Wetlands of Cook Inlet Basin, Alaska: Classification and Contributions to Stream Flow

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Dedication

To Michele

Abstract

Wetlands face threats from global change, even as protections have been institutionalized to conserve the amenities they provide. These institutional protections frequently rely on a wetland classification system to guide conservation. In the Cook Inlet Basin of Alaska, USA (CIB), for example, best wetland assessment practices require the use of a classification system to ensure the conservation of the most valuable amenities. However, the systems used widely in the USA outside of Alaska, where peatlands are not common, inadequately describe the diversity of peatlands on the glaciated landscape of the CIB. Here I present a new Cook Inlet Classification system (CIC) organized around the hydrogeologic settings of wetlands in the CIB. The variables most strongly correlated with ecological differences within major geomorphic classes were used to construct a system supported by ample field data. The CIC produced greater within-class similarity than other widely-used systems, likely due to the overriding importance of the seasonal variability of water levels in CIB peatlands. The CIC has been mapped over an area of 7600 km^2 and has guided wetland functional assessments in the CIB, and may be adaptable to any region supporting peatlands on glacial landforms.

The harmful effects of a warming climate on aquatic resources may be partially ameliorated by discharge of shallow groundwater from peatlands to streams. This potential benefit of peatlands was investigated in the CIB using end-member mixing analysis (EMMA) and a sensitivity analysis of a water budget to quantify the contribution from extensive peatlands formed over glacial lake deposits to stream flow during the dry-season. Although peatlands in this hydrogeologic setting are common globally, the discharge from them is challenging to quantify. A spatially distributed sampling protocol at a single point-in-time produced a reliable EMMA showing that over half of stream flow on a day during the summer dry period originated near the surface of peatlands. This finding is being used to establish the value of peatlands for buffering increases in stream temperature, which have exceeded tolerances of commercially important fishes in the CIB. The analysis also suggests that differences in hydrogeologic setting influence shallow groundwater hydrology in peatlands.

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Preface

This dissertation is composed of four chapters, the second two of which are published in the peer-reviewed literature as Open Access articles under the CC BY 4.0 license (Creative Commons 2013). The first chapter describes the development and analysis of a wetland classification system that has been mapped over a wide area of southcentral Alaska for use by wetland managers. The second chapter was published in the journal *Wetlands Ecology and Management* with Paul Glaser as coauthor. It evaluates the performance of the classification system against other widely used systems. The third chapter was published in the *Journal of Hydrology* with Mary Moffett, Don Siegel, and Paul Glaser as co-authors. It analyzes stream flow contributions during the dry season of the most common classes of peatlands mapped using the classification system. The fourth chapter is a brief conclusion.

The first chapter adds rigor to the development of a wetland classification system intended for mapping and management. The chapter begins with an extensive description of the climatic and geomorphologic setting of the region. It then describes the rationale behind the choices of the classification criteria, augmented with a careful analysis using data collected across the region to demonstrate how well those criteria define wetlands sharing similar characteristics. The analysis begins by showing how the major classes of wetlands are related, and ends by demonstrating which variables best separate wetlands within each major class.

The second chapter continues the rigorous analysis of the reliability of the Cook Inlet wetland Classification system by testing it against three other widely used systems. It was co-authored by Paul Glaser, of the University of Minnesota, who provided many valuable insights on peatland processes, guided the framing the manuscript for a scientific audience, interpreting the results, placing them into a broader global context, and provided numerous helpful editorial suggestions. Otherwise, the conception, design, analysis, and writing are my original work. Because many of the wetlands in the region are peatlands, and because peatlands are not prevalent in other regions of the USA, the test evaluates how well the systems classify undisturbed peatlands by using ecologically relevant measures to compare the within-group similarity within the classes of each system.

The third chapter applies the classification system by analyzing how the two most extensive classes of peatlands perform in contributing to stream flow during the summer dry period, a wetland hydrologic function that is often assessed for management purposes. It was co-authored by Mary Moffett, of the US Environmental Protection Agency Mid-Continent Ecology Division lab in Duluth, Minnesota, USA, who provided valuable contributions to water sample analysis, suggested data collection locations, and protocols, and assisted in sampling; by Don Siegel of Syracuse University, who provided invaluable guidance on aquatic chemistry; and by Paul Glaser, of the University of Minnesota, who greatly helped in framing the manuscript for a scientific audience, interpreting the results, placing them into a broader global context, and provided helpful editorial guidance. Otherwise, the conception, design, analysis, and writing are my own. The literature on peatland contributions to dry-season stream flow is equivocal; the use of the mixing analysis technique can be problematic, and the quantification of evapotranspiration is often the weakest link in the water budget. In addition to analyzing peatland contributions to stream flow, this chapter shows how a spatial sampling procedure can offset problems produced by watershed fractal filtering in time series of aquatic chemistry data, and presents for the first time in the peer-reviewed English-language literature a variation on a widely-used technique of determining evapotranspiration from the diurnal variation in a water table hydrograph from a wetland.

Introduction

Ecological functions of wetlands provide important benefits to human health and well-being (Ramsar Convention 1987, Millennium Ecosystem Assessment 2005). Benefits can be preserved by strong institutional protections, which may be implemented once losses caused by human disturbance require restoration. Protection is rarely institutionalized prior to loss because if a resource is only lightly used then users may not appear to gain advantages from organizing (Ostrom et al. 1999). With restoration, which rarely, if ever, will attain original conditions (Suding 2011), an assessment is often used with a classification system to prioritize the ecological functions that provide more valuable benefits to a greater extent (Stein et al. 2009, Smith et al. 1995). Because losses are due to human disturbance, the assessment is frequently scaled along a disturbance gradient (e.g. Brinson 1995). Wetland assessment in Alaska deviates from this paradigm because, although few benefits have been lost, strong institutional protections are in place. Because ecological functions are largely intact, the conservation goal is often maintenance, which should be more effective than restoration at preserving the benefits of wetlands to society (Rey Benayas et al. 2009). Additionally, because a disturbance gradient is lacking, the focus of assessment shifts to the natural drivers in the hydrogeologic setting of the wetland. The strength of the relationship between these drivers and the classification system may determine how effectively the system can be used to identify and conserve beneficial ecological functions.

Wetland management in Alaska also differs because a large proportion of the landscape is covered by wetlands, and a large proportion of those wetlands are peatlands. Alaska has more area of wetlands than the other 49 US states combined (Dahl 1990). In regions where wetlands cover only a small portion of the landscape, disturbance to them is frequently avoidable. However, where wetlands cover large areas, avoidance of impacts is often impracticable. Because avoidance is often impracticable, an assessment of beneficial functions (functional assessment) is more often required; a requirement that is difficult to implement because assessments are frequently scored on a scale related to the degree of human disturbance. For example, the hydrogeomorphic model (HGM) is widely-used in the U.S. for functional assessment under institutionalized guidelines. HGM assessments rate functions within classes based on a hydrogeomorphic classification system. However, HGM is not intended to describe differences among undisturbed wetlands (Brinson 1995). Implementation of institutional protections in Alaska could therefore be improved if assessments were based on a classification system related to fundamental drivers of wetland ecological functions.

Peatlands, where present, are minor components of the landscape in much of the USA outside of Alaska and therefore infrequently require functional assessment. For example, an HGM classification system in wide use contains only a single class for peatlands, based on a single site in Wisconsin (Magee 1998). Because peatlands infrequently occur outside of Alaska, scientific knowledge of peatland processes has generally not been transferred to wetland functional assessment in the USA, and in Alaska the need for transferring this knowledge is increasing as the state continues to develop. Therefore, a classification system that can be used to map peatlands according to fundamental drivers of ecological function will be useful for implementing institutionalized protections of wetlands.

The wetland classification systems currently used in North America were developed for purposes not necessarily related to the drivers of ecosystem functions. The system used by National Wetlands Inventory (NWI) of the USA was created to describe wetlands with similar natural attributes in a nationwide system useful for management, inventory, and mapping while unifying concepts and terminology. The NWI system is primarily based on plant physiognomy, soils, and flooding frequency (Cowardin et al. 1979). While these factors adequately describe differences among wetlands at a national scale, they are too general for regional use. For example, two-thirds of the wetlands mapped in Alaska fall into the single NWI category of Palustrine shrub-scrub, and peatlands are not specifically addressed (Zoltai 1988).

The Canadian system was intended to group like forms together to facilitate communication with a focus on differences among boreal peatlands, but this system does not cover all boreal peatland types. The Canadian system is hierarchical, first based on five broad classes, then on air-form patterns and the morphology of vegetation (Zoltai et al. 1988). These patterns can be mapped broadly, but require refinement for detailed regional use. For example, in the Fen class, a wetland classified as a Horizontal Fen can support much variation in vegetation within its boundaries, driven by seasonal variation in water levels. Water level variability is a fundamental driver of differences among peatlands (Foster et al. 1988, Glaser et al. 1990), therefore a single class encompassing too much variability will not be useful in a functional assessment.

Recognizing the need to create a classification system related to the master variables of wetland function, a hydrogeomorphic (HGM) classification system was created for the assessment of wetland functional capacity in the USA (Brinson 1993; Smith et al. 1995). The HGM system uses inferred flow path as the hydrologic factor and broad landform descriptors as the geomorphologic factor to classify wetlands. For example, a wetland could be classified either as an outflow, inflow, or throughflow basin. This system places bogs in the geomorphic class Flats, distinguished by vertical hydrodynamics and it places fens in the class Slope distinguished by horizontal hydrodynamics. Managers in Southcentral Alaska attempting to adapt the HGM classification system to the conditions of peatlands in the region merged these two geomorphic classes into a single class: Slope/Flat (Hall et al. 2002). However, peatlands, both bogs and fens, exhibit complex interacting hydrodynamics along both horizontal and vertical flow vectors (Ingram 1983; Foster & King 1984; Siegel & Glaser 1987; Siegel et al. 1995; Reeve et al. 2001; Spence et al. 2011). Therefore, a class comprised of wetlands exhibiting a single combined hydrologic flow path, such as the Slope/Flat class, is almost certainly inadequate to describe natural ecological differences within and among peatlands. Therefore, in order to conserve the ecological benefits of wetlands to society in the unique environment of Alaska, a robust wetland classification system is needed that groups peatlands according to natural ecological differences that can be used to assess wetland functions. The first two chapters of this dissertation describe the rigorous development and testing of such a classification system.

The findings of the first two chapters are applied in the third chapter, which is an analysis of one of the hydrologic functions performed by the most extensive class of peatlands in the system. The first two chapters demonstrate that the variability of water levels in peatlands is an overriding factor driving natural ecological differences among these wetlands. The third chapter addresses the question: What quantity of dry-season stream flow originates in extensive peatlands with variable water levels? Analysis of this beneficial function of peatlands has proven difficult because diffuse contributions to stream flow cannot be measured at a point of discharge; water budgets are notoriously error-prone (Winter 1981); and end-member mixing analysis (Hooper 2003) can be confounded by watersheds acting as fractal filters on time series' of stream water chemistry data (Kirchner & Neal 2013).

Chapter 1 The Cook Inlet Classification

INTRODUCTION

Wetland classification systems are useful for mapping and management because wetlands exhibit obvious differences and these differences likely influence the value of the wetlands to society. Based on a review of the literature, many objective criteria could be chosen to separate wetland classes because different drivers are responsible for the many differences among wetlands. For example, Lugo and Snedecker (1974) report on the importance of bidirectional water flow in mangrove wetlands, and Sjörs (1950a) demonstrates a fundamental division between two classes of peatlands, bogs and fens, based on water chemistry. Although these, and many other characteristics have long been known to be important, their power to define wetland classes that exhibit similar ecological functions is rarely quantified. For example, the classification system used for a national inventory of wetlands across the USA (Cowardin et al.1979), is defined solely by using objective criteria to separate the hierarchical units. Similarly, the Canadian system begins with a literature review of different classification criteria that have been used for peatlands, such as landform, water chemistry, micro-topography, and water source (Zoltai 1988). The system then synthesizes data from several sources to show similarities and differences in water chemistry among four or five major classes, but finally relies upon “well-known concepts developed in Europe and North America” to define its five classes and 48 forms into a hierarchy composed of 70 different types of wetlands. The hydrogeomorphic classification for wetlands (Brinson 1993), is a template populated with examples from the literature showing the types of geomorphic settings, water sources, and hydrodynamics that may be used to separate classes. A similar system developed in the northeastern USA for use with the National Wetlands Inventory, named the Landscape position, Landform, Water flow path and Waterbody type (LLWW) system (Tiner 2011), provides numerous descriptors for combination with NWI, and a dichotomous key to identify classes. However, none of these classification systems present quantitative analyses using ecologically relevant measures to demonstrate the strength of class divisions. Here, findings from the literature are combined with quantitative analyses in the context of the regional hydrogeologic setting to demonstrate similarities and differences among wetland classes.

This chapter presents a classification system that has been used to map 2900 km^2 of wetlands over an area of 7589 km^2 of the Cook Inlet Basin, Alaska, more wetlands than have been mapped in 21 different U.S. states (*c.f.* Dahl 1990). With exceptions, the binomial classification system assigns wetlands to geomorphic classes defined by specific landform names and hydrologic classes defined by the average position and variation in water levels. The classes are constrained by the requirement that features be detectable on aerial imagery and other remote sensing techniques. By employing hydrology and geomorphology, the master variables of wetland function (Brinson 1993), and by demonstrating their strength at defining class divisions with quantitative analyses, this classification system groups wetlands into classes with similar ecological functions that can be assessed for management purposes.

The objective of this chapter is to describe the hydrogeologic setting, the quantitative methods, and the characteristics of the classes. Wetlands here are defined according to the criteria in the U.S. wetland delineation manual (Environmental Laboratory 1987) and its regional supplement for Alaska (USACE 2007). The term upland is used to describe areas that are not wetlands. Tidal, riverine, and mineral soil wetlands are described; however, the focus is on peatlands because they are the most extensive wetland type in the region and the least-well described for management purposes.

The regional hydrogeologic setting is comprised of the landforms and climatic gradients that influence the distribution, diversity, and development of wetlands. Nearly 1500 wetland plots were placed along these gradients to sample the diversity of wetland conditions. The plots were separated into major groups broadly defined by landforms such as tidal wetlands, riverine wetlands, mineral soil wetlands at toe-slope positions, and peatlands. This classification system was focused on peatlands, therefore other systems were adapted for non-peatland plots. For example, Rosgen’s system (Rosgen & Silvey 1996) was used for riverine wetlands, and Vince & Snow’s (1984) zones were used to define tidal wetlands. Peatland plots were assigned to one of seven more specific landform types, such as kettles and relict glacial lakebeds. Most non-peatland plots occurred in a single landscape position, foot- and toe-slopes. For these non-peatland plots and for the peatland plots, multivariate techniques and correlation analyses were used to identify the variables most strongly related to differences among plots. For example, seasonal water level variability was found to be more strongly related to differences in peatland plots than it was in non-peatland plots at foot- and toe-slope positions. Chapter 2 (Gracz & Glaser 2016) is an evaluation of the system compared to other widely used systems.

STUDY REGION

Cook Inlet Basin (CIB), Alaska lies between 59^{o}N and 63^{o}N latitude and drains to Cook Inlet, a large marine embayment formed in a rapidly subsiding fore-arc basin (Hartman et al. 1971) at the northern reaches of the Pacific Ocean. The 101,635 km^2 CIB is surrounded by glaciated mountainous terranes of diverse lithology (Silberling et al. 1994), including the highest point in North America (Sheet 1). The lowland portion of CIB is composed of sediments of Paleo- & Neogene age (65.5-2.6 mya) up to 8,700 m thick (Hartman et al. 1971) that are mantled with glacial deposits up to 2,800 m thick (Freethy and Scully 1980). Alpine glaciations of the Pleistocene (2.6 mya – 11.7 kya) originating in the surrounding mountain ranges produced a geomorphologically complex lowland landscape marked by poorly-integrated drainage patterns (Karlstrom 1964). The region supports two major fault systems and is tectonically active. The 1964 Great Alaskan Earthquake (9.4 moment magnitude) was centered just outside the CIB and had distinct hydrologic effects in the basin including the drainage of surface water features (Waller 1966, Plafker 1969). The effects extended throughout North America, and as far away as Israel (Vorhis 1967). A zone within the basin subsided more than 2 meters, and outside of the basin a zone 15 km wide was uplifted more than 11 meters by the event (Plafker 1969). Within the CIB, the net effect on the relative position of modern sea level is obscured by complex interactions among tectonic uplift and subsidence, isostatic rebound, and eustatic sea-level rise (Reger et al. 2007).

The basin has been frequently blanketed by layers of volcanic ash since at least 10.5 mya (Fournelle et al. 1994). Beginning in the Pleistocene the eruptions have been centered at four active volcanoes along the west side of Cook Inlet (Miller et al. 1998). Five tephra-producing eruptions have occurred at these volcanoes since 1986 (Alaska Volcano Observatory 2013). A notable eruption at Mt. Hayes between 3500 and 3800 ya covered the southern portion of the Susitna Valley with 1-10 cm of tephra (Riehle et al. 1990). This thick layer of ash is frequently encountered in peat profiles in the Susitna Valley and probably influences porewater movement. Because upland soils are frequently weathered in the ash, the solum is much thicker than would be expected under the cool boreal climatic regime of the CIB.

The physiography of the basin supports a complex maritime-to-continental climatic gradient. Winter minimum temperatures always fall below -40ºC in the interior, while at coastal stations they rarely drop below -20ºC (Sheet 1). Annual precipitation ranges from 300-1000 mm in the lowlands, and can be as high as 9000 mm at glaciated mountain passes (PRISM Climate Group 2011, Sheet 1). Nearly half of the annual precipitation falls from September-December, whereas less than 20% falls from April through July (Utah Climate Center 2013). Evapotranspiration can exceed precipitation in a small area of rain shadow formed by the surrounding mountains. Wetlands still occur in this pocket of moisture deficit because recharge in the surrounding mountains, where precipitation far exceeds evapotranspiration, is rapidly transmitted to the lowlands through permeable bedrock and glaciofluvial deposits (Jokela et al. 1991, Kikuchi 2013). Over most of the lowlands, however, precipitation is ample and approximately 20% of the surface is covered by peatlands.

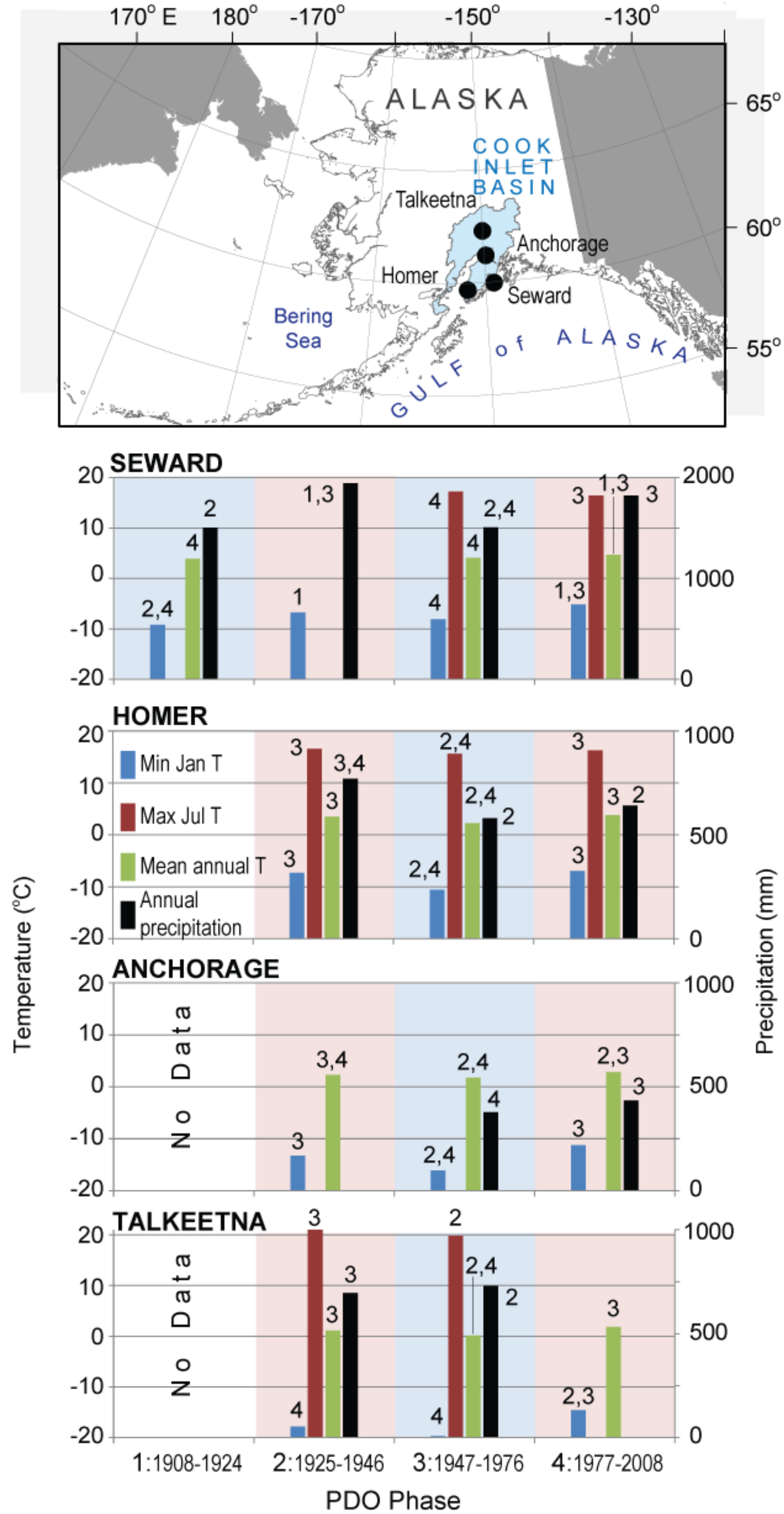
Precipitation and temperature are further affected by the phases of the Pacific Decadal Oscillation (PDO) (Mantua & Hare 2002, Newman et al. 2016). The oscillation of index values alternates between cool and warm phases. In southcentral Alaska, cool phases produce depressed winter low temperatures (cool) and warm phases produce increased precipitation (Hartmann & Wendler 2005). The effects attenuate inland. For example, near the Gulf of Alaska coast at Homer and Seward both temperatures and precipitation remain significantly different between contrasting cool and warm phases, while inland at Anchorage and Talkeetna only temperatures are consistently different (Fig. 1). Differences inland at Talkeetna are smaller and were less consistent with the 1976 shift, perhaps partly reflecting improved instrumentation. Average annual temperature differences between phases appear to be more strongly driven by differences in winter minimum temperatures, which are significantly different between all contrasting phases at all stations and are larger than summer differences. Differences appear to be strengthening. For example, differences in maximum July temperature at Seward and precipitation at Anchorage only become significant between the last two phases (Fig. 1). Perhaps the most influential differences for wetlands are the effects of precipitation variability on peatlands. Annual precipitation is near the lower limits for peatland development at many stations (500 mm; Gignac & Vitt 1994), especially considering the relatively small portion of precipitation that falls during the bulk of the growing season (climate diagrams, Sheet 1). Variability is further enhanced by PDO effects, which could produce lengthy periods of droughty conditions (Mantua & Hare 2002). For example, the annual precipitation at Homer, where the long term average is 625 mm, showed a maximum of 976 mm in 1981 during a warm phase of the PDO, but was only 402 and 395 mm for two consecutive years (1950-51) during a cool phase, and fell to a minimum of 339 mm in 1996.

Hydrogeologic Setting of Wetlands

Approximately 20% of the total area mapped in CIB is covered by peatlands, defined as where the organic layer is >40 cm thick due to saturated conditions. Peatlands have long been classified into two basic types, bogs and fens (Weber 1902, Du Rietz 1949, Kulczynski 1949, Sjörs 1950a, Moore & Bellamy 1974). Bogs are layers of peat fed primarily by direct precipitation, whereas fen peat is also fed by groundwater discharge. In porewaters of both types, lateral flow vectors predominate, however the gradient is generally downward in bogs and upward in fens. In the absence of detailed hydrological measurements, bogs are recognized as having pH < 4.2 and calcium concentrations of < 2 mg/l, and lacking fen indicator plant species. Fens have higher pH and calcium concentrations, which support plants that cannot tolerate the acidic, low calcium environment of bogs. (Sjörs 1950a, Glaser 1992). Typical peatlands are mixtures of fen and bog peat, often with a layer of fen peat underlying a surface layer of bog peat. Bogs have been mapped over at least 18 000 ha in the CIB.

The geomorphic setting of a wetland will affect porewater chemistry by influencing flow paths and volumes of groundwater discharge. The geomorphic setting of a wetland can be an important component of a classification system because geomorphologic variables may interact with other physical, chemical, and biological variables to define ecologically distinct wetlands (Brinson 1993, Bridgham et al. 1996, Mitsch & Gosselink 2007). On the Cook Inlet Lowlands, geomorphic setting is frequently

Figure 1. The effect of PDO phases on climate at four stations in CIB. The stations are shown on the map of Alaska (top). Cool phases are shown with a blue background, warm phases with pink, and years of each numbered phase are shown along the x-axis. Temperatures are shown along the left-hand axis, and precipitation on the right. Bars show: average daily minimum temperature for January (blue); average daily maximum temperature for July (red); average annual temperature (green); and annual precipitation (black). Numbers above bars indicate significant differences among PDO phases using the Mann-Whitney U-test with α < 0.05 corrected for multiple comparisons using the Holm-Bonferroni method. Only the bars with significant differences are shown.



controlled by glacial landforms, which are not distributed evenly throughout the CIB. Therefore, geomorphic differences interact with climatic gradients to control wetland distribution, diversity, and development. The glacial landforms on the CIB lowlands can be divided into six general types, in order of decreasing extent: 1) lakebeds; 2) foot and toe-slopes on glacial till; 3) kettle and knob terrain; 4) drainageways, 5) outburst flood sediments or sediments of uncertain origin; and 6) modified deposits of older glaciations.

The lakebeds occur as terraced features on the western half of the Kenai Peninsula (Reger et al. 2007) where precipitation is moderate and temperature moderated by maritime influences. Lakebeds have also been mapped at low-resolution in the Susitna Valley (Karlstrom 1964) where climate is more continental. Extensive peatlands likely have formed on the lakebeds by the process of primary peat formation, where poorly-drained sediments enhance the saturated conditions that retard decomposition (Rydin & Jeglum 2006). Wetlands on lakebeds are extensive: these landforms underlie 18% of the total number of wetland polygons mapped, but cover 26% of the area mapped as wetland.

Foot and toe-slopes on glacial till are found primarily in the southern portion of the area mapped, where hummocky till deposits abut steeper terraced surfaces that were not covered by the glacial advances of the MIS II stage (14-29 ka, Lisiecki & Raymo 2005), and perhaps not during MIS stage IV (71-57 ka). Precipitation exceeds evapotranspiration in this area, however water tables are typically deeper in these geomorphic positions and peat generally does not accumulate. Wetlands are probably fed primarily by shallow groundwater percolating through more permeable soils developed in the thick volcanic ash deposits lying upslope. The groundwater probably discharges to the surface when it encounters the less-permeable till deposits on the gentler lower slopes. Groundwater may also discharge directly to the surface through more permeable lenses in ice-contact deposits. Wetlands overlying mineral soil at these foot- and toe-slope positions comprise 17% of the wetland area mapped.

Kettle-and-knob terrain is found throughout the lowlands near terminal moraines and ice-contact deposits of the last glaciation. Deposits of significant extent occur on the south- and northwestern Kenai Lowlands and west of Knik Arm. The climate over these deposits varies; the moderating influence of the Gulf of Alaska on winter low temperatures rapidly attenuates northward and precipitation is higher in the south and further west of the rain shadows of the Kenai, Chugach, and Talkeetna mountain ranges (Sheet 1). Kettle features often grade to lakebed features toward the direction of ice origin. Open-basin kettles comprise 26% of the total number of wetland polygons and cover 16% of the area mapped as wetland. Closed-basin depressions are smaller, they comprise 14% of the polygons but only 3% of the wetland area.

Relict drainageway features are common throughout the Cook Inlet Lowlands. These are features where meltwater from formerly extensive glaciers shaped valleys whose form no longer matches the scale of modern fluvial processes. Modern streams often flow in the underfit valleys, which are frequently filled with fen peat and supported by groundwater discharging through stratified fluvial deposits. Drainageways comprise 12% of the total number of polygons and cover 11% of the area mapped as wetland.

Drumlin or mega-flute-like features that have not been mapped or described in detail elsewhere are found in the Susitna Valley, especially the area west of the town of Talkeetna. Approximately one-third of the peat mapped as bogs has developed in the low-lying areas between the drumlin-like features. The features are composed of poorly-sorted till, at least near the surface, and occur in the form of low ridges (5-20 m high) that are elongate (1-2 km long and 100-300 m wide) and oriented parallel to the direction of Pleistocene glacier flow. These features are flat-topped, i.e. they lack the typical streamlined profile of drumlins, and they lie in a matrix of anastomosing channel-like features (100-300 m wide), which may have been scoured from the till during the initial stages of a glacial-lake outburst flood that drained down the Susitna Valley (Williams & Galloway 1986). The features may be modified drumlins or megaflutes, or could be interpreted as remnants of the original till-plain surface that was eroded during the brief initial period of the outburst flood, before the flow became incised into pronounced channels. Regardless of the genesis of the features, the bogs between them likely formed because precipitation increases northward up the Susitna Valley, its variability is less affected by PDO phases, and it falls more abundantly during the months of the growing season. The wettest months nearby in Talkeetna are July-September, in contrast, further south the wettest months are September-November (Sheet 1).

The glacial deposits in the area between Palmer and Wasilla have also been reported to be of outburst-flooding origin, but their genesis is not as well-established (Wiedmer et al. 2010, Reger et al. 2011, Wiedmer et al. 2011). Especially controversial is the genesis of a set of about 25 regularly-spaced wave-form ridges oriented transverse to Pleistocene ice flow and with crests of progressively lower amplitude down-valley: the Very Large Dunes (VLDs) (Weidmer et al. 2010). The VLDs are up to 7 km in length, cover an area of about 100 km^2, are 900 m crest-to-crest, and have heights ranging down-valley from 34 m to 5 m (Sheet 1). Peatlands formed in the troughs between the VLDs support fen porewater chemistry, but bogs have developed at the western-most extreme of the VLDs, where precipitation is higher. The fen chemistry suggests ample groundwater flow through permeable unconsolidated deposits. Precipitation roughly balances with evapotranspiration in this area and winter low temperatures are only weakly moderated by maritime influences. These peatlands cover 0.7% of the area mapped as wetland. In the area to the east of the VLDs, evapotranspiration exceeds precipitation, and the peatlands there are fed by groundwater recharged through the vertically-oriented strata of the arkose of the adjoining mountains, where precipitation is much higher. Many peatlands are formed in closed-basin depressions of permeable outwash, which readily transmits groundwater (Kikuchi 2013). These peatlands cover 0.4% of the area mapped as wetland.

Modified deposits of older glaciations (pre-MIS 2 (29 ka), and probably pre-MIS 4 (71 ka)), are discontinuously distributed in the Caribou Hills, a highland physiographic sub-province on the southern Kenai Peninsula (Karlstrom 1964). These perched deposits of older till are separated from lower-elevation sediments of the last glaciation by steep, well-drained slopes that generally lack unconsolidated deposits. Precipitation is greater over the Caribou Hills, and more frequently occurs as snow than over the adjacent lowlands. Snow patches linger into summer during some years and temperature is only partially moderated by the shallow marine waters of nearby Cook Inlet and Kachemak Bay. Wetlands form over discontinuous patches of poorly-sorted till, where low hydraulic conductivity impedes drainage and the snow-free season is brief. Peat is generally absent, although minor amounts have accumulated in low topographic positions along abandoned drainage courses and in depressions. These mineral soil wetlands cover 0.8% of the area mapped as wetland.

METHODS

Recognizing that geomorphology and hydrology are together the “master variables of wetland function” (Brinson 1993), a classification system using a geomorphic and a hydrologic component and that could be mapped across a wide area with limited access was desired. Wetlands were first named for the surrounding and underlying landforms they occurred on using the geomorphic units described above, which can be identified on aerial photographs. It was hypothesized that wetlands on these different landforms would have different water chemistry. It was also hypothesized that water level variation was an important hydrologic variable, and this variable could be assessed directly by measuring the depth to the water table, and indirectly by recording the percent cover of plants growing in representative plots and using the Wetland Indicator Status assigned to each plant species. Therefore, vegetation, water level, and chemistry data were collected at homogeneous areas of wetland to determine if these variables defined strong classification criteria.

