2011

Tracing the source of groundwater for three different coastal peatlands along Lake Superior

Margus Paesalu
Michigan Technological University

Recommended Citation

Paesalu, Margus, "Tracing the source of groundwater for three different coastal peatlands along Lake Superior", Master's Thesis, Michigan Technological University, 2011.
https://doi.org/10.37099/mtu.dc.etds/149

Follow this and additional works at: https://digitalcommons.mtu.edu/etds
Part of the Forest Sciences Commons

TRACING THE SOURCE OF GROUNDWATER FOR THREE DIFFERENT COASTAL PEATLANDS ALONG LAKE SUPERIOR

By

MARGUS PAESALU

A THESIS

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

Forest Ecology and Management

MICHIGAN TECHNOLOGICAL UNIVERSITY

2011

This thesis, “Tracing the Source of Groundwater for Three Different Coastal Peatlands along Lake Superior,” is hereby approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE IN FOREST ECOLOGY AND MANAGEMENT.

School of Forest Resources and Environmental Science

Signatures:

Thesis Advisor ________________________
Dr. Thomas Grant Pypker

Thesis Co-advisor ________________________
Dr. Eric Agestam

Committee Member ________________________
Dr. Rodney A. Chimner

Committee Member ________________________
Dr. John S. Gierke

Dean ________________________
Dr. Margaret R. Gale

Date ________________________

Table of Contents

List of figures

List of Tables

Acknowledgements

First and foremost, I'd like to thank my advisor Thomas Pypker for always being there when I needed encouraging or directions throughout the project, his inspiriting instruction and professional demeanor has been invaluable. I owe a special thanks to Rodney Chimner for constructive suggestions and a positive attitude towards my work, which was both helpful and motivating. I'd like to thank John Gierke and Eric Agestam for being in my committee and I'm grateful to Tord Magnusson for providing helpful advice towards the end of the thesis writing in this collaborative dual degree program involving Michigan Technological University and Swedish University of Agricultural Sciences.

A word of gratitude goes out to the aidant fellow students of the School of Forest Resources and Environmental Science. John Hribljan and Laura Kangas provided critically important tips for starting the project, as well as know-how on to use the laboratory equipment. Tamara Baker was of great help conducting the vegetation survey, Stephen Curelli came out with me to the field sites in early November snow to carry out the high resolution GPS landscape and peat depth survey. I owe a spcial thanks to Anna Hess, who helped me compile site maps at the last minute.

This project was partially funded by the Michigan Technological University's Ecosystem Science Center. I am thankful to Michael Hyslop, Ann Maclean and Eugene Levin for providing tips on precise GIS surveying on a landscape. I would also like to express my gratitude to Jennifer Eikenberry, who assisted with laboratory work.

On a personal note, I'd like to thank Christopher Johnson, Kassidy Yatso, James Bess, Arvo Aljaste, Alex Collins, Scott Robinson and many other students of the SFRES that have been helpful in providing advice, as well as being amicable and supportive in everything that I undertook during my graduate studies in Michigan. The friends made along the way and the experience gained has made it a very special time in my life. I want to thank you all for this!

Abstract

The goal of this project was to investigate the influence of a large inland lake on adjacent coastal freshwater peatlands. The specific aim was to determine the source of groundwater for three differently formed peatlands located on the southern shore of Lake Superior. The groundwater study was conducted at Bete Grise, a peatland complex in a dune-swale system; Pequaming, a peatland developed in the swale of a tombolo; and Lightfoot Bay, a peatland developed in a barrier beach wetland complex.

To determine the source of groundwater in the peatlands, transects of six groundwater monitoring wells were established at each study site, covering distinctly different vegetation zones. At Pequaming and Lightfoot Bay the transects monitored two vegetation zones: transition zone from upland and open fen. At Bete Grise, the transects monitored dunes and swales. Additionally, at all three sites, upland groundwater was monitored using three wells that were installed into the adjacent upland forest. Biweekly measurements of well water pH and specific conductance were carried out from May to October of 2010. At each site, vegetation cover, peat depths and surface elevations were determined and compared to Lake Superior water levels. From June 14 – 17, July 20 – 21 and September 10 – 12, stable isotopes of oxygen ($^{18}O/^{16}O$) ratios were measured in all the wells and for Lake Superior water. A mixing model was used to estimate the percentage of lake water influencing each site based on the oxygen isotope ratios.

During the sampling period, groundwater at all three sites was supported primarily by upland groundwater. Pequaming was approximately 80 % upland groundwater supported and up to 20 % Lake water supported in the uppermost 1 m layer of peat column of the transition zone and open fen. Bete Grise and Lightfoot Bay were 100 % upland groundwater supported throughout the season. The height of Lake Superior was near typical levels in 2010. In years when the lake level is higher, Lake water could intrude into the adjacent peatlands. However, under typical hydrologic conditions, these coastal peatlands are primarily supported by upland groundwater.

Introduction

Peatlands are terrestrially occurring wetlands where ecosystem respiration rates are lower than the net primary production, thus creating favorable conditions for organic soil accumulation in the form of peat (Wieder and Vitt 2006). The anoxic environment caused by waterlogged conditions is the most important factor contributing to this unique habitat. Different criteria apply for the classification schemes, but the most common being organic soil depth of greater than 30 or 40 cm (Gorham 1991).

Peatland development is the result of terrestrialization, paludification or primary peat formation. Terrestrialization is the slow process of peat development in open bodies of stagnant water, gradually closing in from the edges with a floating mat of vegetation. Paludification is the most common form of peat formation, a process also known as swamping. In this process, peat accumulation begins directly over previous drier mineral soil. Primary peat production is a process described by peat formation directly on bare wet mineral soil, creation of which favored by the glacial retreat and the resulting land rise owing to the isostatic rebound (Wieder and Vitt 2006).

Peat accumulation speeds vary greatly depending on the decomposition (mineralization) rate, which is mainly driven by water saturation and ambient temperature, as well as aerobic or anaerobic conditions (Moore and Dalva 1993; Yavitt *et al.* 1997; Glatzel *et al.* 2004). In Ecuador, for example, Chimner and Karberg (2008) have determined the accumulation rate of 1.3 mm year^{-1}. Several studies show the average height accumulation of 0.6 mm year^{-1} for Northern Europe (Aaby 1986) and 0.6 – 0.8 mm year^{-1}for boreal areas of the Russian Federation (Botch and Masing 1983). Gorham and others (unpublished) have estimated the overall average peat accumulation of 0.48 mm year^{-1} for Canada.

Geographic range

Peatlands are found in every ecoregion of the world, from arctic to tropical climates, (Gore 1983; Immirzi *et al.* 1992; Gignac and Vitt 1994; Lappalainen 1996; Charman 2002). Wetlands (marshes, mires, swamps and peatlands) cover about or between 4 to 6 %, or 4 × 10^6 km^2 of land area on Earth in total (Mitch and Gosselink 2000, Rosa 2008). Nearly 93% of them are found in six predominantly boreal countries (Gorham 1991, Mitsch and Gosselink 2000, Joosten and Clarke 2002, Wieder and Vitt 2006). The largest intact area of peatlands in the world is on the vast West Siberian Plain in the Russian Federation (Neishtadt 1977, Walter 1977, Neustadt 1984, Gorham 1991). The second largest area is the Hudson Bay Lowland of Canada (Gorham 1991).

The majority of peatlands are located in the boreal zone due to several factors, the most important of which being the positive water balance in the region during all or part of the growing season. The positive water balance allows local water tables to stabilize (Wieder and Vitt 2006).

The importance of wetlands and their functions

Global carbon cycle

Peatlands are an important sink of carbon. CO_2 fixed by plants, subsequently is deposited as dead plant material (Wieder and Vitt 2006). The fixation of carbon by plants is counterbalanced by the release of carbon via plant and soil respiration, the loss of dissolved organic carbon (DOC) through the groundwater and the release of CH_4 because of methanogenesis (Wieder and Vitt 2006). The high water tables in peatlands create anaerobic conditions that prevent the decay of the dead plants, thereby causing the peatland to be a carbon sink. The ratio of net primary production (NPP) and peat accumulation is estimated to be between 1 to 20 % (Tolonen 1979; Tolonen *et al.* 1992; Warner *et al.* 1993; Francez and Vasander 1995; Moore *et al.* 2002; Feng 2002, Wieder and Vitt 2006). Therefore, peatlands act as an important reservoir of carbon storage.

More than 1/3, or 455 petagrams (455 x 10^{15} grams), of the world's soil carbon is stored in the organic soils of peatlands (Gorham 1991), while occupying only 3 – 4 % of global land area (Mitsch and Gosselink 2000). The carbon stored in these peatlands has been estimated to range between 50–150 kg C m^{-2} and the accumulation rates are estimated to range between 10 and 30 g C m^{-2} y^{-1} (Gorham 1991; Turunen *et al.* 2001, Wieder and Vitt 2006).

The large carbon stores may have several adverse effects on the global emissions to the atmosphere. For example, single large scale fire events can release vast quantities of carbon through peat combustion thereby altering the global atmospheric carbon balance. Page *et al.* (2002) estimated that the burning of 730 000 ha of tropical peatlands in 1997 released approximately 0.19 – 0.23 Gigatonnes (10^9 tons) to the atmosphere. The authors extrapolated the figures to the whole of Indonesia for one season of peat fires and concluded that between 0.81 – 2.57 Gt of carbon was released. Hence, peat fires in Indonesia represented one tenth to two fifths of the 6.4 Gt of carbon released globally by fossil fuels in 1957 (Page *et al.* 2002).

In the light of increasing global temperatures of the atmosphere, peatlands that have been regarded as net carbon sinks are now being studied in great detail with regards to becoming potential net producers of carbon into the atmosphere. The shift of temperatures is expected to be most significant in boreal zone (Houghton *et al.* 1992), where summers will likely have higher temperatures and, thus, along with the drawdown of the water table, the mineralization or decomposition of peat could occur at a higher speed.

Peatlands not only store carbon dioxide, but also produce two other greenhouse gases, CH_4 and nitrous oxide. According to Bartlett and Harriss (1993), peatlands contribute up to 9% of the Earth's CH_4 from natural sources due to anoxic conditions often found in peatlands. CH_4 is 23 times better at absorbing ultraviolet radiation than carbon dioxide, but has a much shorter atmospheric residence time (14.4 years compared to 230 years of CO_2) (Gorham 1991, Meehl *et al.* 2007, Watterson 2008). CH_4 is produced by the splitting of acetate, which comes from the fermentation of organic matter (Kelley *et al.*1992).

The answer to whether one third of world's sequestered soil carbon will affect the climate as the temperatures rise is yet unclear. Complex processes within peatlands – vegetation dynamics, water table fluctuations, biochemical processes within the peat and other factors have high variability, hence each eco-zone has to be studied independently and no broad conclusions have yet been made. Large biotic feedbacks are expected to occur in northern wetlands, as the global temperatures rise (Houghton *et al.* 1992). A comprehensive study conducted by Bridgham *et al.* (1998) of carbon, nitrogen and phosphorus mineralization rates in northern peatlands concluded that carbon mineralization rates were relatively constant over different sites, while methane production varied greatly. The authors suggested that the respiratory response of the soil to changes in climatic patterns will likely be very different for these two important greenhouse gases (Bridgham *et al*. 1996*).*

Peatland types

Peatlands are directly dependent on a long term water supply that is relatively constant, while the origin of the water determines the form and function of the peatland (Rydin and Jeglum 2006). Ground water and precipitation are the two main sources of water. Water and nutrient availability for the peatland flora is influenced by seasonal precipitation patterns and the height of the groundwater table. Seasonal variations in hydrology force the vegetation to adapt to constantly changing environments. Specific propagation strategies and differences in nutrients absorption have developed over time in many of the plant species that are found in these ecosystems. For example, carnivorous plants like sundew (*Drosera spp*) and pitcher plant (*Sarracenia spp*) have adapted to catch and digest bugs using enzymes to compensate for the lack of nutrients of the habitat (Bridgham *et al.* 1998).

Northern peatlands are structured into two broad categories – fens and bogs. The two main peatland types are delineated based on the physiochemical properties of the groundwater supporting them. Fens have inputs of groundwater or surface runoff enriched in bases and nutrients, that originate from surrounding uplands and thus are termed minerotrophic fens. Fens can be further divided into rich and poor. Rich fens have greater quantities of nutrients in the ground water, mostly calcium, relative to poor fens, which are more nutrient limited. There is no uniform set limit for pH that can help classify fens only by their surface water pH, but according to Malmer (1986) poor and rich fens can differentiated by the acidity-alkalinity gradient of pH 5.5 in northwestern Europe. In contrast to fens, bogs are termed ombrotophic, which is explained by the domed shape above the surrounding landscape which disconnects them from the groundwater supply, and thus bogs rely on atmospheric inputs of nutrients and bases to the peat surface (Gorham 1991, Bridgham *et al.*1998). As a result, bogs are more acidic, with the pH of the surface water ranging approximately from 3.5 to 4.5 (Malmer *et al.*1992). Bog surface waters have low pH, because of the water input from the atmosphere lacks the alkalinity to neutralize the strong acids that are released from decomposing peat (Hemond 1980; Gorham *et al.* 1985; Reeve 1996; Glaser *et al.* 2004; Siegel *et al.* 2006). The difference in available nutrients affects the vegetation communities.

Vegetation of the boreal peatlands ground layer was first classified according to the rich or poor fen gradient by DuReitz (1954). Wieder and Vitt (2006) described the minerotrophic, acidophilous Sphagnum-dominated plant communities with rather low species diversity were termed as poor fens, while species with high fidelity for nearly neutral soil pH or calcareous conditions were found in rich fens. Rich fens usually do not have a significant cover of Sphagnum peat mosses, rather they have a number of true mosses. Sphagnum mosses dominate only in precipitation fed bogs and precipitation and groundwater fed poor fens, however, this rule does not always apply, since Sphagnum mosses are also found in some rich fens. The type of the ground covering layer retains a critical difference for classification between bogs and poor fens, as several authors have suggested (Gorham and Janssens 1992; Vitt 2000; Wheeler and Proctor 2002).

Peatland Hydrology

Peatland formation and function is determined by the origin of the constant, long-term water supply. The link between peatland biota and hydrology has been known for more than a century. Dau (1823) was one of the first scientists to recognize and document three types of peatlands, according to the origin of water. Weber (1902) developed the concept of a raised bog, which is fed only by atmospheric precipitation. The movement of water in peatlands with the water table height fluctuations influences plant growth, resulting in the distinct vegetation patterns of hummocks, hollows, and pools (Gorham 1953; Iversen 1973; Sjörs 1963, Siegel and Glaser 2006).

Groundwater is defined as “subsurface water that flows through any saturated porous media regardless of its composition (mineral or organic), degree of consolidation (rock or sediment), or location (terrestrial or marine)” (Siegel and Glaser 2006). The rate of groundwater flow is determined by the physical properties of the porous media. Not all pores are connected and, thus, groundwater movement is limited to the connected pores, which is termed as effective porosity (connected pores which are 0.5 mm or greater).

> Siegel and Glaser (2006) have summarized the basic principles of groundwater hydrology regarding petlands:
>
> “Primary porosity develops when a rock or soil is formed. Although the total porosity of any rock or mineral soil is spatially variable, it remains relatively constant over decadal or century time scales. In contrast, the effective porosity of peat continually changes both spatially and temporally because of biological processes. Microbial decomposition, for example, continually breaks down the solid-phase peat skeleton, reducing the size of the pores and increasing the bulk

> density of the peat. As the pores become smaller the capillary tension between the pore waters and peat walls increases exponentially, thereby restricting the movement of water under the force of gravity or pressure." Additionally, it is of crucial importance to consider the multi-directional factors that affect the flow of groundwater. "The hydraulic conductivity of all porous media usually changes with direction. In the event of no formation of secondary porosity, hydraulic conductivity will decline exponentially with depth as various biological and physical processes reduce the volume of interconnected pore space" (Siegel and Glaser 2006).

Different peats have different hydraulic properties, for example a 100 to a 1000 fold discrepancy can occur in the hydraulic conductivity of well-humified Sphagnum peat (10^{-6} cm s^{-1}) compared to fibric sedge peat (10^{-4} cm s^{-1}) (Podniesinski and Leopold 1998). Such variation can draw a difference in the ground water flow paths through the site.

Ingram (1978) proposed the concept of the uppermost surface layer of acrotelm, consisting of poorly to well decomposed organic material, where water levels fluctuate throughout the year, and underneath, the permanently saturated zone made of well decomposed peat – the catotelm (Rosa 2008). Hydraulic conductivity is higher near surface of the acrotelm, while it is much lower in the catotelm (Ingram 1978, Fraser *et al* 2001, Drexler *et al* 1999). However, the acrotelm-catotelm concept has been considered ambiguous, because it is vaguely described and mostly site dependent (Amon *et al.* 2002).

Coastal wetlands

Coastal wetlands usually lie in the bordering and transition of terrestrial ecosystem zone into aquatic ecosystem and thus, are directly affected by both. Several categories of coastal wetlands occur, some of which border the oceans while others occur in freshwater systems.

Coastal Great Lakes peatlands

The Great Lakes region of the United States was shaped by glaciation. The lake levels have shifted by tens of meters as the geological processes evolved in post-glacial periods as the ice retreated, and have been more stable and at levels as we know them today for less than 5 000 years (Herdendorf 1992, Booth *et al.* 2002). Four types of stream and shoreline processes provided favorable sites for wetlands as the lakes became established: (1) delta formation, (2) estuary formation, (3) sandbar and dune formation creating coastal lagoons, and (4) solution lagoons (Herdendorf 1992).

