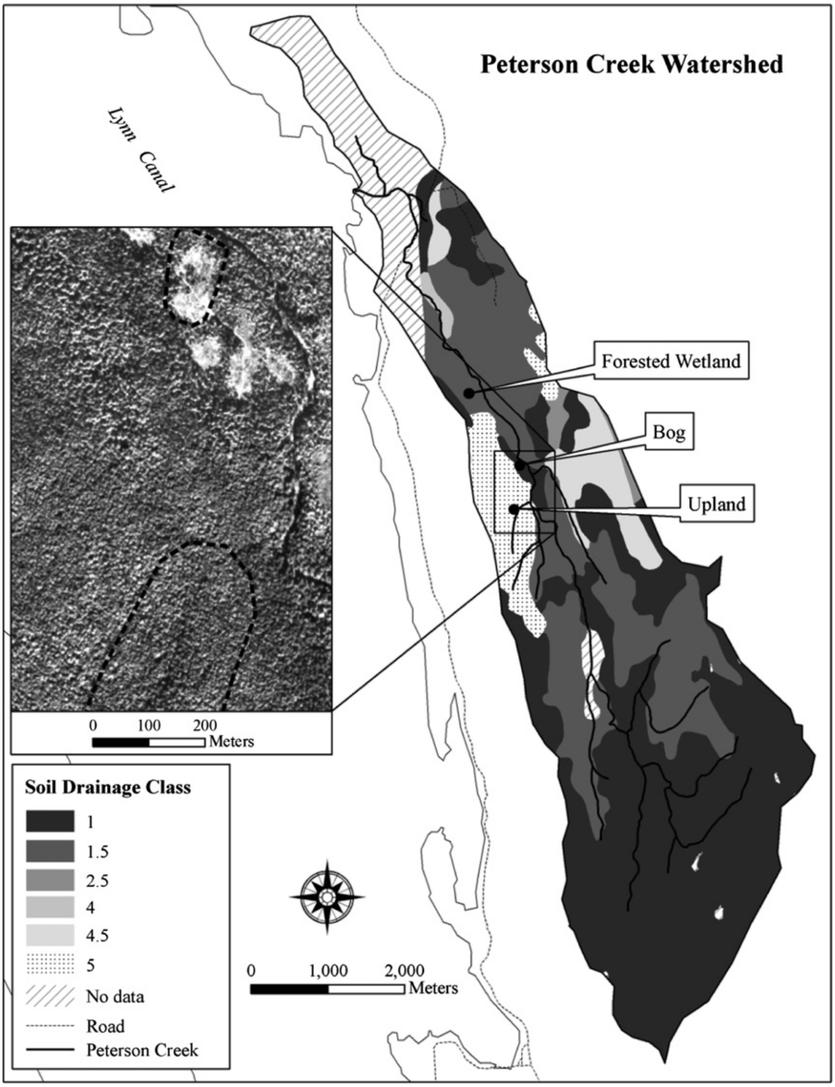

FIGURE 4 Soil drainage classes delineated in Peterson Creek watershed by average soil map unit composition. The aerial photograph shows outlines of the upland and sloping bog hydropedologic units. Soil drainage classes: 1 = very poorly drained; 2 = poorly drained; 3 = somewhat poorly drained; 4 = moderately well drained; 5 = well drained. Note that all classes are not represented due to averaging by soil map unit composition of soil drainage classes.

of a distinct spatial arrangement associated with pedologic and geomorphic structure that influences hydrologic gradients present on the landscape.

Tongass soil map units are closely associated with ecosystem types defined on landforms and were based primarily on soil–vegetation relationships during soil and ecosystem mapping (USDA Forest Service, 1996). Therefore, the Tongass soil resource inventory provides the building blocks for a preliminary hydropedologic framework across the region with spatially explicit maps of soil–vegetation assemblages associated with order 3 and 4 soil surveys. However, there are many variants to established soil series due to the heterogeneity caused by small-scale disturbance, such as windthrow and landslides. Soil map unit associations and complexes are common because soil development can vary substantially due to the small-scale variation of soil-forming factors caused by these localized disturbances. To address this variability, we integrate wetlands into the hydropedologic framework as they are a clear landscape feature and an obvious choice for a soil/vegetation class as they cover approximately 21% of the NCTR. The readily available landscape classification of wetlands across the U.S. portion of the NCTR through the National Wetland Inventory (USFWS, 2009) makes applying this ecosystem classification quite useful. The NWI mapping does not capture many of the wet forests that do not meet the jurisdictional requirements of wetland delineation, so the combination of soil maps and wetland delineations provides a means to capture functional units on the landscape.

We use the term hydropedologic unit to define the combination of the soil and wetland map unit with biogeochemical function. The hydropedologic units had soil characteristics that were hypothesized to control soil hydrology and influence the overall hydrologic and biogeochemical behavior of the subcatchment (Table 1). We chose three hydropedologic units that can be identified through soil surveys and wetland inventories for intensive sampling: upland mineral soils, forested wetland soils, and peatland bog soils. The three hydropedologic units are closely associated with the soil map unit designation and associated drainage class (Table 1). Therefore, similar hydropedologic units were located in each of the subsections (Fig. 3). Three individual subcatchments of each type were delineated within the watershed blocks by soil and vegetation maps and verified in the field to assure that they adequately represented the selected hydropedologic units (Table 1; Fig. 3). The hydrologic control section was defined by the presence and depth of the acrotelm and catotelm in the wetland soils (D'Amore et al., 2010). The upland soils were located on relatively steep hillslopes defined by a lack of soil saturation and bedrock hydrologic control (Fig. 2). The subcatchments within each watershed were delineated to locate flow-gauging weirs to measure chemical export from each site to test the hypothesis that hydrologic fluctuations were related to biogeochemistry of the catchment.

Wetlands are roughly mapped by the National Wetland Inventory (NWI), but low resolution and inaccuracies dictate that field observations of soil patterns be used to more accurately delineate the boundaries of those classes in the field. We use the NWI nomenclature for classes of forested wetland and upland. We have established a "sloping bog" class as a modification to the NWI nomenclature for the palustrine emergent class that combines the features

TABLE 1 Watershed Location, Hydropedologic Units, and Soil Attributes for Experimental Catchments in the Juneau, AK Area. Drainage Class is based on Modal Soil Pedon Morphological Characteristics from the Tongass National Forest Soil Resource Inventory. Drainage Control is based on Either the Presence of a Slowly Permeable Subsurface Aquitard (Catotelm and Bedrock) or a Zone of Saturated Lateral Flow near the Soil Surface (Acrotelm)

Watershed	Hydropedologic unit	Soil classification	Drainage class	NWI category*	Drainage control
Peterson	Sloping bog	Typic Cryohemist	1.0	PEM	Catotelm
	Forested wetland	Histic Cryaquept	1.5	PF	Acrotelm
	Upland	Lithic Haplocryod	5.0	UP	Bedrock
McGinnis	Sloping bog	Typic Cryohemist	1.0	PEM	Catotelm
	Forested wetland	Terric Cryohemist	2.5	PF	Acrotelm
	Upland	Typic Humicryod	4.5	UP	Bedrock
Eaglecrest	Sloping bog	Typic Cryohemist	1.0	PEM	Catotelm
	Forested wetland	Terric Cryohemist	2.5	PF	Acrotelm
	Upland	Typic Haplocryod	5.0	UP	Bedrock

** National Wetland Inventory (NWI) categories: PEM = palustrine emergent; PF = palustrine forested; UP = upland (Cowardin et al., 1979).*

associated with fens and bogs. Sloping bogs have water flow derived from groundwater, similar to fens, which flows through vegetation communities more commonly associated with bogs. The slope bog is recognized in the Canadian wetland classification (NWWG, 1998), but is not identified in the NWI. Therefore, we have established a class of hydropedologic unit that can be used across the entire NCTR.