Unlike in many regions where single wetlands frequently comprise discrete units encompassing areas of a few hectares, in Cook Inlet Basin, single areas of wetland can be extensive complexes (>50,000 ha) spanning diverse geomorphic settings. For example, on the southern Kenai Peninsula a single contiguous boundary between wetland and upland conditions can be drawn around an area of 100,000 ha that encompasses the floodplains of rivers, high elevation plateaus, extensive peatlands on lakebeds, discharging groundwater over mineral soil slopes, and headwater fens (Sheet 1). To refer to this large diverse area as a single wetland is impractical. Although endpoints, such as floodplain and extensive peatland, are readily recognizable as different wetland types, boundaries between them may be difficult to delineate where gradients are gentle. Sampling was therefore conducted in plots placed in homogeneous areas of vegetation where endpoints appeared to be distinct.

Field data collection

To avoid bias, sampling areas were chosen each year so that the complete range of landforms were sampled in proportion to their occurrence on the landscape. Physical access and land ownership occasionally constrained plot selection, but these constraints probably did not introduce significant biases in data collection. Our primary aim was to sample from a plot representing consistent environmental conditions, as represented by relatively homogeneous vegetation. Polygons exhibiting uniform wetland conditions had been delineated on air photos prior to field visits for mapping purposes. The visits were designed to field-check the polygon boundaries and to collect data to guide the selection of classification criteria and to describe the diversity of wetlands present in the Basin.

Individual plots were sited in areas of homogeneous vegetation, guided by air photo signatures and refined by conditions observed during the field visits. Where human disturbance is largely absent, environmental gradients frequently occur over short distances, as expressed by distinct changes in plant species composition. Therefore, the sampling challenge was almost always finding an area with a sufficiently large patch of homogeneous vegetation to accommodate a sufficiently-sized plot while avoiding species from nearby patches that were of distinctly different composition or in ecotones. Where the scale of patches of homogeneous vegetation covered larger areas, such as in forested plots with an understory of tall alders, a larger plot size was required to completely represent all the plants in the homogeneous area. At open peatlands where low shrubs and herbs were dominant, patches were smaller, therefore a smaller plot size could simultaneously represent the full range of species present and avoid sampling from nearby areas of different species composition. For example, in plots dominated by low shrubs and herbaceous vegetation, plot size nearly always approximated 10 x 10 m, and in tall shrub and forested plots, plot size approximated either 20 x 20 m or 30 x 30 m, based on the scale of patches observed. Smaller plots were used in forests where a closed canopy covered a simple herbaceous layer, and larger plots were required when the canopy was open and interspersed with tall shrubs. The square shapes were often distorted to accommodate the pattern of patches and still achieve an equivalent plot area (e.g. 100, 400, 900 m^2). At each plot, percent cover was visually estimated to the nearest ten percent to at least the species level. When cover was less than eight percent, values were recorded to the nearest one percent. Taxa present at less than 0.5% cover were recorded as 0.1%. Technicians frequently re-calibrated their percent cover estimates against each other and the primary investigator, especially at the beginning of each sampling season.

In addition to plant cover, the water level below the surface was measured in a small hole dug for the purpose, and when the water level was less than 30 cm from the surface, specific conductance (25^{o} C) and pH of the water was also measured in the same hole using a YSI 63 meter calibrated between measurements and cleaned daily. When surface water was present, chemistry and depth were measured from it. Soils data were also collected to help characterize the wetland classes. The thickness of the organic layer was recorded and layers of volcanic ash greater than 2 cm thick were noted. In plots with deep peat deposits, organic layer thickness could only be measured as a minimum value depending on the length of the sampling tools carried to the site. Peatlands have organic soils, and an organic soil (Histosol) is defined as one with an organic horizon greater than 40 cm thick (Soil Survey Staff 1999). In non-organic soils the depth to redoximorphic features was recorded at a subset of plots. Overall, 1477 plots were sampled using this methodology. Further, water samples were collected at a representative subset of peatlands and analyzed for, at minimum, major cations, anions, and δD and $\delta^{18}O$.

Prevalence Index and class assignment

Plant Prevalence Index was calculated for each plot (USACE 2007) to be used a proxy for the seasonal variation in water levels. Prevalence Index uses the wetland indicator status assigned to many plant taxa in a calculation based on percent cover as a method to satisfy the vegetation criterion for definition of a wetland for regulatory purposes. The index ranges from 1-4, with lower values indicating a higher percent cover of plants that are wetland obligates (occur in wetlands > 99% of the time). To calculate the Plant Prevalence Index for a plot, each decimal cover value for each plant taxon is multiplied by the indicator status for that taxon, the values are summed, and the sum is divided by total plant cover in the plot. A value greater than three indicates that the plot may not be a wetland according to the criterion. Lower values indicate stable water levels nearer the surface and higher values suggest deeper, more variable water levels (Gracz & Glaser 2016).

Because the variation of water levels was being tested as a classification criterion, hydrologic classes were assigned during field visits to represent water level variability. These classes were represented by numbers, with lower values representing plots presumed to have more stable water tables closer to the surface for a longer portion of the growing season, and higher numbers representing plots with deeper, more variable water tables. Geomorphic classes covering more extensive areas support a greater number of hydrologic classes, although a lower numeric value is always assigned where the water table was inferred to be elevated for a longer period of the growing season. The physiognomy of the plant community, and the presence of water at or near the surface, both of which can be detected on aerial photographs, helped determine the numeric value of the hydrologic class. For example, a hydrologic class = 2 was assigned to plots where the water table was at or near the surface for much of the growing season; in peatlands, these plots are typically dominated by sedges and show darker-colored signatures on the photographs. Forested plots were assigned higher values.

At foot-and toe-slopes on glacial till, the geomorphic class was named Discharge Slope, and this class contains most of the non-peat wetlands found in the region. On Discharge Slopes, water level variation occurred uniformly deeper in the soil profile and did not appear to be related to differences in plant species among plots. Therefore, the hydrologic classes in Discharge Slopes were based on the dominant plant species in the overstory, which can be remotely-sensed for mapping purposes. For example, a plot dominated by willows (*Salix* spp., often *S. barclayi*) was assigned a vegetation class **S**, and one dominated by black spruce (*Picea mariana*) was assigned to the class **M**. Combinations of seven species of plant dominants were sufficient to name nearly all of the hydrologic classes on Discharge Slopes. In the geomorphic classes Riverine and Tidal, class names were assigned based on other classification systems; these are described below, but were not a focus of the analysis. Additionally, two uncommon geomorphic classes, Late Snow Plateaus (non-peatlands) and Floating Islands (peatlands), were not divided into subclasses because they were relatively uniform.

Analysis

Multivariate ordination techniques such as DCA and NMS are used to calculate axis scores based on differences in plant species composition and abundance (percent cover). Those axis scores should be proxies for environmental differences among plots, and therefore the environmental variables that correlate most highly to scores on axes explaining the most variance should be the most useful in a classification system. The multivariate analyses of plant cover data were not used to classify plant communities, a common use of such analyses, but only to determine which of the environmental variables, especially the chemistry variables pH and specific conductance, and Prevalence Index, the proxy for water level variation, could be most useful for classification.

Detrended Correspondence Analysis (DCA) was first used to examine the degree to which major groups of wetlands separated, such as tidal wetlands, wetlands only influenced by the extreme tides of the 18.6-year tidal cycle, riverine wetlands, and other freshwater wetlands. Broad differences in chemistry and plant species richness among the geomorphic classes were then examined, and a Quadratic Discriminant Analysis (QDA) was used to assess the ability of the two water chemistry variables, pH and SC, to predict geomorphic class membership among non-riverine freshwater wetlands. QDA is a non-parametric classification technique that uses non-linear equations to delineate class boundaries (Sanchez 2013). Prior probability of class membership in QDA was set as the number of plots in each class divided by the total number of plots.

The primary objective of the subsequent analyses was to determine if variation in water levels is a strong driver of differences among all non-riverine freshwater wetlands, both peatlands and non-peat wetlands. The strength of the relationships helped evaluate hydrologic class assignments. DCA and Non-metric Multidimensional Scaling (NMS) were used in PCORD 6.08 (McCune & Mefford 2011) with plant cover data from peatland and non-peatland plots to compare the correlation of scores for plots (i.e. not plant species) on axis one with the hydrologic class membership and Prevalence Index. DCA calculates axis scores for matrixes of entities (plots) by attributes (percent cover of taxa) using reciprocal averaging (RA) and forced removal of the arch structure produced by RA in the second and subsequent axes (Gauch 1982). Default conditions provided by PC-ORD were used for DCA except that rare species were down-weighted using the default values provided by the software. An alternative to DCA, NMS is an iterative search for the ordination matrix with distances minimized compared to the dissimilarity (Bray-Curtis) in the original matrix. The difference between the ordination distances and the original dissimilarity is expressed as stress (McCune & Mefford 1999). A random starting point and 250 iterations in 6-dimensions were used to find the optimal dimensionality and scores of the ordination matrix. Additional dimensions were not used if they reduced stress by less than 5%. A Monte-Carlo simulation using 250 runs was compared to real data to assess departure from random organization.

Prevalence Index (PI) is a proxy for water level variation (Gracz & Glaser 2016). If scores on the axis explaining the most variance among the plots are highly correlated to PI, then water level variation explains important ecological differences among plots. Pearson’s r was used to assess correlation of PI with scores on axis one. If PI correlated highly with scores on axis one, then distinct hydrologic classes should group plots with similar values of PI. Kruskal-Wallis and pairwise Dunn tests were used to evaluate differences in PI among hydrologic classes.

Once classes were defined by geomorphic and hydrological variables, idealized landscape cross sectional drawings were created to facilitate visualization of the most common wetland classes. The drawings include selected common plant species that occur in each class, based on frequency of occurrence and average percent cover. Therefore, although plant cover data were used extensively to evaluate and select classification criteria, the classes themselves are defined by only by geomorphology and hydrology, and these classes may or may not be strongly related to any specific plant associations that may be defined for the region.

Elevation and Slope

Bare earth models created from Light Detection and Ranging (LiDAR) data flown by the Matanuska-Susitna Borough during May, 2011 (Matanuska-Susitna Borough 2012) were used to measure elevations and determine slopes. The LiDAR data were collected at a nominal pulse spacing of 0.6 m though overlapping flight lines, meeting US Geological Survey and Federal Emergency Management Agency standards. The bare earth model was constructed at 1 m resolution, the true nominal pulse spacing of the laser. The vertical reference datum was North American Vertical Datum of 1988 (NAVD88).

RESULTS

DCA ordination

After a single outlier plot was eliminated (a near monoculture of the uncommon mannagrass *Glyceria grandis* S. Watson), the second run of the DCA ordination identified 14 plots that forced the remaining plots to have nearly identical scores on the first DCA axis. The 14 plots were dominated by halophytes, plants influenced by the daily oceanic tides. Once those 14 plots were removed from the analysis, the third DCA ordination showed weak separation along the second axis of mineral soil wetlands (lower scores; n = 257) from riverine wetlands, those along rivers and streams (higher scores; n = 142). Nine plots influenced by only the 18.6-year tidal cycle plotted in a generally intermediate position on the ordination diagram (Figure 2). Peatland plots (n = 1054) likely did not form a distinct cluster because many plants occur on both peatlands and non-peatlands. Although groupings were indistinct, likely due to the generalist

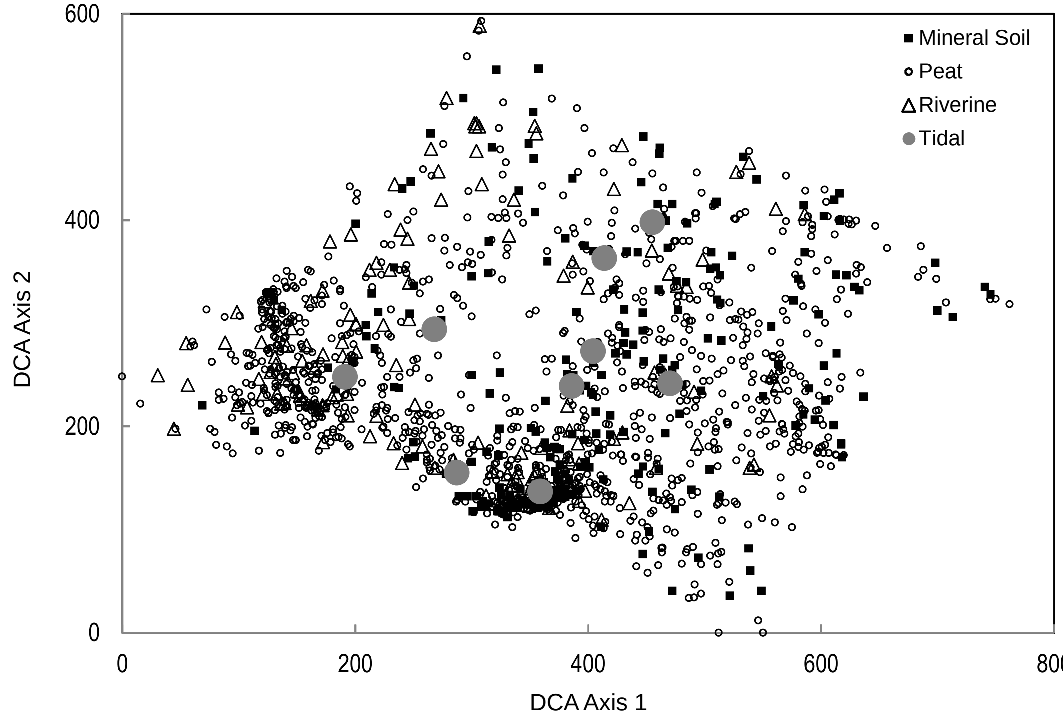


Figure 2. DCA ordination excluding plots dominated by halophytes and the mannagrass plot. General wetland categories are indicated by the legend. The "tidal" plots are influenced by the extreme tides of the 18.6-year cycle; please refer to the discussion under Tidally-Influenced Drainageways (p 34).

nature of boreal taxa, axis one scores exhibited a strong inverse correlation to PI (Table 1). Common plants with high scores on axis one were species that are tolerant of saturated conditions, such as: *Rhynchospora alba* (L.) Vahl, *Utricularia intermedia* Hayne, *Menyanthes trifoliata* L. and *Carex livida* (Wahlenb.) Willd.. Common plants with low scores on axis one were species that grow in drier conditions, such as: *Gymnocarpium dryopteris* (L.) Newman, *Dryopteris expansa* (C. Presl.) Fraser-Jenkins & Jermy, *Achillea millefolium* L. var. *borealis* (Bong.) Breitung, and *Heracleum maxium* W. Bartram.

Table 1. Correlations of scores on axis one with PI and other ordination metrics. Axis 1 vs. PI is the Pearson correlation between score on axis one and Plant Prevalence Index. All correlations were significant at $p << 0.001$. Axis 1 c.d. is the coefficient of determination between axis one scores and Bray-Curtis similarity. Axis 1 stress is the difference between the ordination distances and the similarity. 2d-3d stress is the reduction in stress between a 2-d and 3-d NMS solution. The random peat runs used a random selection of the same number of peat plots as mineral soil plots (n=257) in 10 independent runs of NMS.

		DCA & NMS		NMS	
	Run	Axis1 vs. PI	Axis1 c.d.	Axis 1 stress	2d-3d stress
DCA	All	-0.84	.201	-	-
	Mineral	-0.74	.272	-	-
	Peat	-0.84	.204	-	-
NMS	All	-0.80	.242	34.7	4.89
	Mineral	-0.67	.338	40.4	7.32
	Peat	-0.83	.241	37.2	5.76
	Random peat	0.84[1]	.246	36.6	5.74

[1]Absolute value. Some correlations were positive whereas others were negative in the ten runs.

Geomorphic classes

With the Tidal and Riverine plots removed from further analyses, the remaining geomorphic classes show differences in pH and specific conductance (SC) with generally higher values in the non-peat geomorphic class of Discharge Slope and in the peatland class Drainageway, and lower values in the peatland class Depression. Plots in the classes Spring Fens, VLD Troughs, and Kettles exhibit progressively lower values in both pH and SC, a trend that matches the inferred strength of the influence of groundwater in the respective hydrogeologic settings of these peatlands (Figure 3).

Spring Fens and VLD troughs are found in areas of lower precipitation over permeable unconsolidated deposits, whereas Kettles are widespread, often formed over less-permeable glacial till. However, values among classes are broadly overlapping, and wetlands in different classes may exhibit the distinctive chemistry indicating bog conditions (Figure 4). Further, QDA shows that knowledge of pH and SC alone is not sufficient to predict geomorphic class membership (Table 2). The geomorphic classes of the CIC are compared to classes of other classification systems in Chapter 2.

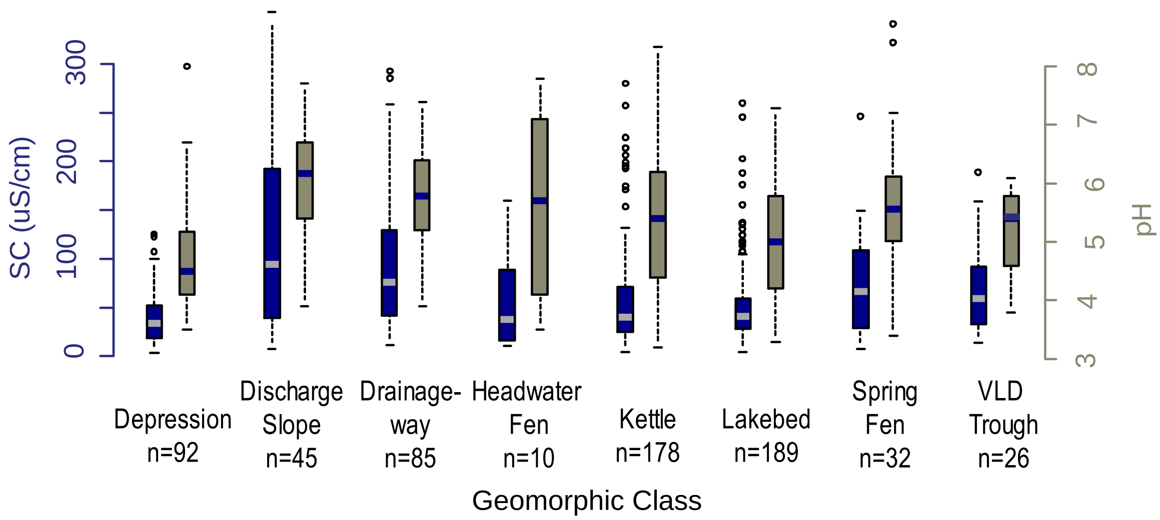


Figure 3. The relationship of pH and SC to geomorphic classes. Darker boxes are SC (LH axis) and lighter-colored boxes are pH (RH-axis). Boxes enclose the inner two quartiles of values. The horizontal lines inside the boxes are median values, and the whiskers extend to the last value within 1.5 times the inner quartile range. Values outside of the whiskers are plotted as circles.

Table 2. Confusion table for the Quadratic Discriminant Analysis of the ability of pH and SC to predict the geomorphic class of 657 plots. Numbers are the number of plots. The overall misclassification rate was 0.696.

	Predicted Geomorphic Class								
Original Class	Depress	D'way	H Fen	Kettle	Lakebed	VLD T	D Slope	Spring Fen	**Total**
Depression	29	2	0	2	59	0	0	0	92
Drainageway	9	19	0	9	45	0	3	0	85
Headwater Fen	1	1	0	2	6	0	0	0	10
Kettle	37	10	0	19	110	0	2	0	178
Lakebed	41	10	0	9	129	0	0	0	189
VLD Trough	4	2	0	3	17	0	0	0	26
Discharge Slope	4	9	0	10	18	0	4	0	45
Spring Fen	2	3	0	7	20	0	0	0	32
Total	127	56	0	61	404	0	9	0	657

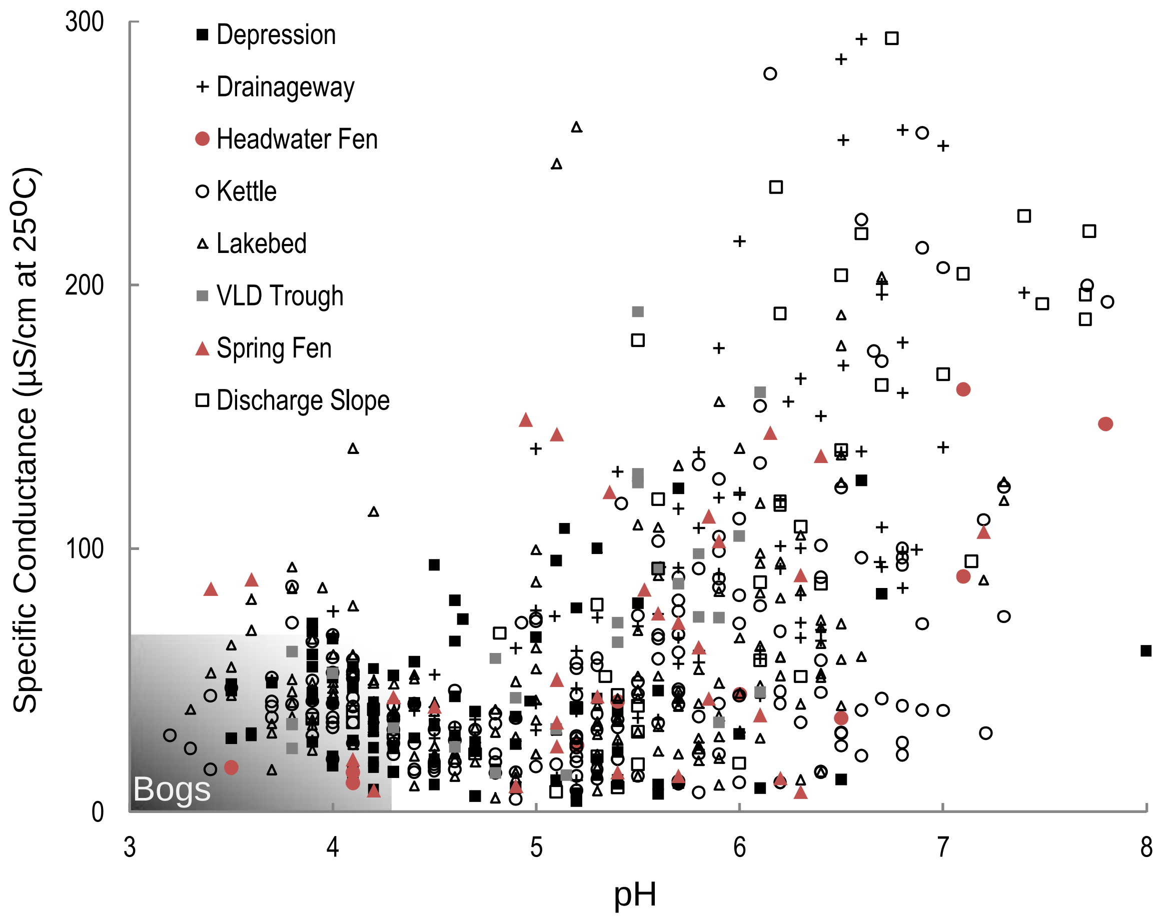


Figure 4. Specific conductance and pH at 657 wetland plots in the Cook Inlet Lowlands classified according to geomorphic class. The zone of bog chemistry is indicated by the shaded area near the origin (pH < 4.2 and specific conductance < ~50 µS/cm).

Although vascular plant species richness was generally uniform, there was a distinct difference between non-peatland and peatland geomorphic classes. The non-peat classes of Discharge Slope and Late Snow Plateau show median values of richness above the inner quartile range of the other classes (Figure 5). Riverine wetlands, which have both peat and non-peat plots, show intermediate values, and the peatland class Depression shows the lowest values. These patterns likely reflect the stronger influence of groundwater in non-peatlands versus in peatlands, which is demonstrated by the higher SC measured in Discharge Slope wetlands versus the low SC measured in Depressions (Figure 3). The groundwater likely transports minerals to plants that cannot tolerate the low concentrations found in peatland porewaters, especially those peatlands exhibiting bog chemistry.

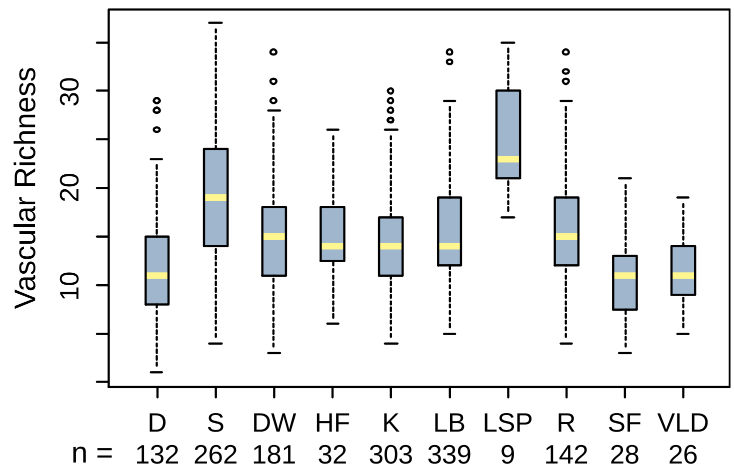


Figure 5. Vascular plant richness in geomorphic classes. **D** = Depression; **S** = Discharge Slope; **DW** = Drainageway; **HF** = Headwater Fen; **K** = Kettle; **LB** = Lakebed; **LSP** = Late Snow Plateau; **R** = Riverine; **SF** = Spring Fen; **VLD** = VLD Trough. Sample n given at bottom. Box symbols as in figure 3.

Peatland classes

Using only peatland plots in a DCA, plots assigned to different hydrologic classes are arrayed in descending order along the first DCA axis, which has a strong inverse correlation with PI (r = -0.84), suggesting that the classes describe wetlands with distinct hydroperiods (Figure 6, Table 1). Common plants with high scores on axis one were many of the same species that are tolerant of saturated conditions found in the ordination shown in Figure 2: *Rhynchospora alba* (L.) Vahl, *Utricularia intermedia* Hayne, *Menyanthes trifoliata* L. and *Carex livida* (Wahlenb.) Willd.. Common plants with low scores on axis one were a slightly different set of species than found in the ordination shown in Figure 2, but that also grow in drier conditions and that are not commonly associated with peatlands such as: *Menziesia ferruginea* Sm., *Dryopteris expansa* (C. Presl.) Fraser-Jenkins & Jermy, *Sambucus racemosa* L., and *Streptopus amplexifolius* (L.) DC..

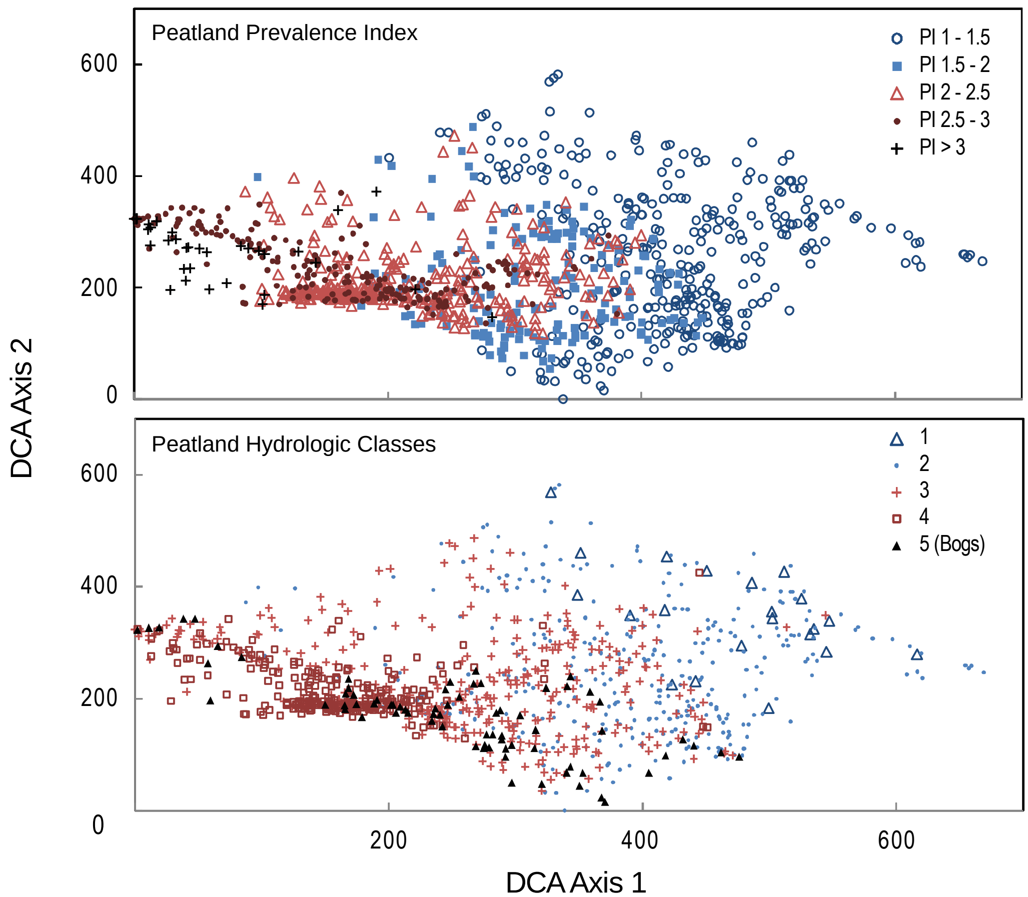


Figure 6. Ordinations of peatland plots by prevalence index (top) and hydrologic class (bottom). Symbols according to the legends.

Pairwise comparisons of rank sum of PI among the hydrologic classes show that the classes form distinct groups, because PI is significantly different between most hydrologic classes, shown by the increasing numeric values for hydrologic class following increasing values of PI (Table 3). Exceptions are the comparison of the class defined by open water with the class defined by water at the surface for much of the growing season, and the comparison of bogs with shrubby peatlands (Table 3). Besides these two exceptions, hydrologic classes are strongly related to variations in hydroperiod as represented by PI, which appears to explain a relatively large portion of the variation in scores along axis one among peatland plots. These strong relationships justify the use of the numeric hydroperiod classes to distinguish among peatlands. Geomorphic classes exhibit broadly overlapping differences in chemistry, however, the seasonal variation in water levels explains more of the difference among plots.

Table 3. Rank sum of PI in comparisons among peatland classes. Median values of PI are listed for each hydrologic class: 1- open water; 2- water at or near the surface, sedges; 3- deeper water table, shrubs; 4- deepest water table, forest. Matrix values are p-values for Dunn's pairwise tests.

Hydrologic Class	Rank Sum	1	2	3	4	Bogs
1	1.01	-	0.08	<0.001	<0.001	<0.001
2	1.23	-	-	<0.001	<0.001	<0.001
3	2.13	-	-	-	<0.001	> 0.4
4	2.45	-	-	-	-	<0.001
Bogs	2.02	-	-	-	-	-

Non-peatlands

In contrast, a separate DCA ordination using only the non-peat wetlands produced a lower correlation of PI to scores on axis one, but a higher portion of the variance was explained by this axis than in the ordination of the peatland plots (Table 1). Common plants with high scores on axis one were once again associated with wetter conditions, but were mostly a different set of species, such as: *Menyanthes trifoliata* L., *Trichophorum cespitosum* (L.) Hartm., *Picea mariana* (Mill.) Britton, Sterns & Poggenb., *Rhododendron tomentosum* Harmaja, and *Chamaedaphne calyculata* (L.) Moench. Common plants with low scores on axis one were associated with better drainage, such as: *Chamerion angustifolium* (L.) Holub, *Salix alaxensis* (Andersson) Coville, *Sambucus racemosa* L., and *Gymnocarpium dryopteris* (L.) Newman. However, all but one of the non-peat plots had a PI of greater than two, indicating drier conditions overall. A plot where PI = 2 is analogous to a wetland indicator status of "facultative wet" (a plant that occurs in wetlands 67-99% of the time).

Hydrologic classes in the geomorphic class Discharge Slope, the class with most of the non-peat wetlands, show distinctively higher median values for PI than in the peatland classes (see: Plant Prevalence Index in Common Wetland Mapping

Components, Sheet 1). The lower correlation combined with the uniformly high PI values suggest that a moisture gradient explains a smaller portion of differences in plant species composition in non-peatland plots than in peatlands. However, the contrasting results could possibly be an artefact of the differences in sample size between the peatlands and non-peat wetlands. The latter possibility is examined using NMS.