The coastal wetlands in the Great Lakes region today hold a diversity of functions which are a mix of ecological and social uses can be categorized as (1) wetlands as habitats (fish production, spawning and nursery; waterfowl migration, wintering, and nesting; invertebrate and mammal habitat), (2) economical values (agricultural use, peat, blueberries, wild rice, etc.; commercial and sport fishing; waterfowl hunting; non-consumptive recreation (bird watching, canoeing, hiking, etc.)), (3) physical functions of wetlands (groundwater recharge and flood storage; sedimentation basins; pollution control (waste assimilation, toxic substance absorption, nutrient uptake, etc.; coastal protection (attenuate wave attack) (adopted from Herdendorf 1992, Jaworski *et al.* 1978).

Coastal peatlands are a specific type of peatlands that have been formed by the combination of high energy waves occurring at the shoreline, the fluctuations of the water level and the land forms created by the retreat of the Pleistocene ice sheets (Herdendorf 1992). These factors contribute to sediment build-up over time, resulting in a variety of differently formed and functioning wetlands. For example, in peatlands of the northern Great Lakes region, trees are often stunted in growth, or do not appear at all, due to saturated growing conditions of the open fen or the seasonally dry conditions of an ombrotrophic bog. In some instances trees can thrive in mineral rich fens, often forming cedar swamps. Albert *et al.* (2005) developed a classification scheme for Great Lakes coastal wetlands, based on their specific hydrological and geomorphological conditions. According to their hydrogeomorphic (HGM) model, three main types of wetlands –

lacustrine system, riverine system and barrier-enclosed systems occur in the Great Lakes Region.

Lacustrine, riverine and barrier-enclosed wetlands form under different conditions. Lacustrine systems are exposed, having little or no protection from the near-shore processes such as seiches, lake-level fluctuations, near-shore currents and ice scour of the lake, thus restricting vegetation development. Riverine systems occur along and within rivers, but are less affected by coastal processes. Barrier-protected systems are formed by either coastal or fluvial processes, but are separated from the lake by a barrier feature, often a barrier beach. The isolation from lake creates a suitable environment for wetland initiation, which usually occur in the swales behind the sand barrier. If several sand ridges parallel to the shoreline have formed over the course of the time, a distinguished form of wetlands emerge in the swales between the dunes – thus called the ridge and swale or dune and swale complexes. These usually occur in embayments, where enough supply of sediment is available. In the upper Great Lakes region alone, more than 100 of these complexes have been determined (Cromer and Albert 1991, Cromer and Albert 1993, Baedke *et al.* 2004).

Additionally, if an island is attached to the mainland by barrier beaches, a deposition landform called tombolo emerges (Hsu and Silvester 1990). The sediment accretion, also known as a salient, is developed by waves diffracting around the offshore barrier (an island), thereby slowing down and depositing sediment along the centerline, over time connecting the offshore barrier to the mainland. The resulting barrier enclosed system within a tombolo with more isolated and stable hydrologic conditions usually sustains a suitable environment for a wetland in the swale of a tombolo (Albert *et al.* 2005).

Stable isotopes of oxygen

Stable isotopes have emerged during the recent decades in ecological studies, providing previously unavailable opportunities to utilize them as geochemical tracers to determine the function or a process within a large frame of different applications (Hoffmann *et al.* 2000). The isotopes of any given element are characterized by their number of neutrons. Stable isotopes of oxygen ^{16}O, ^{17}O and ^{18}O are components of naturally occurring oxygen. The most abundant is ^{16}O, comprising for more than 99% of all oxygen isotopes. The stable isotopes of water molecules of lighter atomic mass are more likely to evaporate and fall as precipitation, thus building up concentrations of heavier isotopes in different hydrologic cycles. Mass spectrometry enables us to quantify the isotope ratio ($^{16}O/^{18}O$) or the relationship between atomic number and mass of a given example of water and express the values in an internationally recognized standard. For water samples, the VSMOW or Vienna Standard Mean Ocean Water scale is often used (Hoffmann *et al.* 2000).

Stable isotopes can applied to a broad scale of hydrologic questions. Past research have used stable isotopes to determine the source of water used by plants (e.g. Dawson and Ehleringer, 1991; Dawson, 1993). For example, Chimner and Cooper (2004) studied a site in Colorado to determine the water source for native shrubs in San Luis Valley. The root system of the endemic shrubs is adapted to different water table heights, changing their water uptake source according to the seasonal monsoon rains. Additionally, the movement of water can be traced. For example, Ronkanen *et al.* (2007) determined the flow patterns of water in a constructed wetland treating municipal wastewater in Finland. The isotope study helped to determine both active flow volume and preferential pathways, which turned out to be in the top 40 cm layer in the peatland. A study of this type helped to determine the area-efficiency of the wastewater treatment and potential improvements. Lastly, Wilcox *et al.* (2004) quantified the flows of groundwater using isotopes in the North-East Everglades in Florida to determine whether groundwater pumping for human use affected the aquifer underlying the Everglades. Isotopic analysis helped them determine that up to 60% of water beneath the Everglades was removed by pumping water for municipal use. Hence, environmental isotopes can be used in a variety of ways to better understand the hydrology of peatlands.

Study questions

The hydrologic conditions of each of the coastal wetland type in the Great Lakes region have been characterized only in general terms by Albert *et al.* 2005, but the influence of lake water to these differently formed peatlands has not been partitioned. This project uses stable isotopes to determine the source of groundwater for three barrier-enclosed coastal freshwater systems in Lake Superior. The three peatlands are described as a dune and swale complex, a barrier beach lagoon and a tombolo.

The hypotheses of this study were: (1) groundwater dominates the dune and swale complex and the barrier beach lagoon peatland, (2) while the more exposed tombolo at Pequaming is supplied primarily by lake water.

Methods

Study sites

The study occurred in three coastal peatlands, Bete Grise, Pequaming and Lightfoot Bay that are located in the Upper Peninsula of Michigan, United States (Figure 1). All three peatlands are located on the southern shore of Lake Superior and were formed under its geomorphic conditions (Boisvert 2009). The bedrock in all study sites is mostly Jacobsville sandstone of Precambrian origin (Doonan and Byerlay 1973).

Bete Grise

Bete Grise is a dune and swale wetland complex (latitude 47°21'53.51" N longitude 87°57'56.15" W, Figure 2). The dunes primarily support conifers (e.g. balsam fir (*Abies balsamea*), paper birch (*Betula papyrifera*), black spruce (*Picea mariana*) and northen white cedar (*Thuja occidentalis*) and swales supporting poor fen communities (Boisvert 2009). The poor fen consists primarily of bryophytes (*Sphagnum spp*), three-seeded sedge (*Carex trisperma*), labrador tea (*Ledum groenlandicum*), tag alder (*Alnus incana*), willows (*Salix spp*), black spruce (*Picea mariana*) and tamarack (*Larix laricina*). Boisvert (2009) determined that at Bete Grise the basal zone of the shallow peat layer consisted of very humic, granular peat, which had a poorly humic *Sphagum* peat atop.

Pequaming

Pequaming is a wetland complex formed in the swale of a tombolo (latitude 46°51'9.72" N longitude 88°22'35.41" W, Figure 3), consisting of a large expanse of island mixed mire (Rydin and Jeglum 2006) with large expanses of floating sedge and *Sphagnum* mat interspersed with small bog-like treed islands (Boisvert 2009). Boisvert (2009) showed that the basal zone of peat consisted of very humic peat, with partly humic peat with traces of Sphagnum moss atop, the uppermost zone poorly decomposed peat of *Carex ssp* and *Sphagnum ssp.* The transition zone from upland into open fen at Pequaming is a thick cedar swamp with distinct microtopography of hummocks covered mainly by northern white cedar (*Thuja occidentalis*), tag alder (*Alnus incana*), bryophytes (*Sphagnum spp*), horsetail (*Equisetum spp*), labrador tea (*Ledum groenlandicum*), royal fern (*Osmunda regalis*) and bluejoint (*Calamagrostis canadensis*). The open fen has sparsely spaced tree islands populated by stunted tamarack and northern white cedar and that were less than 2 m in height. Both the hummocks and lawns were covered by bryophytes (*Sphagnum spp*), bog-rosemary (*Andromeda polifolia*), bog golden rod (*Solidago uliginosa*), pitcher plant (*Sarracenia purpurea*), horsetail (*Equisetum spp*), wiresedge (Carex lasiocarpa), royal fern (*Osmunda regalis*), northern white cedar and sweetgale (*Myrica gale*).

Lightfoot Bay

Lightfoot Bay is a barrier beach peatland, with a sand ridge separating the wetland from the lake (latitude 46°54'6.47" N longitude 88°10'42.81" W, Figure 4). The peat cores have fine granular peat, likely a gyttja, in the basal zone, partly humic sedge remains in the second zone, poorly decomposed brown moss in the third zone and near-surface zone consisted mainly of poorly decomposed Sphagnum, roots of *Carex ssp* and leatherleaf (Boisvert 2009). The upland at Lightfoot Bay supports mixed forest of trees. The upland transitions to a treed wetland that has sparse tamarack, northern white cedar and black spruce underlain by bryophytes (*Sphagnum spp*), small cranberry (*Vaccinium oxycoccus*), royal fern (*Osmunda regalis*) sweet gale and leatherleaf (*Chamaedaphne calyculata*). In the center of the wetland and open floating mat section contains only sparse clumps of northern white cedar seedlings. The herbaceous layer is dominated by bryophytes (*Sphagnum spp*) and narrow-panicle rush (*Juncus brevicaudatus*) with quite densely distributed pitcher plant (*Sarracenia purpurea*).

Sampling protocol and well placement

For sampling purposes, we divided the sites into distinctly differing vegetation zones at each of the peatlands. At each of the three peatlands six wells were installed along a transect. In addition to the wells located in the peatland, three wells were installed in the adjacent upland forest (Figures 2 – 4). All wells inserted into the peatlands were made of 150 cm long, 5.08 cm (2”) outer diameter polyvinyl chloride pipe. The upland wells were 3.175 cm (1 ¼”) in diameter and with pointed tips, to make inserting them into hand-augered holes as easy as possible. Slits were cut along the bottom 3/5 (90 cm) of the length of the pipes and covered with geotextile to prevent fine peat matter from seeping into the wells. The tops of the wells were capped to prevent precipitation from directly entering the wells. Due to the different formation patters of the three sites, the wells had to be inserted into different depths to sample ground water throughout the relatively dry summer season. At Pequaming and Lightfoot Bay the wells were inserted approximately 1 m into the soil, while the existing groundwater monitoring wells and pizeometers (BG4, BG9) reached up to 363 cm below ground elevation at Bete Grise.

The peatland at Bete Grise has shallow peat that overlays a sandy mineral soil (Figure 5). At Bete Grise we took advantage of an existing network of ground water monitoring wells and piezometers. At Bete Grise, the continuously altering dunes and swales resulted in the locations of wells being evenly spread across the peatland. At Bete Grise, the dune and swale complex (groundwater monitoring wells 4 – 9, Figure 2) was pooled as one vegetation zone because of the locations of the wells altering between sand ridges and peat covered swales, while the upland (wells 1, 2 and 3) was used a reference for groundwater. At Pequaming and Lightfoot Bay, three wells were inserted in the open fen and three were inserted in a transition zone consisting of tag alder and cedar.

Ground elevation and peat depth survey

Trimble® GNSS system

To obtain precise elevation values of the ground water monitoring wells and ground elevations across the sites, a Trimble® Global Navigation Satellite System (GNSS) rover equipped the R8 receiver with the TSC2™ data controller was used. A temporary reference station, with an additional R8 receiver, was set up at each field site before beginning the GIS survey to obtain Real Time Kinetic (RTK) GIS data with the highest possible precision. The normalized Root Mean Squared values for elevation precision were 0.255 m for Lightfoot Bay, 0.011 m for Pequaming and 0.267 m for Bete Grise. The WGS84 datum was used as the standard reference. For coordinate calculations between two points in the landscape in order to construct the cross sections of study sites, an online tool available from http://boulter.com/gps/distance/ was used.

To map the peat depths, a 3 meter long, 1 cm diameter metal probe was used to penetrate through the peat until reaching the underlying mineral soil. Mineral soil was sand for all of the sites and was distinctively harder to push the rod into. Peat depth, ground elevation and GPS coordinates were recorded at each probing location throughout the sampling transect.

The maps of the locations of the groundwater wells were created based on the recorded GPS coordinates using ArcMap ver. 9.3.1. from ESRI Inc., Redlands, California, U.S.A. Aerial photos date from the 2005 National Agricultural Inventory Program (NAIP) and were obtained from the Michigan Geographic Data Library (http://www.mcgi.state.mi.us/mgdl/).

Specific conductance and pH measurements

From 28 May to 27 October 2010, specific conductance was measured on a at least a bi-weekly basis Specific conductance and pH of each well was measured with handheld pH, conductivity, salinity and temperature system (YSI model 63, YSI incorporated, Yellow Springs, Ohio, U.S.A.). The specific conductance errors are made of instrument accuracy and cell-constant errors, which both account for .5% maximum (YSI 63 manual). To measure specific conductance, water samples from the wells were collected by first discharging it with a Jack Rabbit™ hand pump and then, after 5 to15 minutes, when the groundwater had gradually recharged the well, water was pumped into an open polyvinyl chloride container approximately 4 liters in volume. The container was rinsed thoroughly using distilled water at each well. Lake Superior water was also sampled in a similar manner from the closest beach to the well transect.

Automatic water table monitoring

The year round water table data was available only for one site of the three. The automatically recorded water table levels were obtained from the permanent study plot located at the northeast corner of the Pequaming complex (Figure 3). Water table height was measured in a well using a level logger (model 3001 Levelogger® Junior, Solinst®, Georgtown, Ont. Canada). The water table data was air pressure corrected from the recorded dataset using barologger (model 3001 Levelogger® Gold, Solinst®).

Water samples for stable isotope ratios of oxygen ($^{18}O/^{16}O$)

Water samples were collected on 15 June, 7 July and 10 September at Bete Grise, from Pequaming and Lightfoot Bay on 17 June, 21 July and 12 September, using a similar collection method as described for the specific conductance measurements of the water in groundwater monitoring wells.

Water samples from groundwater monitoring wells and Lake Superior were stored in Nalgene® scientific 125 ml plastic bottles and kept on ice on the way back to the laboratory where they were frozen until running them in the mass spectrometer. Freezing of the samples was carried out to prevent the potential diffusive fractionation of water isotopes during evaporation (Merlivat and Jouzel 1979). The water samples were analyzed on a ThermoFinnigan Delta^{plus} Continuous Flow-Stable Isotope Ratio Mass Spectrometer located in Sam Horner Hall of the School of Forest Resources and Environmental Science of Michigan Technological University. Internationally recognized reference water samples were used to calibrate the equipment before running the field specimens. VSMOW (Vienna Standard Mean Ocean Water), SLAP (Standard Light Arctic Precipitation), and GISP (Greenland Ice Sheet Project) certified isotopic standards were run at the beginning of each analysis. Values were reported on the VSMOW scale. The standard deviation of repeated measurements of a laboratory reference water is 0.2 ‰.

To estimate the amount of ground water present at each vegetation zone of the site a mixing model was used to calculate the percentage from the $^{18}O/^{16}O$ results from the mass spectrometry:

$$\%\, ground\ water = \frac{sample\ value - lake\ water}{-lake\ water + upland\ reference}$$

This method assumes there are only two end members affecting the isotopic signature of the ^{18}O isotopes in the peatland groundwater. However, this signature will also be affected by evaporation and precipitation water. Therefore, when interpreting the results, this must be considered.

Statistical inferences

One-way analysis of variance (ANOVA) tests were run in SigmaPlot (version 11.0 from Systat Software, Inc., Chicago, IL, U.S.A.) to compare the specific conductance values of each vegetation zone at each site against each other and lake water using pairwise multiple comparison procedures (Tukey Test). Additionally, pairwise T-tests for means were run in SigmaPlot to compare the $^{18}O/^{16}O$ ratios for each vegetation zone (three pooled sampling dates, 3 values per each zone, 6 for Bete Grise pooled dune and swale) against each other and against the Lake water values. For the significance level of the test, a commonly used p-value of 0.05 was used as the criterion. Additionally, 95% confidence intervals were built around the isotopic signature means for each vegetation zone and Lake water to show the differences amongst groups.

Meteorological data

Monthly average temperature and precipitation data was obtained from the United States of America's National Oceanic and Atmospheric Administration's (NOAA) National Climatic Data Center (NCDC) Station number 14858, Houghton County Memorial Airport (CMX) at latitude 47°10'8.40" N and longitude 88°30'21.60" W, with an elevation of 314 meters ASL. Controlled data dates back to December of 1889 to present day. All of the study sites, Bete Grise, Pequaming and Lightfoot Bay, are located less than 50 km in a straight line from the weather station.

Lake Superior levels were summarized from the verified data of the National Oceanic and Atmospheric Administration's (NOAA) Center for Operational Oceanographic Products and Services, Great Lakes station number 9099018 in Marquette, Michigan, at latitude 46° 32.7' N and longitude 87° 22.7' W. Lake level readings date from 1918 to 2010.

Results

Weather conditions and the water table height

The weather patterns of the first half of 2010 deviated from those recorded over the long term. In 2010 the precipitation summed 650 mm, 184 mm less than the 121 year mean of 834 mm. The accumulated precipitation for the spring months was 76 mm in 2010, substantially lower than the long-term mean of 173 mm. In 2010, June and September received the greatest precipitation, 126 mm and 179 mm, respectively (Figure 8). The long-term climatic data describes an even distribution of precipitation throughout the year, with none of the values showing more than 100 mm per month.