3. A FRAMEWORK FOR INTEGRATED HYDROPEDOLOGIC STUDIES IN THE NCTR

The hydropedologic framework can be used to test the strength of association of hydrologic fluctuations and biogeochemical transformations within the provisional hydropedologic units through plot-based studies that quantify terrestrial–aquatic biogeochemical fluxes. The hydropedologic units can be used to estimate biogeochemical fluxes from entire watersheds by extrapolation of fluxes across similar hydropedologic units delineated by the soil resource inventory. Our integrated research fills a need to understand soil hydrology and watershed biogeochemical fluxes in the NCTR. Five key issues provided guidelines for describing our hydropedologic research: structure, function, scale, integration, and disturbance (Lin et al., 2006a). We use these issues as a framework to present the information gathered through our research at the Juneau hydrologic observatory and evaluate the potential of future hydropedologic research in the NCTR.

3.1. What are the Hierarchical Structures of Soil and Water in the NCTR?

The NCTR provides an excellent natural laboratory for the hydropedologic model. It is the largest intact contiguous expanse of coastal temperate rainforest in the world and contains thousands of watersheds largely devoid of major human disturbances. These watersheds contain a wide range of relative proportions of our defined units (e.g. 5–95% wetland) allowing us to verify watershed biogeochemical models across a broad geographic area. The application detailed here provides a first approximation for defining hydropedologic units and using these units to describe biogeochemical cycles at the watershed scale. Thus, our examples provide a hierarchal structure to help explain biogeochemical cycling in individual hydropedologic units with the ultimate goal of identifying biogeochemical signatures of the entire watershed.

The storage, flux, pathway, and residence time of water are distinctly different within our three classes, confirming that they span multiple dimensions of variability across the landscape. The NCTR has a moisture excess during most of the year, but the balance between precipitation and evapotranspiration creates conditions that influence soil profile saturation patterns (Fig. 5). The water tables among the three units were stratified as expected from the initial landscape partitioning where deep water tables were measured in upland mineral soils and shallow water tables were measured in forested wetland and sloping bog soils (Fig. 6). Although this relationship was expected, the consistency among the replicate units (e.g. three sloping bog sites) supported the premise that these units provide adequate first approximations of general water-table fluctuations across the drainage gradient.

The water-table depth in the mineral soils is limited by impermeable bedrock and slightly weathered regolith. Water moves through the soils on the ‘upland’ landscape positions, but there are fluctuations within the profile

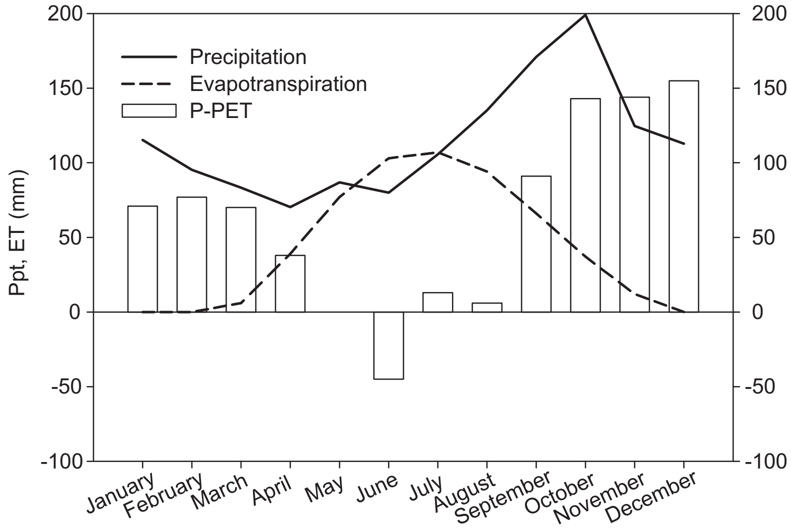

FIGURE 5 Patterns of annual precipitation and evapotranspiration in the Juneau, Alaska area. Precipitation, evapotranspiration, and the calculated moisture surplus or deficit (Precipitation [P]–Potential evapotranspiration [PET]) are shown over an annual cycle. Data were derived from the potential evapotranspiration estimates of Patric and Black (1968).

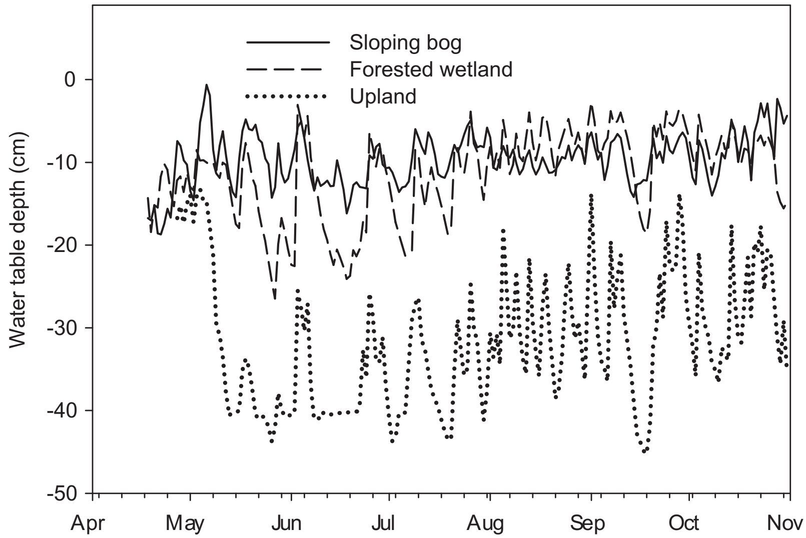

FIGURE 6 Water-table fluctuations in uplands, forested wetlands, and sloping bogs. Data from three replicates of each hydropedologic unit, which were measured during 2006–07 (data adapted from D'Amore, 2011). The period of moisture deficit relative to the surface can be seen most clearly in the water-table depression of the forested wetland site from late May to late July.

consistent with a groundwater flux across the bedrock interface. Recharge is the dominant water-flow pathway downward through the fibric surface horizon and spodic mineral horizon toward the impermeable bedrock. After it rains, water infiltrates down through the soil profile as recharge with no overland or near-surface flow and is then redirected laterally across the bedrock interface (Fig. 2).

The flow regime of the forested wetland and sloping bog is regulated by the depth of the permeable, surface acrotelm horizon (D'Amore et al., 2010). There are two distinct cycles within these peatland soils: a distinct water-table drawdown in June–August and near-surface saturation in the fall during higher rainfall (Fig. 7). The near-surface saturation (<10 cm) is quite similar within the two wetland soils with nearly complete saturation of the soil profile, but forest wetland water tables drop faster and to deeper depths during drawdown periods. The water-table drawdown indicates the presence of an unknown water export pathway, either a much deeper zone of flow within the forested wetland soils or evapotranspiration by trees. Rainfall events create subsurface flow and pressure heads within the soil matrix that lead to ephemeral increases in water-table height and incursions into the unsaturated soil zone (i.e. acrotelm) from the saturated zone below. These incursions are much more

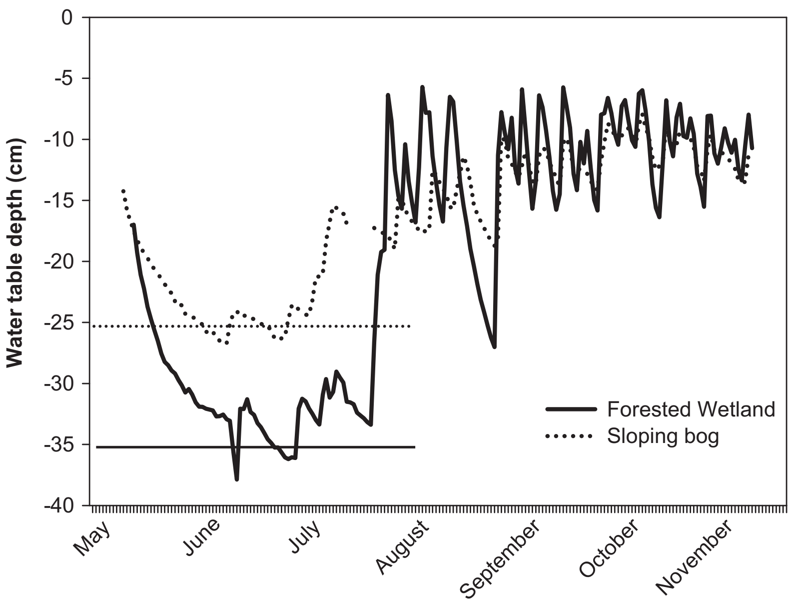

FIGURE 7 The depth and duration of the water table measured in the acrotelm (surface organic horizon) of the forested wetland and sloping bog at the McGinnis Creek watershed from May to November of 2004 (adapted from D'Amore et al., 2010). Horizontal lines represent depth of the acrotelm (aerobic surface horizon) in each soil during the annual period of moisture deficit.

dramatic in the forested wetland due to the deeper acrotelm. The depth and duration of aerobic conditions in the acrotelm are similar to other regions with extensive peatlands (Holden and Burt, 2003; Worrall et al., 2002, 2003), but the frequency and magnitude of water-table fluctuations are more dynamic in NCTR peatlands.