Non-metric Multidimensional Scaling

Overall, NMS produced similar results in all metrics as in the DCA ordinations, indicating robust trends. In NMS, the correlation of PI with scores on axis one showed the same pattern as in DCA: the correlation was lower for the ordination using the non-peat plots versus all of the plots, again suggesting that a moisture gradient exerts less of an influence on differences among non-peat plots (Table 1). A weaker influence of the moisture gradient is further supported by the greater variance explained by axis one and the greater stress. Because the first axis is less strongly related to a moisture gradient, its stronger explanatory power could suggest a stronger role for other influences. The greater stress suggests a weaker influence for the role for any individual variable, including moisture. Moreover, the reduction in stress from a 2-dimensional to a 3-dimensional NMS solution was also greater, further demonstrating that a more complex suite of variables shaped differences among non-peat wetlands. A NMS ordination using only the peatland plots restored the high correlation of PI with scores on axis one with lower stress (Table 1). However, these results of the multivariate analyses using peat and non-peat plots do not address the possibility that unequal sample sizes may confound the strength of the relationships of PI to axis scores, PI, c.d., and stress.

To evaluate the effect of the unequal sample size on the ordination metrics, ten NMS ordinations were run using a random selection of the same number of peat plots as non-peat plots (n = 257). The reduced number of peat plots had little effect on c.d., stress, or the strength of the correlation between PI and scores on the first ordination axis. The strongest effect was on stress, which was slightly reduced using the lower sample n (Table 1). Therefore, the differences in correlation, c.d., and stress are not due to differences in sample size. A moisture gradient explains less variance among mineral-soil wetlands than among peatlands in the CIB.

Mineral-soil wetland classification

Three other characteristics of the analysis of mineral soil wetlands support the weaker influence of moisture in distinguishing among plots on Discharge Slopes. 1) Some dominant plants tend to occur in plots with a wider range of PI. For example, plots dominated by willow or Lutz spruce span a wide range of PI (Figure 7). 2) Other taxa form clusters along the second ordination axis, which is not strongly related to PI. For example, plots dominated by Alaska birch (*Betula neoalaskana* Sarg.) or thinleaf alder (*Alnus incana* ssp. *tenulfolia* (Nutt.) Breitung), separated more strongly along the second DCA axis (Figure 7), which has a higher c.d. (0.219) than the second axis of the peatland DCA (0.117) and is only weakly correlated with PI ($r = -0.20$, $P = 0.001$). 3) If groups defined by plant dominants are ranked according to PI, they do not consistently exhibit significant pairwise differences in rank sum (Table 4).

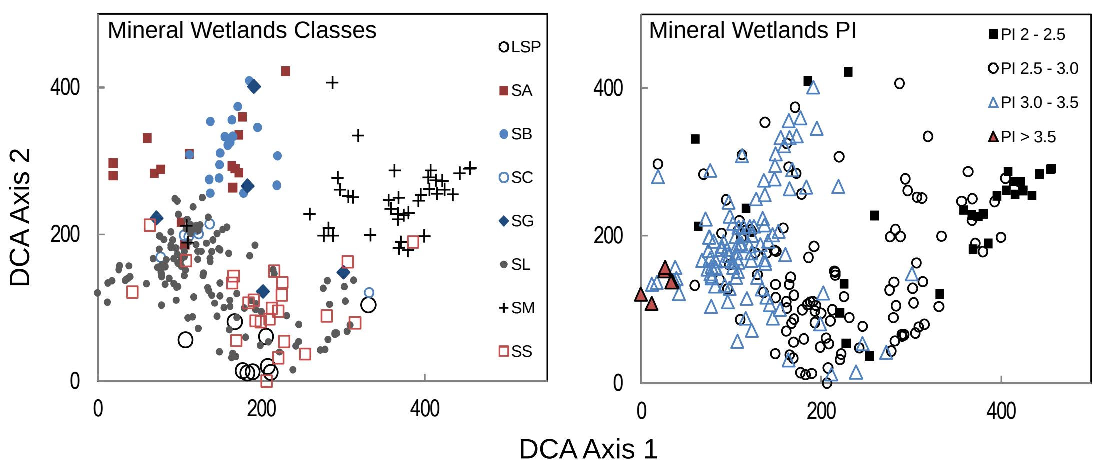


Figure 7. Ordinations of mineral soil wetlands showing groupings according to classes of plant dominants (left) and PI (right). The classes are: Alder (SA), Birch (SB), Bluejoint reedgrass (SC), White spruce (SG), Lutz spruce (SL), Black spruce (SM), and willow (SS) Discharge Slopes, and Late Snow Plateau (LSP).

Table 4. Rank sum of PI comparisons among the non-peat Discharge Slope class. Median values of rank sum are listed for each class. SA are plots dominated by alder, SB, by birch; SL, by Lutz spruce; SM, black spruce; and SS, by willow. Values shown are p values for Dunn's pairwise tests.

Class	Rank Sum	SA	SB	SL	SM	SS
SA	3.01	-	> 0.4	> 0.4	0.015	> 0.4
SB	3.06	-	-	> 0.4	< 0.001	0.09
SL	3.01	-	-	-	< 0.001	< 0.001
SM	2.51	-	-	-	-	> 0.4
SS	2.78	-	-	-	-	-

Plots dominated by birch, and by black and Lutz spruce produce the most differences in rank-sum in the comparisons. However, the differences can be attributed to three factors not related to the moisture conditions at a site: 1) The status of black spruce as a “facultative wet” taxon (indicator status = 2 in the PI calculation), even as it occurs on dry uplands as well as wet sites (Viereck et al. 1992). When black spruce occurs on a drier site, PI there may be artificially lowered by its low indicator status compared to a site with similar dryness but without black spruce, creating a spurious difference in PI between two sites with similar dryness. 2) The indicator status of birch as “facultative” (indicator status = 3 in the PI calculation), although it has a similar bimodal ecological distribution (wet/dry) as black spruce (Viereck et al. 1992). When birch occurs on a wet site it will artificially elevate PI compared to a similarly wet site, creating a spurious difference in PI at similarly wet sites. 3) The lack of an indicator status for Lutz spruce, forcing PI to be driven by understory species present at lower cover values. Lutz spruce should be classified as “facultative” (occurs on wetlands 34-66% of the time) based on its nearly equal frequency of occurrence in wetlands (47%) as on uplands (54%) in plots sampled on the Western Kenai Soil Survey (n = 576/1225 plots vs. n = 1525/2824 plots respectively) (Van Patten 2005).

In summary, four results from the analyses indicate that a more complex suite of variables in mineral-soil wetlands drives differences in plant species composition than in peatlands. In mineral wetlands there are: 1) fewer significant differences in rank sum of PI among classes, 2) weaker correlations of PI with scores on axis one along with a 3) relatively high c.d. of axis one and 4) a higher reduction of stress in the NMS solution with three axes. Although a moisture gradient is related to differences among the mineral-soil wetlands, a proxy for it cannot be reliably identified using remotely sensed images probably because the gradient alone is not sufficiently strong to drive identifiable differences in plant cover.

However, plots with similar dominant plant species do cluster together on the ordinations probably in response to a complex suite of drivers including moisture (Figure 7). Other drivers may include: porewater chemistry, particle size distribution of the mineral substrate, slope, and aspect. Slope and aspect can be identified remotely using high-resolution LiDAR data. However, the other factors present greater challenges to remote identification, and the nature of their interactions presents a challenge to classification. For example, many permutations of different class names such as: “a seasonally-saturated, acidic, steep, north-facing Discharge Slope over silt loam” and “a permanently-flooded, acidic, gentle, east-facing Discharge Slope over sandy gravel” could produce an unwieldy proliferation of class names. By contrast, a relatively few dominant plant species that can be identified using remote sensing can serve to integrate the effects of the interacting drivers and produce simpler class names such as “Lutz spruce / Willow Discharge Slope” and “Black spruce Discharge Slope”. Therefore, the use of plant dominants to classify mineral-soil wetlands in CIB is supported even as the complex interactions among the ecological factors driving the differences among the wetlands have not been fully identified.

THE COOK INLET CLASSIFICATION

The Cook Inlet Classification is composed of geomorphic and hydrologic classes. The geomorphic classes correspond to the major landform types found in the lowlands. They are: Tidal, Riverine, Lakebed, Kettle, Depressions, Spring Fens, Headwater Fens, Drainageways, VLD Troughs, Late Snow Plateaus, and Discharge Slopes. A few classes of limited extent were also classified in the area that was mapped: Tidally-influenced Drainageways, Abandoned Meander Terraces, and Floating Islands.

Many of the geomorphic classes support peatlands, which are further divided by numbered hydrologic classes, supported by the multivariate analyses described above. These numbers range in value from 1-6, with higher values corresponding to drier conditions. For mapping purposes, different hydrologic classes may be combined within a geomorphic class to produce a map unit name. For example, the map unit K23 describes a peatland polygon classified in the geomorphic class Kettle (K) containing two different hydrologic classes (2 and 3) present at a scale too fine to delineate separately at the nominal scale of mapping. The nominal mapping scale ranges from 1:12,500 (City of Homer) to 1:24,000 (Kenai Peninsula). The wetlands in the Matanuska-Susitna Valley were mapped at a nominal scale of 1:18,000.

Two exceptions to the scheme of numbered hydrologic classes are the Discharge Slope geomorphic class and the Riverine class. In Discharge Slopes, plant species dominants serve as hydrologic classes. In Riverine wetlands, a modified version of Rosgen's classification is used. Rosgen classifies rivers and streams according to valley landforms, channel patterns and dimensions, and the dominant particle size class of the substrate (Rosgen & Silvey 1996).

Three other geomorphic classes present in CIB are relatively uniform in composition or limited in extent and therefore require no further division into hydrologic classes. These are, in order of decreasing abundance, Late Snow Plateaus, which are mineral-soil wetlands found in the highlands of the southern Kenai Peninsula; Abandoned Meander Terraces, which are peatlands on elevated terraces found along a few larger streams and rivers; and Floating Islands, which are found where peatlands have been flooded by outlet blockage, usually due to road construction.

Each geomorphic class is described below along with its hydrologic classes. The descriptions are arranged in groups beginning with the classes of tidally-influenced wetlands, followed by the riverine wetlands, the two classes of mineral-soil wetlands, and ending with the ten classes of peatlands. Although all of the wetland classes are described, the emphasis is on the Discharge Slope mineral soil class and the peatland classes, which are the most abundant. Idealized landscape drawings depict relationships of selected plant species to the hydrologic classes within the most common geomorphologic classes. Data on important wetland indicator variables and water chemistry are summarized. See also: Wetlands & Climate (Sheet 1) for a map with a comprehensive legend and graphical summaries of the geomorphic and hydrologic classes along with climate information. Electronic mapping files of the wetlands that can be used in GoogleEarth™ or ArcGIS© can be downloaded from http://cookinletwetlands.info. The maps link wetland polygons to summary data and over 3000 photographs.

Tidal Wetlands

Wetlands influenced by marine tides are not a focus of the CIC, however, they were sometimes encountered within mapping boundaries therefore they are described here. Tidal wetlands are inundated by at least the highest annual oceanic tides. In Cook Inlet, which has the second greatest tidal range on Earth, (> 12 meters), tidal zones can be protracted, particularly where topographic gradients are slight. Tidal wetlands are assigned to the geomorphic class 'T', which is divided into hydrologic classes related to the zones defined by the frequency and duration of tidal inundation that were described by Vince & Snow (1984). Lower numeric values for the classes correspond to more frequent flooding of a longer duration. Each zone defined by Vince & Snow (1984) is characterized by one or more plant taxa (Figure 8). If more than one zone is present at a scale too fine to delineate separately at the nominal mapping scale, the zones can be combined. By convention, up to two zones may be combined, unless they are consecutive. For example, a Tidal wetland with small areas of Lyngbye's sedge (zone 6) and larger areas of Ramensk's sedge (zone 5) will be classified as T56, with the more extensive zone listed first. The same Tidal wetland, but including small areas of beachrye (zone 7) will be classified as T5-7. The following list and figure summarizes the key characteristics of Tidal Wetland hydrological classes and their relation to Vince and Snow's (1984) zones where applicable (Figure 8).

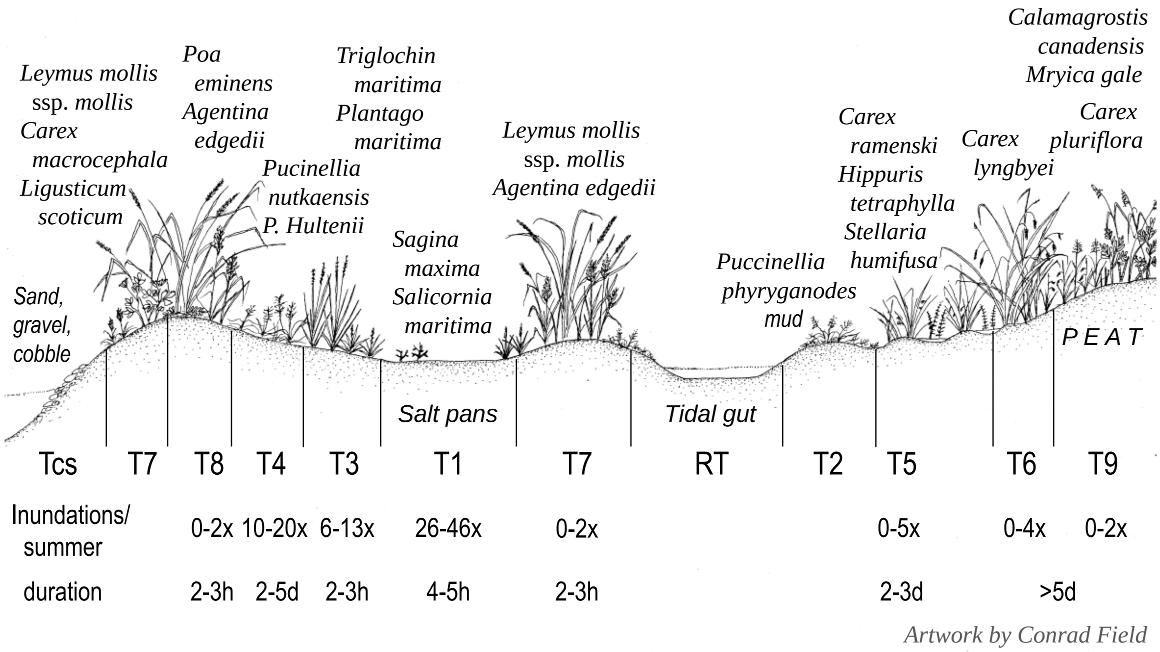


Figure 8. Common plants associated with the hydrologic classes of Tidal wetlands. Classes are based on zones that were related to plant distribution and the frequency and duration of tidal inundation found by Vince and Snow (1984). Plant species were chosen to match those in Vince & Snow (1984) where possible, otherwise they were the taxa with the highest frequency and cover at plots assigned to each zone.

T0: Bare mud.

T1: salt pannes. Sparse, low glasswort (*Salicornia maritime* Wolff & Jefferies) and pearlwort (*Sagina maxima* A. Gray).

T2: Mud with creeping alkaligrass (*Puccinellia phryganodes* (Trin.) Scrib. & Merr.). Vince and Snow's (1984) "Outer Mudflats zone 1". Inundated 26-46 times per summer (mean = 34) for an average duration of 4-5 hours.

T3: Bare ground with goosetongue (*Plantago maritima* L.) and seaside arrowgrass (*Triglochin maritima* L.). Vince and Snow's (1984) "Inner Mudflats zone 5". Inundated 6-13 times per summer (mean = 8) for an average duration of 2-3 hours.

T4: Alkali grasses (*Puccinellia nutkaensis* (J.Presl) Fernald & Weath. and *P. Hultenii* Swallen) dominate, usually with beachrye (Leymus mollis ssp. mollis). Loosely follows Vince and Snow's (1984) "Outer Mudflats zone 2" which is inundated 10-20 times per summer (mean = 15) for an average duration of 2-5 days.

T5: Ramensk's sedge (*Carex ramenskii* Kom.) dominates with pools of open water. Mare's tail (*Hippuris tetraphylla* L.), spikerush (*Eleocharis* R. Br. spp.), saltmarsh starwort (*Stellaria humifusa* Rottb.) are found in and around the pools. Vince and Snow's (1984) "Outer Sedge Marsh zone 3". Inundated 0-5 times per summer (mean = 3) for an average duration of 2-3 days.

T6: Lyngbye's sedge (*Carex lyngbyei* Hornem.) cover is nearly continuous. Vince and Snow's (1984) "Inner Sedge Marsh zone 7". Inundated 0-4 times per summer (mean = 2) for an average duration of > 5 days.

T7: A diverse plant community with beachrye (*Leymus mollis* ssp*. mollis*) on storm berms, corresponding to Vince and Snow's (1984) "Riverbank Levee zone 6", which is inundated 0-2 times per summer (mean = 1) for an average duration of 2-3 hours.

T8: Pacific silverweed (*Argentina egedii* (Wormsk.) Rydb.) and largeflower speargrass (*Poa eminens* J. Presl.) dominate. T8 is a combination of Vince and Snow's (1984) "Riverbank Levee zone 6" and "Inner Mudflats zone 4", which are inundated 0-2 times per summer (mean = 1) for an average duration of 2-3 hours; and 8-13 times (mean = 11) for 4-9 hours, respectively. On the Kenai Peninsula, "Riverbank Levees" support a high cover of beachrye.

T9: Upper reaches of low-gradient river mouths; dominated by manyflower sedge (*Carex pluriflora* Hultén). Vince and Snow's (1984) "Inner sedge marsh zone 8". Inundated 0-2 times per summer (mean = 1) for > 5 days. At the mouth of the Kenai River, and possibly elsewhere, this zone is formed where peatlands subsided to below the range of the highest spring tides during the 1964 earthquake.

TR: A mapping complex with more than two non-consecutive hydrologic classes where gradients are steep, such as along tidal guts or at the mouths of streams.

Wetland indicator variables and water chemistry data are given below for the few sites where they were recorded (Table 5).

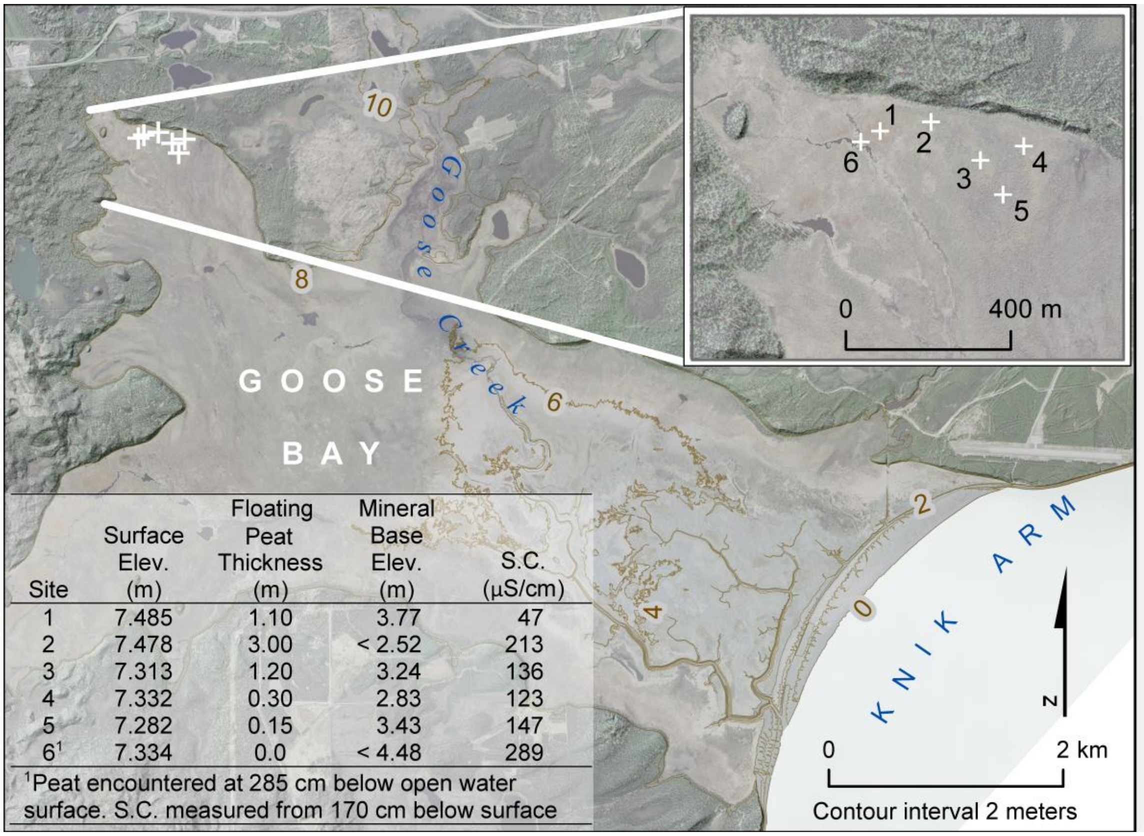
Table 5. Wetland indicators in Tidal plots.

Organic layer thickness (n = 12)	Water level (n = 13)	pH (n = 11)	Specific Conductance (25°C, n = 4)	Plant Prevalence Index (n = 16)
36 cm	28.5 cm	7.3	1153 µS/cm	1.53

Tidally-Influenced Drainageways

Tidally-Influenced Drainageway wetlands are found where saltwater and freshwater mix in settings where the tidal range is extreme and discharge from glacier-fed rivers and through permeable glacial sediments is high. In Cook Inlet Basin these wetlands are found in toe-slope positions near the upper reaches of Knik Arm, where the second greatest tidal range on Earth (12.573 m at Anchorage, NOAA 2015) mixes with flow from two large glacier-fed rivers and groundwater discharging through permeable unconsolidated deposits. The waters mix over an extended zone created by the slight topographic gradient found in this geomorphic position. Salinity is moderated by four factors: 1) surface water discharge; 2) groundwater discharge; 3) the daily, monthly, annual, and 18.6 year cycles of tidal variability, and 4) elevation. Surface and groundwater discharge can reduce salinity in the open waters of upper Cook Inlet to 4 Practical Salinity Units (PSU) (Smith et al. 2005). Different tidal cycles produce different effects. For example, the difference between the highest tide during the minimum and the maximum phases of the 18.6-year tidal cycle combined with the shallow topographic gradient (0.16%) produces a zone greater than 350 m wide that is influenced by tides less frequently than annually. Similar protracted zones with effects at different tidal periodicities occur at other positions along the slight topographic gradient. Due to the large tidal range, the residence time of saltwater intrusion at the upper extent of the highest tides is brief. For example, during the highest tide measured, a zone approximately 590 meters wide was inundated over the span of one hour, a horizontal rate of movement of almost 10 meters per minute. These factors combine to support plants that are not salt tolerant, including poplar forest (*Populus balsamifera* L.) over soils showing periodic tidal inundation.

The water that maintains wetland conditions is frequently not saltwater in these tidally-influenced systems. For example, in the upper reaches of Goose Bay, which is a wetland complex and not a marine embayment, a floating peat mat appears to be maintained by freshwater discharge from surface and groundwater. The outer reaches of the “bay” are Tidal wetlands (influenced by at least the monthly tidal cycle). The surface of the peat mat lies near the elevation of the maximum observed tide (7.426 m), but low SC at the surface indicates freshwater conditions ($\bar{x}$ = 133 μS/cm; n = 5). However, the mat is floating above a gleyed (5G 7.5/1) silty-clay bottom that lies well below the elevation of mean higher high tide (Figure 9).



Site	Surface Elev. (m)	Floating Peat Thickness (m)	Mineral Base Elev. (m)	S.C. (µS/cm)
1	7.485	1.10	3.77	47
2	7.478	3.00	< 2.52	213
3	7.313	1.20	3.24	136
4	7.332	0.30	2.83	123
5	7.282	0.15	3.43	147
6[1]	7.334	0.0	< 4.48	289

[1]Peat encountered at 285 cm below open water surface. S.C. measured from 170 cm below surface

Figure 9. Goose Bay Tidally-Influenced Drainageway freshwater wetlands. Inset shows locations of sites sampled. Table shows surface elevations of the floating peat mat (from LiDAR), the thickness of the peat mat, the elevation of the mineral substrate beneath the mat, and specific conductance (S.C.) of surface water at each site, except site 6, see table footnote. An S.C. of 5167 µS/cm equals a salinity of 4 PSU at 10ºC. Elevation contours are shown up to 10 m. The elevation of Mean Higher High Water is 5.691 m, the highest observed tide was 7.426 m. Elevation datum reference is NAVD88. Knik Arm, indicated in the southeast corner of the map, is saltwater.

Freshwater discharge must maintain the relatively low SC measured at the surface of the floating peat. Tectonic subsidence likely lowered the base of the peat to help create this unusual hydrogeologic setting, which is further controlled by the accumulation of tidal silt across the middle of the bay, near the elevation of mean higher high water

(5.691 m) (NOAA 2015). It is difficult to conceive of an alternative process whereby an extensive floating freshwater peat mat could develop over such a depth of water that has a base below the level of the daily high tides. The tremendous annual glacial outburst floods along the Knik River between the years 1914 and 1966 (Stone 1963, Post & Mayo 1971, Hulsing 1981) may have played an additional role by scouring the bay.

Tidally-Influenced Drainageway wetlands are divided into two classes, one where the tidal influence appears to dominate (TDW), and one where freshwater appears to dominate (DWT) (Sheet 1). The classes are further divided by hydrologic classes ranging in value from 1-4. Lower values indicate that higher water levels persist longer through the growing season. The hydrologic classes can be combined to describe site conditions. For example, a wetland classified as TDW32 is one where a tidal influence appears to dominate over freshwater influences (TDW) and is composed of a greater area with more variable water levels (3, often shrubby) intermixed with smaller areas of persistently high water levels (2, often dominated by sedges) at a scale too fine to delineate separately at the nominal mapping scale. A wetland polygon classified as DWT2-4 consists of a wetland where the freshwater influence dominates (DWT) and supports a range of hydrologic conditions (2-4): areas where the water table remains near the surface during the growing season (2), areas where the water table is more variable (3), and forested areas, where the water table variation is even greater (4). All of the areas are present at a scale too fine to delineate separately at the nominal mapping scale.

Riverine Wetlands

Riverine wetlands are rivers and streams and their adjacent valley bottoms. The adjacent valley bottoms may not always meet wetland regulatory criteria, but channel position will shift through time, potentially affecting all areas of the valley bottom. However, many valleys in the Cook Inlet Lowlands are underfit features; features formed by larger streams that were fed by more extensive glaciers in the late Pleistocene through mid-Holocene (130-8 ka). Because they are underfit, many valley bottoms resemble modern floodplains, however the meander radii of the valley-walls grossly mismatch those of the modern stream. Valley bottoms of underfit streams more frequently support wetland conditions, maintained by groundwater discharge. The Cook

Inlet Classification adapts a modified version of Rosgen's classification to name Riverine classes (Rosgen & Silvey 1996). Riverine wetlands are assigned the geomorphic class ‘R’ and Rosgen’s Level I is used to further subdivide these wetlands. Level I has seven classes, six of which are common in the Cook Inlet Basin: Types A, B, C, D, E, and DA. For example, a Riverine wetland adjacent to a type B stream is classified as RB. The classes are summarized below.

A- rapids and waterfalls with narrow wetland margins occurring along a few streams flowing directly into Kachemak Bay or Cook Inlet such as Happy Valley, McNeil, and Falls Creek.

B- moderately entrenched, riffle-dominated reaches with narrow fringing wetlands;

C- riffle/pool morphology with point bars and broad active floodplains;

D- braided glacial rivers;

E- slightly entrenched, stable, pool-dominated channels within relict channels (underfit). E streams support wide fringing wetlands and may have beds and banks composed entirely of peat;

DA- braided channel reaches formed as the stream fans out onto a glacial terrace, usually in a peatland.

Type **B** reaches are moderately entrenched and dominated by riffles. Pools are widely spaced. On the Cook Inlet Lowlands, type B reaches are most common where upper stream reaches flow over the moderately steep surfaces of the penultimate glaciation. These erosional surfaces are generally devoid of glacial deposits, and are more common on the southern Kenai Peninsula. The most common type of B stream in the lowlands at level II in Rosgen's classification is B4, with moderately steep valley walls and beds dominated by gravels, and B3, where cobbles dominate the bed material (Rosgen & Silvey 1996). B reaches have a very narrow wetland fringe, if any.

Type **C** reaches have well-developed floodplains and cut-bank and point-bar features. Many areas along the valley bottom of actively meandering C reaches may be uplands. Wetlands on the floodplain may be fed by shallow groundwater discharge at the toe-slopes of the valley walls or lie in abandoned oxbows, fed by hyporrheic discharge or overbank flooding. Uncommonly, some peatlands perched on terraces above C reaches are classified as “abandoned meander terraces”; features formed as the modern river became entrenched below its former, wider floodplain. The former floodplain was wider because the river was fed by the meltwater of a glacier that has since receded, often beyond the modern headwaters of the stream. The lower portion of Willow Creek has several abandoned meander terraces.

Type **E** reaches are the most common stream type on the lowlands of Cook Inlet Basin, and this category of Rosgen’s classification has been modified to reflect conditions there. E reaches are slightly entrenched, stable, low-gradient, pool-dominated reaches with low width/depth ratios, densely vegetated banks, and varying sinuosity (although Rosgen & Silvey’s (1996) E reaches are of high sinuosity). E reaches have narrow active floodplains, although occasional abandoned channels and oxbows are evident. In Cook Inlet Basin, these reaches are underfit features flowing across shallow-gradient glacial deposits, especially relict lakebeds and drainageways, or through peat overlaying these deposits. The radii of meander bends of the valley walls will be orders of magnitude larger than those of the modern channel. The E reaches may flow over beds of coarse-grained mineral materials, or be incised entirely into peat. At level II in Rosgen’s classification, the most common reach types flowing over mineral deposits are E3 or E4, with cobble or gravel beds, respectively (Rosgen & Silvey 1996). These types have high sinuosity.

In the CIB, a common, but undescribed stream type at level II is an E stream completely incised into a peat substrate with a peat bed that can exceed one m in thickness and have low sinuosity (<1.2). Because of unique geomorphic controls, these streams could potentially be classified as a completely different type of stream; one not covered by Rosgen’s system (Rosgen & Silvey 1996), and not regulated according to bankfull discharge theory (Andrews 1980). Watters and Stanley (2007) provide the only other detailed geomorphic description of a similar type of stream, entrenched in peat and with long reaches with low sinuosity, flowing through peatlands overlying sandy glacial deposits in Northern Wisconsin. They note many departures in form and process from alluvial systems formed in mineral beds and banks. For example, channel width does not respond to increases in flow and thalwegs are not adjacent to what appear to be cut banks, i.e. the banks are not steepened by hydraulic forces. They show that the peat stream lacked the canonical response to flow and sediment transport found in mineral-based systems, and suggest that unique biological and ecological controls likely drive channel morphology. Although these processes also probably play an important role in Cook Inlet Basin, the stream in Wisconsin flowed through a steep-sided basin across a peatland formed by lake-infilling. In Cook Inlet Basin, peat streams with similar planform occur on peat that has accumulated on relatively featureless lakebeds through the processes of primary peat formation or paludification. More research on the fluvial geomorphology of streams entirely formed in peat is required to understand geomorphic drivers in these systems.

In the CIB, Rosgen's classification (Rosgen & Silvey 1996) is modified for E reaches. Theses reaches are classified into four sub-types based on channel sinuosity, size, and water level:

- Sub-type **'l'** is a linear E reach, with a sinuosity (channel length/valley length) of less than 1.3 (often <1.2). Bed and banks may be formed in peat.
- Sub-type **'s'** is an E reach with a sinuosity greater than 1.3. They often have beds composed of mineral deposits and may have peat banks.
- Sub-type **'a'** is an E reach where channels are not visible on aerial photography at a scale of 1:24,000, but are inferable from vegetation patterns, such as a forested or alder ribbon traversing an open peatland.
- Sub-type **'b'** is a bank-full E reach. These reaches are blocked by an obstruction, such as a beaver dam or culvert that is improperly sized. They can be linear or sinuous.

Type **D** reaches are aggrading braidplains of rivers fed by glacial discharge. Aggradation is extreme in some settings, such as on the Resurrection and Salmon Rivers near Seward, Alaska, where single flood events can raise the stream bed a meter or more above the pre-event base level (Jones & Zenone 1988). Braidplain activity often prevents vegetation establishment, but braidplains do support wetlands in abandoned channels fed by hyporrheic discharge and over-bank flooding.