The mean daily air temperatures from 1889 to 2009 for the spring months of March, April and May in nearby Houghton, Michigan (46.4 km from the furthest peatland), were -4.4 °C, 3.0 °C and 9.8 °C, respectively. In contrast, in 2010, the mean air temperatures were 1.9 °C, 7.3 °C and 12.4 °C, respectively. The early and quick melting of the snow pack in March resulted in the presence of surface water at all vegetation zones of the study sites, including the upland areas. Hence the height of the water table peaked from the middle of March to early April, at the permanent study site of Pequaming complex (Figure 10). The summer of 2010 showed higher air temperatures than usual, with the mean for June, July and August being 18.4 °C, in contrast with the 17.0 °C for the long-term mean. The warmest months of the summer were July and August (Figure 8). The accumulated precipitation for the summer period was within 40 mm of the long-term average.

Lake Superior levels

In 2010, the annual level of Lake Superior was 0.25 m lower than the average recorded annual mean of 183.41 m ASL. Lake levels declined from January to May, which contrast with the long-term trend of gradual increase of the level starting from April. Lake levels of 2010 rose until mid-September and then began to decline. This fluctuation cycle matches with the long-term trend, but the overall lake level remained below the average for the entire year (Figure 9).

Isotope and specific conductance measurements

The results demonstrate that the source of water for all three sites was primarily from upland groundwater. Results from the stable oxygen isotope ratios from the three sampling dates showed distinctly different signatures to that of the lake water for all of the sites and vegetation zones (Tables 1, 2).

Bete Grise

The isotopic analysis for the three measurement dates suggests that 100% of the groundwater in the peatland originated from the upland (Figure 12). The isotopic signature over the measurement period averaged -13.4‰ ± 0.2 (95% CI) to -14.0‰ ± 0.1 (95% CI) for the upland and from -13.4‰ ± 0.9 (95% CI) to -14.0‰ ± 0.8 (95% CI) for the dune and swale complex (Table 1). The $^{18}O/^{16}O$ isotope ratios of the lake water at Bete Grise Bay averaged (-8.84‰ ± 0.43 (95% CI)) and were statistically different from the peatland water (upland p-value = 0.003, dune and swale complex p-value = 0.003) water (Table 2). The upland and dune and swale complex water isotope ratios did not show a statistical difference (p-value >0.05).

The specific conductance of the lake averaged 89.4 μS/cm, 76.9 μS/cm for the dune and swale complex and 59.9 μS/cm for the upland (Figure 11 C). The specific conductance of the upland was statistically different from lake water (p-value <0.05), however, there was no statistical difference between the dune and swale complex compared to both upland and the lake water (Table 3). For the measurement period, the pH in the upland and the dune swale complex averaged 4.9 and 4.72, respectively.

Pequaming

The transition zone from upland and the open fen had up to 20% lake water in the uppermost 1 m of the peat column (Figure 12). Over the measurement period, the isotopic signatures averaged -12.21‰ ± 0.9 (95% CI) to -13.39‰ ± 1.54 (95% CI) for upland, -12.27‰ ± 0.62 (95% CI) to -12.57‰ ± 0.12 (95% CI) for the transition zone and -12.31‰ ± 1.21 (95% CI) to -12.46‰ ± 0.53 (95% CI) for the open fen (Table 1). Lake water $^{18}O/^{16}O$ isotope ratio averaged -8.79 ± 0.54 (95% CI) and was statistically different from the peatland (upland p-value = 0.008, transition zone p-value <0.001, open fen p-value <0.001) water (Table 2). The vegetation zones within the peatland did not show statistical difference in the isotope ratios (p-values > 0.05).

The specific conductance of the lake water averaged 87.5 µS/cm, 93.5 µS/cm for upland, 68.7 µS/cm for the transition zone and 55.3 µS/cm for the open fen. The specific conductance of the upland differed from open fen (p-value <0.05), lake water differed from transition zone (p-value <0.05) and open fen (p-value <0.05) (Table 3). The pH for upland, transition zone and open fen averaged 5.92, 5.67 and 5.25, respectively.

Lightfoot Bay

Over the course of the sampling season, the isotopic signatures averaged -12.29 ± 0.48 (95% CI) to -12.76‰ ± 0.58 (95% CI) for upland, -12.54‰ ± 0.64 (95% CI) to -12.72‰ ± 1.91 (95% CI) for the transition zone, and -12.29‰ ± 1.23 (95% CI) to -12.66‰ ± 1.79 (95% CI) for the open fen. Lake water $^{18}O/^{16}O$ isotope ratios at Lightfoot Bay averaged -8.78 ± 0.7 (95% CI) and were statistically different from the peatland (upland p-value <0.001, transition p-value = 0.001, open fen p-value <0.001) water (Table 2). The vegetation zones within the peatland did not show statistical difference in the isotope ratios (p-values >0.05).

Specific conductance averaged 91.3 μS/cm for the lake, 95.13 μS/cm for the upland, 86.6 μS/cm for the transition zone and 60.1 μS/cm for the open fen. Open fen specific conductance differed from the upland (p-value <0.05), lake water (p-value <0.05) and transition zone (p-value <0.05) (Table 3). The pH for the upland, transition zone and open fen averaged 5.79, 5.37 and 5.42, respectively.

Discussion

Peatland hydrology

The combination of isotope data and specific conductance shed light on the source water for these poor fens. The isotope data clearly demonstrates that most of the water in all three fens is not from Lake water for the study period (Figure 12). Of three wetlands, only the fen complex at Pequaming may have derived a portion of its groundwater from Lake Superior during the measurement period. Therefore, the water present in each of the peatlands came from upland groundwater or rainwater.

The results of this study support past research which demonstrated that barrier enclosed coastal peatlands in the Great Lakes region are not primarily supported by lake water (Albert *et al.* 2005). For example, a similar study conducted in a protected barrier dune system coastal peatland of Lake Ontario showed ground water movement towards the lake despite the correlation between water-table elevation and the condition of the barrier beach (breaches in the barrier opening and closing) (Bailey and Bedford 2003).

The data does not support past work that suggested that first couple of swales closest to the beach in a dune and swale complex can have direct hydrological connection to the lake, which can continue for hundreds of meters inland (Comer and Albert 1991, Albert *et al.* 2005). However, this connection could be mainly dependent on the surface water from the lake that inundates the peatland. The closest ground water well to the lake, BG9, was located on the first ridge, 43 meters from the shoreline (distance calculated from GPS coordinates). The depth of well BG9 was 363 cm below ground elevation of the sand ridge at 185.43 m ASL, which is a greater depth than that of other wells in the site. The well reaches 1.6 meters below the annual average lake levels since 1918**.** Oxygen isotope measurements do not support increasing influence of lake water with proximity to the lake for the Bete Grise dune and swale complex. When the pooled isotopic signatures from BG9 were compared to lake water in the mixing model, the source was 100% upland groundwater. The average isotopic signature of $^{18}O/^{16}O$ in well

BG9 was -14.27‰ (N=3) throughout the season, while Lake Superior water at Bete Grise Bay averaged -8.87‰ (N=3) $^{18}O/^{16}O$ ratios. The hydraulic head at BG, as measured by piezometric data, has shown that water is moving downward, thereby indicating that water is not moving into the area, but away from the peatland (Chimner, personal communication). Hence, it is not likely that lake water is moving into the peatland.

The isotopic data provides conclusive data that these sites are supported primarily by upland groundwater. At all three sites rainwater and evapotranspiration will further influence the isotopic composition of the fen water. Evapotranspiration will cause the peatland groundwater to become less negative. Hence, one would expect the peatland water to be heavier than its source. Since the peatland water is much lighter than the lake and, in general, heavier than the upland groundwater, the results indicate that most of the water at all sites in 2010 was from upland groundwater. At Pequaming, the up to 20% of the peatland ground water may come from the Lake. This value is based on the mixing model and likely represents the upper bound of the amount of lake water in the system because a portion of the isotopic change may result from instrument error and evapotranspiration. Evapotranspiration ration would result in the isotopic signature being less negative. Hence, evapotranspiration would make the groundwater in the peatland appear to be partially derived from the Lake. However, if the peatland groundwater originated entirely from the lake, the isotopic signature would be less negative than the lake because of evapotranspiration. However, this was not the case as the peatland groundwater more closely represents the upland groundwater. Furthermore, rainwater is not likely to be the main contributor to the water found in any of these fens. If these fens were rainwater dominated, their pH would consistently reflect that of a bog, rather than a fen. Except for one sampling date on Oct 26, the pH at these fens remained above 5, with values typically ranging between 5.1 and 5.5 (Appendix table pH). These pH values are more indicative of a groundwater fed system (Mitch and Grosselink 2006).

The specific conductances in the peatlands differed from the upland groundwater. It is possible that the specific conductances were more similar in the spring after snow melt and then diverged because of differences in evapotranspiration driven by changing vegetation. Alternatively, groundwater with lower specific conductance may upwell into the peatland. This might be possible as both Lightfoot Bay and Pequaming have extensive floating mats that would not impede the flow of groundwater up from below (Boisvert 2009). For this to be true, however, the isotopic composition of the deeper groundwater would have to be nearly identical to the upland groundwater measured in this study. Therefore, this study demonstrates that groundwater is the likely the main source of water for these fens, but the mechanisms are still not entirely clear.

Temporal changes in the stable isotope data

The relatively stable readings for oxygen isotopes of groundwater and Lake Superior water samples of this study can reflect the temporal scale limitation of three sampling dates over the course of four months. An extensive groundwater study conducted by Huddart *et al.* (1998) of a transient barrier sand-bar that separates a coastal freshwater marsh from Lake Erie, Canada, showed high spatial and temporal variability in the marsh water ($\delta\ ^{18}O$ -8.4 ‰ to -0.1 ‰) compared to relatively stable Lake water ($\delta\ ^{18}O$ = -7.5 ‰ to -6.7 ‰ VSMOW) over the period of 21 months. The benefit of extensive sampling helped determine that groundwater flowed from the marsh to the lake during winter months, but the flow reversed the following spring, and again the following autumn. The effect of spring-melt recharge was noticeable as the head reversed and the total distance of groundwater travelling back and forth was determined to be at least 96 meters per year (Huddart *et al.* 1998). Similarly with the Lake Erie study (Huddart *et al.* 1998) the isotopic signature of precipitation fell within the brackets of local meteoric water lines of $\delta\ ^{18}O$ = -10 ‰ to -15 ‰, suggested by Dansgaard (1964) and Hoffmann *et al.* (2000). A flow reversal could occur in the peatlands in the present study if Lake Superior levels were higher.

Potential influence of fluctuating lake levels

In the past, the Lake Superior region has been influenced by altering climatic conditions. About 5,000 years B.P. the Upper Midwest region of North America shifted from a warm and dry climate to cooler and wetter conditions (Delcourt *et al.* 2002). The shift occurred because previously dominated dry North Pacific air gave way to increased transport of warm and moist air from the Gulf Coast during summer, and a combination of Pacific and Gulf air masses during winter (Delcourt *et al.* 2002). This has resulted in an increase in the precipitation events that could affect the source water for coastal peatlands in Lake Superior.

The absolute recorded lake level minimums for August and September occurred in 2007, when Lake Superior levels reached 183.01 m ASL and 183.02 m ASL, respectively. The minimums for all the other months occurred in the 1920s (NOAA, NWS Marquette, MI 2011). Lake Superior minimum monthly mean levels usually occur at the end of the winter season, because during winter months, the dominating western winds carry dry air masses through the area, which then obtain moisture from the lake surface. This subsequently results in exceptionally heavy, lake effect snowfalls along the southern and eastern shore of Lake Superior. According to Delcourt *et al.* (2002) the lake effect precipitation events driven by the midwinter (from November to March) frigid air from Canada reach up to 100 km inland in the western Great Lakes region.

In 2010, Lake Superior levels averaged to an annual level 183.16 m ASL, which is only slightly lower than the long term average of 183.41 m. Higher lake levels could result in a greater Lake water influence on groundwater at these peatlands. In particular, the groundwater at Pequaming could experience the greatest lake water influence, because it is the closest to the lake elevation (Figure 6) and is exposed to the lake from two sides (Figure 3).

The lake level influence observed in the open fen and transition zone of Pequaming, however, does not extrapolate to the whole open fen section. The limiting factor is that the transect of ground water monitoring wells was in the middle of the peatland, which is approximately 800 meters from the closest shoreline of Lake Superior. Additionally, there was no isotope water sample collected from the more hydraulically conductive and thus semi-transient sand barrier regions that isolate the peatland complex from the lake (Figure 3). In central portion of Pequaming peatland complex up to 20% of the ground water in the open fen and transitional vegetation zones may come from lake water (Figure 12). However, there was no data collected from proximity of the barriers that border the peatland in the northeast and southwest. The potential lake water intrusion to the site would occur after a very dry summer which draws down the groundwater at the peatland, while Lake Superior reaches its annual maximum in August and September (Figure 9). This is further supported by the fact that the open floating mat portion of Pequaming is roughly only 31 cm (183.7 m ASL) higher from Lake Superior long term recorded mean of 183.41 m ASL. According to the long term monthly maximum levels, lake levels could be higher during 8 months of the year and, thus, inundate the Pequaming floating mat portion (Figure 6).

Other coastal freshwater wetlands in the Great Lakes region are occasionally inundated by lake water. For example, a coastal freshwater marsh study conducted by Huddart *et al.* (1999) at Lake Erie, Canada, determined two sources of water inputs: precipitation and groundwater discharge. However, in a decadal time scale Lake Erie occasionally inundates the marsh, when a portion of the isolating coastal sand barrier disintegrates because of wave action (Huddart *et al.* 1999). The southwestern barrier of Pequaming complex has a culvert beneath the road that runs along the barrier that could be an outlet of surface water for exceptionally high water levels in the open floating fen mat after spring-melt, or provide direct inlet into the peatland in the event of higher Lake Superior levels.

It is assumed, that the large ground water dominance at Pequaming is solely driven by the hydraulic head of adjacent upland bordering the southern edge. To determine exact interactions with the lake, an extensive network of piezometers and water level monitoring systems would have to be established.

Conclusion

This study demonstrates that despite Lake Superior contributing to the formation of these sites, they are mostly supported by groundwater input s from adjacent upland areas. The hypothesis that groundwater at Pequaming was primarily lake water dominated because the peatland was the most exposed to the lake was refuted. However, it is the only site that was moderately influenced by Lake and had partial presence of lake water in the groundwater mix. It is likely that the proportion of lake water present in the subsurface areas of transition zone and open fen at Pequaming are affected by snowmelt during springtime, and in longer temporal scale, Lake Superior water level fluctuations. Since records begin in 1918, Lake Superior water levels have reached higher levels than the open floating mat fen at Pequaming during 8 months of the year, suggesting that the open fen at Pequaming is periodically inundated with lake water.

List of References

Aaby B. 1986. Paleoecological studies of mires. Pages 145-164 in B. E. Berglund, editor. Handbook of Holocene palaeoecology and palaeohydrology. John Wiley & Sons, New York, New York, U.S.A.

Albert DA, Wilcox DA, Ingram JW, Thompson TA. 2005. Hydrogeomorphic classification for Great Lakes coastal wetlands. Journal of Great Lakes Research. 31:129-146.

Amon JP, Thompson CA, Carpenter QJ, Miner J. 2002. Temperate zone fens of the glaciated Midwestern USA. Wetlands. 22(2):301-317.

Baedke SJ, Thompson TA, Johnston JW and Wilcox DA. 2004. Reconstructing Paleo Lake Levels from Relict Shorelines along the Upper Great Lakes. Special Issue on Lake Superior. Aquatic Ecosystems Health & Management. 7:435–449.

Bailey KM and Bedford BL. 2003. Transient geomorphic control of water table and hydraulic head reversals in a coastal freshwater peatland. Wetlands. 23(4):969-978.

Bartlett KB and Harriss RC. 1993. Review and assessment of methane emissions from wetlands. Chemosphere. 26:261-320.

Boisvert EA. 2009. Initiation and Development of Three Lake Superior Coastal Peatlands. School of Forest Resources and Environmental Science. Houghton, MI, Michigan Technological University. M.S. 75 p.

Booth RK, Jackson ST, Thompson TA. 2002. Paleoecology of a northern Michigan lake and the relationship among climate, vegetation, and Great Lakes water levels. Quaternary Research. 57(1):120-130.

Botch MS and Masing VV. 1983. Mire ecosystems in the U.S.S.R. Pages 95-152 in A. J. P. Gore, editor. Eco-systems of the world, 4B. Mires: swamp, bog, fen and moor, Regional studies. Elsevier, Amsterdam, The Netherlands.

Bridgham SD, Pastor J, Janssens J, Chapin C and Malterer T. 1996. Multiple limiting gradients in peatlands: a call for a new paradigm. Wetlands. 16:45-65.

Bridgham SD, Updegraff K, and Pastor J. 1998. Carbon, nitrogen, and phosphorus mineralization in northern wetlands. Ecology. 79(5):1545-1561.

Charman D. 2002. Peatlands and environmental change. Chichester, England: John Wiley & Sons Ltd. 301 p.

Chimner RA, Cooper DJ. 2004. Using stable oxygen isotopes to quantify the water source used for transpiration by native shrubs in the San Luis Valley, Colorado USA. Plant and Soil. 260(1-2):225-236.

Chimner RA, Karberg J. 2008. Long-term carbon accumulation in two tropical mountain peatlands, Andes Mountains, Ecuador. Mires and Peat 3:Art. 4.