Understanding how soil saturation interacts with biogeochemical transformations within each hydropedologic unit provides insight into material transfers and biogeochemical transformations within a watershed. The duration and fluctuation of water tables in peatlands have been clearly linked to biogeochemical shifts (Strack et al., 2008). Although aerobic surface horizons persist in wetland soils even during periods of heavy rainfall (D'Amore et al., 2010), redox potential varied with soil saturation at the water-table interface (Fig. 8). The responsiveness of redox potential to changes in soil saturation suggests highly dynamic shifts in microbial metabolism at the interface between the acrotelm and catotelm. The anaerobic–aerobic boundary is a highly reactive zone for microbial activity and, hence, biogeochemical transformations (Gutknecht et al., 2006). Redox potential measurements are a surrogate measure for potential biogeochemical transformations within soils and riparian sediments (Miller et al., 2006). For example, the soils are a rich source of reduced DOM, which is an important substrate for microbial communities that oxidize and alter the nature of dissolved organic carbon (DOC) in soil and soil solution. The

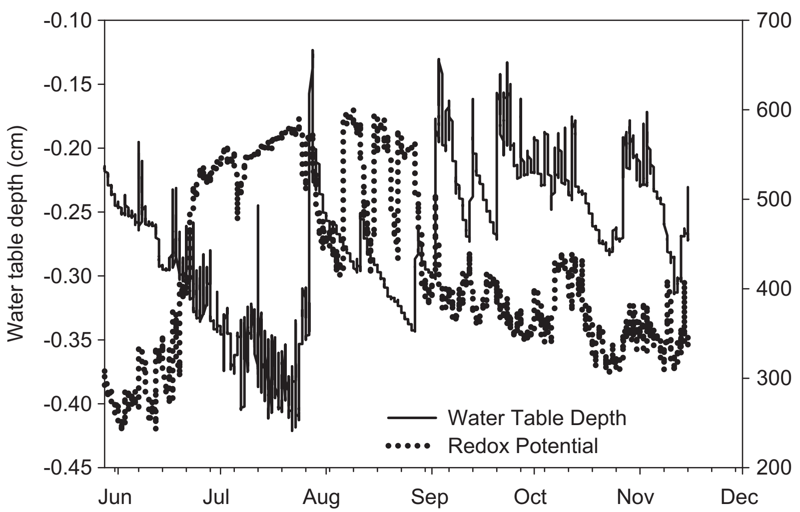

FIGURE 8 Fluctuations in water-table depth and redox potential at in the McGinnis forested wetland site from June to November 2004. Redox potential was measured with permanently installed platinum electrodes in the lower part of the surface organic horizon (acrotelm). See D'Amore et al., 2010 for detailed methods.

sequential processing of DOM by soil microbes contributes to electron transfers and is closely tied to the degradation of organic acids and other chemical transformations such as denitrification (Miller et al., 2009). The combination of water-table fluctuations and redox potential shifts provides a means to identify discrete zones of fine-scale biogeochemical activity in soils. The hydrodynamics of the hydropedologic units provide a means to distribute water-table fluctuations to broader landscapes through extrapolation of function to similar mappable units.

3.2. How can Function be Integrated into the Structure of the Soil Hydrologic System of the NCTR?

Flow-path integration describes how the flow path of water, and the material entrained in the flow path, integrates stream and landscape heterogeneity (Fisher and Welter, 2005). Flow-path integration highlights how small-scale biogeochemical transformations that occur in three-dimensional space are integrated into net cumulative fluxes from the watershed (Fisher et al., 2004). The key concept in this approach is how nutrient retention and cycles associated with different ecosystem types control the composition of water flowing through the sequence of structural forms encountered on the landscape (Giblin et al., 1991; Fisher et al., 2007). Hydropedology and flow-path integration emerge from two different disciplines, but both strive to understand the linkage between the production, transformation, and export of DOM from terrestrial to aquatic ecosystems. Interdisciplinary concepts such as these are not often applied by a broad and diverse group of scientists, but remain within the discipline from which they have emerged. However, these concepts and the ability to integrate terrestrial and aquatic biogeochemical research are highly desirable in the NCTR. The concepts of terrestrial nutrient cycles and exports to aquatic ecosystems can provide a means to address the effects of alterations to functions in both systems and related maintenance of coastal marine food webs. Ultimately, the system must be viewed as a unified flow path to achieve this goal (Fisher et al., 2004). The hydropedologic approach is a compromise that uses discrete units to quantify the continuous flow of material to aquatic ecosystems.

The hydropedologic units are tools for organizing drainage units by function. The observed water-table fluctuations and redox potential shifts within hydropedologic units can be linked with biogeochemical cycling and potentially to landscape unit function. The hydropedologic units are useful for describing DOM export from terrestrial to aquatic environments in the NCTR. In the same way, the hydropedologic unit approach can also provide insight into the quality of the DOM produced and exported from the landscape, which has important implications for productivity in downstream aquatic ecosystems.

The distinction between upland and wetland is a good predictive distinction for determining the DOM flux from a watershed (Mulholland and Kuenzler, 1979; Mulholland, 2003). Soil attributes, such as soil C:N, have also been used effectively to predict watershed DOM export across a broad array of systems (Aitkenhead and McDowell, 2000). Our watershed stratification provides a good estimate for DOM concentrations (measured as DOC) using the wetland distinction. There is a strong relationship between wetland extent and DOC concentrations in NCTR streams (D'Amore et al., submitted for publication; Fig. 9), which is also apparent in the subcatchment outlet streams for the hydropedologic units (Fig. 10). The hydrodynamics and intensity of the biogeochemical exchange in the acrotelm differ between the sloping bog and forested wetland provide an explanation for the local strength of the association between depth to water table and soil DOC concentrations (D'Amore et al., 2010).

Integrating physical and biogeochemical cycles is essential in creating a useful tool to understand the effect of soil hydrologic cycles on DOM export. Surface organic horizons in both mineral and organic soils provide highly conductive flow paths that facilitate the transfer of water and DOM through the soil and into surface water channels. Deeper, organic horizons have much lower conductivities and transfer water through the soil more slowly allowing for longer soil residence times for DOM and associated nutrients. The internal drainage of mineral soils shifts the chemical transformations from anaerobic to

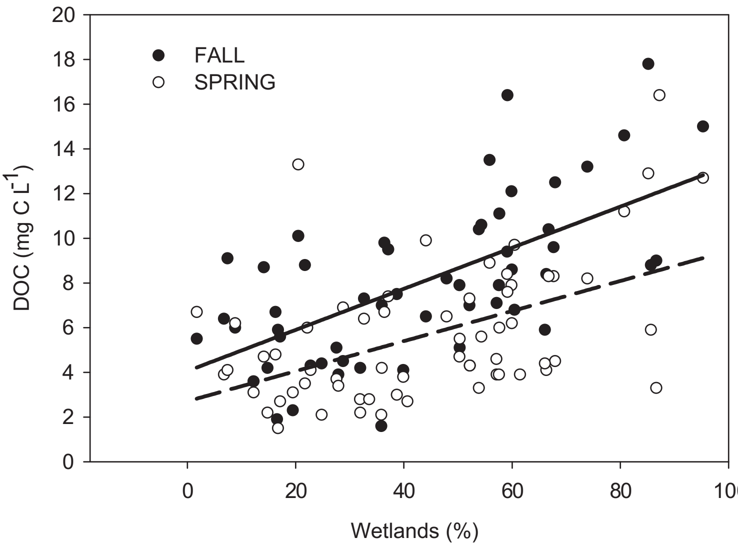

FIGURE 9 Relationship between the extent of wetlands and the concentration of dissolved organic carbon (DOC) in streams in the Alaskan portion of the northern coastal temperate rainforest.