Type **DA** reaches are anastomosing flow across peatlands. These reaches are unlike the DA type described by Rosgen & Silvey (1996) because in CIB they have a bed and banks entirely formed in peat. Although Rosgen's DA reaches have mineral beds, the same overall controls they describe, aggradation and tectonic subsidence, may be responsible for the maintenance of the analogous channel form on peatlands in the Cook Inlet Lowlands. DA reaches are uncommon features usually found in relict glacial drainageways. Elsewhere in the literature, a similar type of peat stream with an anastomosing channel form is only briefly described as originating from a densely ditched portion of a blanket bog in the East Midlands of England (Tallis 1973). There, ditching disturbance likely exerts different controls on channel form than found in the un-ditched setting of Cook Inlet peatlands.

Mineral Soil Wetlands

Discharge Slope Wetlands

Discharge Slope wetlands are freshwater wetlands fed by groundwater discharging through mineral substrates at pronounced slope breaks. These wetlands often occur at the fringes of peatlands and Riverine wetlands, forming the up-gradient boundary between wetlands and uplands. Discharge Slope wetlands are most frequently encountered in the hydrogeologic setting of toe-slope positions over terraced glacial till on the southern Kenai Peninsula, where a diversity of Discharge Slope wetlands is found. Further north, permeable glacio-fluvial deposits apparently limit wetland formation but Discharge Slope wetlands are found as black spruce (*Picea mariana* (P.Mill.) B.S.P.) forests at the margins of bogs. Discharge Slope wetlands may be fed by groundwater discharge through permeable lenses in the till (e.g. Roulet 1990) or some other process such as return flow when shallow groundwater percolating downslope through permeable andisols encounters less-permeable till.

Although they are fed by groundwater, water levels in these wetlands are typically more variable than in peatlands, and the water table is often found deeper beneath the surface (Table 6). If shallower levels were more stable then peat would likely accumulate in this geomorphic position (e.g. Roulet 1990), as it does at some sites, especially under alder (Table 6). Discharge Slopes mapping units are assigned the geomorphic class ‘S’, and hydrologic classes are based on the scientific binomials of the dominant plants (Figure 10). If more than one species covers more than 10% of a wetland polygon, the polygon is classified as a mixture, with the plant covering the most area listed first. For example, a wetland classified as SS is a Discharge Slope (S) with greater than 10% cover of willow (S), whereas a Discharge Slope wetland covered by

50% Lutz spruce (L) and 20% alder (A) is classified as SLA. Together or monotypically, only eight taxa have been found to occur at cover values greater than 10% on Discharge Slopes:

SA: *Alnus incana* ssp. *tenuifolia* (Nutall) Breitung. Thinleaf alder. Peat frequently greater than one meter thick.

SB: *Betula neolaskana* W.H. Evans or *B. kenaica* Sargent. Alaska birch and Kenai birch. Alaska birch is more common northward.

SC: *Calamagrostis canadensis* (Michx.) Beauv. Bluejoint reedgrass.

SG: *Picea glauca* (Moench) Voss. White spruce.

SL: *Picea* X *lutzii* Little. Lutz spruce, a hybrid between *P. glauca* and *P. sitchensis* (Little 1953). Dominant on the southern Kenai Peninsula.

SM: *Picea mariana*. Black spruce.

SP: *Picea sitchensis* (Bong.) Carr. Sitka spruce, found around Seward only.

SS: *Salix* spp. Willow. Most frequently *S. barclayi* Anderss. and *S. planifolia* ssp. *pulchra* (Cham.) Argus.

SZ: High elevation diverse forb meadows on Baldy Ridge, above Wasilla.

In regions of peat formation, groundwater-fed wetlands have been described elsewhere, such as the spring swamps of the Canadian Wetland Classification system (Zoltai et al. 1988, Roulet 1990). However, those swamps support stable water tables throughout the growing season and peat formation. On the Cook Inlet Lowlands, peat formation in these types of wetlands is only common under alder. Otherwise, in regions that support peatlands, mineral soil wetlands that have formed at zones of groundwater discharge where water tables are variable are not described in the literature. Some Discharge Slope wetlands might be more accurately named return-flow wetlands, because throughflow from deep andisols lying upslope may be forced to the surface downslope when it encounters relatively impermeable glacial till. More work is required to understand the variables that control the fundamental ecosystem processes in these uncommon wetlands such as water table variation, slope, particle size-class distribution, aspect, and watershed position.

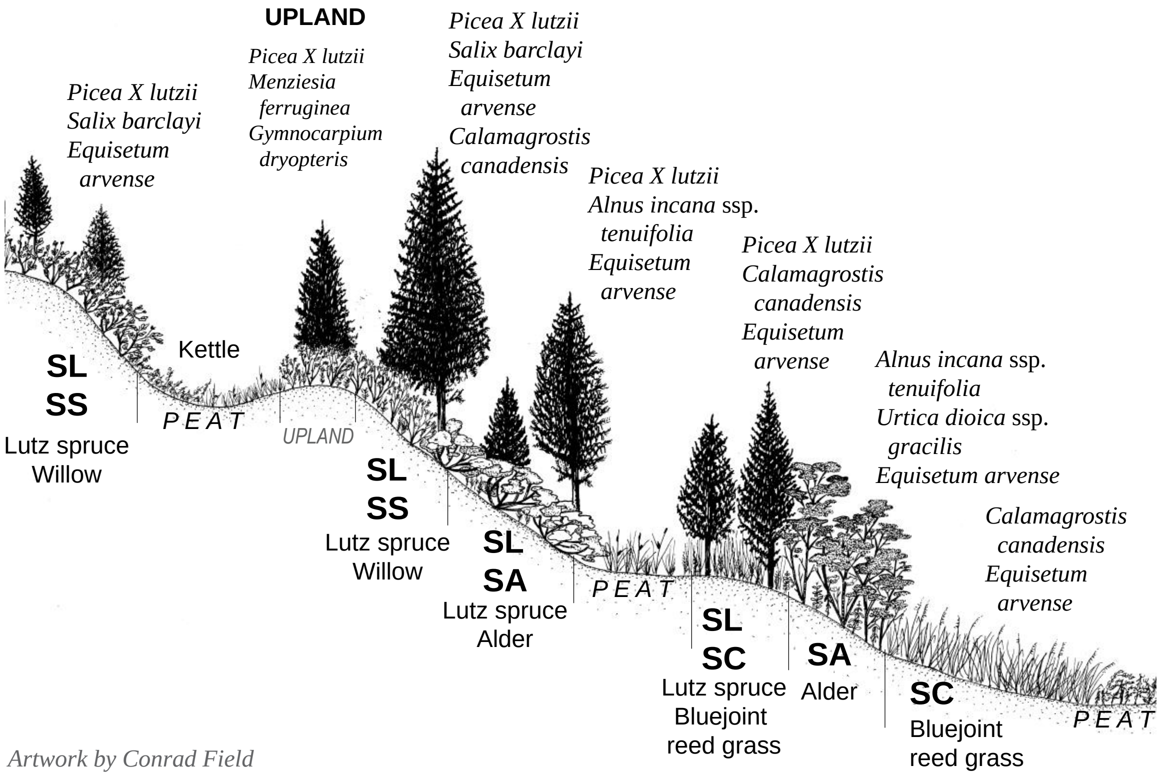


Figure 10. Idealized landscape cross-sectional drawing showing selected hydrologic classes of the Discharge Slope geomorphic class of the Cook Inlet Classification. Plants depicted within each class are the dominants reflected in the class names, and selected plants having a high frequency of occurrence and/or average percent cover.

Table 6. Water chemistry and wetland indicators for Discharge Slope wetland classes. Number of samples is in parentheses. Redox features have been measured since 2002, and thus may not always meet the criteria in the 2007 Alaska regional supplement to the delineation manual (USACE 2007). Redox feature depth was not recorded when peat thickness exceeded 20 cm.

Class	Peat thickness (cm)	Water table (cm)	Redox features (cm)	Saturation (cm)	pH	Alkalinity (mg/l as $CaCO_3$)	Specific Conductance (µS/cm 25°C)	Plant Prevalence Index
SA	90 (16)	26 (15)	23 (6)	3 (7)	6.2 (8)	39.0 (3)	177 (5)	2.92 (16)
SB	82 (19)	54 (19)	29 (15)	42 (18)	6.5 (10)	61.6 (2)	182 (9)	2.99 (23)
SC	57 (7)	71 (5)	24 (6)	-	7.0 (1)	-	-	2.93 (7)
SG	20 (5)	52 (5)	14 (4)	47 (4)	5.7 (4)	3.0 (1)	75 (4)	3.16 (5)
SL	31 (128)	38 (108)	26 (82)	-	5.4 (9)	4.8 (4)	49 (2)	3.05 (132)
SM	46 (40)	37 (32)	34 (15)	28 (24)	5.4 (12)	0.0 (4)	62 (10)	2.49 (40)
SS	43 (22)	27 (18)	28 (9)	9 (3)	6.7 (5)	84.3 (4)	259 (5)	2.72 (25)
SZ	23 (1)	1 (1)	-	1 (1)	6.0 (1)	-	18 (1)	2.35 (1)

Late Snow Plateaus

Late Snow Plateaus are found at higher elevations where discontinuous glacial deposits are older than those of Marine Isotope Stage 2 (>29 ka) (Lisiecki & Raymo 2005; Karlstrom 1964). Late Snow Plateaus have been mapped on plateaus above 460 m elevation in the Caribou Hills on the southern Kenai Peninsula. The older glacial deposits in the Caribou Hills are slowly permeable, and the snow-free period is typically only five months long. The slow permeability often creates saturated conditions near to the ground surface for a sufficient percentage of the short growing season to maintain wetland conditions. Median dates for snow cover were 26 October through 25 May during the period 1981-2010 for a site at 504 m elevation in the Caribou Hills (NRCS 2015).

All wetlands that have been classified as Late Snow Plateaus are assigned the single class LSP. Water tables are generally deep and organic layers are thin compared to other wetland types (Table 7). The primary indicators that wetland conditions exist are shallow redoximorphic features in the soil profile and low values for plant prevalence index (Table 7). Vegetation is dominated by willows, especially *Salix barclayi,* and the understory is a diverse assemblage of herbs (Table 8). Soils are Typic cryaquods of the Snowdance series.

Table 7. Wetland indicators in Late Snow Plateau plots. pH was measured by NRCS using a colorimetric soil test kit.

Organic layer thickness (n = 15)	Water level (n = 14)	Redoximorphic feature depth (n = 9)	pH (n = 2)	Plant Prevalence Index (n = 9)
7.8 cm	36.9 cm	28.7 cm	4.7	2.91

Table 8. Number of occurrences (n) and average cover of plants in 9 plots surveyed in Late Snow Plateau wetlands.

Plant	n	Cover
Salix barclayi	7	92.9
Calamagrostis canadensis	8	8.3
Sanguisorba canadensis	7	21.9
Equisetum arvense	5	26.4
Valeriana capitata	7	8.4
Rubus arcticus	6	2.2
Veratrum viride	7	1.5
Chamerion angustifolium	6	1.6
Geranium erianthum	6	8.2
Swertia perennis	6	3.2
Erigeron peregrinus	5	4.1
Rhodiola integrifolia	5	5.0
Senecio triangularis	6	0.7
Angelica lucida	6	0.2
Polemonium acutiflorum	7	0.5
Trientails europea	7	0.1

Peatlands

Depressions

In the Cook Inlet Classification, Depressions are peatlands in closed basins underlain by till or other slowly-permeable unconsolidated deposits. These basins are most closely associated with moraines of the last glacial advance. Another class of closed basin peatlands, Spring Fens, is found on permeable unconsolidated deposits in an area of moisture deficit (where potential evapotranspiration exceeds precipitation). Depressions are found in areas of moisture surplus.

The peat surface in Depressions tends to lie further above the underlying mineral substrate because either the peat layer is thicker or it is floating on a lens of water. At 16 of the 23 sites where the peat surface was found to be greater than 3 meters above the mineral substratum in Depressions the measurements were minimum estimates because the depth to the mineral substratum exceeded sampling capability on the day of measurement. Peatlands formed over lakebeds, by contrast, had fewer plots with a peat thickness of greater than 3 meters and fewer of those measurements were minimum estimates. Peatlands formed in open basins (Kettles), which are also associated with moraines of the last glacial advance, show intermediate values for thickness and minimum thickness estimates (Figure 11). In Depressions, the peat mass is confined by the steep sides of the relatively small closed basins. Therefore, hydrologic factors such as the rate of porewater leakage through the upper layers of peat and distance to bounding waters, which may limit peat thickness on broader landforms and in open basins (Ingram 1982, Glaser et al. 2004a), will not necessarily limit the thickness of the peat in Depressions. Instead, the rate of groundwater leakage through the material comprising the landform surrounding the closed basin could limit the elevation of the water table in the Depression. If that rate of leakage is lower than the rate through the porewaters of the peat, then the thickness of the peat could be either controlled by it, or by a biologic factor: the ratio of the recruitment of organic matter to the catotelm (the lower, permanently saturated layer of peat) to the depth-integrated decay rate there (Clymo 1984). If the depth-integrated decay rate became equal to the recruitment rate, peat would cease to accumulate even if the water table could potentially reach a higher level. Control by either could allow a greater thickness of peat to develop in Depressions than on broader landforms. If the rate of groundwater leakage is greater than leakage from the porewaters of the peat, then any peatland that might form would likely be classified as a Spring Fen (see below).

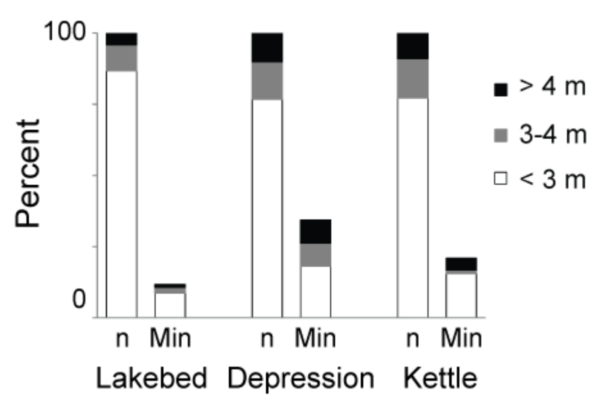


Figure 11. Peat thickness in different geomorphic classes. Bars labeled n refer to the percentage of measurements in each thickness category, shown by the legend. Bars labeled Min refer to the percentage of the measurements in each category that were minimum thickness estimates.

The peat in Depressions tends to exhibit bog chemistry, showing the lowest pH and SC values of any of the geomorphic classes in the CIC (Figure 2). This chemistry suggests that the water in Depressions is either derived primarily from meteoric sources, or that the surface layer of peat is isolated from any groundwater discharge that may occur deeper in the profile. Water levels are likely controlled by evapotranspiration and seepage recharge to deeper groundwater. Analysis of the stable isotopes of oxygen and hydrogen in water has not been accomplished, but could reveal the role that evaporation plays in regulating water levels in Depressions (Clark & Fritz 1997). Although Depressions more frequently exhibit bog chemistry, all Depressions are not necessarily bogs. Some exhibit wide variation in water levels and support fen indicator plants such as the grass *Calamagrostis canadensis.*

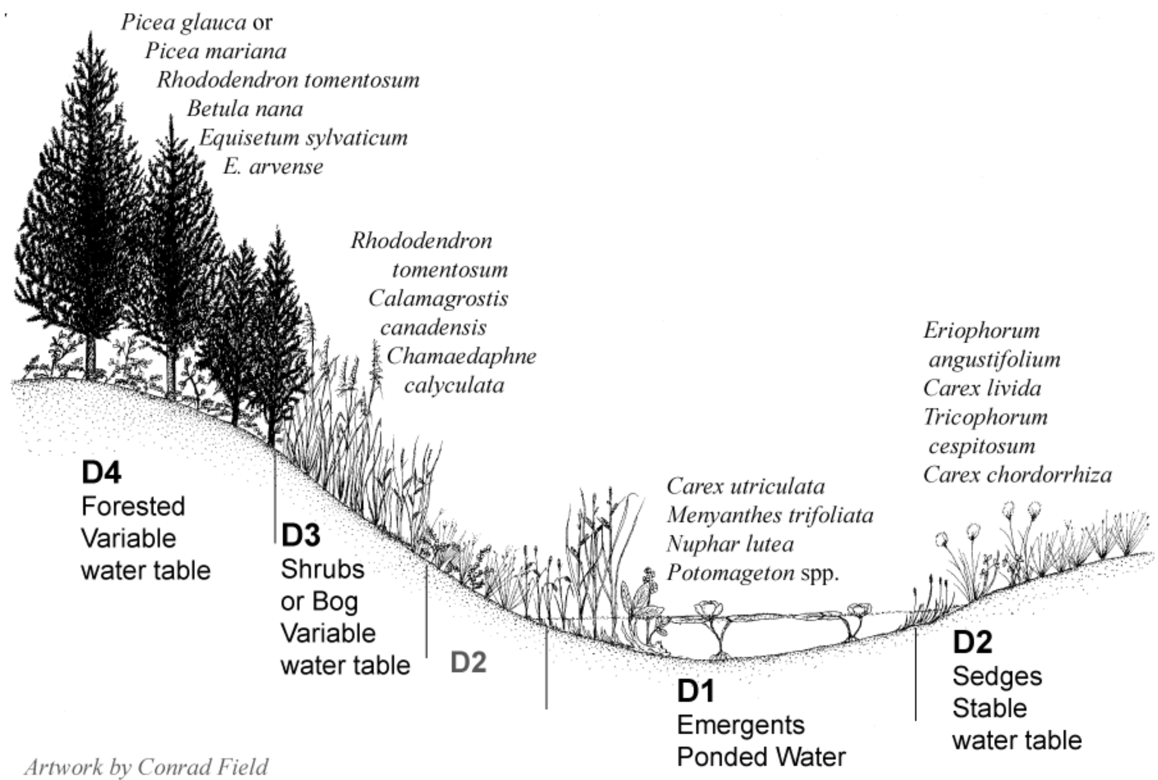


Figure 12. Idealized landscape cross-section depicting selected common plant taxa and their relationship to the hydrologic classes of the Depression geomorphic class of the Cook Inlet Classification. Plants shown are based on those with the highest frequency of occurrence and/or percent cover. Plant species are not diagnostic; they are depicted only to convey a general sense of the classes. Only the landform name and water level variation are diagnostic of class membership.

Depressions are assigned the Geomorphic class ‘D’ in the Cook Inlet Classification. Numeric hydrologic classes in Depressions range in value from 1-4 based on the average position and variability of the water table. Lower values are assigned to wetter sites. Within Depressions, wetland plant communities are often arranged in concentric rings according to hydrologic class (Figure 12). Plant prevalence Index tends to be lower in the class D2 than for comparable classes in other Geomorphic types, however Classes D3 and D4 tend to have higher PI than in comparable classes in other geomorphic types (Sheet 1, Prevalence Index in Common Wetland Mapping Classes). Table 9 summarizes water chemistry and values for wetland indicator variables found in Depressions classes.

Table 9. Water chemistry and wetland indicators in Depression hydrologic classes. Number of samples is in parentheses. Redox features have been measured since 2002, and thus may not always meet the criteria in the 2007 Alaska regional supplement to the delineation manual (USACE 2007). Feature depth was not recorded when peat thickness exceeded 20 cm.

Class	Peat thickness (cm)	Water table (cm)	Redox features (cm)	Saturation (cm)	pH	Alkalinity (mg/l as $CaCO_3$)	Specific Conductance (µS/cm 25°C)	Plant Prevalence Index
D1	-	-136 (1)	-	0 (5)	5.4 (17)	1.6 (11)	16 (20)	1.46 (2)
D2	220 (34)	1 (36)	-	0.3 (30)	4.5 (29)	0.2 (25)	38 (28)	1.31 (36)
D3	178 (50)	14 (40)	67 (4)	8 (39)	4.4 (29)	0.8 (23)	48 (30)	2.29 (49)
D4	135 (44)	30 (37)	35 (10)	9 (27)	4.6 (15)	0.7 (12)	52 (15)	2.57 (45)

Floating Islands

Floating Islands are unmoored peat mats floating on the surface of lakes; only 7 polygons have been mapped as Floating Islands. The few Floating Islands that have been observed occur on lakes that were originally peatlands but now have their outlets dammed by roads. The largest Floating Island mapped in the Cook Inlet Basin is approximately 0.5 hectares in size floating on Suneva Lake, on the northern Kenai Peninsula. It was observed drifting 1 km in three hours with a breeze of less than

2.2 $m \cdot s^{-1}$. Floating Islands are assigned the Geomorphic Class ‘FI’ with no further subdivision. Dominant plants on the interior of the island on Suneva Lake were *Equisetum fluviatile* L. and *Circuta douglasii* (DC.) J.M. Coult. & Rose. At the margins grew *Carex aquatilis* var. *dives* (T. Holm) Kük., *Carex inflata* var. *utriculata* (Boott) Druce, and *Carex stipata* Muhl. ex Willd.. The introduced weed *Bidens cernua* L. was collected from one mat on the lake.

Headwater Fens

Headwater Fens are small peatlands above or near treeline formed in open basins at the headwaters of first-order streams. Specific conductance, pH and species richness tend toward higher values in Headwater Fens compared to other peatlands (Figures 3 & 5), indicating a stronger influence of groundwater discharge. These peatlands occur where glacial deposits are thin and discontinuous, and the underlying bedrock is relatively permeable. In one watershed, a mixing analysis showed that the bedrock was the source of 41% of stream flow during a dry period (Gracz et al. 2015). Till was found to be a poor source of stream flow (< 5%) likely due to its low hydraulic conductivity. The greater permeability of underlying rocks in these higher elevation settings, above the extent of MIS 2 glacial deposits, likely contributes to the richer porewater chemistry and higher species richness found in these peatlands. A rare plant in Alaska, *Pedicularis groenlandica* Retz., which has been found in only a few locations statewide, is common on the southern Kenai Peninsula, in the Headwater Fens of the Anchor River watershed.

A few peatlands classified as Headwater Fens exhibit bog chemistry, with pH less than 4.2, and specific conductance < 20 µS/cm. Rather than lying in open basins, the three sites with bog chemistry that were sampled were located on ridgetops or straddled a surface-water divide. These are classical geomorphic settings for bogs (e.g. Heinselman 1963), and a new Geomorphic Class may be warranted (e.g. Headwater Bog). However, although these three peatlands exhibited bog chemistry, they also supported fen indicator plant species, such as *Geranium erianthum* DC, and the grasses *Deschampsia cespitosa* (L.) P. Beauv. and *Calamagrostis canadensis*, suggesting influence from groundwater discharge. Due to their low abundance and ambiguous indicators they remain classified as Headwater Fens.

Headwater Fens are assigned the Geomorphic Class ‘H’ in the CIC, and hydrologic class values between 1 and 4, with lower values indicating wetter conditions as they do in Depressions, Kettles, Spring Fens, and VLD Troughs. Headwater Fens are frequently heterogeneous mixtures of herbs, sedges, and shrubs indicating seasonally variable water levels. The mapping classes H2 and H3 are the most common. Headwater Fens generally show richer porewater chemistry and more stable water levels than found for similar hydrologic classes in other peatland Geomorphic Classes (Table 10).

Table 10. Water chemistry and wetland indicators in Headwater Fen hydrologic classes. Number of samples is in parentheses. Redox features have been measured since 2002, and thus may not always meet the criteria in the 2007 Alaska regional supplement to the delineation manual (USACE 2007). Feature depth was not recorded when peat thickness exceeded 20 cm.

Class	Peat thickness (cm)	Water table (cm)	Redox features (cm)	Saturation (cm)	pH	Alkalinity (mg/l as $CaCO_3$)	Specific Conductance (μS/cm 25^oC)	Plant Prevalence Index
H1	-	-5 (1)	-	0 (1)	6.3 (3)	32.3 (3)	83 (3)	1.02 (1)
H2	139 (14)	5 (12)	-	0 (2)	6.0 (3)	36.0 (3)	98 (2)	1.62 (14)
H3	135 (18)	11 (19)	-	1 (2)	4.8 (5)	3.8 (5)	29 (5)	2.08 (16)
H4	13 (1)	28 (1)	20 (1)	-	-	-	-	-

Kettles

In the Cook Inlet Classification, Kettles are peatlands formed in open-basin depressions associated with glacial moraines. Kettles are primarily fens likely fed by groundwater discharging through permeable lenses in the glacial deposits or soil water that discharges to near the surface as it encounters the relatively impermeable glacial till of the moraine after percolating downslope through thick permeable tephra deposits. Bog chemistry in Kettles is uncommon (Figure 4) likely due to groundwater influences or tephra deposition, combined with the effects of low precipitation, a pronounced dry period during the growing season (Sheet 1), and decadal-scale climatic variations (Figure 1). Peat thickness in Kettles is intermediate between that found on Lakebeds and in Depressions (Figure 11) suggesting that the balance between recruitment to the catotelm and decomposition is complicated by hydrologic factors (Clymo 1984) such as hydraulic conductivity and distance to bounding streams (Glaser et al. 2004a).

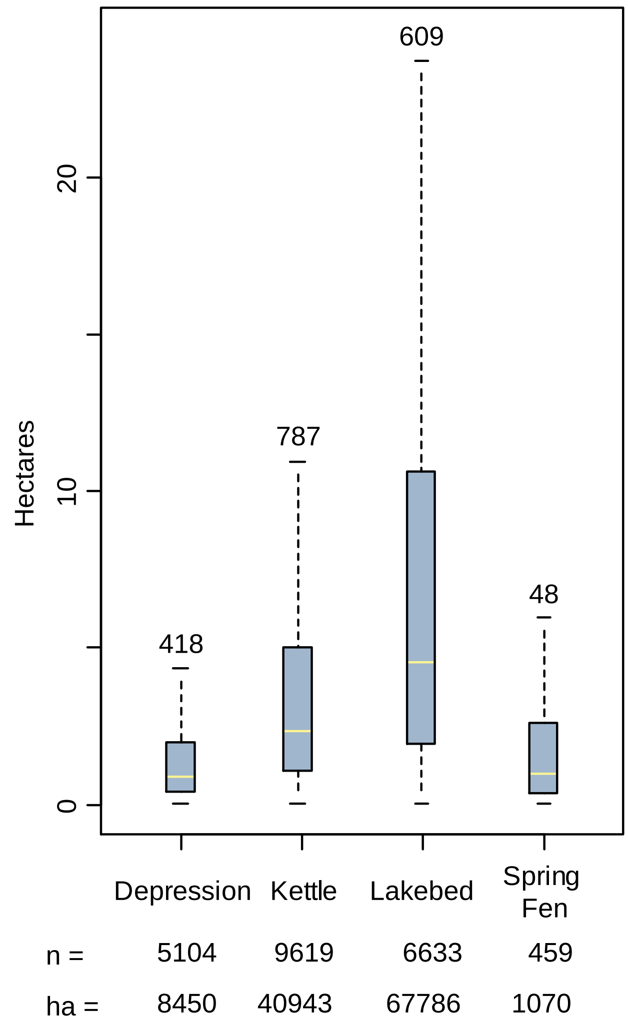


Figure 13. Size and number of peatland polygons mapped in geomorphic classes overlying glacial lakebed sediments. Boxes enclose the inner two quartiles, yellow horizontal lines are medians, whiskers extend to the last value within 1.5 times the inner quartile range, and the number of outliers is shown above each box. Numbers along the x-axis show the total number of polygons (n) and the total area (ha) mapped for each geomorphic class.

Wetland polygons mapped as Kettles tend to be intermediate in size between Depressions and Lakebeds, reflecting the relative size of the landforms (Figure 13). All three of these classes are peatlands formed on lake sediments deposited during the Pleistocene (2.65 to 0.012 Ma) or early Holocene (<11 700 ka), however, unlike Depressions, Kettles are open basins and they are smaller than Lakebeds, which are not formed by wastage of entrained ice-blocks. Where Kettles grade into Lakebeds at the up-valley margin of moraines, smaller size and closer proximity to the moraine are used to differentiate them from Lakebeds.

Kettles are assigned the Geomorphic class ‘K’ in the Cook Inlet Classification. Hydrologic classes in Kettles range in value from 1-4 and are assigned based on the average position and variability of the water table, with lower values assigned to wetter sites. Within Kettles, wetland plant communities are often arranged in concentric rings with wetter hydrologic classes occurring toward the center of the feature (Figure 14). Kettles tend to have higher values for pH, alkalinity, and specific conductance than found in the closed-basins of Depressions (Table 9 & 11) likely reflecting a stronger influence of groundwater discharge. Values are similar to those found in Spring Fens (Table 14), which are peatlands in closed-basin features, but are located in areas of moisture deficit and are fed by groundwater discharge originating in nearby mountains.

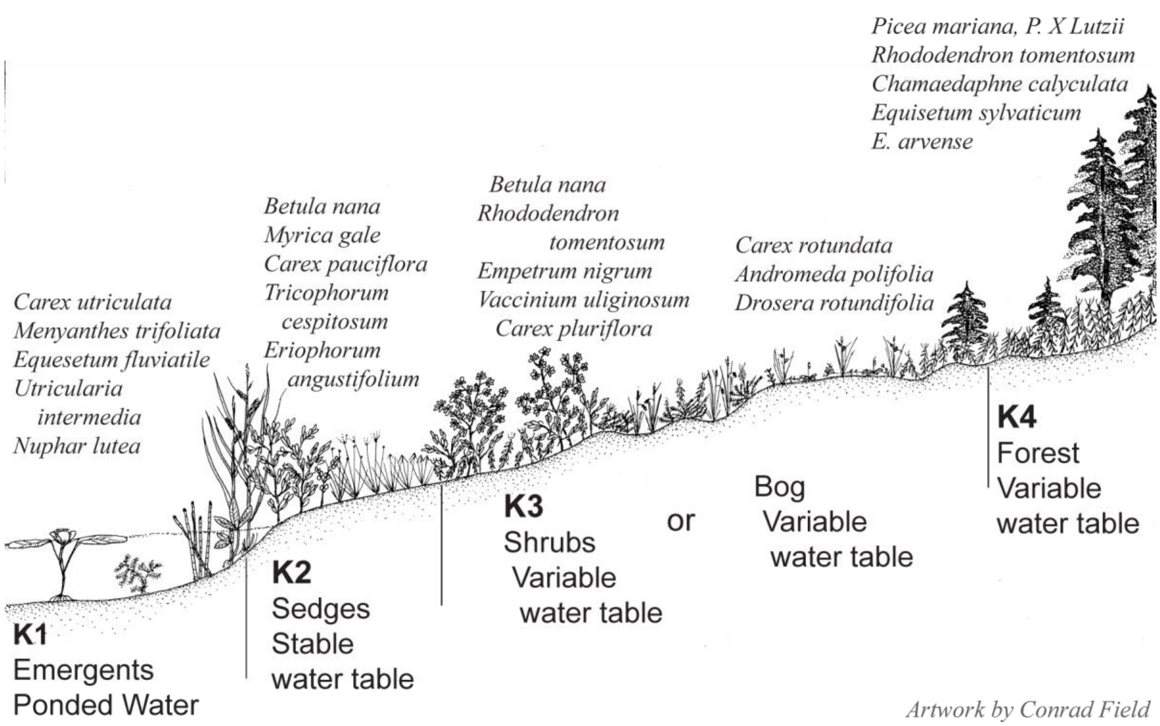


Figure 14. Idealized landscape cross-section depicting selected common plant taxa, and their relationship to the hydrologic classes of the Kettle geomorphic class of the Cook Inlet Classification. Plants shown are based on those with the highest percent cover and/or frequency of occurrence. Plant species are not diagnostic; they are depicted only to convey a general sense of the classes. Only the landform name and water level variation are diagnostic of class membership.

Table 11. Water chemistry and wetland indicators in Kettle hydrologic classes. Number of samples is in parentheses. Redox features have been measured since 2002, and thus may not always meet the criteria in the 2007 Alaska regional supplement to the delineation manual (USACE 2007). Feature depth was not recorded when peat thickness exceeded 20 cm.