Comer PJ and Albert DA. 1991. A Survey of Wooded Dune and Swale Complexes in the Northern Lower and Eastern Upper Peninsulas of Michigan. Michigan Natural Features Inventory, Lansing, MI.

Coordinate Distance Calculator. An online tool available from http://boulter.com/gps/distance/ Accessed [2011-01-06]

Dansgaard W. 1964. Stable isotopes in precipitation. Tellus. 16:436 – 468.

Dau JHC. 1823. Neues Handbuch über den Torf. JC Hinrichsche Buchhandlung, Leipzig, Germany.

Dawson TE. 1993. Water sources of plants as determined from xylem-water isotopic composition: Perspectives on plant competition, distribution and water relations.

In Stable isotopes and plant carbon-water relations. Eds. J R Ehleringer, A E Hall, and G D Farquhar. pp. 465–496. Academic Press, San Diego.

Dawson TE and Ehleringer JR. 1991. Streamside trees that do not use stream water: evidence from hydrogen isotope ratios. Nature. 350:335-337.

Delcourt PA, Nester PL, Delcourt HR, Mora CI, Orvis KH. 2002. Holocene lake-effect precipitation in northern Michigan. Quaternary Research. 57(2):225-233.

Doonan CJ and Byerlay JR. 1973. Water investigation 11: Ground water and geology of Baraga County, Michigan. State of Michigan Department of Natural Resources, Geological Survey Division, Lansing, Michigan.

Drexler JZ, Bedford BL, Scognamiglio R, Siegel DI. 1999. Fine-scale characteristics of groundwater flow in a peatland. Hydrological Processes. 13(9):1341-1359.

Feng X. 2002. A theoretical analysis of carbon isotope evolution of decomposing plant litters and soil organic matter. Global Biogeochemical Cycles. 16:1119. DOI 10.1029/2002GB001867.

Francez AJ, Vasander H. 1995. Peat accumulation and peat decomposition after human disturbance in French and Finnish mires. Acta Oecologica. 16:599–608.

Fraser CJD, Roulet NT, Lafleur PM. 2001. Groundwater flow patterns in a large peatland. Journal of Hydrology. 246:142–154.

Gignac LD, Vitt DH. 1994. Responses of Northern Peatlands to Climate Change: Effects on Bryophytes. Journal of the Hattory Botanical Laboratory. 15:119-132.

Glaser PH, Chanton JP, Morin P, Rosenberry DO, Siegel DI, Ruud O, Chasar LI, Reeve AS. 2004. Surface deformations as indicators of deep ebullition fluxes in a large northern peatland. Global Biogeochemical Cycles. 18:GB1003. DOI 10.1029/2003 GBO02069.

Glatzel SN, Basiliko N, Moore TR. 2004. Carbon dioxide and methane production potentials of peats from natural, harvested and restored sites, eastern Québec, Canada. Wetlands. 24:261–267.

Gore AJ. 1983. Ecosystems of the world. Mires: swamp, bog, fen and moor. 4A, General studies, and 4B, Regional studies. Elsevier, Amsterdam, The Netherlands.

Gorham E. 1953. Some early ideas concerning the nature, origin, and development of peat lands. Journal of Ecology. 41:257–274.

Gorham E. 1991. Northern Peatlands - Role in the Carbon-cycle and Probable Responses to Climatic Warming. Ecological Applications. 1(2):182-195.

Gorham E, Eisenreich SJ, Ford J, Sandtelmann MV. 1985. The chemistry of bog waters. In: Stumm W (ed) The chemical processes in lakes. Wiley, New York, pp 330–363.

Gorham E, Janssens J. 1992. Concepts of fen and bog reexamined in relation to bryophyte cover and the acidity of surface waters. Acta Societatis Botanicorum Poloniae. 61:7–20.

Hemond HF. 1980. Biogeochemistry of Thoreau's Bog. Concord, Massachusetts. Ecological Monographs. 50:507–526.

Herdendorf CE. 1992. Lake Erie Coastal Wetland - An Overview. Journal of Great Lakes Research. 18(4):533-551.

Hoffmann GJ, Jouzel, Masson V. 2000. Stable water isotopes in atmospheric general circulation models. Hydrological Processes. 14(8):1385-1406.

Houghton JT, Callander BA and Varney SK. 1992. Climate change 1992: the supplementary report to the IPCC scientific assessment. Cambridge University Press, Cambridge, UK.

Hsu JRC and Silvester R. 1990. Accretion Behind Single Ooffshore Breakwater. Journal of Waterway, Port, Coastal, and Ocean Engineering-ASCE. 116(3):362-380.

Huddart PA, Longstaffe FJ, Crowe AS. 1999. Delta D and delta O-18 evidence for inputs to groundwater at a wetland coastal boundary in the southern Great Lakes region of Canada. Journal of Hydrology. 214(1-4):18-31.

Immirzi CP, Maltby E and Clymo RS. 1992. The Global Status of Peatlands and their Role in Carbon Cycling. A report for the Friends of the Earth by the Wetland Ecosystems Research Group, Department of Geology, University of Exeter. Friends of the Earth, London.

Ingram HAP. 1978. Soil layers in mires: function and terminology. Journal of Soil Science. 29:224–227.

Ingram HAP. 1983. Hydrology. In: Gore AJP (ed) Ecosystems of the world 4A. Mires: swamp, bog, fen, and moor. General studies. Elsevier, Amsterdam, pp 67–158.

Jaworski E and Raphael CN. 1978. Fish, wildlife and recreational values of Michigan's coastal wetlands. U.S. Fish & Wildlife Service, Twin Cities, MN.

Joosten H, Clarke D. 2002. The Wise Use of Mires and Peatlands – Background and Priciples including a Framework for Decision-making. International Mire Conservation Group & International Peat Society.

Kelley CA, Dise NB, Martens CS. 1992. Temporal variations in the stable carbon isotopic composition of methane emitted from Minnesota peatlands. Global Biogeochemical Cycles. 6:263–269.

Lappalainen E. 1996. General review on world peatland and peat resources. p. 53–56. In E. Lappalainen (ed.) Global Peat Resources. International Peat Society and Geological Survey of Finland, Jyska, Finland.

Malmer N. 1986. Vegetational gradients in relation to environmental conditions in northwestern European mires. Canadian Journal of Botany. 64(2):375-383.

Malmer N, Horton DG, Vitt DH. 1992. Element Concentrations in Mosses And Surface Waters Of Western Canadian Mires Relative To Precipitation Chemistry And Hydrology. Ecography. 15(1):114-128.

Meehl G. 2007. Global climate projections, in Climate Change 2007: The Physical Science Basis, edited by Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M and Miller HL, pp. 747 – 845, Cambridge University. Press, New York, NY, U.S.A.

Merlivat L, Jouzel J. 1979. Global climatic interpretation of the deuterium-oxygen 18 relationship for precipitation. Journal of Geophysical Research. 84:5029-5033.

Mitch WJ and Gosselink JG. 2000. Wetlands, 3rd Edition. John Wiley & Sons, Inc. New York.

Moore TR, Bubier JL, Frolking SE, Lafleur PM, Roulet NT. 2002. Plant biomass and production and CO2 exchange in an ombrotrophic bog. Journal of Ecology. 90:25–36.

Moore TR, Dalva M. 1993. Influence of temperature and water table position on carbon dioxide and methane emissions from columns of peatland soils. Journal of Soil Science. 44:651–664.

National Oceanic and Atmospheric Administration's (NOAA) Center for Operational Oceanographic Products and Services, Great Lakes station number 9099018 in Marquette, Michigan. Website. http://www.weather.gov/climate/index.php?wfo=mqt [accessed 2011-01-10]

Neishtadt MI. 1977. The world's largest peat basin, its commercial potentialities and protection. International Peat Society Bulletin. 8:37-43.

Neustadt MI. 1984. Holocene peatland development. Pages 201-206 in A. A. Velichko, editor. Late Quatemary envi- ronments of the Soviet Union. University of Minnesota Press, Minneapolis, Minnesota, USA.

Page SE, Siegert F, Rieley JO, Boehm HDV, Jaya A, Limin S. 2002. The amount of carbon released from peat and forest fires in Indonesia during 1997. Nature. 420(6911):61-65.

Podniesinski GS and Leopold DJ. 1998. Plant community development and peat strategy in forested fens in response to ground-water flow systems. Wetlands. 18(3):409-430.

Reeve AS. 1996. Numerical and multivariate statistical analysis of hydrogeology and geochemistry in large peatlands. PhD dissertation, Syracuse University, Syracuse.

Ronkanen AK and Klove B. 2007. Use of stabile isotopes and tracers to detect preferential flow patterns in a peatland treating municipal wastewater. Journal of Hydrology. 347(3-4):418-429.

Rosa E, Larocque M. 2008. Investigating peat hydrological properties using field and laboratory methods: application to the Lanoraie peatland complex (southern Quebec, Canada). Hydrological Processes. 22:1866-1875.

Rydin H, Jeglum JK. 2006. The Biology of Peatlands. Oxford University Press. 354 p.

Siegel DI and Glaser PH. 2006. The Hydrology of Peatlands, In: Boreal Peatland Ecosystems, Ed. R. Kelman Wieder and Dale H. Vitt, Springer Berlin Heidelberg. p. 289-311

Siegel DI, Glaser PH, So J, Janecky DR. 2006. The dynamic balance between organic acids and circumneutral groundwater in a large boreal peat basin. Journal of Hydrology. 320(3-4):421-431.

Sjörs H. 1963. Bogs and fens on Attawapiskat River, northern Ontario. National Museum of Canada Bulletin Contributions to Botany. 171:1–31.

Tolonen K. 1979. Peat as a renewable resource: long-term accumulation rates in northeuropean mires. In: Kivinen E, Heikurainen L, Pakarinen P (eds) Classification of peat and peatlands. International Peat Society, Helsinki, Finland, pp 282–296.

Tolonen K, Vasander H, Damman AWH, Clymo RS. 1992. Preliminary estimate of long-term carbon accumulation and loss in 25 boreal peatlands. Suo. 43:277–280.

Turunen J, Tahvanainen T, Tolonen K, Pitkänen A. 2001. Carbon accumulation in West Siberian mires, Russia. Global Biogeochemical Cycles. 15:285–296.

Vitt DH. 2000. Peatlands: ecosystems dominated by bryophytes. In: Shaw AJ, Goffinet B (eds) Bryophyte biology. Cambridge University Press, Cambridge, pp 312–343.

Walter H. 1977. The oligotrophic peatlands of Westem Siberia-the largest peino-helobiome in the world. Vegetatio. 34:167-178.

Warner BG, Clymo RS, Tolonen K. 1993. Implications of peat accumulation at Point Escuminac, New Brunswick. Quaternary Research. 39:245–248.

Watterson IG. 2008. Calculation of probability density functions for temperature and precipitation change under global warming. Journal of Geophysical Research. 113, D12106, doi: 10.1029/2007JD009254.

Weber CA. 1902. Über die Vegetation und Entstehung des Hochmoors von Augstumal im Memeldelta mit vergleichenden Ausblicken auf andere Hochmoore der Erde. Parey, Berlin, Germany.

Wheeler BD, Proctor MCF. 2002. Ecological gradients, subdivisions and terminology of north-west European mires. Journal of Ecology. 88:187–203.

Wieder RK, Vitt HD, 2006. ed. Boreal Peatland Ecosystems. Ecological Studies, ed. D. Czeschlik. Vol. 188. Springer-Verlag Berlin Heidelberg.

Wilcox WM, Solo-Gabriele HM, Sternberg LOR. 2004. Use of stable isotopes to quantify flows between the Everglades and urban areas in Miami-Dade County Florida. Journal of Hydrology. 293(1-4):1-19.

Yavitt JB, Williams CJ and Wieder RK. 1997. Production of methane and carbon dioxide in peatland ecosystems across North America: effects of temperature, aeration, and organic chemistry of peat. Geomicrobiology Journal. 14:299–316.

YSI Model 63 Handheld pH, Conductivity, Salinity and Temperature System. Operations Manual. 1998 YSI Incorporated, 1725 Brannum Lane Yellow Springs, Ohio 45387 USA.

Figures and Tables

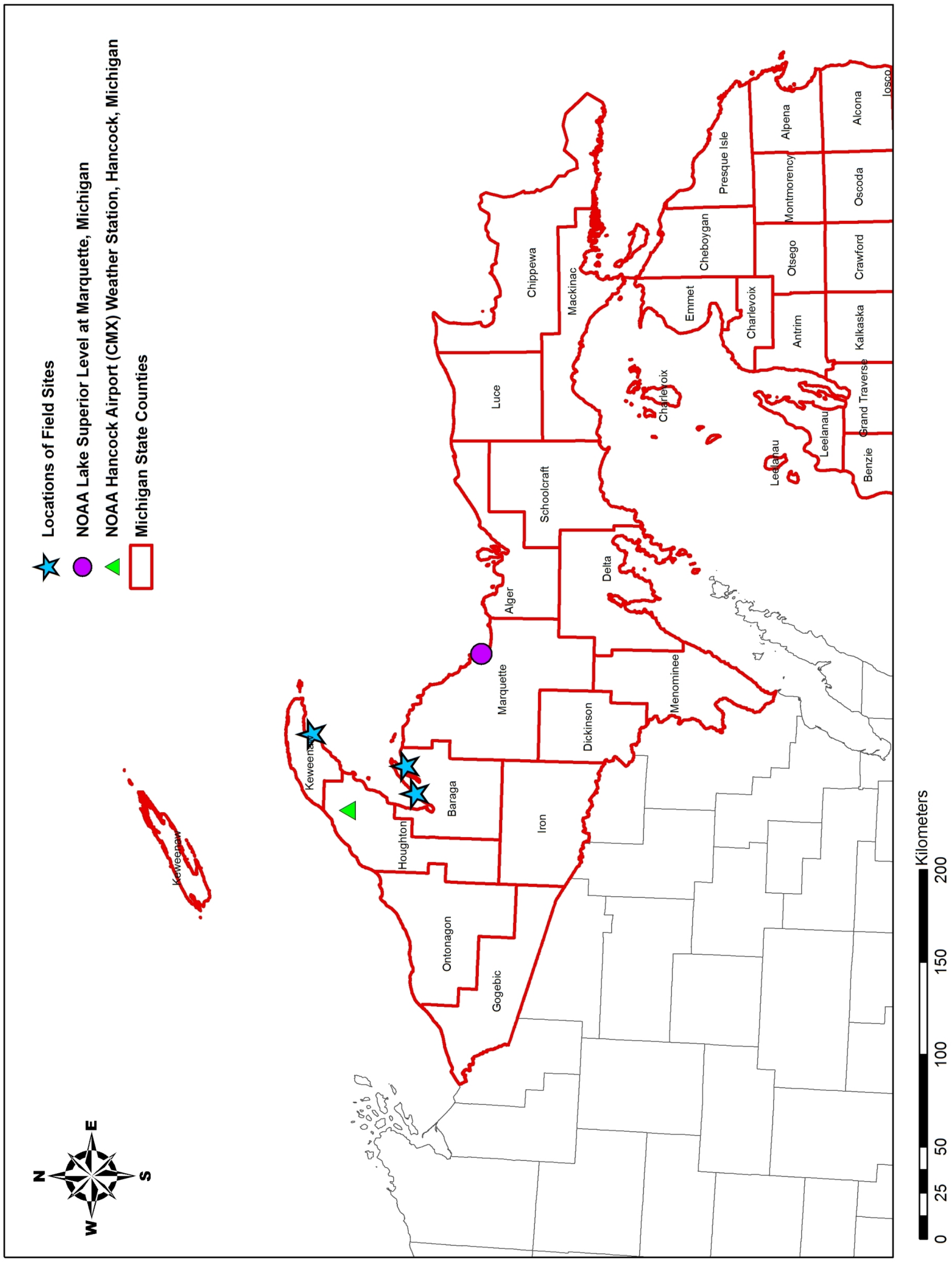

Figure 1. Study sites in the vicinity of the Keweenaw Peninsula in Upper Michigan of the United States