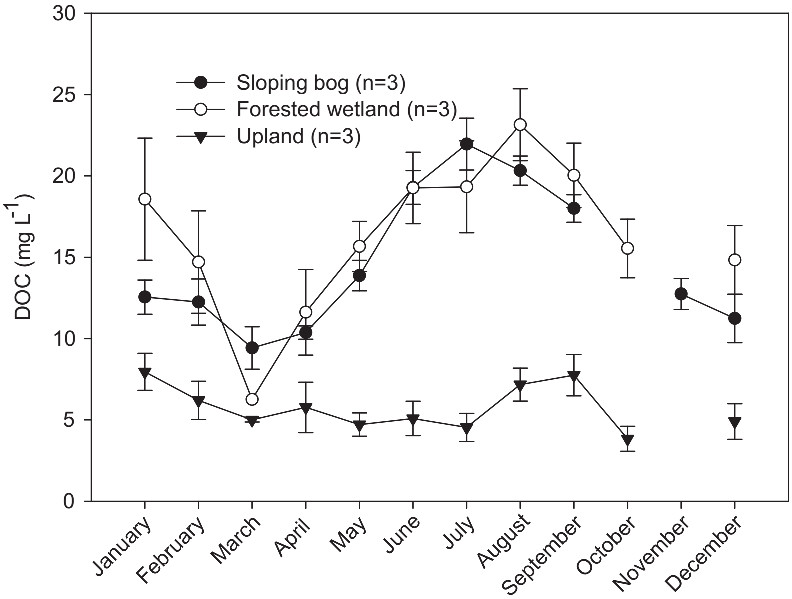

FIGURE 10 Monthly concentrations of dissolved organic carbon (DOC) measured in outlet streams draining the sloping bogs, forested wetlands, and uplands in the Juneau, AK area in 2006–07 (adapted from D'Amore, 2011). Means (±1 standard error) for measurements taken every 1–4 weeks are averaged by month for each hydropedologic unit.

aerobic conditions, which is in direct contrast to peatland soils. These conditions vary seasonally, as warmer periods and similar or reduced rainfall alter the late spring and early summer soil saturation dynamics.

Dissolved organic matter characterization provides a means for distinguishing biogeochemical signatures and potential ecological function among the hydropedologic units (Fellman et al., 2008). For example, ordination analysis clearly distinguishes the hydropedologic units into distinct classes based on the relationship between protein-like and humic-like fluorescence components (Fig. 11). These differences in the chemical properties of DOM are reflected in DOM bioavailability, as significant seasonal differences are observed both within and among hydropedologic units (Fig. 12). The movement of water through the forested wetland is controlled by the depth of the permeable surface peat (acrotelm) and the intensity and duration of rainfall (D'Amore et al., 2010). The sloping bog has a much smaller acrotelm and the water flow is dominated by the near-surface, slowly permeable catotelm. The upland soils are dominated by water flow downward in the profile and transport across the slowly permeable bedrock or paralithic contact. The distinct quality of DOM and the differences in dominant hydrologic flow paths among the hydropedologic units suggest that

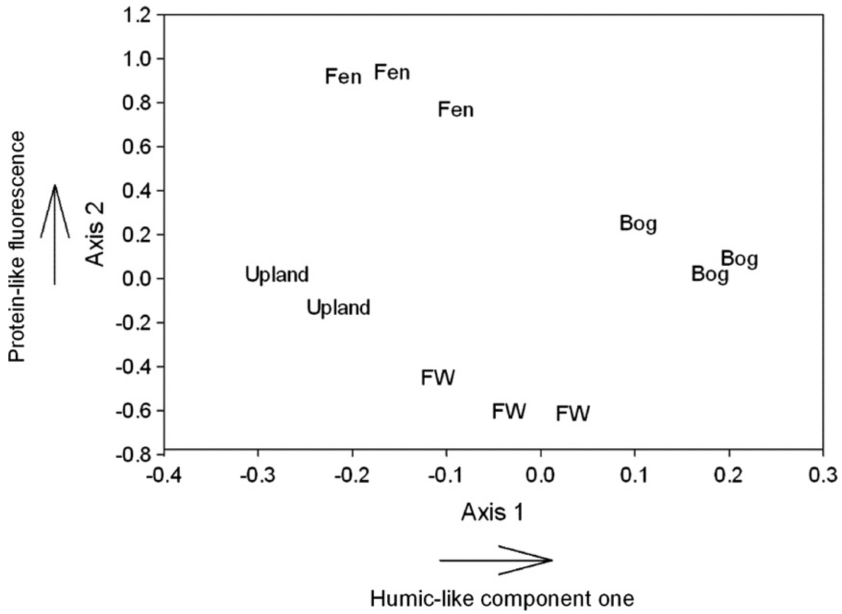

FIGURE 11 Ordination of hydropedologic units according to component composition modeled with parallel factor analysis (PARAFAC). Axis 1 is derived from humic components and axis 2 is derived from protein components identified through PARAFAC of the dissolved organic matter in soil solution. FW = forested wetland.

the aggregated collection of hydropedologic units has the potential to alter watershed-scale biogeochemical processes by influencing patterns in labile DOM delivery to streams.

Differences in chemical export within hydropedologic units and seasonal variability among these units have implications for the biogeochemical function of the entire watershed (Fellman et al., 2009b). For instance, low biotic demand and short soil residence time from predominantly surface soil flow paths lead to a pulse of labile DOM during spring snowmelt for wetland sites, but less so for upland sites (Fig. 12). In the wetland sites especially, DOC concentrations can be quite low during the spring snowmelt because of simple dilution in relation to the mass of water. Competition between DOM transport and transformation is ultimately mediated by soil hydrologic flow rate, or contact time (Randerson et al., 2002). Thus, reduced DOM concentrations may also result from a stable water table that restricts organic matter mineralization and diminishes the pool of leachable DOM.

During the summer growing season, water-table drawdown occurs in the bog and forested wetland and water moves predominantly through deep and less conductive flow paths (Fig. 7). High biotic demand for labile DOM by soil microbes and long soil residence time results in the delivery of mainly