Class	Peat thickness (cm)	Water table (cm)	Redox features (cm)	Saturation (cm)	pH	Alkalinity (mg/l as $CaCO_3$)	Specific Conductance (μS/cm 25°C)	Plant Prevalence Index
K1	139 (9)	-24 (12)	-	0 (11)	6.4 (50)	25.9 (10)	65 (51)	1.01 (8)
K2	194 (87)	3 (97)	61 (3)	1 (63)	5.3 (58)	17.0 (35)	84 (52)	1.44 (87)
K3	169 (115)	18 (117)	42 (4)	5 (61)	4.8 (62)	4.3 (48)	53 (52)	2.10 (117)
K4	114 (74)	30 (76)	36 (21)	21 (37)	5.1 (19)	6.3 (12)	64 (16)	2.43 (74)

Lakebeds

In the Cook Inlet Classification, Lakebeds are peatlands formed on extensive glacial lakebed deposits. In this hydrogeologic setting the regional climate coupled with the hydraulic conductivity of the peat and the distance to bounding rivers is probably the primary control on the thickness of peat accumulation (Glaser et al. 2004a). Peat accumulation on Lakebeds is almost always less than 3 meters, and the thickness did not often exceed the capacity for measurement in the field (Figure 11).

Peat porewater chemistry generally indicates that fen conditions are prevalent on the southern portion of the CIB, and bogs are more prevalent farther north; 85% of bogs were mapped in the north. This difference may not be primarily controlled by groundwater discharge because the underlying mineral materials in the south more frequently have hydraulic conductivity values too low to support significant discharge. At nearly half of Lakebeds at southern sites the texture of the underlying material was silty or finer (46%), and only 5% were sandy or coarser, whereas in the north 40% of sites were sandy or coarser and 35% were silty or finer. Although coarser materials do not always signify a groundwater discharge gradient, they are necessary to produce sufficient discharge to influence porewater chemistry. Therefore, the lack of bogs in the south compared to the north is contrary to the expected trend because the potential for groundwater influence is lower through the less-permeable sediments found there. Frequent tephra deposition and climate may limit the establishment and growth of

Sphagnum mosses in the south due to small amounts of calcium in the tephra, combined with periodic phases of low precipitation amounts (Figure 1) during the normal dry period of the growing season (Sheet 1). The precipitation may be insufficient to dilute the calcium concentration of surface water to a level tolerated by *Sphagnum papillosum* (Boatman & Lark 1971, Bridgham et al. 1996), a bog colonizer (Weber 1902, Gorham 1957). The growing-season dry-period is not as pronounced in the north, nor is the prevalence of tephra layers. For example, in the northern town of Talkeetna, 43% of annual precipitation occurs May-July compared to 27% in Homer, in the south, which is drier overall (Climate diagrams on Sheet 1). Therefore, the peatlands in the south that have formed over fine-grained materials such as silt and clay, may be functioning hydrologically as bogs in that they are ombrotrophic systems dominated by recharge and lateral flow vectors (Siegel 1983), even as they lack the low pH produced by *Sphagnum* mosses (Skeene 1915, Clymo & Hayward 1982), and contain the small amounts of calcium present in the tephra layers (Riehle 1985). The higher pH and calcium concentration, which is not excessively diluted by precipitation during the relatively dry growing season, probably both allow a few fen indicator plants, such as *Carex aquatilis* Wahlenb. (Glaser 1992) to survive in the otherwise ombrotrophic conditions of the peatlands on the southern Kenai peninsula.

Lakebeds are assigned to the geomorphic class ‘LB’ in the Cook Inlet Classification. Numeric values for hydrologic classes on Lakebeds range from 1-6 with lower values indicating a water table closer to the surface for a longer portion of the growing season (Figure 15). On Lakebeds, the numeric class value of 3 is used to indicate bogs. Where bogs are forested and when forest dominates the surface cover the mapping unit LB63 is used, and the unit LB36 is used when open conditions are prevalent. Open bogs that have progressed past a forested stage (Glaser & Janssens 1986) have not been found in the CIB, likely because low summer precipitation limits bog development. The hydrologic class 4 is used in the uncommon instances where bluejoint reedgrass dominates lakebed peatlands. On larger lakebed features, patterned fens are common. These features consist of a mosaic of pools, flarks (low mud-bottoms), strangs (shrubby ridges), and sometimes forest, at a scale too fine to delineate separately at the nominal mapping scale. These features are mapped in a unique class: ‘LBSF’.

The peat on Lakebeds is rarely greater than 3 meters thick, and often less than 2 meters, likely reflecting limitations of regional climate coupled with tectonic and geomorphic controls on interfluve breadth (Glaser et al. 2004a). Peat porewater chemistry on Lakebeds tends toward poor fen conditions with low specific conductance and acidic pH (Table 12) reflecting the general absence of bogs. Richer fen chemistry has not been encountered because alkalinity is likely limited by the paucity of calcareous rocks in the basin.

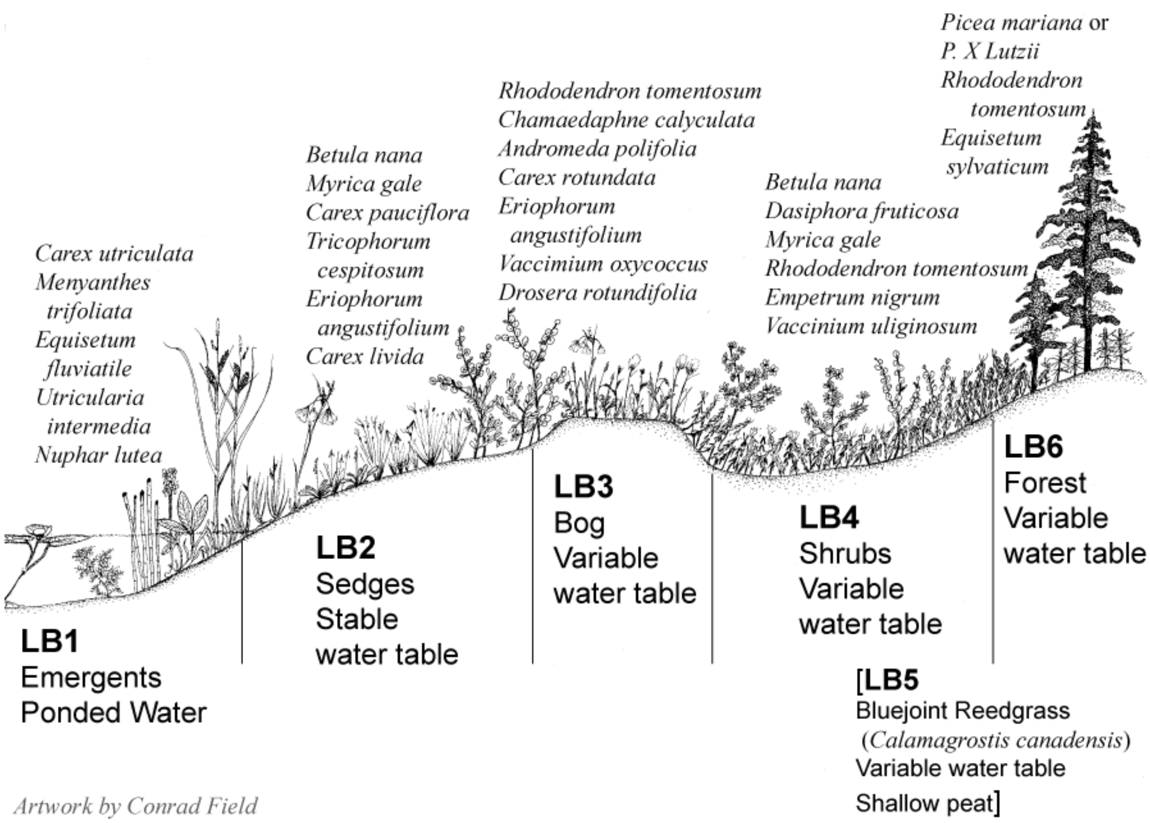


Figure 15. Idealized landscape cross-section depicting selected common plant taxa, based on those with the highest frequency of occurrence and/or percent cover, and their relationship to the hydrologic classes of the Lakebed geomorphic class of the CIC. Plant species are not diagnostic; they are depicted only to convey a general sense of the classes. Only the landform name and water level variation are diagnostic of class membership.

Table 12. Water chemistry and wetland indicators in Lakebed hydrologic classes. Number of samples is in parentheses. Redox features have been measured since 2002, and thus may not always meet the criteria in the 2007 Alaska regional supplement to the delineation manual (USACE 2007). Feature depth was often not recorded when peat thickness exceeded 20 cm.

Class	Peat thickness (cm)	Water table (cm)	Redox features (cm)	Saturation (cm)	pH	Alkalinity (mg/l as $CaCO_3$)	Specific Conductance (µS/cm 25°C)	Plant Prevalence Index
LB1	241 (7)	-61 (10)	-	0 (8)	5.8 (18)	3.3 (10)	35 (19)	1.02 (6)
LB2	188 (123)	3 (112)	108 (2)	0.4 (69)	5.3 (87)	6.9 (60)	55 (82)	1.34 (114)
LB3	183 (51)	12 (40)	-	7.5 (31)	4.4 (34)	0.1 (27)	44 (32)	1.85 (47)
LB4	130 (70)	19 (65)	55 (12)	7 (20)	5.3 (28)	5.1 (13)	61 (22)	2.10 (69)
LB5	95 (6)	38 (6)	-	15 (5)	5.1 (4)	8.0 (2)	72 (3)	2.45 (5)
LB6	99 (91)	29 (75)	49 (22)	12 (31)	4.7 (30)	6.3 (18)	64 (22)	2.42 (60)

Drainageways

Drainageways are peatlands formed in the meltwater channels that drained formerly extensive glaciers. The abandoned meltwater channels frequently support modern stream flow but with a channel geometry that is grossly mismatched to the geometry of the meltwater valley. The peat layer in drainageways tends to be thinner than in other geomorphic settings (compare values in Table 13 with Figure 11) and peat porewater chemistry indicates fen conditions (Table 13, Figures 3 & 4). The peat is more frequently underlain by sandy or coarser deposits (78%) rather than by silt or finer fractions (22%), reflecting the glaciofluvial origin of the landform. Presumably, the coarser, sorted materials facilitate the groundwater discharge that supports fen conditions. Bogs will develop on Drainageways where precipitation is sufficient and the influence of groundwater discharge to the surface is dilute, although dilute groundwater discharge may augment precipitation to support bog conditions in drier locations (Glaser et al. 1997). These conditions for bogs are most frequently met at the margins of the features, where forested bogs may develop.

Drainageways are assigned to the geomorphic class 'DW' in the Cook Inlet Classification. Numeric values for hydrologic classes range in value from 1-5A, with 5A indicating forested conditions, 5 indicating bogs and 4 indicating bluejoint reedgrass (Figure 16). Wetlands of the same hydrologic class are often oriented in zones parallel to valley walls. However, in polygons where multiple zones are too narrow to delineate separately at the nominal mapping scale the unique class 'DWR' may be assigned.

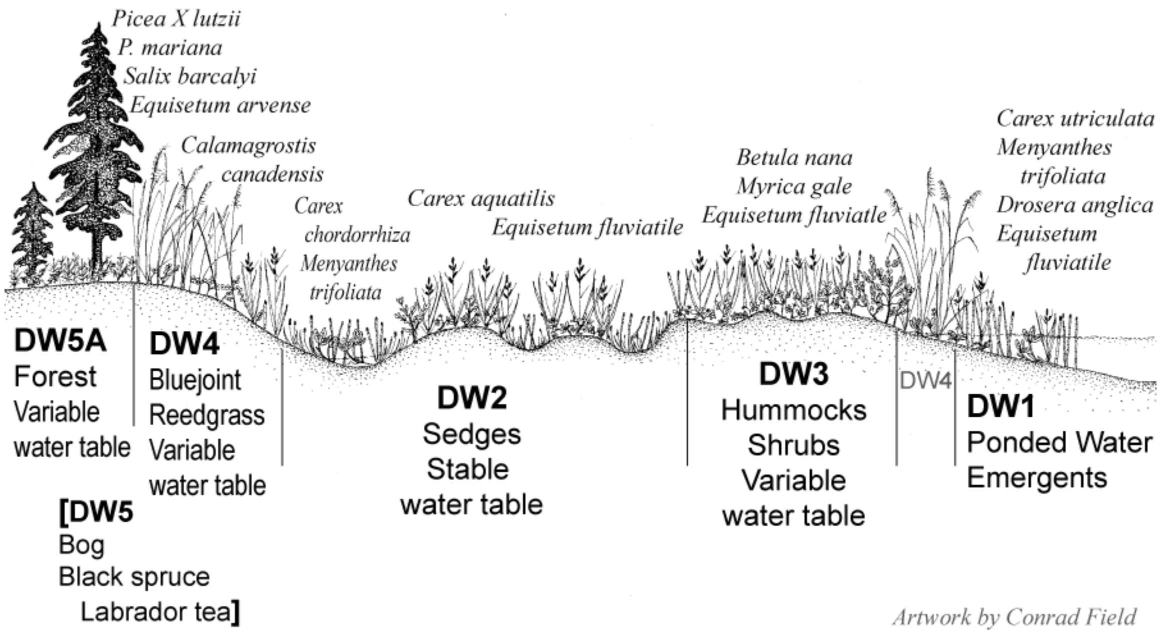


Figure 16. Idealized landscape cross-section depicting selected common plant taxa, based on those with the highest frequency of occurrence and/or percent cover, and their relationship to the hydrologic classes of the Draingeway geomorphic class of the CIC. Plant species are not diagnostic; they are depicted only to convey a general sense of the classes. Only the landform name and water level variation are diagnostic of class membership.

Peat thickness on Drainageways was measured to be greater than 3 m at only 6% of sites (n = 10), and greater than 4 m at only 2% of sites (compare Table 13 & Figure 11). At 11% of sites (n = 41) peat thickness was a minimum measurement, however only five of those measurements exceeded 2 meters. Peat thickness on many Drainageways may be constrained by the distance to the stream, which will efficiently transport porewater discharge from the peatland. A short distance, along with limited precipitation (recharge) and hydraulic conductivity will control the height of the water table mound necessary to support the anaerobic conditions favorable to peat accumulation (Ingram 1982, Glaser et al. 2004a).

Table 13. Water chemistry and wetland indicators in Drainageway hydrologic classes. Number of samples is in parentheses. Redox features have been measured since 2002, and thus may not always meet the criteria in the 2007 Alaska regional supplement to the delineation manual (USACE 2007). Feature depth was often not recorded when peat thickness exceeded 20 cm.

Class	Peat thickness (cm)	Water table (cm)	Redox features (cm)	Saturation (cm)	pH	Alkalinity (mg/l as $CaCO_3$)	Specific Conductance (µS/cm 25°C)	Plant Prevalence Index
DW1	0 (1)	-10 (3)	0 (1)	0 (2)	6.5 (5)	-	130 (5)	1.00 (6)
DW2	173 (51)	6 (53)	148 (5)	1 (23)	5.8 (40)	17.8 (10)	96 (31)	1.43 (114)
DW3	113 (68)	20 (62)	67 (7)	3 (27)	5.9 (36)	17.1 (13)	107 (30)	2.09 (47)
DW4	104 (2)	23 (2)	-	-	4.5 (1)	0.0 (1)	-	2.92 (69)
DW5	165 (23)	29 (4)	59 (4)	8 (8)	4.8 (12)	1.1 (7)	57 (10)	2.44 (5)
DW5A	67 (35)	31 (32)	36 (7)	14 (9)	5.9 (7)	42.1 (3)	115 (6)	2.64 (60)

Spring Fens

Spring Fens are peatlands in closed-basin depressions where potential evapotranspiration exceeds precipitation. For peat to accumulate in a climatic setting with a moisture deficit it must be fed by groundwater originating from a nearby source where precipitation exceeds evapotranspiration, such as in the surrounding mountains. This uncommon setting exists between Anchorage and Wasilla in the rain shadow of the Chugach Mountains. The ratio between precipitation and potential evapotranspiration (using the Thornthwaite (1948) method) at the Anchorage climate station is 401 mm : 514 mm (0.78), and it is 390 : 542 (0.72) at the Matanuska Experimental Farm, 50 km to the northeast, although precipitation is modeled at over 1000 mm in the surrounding mountains (Sheet 1). Baldy Ridge, the east-to-west running ridge to the north of Palmer and Wasilla (Sheet 1), is composed of vertically-oriented strata of siliceous arkose that can rapidly transmit recharge in the form of both snowmelt and rainfall to the unconsolidated glacial deposits filling the valley bottom (Jokela et al. 1991; Kikuchi 2013). The peat of Spring Fens accumulates in closed-basin depressions that formed in the deposits, fed by recharge originating in the mountains. Because the peat in Spring Fens is fed by groundwater recharge, water levels are stable and the peat porewater chemistry indicates fen conditions (Figure 3 & 4; Table 14).

Spring Fens are assigned to the geomorphic class ‘SF’ in the Cook Inlet Classification and the values for hydrologic classes range from 1-4 (Figure 17). Lower values indicate a shallower water table more persistently near the surface during the growing season. Although different plant communities are related to the hydrologic classes, Spring Fens are most frequently dominated by a single community with plants that are tolerant of stable water levels near the surface such as *Carex chordorrhiza, Menyanthes trifoliata,* and *Comarum palustre* (Figure 17).

Table 14. Water chemistry and wetland indicators in Spring Fen hydrologic classes. Number of samples is in parentheses. Redox features have been measured since 2002, and thus may not always meet the criteria in the 2007 Alaska regional supplement to the delineation manual (USACE 2007). Feature depth was not recorded when peat thickness exceeded 20 cm.

Class	Peat thickness (cm)	Water table (cm)	Redox features (cm)	Saturation (cm)	pH	Alkalinity (mg/l as $CaCO_3$)	Specific Conductance (µS/cm 25^oC)	Plant Prevalence Index
SF1	176 (4)	-28 (6)	-	0 (3)	6.2 (14)	0.0 (1)	62 (14)	1.05 (2)
SF2	175 (14)	2 (17)	-	0.4 (17)	5.1 (9)	18.8 (4)	81 (9)	1.71 (15)
SF3	246 (6)	11 (6)	-	5.5 (6)	4.8 (5)	0.0 (2)	79 (5)	2.13 (6)
SF4	180 (5)	7 (6)	-	2.3 (6)	5.6 (4)	-	85 (4)	1.96 (5)

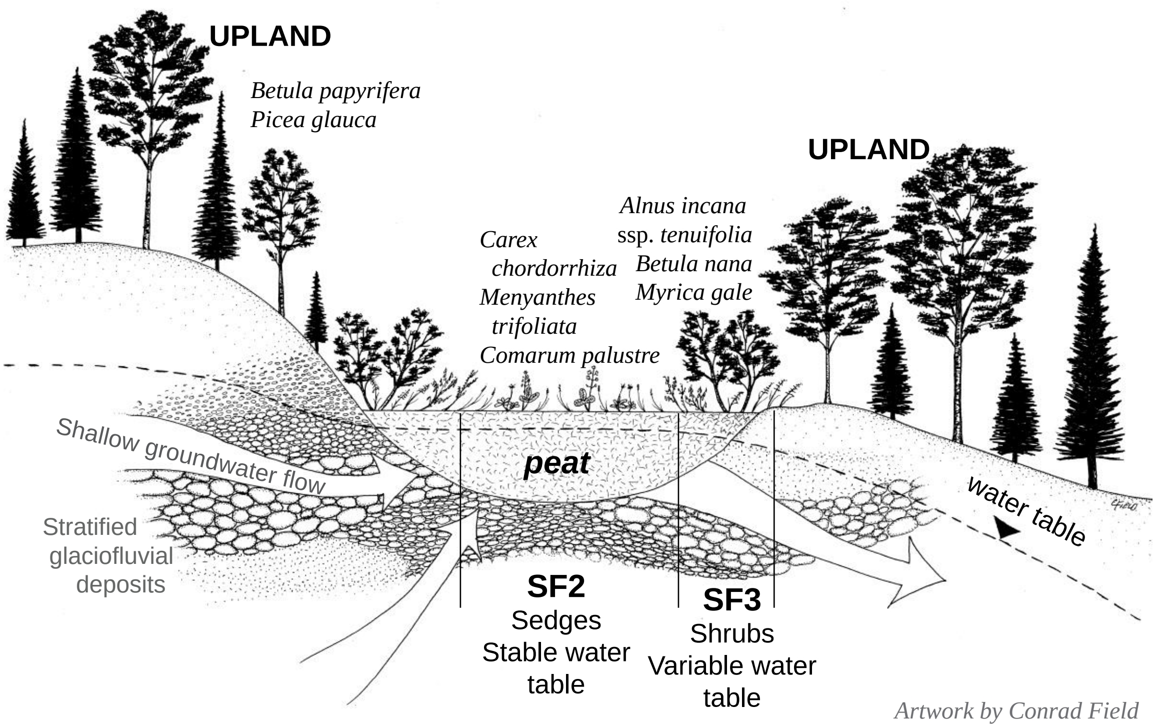


Figure 17. Idealized landscape cross-section depicting selected common plant taxa, based on those with the highest frequency of occurrence and/or percent cover, and their relationship to the hydrologic classes of the Spring Fen geomorphic class of the CIC. Plant species are not diagnostic; they are depicted only to convey a general sense of the classes. Only the landform name and water level variation are diagnostic of class membership.

VLD Troughs

VLD troughs are peatlands located in the valleys between the series of approximately 25 very large dune (VLD) features in the Meadow Lakes area (Sheet 1), which have been proposed to be of late Pleistocene (15.5-26 ka) megaflood origin. The VLDs are symmetrical ridges with smooth rounded crests oriented transverse to flow direction. They average 7 km in length with a mean crest-to-crest distance of 900 meters and decrease regularly in height from 34 m to 5 m down-valley (Wiedmer et al. 2010). The porewater chemistry of the peatlands in this unusual hydrogeologic setting appears to be intermediate between that of Drainageways and Kettles, which matches the intermediate form of the VLD features. The composition of the unconsolidated VLD deposits suggests a high hydraulic conductivity, which would support a sufficient flux of groundwater discharge to maintain the fen conditions shown by the chemistry of these peatlands (Table 15). Many of the peatlands lie adjacent to streams draining the lakes that have formed between the larger ridges. Therefore, peat thickness is likely limited by hydraulic conductivity of the peat and the distance to the stream (Ingram 1982, Glaser et al. 2004a). A total of 316 wetland polygons covering 1674 ha have been mapped in the troughs of VLDs.

VLD troughs are assigned to the geomorphic class ‘RT’ in the Cook Inlet Classification and the values for hydrologic class range from 1-4. Lower values indicate a shallower water table more persistently near the surface during the growing season.

Table 15. Water chemistry and wetland indicators in VLD Trough hydrologic classes. Number of samples is in parentheses. Redox features have been measured since 2002, and thus may not always meet the criteria in the 2007 Alaska regional supplement to the delineation manual (USACE 2007). Feature depth was not recorded when peat thickness exceeded 20 cm.

Class	Peat thickness (cm)	Water table (cm)	Redox features (cm)	Saturation (cm)	pH	Alkalinity (mg/l as $CaCO_3$)	Specific Conductance (µS/cm 25°C)	Plant Prevalence Index
RT1	-	-	-	-	5.3 (3)	-	40 (3)	1.01 (1)
RT2	253 (9)	-1.8 (12)	-	0 (13)	5.3 (9)	-	73 (9)	1.33 (8)
RT3	174 (10)	13 (10)	-	4 (10)	4.9 (10)	-	62 (10)	2.17 (10)
RT4	20 (5)	52 (4)	14 (4)	47 (4)	5.2 (4)	-	94 (4)	2.39 (8)

Abandoned Meander Terraces

Abandoned Meander Terraces (AMT) are peatlands formed on fluvial terraces that are elevated above the active floodplain. AMTs occur sparsely along larger streams and rivers on the Cook Inlet Lowlands. The terraces may have formed by tectonic uplift, or be relict features deposited by the greater river discharge that was produced by formerly more extensive glaciers, or by a combination of both processes. Only 181 wetland polygons have been mapped as AMT (of 38,691), covering a total of 1566 ha, therefore only two sites have been visited to describe them (Table 16). Peat appears to be thin, perhaps reflecting the presumed younger age of the landforms. However, climate and other factors may be more important than landform age as the primary control on peat development (Glaser et al. 2004b).

Table 16. Conditions on two Abandoned Meander Terraces.

Setting	Peat thickness (cm)	Basal Material	Water table (cm)	Saturation (cm)	pH	Specific Conductance (µS/cm 25°C)	Plant Prevalence Index
Underfit headwaters	21	-	15	-	-	-	2.91
Glacier-fed braided river	109	clay	5	0	4.4	24	1.14

Other Classes

Four other classes are used to classify the wetlands in the Cook Inlet Basin. The first are Upland/Wetland complexes, where wetlands cover more than 30% of the area, but are intermingled with uplands at a resolution too fine to delineate separately at the nominal mapping scale. Wetland/Upland complexes (WU) are most often found on hummocky topography. WUs are subdivided according to the percent covered by wetlands in 10% categories. For example, the class WU60 is a Wetland/Upland complex that is covered by 60% wetlands.

Two of the other classes are used to describe human disturbance levels; the first is a lowercase suffix ‘d’, which indicates that at least 10% of the area of a wetland is disturbed, but the pre-disturbance class can be recognized. For example, a wetland classified as K2d is in the geomorphic class Kettle (K) with a stable water table near the surface (2), but at least 10% of the area is disturbed by humans (d). The second class, ‘DISTURB’, is used when the wetland class is unrecognizable. An example of the where the suffix –d is used is where braided ATV trails traverse peatlands, and an example of where the class DISTURB is used is where fill obscures the original vegetation, soils, and hydrology of the wetland.

A third class is also related to human influence. It is where the lowercase suffix ‘c’ is appended, and refers to a wetland that was created by humans. Most of these wetlands are either located in small basins now filled with ponds, or new channels that were excavated in valley bottoms. Of the 38,691 wetland polygons mapped over the 2900 km^2 of wetlands that have been mapped in the CIB, a total of 220 wetland polygons covering 612 ha were classified as disturbed (-d), 125 wetlands covering 491 ha were classified as DISTURB, and 83 wetlands covering 214 ha were classified as created (-c).

Chapter 2 Analyzing the performance of a new peatland classification system for wetland mapping and management in Alaska (Gracz & Glaser 2016)

ABSTRACT

Several wetland classification schemes are now commonly used to describe wetlands in the contiguous United States to meet local, regional, and national regulatory requirements. However, these established systems have proven to be insufficient to meet the needs of land managers in Alaska. The wetlands of this northern region are predominantly peatlands, which are not adequately treated by the nationally-used systems, which have few, if any, peatland classes. A new system was therefore devised to classify wetlands in the rapidly urbanizing Cook Inlet Basin of southcentral Alaska, USA. The Cook Inlet Classification (CIC) is based on seven geomorphic and six hydrologic components that incorporate the environmental gradients responsible for the primary sources of variation in peatland ecosystems. The geomorphic and hydrologic components have the added advantage of being detectable on remote sensing imagery, which facilitates regional mapping across large tracts of inaccessible terrain. Three different quantitative measures were used to evaluate the robustness and performance of the CIC classes relative to that of other commonly used systems in the contiguous United States. The high within-group similarity of the classes identified by the CIC was clearly superior to that of the other systems, demonstrating the need for improved wetland classification systems specifically devised for regions with a high cover of peatlands.

INTRODUCTION

Peatlands cover approximately 20% of all boreal landscapes (Vitt 2006) including the lowlands of the Cook Inlet basin in southcentral Alaska. The 102,000 km^2 Cook Inlet Basin (CIB) is located at the northern reaches of the Pacific Ocean and supports spawning habitat for healthy populations of all five species of Pacific salmon. The peatlands of the CIB lowlands contribute to stream flows and thereby help to maintain fluvial habitats required for the survival of healthy salmon stocks (Gracz et al. 2015). These peatlands also provide a variety of other ecosystem services that affect human population centers such as flood regulation, recreational opportunities, and water purification (Millennium Ecosystem Assessment 2005). As the population of Alaska continues to grow so has the need to implement a classification system for use in wetland assessment that emphasizes the linkages between the hydrogeologic settings of oligotrophic peatlands and their functions and services.

Land managers need a classification system that can be used to classify oligotrophic peatlands, which have been generally differentiated into discrete types based on airform patterns or hydrochemical properties (Gore 1983; Zoltai et al. 1988; Charman 2002; Wieder et al. 2006; Rydin & Jeglum 2006). In practice however, the classification and mapping of peatlands is constrained by site access limitations. In regions where wetlands cover large areas and the road network is sparse, remote sensing provides the best means to scale up local field measurements to the regional landscape. Although a classification system could be devised based on the hydrochemical factors that determine the potential directions of peatland development in such regions, this type of classification system would require an impractical degree of field sampling to implement. For example, the calcium concentration and pH of surface waters have been linked to the different types of peatlands in boreal regions (e.g. Weber 1902; Sjörs 1950a; Glaser et al. 1981; Rydin & Jeglum 2006; Wieder et al. 2006; Ye et al. 2012). However, unless these hydrochemical indicators can be inferred from proxy evidence that is visible on remote sensing imagery they will have limited value for mapping peatland types across any broad region.

The geomorphic setting and hydrology of a wetland have been recognized as fundamental determinants of wetland ecosystems that are intrinsically related to wetland functions (e.g. Brinson 1993). The geomorphic setting of a peatland imposes physical constraints on hydrologic flow systems that provide the source for the dissolved mineral solutes long been recognized as the fundamental factor responsible for distinguishing different peatland types (Weber 1902; Du Rietz 1949; Kulczyński 1949; Sjörs 1950a; Glaser et al. 1990). A fundamental hydrologic factor controlling peatland vegetation patterns is the average elevation of the water table (Sjörs 1950b; Malmer 1986; Foster et al. 1988; Waddington & Roulet 2000). For example, in northern Minnesota and in the Hudson Bay Lowlands, indirect gradient analyses first aligned vegetation samples according to the elevation of the water table, with the inundated flark plots at one end of the ordination and the better-drained forested plots at the other (Glaser 1992; Glaser et al. 2004a). Striking landform patterns in large peat basins have been successfully used to define the most important types of bog and fen on remote-sensing imagery because of the sensitive adjustment of these ecosystems to the local and regional hydrogeology (e.g. Sjörs 1963; Glaser et al. 1981, 2004a; Siegel & Glaser 1987). Despite the fundamental importance of hydrology and water chemistry in the peatland literature, these factors have not been explicitly incorporated into wetland classification systems currently in use in the U.S.A.

Two classification systems are widely used across the U.S.A., the National Wetlands Inventory (NWI) and the HGM classification system (Brinson 1993; Smith et al. 1995). NWI (Cowardin et al. 1979) does not differentiate among peatland classes because these peatlands are less common in the contiguous United States except for the northeastern and Atlantic coastal states (Kivinen & Pakarinen 1981). The classification system of the hydrogeomorphic model (HGM) of wetland functional assessment uses hydrologic and geomorphologic factors to distinguish among wetlands, but only has a single class exclusively for peatlands (Smith et al. 1995). Further, when local managers attempted to classify peatlands in the CIB to develop an HGM guidebook for a representative class, they recognized that none the seven national-level classes of the HGM system adequately represented the common peatlands in this region. The HGM class *Organic Soil Flats*, for example, is described as bogs with predominantly vertical hydrodynamics, whereas the broad class of *Slope* wetlands includes fens defined as having horizontal hydrodynamics (Smith et al. 1995). However, peatlands frequently comprise a mosaic of bogs and fens exhibiting complex interacting hydrodynamics along both horizontal and vertical flow vectors (Ingram 1983; Siegel & Glaser 1987; Siegel et al. 1995; Reeve et al. 2001; Glaser et al. 2004b; Spence et al.

2011). As a compromise, Hall and colleagues (2002) hybridized the two classes into a Slope/Flat type while developing the guidebook. However, a single class is insufficient to distinguish important functional differences among the diverse peatland complexes in CIB that have important implications for wetland assessment and management.

Objectives

Here we describe the development of the Cook Inlet Classification (CIC) system, which was specifically designed to distinguish the principal types of oligotrophic peatlands in the CIB, and then use a multivariate analysis to evaluate the within-group similarity of the classes of the CIC. Because multivariate analysis has limited capacity for statistical inference, standards of comparison are needed to compare the relative robustness of the classes. For this comparison, the within-group similarity of the classes distinguished by the CIC system is compared to the within-group similarity produced by three other wetland classification systems: 1) NWI (Cowardin et al. 1979), 2) the Landscape position, Landform, Water flow path, and Waterbody system (LLWW), which was developed in the glaciated northeastern region of the USA for use with NWI (Tiner 2011), and 3) NWI+LLWW, a combination of 1 and 2 above (Brooks et al. 2011). The CIC should provide a useful basis for land management decisions if it produces a within-group similarity that surpasses that of the other wetland classification systems while also providing insights on the relationship between the hydrogeologic setting and controls on the ecosystem function of oligotrophic peatlands.