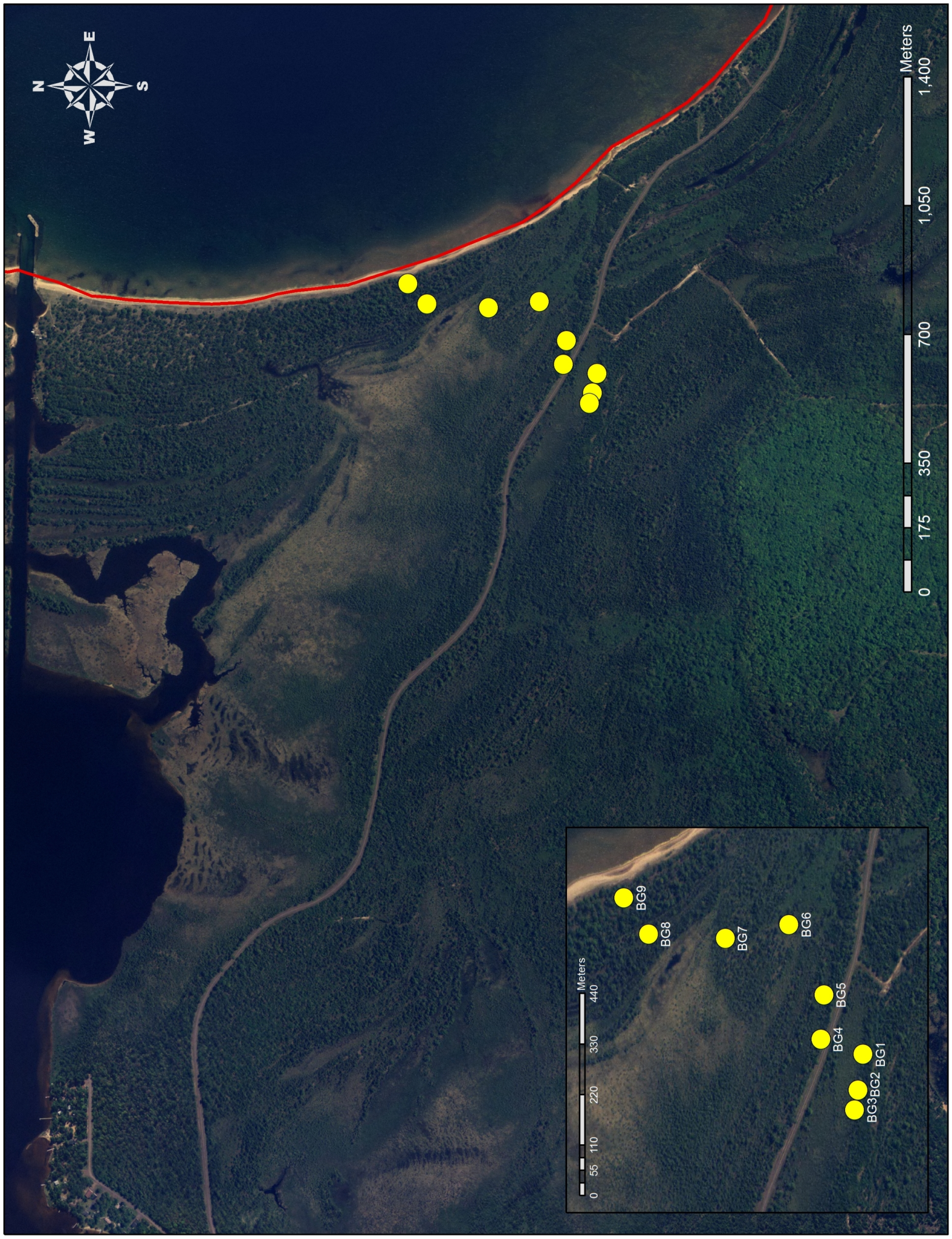

Figure 2. Transect of installed wells at Bete Grise

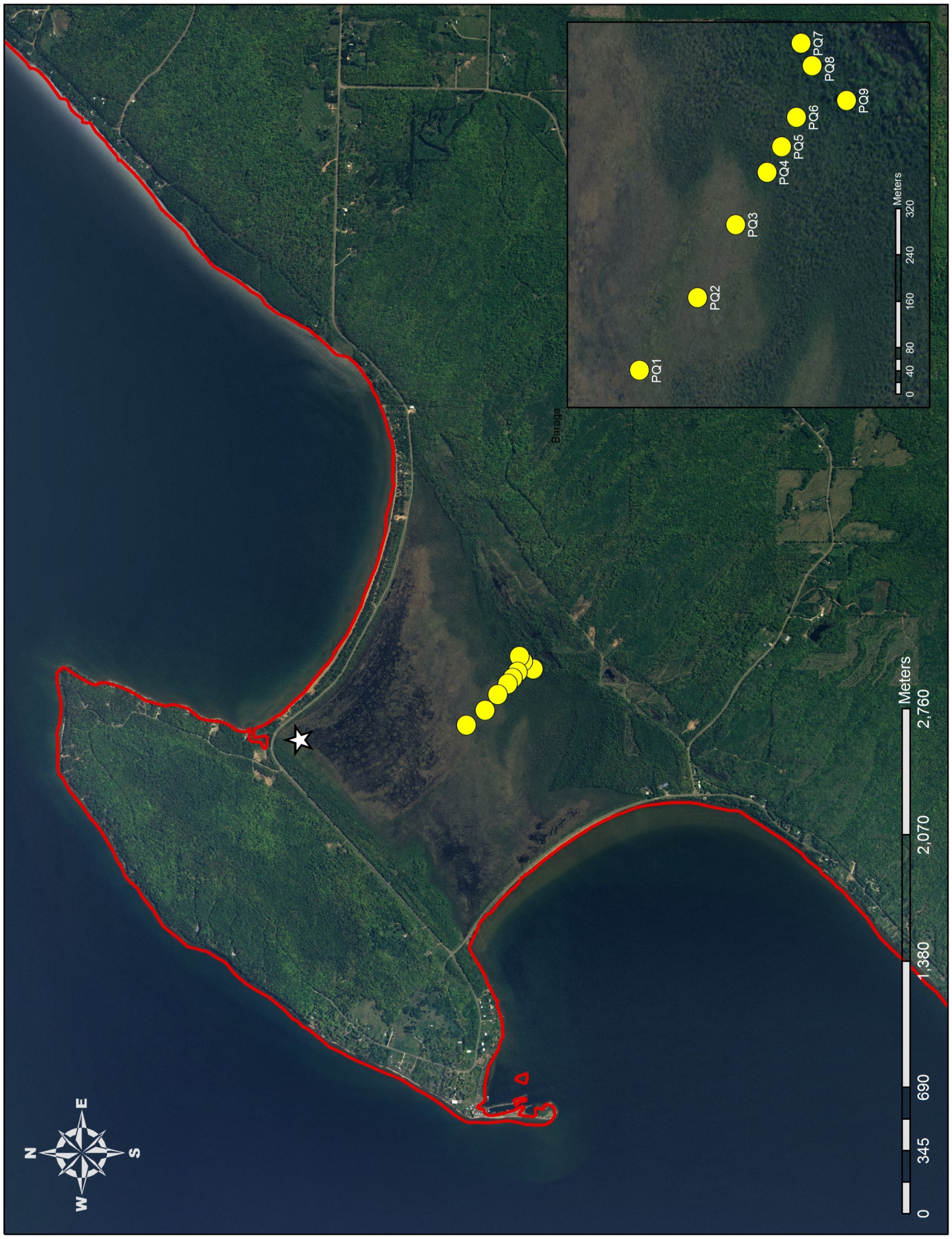

Figure 3. Transect of ground water monitoring wells at the tombolo peatland, Pequaming. The star marks the position of the permanent study site with the water table logger

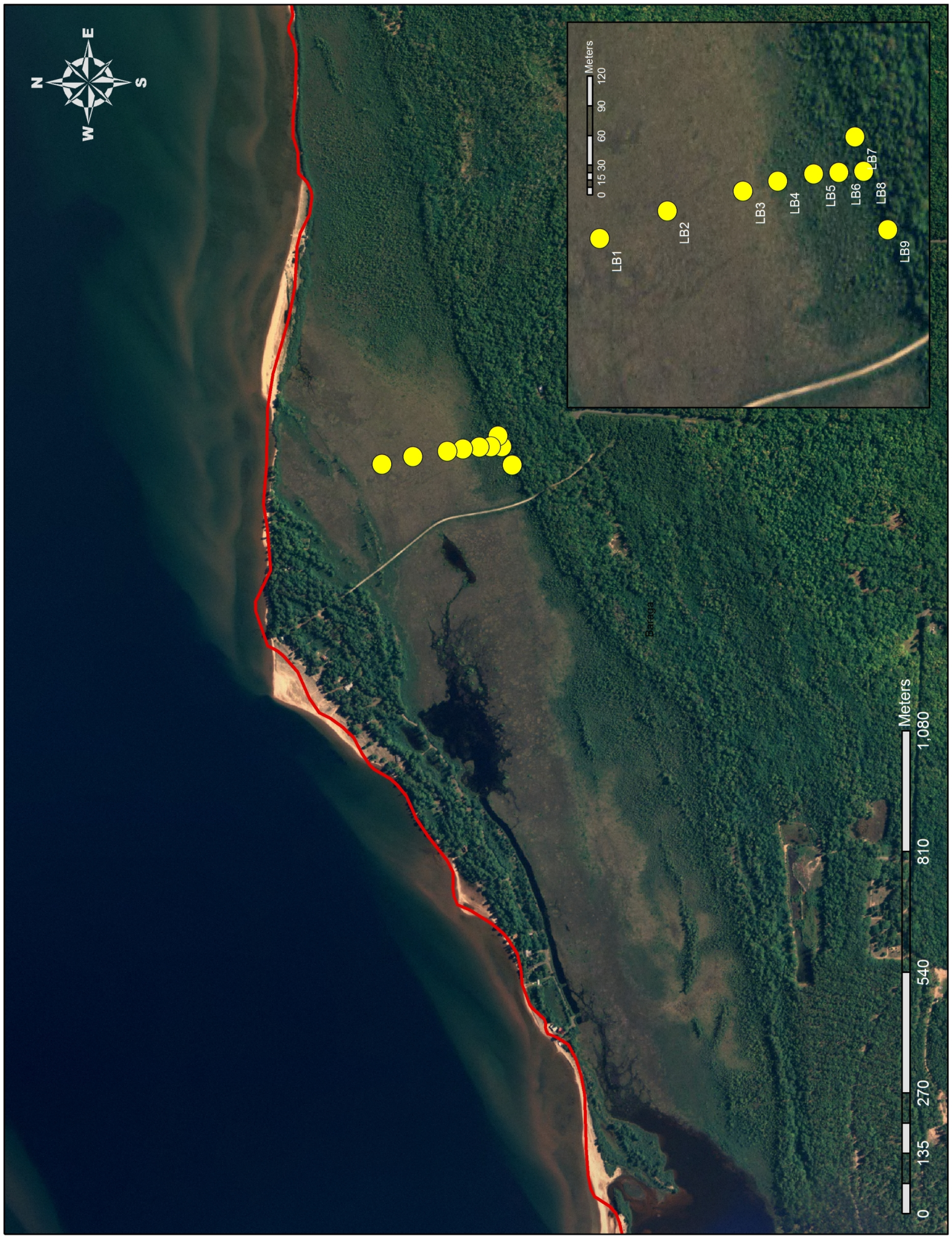

Figure 4. Transect of ground water monitoring wells at Lightfoot Bay peatland complex

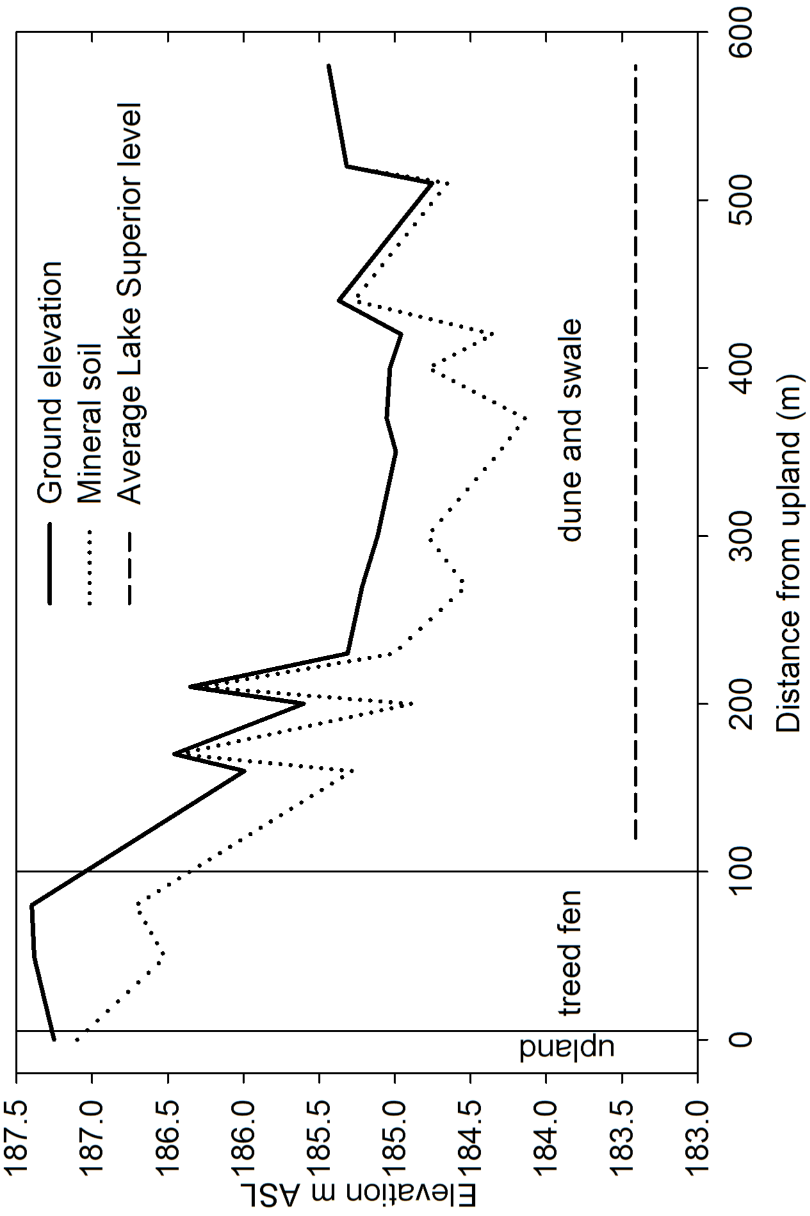

Figure 5. Cross section of probed peat depths of Bete Grise dune and swale complex