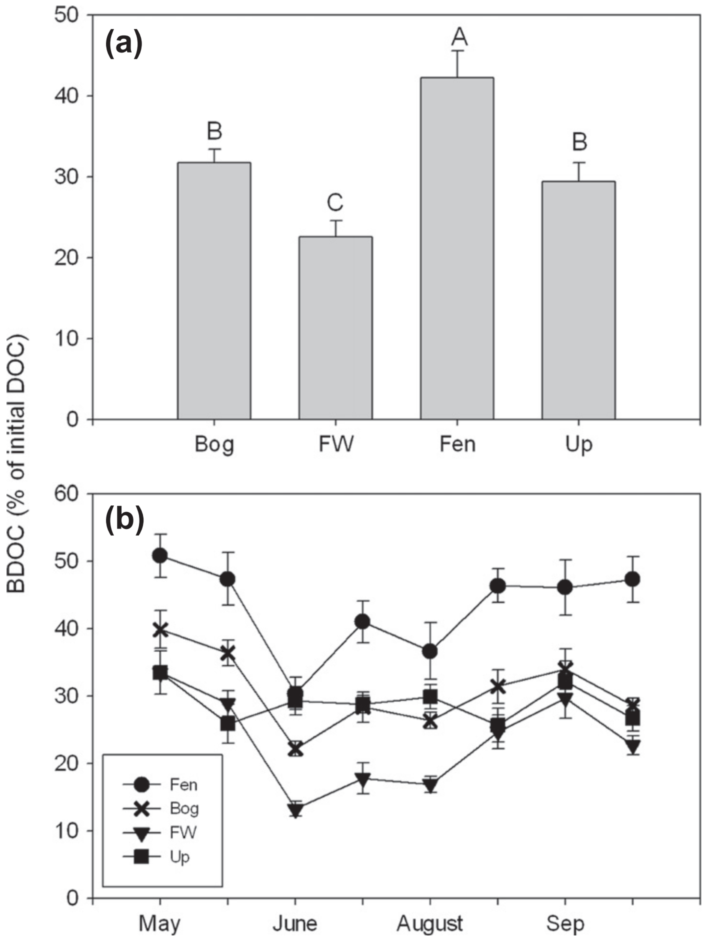

FIGURE 12 Solution biodegradable dissolved organic carbon (BDOC) in four soil types. Patterns of (a) average BDOC in soil and (b) time series for the four soil types collected across the range of sample dates. Significant differences among soil types are indicated by different capital letters above the columns; error bars indicate ±1 SE and $N = 3$ for all soil types. Abbreviations: FW, forested wetland and Up, upland forest. *(Adapted from Fellman et al., 2008)*

recalcitrant DOM to streams from wetland sites. Consequently, the quality and biodegradability of the streamwater DOM may vary dramatically with source material and season among the distinct units (Fellman et al., 2009a). These observed differences in DOM biogeochemistry clearly demonstrate that these hydropedologic units may have different functional roles in terms of biogeochemistry within the watershed.

Our work along the hydropedologic gradient has also provided new insights into the role of discrete landscape units for providing labile organic matter to aquatic ecosystems. In particular, research in the NCTR has demonstrated the importance of wetlands for the export of labile DOM that can support stream heterotrophic productivity (Fellman et al., 2008, 2009a). This highlights a fundamental change in our view of wetland ecosystems, which have typically been seen as sources of highly degraded dissolved material. The recognition of the importance of terrestrial nutrient subsidy to aquatic systems has been an important shift in our understanding of material flows in the NCTR. The transfer of material from the terrestrial to aquatic ecosystems in the NCTR provides important nutrient subsidies for both freshwater and marine ecosystems (Hood et al., 2009; Fellman et al., 2010). This finding also illustrates the importance of understanding how hydropedologic factors influence terrestrial biogeochemical cycles which can then be linked to soil-water export pathways of dissolved reactive materials.

3.3. What is the Potential for Scaling Functions across the Complex Landscape of the NCTR?

We must derive soil–geomorphic relationships from existing data such as soil map unit classifications to establish initial hypotheses related to functional responses in the absence of high-resolution topographic maps. Finely delineated terrestrial landscape attributes can be determined using high-resolution morphometric analyses such as light detection and ranging (LiDAR) imagery. However, LiDAR mapping is not available on much of the NCTR. In any case, the delineation of these highly resolved landscape attributes (e.g. 1 m^2) generally exceeds our ability to accurately measure the functional attributes of such small features. To constructively stratify the landscape, a broad grouping of 'subject' landscape types was chosen to represent hydropedologic units. The resolution of current digital elevation models (DEMs) and wetland and vegetation maps do not support a finer parsing of the landscape than the three fundamental types we used. Finer distinctions could be made of these types, but because our intent was to upscale these fundamental units to the watershed scale, we used classes that could readily be predicted using available GIS data layers. These landscape units occur at different locations along the hydrologic gradient, and so represent rational ways to partition the landscape to study the functional linkages between soils and hydrology.

The highly dissected nature of the landscape of the NCTR is evident from coalescing flow on hillslopes during storms, and the integrated response of this water delivery system is quite profound. For instance, during intense storms, streamwater DOC concentrations often dramatically increase as terrestrial source pools and hydrologic flow paths are different between baseflow and stormflow (Fellman et al., 2009b). As soils become saturated, water moves through shallow soil layers or at the acrotelm/catotelm interface (D'Amore et al., 2010) and differing flow paths can entrain DOM with different chemical properties. Thus, temporally transient water fluxes influence shifts in biogeochemical patterns. It is also possible that DOM export during storms accounts for a large fraction of the annual watershed flux as found in studies from a similar humid region in the United Kingdom (Worrall et al., 2002, 2003), which highlights the importance of individual storms for watershed biogeochemical budgets. Partitioning the watershed into hydropedologic units and understanding their biogeochemical response to high flow events could be used to improve annual estimates of watershed-scale and regional DOM fluxes.

The hydropedologic stratification provides a framework for downscaling models of climate drivers to plots for modeling soil hydrology in connection with regional weather patterns. The parameter-elevation regressions on independent slopes model (PRISM Climate Group, 2010) provides estimates of precipitation and temperature at a resolution of 0.8 km. Precipitation and temperature data analyzed by PRISM models can be used to estimate evapotranspiration, which strongly influences the accumulation and flow of water in soils during the growing season. This information can provide support for developing watershed or regional water budgets by constraining estimates of fluctuations in soil water storage. The potential influence of deviations in soil saturation can also be applied to modeling plant responses across watersheds to guide vegetation-monitoring programs.

The distribution of frequently saturated soils can predict the presence of plant communities, which is especially important in the face of shifting populations of plants due to climate change (Hennon et al., 2011). Hydric soils have been successfully used as a predictor variable to describe differences in timber volume classes across the Tongass (Caouette and DeGayner, 2005). However, a hydric soil class merely assigns a wet or dry state, but does not provide any details of how the underlying soil nutrient turnover may influence the specific vegetation assemblages. The hydropedologic approach provides a framework to design experiments to examine small-scale processes in soils and the broader control on vegetation structure. This can then be linked to the biogeochemical properties such as DOM bioavailability to complete an assessment of the feedback mechanisms and interactions among all these key elements in vegetation response to watershed biogeochemical characteristics. Yellow-cedar is a particularly good example of a potential application of this approach because its distribution is closely linked to soil moisture patterns. The yellow-cedar tree is not obligated to saturated soils (D'Amore and Hennon, 2006) but follows a niche strategy to persist in marginal conditions with low nutrient turnover and nearly saturated soil conditions (D'Amore et al., 2009). The prediction of future yellow-cedar decline will rely on accurate spatial models of soil saturation as well as changes in those patterns over time (Hennon et al., 2012).

3.4. How can Information from Diverse Research Studies be Integrated into a Hydropedologic Model in the NCTR?

We provide a framework for predicting biogeochemical cycling in catchments that is similar to the geochemical catena (Johnson et al., 2000; Palmer et al., 2004). The influence of soil hydrology on biogeochemical cycles has not been clearly articulated in the coastal temperate rainforest research. Therefore, a working model using this approach and implementation of an integrated hydrologic observatory is useful for addressing goals associated with biogeochemical research in the NCTR. Our study outlines a method to demonstrate how linking terrestrial and aquatic research through the use of well-defined hydropedologic units can provide benefits to both fields. Traditionally, these disciplines have shared similar biogeochemical concepts such as the study of limiting nutrients, but measurements and perspectives regarding applications of these measurements vary (Grimm et al., 2003). For example, aquatic ecologists are now exploring the potential for wetlands to impact stream productivity beyond lakes and ponds. Another key example is the ability to derive information regarding wetland function from structural aspects of wetland ecology (Bridgham et al., 1996).

The hydropedologic unit delineation can provide a link between disciplines as water flow is the key nexus between terrestrial and aquatic environments. Soil functional attributes can be applied to hydropedologic units for estimates of specific aspects of biogeochemical functions among individual hydropedologic units and these functions can be extrapolated to entire watersheds. For example, quantifying seasonal soil saturation across different hydropedologic units can be applied to key nutrient turnover measures. Denitrification rates are influenced by soil factors such as texture and moisture content which control soil saturation and redox potential (Pinay et al., 2003). A hydropedologic model provides a means to estimate zones of high denitrification potential, such as riparian zones and seeps, based on the stratification of the landscape according to soil factors. Using this approach, replicated studies can be designed to quantify denitrification rates that will enable more accurate estimates of nitrogen fluxes from specific areas within a watershed. The spatial resolution of these hot spots for denitrification can be combined with other N flux pathways that can then be appropriately scaled to estimate the overall watershed nitrogen flux.