Study Area

Cook Inlet Basin (CIB), Alaska is centered at 151^{o} W longitude between 59^{o}N and 63^{o}N latitude and drains to Cook Inlet, a large marine embayment formed in a rapidly subsiding fore-arc basin (Hartman et al. 1971). The 101,635 km^2 basin is surrounded by numerous glaciated mountainous terranes of diverse lithology (Silberling et al. 1994), including the highest point in North America (Fig. 18). The lowland portion of the Basin is composed of sedimentary rocks and sediments of Paleogene to Neogene age (65.5-2.6 mya) up to 8,700 m thick (Hartman et al. 1971) derived from the surrounding diverse lithologies of the mountainous terranes including: sandstone, arkose, argillite, greywacke, slate, granodiorite, breccia, and intermediate-to-felsic volcanic rocks (Beikman 1994). These sedimentary rocks and sediments are mantled by glacial deposits of Pleistocene age (11.7 ka – 2.65 ma) up to 2,800 m thick (Freethy & Scully 1980) that form a geomorphologically complex landscape. For at least the past 10.5 ma, active volcanos along the western margin of CIB have blanketed the entire basin with volcanic ash of diverse composition, from dacite to calc-alkaline tephras (Fournelle et al. 1994; Riehle 1985).

The physiography of the basin supports a strong but complex maritime-to-continental climatic gradient. Winter temperatures always fall below -40^{o}C in the interior, while at coastal stations they rarely reach -20^{o}C (Fig. 18). Annual precipitation ranges from 300-1000 mm in the lowlands, and can be as high as 9000 mm at glaciated mountain passes (PRISM Climate Group 2011; Sheet 1). Nearly half of the annual precipitation falls from September-December, whereas less than 20% falls from April through July (Utah Climate Center 2013). Evapotranspiration can exceed precipitation in a small area of rain shadow formed by the surrounding mountains. Wetlands still occur in this pocket of moisture deficit because recharge in the surrounding mountains, where precipitation far exceeds evapotranspiration, is rapidly transmitted to the lowlands through permeable bedrock and glaciofluvial deposits (Jokela et al. 1991; Kikuchi, 2013). Over most of the lowlands, however, precipitation is ample to support peatlands that cover approximately 20% of the CIB lowland.

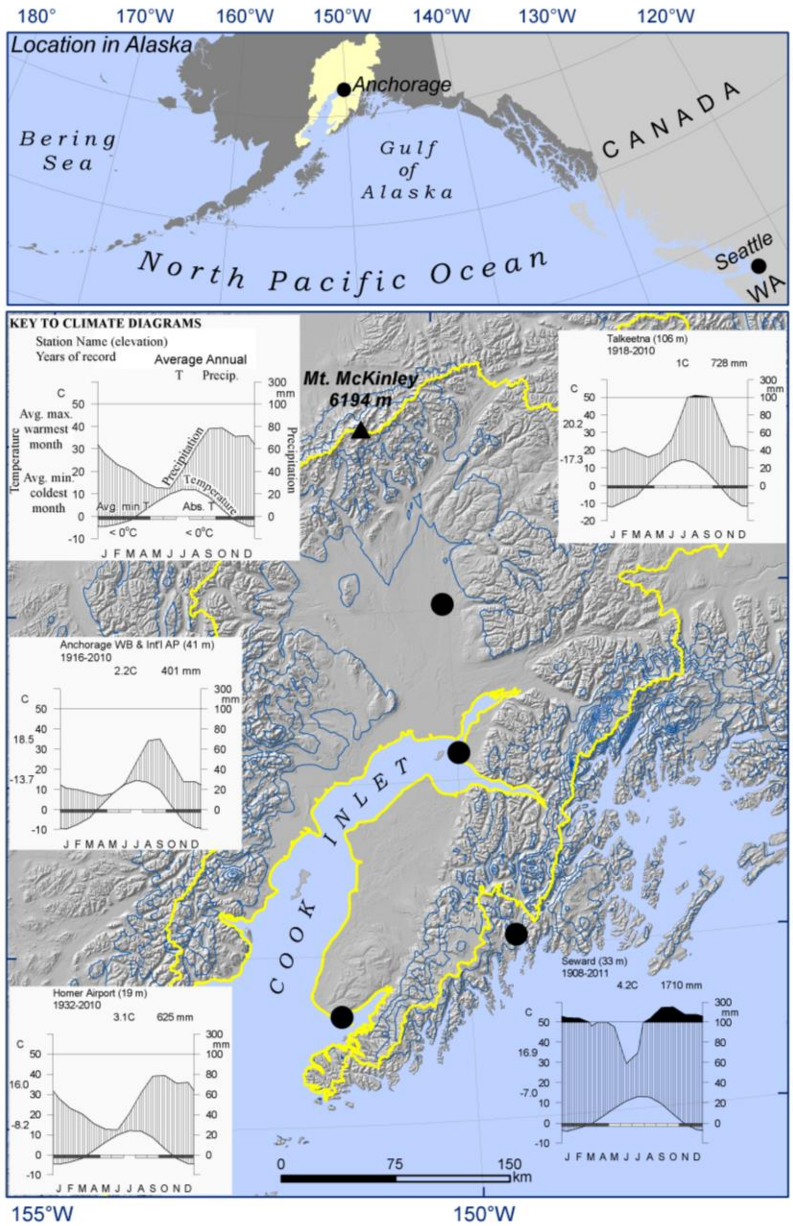


Figure 18. Location, physiography, and climate of Cook Inlet Basin, Alaska, shown by *yellow polygon* (top) and outlined in *yellow* (bottom). *Blue lines* show 1000 mm isohyets (bottom). *Black circles* on bottom map show locations of climate stations. Climate diagrams follow Walter & Leith (1960).

METHODS

Cook Inlet Classification System

The Cook Inlet Classification (CIC) system has been used to map 1508 km^2 of peatlands over an area of 7589 km^2 (Sheet 1). The system is comprised of geomorphic and hydrologic classes that are readily detectable on stereo-paired aerial photographs or in combination with shaded-relief images of digital elevation models derived from high-resolution bare-earth Light Detection and Ranging (LiDAR) data. Wetlands underlain by mineral substrates are also described in the CIC, such as tidal and floodplain wetlands. A complete guide to of all of the wetlands mapped in the CIB is presented in a map (Sheet 1), which contains a detailed legend, idealized cross-sectional diagrams of plant associations, and graphical summaries of climatic, water chemistry, and plant prevalence index data.

The CIC uses seven Geomorphic Components and six Hydrologic Components to form classes for the oligotrophic peatlands of the CIB. The Geomorphologic Components of the CIC system were developed using an iterative approach guided by the regional geologic literature, soil maps, field observations, and discussions with regional experts. These components were designed to capture the principal hydrogeologic settings of wetlands within the Cook Inlet Basin that impose geomorphic constraints on the local hydrology and water chemistry. To discover which geomorphic features best defined distinct peatland classes, the peatlands in two small pilot areas were mapped and then sampled in the field to determine their hydrology (i.e. water table elevations) and water chemistry (e.g. Ca concentrations, pH etc.), and to characterize vegetation assemblages. Different names for the Geomorphic Components were applied and adjusted until an adequate set of names appeared to separate peatlands with discrete hydrological, chemical, and biological characteristics. After the pilot areas was satisfactorily classified, new Geomorphic Components were added to the classification system as the mapping area broadened during subsequent years. Plant cover and water chemistry data were evaluated along with data from instrumented wells and piezometers to refine the names or support new designations.

This iterative approach was modified to account for the practical needs of regulatory jurisdiction and management. For example, kettle depressions are common features in many areas of the CIB. However, these kettles can be further characterized as: 1) closed basin, which is an important jurisdictional criterion for wetland permitting, 2) closed basin, but strongly connected to groundwater flow within a zone of moisture deficit, and 3) open basin, i.e. connected by surface water to a navigable water body. Although these three types of landforms could all be classified as kettles, they clearly lie in different hydrogeologic settings, some of which may not be subject to regulatory authority. Therefore, different Geomorphic Component names were assigned to each of them: 1) *Depressions* are kettles in closed basins (Neuendorf et al. 2005) lacking a strong hydrologic connection to groundwater discharge, 2) *Spring fens* are closed basins strongly connected to groundwater flow (Zoltai et al. 1988) in a zone of moisture deficit, and 3) *Kettles* are open basins (Table 17).

In the CIC, the Hydrologic Components are represented as numbered values describing the seasonal variability of water levels. Lower values represent wetlands with water levels at or above the land surface throughout the growing season, whereas higher values represent wetlands with more variable water levels found on average deeper below the surface. Seasonal water-level variation was used to define Hydrologic Components because a large number of vegetation studies in a variety of settings, including peatlands, relate the first ordination axis of plant presence and abundance data to a moisture gradient (Bray & Curtis 1957, Curtis 1959, Whittaker 1970, Peet 1980, Kormárková 1981, Foster et al. 1988, Dunham 1989, Glaser 1992, Pinder & Rosso 1998, Glaser et al. 2004a, Zelnik & Čarni 2008).

We define wetlands using the criteria in the Alaska Regional Supplement (USACE 2007) to the delineation manual (Environmental Laboratory 1987). In general, these manuals define wetlands according to the relative persistence of the water table near the ground surface as a proportion of the growing season length. Because of the short growing season in the CIB (USDA 2011), sites that support water levels within 30 cm of the ground surface for approximately two weeks during the growing season usually satisfy the wetland criteria in the manuals. However, the peatlands described here often support such elevated water levels throughout the growing season.

Table 17. The Geomorphic Components of freshwater peatlands in the Cook Inlet Classification. All three of the NWI classes of PEM, PSS and PFO occur in all of the CIC classes.

CIC Geomorphic Component	LLWW Synonyms	Landform	Diagnostic Characteristics in CIC
Depression	Terrene Basin Isolated; Terrene Basin Isolated Lotic Fringe	Closed basin ice-block depression	Surrounded by upland, Precipitation > Evapotranspiration
Kettle	Terrene Basin Throughflow; Terrene Basin Headwaters; Lotic Fringe Throughflow	Open basin ice-block depression	Connected to navigable water by surface water or wetland
Spring Fen	Terrene Basin Throughflow Groundwater; Lotic Fringe	Closed basin ice-block depression	Surrounded by upland, P ≤ ET, in depressions fed by strong groundwater discharge
Headwater Fen	Terrene Basin Outflow Headwaters; Terrene Basin Throughflow Headwaters	Cirque	Headwater peatland of a first-order stream near or above treeline
Relict Glacial Drainageway	Terrene Slope Headwaters; Terrene Slope Throughflow; Lentic Slope Fringe	Abandoned or underfit stream valleys	Broadly linear features filled with peat, with or without modern stream channels
Relict Glacial Lakebed	Terrene Slope Throughflow	Extensive peatlands over proglacial lake deposits	Large, low-gradient peatlands
VLD Trough	Lotic Fringe Throughflow; Terrene Slope Throughflow	Valleys between “Very Large Dunes”[a]	Poorly understood ripple-like features in the Meadow Lakes area of the Matanuska Valley

[a]As described by Wiedmer and colleagues (2011) in a paper proposing the genesis of the dunes by a late-Pleistocene megaflood.

CIC: Class assignment

Wetland class assignments in the Cook Inlet Classification were initially made in the lab, guided by a variety of resources including geologic maps, soil maps, NWI mapping, and stereo-paired aerial photographs. Once made, a representative sample of the class assignments was subsequently corrected during site visits. Corrected CIC class names were matched (cross-walked) to LLWW class names in 2005 by R. Tiner, the developer of the LLWW, using descriptions written for the CIC. The five Landform classes of LLWW that matched CIC classes were: Terrane Slope, Basin, and Headwaters; and Lentic and Lotic Fringe. Landforms names were used with three water flow-path classes: Throughflow, Inflow, and Outflow, occasionally modified by: Groundwater, Headwaters, and Lotic Fringe. Although much more complex names are possible in the LLWW system, we limited the names so that similar levels of classification could be compared across the systems. The limit further allowed us to evaluate the ability of a simple dichotomous naming system to create high within-group similarity based on relevant ecological measures.

The Palustrine System of NWI was assigned to each plot along with one of the three NWI plant physiognomic classes: emergent (PEM), shrub-scrub (PSS), and forested (PFO), using NWI maps (USFWS 2010). Brooks and colleagues (2011) suggest that combining a hydrogeomorphic model (HGM) classification system with the NWI system would produce a system emphasizing fundamental hydrogeomorphic characteristics built on existing NWI terminology. To compare CIC to such a classification scheme, we combined the NWI classes with LLWW names for each plot. Because the developers of each classification essentially made the class assignments, errors related to misclassification are negligible. Although mapping errors are possible in NWI (Dvorett et al. 2012), we assigned classes based on the conditions found during the field visit.

Field Measurements

In the field we measured: water level, plant cover by species, specific conductance (SC), and pH of surface water at 222 plots with homogeneous vegetation stratified across the CIC peatland classes in proportion to their occurrence. Percent cover class was estimated for each plant taxon. All vascular taxa covering 1% or more were identified at least to the species level. Cover classes were in 10% categories, except between 1-7% where one percent classes were used. Cover less than 0.5% was tabulated as 0.1%. Measurements of SC and pH were taken in surface water, where available, or in a shallow pit excavated no more than 30 cm deep. Measurements were made using a YSI 63 meter, which was two-point calibrated for pH between each measurement and cleaned daily. Estimates were made of the depth of the water table below the surface at 957 plots sampled as part of this study and during the Western Kenai Soil Survey (Van Patten 2005) to calibrate a proxy for water-level variation.

Plant Prevalence Index and Detrended Correspondence Analysis

Two separate procedures were used to evaluate the within-group similarity produced by the CIC and the other common classification schemes. The first procedure used SC, pH, and plant prevalence index. Specific conductance should be strongly correlated with calcium concentration because calcium is typically the major cation balancing charge in most surface waters. The calcium concentration and pH of peatland surface waters are the two chemical factors most closely related to plant distribution and other processes in oligotrophic peatlands (Weber 1902; Kuczyński 1949; Sjörs 1950a; Glaser et al. 1981, 1990; Foster et al. 1988; Ye at al. 2012). Peatland pore waters represent varying mixtures of precipitation and groundwater from the underlying mineral substratum, which therefore has a strong influence on the range of peatland types across any given region (Siegel & Glaser 1987; Hill & Siegel 1991; Siegel et al. 1995; Glaser et al. 2004b).

Plant Prevalence Index (PI) was used as a proxy for the seasonal variability of water levels in place of the single water depth measurement from each site. Single measurements are not representative of the range and duration of water table fluctuations in a wetland. Further, reliable measurements of water levels throughout the season and over multiple years requires an impractical intensity of data collection across large regions with limited site access. The PI calculation uses the wetland indicator status of each plant in a plot as a criterion for wetland definition in the Alaska Regional Supplement to the Delineation manual (USACE 2007) and elsewhere (De Steven 2015). Wetland indicator status was assigned to each sampling site using the values in the PLANTS database (USDA 2010). The suitability of PI as a proxy for water level variability was then assessed by comparing PI to measurements of water table depth at 957 plots.

The second procedure evaluated the within-group similarity produced by each classification system using the axis scores from a Detrended Correspondence Analysis (DCA) of plant cover data (Hill 1979; McCune & Mefford 1999). DCA is a modified reciprocal averaging technique that produces multiple axis scores for samples based on the presence and abundance of entities. It is appropriate for matrices with many zeros, such as those associated with plant cover data.

Multi-Response Permutation Procedure

Multi-Response Permutation Procedure (MRPP) was used in PC-ORD to assess within-group similarity (McCune & Mefford 1999). MRPP is a non-parametric procedure that produces a *P*-value describing whether or not class assignments differ from random. With a large sample size, such as the CIB samples, *P*-values are often statistically significant, and the challenge becomes the interpretation of the ecological significance of the non-random groupings. To assist with this ecological interpretation, MRPP produces an A value, the chance-corrected within-group agreement, which ranges from zero to one. When $A = 1$ all plots in each group are identical to each other. Values for $A \geq 0.1$ can be ecologically meaningful, and $A = 0.3$ is “fairly high” according to McCune & Mefford (1999). In the procedure using PI, pH, and SC, the measurements were made commensurate by normalization (Mielke et al. 1981). This procedure was first run with the CIC using only its Hydrologic Components; second, using only its Geomorphic Components; and finally, with the complete classes, so that the relative contribution of each component could be evaluated separately.

RESULTS

CIC Classes

Each Geomorphic Component of the CIC supports a somewhat different combination of pH, specific conductance, and seasonal variation in water levels (Fig. 19). Most Geomorphic Components have Hydrologic Components similar in character to those of *Kettles*, which were assigned Hydrologic Component values ranging from 1-4 (Fig. 14). These values are reflected in the vegetation found within the wetland. For example, sites classified as the Geomorphic Component *Kettle* (*K*), with a Hydrologic Component = *1* (i.e. mapped as *K1*), support open ponded water with emergent plants such as yellow water-lily (*Nuphar lutea* (L.) Sm.) and water horsetail (*Equisetum fluviatile* L.). In contrast, sites classified as *K4* are in *Kettles* that frequently support a forest of black spruce (*Picea mariana* (Mill.) Britton, Sterns & Poggenb.) over an understory of Labrador tea (*Rhododendron groenlandicum* (Oeder) K.A. Kron & W.S. Judd) (Fig. 14, Sheet 1).

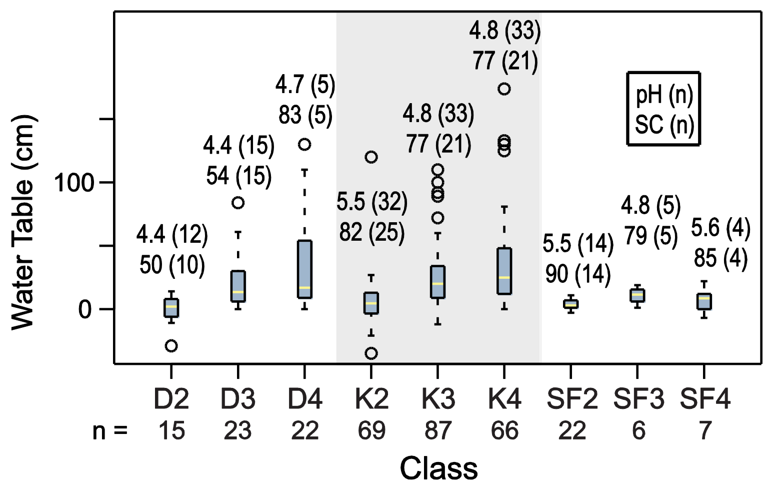


Figure 19. Water levels and chemistry of peatlands in kettle landforms. *D2-4* are *Depressions*, *K2-4* are *Kettles*, and *SF2-4* are *Spring Fens* in the Cook Inlet Classification system. *Blue boxes* enclose the inner two quartiles, the *yellow horizontal lines* inside the boxes are median values, and the *whiskers* extend to the last value within 1.5 times the inner quartile range. Values outside of the inner quartile are plotted as *circles*. Numbers are pH, specific conductance, and sample n according to the key in the box

Two extra hydrologic classes (*5* & *6*) were required in the Geomorphic Components *Drainageways* and *Lakebeds* because peatlands form extensive complexes on these landforms. One of the extra Hydrologic Components represents bogs, which often occur as small recharge mounds within larger fens, or as forested margins on relict glacial drainageway features *(LB3* in *Lakebeds* & *DW5* in *Drainageways*). The bog class is supported because the fundamental dichotomy between bogs and fens has long been recognized in peatland classification (Du Rietz 1949; Sjörs 1950a; Glaser et al. 1990; Keimowitz et al. 2013). The other Hydrologic Component unique to *Lakebeds* and *Drainageways* represents zones dominated by blue-joint reedgrass (*Calamagrostis canadensis* Michx. P. Beauv.), a common grass occasionally encountered on shallower peat deposits in the CIB (*LB5* on *Lakebeds* & *DW4* in *Drainageways*) (Fig. 15 & 12). Both of these additional components can be distinctive over extensive areas on these larger peatland complexes.

For mapping purposes, within any Geomorphic Component the values for the Hydrologic Component can be combined to name a mapping unit. For example, the mapping unit *K32* indicates a polygon mapped in a *Kettle* peatland with a mixture of Hydrologic Components *3* and *2* at a scale too fine to be delineated separately at the nominal mapping scale. The first-named Hydrologic Component covers a greater area of the polygon. Polygons, rather than wetlands, were classified because individual peatlands are frequently extensive complexes covering tens of thousands of hectares and composed of many different types of wetland (Sheet 1).

Plant Prevalence Index

Sites characterized by low PI values are more likely to support water levels that remain close to the land surface, whereas sites with higher PI values are associated with deeper and more variable water levels (Fig. 19). Plots with a PI between 1 and 2 are those supporting a predominance of wetland obligate plants (occur in wetlands > 99% of the time) and plants that occur in wetlands more than 67% of the time (taxa classified as *Facultative-Wet*). The median water level in these plots is close to the surface (-2 cm), and they typically exhibit a lower variability in water levels throughout the year (s.d. = 20.6 cm) than plots scoring between 2 and 3 (-5 ± 30.1 cm). Plots with a PI value of greater than three typically have a water level that is even deeper below the surface (median = 17 cm) and exhibits greater variability (s.d. = 36.0 cm) (Fig. 20).

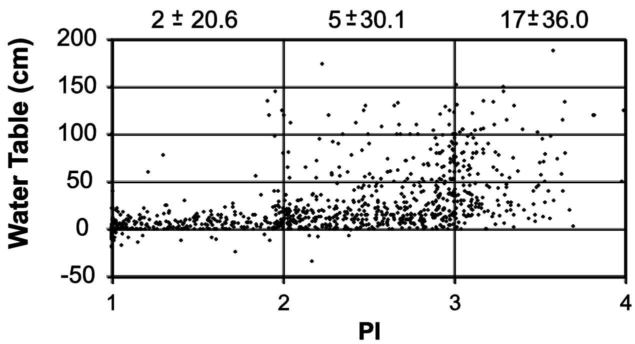


Figure 20. Plant Prevalence Index (PI) compared to estimates of the depth to the water table at 957 plots across CIB. Negative values indicate water above the surface. *Numbers along the top* are the median and standard deviation (cm) of the water table estimates for each corresponding range of PI values.

MRPP

The MRPP analysis indicates that all four classification schemes produce non-random groups of plots with $P < 0.001$. The analysis of the LLWW system by itself produced the lowest chance-corrected within-group agreement ($A < 0.05$). The within group agreement among the NWI and NWI+LLWW classes remained less than 0.1 for procedures using PI, pH, and SC. However, the NWI system produces relatively higher within-group similarity for the procedure using DCA axis scores ($A = 0.13$), as does NWI+LLWW ($A = 0.18$). Similarly, the analysis of the CIC using only Hydrologic Components produced a relatively low A value (0.06); as did the analysis using only Geomorphic Components ($A = 0.05$). However, the combined Hydrologic and Geomorphic Components of the CIC system produce the highest within-group agreement in analyses using PI, pH, and SC ($A = 0.12$), or the analyses using the DCA scores from plant cover data ($A = 0.21$) (Table 18).

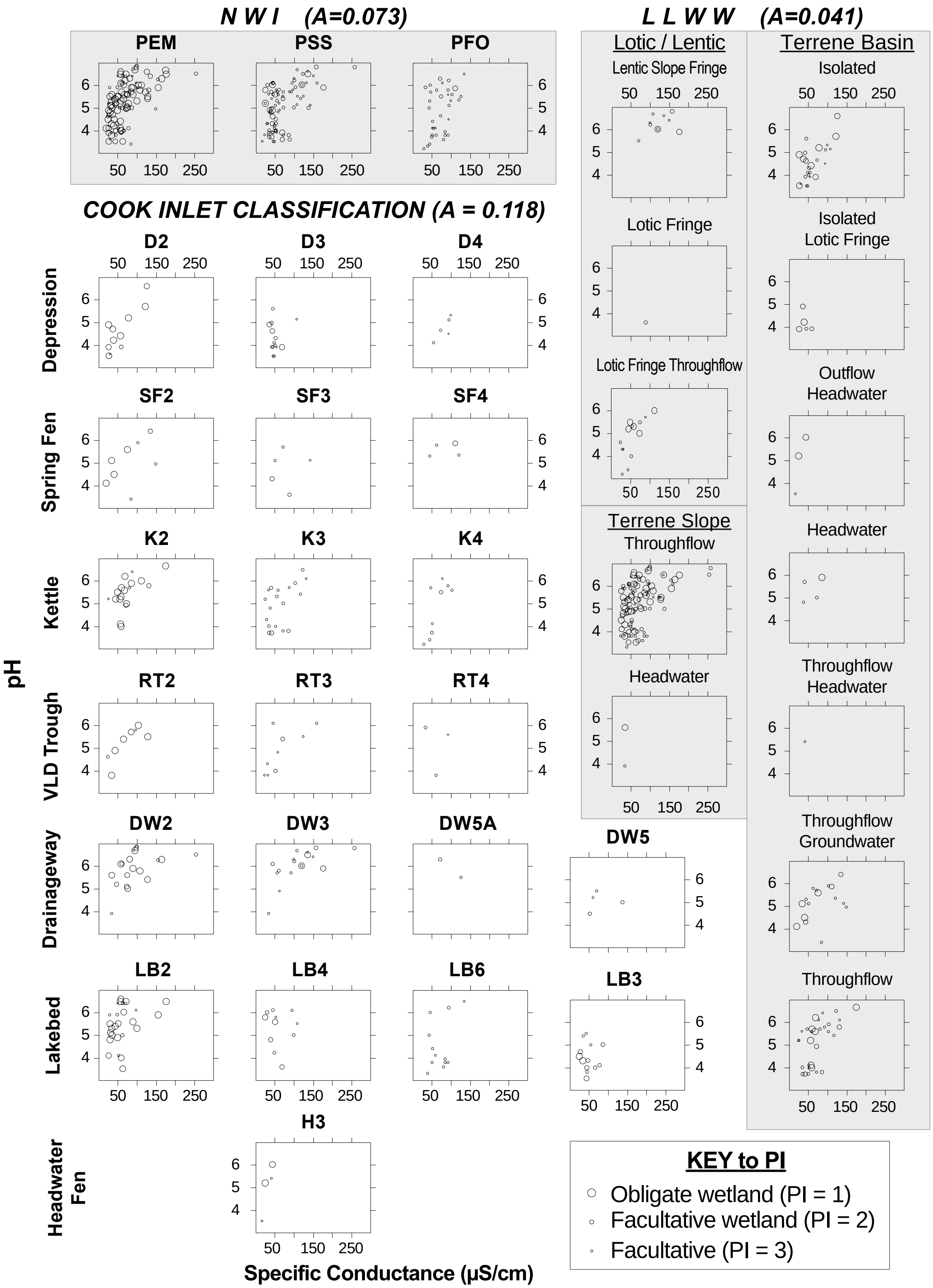
Table 18. MRPP *A* scores for the four classification schemes in the two procedures. DCA is the MRPP using the first three axis scores from a Detrended Correspondence Analysis of plant cover data. PI, pH, SC is the procedure using physical and chemical variables where PI is Prevalence Index, and SC is specific conductance. CICHydro uses only the hydrologic classes of the CIC, and CICGeo uses only the geomorphic classes.

	MRPP	
Classification System	**DCA**	**PI, pH, SC**
NWI	0.13	0.07
LLWW	0.03	0.04
NWI+LLWW	0.18	0.10
CICHydro	-	0.06
CICGeo	-	0.05
CIC	0.21	0.12

The CIC plots are distributed evenly among the three NWI classes. These three classes (Palustrine emergent (PEM), shrub-scrub (PSS), and forested (PFO)) produce groups of plots characterized by similar values for PI, but plots within these groups exhibit a wide range of values for pH and SC (Fig. 21). In the LLWW system, most plots fall into five of the twelve classes (Fig. 21). Two of the classes, Lentic Slope Fringe and Inflow Lotic Fringe, separate two groups of peatlands: one with high values for pH and SC and the other with lower values. The hydrologic factor Throughflow differentiates some plots based on water chemistry because Throughflow peatlands in the landform classes Terrene Slope and Terrene Basin both contain plots with the highest values for SC (Fig. 21). However, these classes do not separate plots with different ranges in values for PI or pH, and patterns in PI, pH, and SC are similar between Throughflow peatlands in both the Terrene Slope and Terrene Basin classes (Fig. 21). Flow path classes do not appear to strongly differentiate plots based on PI, pH, and SC within any single geomorphic class. For example, the three flow-path sub-classes (Isolated, Throughflow Groundwater, and Throughflow) within the Terrene Basin class all exhibit a wide range of values for at least two of the variables (Fig. 21).

Peatland plots are evenly distributed among the 21 CIC classes, each of which broadly exhibits similar values for PI, pH, and SC. Although substantial overlap is evident, plots classified within each Hydrologic Component have similar PI values across Geomorphic Components (columns in Fig. 21), whereas plots within the same Geomorphic Component generally exhibit similar patterns in pH and SC (rows in Fig. 21). For example, PI values are similar between K2 & D2, or K4 & D4, whereas pH and SC are lower on shrubby *Lakebeds* (*LB4*) than in shrubby *Drainageways* (*DW3*) (Fig. 21). Plots with higher values for both pH and SC tend to occur in *Drainageways*, whereas those with lower values occur in *Depressions*, and those in *Kettles* have intermediate values overall. An exception is bogs in *Lakebeds* (*LB3*), which exhibit a relatively wide range in values for PI (Fig. 21).

Figure 21 (next page). Specific Conductance, pH and PI for the three classification systems: Cook Inlet Classification (CIC), National Wetlands Inventory (NWI), and LLWW. The *size of the circles* is scaled continuously to plant Prevalence Index (PI), the key shows sizes corresponding to three important values of PI. CIC and NWI classes are arranged left-to-right from wetter to drier so that similar hydrologic classes are arranged in columns.


N W I (A=0.073)
PEM
PSS
PFO
L L W W (A=0.041)
Lotic / Lentic
Lentic Slope Fringe
Lotic Fringe
Lotic Fringe Throughflow
Terrene Slope
Throughflow
Headwater
Terrene Basin
Isolated
Isolated Lotic Fringe
Outflow Headwater
Headwater
Throughflow Headwater
Throughflow Groundwater
Throughflow
COOK INLET CLASSIFICATION (A = 0.118)
Depression
D2
D3
D4
Spring Fen
SF2
SF3
SF4
Kettle
K2
K3
K4
VLD Trough
RT2
RT3
RT4
Drainageway
DW2
DW3
DW5A
DW5
Lakebed
LB2
LB4
LB6
LB3
Headwater Fen
H3
pH
Specific Conductance (µS/cm)
KEY to PI
Obligate wetland (PI = 1)
Facultative wetland (PI = 2)
Facultative (PI = 3)

DISCUSSION

Peatlands form autochthonously though the accumulation of organic matter, and as a result they would be expected to exhibit different responses to environmental factors than those of other types of wetlands in which the vascular plants are directly rooted in mineral soil. In raised bogs, for example, the accumulation of peat creates a mounded landform, which in turn gives rise to a new set of hydrologic flow conditions that were not originally present at the site prior to the onset of peat formation (Glaser & Janssens 1986; Siegel et al. 1995; Glaser et al. 1997). Because the hydrogeologic factors of the CIC system are more directly related to the fundamental ecological controls of oligotrophic peatlands than the more generalized factors used by the NWI, LLWW, or NWI+LLWW systems, the CIC produced greater within-group agreement. The hydrologic factor of water level variation appears to be the most important control, similar to the findings of Foster and colleagues (1988), who discovered that surface patterns and peat accumulation rates in patterned fens in eastern Canada were primarily controlled by water table elevations. In northern Minnesota, moisture tolerance controlled the arrangement of plots in a gradient analysis (Glaser 1992). In in northern Sweden, Waddington and Roulet (2000) found that methane production and carbon cycling were related to topographic position, which in turn is related to soil moisture. Glaser and colleagues (2004a) found that species richness of both vascular plants and bryophytes declined in a nearly linear relationship with increasing water level on the Hudson Bay Lowland, the most extensive peatland complex in North America.