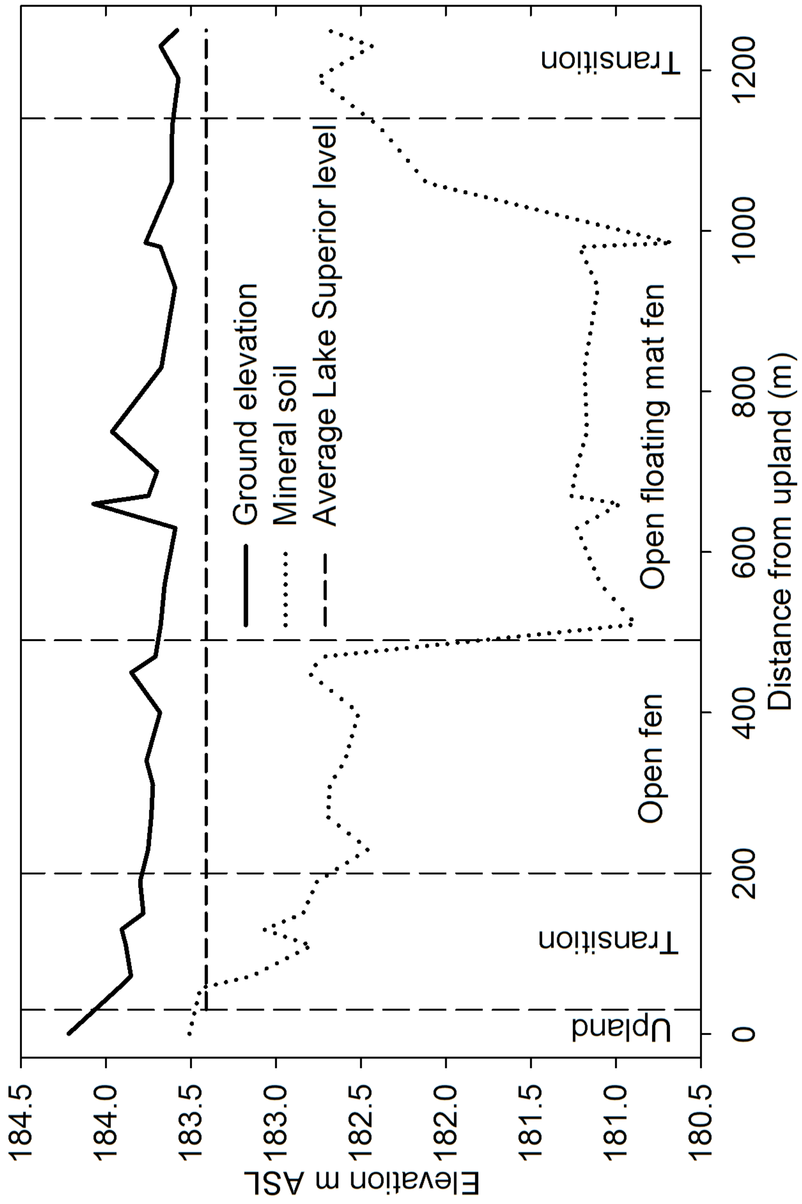

Figure 6. Cross section of probed peat depths of the Pequaming peatland complex

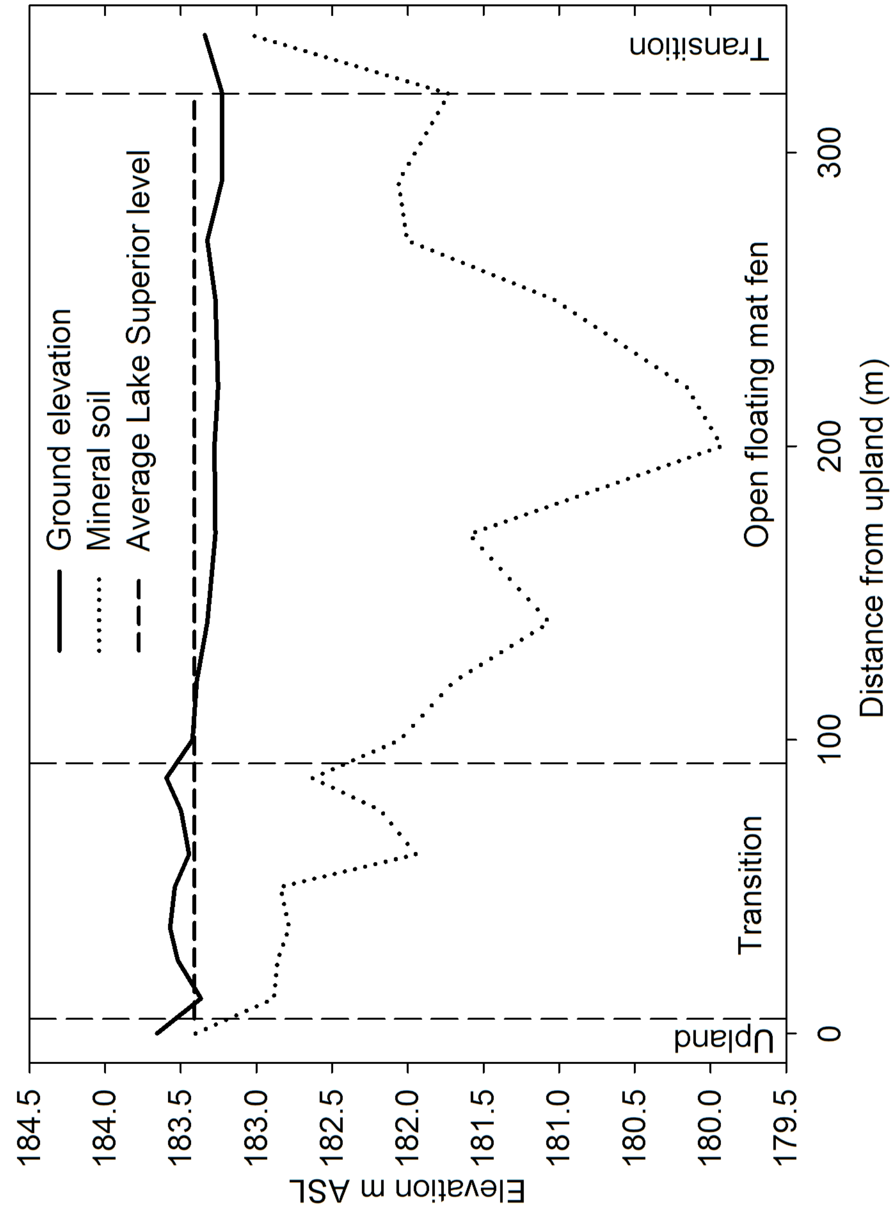

Figure 7. Cross section of probed peat depths of Lightfoot Bay peatland complex

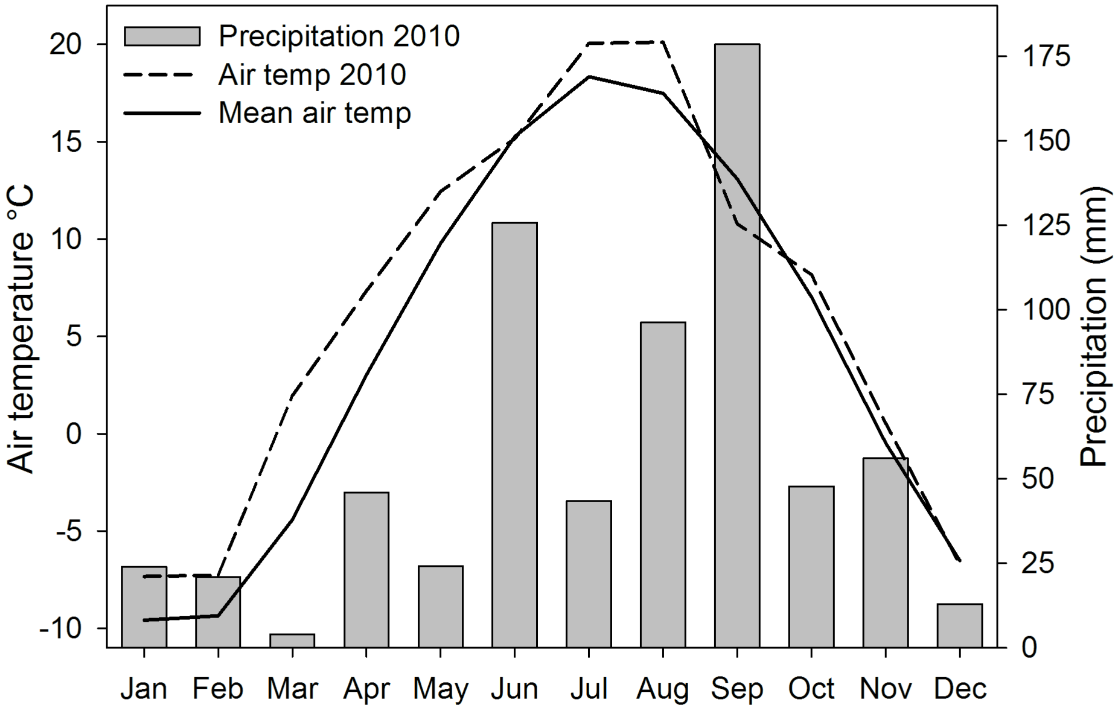

Figure 8. Houghton County mean daily air temperatures and monthly accumulated precipitation, Jan 2010 to Dec 2010. Long term mean temperature data dates from 1889 to 2009

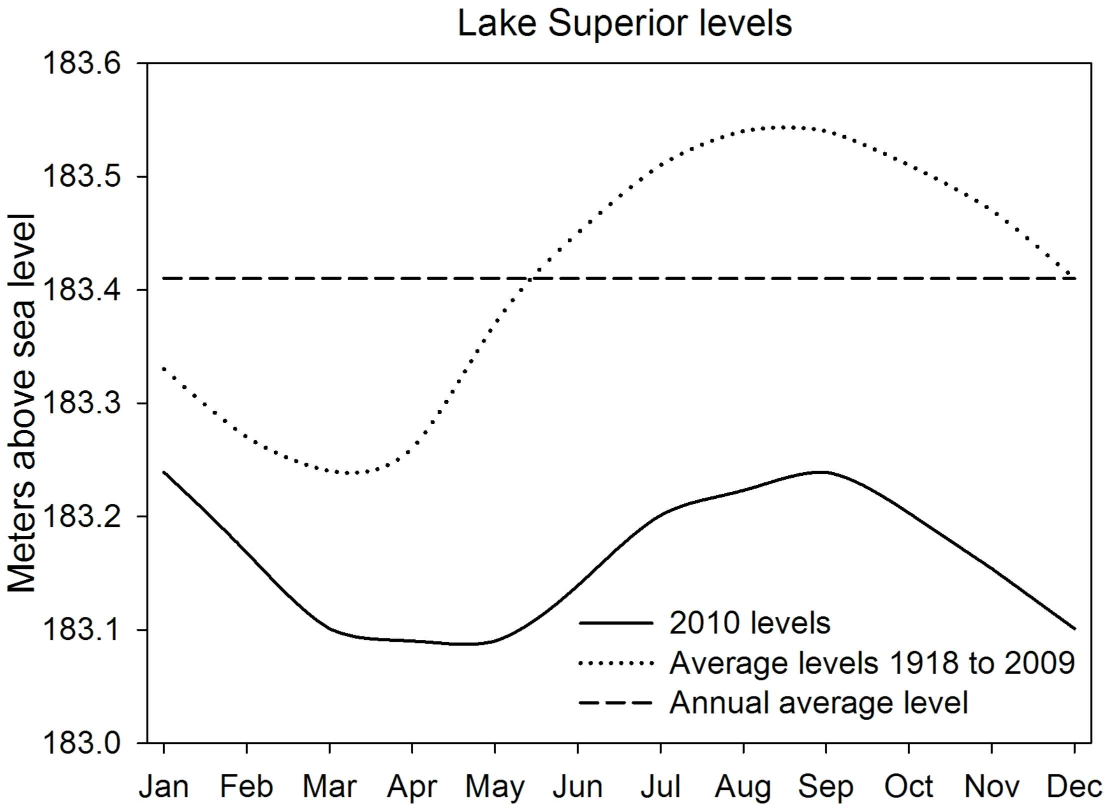

Figure 9. Lake Superior monthly levels of 2010, average monthly levels from 1918 to 2009, and annual average level

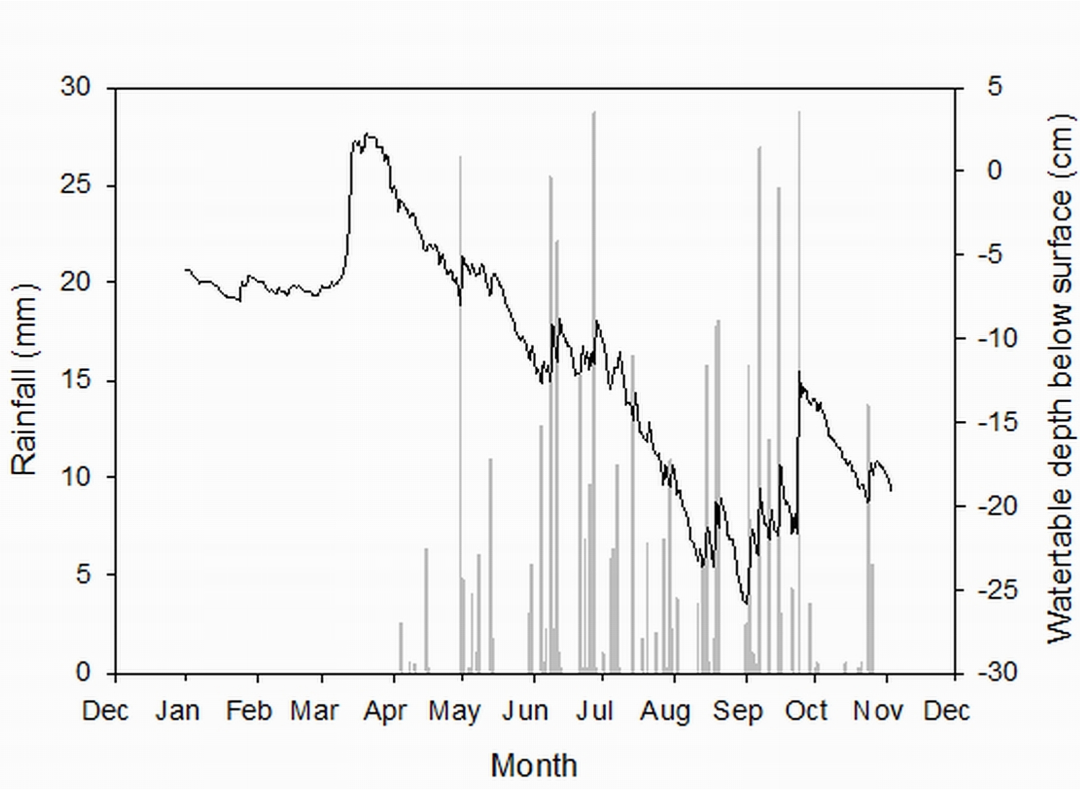

Figure 10. Water table height and precipitation at Pequaming

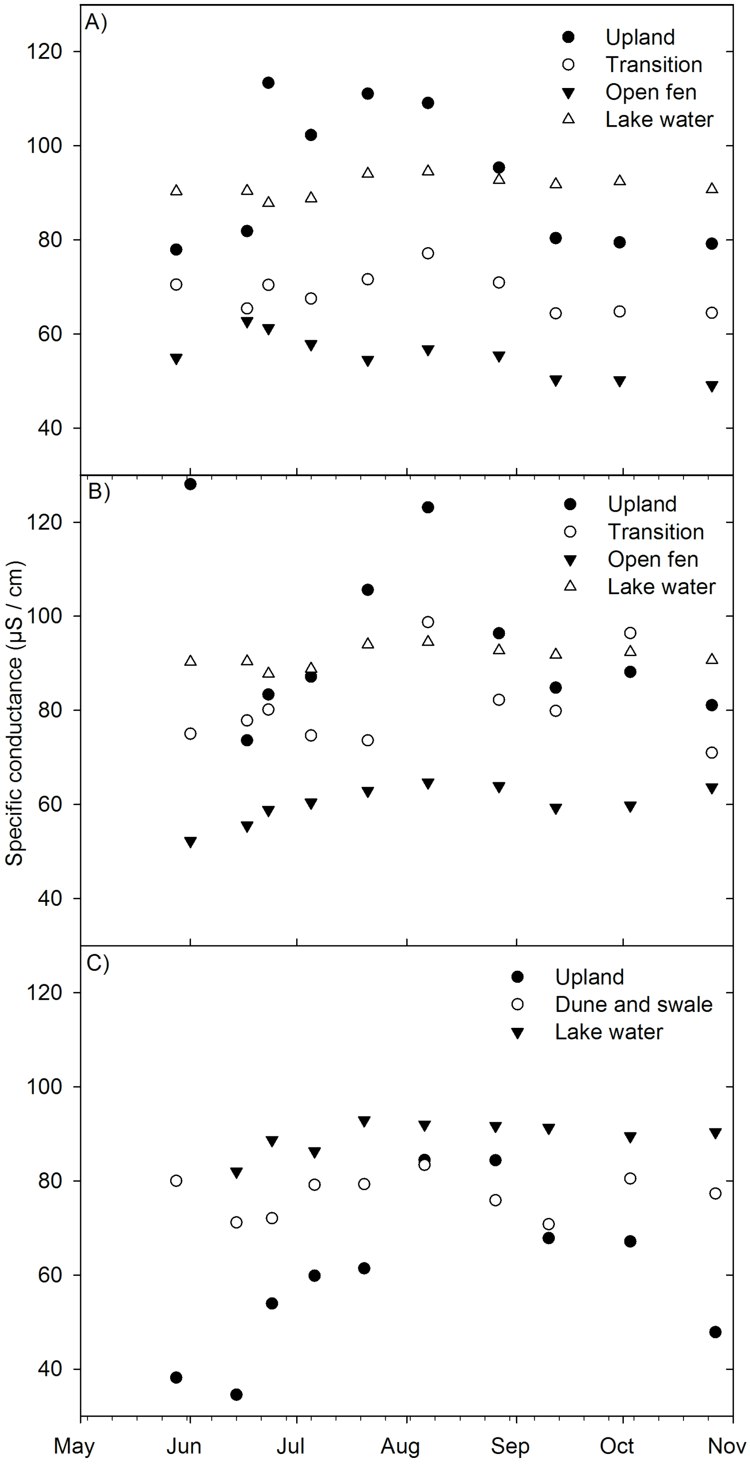

Figure 11: Specific conductance at all sites (A) Pequaming, (B) Lightfoot Bay, (C) Bete Grise

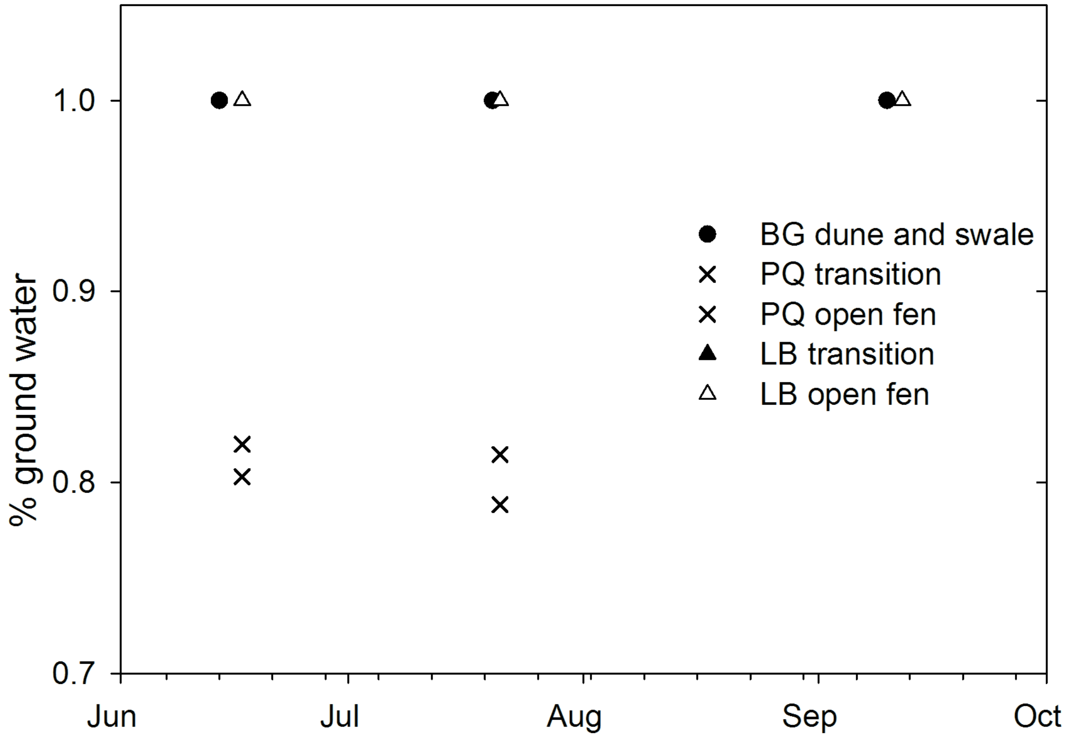

Figure 12. Delta $^{18}O/^{16}O$ isotope ratios showing the amount of ground water supporting each site. Note that Pequaming (PQ) is missing the third sampling date due to potential sampling error from surface water

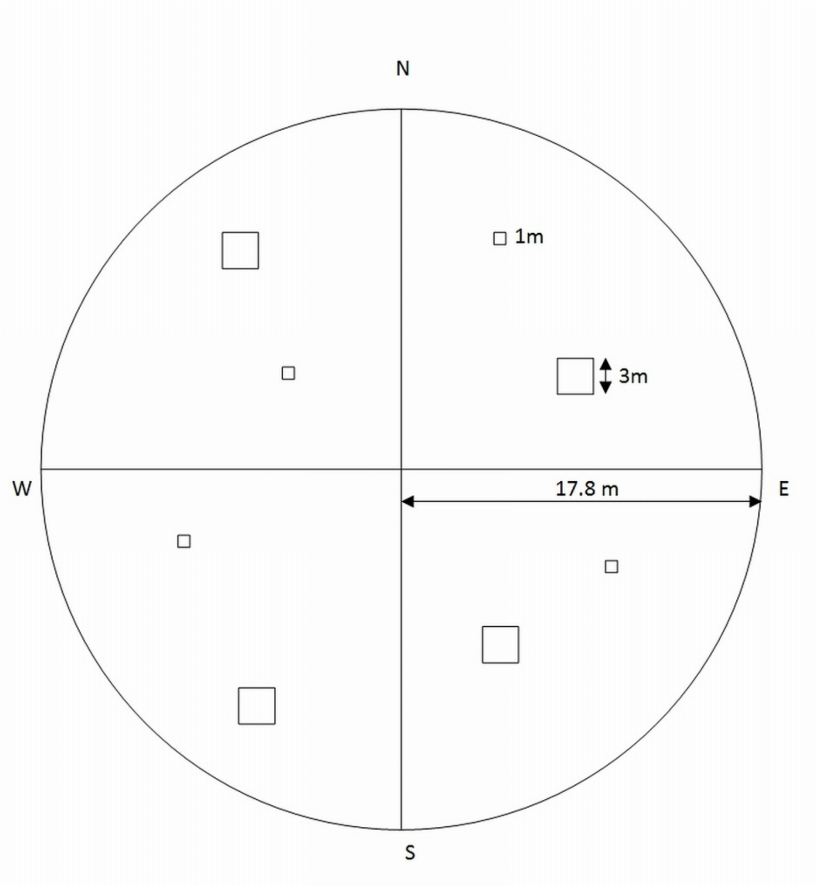

Figure 13: Layout of the 0.1 ha circular vegetation survey plots. The circle was divided into four quarters according to cardinal directions. 3x3 m plots were used for shrub layer sampling and 1x1m plots for the herbaceous layer, all placed randomly within the quarters.