3.5. How does Anthropogenic Disturbance Interact with Hydropedologic Functions?

The ecosystems of the NCTR are primarily driven by small-scale natural and anthropogenic disturbance over short time scales. Because fire is uncommon, wind is the primary driver of change in forest structure through disturbance (Kramer, 2001). The major anthropogenic disturbance in the NCTR has been timber harvest and to a lesser extent the construction of roads, especially through wetlands. In the southeast Alaskan portion of the NCTR, approximately 220,000 ha of forest have been logged (USDA Forest Service, 2008). It is unclear how harvesting and road building have affected watershed hydrology and the delivery of water and materials to streams. Timber harvest covers approximately 3% of the total area of the Tongass and appears not to exert a large influence on the overall landscape. However, individual landscape features and soil types such as karst formations have been heavily used for timber harvest. The loss of large stature trees can alter evapotranspiration in stands and the subsequent timing and delivery of water from soils to streams. Although this type of change affects surface and subsurface water flow, its effects on soil attributes including soil development and biogeochemical cycling are unknown. The change in trajectory of soil development following disturbance for individual landscape units should be considered in overall hydropedology models.

Road networks are closely associated with timber harvest in the NCTR. The impact on groundwater quality and flow along with the alteration of material delivered to streams due to the presence of roads are not well understood. Therefore, road construction and associated impacts to watershed hydrologic cycles remain a concern for forest managers. The few existing hydrologic studies on roads have not identified any major impacts on peatland (Kahklen and Moll, 1999) or mineral soil (McGee, 2000) hydrology. However, linear road features have potentially disrupted flow paths and created biogeochemical interactions between soil water and crushed rock that may reduce the residence time of water within soils before delivery to the stream channel. Further, the increased rock–water interaction may alter the biogeochemical signature through oxidation of DOM and altered pH.

4. FUTURE APPLICATIONS AND CONCLUSIONS

The sheer volume of water draining through the NCTR and the magnitude of dissolved material export underscores the need for a process-based understanding of what regulates water and material fluxes. The large number of watersheds, their heterogeneity, and the isolated nature of the region make prediction and management a challenge in the NCTR. A systematic modeling approach that is both scalable and representative of the diverse range of watersheds will allow land managers to make predictions at both local and regional scales. We suggest that hydropedology offers an opportunity to address these needs in the NCTR.

We posed the hypothesis that hydropedologic units encompass soil hydrology and associated biogeochemical behavior at a resolution that balances fine-scale variability with larger-scale reproducible measureable outputs. Hydropedologic units are a logical link between regional-scale climate models and reach-scale predictions of habitat response because they are fundamental functional units that can be readily mapped within a watershed. Our review synthesizes the close association between DOM with the different units as an example of a key biogeochemical process. We provide evidence that the interaction of soil hydrologic and biogeochemical transformations controls the unique attributes of DOM in catchments. Our work quantified the magnitude of water-table fluctuations and identified the role that hydrodynamics played as a key characteristic that controls DOM and at scales detectable in a watershed. Because these units represent a broad class of various soil map units that are available across the NCTR, we have provided a tool for extrapolating biogeochemical functions across landscapes such as that illustrated in Fig. 2.

Although there is a growing understanding of the interaction among topography, subsurface structure, and flow control (Lin et al., 2006b; Lin, 2010), we are just beginning to conduct experiments and understand flow regimes within the soils of the NCTR. The complexity of forested watershed hydrology is related to the landscape geomorphology. Resolving the opaque nature of the subsurface with integrated models of water and material flows is a high priority. Landscape units that are operationally defined by quantitative geomorphometry are much more useful in delineating areas of water flow and coalescence. Soil geomorphic models rely on accurate and preferably high-resolution digital elevation measurements along with good information on soil moisture patterns for calibration. The current challenge is to create a more refined model linking soil geomorphic associations and biogeochemical function to flow paths delineated with topographic models. A model of subsurface flow paths we created using the existing 60-m DEM of the NCTR provides a satisfactory resolution for the Peterson Creek drainage, with a good correspondence between predicted groundwater levels and existing hydropedologic units (Fig. 13). The application of high-resolution imagery can greatly improve the ability to delineate hydropedologic units and design hypothesis tests of functions. Once more accurate topographic imagery is available for a greater portion of the landscape of the NCTR, we can link the two approaches and create higher-resolution functional maps.

Hydropedology is a valuable tool that will continue to play an important role in terrestrial and aquatic research in the NCTR. The main conclusions we can draw from the current state of the research in the NCTR are:

1) Hydropedology is a flexible and robust approach that infuses soil and wetland delineations with function by providing a link between soil hydrology and DOM biogeochemistry;
2) Hydropedology provides an approach to scale up biogeochemical fluxes from individual hydropedologic units to the watershed scale;
3) Hydropedologic units provide a response variable for predicting functional alterations in watersheds from changes in land use and climate in the NCTR.

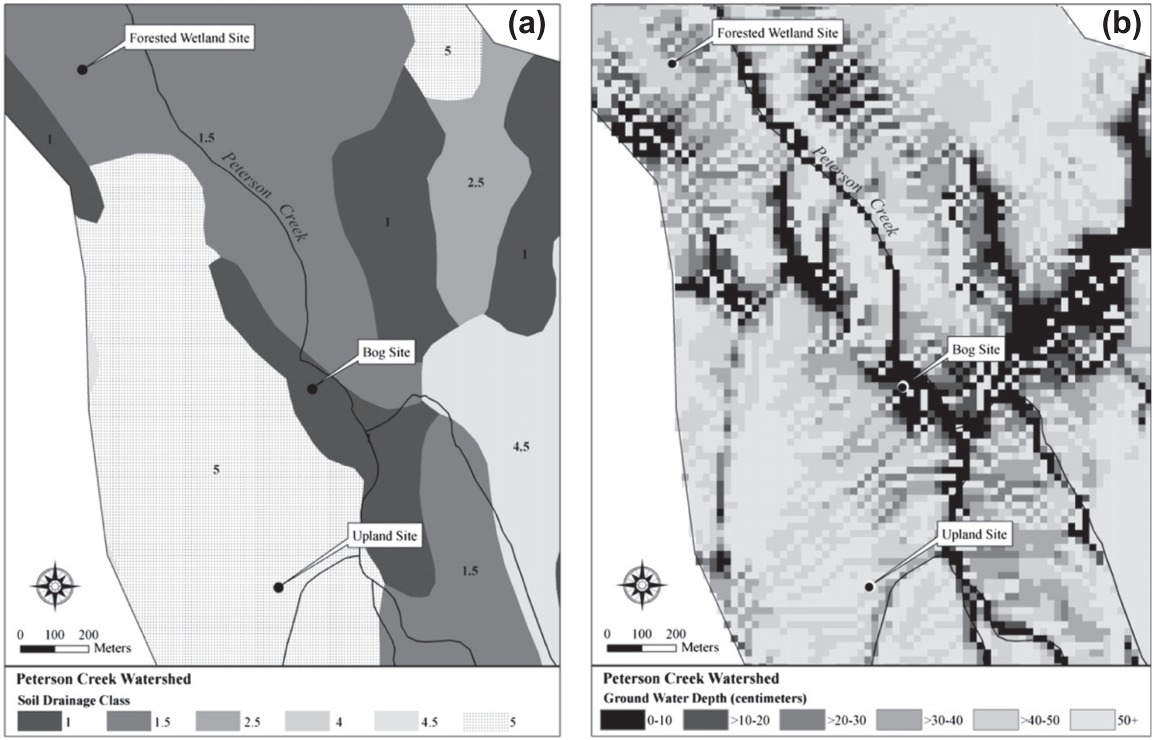

FIGURE 13 Soil drainage class and flow paths in the Peterson Creek watershed. Distribution of (a) soil drainage classes and (b) flow paths predicted from a compound topographic index model. Soil drainage classes are: 1 = very poorly drained; 2 = poorly drained; 3 = somewhat poorly drained; 4 = moderately well drained; 5 = well drained. Note that not all classes are represented due to averaging by soil map unit composition of soil drainage classes. Groundwater depth is estimated in six 10-cm depth classes arrayed in 20-m pixels through the use of a downscaled 60-m digital elevation model.