In the CIB, water-level variation may be even more decisive in creating different peatland types because of the uneven distribution of seasonal precipitation. In contrast to continental regions, where summer convective storms provide an equable distribution of precipitation throughout the growing season, peatlands in the CIB are exposed to high water tables at the beginning of the season following the flush of spring snowmelt, whereas the driest months immediately follow. The wet season does not begin until late summer and early fall with the deepening of the Aleutian Low pressure system (climate diagrams in Fig. 1, Sheet 1). The long lag between substantial recharge from spring snowmelt and the onset of fall rains regularly allows for a period of water level drawdown during the short growing season in CIB.

The classes identified by the CIC system are characterized by high within-group similarity in PI, a proxy for water level variation. Similarly, the three plant life-form classes used in the NWI system are likely related to water level variations, so it is not surprising that this classification system produces the next best within-group agreement. In contrast, the hydrologic classes of LLWW, which are defined by inferred water flow-path, produce low within-group similarity. The low similarity produced by the LLWW system agrees with findings of other investigations (*cf*. Shafer et al. 1999). Although Cole and colleagues (1997, 2000) found similarities in hydrological conditions among flow-path classes within the state of Pennsylvania (USA), the within-class similarity was low when the classes were applied over a wider region (Cole et al. 2008) or in the distant state of Oregon (Cole et al. 2002). Morrice and colleagues (2008) found that a similar classification system using flow path as a hydrologic factor did not define hydrologically distinct groups of Great Lakes coastal wetlands. These classification systems based on flow-path were apparently unable to produce distinct groupings in some regions because of the complexity of groundwater flow systems that can vary, or even reverse seasonally within the same wetland (Siegel & Glaser 1987; Siegel et al. 1995; Spence et al. 2011). Although shallow flow paths in peatlands can be assigned using the presence or absence of inlet and outlet streams, these relatively small streams may have little effect on the overall hydrodynamics in a peatland (Spence et al. 2011).

The seven specific landform names of the CIC system produce greater within-group agreement than the geomorphic factors employed in NWI, LLWW, or NWI+LLWW. Geomorphology should be related to water chemistry as long as the hydrogeologic setting is understood (Foster et al. 1988; Glaser et al. 1997; Glaser et al. 2004a). NWI uses only a single geomorphic factor to classify freshwater peatlands (Palustrine) and the physiognomic classes produce low within-group similarity based on the chemistry variables. These problems likely arise because different species within each life-form class can exhibit wide ecological tolerances with respect to pH and calcium concentration (Sjörs 1950a; Glaser 1992). For example, whereas the shrub sweetgale (*Myrica gale* L.) will occur only on minerotrophic fens and not on ombrotrophic bogs, the shrub Labrador tea (*Rhododendron groenlandicum* (Oeder) Kron & Judd) occurs on both bogs and fens (Glaser 1992).

When applied to peatlands in the CIB, the LLWW system uses five landform types with respect to geomorphology, and those types show some similarity in water chemistry.

However, LLWW produced low within-group similarity overall, which agrees with findings from other investigations. For example, LLWW did not produce groups of wetlands with similar water chemistry in the state of New York, USA (Azzolina et al. 2007), and a classification system employing similar geomorphic classes also produced low within-group similarity of water chemistry in the coastal wetlands of the North American Great Lakes region (Morrice et al. 2008). Used alone, the Geomorphic Components of the CIC system produce greater within-group agreement than the combined geomorphic and hydrologic classes of the LLWW.

The importance of water level variation in producing within-group similarity is further demonstrated by the results of the MRPP analysis using the combined NWI+LLWW classification system. In the procedures using PI, pH, and SC, the increase in within-group agreement of NWI+LLWW is small over either the NWI or LLWW systems by themselves. By itself, the LLWW system produces the lowest within-group agreement. The higher within-group agreement produced by the NWI system by itself is likely due to the strong relationship between water-level variation and its physiognomic classes. When the NWI and LLWW systems are combined, the small increase in within-group agreement suggests that the physiognomic classes of NWI are the primary driver of the increase, probably because the weak relationship between water-level variation and the LLWW classes imposes a limit on any potential increase in within-group agreement. By contrast, combining the Hydrologic and Geomorphic Components of the CIC produces a synergistic increase in within-group agreement. A system based on a combination of similar components may produce equally high within-group similarity across the region of boreal peatlands.

The relatively high within-group agreement produced by the combined Hydrologic and Geomorphic Components of the CIC shows that classes detectable on remotely-sensed imagery can better separate wetlands based on their response to fundamental drivers of ecosystem function. National-scale classification systems, in contrast, probably lack the resolution necessary to match the within-group agreement that can be produced by any regionalized system. Morrice and colleagues (2008) reached a similar conclusion when they found that a classification system they devised for coastal wetlands in the Great Lakes of North America performed better than a standard classification system based on flow paths and broad landforms. In the Great Lakes, their system, which was based on a ratio between seiche and tributary hydrodynamics, was a better predictor of chloride concentration and variability than were the classes of the standard system, which were based on flow path and landform. Chloride is an indicator of water source and human disturbance, both fundamental controls on the ecological function of these Great Lakes wetlands. Regardless of the factors, a regionally-specific system that produces high within-group similarity based on important ecological variables should be a useful tool for managers responsible for the maintenance of wetland ecosystem services.

We used simplified proxies for fundamental drivers of ecosystem function. In oligotrophic peatlands, specific conductance is strongly related to calcium concentration, which is generally the major cation balancing charge in most surface waters and also the chemical variable most closely related to differences in vegetation along with pH (Vitt & Chee 1990). However, high calcium concentrations can inhibit the normal development of *Sphagnum papillosum* protonemata (Boatman & Lark 1971; Clymo & Hayward 1982), whereas other solutes, especially nitrogen and phosphorus, may also limit *Sphagnum* growth at elevated concentrations (Bridgham et al. 1996). If limiting or toxic solutes are important, specific conductance alone may not be a reliable proxy for water chemistry.

It seems interesting that the NWI system produced a higher A value than that of the CIC based only on its Hydrologic Components for analyses employing the variables PI, pH, and SC. Interestingly, the NWI system produces higher within-group agreement than the Hydrologic Components of the CIC system when used alone in the analysis employing the variables PI, pH, and SC. This higher agreement is perhaps due to the fewer groups in NWI and the overriding ecological importance of water level variations (as indicated by PI) over chemistry (specifically pH & SC). The physiognomic classes of the NWI system are related to water level variation, but the Hydrologic Components of the CIC system require combination with its Geomorphic Components to achieve high within group similarity. Although water level variability appears to be an overriding controlling factor in peatlands, the fundamental dichotomy of classifying peat landforms as either ombrotrophic bogs or minerotrophic fens is controlled by the general direction of groundwater flow: downward in bogs and upward or laterally in fens. The groundwater hydrology largely determines the chemistry of peatland pore waters, with ombrotrophic bogs having dilute acidic surface waters solely supplied by precipitation and the release of organic acids from decaying *Sphagnum*, whereas waters from minerotrophic fens have higher cation concentrations and alkalinity due to groundwater inputs (Siegel & Glaser 1987: Hill & Siegel 1991; Siegel et al. 1995; Glaser et al. 1997, 2004a). The CIC includes two hydrologic classes for bogs (e.g. *DW5* in *Drainageways* and *LB3* on *Lakebeds*). However, raised bogs in the CIB exhibit a wide range of variation with respect to water levels and microtopographic variation, from sedge-dominated lawns where the water table is very close to the peat surface, and shrubby hummocks or ridges with intermediate water depths, to forested bog crests with deeper water tables (Glaser & Janssens 1986). This variation within the bog classes, especially the common *LB3* class of the CIC, may partly explain why the hydrologic classes of the CIC when examined alone produced slightly lower within-group agreement using PI, pH, and SC than did NWI by itself, which groups wetlands only according to life form. Although the fundamental division of peat landforms into bogs and fens can be identified using water chemistry and plant indicators (Sjörs 1950a; Glaser 1992), peatland classes based on differences in water level variation appear to form more distinct groups, at least where precipitation limits the diversity of bog landforms, as it likely does in the CIB.

Research, Management, and Wetland Assessment

Researchers have used the classification system to stratify sampling in headwater streams according to geomorphic setting. Using this stratification scheme, King and colleagues (2012) found that macroinvertebrate and fish community structure were most strongly correlated to flow-weighted slope (similar to topographic wetness index, Sorensen et al. 2006), which was mediated by wetland geomorphic class and other physical and chemical variables. Walker and colleagues (2012) also found that water chemistry was also strongly related to flow-weighted slope. Whigham and colleagues (2012) found that although reach-scale factors were correlated to plant species distributions, differences in these factors did not produce distinct plant communities in headwater streams. Callahan and colleagues (2015) found significantly higher stream temperatures in salmon-bearing streams flowing through *Drainageways* compared to those flowing through *Discharge Slopes*, two of the hydrogeologic settings defined by the CIC.

Managers in the CIB are currently using the distinct Hydrologic and Geomorphic Components of the CIC to guide wetland functional assessment (Matanuska-Susitna Borough 2014). The Hydrologic Components are used to assign principle hydrologic functions to peatlands by relating contrasts among the different Components to categories of storage, recharge, and discharge. For example, peatlands with stable high water tables (Hydrologic Component less than 3) are rated as principally transmitting discharge. Geomorphic Components are used to rate peatlands based on differences in the degree of hydrologic isolation and the transmissivity of the underlying sediments. As an example, isolated peatlands underlain with impermeable sediments (*Depressions*) are largely assumed to perform the hydrologic function of storage (Matanuska-Susitna Borough 2014). However, the relationships of these two components to actual peatland characteristics may vary in different geographic regions. A mosaic of different bog and fen types, for example can develop over carbonate and silicaceous terrain depending on the local hydrogeologic setting, and in regions with much higher precipitation the development of raised bogs and patterned fens may be linked to changing distance between the bounding rivers and rapid rates of glacial isostatic uplift (Glaser & Janssens 1986, Glaser et al. 2004a). However, since water level variation and chemistry are primary sources of ecological variation among peatlands worldwide, a classification system based on these factors is likely to be useful to managers and scientists beyond Alaska.

Chapter 3 Analyzing Peatland Discharge to Streams in an Alaskan Watershed: An Integration of End-Member Mixing Analysis and a Water Balance Approach (Gracz et al. 2015)

ABSTRACT

Peatlands are the dominant landscape element in many northern watersheds where they can have an important influence on the hydrology of streams. However, the capacity of peatlands to moderate stream flow during critical dry periods remains uncertain partly due to the difficulty of estimating discharge from extensive peat deposits. We therefore used two different approaches to quantify diffuse pore water contributions from peatlands to a creek within a small watershed in Southcentral Alaska. A sensitivity analysis of a water budget for a representative peatland within this watershed showed that a substantial surplus of pore water may remain available for subsequent discharge during a dry period after accounting for water losses to evapotranspiration. These findings were supported by end member mixing analysis (EMMA), which indicated that 55% of the stream flow during a dry period originated from the near surface layers of peatlands within the watershed. Contributions from peatlands to stream flow in northern coastal regions may therefore provide an important buffer against the potentially harmful effects of changing climatic conditions on commercially important fish species.

INTRODUCTION

In regional predictions for global warming, the second greatest warming is predicted to occur in Alaska, where a winter temperature rise of 4.4-11.0ºC becomes clearly discernable by 2037, and a 1.8-5.7ºC rise in summer temperatures becomes clearly discernable by 2032 (Christensen et al. 2007). Rising air temperatures will probably perturb stream ecosystems particularly during droughts when low flow rates are less capable of buffering stream temperatures (Cowx et al. 1984; Jones & Petreman 2013). In Southcentral Alaska, stream temperatures have already exceeded the threshold for spawning king salmon (*Oncorhynchus tshawytscha*) during the yearly dry season (Mauger 2005), and this type of environmental stress may be pervasive elsewhere. Since dry-season flow is dependent on groundwater inputs from different sources, identifying the relative contributions from different source is critical to understanding stream ecology.

Peatlands cover approximately 25% of the land surface in northern regions above 45º N. latitude but are especially prominent in coastal areas and continental lowlands (Kivinen & Pakarinen 1981, Wieder & Vitt 2006; Rydin & Jeglum 2006). Despite their abundance and the high water-holding capacity of peat (e.g. Clymo 1983), the evidence for peatland contributions to stream flow remains equivocal. Two thirds of the studies reviewed by Bullock and Acreman (2003) concluded that peatlands in a wide range of physiographic settings are associated with reduced stream flow during dry seasons. Although these studies were largely based in Europe and North America they are supported by overwhelming evidence that evapotranspiration rates are higher in wetlands than in non-wetlands in the same watershed (Bulllock & Acreman 2003).

Other explanations for the relationship between peatlands and lower stream flows during dry seasons are a) insufficient water storage in the relatively porous upper layers of peat deposits (Bay 1969, Ingram 1983, Evans et al. 1999) and b) poor drainage related to the low hydraulic gradient and permeability of peat deposits (Boelter & Verry 1977, Siegel 1988, Burt 1995). In contrast, Panu (1988) reported higher dry-season flows in streams from Newfoundland in which the watersheds contained a high cover of relatively pristine peatlands. Other studies of peatlands from Minnesota, Great Britain, and Sweden associate a high cover of peatlands with relatively high stream flows during droughts (Ackroyd et al. 1967, Newson 1980, Brandesten 1988).

The absence of a consensus among these studies may be a product of comparing peatlands in different hydrogeologic settings (Siegel 1988, Johansson & Suena 1994, Burt 1995, Spence & Woo 2006). Boelter & Verry (1977), for example, suggest that while flow may be straightforward to quantify from peatlands in small depressions that have a single outlet stream, these small peatlands may be poor contributors to stream flow because they lack sufficient storage or comprise only a small portion of a watershed. In contrast, a more common setting for peatlands in many boreal watersheds are broad lowlands overlying gently sloping deposits of glacio-lacustrine sediment or glacial till (Gore 1983, Rydin & Jeglum 2006). The extensive peatlands that spread over these deposits commonly lack well-defined outlet streams and may only produce diffuse discharge from pore waters.

Quantifying peatland contributions to stream flow presents an array of challenges. Studies based solely on water budgets are prone to compounding measurement and estimation errors particularly when terms are calculated as residuals (Winter 1981). Although advances in instrumentation have permitted more precise estimates of ET using tower based instruments (e.g. energy balance and eddy covariance) sources of error still remain (e.g. Twine et al. 2000; Wilson et al. 2002; Drexler et al. 2004). Holden and colleagues (2004) therefore identified a need for process-based investigations to understand the dynamics of peatland contributions to stream flow. An alternative approach is provided by End-Member Mixing Analysis (EMMA) which has been used to assess end-member contributions to event flows in a range of watersheds (Christophersen et al. 1990, Christophersen & Hooper 1992, Hooper et al. 1990, Liu et al. 2008). EMMA uses the chemical signature of water originating from potential end-members within a watershed to determine the percent that each contributes to a final mixture. We therefore compared an end-member mixing analysis with a water budget approach to quantify peatland-stream interactions in a small watershed from Southcentral Alaska. This watershed is typical of many in Southcentral Alaska and serves as a useful template to characterize the climatic sensitivity of these ecologically important streams, which provide spawning habitat for salmon.

Study region

The 1516 ha Limpopo Creek watershed lies in the Cook Inlet Basin of Southcentral Alaska. The two tributaries of the 17.3 km-long Limpopo Creek flow down a gradient of 5-7% from their headwaters near tree line at an elevation of 250 m through alder (*Alnus viridis* (Chaix) DC.) and open meadows overlying weakly-lithified sedimentary deposits. The tributaries then flow at a gradient of 1-2% through a landscape of Lutz spruce forest (*Picea* X *lutzii* Little) and peatlands that developed on glacial deposits. The tributaries eventually join 2.4 km above the creek's confluence with the Anchor River. Both tributaries are confined to a single channel along most of their length except for a reach of a few hundred meters where the northern tributary anastomoses as un-channelized flow over peat (Fig. 22). Peatlands cover 22% of the watershed and consist of fens or poor fens supporting either a Lutz spruce woodland, or non-forested assemblages dominated by ericaceous shrubs and sedges interspersed with pools.

The upper third of the watershed generally lacks glacial deposits, and is primarily underlain by alluvial sedimentary deposits, carbonaceous shale, and lignite beds of the thick Sterling Formation (Flores et al. 1997). These deposits were eroded from the surrounding mountains, which support diverse lithologies, including: sandstone, arkose, argillite, greywacke, slate, granodiorite, breccia, and intermediate-to-felsic volcanic rocks (Beikman 1994). The lower watershed is underlain by glacio-lacustrine and poorly-sorted till deposits of the last glacial advances (Reger et al. 2007, Petrik 1993). Peatlands are primarily restricted to these low-permeability, surficial materials. In addition, the entire watershed has frequently been blanketed by volcanic ash for at least 10.5 ma (Fournelle et al. 1994). Ash deposition has created tephra layers whose composition ranges from high-silica andesite through low-silica dacite to calc-alkaline glass (Riehle 1985). Mineral soils are generally entisols where wet, and andisols and humicryods where mesic to well-drained (Van Patten 2005). Two gravel roads cross the watershed, which is inhabited by fewer than a dozen families.

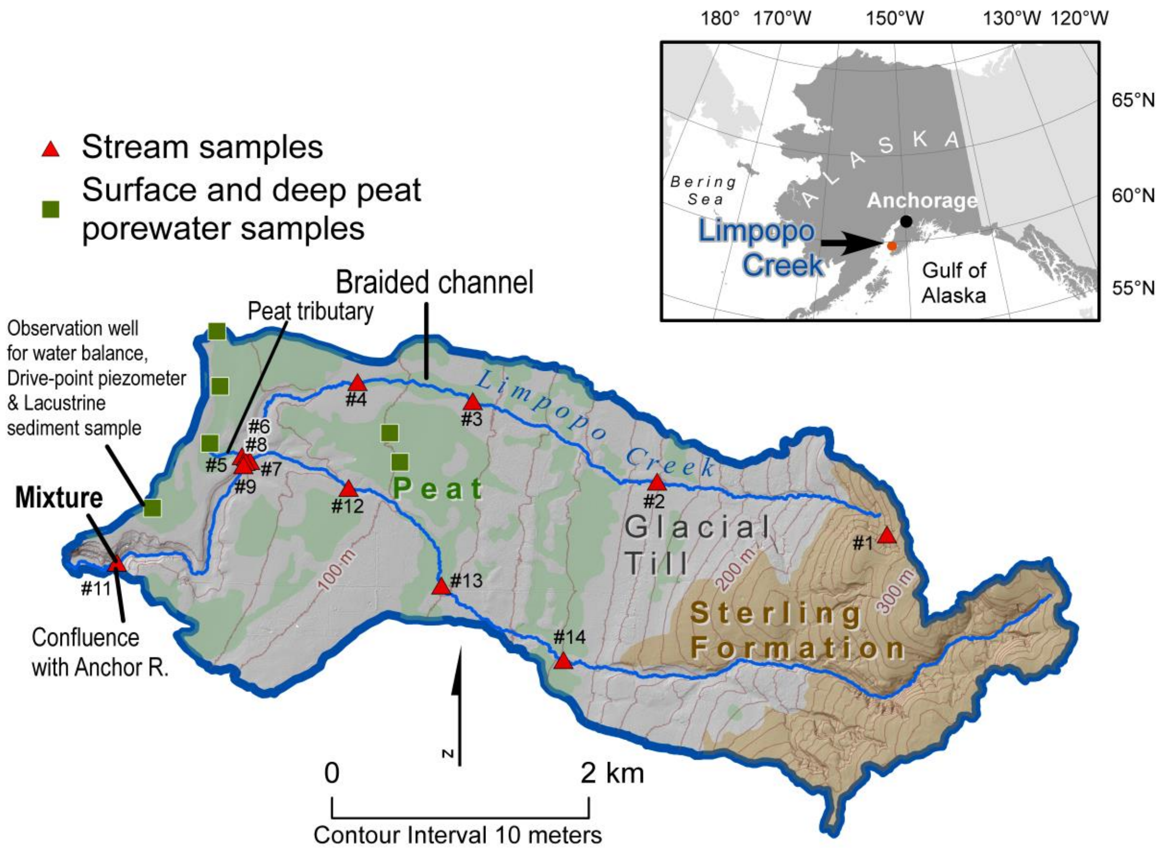


Figure 22. The Limpopo Creek Watershed in Southcentral Alaska. The steeper eastern third of the watershed is underlain by the Sterling Formation (tan), whereas the western two-thirds is composed of glacial till (gray) and lacustrine deposits overlain by peatlands (green). Sample locations are numbered and marked by triangles for stream samples and squares for EMMA end-members. The northern tributary of Limpopo Creek flows as a braided channel where indicated.

The cool temperate climate of the watershed is moderated by its proximity to the Gulf of Alaska. Annual precipitation averages 625 mm at the nearest station with a long record (Homer), although a station near the headwaters of the Limpopo watershed reports an average of 748 mm (Utah Climate Center 2013). More than half of the precipitation falls late in the year (August-December), whereas less than 20% falls during the yearly dry-period (April-July). Average annual temperature is 3.1^{o} C, and the average July maximum is 16.0^{o} C. The ratio of precipitation to potential evapotranspiration is 1.27 by the Thornthwaite method.

METHODS

Two independent methods were used to estimate peatland contributions to stream flow in the Limpopo watershed during dry periods to assess the reliability of their results. Water budget surpluses were first calculated for a representative peatland within this watershed using a sensitivity analysis and these results were then compared to EMMA calculations. The water budget was based on the drawdown at a peatland observation well in the watershed during a well-defined dry period, whereas the EMMA provides a snapshot of geochemical mixing of end-members in the stream during conditions of low flow.

Water budget

Stream flow was measured three times in Limpopo Creek to estimate the amount of flow during the dry season for comparison with the quantities produced by the water budget and to scale the percentages calculated by the mixing analysis. The first flow measurement was made on July 13, 2010 at the end of the normal-summer dry period and two days prior to the stream sampling for water chemistry. Flow was re-measured a week later on July 22 following a storm, and also on September 23, 2010, at the end of an unseasonable late-summer dry-period. Measurements were made with a Pygmy current meter along a 14-point transect across the three-meter wide channel 400 m above the confluence with the Anchor River.

To evaluate changes in peatland water storage during a dry period, an observation well was installed to a depth of 98 cm just above the base of a representative peatland in the watershed and instrumented with a U20-series water-level logger in 2005 (Fig. 1). The observation well was calibrated upon installation and changes in barometric pressure were compensated for by an additional logger suspended in the wellhead. Water level drawdown in the well during the longest rainless period (August 5-12, 2005) was used in the following water budget to determine the quantity potentially available for stream flow:

$$Q = P + GW_i - GW_o + SW_i \pm \Delta S - ET \qquad (1)$$

where Q is discharge from peatland porewater, P is precipitation, GW_i is input from deeper groundwater, GW_o is output to deeper groundwater, SW_i is surface water input, ΔS is the change in storage (water level), and ET is evapotranspiration. P = 0 during the period and we assumed that $GW_i = GW_o$, and $SW_i = 0$. These assumptions are reasonable given: the topographically high setting of the peatland; the low permeability of the underlying lacustrine sediments; the absence of streams flowing into or out of this peatland; and the form of the water level hydrograph during the dry period, which suggested only discharge from porewater (Laine 1984). The hydrograph indicates a steeper decline during the day than at night (Fig. 2). Equation (1) thus simplifies to:

$$Q = \Delta S - ET \qquad (2)$$

The effect of ET on storage was estimated by two methods. First, the Thornthwaite method (Thornthwaite 1948) was calculated using an MS Excel spreadsheet (Lehre 1994). The Thornthwaite method has been widely used as a complementary method to estimate ET from peatlands in both Europe and North America (e.g. Bay 1968; Ingram 1983; Bridgham et al. 1999; Brooks et al. 2011). To calculate flow by this method (Equation 2), ΔS is obtained by multiplying the change in water level by specific yield (S_y) after accounting for recharge (White 1932, Laine 1984, Mitsch & Gosselink 2007). S_y is the proportion of water in a saturated soil column that freely drains between 0 and ~ −0.1 atm (Freeze and Cherry 1979). This method of calculation produces a reliable estimate for ΔS in wetlands where water levels are close to the surface, or where recharge is sufficient to raise the water level each night. However, because the water level was falling steadily from deeper in the peat profile in the absence of recharge, a significant amount of vadose water (stored in the unsaturated zone between field capacity and the wilting point) is available to meet ET demands. It is possible that all of the ET demand could be met by from the vadose zone as it is for plants in non-wetland ecosystems (White 1932; Evaristo et al. 2015). In recognition of this possibility, ET was subtracted from the total volume of water (accounting for porosity) before multiplying by S_y. To obtain the flow produced over the entire watershed, the calculated value was then multiplied by the area of similar peatlands and the duration of the drawdown:

$$Q = ((\Phi\Delta W) - ET)S_yAt^{-1} \quad (3)$$

where Φ is porosity (dimensionless), ΔW is the water level decline (m), ET is evapotranspiration (m), S_y is dimensionless, A is the area of similar peatlands in the watershed (m^2), t is the time period of water level decline (s), and Q is in m^3s^{-1}.

The second method uses the diurnal pattern in the water table hydrograph to estimate the portion of ΔS due to ET. During the dry period, the hydrograph from the well was characterized by a lower slope at night that steepened during the day. The slopes differ because only discharge is assumed to be active at night, while both ET and discharge occur during the day. To quantify the difference, the nighttime drawdown rate is projected by linear regression to midnight on the following and preceding days. The average difference between the actual water level at midnight and the level predicted by the regression (multiplied by S_y) is attributed to ET (Fig. 2). The two estimates for each day are averaged to account for an inconstant rate of drawdown (Laine 1984).

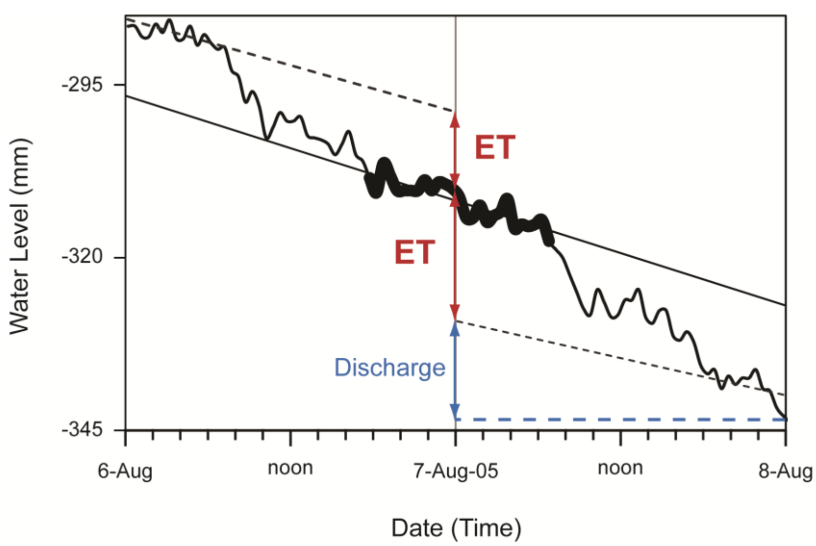


Figure 23. Estimation of ET using the diurnal variation of a declining water-level hydrograph in the absence of recharge. Linear regressions (straight sloping lines) are fitted to the slower discharge rate during the evening and morning when only discharge is active (thicker black line for 7 August) then extended to predict the water level at midnight on both the previous and following day (middle sloped line). The average difference between the predicted water level and the actual water level is attributed to ET, which is active along with discharge during the daytime (two-headed arrows). The partial regression lines from day 1 and day 3 are also shown (dotted sloping lines). Data are from the observation well.

We evaluated the sensitivity of Q in equation (3) by varying Sy, Φ, and Q. For the Thornthwaite method Sy was set to 0.05, 0.14, 0.25, and 0.45 with porosity equal to both 0.8 and 0.9 while Q was allowed to vary. We then set Q equal to 0 and allowed porosity to vary to estimate the porosity value necessary for the total measured decline in the water level to be due to Thornthwaite PET. We then set Q equal to 0.06 and porosity to 0.8 (following Boelter 1972) to determine the value for Sy that would produce all of the lowest flow measured in Limpopo Creek. For the diurnal method we set Sy = 0.05, 0.1, 0.14, and 0.45 and allowed Q to vary. We then set Q = 0.06 and 0.03 to determine if a reasonable value for Sy could produce all or half the lowest stream flow measured in the creek.

Antecedent moisture

Antecedent moisture conditions were evaluated by installing a shallow drive-point piezometer near the observation well from 16 June until 9 October 2010. The shallow drive-point piezometer was installed at depth of 30 cm and instrumented with a water-level logger as above except that it was calibrated monthly against an arbitrary datum driven into the underlying lacustrine sediments. The elevation of the datum was estimated from 1.23-m resolution bare-earth LiDAR data collected in 2009.

EMMA sampling

Water samples were collected from Limpopo Creek for the EMMA snapshot on July 15, 2010 at 12 points distributed downgradient from the headwaters to just above the confluence with the Anchor River, where the stream flow was measured. This date was selected as the most likely time to sample the lowest stream flow of the summer based on observations from past years. The furthest-downstream sampling point, located just above the confluence with the Anchor River, represented the final mixture in the EMMA. On the same day, surface water samples were collected from other potential end-members. These samples were collected from a) near the headwaters of the stream where only groundwater from the Sterling Formation could contribute to stream flow, b) a spring originating in the glacial till just above the creek, and c) a short rivulet originating from within a peatland (Fig 1). During July and August in 2010, samples were also collected from two additional end-members (the deep peat and the glacio-lacustrine sediment) by installing seven piezometers in peatlands in the watershed (Fig. 1). The peatland piezometers were installed near the base of the peat profile (at depths of 98 to 210 cm) or into the underlying lacustrine sediment (140 cm). Pointed inserts facilitated pounding the piezometers to depth (Chason & Siegel 1986). All piezometers were bailed until they produced clear water and then were left to equilibrate overnight before being sampled the next day. The piezometer in the lacustrine sediment required five days of equilibration to produce an adequate sample volume. Water from an additional end-member, the peat surface, was also collected near the piezometers. All samples were filtered through a 0.45µ capsule filter using a peristaltic pump and kept cool until analysis.

Samples were analyzed for $\delta^{18}O$ vs. VSMOW at the Stable Isotope Laboratory at University of Alaska, Anchorage (UAA) using a Picarro L-1102i WS-CRDS analyzer. The samples were then acidified and analyzed on an Agilent inductively-coupled plasma mass-spectrometer at the Applied Science Engineering & Technology lab at UAA for cation concentrations. Samples collected in separate bottles were analyzed at the Mid-continent Ecology Division lab of the United States Environmental Protection Agency (EPA) for chloride and sulfate using EPA method 300.0 with NaOH eluent on a Dionex-DX-600 ion chromatograph using Chromeleon v6.6 software.

EMMA calculations

EMMA was used to estimate the percent contribution from each end-member to the ultimate geochemical mixture at the mouth of the stream. An end-member is defined as the waters originating from a discrete watershed element, which ideally could be distinguished by a distinct geochemical mixture. Samples collected along the length of the creek would be expected to show the shifting chemistry of the stream in response to inputs from different end-members. In EMMA, the shifting chemistry of the stream samples is analyzed by Principal Components Analysis (PCA) to determine the appropriate tracers, the concentrations of which are used to project stream sample points onto PCA axes. Residual analysis guides the evaluation of conservative mixing, and the number of principal components identifies the number of end-members responsible for the variance in the chemistry of the stream samples. The contributing end-members are identified by plotting end-members and stream samples on a mixing diagram using the prediction equation for the stream samples. Percent contribution is then solved for each contributing end-member by using matrix algebra to solve the simultaneous equations of complex mixing. The conceptual model was that water originating in the Sterling Formation at the headwaters mixed with other end-members to form the final mixture in the sample collected near the confluence with the Anchor River. A series of centered PCAs were performed on the correlation matrix of stream samples (rows) by tracer concentrations (columns), in the software PC-ORD™ 6 (McCune & Mefford 2011) to find the combination of tracers that explained the most variance in the stream samples with the fewest principal components. Residual plots (which are in units of concentration) were examined for non-linearity and deviation from errors greater than laboratory detection limits, both of which are diagnostic of non-conservative mixing (Hooper 2003).