Table 1.
^{18}O stable oxygen isotope ratios of all sites with 95% confidence intervals

Site	**Vegetation**	**14 – 17.06.2010**	**20 – 21.07.2010**	**10 – 12.09.2010**
Bete Grise	Upland	-13.44 ± 0.16	-13.47 ± 0.2	-13.97 ± 0.13
	Dune and swale	-13.46 ± 0.91	-13.39 ± 0.92	-13.99 ± 0.82
	Lake water	-9.00	-8.87	-8.65
Pequaming	Upland	-13.18 ± 0.45	-13.39 ± 1.54	-12.21 ± 0.9
	Transition	-12.27 ± 0.62	-12.57 ± 0.12	-12.34 ± 0.2
	Open fen	-12.33 ± 0.98	-12.46 ± 0.53	-12.31 ± 1.21
	Lake water	-8.55	-8.99	-8.82
Lightfoot Bay	Upland	-12.29 ± 0.48	-12.46 ± 0.75	-12.76 ± 0.58
	Transition	-12.54 ± 0.64	-12.56 ± 1.17	-12.72 ± 1.91
	Open fen	-12.29 ± 1.23	-12.46 ± 1.34	-12.66 ± 1.79
	Lake water	-8.45	-8.94	-8.94

Table 2.
Student's pairwise comparison of ^{18}O isotope ratios between vegetation zones and lake water

PEQUAMING	
UPLAND vs LAKE	P = 0.008
TRANSITION vs LAKE	P = <0.001
OPEN FEN vs LAKE	P = <0.001
LIGHTFOOT BAY	
UPLAND vs LAKE	P = <0.001
TRANSITION vs LAKE	P = 0.001
OPEN FEN vs LAKE	P = <0.001
BETE GRISE	
UPLAND vs LAKE	P = 0.003
DUNE AND SWALE vs LAKE	P = 0.003

Table 3.
One-way ANOVA of specific conductance for each vegetation zone compared to lake water

Comparison	**P <0.05**
PQ lake vs PQ open fen	Yes
PQ lake vs PQ transition	Yes
PQ lake vs PQ upland	No
PQ upland vs PQ open fen	Yes
PQ upland vs PQ transition	No
PQ transition vs PQ open fen	No
LB upland vs LB open fen	Yes
LB upland vs LB transition	No
LB upland vs LB lake	No
LB lake vs LB open fen	Yes
LB lake vs LB transition	No
LB transition vs LB open fen	Yes
BG lake vs BG upland	Yes
BG lake vs BG dune&swale	No
BG dune&swale vs BG upland	No

Appendix

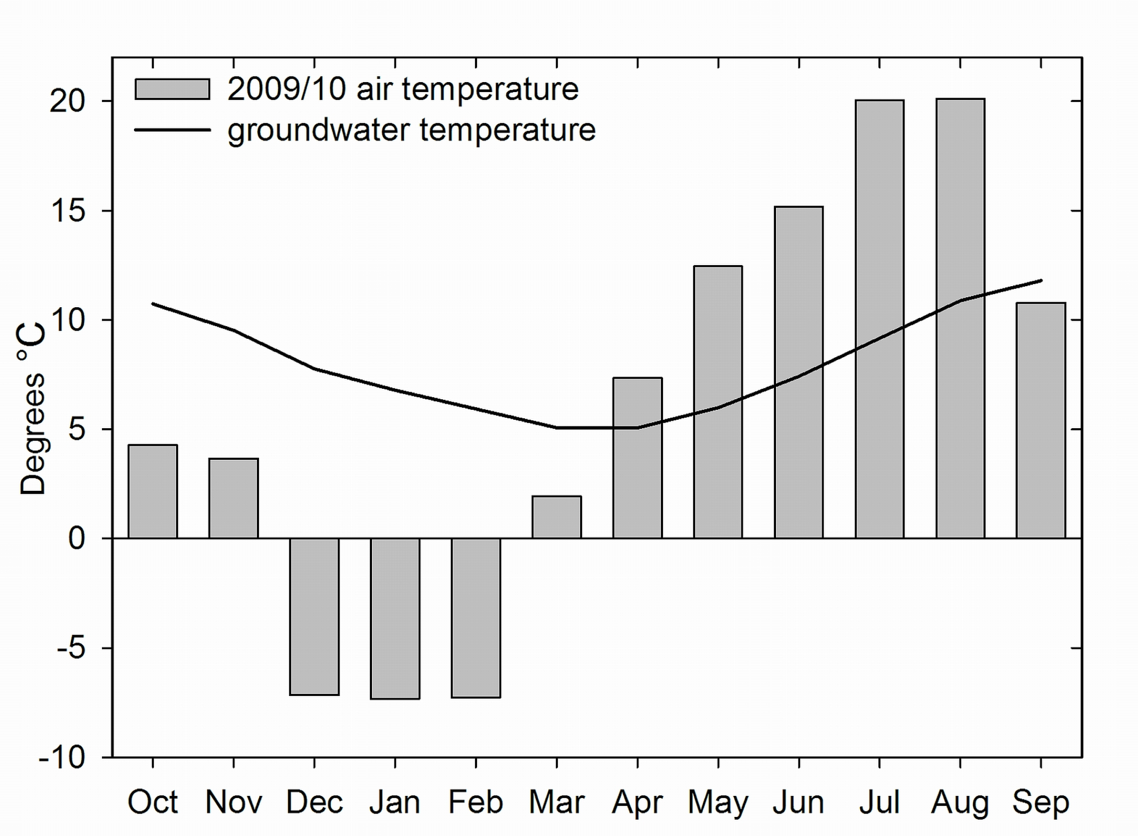

Figure 14. Monthly air and groundwater temperatures at Pequaming

Table 4.
Seasonal summary table of specific conductance (µS/cm) at Pequaming

Date	**May 28**	**Jun 17**	**Jun 23**	**Jul 5**	**Jul 21**	**Aug 7**	**Aug 27**	**Sep 12**	**Sep 30**	**Oct 26**
Up-land	77.90	81.83	113.37	102.27	111.03	109.07	95.37	80.33	79.43	79.17
Tran-sition	70.47	65.40	70.40	67.50	71.60	77.13	70.90	64.37	64.77	64.47
Open fen	54.93	62.77	61.27	57.83	54.53	56.80	55.47	50.33	50.20	49.13

Table 5.
Seasonal summary table of specific conductance (µS/cm) at Lightfoot Bay

Date	**Jun 1**	**Jun 17**	**Jun 23**	**Jul 5**	**Jul 21**	**Aug 7**	**Aug 27**	**Sep 12**	**Oct 3**	**Oct 26**
Upland	128.07	73.63	83.37	87.13	105.60	123.13	96.37	84.80	88.17	81.07
Tran-sition	75.00	77.83	80.13	74.63	73.63	98.73	82.23	79.90	96.40	71.00
Open fen	52.27	55.57	58.87	60.40	62.93	64.70	63.90	59.33	59.80	63.70

Table 6.
Seasonal summary table of specific conductance (µS/cm) at Bete Grise

Date	**May 28**	**Jun 14**	**Jun 24**	**Jul 6**	**Jul 20**	**Aug 6**	**Aug 26**	**Sep 10**	**Oct 3**	**Oct 27**
Up-land	38.17	34.53	53.93	59.83	61.40	84.43	84.37	67.80	67.10	47.83
Dune and swale	80.00	71.13	72.05	79.17	79.30	83.40	75.85	70.78	80.48	77.30

Table 7.
Seasonal summary table of pH at Pequaming

Date	**May 28**	**Jun 17**	**Jun 23**	**Jul 5**	**Jul 21**	**Aug 7**	**Aug 27**	**Sep 12**	**Sep 30**	**Oct 26**
Up-land	5.97	5.96	6.09	5.90	5.88	6.03	6.11	5.76	5.75	5.96
Tran-sition	5.57	5.77	5.70	5.69	5.70	5.76	5.75	5.63	5.67	5.80
Open fen	5.02	5.37	5.38	5.45	5.41	5.29	5.16	5.35	5.29	5.35

Table 8.
Seasonal summary table of pH at Lightfoot Bay

Date	**Jun 1**	**Jun 17**	**Jun 23**	**Jul 5**	**Jul 21**	**Aug 7**	**Aug 27**	**Sep 12**	**Oct 3**	**Oct 26**
Upland	5.87	5.65	5.85	6.06	6.12	5.90	5.93	6.11	5.93	5.92
Transition	5.26	5.49	5.45	5.59	5.50	5.25	5.50	5.45	5.24	5.43
Open fen	5.04	5.51	5.35	5.57	5.48	5.57	5.57	5.47	5.30	5.47

Table 9.
Seasonal summary table of pH at Bete Grise

Date	**May 28**	**Jun 14**	**Jun 24**	**Jul 6**	**Jul 20**	**Aug 6**	**Aug 26**	**Sep 10**	**Oct 3**	**Oct 27**
Upland	4.86	4.64	4.68	5.07	5.82	5.96	5.94	5.49	4.38	4.49
Dune and swale	5.49	5.53	5.09	5.34	5.52	5.43	5.22	5.37	5.03	4.88

Table 10.
Mean daily temperatures and monthly accumulated precipitation from 1889 to 2009 and for 2010

	Average from 1889 to 2009		2010	
	Precipitation (mm)	Average daily temp °C	Precipitation (mm)	Average daily temp °C
January	80.37	-9.58	12.45	-7.33
February	47.00	-9.36	0.51	-7.28
March	46.96	-4.42	5.84	1.94
April	50.69	3.03	45.97	7.33
May	75.39	9.80	24.13	12.44
June	77.67	15.27	125.73	15.17
July	74.32	18.34	43.43	20.06
August	73.34	17.49	96.27	20.11
September	91.19	13.09	178.56	10.78
October	72.59	7.02	47.75	8.17
November	68.84	-0.48	56.13	0.56
December	75.56	-6.53	12.95	-6.72
SUM precipitation	**833.91**		**649.73**	
Annual mean air temperature °C		**4.47**		**6.27**

Table 11.
Lake Superior levels of 2010 and long-term recorded monthly minimum and maximum levels at Marquette, MI

	meters above sea level			
	2010	**1918-2009**	**MIN**	**MAX**
January	183.24	183.33	182.83	183.7
February	183.17	183.27	182.76	183.63
March	183.10	183.24	182.74	183.61
April	183.09	183.26	182.72	183.68
May	183.09	183.37	182.76	183.74
June	183.14	183.45	182.85	183.76
July	183.20	183.51	182.96	183.82
August	183.22	183.54	183.01	183.86
September	183.24	183.54	183.02	183.86
October	183.20	183.51	183.1	183.91
November	183.15	183.47	183.01	183.89
December	183.10	183.41	182.92	183.81
AVG	**183.16**	**183.41**		

Table 12.
Pooled seasonal average specific conductance with respect to distance from upland at Lightfoot Bay and Pequaming

	well	distance	µS/cm		well	distance	µS/cm
Lightfoot Bay	**1**	270	60.8	**Pequaming**	**1**	470	41.6
	2	200	58.5		**2**	340	64.3
	3	120	61.1		**3**	230	60.1
	4	87	68.7		**4**	150	54.4
	5	50	72.1		**5**	110	60.2
	6	25	105		**6**	66	91.5
	UPLAND	0	95.1		**UPLAND**	0	93.5

Table 13.
Air and groundwater temperatures at Pequaming

	Air temperatures 2009/10 °C	Groundwater temperature °C
Oct	4.28	10.73
Nov	3.66	9.53
Dec	-7.16	7.76
Jan	-7.33	6.79
Feb	-7.28	5.93
Mar	1.94	5.07
Apr	7.33	5.06
May	12.44	5.98
Jun	15.17	7.42
Jul	20.06	9.17
Aug	20.11	10.87
Sep	10.78	11.80

Table 14.
Ground elevation and peat depth survey, Lightfoot Bay

			dist (m)	**elevation**	**subsurface**	
LB8	46.90001	-88.178196	**0**	183.657	183.403	upland
203	46.90011	-88.178269	**12**	183.367	182.884	transition
LB6	46.90024	-88.178206	**25**	183.521	182.860	
205	46.90033	-88.178207	**36**	183.571	182.784	
LB5	46.90046	-88.178222	**50**	183.539	182.841	
207	46.90056	-88.17826	**61**	183.445	181.946	
208	46.90069	-88.178348	**76**	183.499	182.178	
LB4	46.90079	-88.178288	**87**	183.595	182.630	
210	46.9009	-88.178331	**100**	183.423	182.051	open fen
LB3	46.90111	-88.178377	**120**	183.394	181.692	
212	46.90128	-88.178431	**140**	183.324	181.063	
213	46.90152	-88.178477	**170**	183.271	181.595	
LB2	46.9018	-88.178559	**200**	183.277	179.924	
215	46.90197	-88.178614	**220**	183.253	180.154	
217	46.90219	-88.178694	**250**	183.271	181.036	
LB1	46.90241	-88.178811	**270**	183.324	182.003	
219	46.90254	-88.178875	**290**	183.229	182.061	
220	46.90281	-88.179017	**320**	183.226	181.727	
221	46.90302	-88.179206	**340**	183.341	183.036	sand barrier
LAKE	46.90475	-88.182656	**630**	183.158	183.158	Lake Superior

Table 15.
Ground elevation and peat depth survey, Pequaming

			dist (m)	**elevation**	**subsurface**	
PQ8	46.84942	-88.3709	**0**	184.219	183.508	upland
303	46.84965	-88.3715	**57**	183.925	183.442	transition
PQ6	46.84966	-88.3716	**66**	183.880	183.449	
305	46.84985	-88.3716	**72**	183.852	183.141	
PQ5	46.84989	-88.3721	**110**	183.882	182.790	
307	46.84998	-88.3723	**130**	183.907	183.069	
PQ4	46.85012	-88.3725	**150**	183.779	182.839	
309	46.85028	-88.3729	**190**	183.798	182.757	
PQ3	46.8506	-88.3733	**230**	183.751	182.456	open fen with hummocks
311	46.85082	-88.3737	**270**	183.733	182.692	
312	46.85104	-88.3742	**310**	183.723	182.682	
PQ2	46.85119	-88.3744	**340**	183.761	182.593	
314	46.85159	-88.3751	**400**	183.681	182.513	
315	46.85196	-88.3755	**450**	183.850	182.809	
PQ1	46.85209	-88.3756	**470**	183.708	182.717	
317	46.85242	-88.376	**510**	183.676	180.882	open floating mat fen
318	46.8527	-88.3765	**560**	183.654	181.089	
319	46.85308	-88.3772	**630**	183.591	181.229	
321	46.85328	-88.3775	**660**	184.074	180.975	
323	46.85329	-88.3775	**670**	183.750	181.261	
324	46.85349	-88.3778	**700**	183.699	181.235	
325	46.8538	-88.3783	**750**	183.963	181.169	
326	46.85426	-88.3792	**830**	183.673	181.184	
327	46.85474	-88.3802	**930**	183.593	181.104	
328	46.85499	-88.3808	**980**	183.679	181.215	
329	46.85502	-88.3808	**985**	183.767	180.668	
330	46.85537	-88.3818	**1060**	183.613	182.114	
331	46.85567	-88.3826	**1130**	183.610	182.391	transition
333	46.85608	-88.383	**1190**	183.573	182.760	
334	46.85639	-88.3835	**1230**	183.679	182.434	
335	46.85653	-88.3836	**1250**	183.581	182.692	