ACKNOWLEDGMENTS

We would like to acknowledge the contribution of Frances Biles to map production and Pat Dryer for assistance with map production and hydrologic mapping.

REFERENCES

Aitkenhead, J., McDowell, W., 2000. Soil C:N ratio as a predictor of annual DOC flux at local and global scales. Glob. Biogeochem. Cycles 14, 127–138.

Alaback, P.B., 1991. Comparative ecology of temperate rainforests of the Americas along analogous climatic gradients. Rev. Chil. Hist. Nat. 64, 399–412.

Alaback, P.B., 1996. Biodiversity patterns in relation to climate: the coastal temperate rainforests of North America. In: Lawford, R.G., et al. (Eds.), High-latitiude Rainforests and Associated Ecosystems of the West Coast of the Americas. Ecological Studies, vol. 116. Springer, NY, pp. 105–133.

Alaback, P.B., McCellan, M.H., 1992. Effects of global warming on managed coastal ecosystems of western North America. In: Mooney, H.A., et al. (Eds.), Earth System Responses to Global Change: Contrasts between North and South America. Academic Press, New York, NY, pp. 299–327.

Bormann, B.T., Spaltenstein, H., McClellan, M.H., Ugolini, F.C., Cromack, J.K., Nay, S.M., 1995. Rapid soil development after windthrow disturbance in pristine forests. J. Ecol. 83, 747–756.

Bridgham, S.D., Pastor, J., Janssens, J.A., Chapin, C.T., Malterer, J., 1996. Multiple limiting gradients in peatlands: a call for a new paradigm. Wetlands 16, 45–65.

Caouette, J.P., DeGayner, E.J., 2005. Predictive mapping for tree sizes and densities in southeast Alaska. Landsc. Urban Plan. 72, 49–63.

Carrara, P.E., Ager, T.A., Baichtal, J.F., 2007. Possible refugia in the Alexander Archipelago of southeastern Alaska during the late Wisconsin glaciation. Can. J. Earth Sci. 44, 229–244.

Chandler, R.F., 1942. The time required for podzol formation as evidenced by the Mendenhall glacial deposits near Juneau, Alaska. Soil Sci. Soc. Am. Proc. 7, 454–459.

Chapin, F.S., Walker, L.R., Fastie, C.L., Sharman, L.C., 1994. Mechanisms of primary succession following deglaciation at Glacier Bay, Alaska. Ecol. Monogr. 64, 149–175.

Cleland, D.T., Avers, P.E., McNab, W.H., Jensen, M.E., Bailey, R.G., King, T., Russell, W.E., 1997. National hierarchical framework of ecological units. In: Boyce, M.S., Haney, A. (Eds.), Ecosystem Management Applications for Sustainable Forest and Wildlife Resources. Yale Univ. Press, New Haven, CT, pp. 181–200.

Cook, J.A., Dawson, N., MacDonald, S.O., 2006. Management of highly fragmented systems: the north temperate Alexander Archipelago. Biol. Conserv. 133, 1–15.

Cowardin, L.M., Carter, V., Golet, F.C., LaRoe, E.T., 1979. Classification of Wetlands and Deepwater Habitats of the United States. U.S. Dept. Int., Fish and Wildl. Serv., Washington, DC.

Crocker, R.L., Major, J., 1955. Soil development in relation to vegetation and surface age at Glacier Bay, Alaska. J. Ecol. 45, 169–185.

D'Amore, D.V. 2011. Hydrologic Controls on Carbon Cycling in Alaskan Coastal Temperate Rainforest Soils. Ph.D. Diss. Fairbanks: University of Alaska Fairbanks.

D'Amore, D.V., Hennon, P.E., 2006. Evaluation of soil saturation, soil chemistry, and early spring soil and air temperatures as risk factors in yellow-cedar decline. Glob. Change Biol. 12, 524–545.

D'Amore, D.V., Fellman, J.B., Edwards, R.T., Hood, E., 2010. Controls on dissolved organic matter concentrations in soils and streams from a forested wetland and sloping bog in southeast Alaska. Ecohydrology 3, 249–261.

D'Amore, D.V., Hennon, P.E., Schaberg, P.G., Hawley, G., 2009. The adaptation to exploit nitrate in surface soils predisposes yellow-cedar to climate change-induced decline and enhances the survival of redcedar. For. Ecol. Manag. 258, 2261–2268.

Fellman, J.B., D'Amore, D.V., Hood, E., Boone, R.D., 2008. Fluorescence characteristics and biodegradability of dissolved organic matter in forest and wetland soils from coastal temperate watersheds in southeast Alaska. Biogeochemistry 88, 169–184.

Fellman, J.B., Hood, E., D'Amore, D.V., Edwards, R.T., 2009a. Seasonal changes in the chemical quality and biodegradability of dissolved organic matter exported from soils to streams in coastal temperate rainforest watersheds. Biogeochemistry 95, 277–293.

Fellman, J.B., Hood, E., Edwards, R.T., D'Amore, D.V., 2009b. Changes in the concentration, biodegradability and fluorescent properties of dissolved organic matter during stormflows in coastal temperate watersheds. J. Geophys. Res. Biogeosci. 114, G01021.

Fellman, J.B., Spencer, R.G.M., Hernes, P.J., Edwards, R.T., D'Amore, D.V., Hood, E., 2010. The impact of glacier runoff on the biodegradability and biochemical composition of terrigenous dissolved organic matter in near-shore marine ecosystems. Mar. Chem. 121, 112–122.

Fisher, S.G., Welter, J.R., 2005. Flowpaths as integrators of heterogeneity in streams and landscape. In: Lovett, G.M., et al. (Eds.), Ecosystem Function in Heterogeneous Landscapes. Springer-Verlag, New York, NY, pp. 311–328.

Fisher, S.G., Heffernan, J.B., Sponseller, R.A., Welter, J.R., 2007. Functional ecomorphology: feedbacks between form and function in fluvial landscape ecosystems. Geomorphology 89, 84–96.

Fisher, S.G., Sponseller, R.A., Heffernan, J.B., 2004. Horizons in stream biogeochemistry: flowpaths to progress. Ecology 85, 2369–2379.

Gehrels, G.E., Berg, H.C., 1994. Geology of southeastern Alaska. In: Plafker, G., et al. (Eds.), The Geology of North America, The Geology of Alaska. Geological Society of America, pp. 451–467.

Giblin, A.E., Nadelhoffer, K.J., Shaver, G.R., Laundre, J.A., McKerrow, A.J., 1991. Biogeochemical diversity along a riverside toposequence in arctic Alaska. Ecol. Monogr. 61, 415–435.

Grimm, N.B., Gergel, S.E., McDowell, W.H., Boyer, E.W., Dent, C.L., Groffman, P., Hart, S.C., Harvey, J., Johnson, C., Mayorga, E., McClain, M.E., Pinay, G., 2003. Merging aquatic and terrestrial perspectives of nutrient biogeochemistry. Oecologia 442, 485–501.

Gutknecht, J.L.M., Goodman, R.M., Balser, T.C., 2006. Linking soil process and microbial ecology in freshwater wetland ecosystems. Plant Soil 289, 17–34.

Hennon, P.E., D'Amore, D.V., Schaberg, P.G., Wittwer, D.T., Shanley, C.S., 2012. Shifting climate, altered niche, and a dynamic conservation strategy for yellow-cedar in the North Pacific Coastal Rainforest. Bioscience 62, 147–158.