Once the criteria in the residual analysis were satisfied, the mixing diagram was constructed. On an adequate mixing diagram, the points representing the end-members should define a convex mixing space that completely encloses the stream sample points. Missing end-members are indicated if any stream values lay far outside the mixing space (Hooper 2003). After an adequate mixing space was defined, the percentage contribution of each end-member to the mixture was calculated by post-multiplying the inverse matrix of PCA scores for the end-members by the column vector of the mixture scores:

$$\mathbf{S_e}^{-1}\mathbf{S_m} = \mathbf{f_e} \qquad (4)$$

where $\mathbf{S_e}$ is the 3x3 matrix of principal component scores (rows) for each end-member (columns), with the first row vector consisting of 1s (ones); $\mathbf{S_m}$ is the 3x1 matrix (column vector) of mixture scores, with the first row element = 1; and $\mathbf{f_e}$ is the 1x3 vector of the fractional contribution of each end-member (multiplied by 100 to obtain percentages). Values of unity were used in the first row of each matrix of scores to force 100% contribution from the end-members (Hooper et al. 1990; Liu et al. 2008). For comparison with the values for peatland discharge produced in the water budget analysis, the percentage contribution from peatland end-member(s) was multiplied by the flow in the creek measured two days prior to EMMA sampling.

RESULTS

Water budget

The peatland observation well provided an estimate for water losses driven by ET in the dry year of 2005. From August 5-12, 2005 the water level in the well fell by 228 mm, from a depth of 256 to 484 mm. Total Thornthwaite PET was estimated at 29.29 mm for this eight-day period. Using this PET estimate, contributions from peatlands to Limpopo Creek varied widely when different values for S_y were used, whereas different values for Φ had a smaller effect (Fig. 3). The lowest values for S_y (0.05) and Φ (0.8) presented by Eggelsmann (1971) (as cited by Ingram 1983 and Siegel 1988) produced a surplus equal to 48% of the lowest stream flow measured in the creek. When the highest value for S_y (0.45) and Φ (0.9), reported by Boelter (1972) were used, the surplus equaled approximately two times the highest flow measured in the creek. An unrealistically low Φ (0.131) was required for the Thornthwaite ET method to explain all of the drawdown observed in the peatland well in August, 2005. However, sufficient surplus remained to support all of the lowest flow measured in Limpopo Creek when Φ = 0.8 and S_y = 0.10.

Using the diurnal method for ET estimation, a higher value for S_y was needed to produce the same flow as the Thornthwaite method (Fig. 3). When S_y is equal to 0.132, all of the lowest stream flow (0.06 m^3s^{-1}) could be produced, and with S_y equal to 0.066 about half of the low flow could be produced. The diurnal method could not attribute all of the observed drawdown to ET alone, however, because discharge was evident at night, in the presumed absence of ET (Fig. 24).

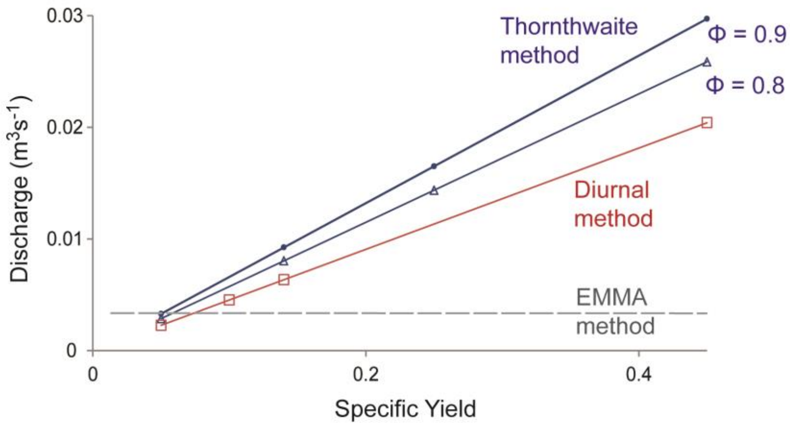


Figure 24. Sensitivity analysis of the potential discharge from peatlands available for stream flow. The uppermost two lines (blue) show discharge calculated with the Thornthwaite method using different estimates of porosity (phi = 0.8, 0.9). The lower line (red) shows the amount calculated using the diurnal method, which does not depend on porosity. For comparison, the lower horizontal dashed line shows the amount of stream flow predicted by the EMMA.

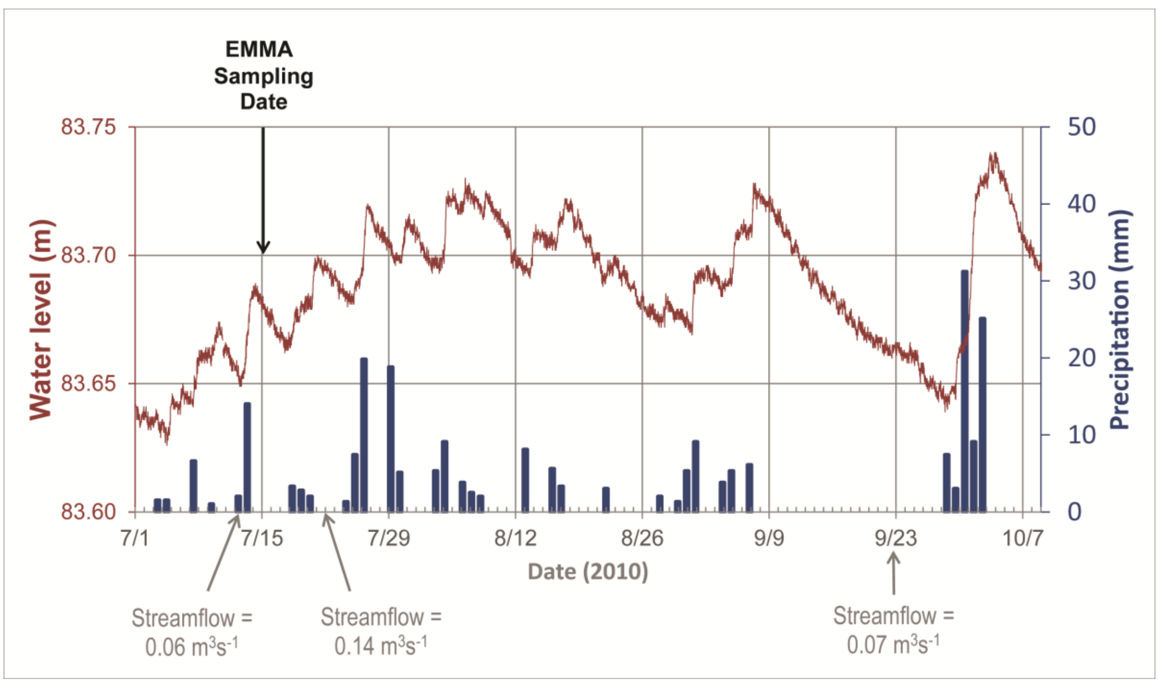


Figure 25. Peatland water levels recorded in the shallow drive-point piezometer (red, left-hand axis); precipitation (bars, right-hand axis); stream flows and sample times (gray arrows); and EMMA sample time at Limpopo Creek (black arrow). The precipitation data are from the Homer Airport, 20 km to the southeast.

Stream flow and antecedent moisture

The lowest flow in the creek (0.06 $m^3\ s^{-1}$) was measured at the beginning of a minor rain event on July 13, 2010 that appeared to have little effect on stream flow by the time of the EMMA sampling, on July 15, 2010 (Fig. 25). The highest flow (0.144 $m^3 s^{-1}$) was measured a week later on July 22 following a much larger rain event that was observed to produce even greater rainfall at the creek than at the nearby Homer climate station. An intermediate flow (0.071 $m^3 s^{-1}$) was measured near the end of an unseasonable dry-period (23 September 2010).

EMMA

The final PCA in the EMMA used five tracers (^{18}O, SO_4^{2-}, K, Ni, and Ba) to explain 95.8% of the variance with two principal components. Plots of the residuals revealed random errors that were smaller in magnitude than laboratory detection limits, supporting the assumption that the tracers mixed conservatively (Fig. 26). Because two principal components were retained, a model with three end-members is required to solve the mixing equation (Equation 4). The three end-members that enclose the mixing space were waters from the Sterling Formation, the surface peat, and the glacial till. These end members enclose all the water samples with the exception of two stream samples that lie somewhat outside the mixing space (Fig. 27). In addition, the coordinates of samples representing potential end-members from the deep peat (-10.9, 5.8) and the lacustrine sediments (113.6, 76.5) plotted far from the stream values.

The EMMA calculations show that the end member represented by the peat surface contributed 54.7% of the composition in the final mixture, the Sterling Formation contributed 40.8% and the glacial till contributed 4.5%. In contrast, the potential contributing volume of peatlands comprises 0.5% of the watershed, whereas the potential contributing volume of the Sterling Formation is 35%, and the till 65%. Contributing volumes are defined as the volume of each potential end-member within a 3D conceptual model of the watershed. The volumes were determined by multiplying the surface area of each end-member by its depth relative to the level of the Limpopo Creek outlet, which is the lowest point in the watershed. The percentage contribution from the peatland surface multiplied by the flow in the stream two days before the EMMA sampling gives a value of 0.03 m^3s^{-1}, which equals the estimates produced by the water budget analysis when Sy equals 0.072 (Fig. 24).

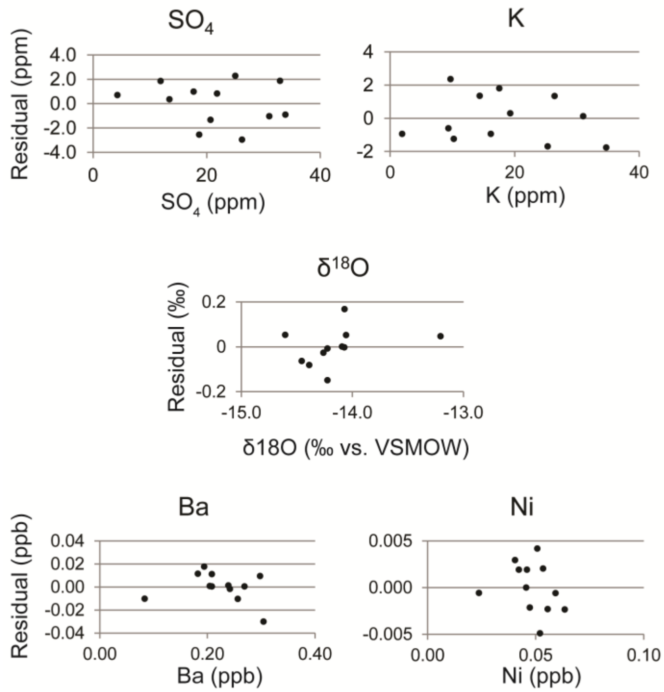


Figure 26. Residual plots of observed versus predicted concentration values for the tracers used in the mixing analysis. Units are all micro-equivalents, except for $\delta^{18}O$, which is ‰ versus VSMOW. The absence of pattern and the low values of the residuals (within the detection limits of the laboratory analyses) is an indication of conservative mixing.

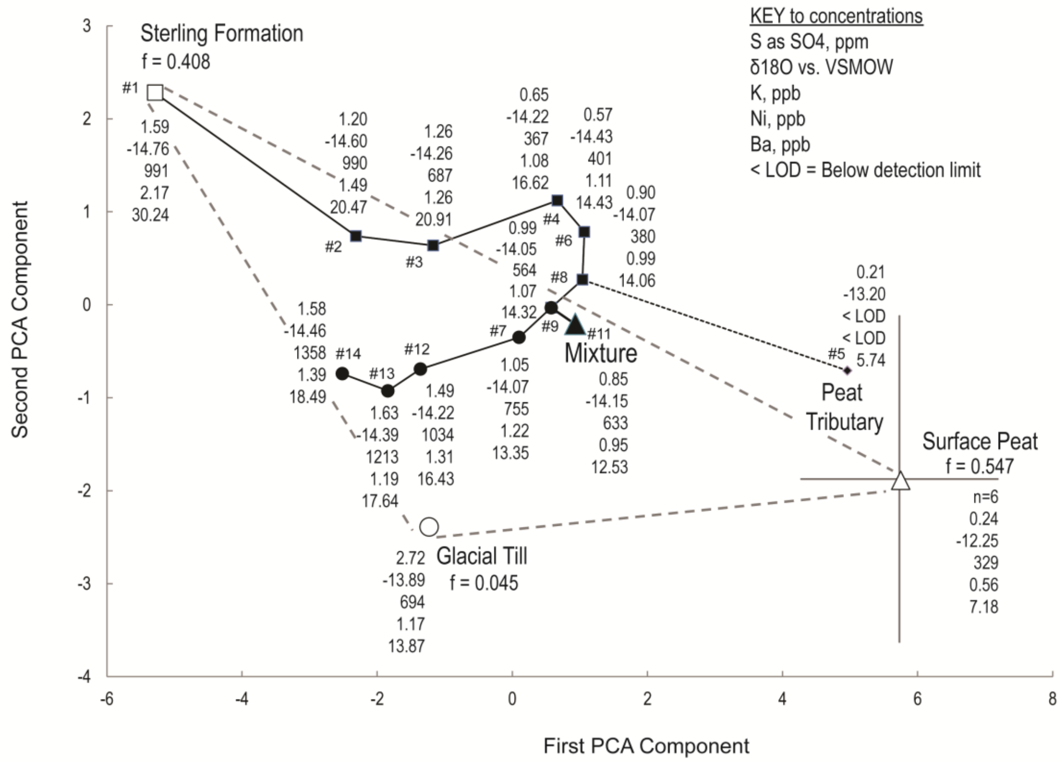


Figure 27. End-member mixing diagram at a single point-in-time during the summer dry-period along the two tributaries of Limpopo Creek. A mixing space (approximated by the dashed lines) is defined by three end-members (hollow squares) enclosing stream samples (solid squares), which are connected in downstream order. Concentrations of the tracers at each point are given in the order shown in the key. The point labeled “peat tributary” represents a sample taken from a small tributary flowing into the creek from a peatland just above the confluence of the two tributaries. The peat surface end-member is depicted with one standard deviation in its projected values (large cross). The f-value listed under each end-member is the fractional proportion that the end-member contributed to the mixture, the sample taken at the mouth of the stream (solid triangle).

DISCUSSION

Peatlands may be confined to topographic depressions or poorly-drained lowlands where saturated soils favor the accumulation of organic matter (Rydin & Jeglum 2006). However, in northern maritime regions peatlands have also spread over sloping terrain creating challenges for quantifying peatland contributions to streams, which are often important for spawning fish populations. These sloping peatlands usually lack a well-defined discharge point that can be monitored for hydrological responses to climatic fluctuations. The peatlands in Limpopo Creek watershed, for example, lack visible outlet pipes that characterize the blanket bogs of the British Isles (Gilman & Newson 1980; Holden & Burt 2002; Evans & Warburton 2007) and similar peatlands in the Maritime Provinces of Canada (Glaser & Janssens 1986). In addition, an extensive peat cover obscures the underlying topography of the mineral substratum that can be responsible for routing subsurface runoff into discrete discharge zones (Allan & Roulet 1994). In these complex settings End-Member Mixing Analysis provides an alternate means to estimate peatland contributions to stream flow. This approach appears to be well suited to the Limpopo Creek watershed, which is composed of five principal watershed elements, which are distinguishable on the basis of the chemical composition of their waters. The results of the mixing analysis can then be compared to a sensitivity analysis of a water budget to independently assess the potential of water stored in peatlands to contribute to stream flow during dry periods.

Estimates from the sensitivity analysis of the water budget indicate that evapotranspiration is sufficiently low and storage capacity and yield appear to be sufficiently high for peatlands to support approximately half the flow measured in Limpopo Creek during dry periods. The proportion of stream flow from peatlands indicated by the EMMA calculations can be reproduced in the water budget approach by setting Sy equal to 0.072 in the diurnal method or either 0.057 (ϕ = 0.8) or 0.049 (ϕ = 0.9) using the Thornthwaite PET method (Fig. 3). These estimates of Sy generally agree with Ingram's (1983) suggestion for using Eggelsmann's (1971) values of between 0.03 and 0.10 for the Sy in peat and Letts and colleagues' (2000) values of 0.26 - 0.125 for more the more humidified layers of peat. Lower values are justified, as the water level in the peatland observation well fell within the deeper and more humified portions of the peat profile. Although these findings are supported by studies of peatlands in paired-watershed studies from other regions (Ackroyd et al. 1967, Newson 1980, Brandesten 1988, Panu 1988), they differ from the conclusions of Bullock & Acreman (2003) that peatlands have minimal effect on flow during dry periods. The contrast between these concepts of peatland-stream interaction may be due to differences in methodology, hydrogeologic setting, or antecedent conditions.

Differences in methodology

EMMA provides an alternative approach for estimating contributions to stream flow from different landscape components that avoids the sources of error related to a water budget approach such as the estimation of recharge, ET, and groundwater flow. Mixing analysis should yield a reliable estimate of peatland contributions to stream flow so long as four fundamental assumptions are met: 1) distinct composition; 2) hydrologic feasibility; 3) conservative mixing; 4) fixed composition.

The first two assumptions are satisfied because the composition of the end-member is sufficiently distinct in the Limpopo watershed to bound the stream samples on the mixing diagram and the mixing diagram reproduces the down-gradient locations of the sample points along the stream tributaries showing that mixing is hydrologically feasible (Fig. 27). The third assumption is at least partially satisfied because three of the five tracers (barium, nickel, and $\delta^{18}O$) should mix conservatively at the concentrations measured. Barium and nickel will not form precipitates at the observed concentrations (Stumm & Morgan 1996, Snodgrass 1980). Complexation of these two elements with larger organic molecules is possible but was not likely to be a major control because their respective stability constants differ by orders of magnitude (Stumm & Morgan 1996) yet their concentrations behaved similarly in the stream (Fig. 27). Complexes with smaller organic molecules and with inorganic ligands would have remained soluble. Furthermore, since the kinetics of complexation generally favors formation at much higher rates than dissociation, any complexes should have formed rapidly near the headwaters, where the concentrations of these two elements was highest, with little effect on mixing further downstream. The stable oxygen isotope (^{18}O) is not fractionated during transpiration (Clark & Fritz 1997). However, the other two tracers (potassium and sulfate) may mix non-conservatively. Potassium is an essential nutrient for plants and other organisms, whereas sulfur can degas as hydrogen sulfide under anaerobic conditions. Additionally, the fourth assumption of fixed composition may have been violated by the end-member represented by the pore waters at the peat surface. Therefore, only the potential non-conservative mixing of potassium and sulfate, and the non-fixed composition of the peatland end-member appear to be potential departures from the fundamental assumptions of mixing analysis. Below, we consider the effects that these departures may have had on the EMMA calculations.

Potassium was apparently present at concentrations that exceeded limiting values for it in local ecosystems, which are limited instead by nitrogen and/or phosphorus (Shaftel et al. 2012). Furthermore, when potassium is excluded from the EMMA, there was little change in the final proportions of contributing end-members (Sterling Formation 44%, surface peat 57%, till 0%). The small amount of uptake of potassium compared to its relatively high concentration likely did not measurably affect the EMMA.

Eliminating sulfate as a tracer in the EMMA also produces little change in the contributing proportions from the original end-members. Non-conservative mixing could only be a problem with sulfate if it excluded the two end-members that were sampled under anaerobic conditions (glacial-lacustrine sediment and deep peat). However, the concentrations of other tracers in the lacustrine sediment and deep peat were incompatible with the composition of the final mixture. With respect to the lacustrine sediment end-member, $\delta^{18}O$ was substantially more depleted (15.98 ‰) and the concentration of barium was much higher (373 ppb) than that of samples from both the headwaters (-14.76 ‰ and 30.2 ppb respectively) and the final mixture (-14.15 ‰, and 7.2 ppb respectively). In the deep peat porewater, the barium concentration was also too high (47.8 ppb) for this end-member to be a significant contributor to the stream due to the excessive dilution that would be required from other end-members. Non-conservative mixing from the anaerobic samples likely did not affect the EMMA.

Two sample points that may lie outside of the mixing space suggest that the peatland end-member may not be of fixed composition (#4 & #5 on Fig. 27). Points lying outside of the mixing space indicate that additional end-members may be unaccounted for in an EMMA (Hooper 2003). On the Limpopo mixing diagram, however, shift in the co-ordinates of the peatland end-member within one standard deviation of its range of variability could define a mixing space encompassing all of the stream samples (Fig. 27). Alternatively, the range of variation of the peat surface water might indicate that it is actually composed of two different end-members, e.g. fens and poor fens. Splitting the peatland end-member might produce a three-dimensional mixing space with four end-members completely bounding the stream samples, yet would not alter the conclusion that peatlands, whether from two types or one, contribute substantially to baseflow.

Hydrogeologic setting

Three major characteristics of the hydrogeologic setting of the Limpopo Creek watershed are most likely responsible for enhancing peatland contributions to stream flow during dry periods: 1) moderate annual precipitation and a relatively high P/ET ratio, 2) extensive peat cover over sloping terrain, and 3) restriction of peatlands to relatively impermeable glacial deposits. In contrast, studies that showed peatlands were not substantial contributors to downgradient streams were largely based in watersheds with 1) relatively high summer rainfall (Ingram 1983; Evans et al. 1999), 2) a small area of peatlands (Siegel 1988), or 3) peatlands confined to small topographic depressions with a single outlet stream (Boelter and Verry 1977).

The large volume of relatively impermeable glacial till in the Limpopo Creek watershed may be especially important because the low conductivity of till likely precludes substantial contributions from this end-member to stream flow. For example, if the area of till traversed by the stream (14 438 m long x 2 m wide) is multiplied by a mean value of hydraulic conductivity for till (10^{-8} m/s) (Freeze & Cherry 1979) a flow rate of 0.0029 $m^3 s^{-1}$ would result. A comparison of this value to the flow measured in the creek (0.06 $m^3 s^{-1}$) suggests that the saturated till in the Limpopo watershed could directly produce only 4.8% of the lowest stream flow measured. This small contribution to stream flow is consistent with the value from the mixing analysis (4.5%) and other reports. Ackroyd and colleagues (1967), for example compared watersheds across Minnesota, USA and found that watersheds with a greater proportion of glacial till produced less runoff during dry periods. In addition, Brandesten (1988) compared eight catchments with different proportions of either bogs or glacial till in Sweden. Bog catchments provided stream flow during a drought, whereas in the till catchments stream flow sometimes ceased altogether.

Antecedent moisture conditions.

Different antecedent conditions could alter the contributing proportions of the end-members to stream flow in the Limpopo watershed. Rain fell two days previous to the EMMA sampling period although the previous 2.5 months experienced lower-than-average precipitation (56 vs. 69 mm) (Utah Climate Center 2013). With even drier antecedent conditions the proportion of contributions from the peat end-member to stream flow may decrease as pore water storage within the peatlands becomes depleted. However, the lowest water-levels measured in the drive-point piezometer at the peatland study site suggest that ample storage remains in the peat during dry periods. Furthermore, the long, steady drawdown during the unseasonable dry period of September 2010, along with the measurement of stream flow near the end of the period shows that discharge from peat at this site continues during much longer dry periods (Fig. 4). In other regions, however, discharge from peat may dry up during a severe drought, as Newson (1980) found in Wales.

Remaining challenges

The variability of natural landscapes in space and time poses a persistent challenge for estimating diffuse discharge from peatlands to nearby streams. This fundamental property of all landscapes introduces an element of uncertainty for determining water budgets for watersheds, particularly with respect to evapotranspiration and the validity of using solutes in groundwater to determine sources of stream flow.

This study relied on two different methods to estimate ET, which represents one of the more problematic values in most hydrological water budgets. The relative simplicity of the Thornthwaite method for estimating potential ET has facilitated its application to a wide range of peatlands (Ingram 1983) including those in regions subject to dry periods (e.g. Bay 1968; Bridgham et al. 1999; Brooks et al. 2011). The diurnal method, in contrast, provides an estimate of actual ET on the basis of water level fluctuations in wells (Todd 1964; Mitsch & Gosselink 2007; Lautz 2008). This method was originally developed by White (1932) and Troxel 1936) but later applied to peatlands in Finland by Heikurainen (1971) and Laine (1984). The Finnish investigators recognized the case of a drawdown in the absence of recharge, which has not been used previously in North American peatlands. Both the Thornthwaite PET and diurnal methods lack the precision of more rigorous methods (e.g. energy balance and eddy covariance) that require intensive instrumentation. However, even these instrumental approaches are not free from errors that can propagate when scaled beyond the footprint of the instruments (e.g. Field et al. 1992; Twine et al. 2000; Wilson et al. 2002; Drexler et al 2006). As a result, we relied on a sensitivity analysis of both the Thornwaite and diurnal methods to provide a probable upper and lower range of values for ET from the Limpopo peatland during a dry period.

We then used EMMA to estimate the proportional contribution of peatlands to stream flow in the Limpopo watershed during a dry period. However, a series of studies in Canada and Wales have raised a serious challenge to the theoretical foundations of End Member Mixing Analysis. James and Roulet (2006) for example noted variable results from their EMMA analysis of a watershed in southern Quebec that were probably caused by temporal changes in the partitioning of water and solute fluxes from different portions of the watershed to a nearby stream. Kirchner and colleagues (2000, 2001) and Kirchner and Neal (2013) have reported spurious trends in stream chemistry from the Plynlimon watershed of Wales that are related to the complexity of solute transport across a sloping watershed. Non-linear trends in the time series of stream chemistry were related to the importance of localized residence times of individual solutes, and relative importance of advection and dispersion as solute transport mechanisms along long flow paths. The complexity of these interactions caused the watersheds to act as "fractal filters" by damping precipitation inputs and producing constantly increasing variance (1/f noise) in the time series of stream chemistry. Our sampling plan partially avoids this problem by substituting spatial sampling at one point in time for the temporal sampling at one sampling point approach traditionally used in EMMA. Therefore, rather than showing shifting stream chemistry in response to mixing from different storm events over the course of several years, our mixing analysis provides a snapshot of the shifting chemistry of the stream along most of its length, as waters from different end-members mix on a single day during a dry period. Sampling end-members very close to or directly from the stream further avoids the problem of 1/f noise.

CONCLUSIONS

Peatlands represent an important source for stream flow in the Limpopo Creek watershed of Southcentral Alaska accounting for more than half of the flow during a dry period. Most of the remaining dry-season flow probably originates in the bedrock of the Sterling Formation, whereas little additional discharge was contributed from the poorly-sorted glacial till. Peatlands may also be important contributors to stream flow in other northern watersheds with similar hydrogeologic settings. The key features are 1) extensive peat cover over sloping terrain, 2) underlying mineral substratum composed of impermeable till or other unconsolidated deposits, and 3) a moist regional climate with a pronounced dry period. Disruption of this sensitive linkage between peatlands and streams by drainage or fill could magnify the effects of global warming on the ecohydrology of streams, which provide important spawning habitats for salmon in Southcentral Alaska.

Chapter 4 Conclusion

The Cook Inlet Classification system (CIC) divides natural wetlands into distinct classes based on landforms and subdivides the geomorphic classes either by stream type, vegetation dominants, or hydroperiod (Chapter 1). In peatlands, which are the focus of this classification system, seven different geomorphic classes are related to broadly overlapping differences in shallow porewater chemistry along a gradient ranging from dilute and acidic to more concentrated and circumneutral. Shallow porewater chemistry has been used widely to classify peatlands along the gradient from bog (dilute, acidic) to extremely rich fen (concentrated, circumneutral), although peat landform names have been used to classify peatlands, surrounding geomorphology has not been used to represent differences in chemistry. The landform classes are currently being used to assess peatland functions in the region and similar classes could be employed elsewhere for the same purpose. For example, Depressions are rated as performing the storage and recharge of shallow groundwater, whereas Spring Fens are rated as transmitting shallow groundwater.

Although many hydrologic measures could be used to distinguish among classes of peatlands, the influence of hydroperiod, the median position and variability of water levels, was found to be more important than chemistry in the Cook Inlet Basin (CIB). Although hydroperiod is also widely reported as an important factor in peatlands, previous classification of peatlands has generally focused on water chemistry. However, the overriding importance of hydroperiod was clearly demonstrated by the high within-class similarity produced by the CIC when compared to another widely-used hydrogeomorphic classification system that did not use hydroperiod to separate hydrologic classes (Chapter 2). The finding that water level variability is of overriding importance in the CIB is already guiding the assessment of hydrologic functions of peatlands in the region and could likewise be employed elsewhere. For example, peatlands in classes exhibiting highly variable water levels are assessed as primarily performing the functions of water storage and discharge of shallow groundwater from storage. Peatlands with more stable water levels are assessed as primarily performing the function of transmission of shallow groundwater (*cf*. Spence et al. 2011).

Using end-member mixing analysis to assess a hydrologic function of peatlands, two of the most extensive peatland classes in the region were found to contribute over half of the stream flow during a summer dry period (Chapter 3). This finding agrees with some previous work, but is in contrast to studies concluding that peatlands do not function as water storage reservoirs. The contrasting investigations had been undertaken in different hydrogeologic settings, which were more straightforward to measure, but are not as globally extensive as the setting investigated in the CIB. Although more work is needed to extend the findings reported in Chapter 3 to other geomorphic settings with extensive peatlands, in the CIB peatlands have now been shown to function as water storage reservoirs. A similar mixing analysis in a different setting, with extensive, low-gradient peatlands formed over porous fan-delta deposits, is currently underway. The mixing analysis supports the attribution of the hydrological function of stream flow support to peatlands with moderately-to-highly variable water levels. The findings of the mixing analysis may be useful elsewhere where similar undisturbed peatlands are assessed to evaluate benefits of proposed projects against losses of hydrologic functions.

Measurement challenges in extensive peatlands were overcome by using an end-member mixing analysis, and problems with mixing analysis were addressed by using a spatially distributed sampling protocol at a single point in time, rather than relying on a time-series of water chemistry data. The results from the mixing analysis were corroborated by a sensitivity analysis of a water budget, and a calculation based on the hydraulic conductivity of glacial till, the most abundant end-member in the watershed. End-member mixing analysis, should therefore not be discounted as a reliable technique, even after recognizing that watersheds act as fractal filters. A space-for-time sampling protocol may overcome this fractal filtering problem as long as the end members have relatively distinct solute composition. Where end-member composition only differs slightly in the concentrations of common solutes, EMMA may not produce reliable results regardless of the sampling technique. Clearly, more investigation into the reliability of spatially distributed sampling in lieu of time series in EMMA is required.

The new peatland classes defined by the CIC represent an advance in wetland management because undisturbed peatlands have not been previously classified with a goal of representing their functional capacity in a wetland assessment. Peatland ecological functions that are beneficial to human health and well-being have not been a focus of wetland management in the USA because peatlands are only widespread in Alaska, which contains more than half of all wetlands in the USA. Additional work performed to quantify other peatland functions, such as bird habitat and nutrient cycling, using classes based on hydroperiod (and landform) may also prove to be productive.

Because the CIC has been mapped across a relatively large region of Southcentral Alaska where peatlands had not previously been classified, the general functions of all peatlands in the region can now be more easily quantified in a wetland assessment. As an example, peatlands of all types are the largest long-term store of carbon in the terrestrial biosphere (Joosten et al. 2016). In the current rapidly warming climate of the Earth, carbon sequestration may be the most beneficial function that peatlands perform. Using estimates of carbon stored and carbon that is annually sequestered in peatlands (Beilman et al. 2008 & Vitt et al. 2000 cited in Rooney et al. 2012) multiplied by an estimate of the social cost of carbon (Nordhaus 2011), gives prices of between ~$21,200 and $66,000 ha^{-1} and ~$7.76 - $9.80 $ha^{-1} \cdot yr^{-1}$ respectively, for the value of this function (in 2015 US dollars). These prices approximately double if treaty goals of maintaining global warming at less than 2^{o} C are to be met (Nordhaus 2011). Additional work is required to more accurately quantify the carbon sequestration function of peatlands by accounting for the spatial variability of this function (Beilman et al. 2008, Vitt et al. 2000). A peatland classification system based on landform names and hydroperiod may be a sound basis for stratifying field measurements to more accurately account for this spatial variability.

The unique setting of wetlands in Alaska presents a unique opportunity for conservation not only because of their extent and relatively pristine condition, but also because of the strong institutionalized protections there. Although restoration of peatlands can be successful if 50 cm of peat remain and the surrounding hydrology is undisturbed (Quinty and Rochefort 2003), temporal losses of beneficial ecological functions are best calculated in units of decades or centuries (Pfadenhaeur & Grootjens 1999, Rochefort et al. 2003). Once the peat becomes extremely degraded, restoration becomes impossible (Schumann & Joosten 2008). Because of the impossibility of creating peatlands once they are lost, along with the long temporal losses of peatland function with restoration, the strong institutionalized protections that Alaskan peatlands enjoy may be essential in conserving ecological functions that are not only economically important for fisheries in the region, but also for the regulation of Earth’s climate.

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