Heusser, C.J., 1960. Late-Pleistocene Environments of North Pacific North America. Amer. Geogr. Soc. Spec. Publ. 35, New York, NY.

Holden, J., Burt, T.P., 2003. Hydrological studies on blanket peat: the significance of the acrotelm-catotelm model. J. Ecol. 91, 86–102.

Hood, E., Fellman, J., Spencer, R.G.M., Hernes, P.J., Edwards, R., D'Amore, D., Scott, D., 2009. Glaciers as a source of ancient and labile organic matter to the marine environment. Nature 24, 1044–1048.

Johnson, C.E., Ruiz-Mendez, J.J., Lawrence, G.B., 2000. Forest soil chemistry and terrain attributes in a catskills watershed. Soil Sci. Soc. Amer. J. 64, 1804–1814.

Kahklen, K., Moll, J., 1999. Measuring Effects of Roads on Groundwater: Five Case Studies. U.S.D.A. Forest Service, Technology and Development Program. SDTDC 9977-1801, San Dimas, CA.

Kramer, M.G. 2001. Maritime Windstorm Influence on Soil Process in a Temperate Rainforest. Ph.D. diss. Oregon State University, Corvallis.

Lin, H., 2003. Hydropedology: bridging disciplines, scales, and data. Vadose Zone J. 2, 1–11.

Lin, H.S., 2010. Linking principles of soil formation and flow regimes. J. Hydrol. 393, 3–19.

Lin, H., Bouma, J., Pachepsky, Y., Western, A., Thompson, J., van Genuchten, R., Vogel, H.J., Lilly, A., 2006a. Hydropedology: synergistic integration of pedology and hydrology. Water Resour. Res. 42, W05301. doi:10.1029/2005WR004085.

Lin, H.S., Kogelmann, W., Walker, C., Bruns, M.A., 2006b. Soil moisture patterns in a forested catchment: a hydropedological perspective. Geoderma 131, 345–368.

Mann, D.H., Hamilton, T.D., 1995. Late Pleistocene and Holocene paleoenvironments of the North Pacific Coast. Quaternary Sci. Rev. 14, 449–471.

McGee, K.L., 2000. Effects of Forest Roads on Surface and Subsurface Flow in Southeast Alaska. M.S. Thesis. Oregon State University, Corvallis.

Meidinger, D., MacKinnon, A., 1989. Biogeoclimatic classification-the system and its application. In: Ferguson, D.E., et al. (Eds.), Proceedings: Land Classifications based on Vegetation: Applications for Resource Management. U.S.D.A. Forest Service Gen. Tech. Rep. INT-257, Moscow, ID, pp. 215–222.

Miller, R.D., 1973. Gastineau Channel Formation: a Composite Glaciomarine Deposit Near Juneau, Alaska. U.S. Geologic. Surv. Bull. 1394, Washington, DC.

Miller, M.P., McKnight, D.M., Cory, R.M., Williams, M.W., Runkel, R.L., 2006. Hyporheic exchange and fulvic acid redox reactions in an alpine stream/wetland ecosystem, Colorado Front Range. Environ. Sci. Technol. 40, 5943–5949.

Miller, M.P., McKnight, D.M., Chapra, S.C., Williams, M.W., 2009. A model of degradation and production of three pools of dissolved organic matter in an alpine lake. Limnol. Oceanogr. 54, 2213–2227.

Mulholland, P., 2003. Large-scale patterns in dissolved organic carbon concentration, flux, and sources. In: Findlay, S., Sinsabaugh, R. (Eds.), Aquatic Ecosystems: Interactivity of Dissolved Organic Matter. Elsevier Science, pp. 139–159.

Mulholland, P., Kuenzler, E., 1979. Organic carbon export from upland and forested wetland watersheds. Limnol. Oceanogr. 24, 960–966.

Muller-Karger, F.E., Varela, R., Thunell, R., Luerssen, R., Hu, C., Walsh, J.J., 2005. The importance of continental margins in the global carbon cycle. Geophys. Res. Lett. 32, L01602. doi:10.1029/2004GL021346.

National Wetlands Working Group (N.W.W.G.), 1988. Wetlands of Canada. Environment Canada, Sustainable development branch, Ottawa, Ontario, Canada. Ecological Land Classification Series 24.

Neal, E.G., Hood, E., Smikrud, K., 2010. Contribution of glacier runoff to freshwater discharge into the Gulf of Alaska. Geophys. Res. Lett. 37, L0604. doi:10.1029/2010GL042385.

Neiland, B.J., 1971. The forest-bog complex in Southeast Alaska. Vegetation 22, 1–63.

Nowacki, G., Krosse, P., Fisher, G., Brew, D., Brock, T., Shephard, M., Pawuk, W., Baichtal, J., Kissinger, E., 2001. Ecological Subsections of Southeast Alaska and Neighboring Areas of Canada. U.S.D.A., Forest Service, Alaska Region, Tech. Publ. R10-TP-75.

Palmer, S.M., Driscoll, C.T., Johnson, C.E., 2004. Long-term trends in soil solution and stream water chemistry at the Hubbard Brook experimental forest: relationship with landscape position. Biogeochemistry 68, 51–70.

Park, S.J., van de Giesen, N., 2004. Soil-landscape delineation to define spatial sampling domains for hillslope hydrology. J. Hydrol. 295, 28–46.

Patric, J.H., Black, P.E., 1968. Potential Evapotranspiration and Climate in Alaska by Thorntwaite's Classification. U.S.D.A. Forest Service, Pacific Northwest Forest and Range Experiment Station Research Paper PNW-71. Juneau, AK.

Pinay, G., O'keefe, T., Edwards, R.T., Naiman, R.J., 2003. Potential denitrification activity in the landscape of a Western Alaska drainage basin. Ecosystems 6, 336–343.

PRISM Climate Group. 2010. http://www.prism.oregonstate.edu/, Corvallis: Oregon State University.

Randerson, J.T., Chapin, F.S., Harden, J., Neff, J.C., Harmon, M., 2002. Net ecosystem production: a comprehensive measure of net carbon accumulation by ecosystems. Ecol. Appl. 12, 937–947.

Strack, M., Waddington, J.M., Bourbonniere, R.A., Buckton, E.L., Shaw, K., Whittington, P., Price, J.S., 2008. Effect of water table drawdown on peatland dissolved organic carbon export and dynamics. Hydrol. Proc. 22, 3373–3385.

USDA Forest Service, 1996. Landforms of the Alaska region classification guide. Alaska Region.

USDA Forest Service, 2008. Tongass Young-Growth Management Strategy Tongass National Forest, Region 10.

USDA Natural Resources Conservation Service, 2004. Land Resource Regions and Major Land Resource Areas of Alaska. http://www.ak.nrcs.usda.gov/technical/lrr.html.

USFWS, 2009. Classification of Wetlands and Deepwater Habitats of the United States. National Wetlands Inventory Website. U.S. Department of the Interior; Fish and Wildlife Service, Washington, D.C. http://www.fws.gov/wetlands.

Ugolini, F.C., 1968. Soil development and alder invasion in a recently deglaciated area of Glacier Bay, Alaska. In: Trappe, J.M., et al. (Eds.), Proceedings, Biology of Alder. U.S.D.A., Forest Service, Pacific Northwest Research Station, Portland, OR, Pullman, WA, pp. 115–139.

Ugolini, F.C., Mann, D.H., 1979. Biopedological origin of peatlands in southeast Alaska. Nature 281, 366–368.

Viereck, L.A., Dyrness, C.T., Batten, A.R., Wenzlick, K.J., 1992. The Alaska Vegetation Classification. U.S.D.A. Forest Service, Pacific Northwest Research Station, Gen. Tech. Rep. PNW-GTR-286.

Worrall, F., Burt, T., Adamson, J., 2003. Controls on the chemistry of runoff from an upland peat catchment. Hydrol. Proc. 17, 2063–2083.

Worrall, F., Burt, T.P., Jaeban, R.Y., Warburton, J., Shedden, R., 2002. Release of dissolved organic carbon from upland peat. Hydrol. Proc. 16, 3487–3504.