Table 16.
Ground elevation and peat depth survey, Bete Grise

			dist (m)	**elevation**	subsurface	
BG2	47.360769	-87.968649	**0**	187.252	187.100	upland
405	47.361017	-87.968101	**49**	187.383	186.519	treed fen
407	47.361117	-87.967717	**80**	187.399	186.713	
BG5	47.361436	-87.966789	**160**	185.994	185.283	dune and swale complex
410	47.361576	-87.966667	**170**	186.458	186.433	
411	47.361825	-87.966511	**200**	185.602	184.891	
412	47.361919	-87.966382	**210**	186.352	186.276	
413	47.362053	-87.966189	**230**	185.312	185.007	
414	47.362183	-87.965809	**270**	185.216	184.530	
416	47.362592	-87.9657	**300**	185.114	184.784	
417	47.363153	-87.965719	**350**	184.994	184.308	
BG7	47.363361	-87.96568	**370**	185.054	184.140	
419	47.363692	-87.965639	**400**	185.033	184.779	open fen
420	47.363928	-87.965567	**420**	184.959	184.349	
421	47.364022	-87.965318	**440**	185.371	185.269	dune
BG8	47.364864	-87.965597	**510**	184.753	184.651	swale
423	47.364933	-87.965536	**520**	185.319	185.319	dune
BG9	47.365347	-87.964887	**580**	185.438	185.438	
LAKE	47.365342	-87.964314	**600**	183.6	183.6	

Table 17.
Specific conductance (SE) all season Pequaming open fen

	µS open fen						
Date	**well 1**	**well 2**	**well 3**	**average**	SE	AVG open	SE open
28-May	41.5	56.6	66.7	**54.93**	7.32	55.33	2.18
17-Jun	44.1	68.5	75.7	**62.77**	9.56		
23-Jun	37.2	73.8	72.8	**61.27**	12.04		
5-Jul	40.9	72.3	60.3	**57.83**	9.15		
21-Jul	38.4	67.6	57.6	**54.53**	8.57		
7-Aug	43.9	68.4	58.1	**56.80**	7.10		
27-Aug	44.5	67.7	54.2	**55.47**	6.73		
12-Sep	41.3	58.4	51.3	**50.33**	4.96		
30-Sep	42.9	55.2	52.5	**50.20**	3.73		
26-Oct	41.3	54.5	51.6	**49.13**	4.01		

Table 18.
Specific conductance (SE) all season Pequaming transition zone

	µS transition						
Date	**well 4**	**well 5**	**well 6**	**average**	SE	AVG trans	SE trans
28-May	56.4	47.2	107.8	**70.47**	18.86	68.7	3.27
17-Jun	50.2	60.9	85.1	**65.40**	10.32		
23-Jun	54.7	60.1	96.4	**70.40**	13.09		
5-Jul	48.8	64.4	89.3	**67.50**	11.79		
21-Jul	54	60.7	100.1	**71.60**	14.38		
7-Aug	57.5	69.8	104.1	**77.13**	13.94		
27-Aug	58.1	63.5	91.1	**70.90**	10.22		
12-Sep	56.8	60	76.3	**64.37**	6.04		
30-Sep	56.1	56.3	81.9	**64.77**	8.57		
26-Oct	51.7	58.8	82.9	**64.47**	9.44		

Table 19.
Specific conductance (SE) all season Pequaming upland and lake water

µS upland							**Lake water**		
well 7	**well 8**	**well 9**	**AVG**	SE	AVG UP	SE UP	**µS**	average	SE
69.4		86.4	**77.90**	8.50	93.50	4.83	90.3	91.34	0.679
49.2	89.2	107	**81.83**	17.12			90.4		
79	154.9	106	**113.37**	22.20			87.8		
70.3	132.7	104	**102.27**	18.03			88.8		
72.6	144.8	116	**111.03**	20.97			94		
72.1	138.1	117	**109.07**	19.46			94.5		
72.2	111.6	102	**95.37**	11.89			92.7		
82.3	73.5	85.2	**80.33**	3.52			91.8		
73.1	79.2	86	**79.43**	3.73			92.4		
66.6	74.4	96.5	**79.17**	8.95			90.7		

Table 20.
Specific conductance (SE) all season Lightfoot Bay open fen

	µS open fen						
Date	**well 1**	**well 2**	**well 3**	**average**	SE	AVG open	SE open
1-Jun	41.2	58.1	57.5	**52.27**	5.54	60.15	1.24
17-Jun	58.2	56.9	51.6	**55.57**	2.02		
23-Jun	63.3	56.4	56.9	**58.87**	2.22		
5-Jul	66.2	57	58	**60.40**	2.91		
21-Jul	68.2	61.1	59.5	**62.93**	2.67		
7-Aug	72.4	60.1	61.6	**64.70**	3.87		
27-Aug	69.4	62	60.3	**63.90**	2.79		
12-Sep	60	59.8	58.2	**59.33**	0.57		
3-Oct	50	56.6	72.8	**59.80**	6.77		
26-Oct	59.3	57.4	74.4	**63.70**	5.38		

Table 21.
Specific conductance (SE) all season Lightfoot Bay transition zone

	µS transition						
Date	**well 4**	**well 5**	**well 6**	**average**	SE	AVG trans	SE trans
1-Jun	72.5	77.5		**75.00**	56.75	81.16	4.07
17-Jun	60.4	52.5	120.6	**77.83**	21.50		
23-Jun	66.8	65.6	108	**80.13**	13.94		
5-Jul	63.4	68.9	91.6	**74.63**	8.63		
21-Jul	58.9	63.2	98.8	**73.63**	12.64		
7-Aug	67	76.3	152.9	**98.73**	27.22		
27-Aug	67.7	72.5	106.5	**82.23**	12.21		
12-Sep	70.3	80	89.4	**79.90**	5.51		
3-Oct	90.2	91.2	107.8	**96.40**	5.71		
26-Oct	69.4	73.6	70	**71.00**	1.31		

Table 22.
Specific conductance (SE) all season Lightfoot Bay upland

	µS upland						
Date	**well 7**	**well 8**	**well 9**	**average**	SE	AVG upland	SE upland
1-Jun	156.6	111.5	116	**128.07**	14.33	95.13	4.95
17-Jun	61.9	62.4	96.6	**73.63**	11.48		
23-Jun	73.7	69.1	107	**83.37**	12.04		
5-Jul	93.1	71.8	96.5	**87.13**	7.73		
21-Jul	120.7	82.9	113	**105.60**	11.55		
7-Aug	173.4	79.6	116	**123.13**	27.29		
27-Aug	106	73.8	109	**96.37**	11.32		
12-Sep	85.1	70.5	98.8	**84.80**	8.17		
3-Oct	90.1	65.5	109	**88.17**	12.57		
26-Oct	59.3	69.5	114	**81.07**	16.92		

Table 23.
Specific conductance (SE) all season Bete Grise upland

	µS upland						
Date	**well 1**	**well 2**	**well 3**	**average**	SE	AVG upland	SE upland
28-May	42.3	34.2	38	**38.17**	2.34	59.94	4.04
14-Jun	31.5	33.6	38.5	**34.53**	2.074		
24-Jun	48	55	58.8	**53.93**	3.163		
6-Jul	53.5	44.4	81.6	**59.83**	11.196		
20-Jul	42.6	44	97.6	**61.40**	18.105		
6-Aug	82.8	58.6	111.9	**84.43**	15.408		
26-Aug	74.9	67.3	110.9	**84.37**	13.447		
10-Sep	62.9	58	82.5	**67.80**	7.485		
3-Oct	58.8	77.1	65.4	**67.10**	5.351		
27-Oct	40.8	36.5	66.2	**47.83**	9.267		

Table 24.
Specific conductance (SE) all season Bete Grise dune and swale complex

	µS dune and swale									
Date	**well 4**	**well 5**	**well 6**	**well 7**	**well 8**	**well 9**	**AVG**	SE	AVG d & s	SE d & s
28-May	47.5		72	150.5		50	**80.00**	24.14	76.95	5.87
14-Jun	59.1	61.1	76.2	145.3	40.6	44.5	**71.13**	15.72		
24-Jun	52.7	56	88.2	149.2	33.7	52.5	**72.05**	17.03		
6-Jul	52.7	51.8	108.1	179.3	31.6	51.5	**79.17**	22.61		
20-Jul	60.6	47	126	157.3	40.3	44.6	**79.30**	20.32		
6-Aug	54.3	39.8	142.1	182.2	40.8	41.2	**83.40**	25.53		
26-Aug	50.1	46.6	125.8	139.7	43	49.9	**75.85**	18.11		
10-Sep	52.4	75.3	141.6		33.1	51.5	**70.78**	18.93		
3-Oct	50.2	118.3	95.1	148.1	30.9	40.3	**80.48**	19.33		
27-Oct	67.6	86.9	85.6	156	22.8	44.9	**77.30**	18.68		

Table 25.
Vegetation survey Bete Grise upland

BG upland 1x1m		Cover class			
Species name	**Latin name**	NE	SE	SW	NW
Tawny Cotton-grass	*Eriophorum virginicum*	5			
Tussock Cotton-grass	*Eriophorum vaginatum*				25
Tag alder	*Alnus incana*	20			
Labrador tea	*Ledum groenlandicum*	5		7	50
Small cranberry	*Vaccinium oxycoccus*	95			
Bog-laurel	*Kalmia polifolia*	30			
Bryophytes		100	5	50	90
Canadian rush	*Juncus canadensis*	5			
Three-leaf Solomon's-seal	*Maianthemum trifolium*	20			
Cinnamon fern	*Osmunda cinnamomea*	10			
Bluejoint	*Calamagrostis canadensis*	<5			
Boreal bog sedge	*Carex magellanica*	7		3	
Bunch berry	*Cornus canadensis*		1	3	
Canada mayflower	*Maianthemum canadense*		2	3	
Bracken fern	*Pteridium aquilinum*		20		
Common lake sedge	*Carex lacustris*				15
Softleaf sedge	*Carex disperma*				2
Oval leaved bilberry	*Vaccinium ovalifolium*		40	25	10
Starflower	*Borealis trientalis*		1		
Red maple	*Acer rubrum*		1		
Balsam fir	*Abies balsamea*		1	1	
Leatherleaf	*Chamaedaphne calyculata*				50
Mountain Ash	*Sorbus americana*		1		
Forest floor		60		85	
Three-leaf goldthread	*Coptis trifolia*			1	
Creeping snowberry	*Gaultheria hispidula*			5	
Lowbush blueberry	*Vaccinium angustifolium*			10	10
Northern Whitecedar	*Thuja occidentalis*			20	
3X3 m		NE	SE	SW	NW
Labrador tea	*Ledum groenlandicum*	75	3	15	25
Mountain Holly	*Nemopanthus mucronata*	<5			
Lowbush blueberry	*Vaccinium angustifolium*	5			
Tag alder	*Alnus incana*	<5			
Northern white cedar	*Thuja occidentalis*	<5	20	40	
Black spruce	*Picea mariana*	<5			30

Table 25 (continued)

BG upland 1x1m		Cover class			
Species name	**Latin name**	NE	SE	SW	NW
Balsam fir	*Abies balsamea*		15	5	
Common bilberry	*Vaccinium myrtillus*		1		
Serviceberry	*Amelanchier*		1		
Eastern Leatherwood	*Dirca palustris*			25	
Paper birch	*Betula papyrifera*				5

Table 26.
Vegetation survey, Bete Grise upland tree data

Trees BG Upland		NE			SE			SW			NW			
Species name	Latin name	#	DBH	H	#	DBH	H	#	DBH	H	#	DBH	H	**st per ha**
Paper birch	*Betula papy-rifera*	3	<5	1.5	21	10	12	36	9	9	17	5	4	**770**
				1		8	6		<5	3		5	6	
				1		10	15		11	14		<5	3	
						12	14		34	17			3	
						10	9		10	9			2	
						10	12		7	8				
						<5	5		8	9				
						6	6		<5	3				
Balsam fir	*Abies balsamea*	15	5	2	94	18	12	56	19	17	15	5	3	**1800**
			<5	1.5		<5	6		7	5		<5	2	
			<5	1.3		<5	4		5	5		5	2.5	
			<5	1		7	5		<5	3		5	5	
						<5	2		12	11		6	5	
							2		<5	2				
Eastern white pine	*Pinus strobus*	5	<5	1				1	35	17	3	11	6	**90**
				1								<5	3	
				1								5	7	
Black spruce	*Picea mariana*	15	<5	1	13	9	9	9	18	15	25	<5	2	**620**
			6	1.5		6	5		15	16		7	4	
			9	6		12	16		10	9		12	9	
			<5	2					14	13		5	3	
			11	8								5	4	
Northern white cedar	*Thuja occidentalis*	5	11	8	12	27	13	18	24	14	18	<5	2	**530**
			<5	2		24	14		14	13			2	
			<5	2		14	7		16	8		13	8	
			<5	2		23	14		5	5		24	17	
			<5	2		34	15		29	16		<5	2	
Tamarack	*Larix laricina*	5	12	5							3	9	10	**80**
			6	4								7	6	
			10	6								<5	4	
			<5	2										
				3.5										

Table 27.
Vegetation survey Bete Grise swale

Bete Grise dune and swale BG6 1x1 m		Cover class			
Species name	Latin name	NE	SE	SW	NW
Threeseeded sedge	*Carex trisperma*	50			
Rattlesnake-mannagrass	*Glyceria canadensis*	1			
Labrador tea	*Ledum groenlandicum*	45	5	75	15
Clubmoss	*Lycopodium spp*	5			
Creeping snowberry	*Gaultheria hispidula*	5			
Bryophytes		85	80	95	95
Velvet leaved bilberry	*Vaccinium myrtillus*	5	5	3	
Balsam fir	*Abies balsamea*	7			
Bluejoint	*Calamagrostis canadensis*	3		1	2
Northern Blue Flag	*Iris versacolor*		35		
Three-leaf Solomon's-seal	*Maianthemum trifolium*		1		
Bracken fern	*Pteridium aquilinum*			50	
Mountain ash	*Sorbus americana*			1	
Bunchberry dogwood	*Cornus canadensis*			7	
Softleaf sedge	*Carex disperma*			5	
Serviceberry	*Amelanchier ssp*			1	
Cinnamon fern	*Osmunda cinnamomea*	15			20
Starflower	*Trientalis borealis*				5
Three-leaf goldthread	*Coptis trifolia*				7
Hairy sedge	*Carex lacustris*	3			
Dwarf birch	*Betula nana*				1
Labrador tea	*Ledum groenlandicum*	25	10	15	50
Black spruce	*Picea mariana*	25		3	
Tag alder	*Alnus incana*	10	25	7	50
Mountain Holly	*Nemopanthus mucronata*		7	10	
Paper birch	*Betula papyrifera*		2	7	
Velvet leaved bilberry	*Vaccinium myrtillus*			5	15
Tamarack	*Larix laricina*	< 1			

Table 28.
Vegetation survey Bete Grise swale tree data

Trees BG6 dune & swale		NE			SE			SW			NW			**st per ha**
Common name	Latin name	#	DBH	H	#	DBH	H	#	DBH	H	#	DBH	H	
Black spruce	*Picea mariana*	3	7 15 20	5 9 18	5	5 6 6	4 4 5	42	14 9 16 11 6	16 6 16 9 7	10	14 8	11 7	**600**
Tama-rack	*Larix laricina*	3	21 15 18	16 14 15	14	7 5 9 8 5	5 3 8 7 5	30	< 5 8 < 5 10 7 5	3 7 2 9 8 5	6	11 16 14 16 17	9 14 8 11 13	**530**
Tag alder	*Alnus incana*	72	< 5	2 3 2 4 2	87	< 5	2 2 1.5 2 2.5	27	< 5	2 2 3 2 2	42	< 5	3 2 2 2 3	**2280**
Balsam fir	*Abies balsamea*	11	5 < 5 12 7	2 2 6 5	6	< 5 6	1.5 1.5 3 1.5 4	9	< 5	2 2 2 3 4	11	< 5	2 2 3 2 3	**370**
Paper birch	*Betula papyrifera*	9	< 5	3 2 3 3 4	10	<5	2 2 2 3 4	9	< 5	2 2 2 4 3	11	< 5	2 2 3 2 3	**390**

Table 28 (continued)

Trees BG6 dune & swale		NE			SE			SW			NW			**st per ha**
Common name	Latin name	#	DBH	H	#	DBH	H	#	DBH	H	#	DBH	H	
Mountain Holly	*Nemopanthus mucronata*							6	< 5	2	11	< 5	2	

Table 29.
Vegetation survey Bete Grise dune

Bete Grise dune and swale well 8 1x1 m		Cover class			
Species name	Latin name	NE	SE	SW	NW
Mayflower	*Epigaea repens*	20			25
Lowbush blueberry	*Vaccinium angustifolium*	25			15
Velvet leaved bilberry	*Vaccinium myrtillus*	60			25
Bryophytes		50	50	10	55
Labrador tea	*Ledum groenlandicum*	35			35
Bracken fern	*Pteridium aquilinium*	25			40
Bunchberry dogwood	*Cornus canadensis*			1	5
Willow	*Salix spp*			25	
Leatherleaf	*Chamaedaphne calyculata*		25	25	
Few-seeded sedge	*Carex oligosperma*		75	60	
Blue joint	*Calamagrostis canadensis*			20	
Bog-laurel	*Kalmia polifolia*		2	5	
Bog-rosemary	*Andromeda polifolia*		7		
Small cranberry	*Vaccinium oxycoccus*		5		
Bog birch	*Betula pumila*		< 1		
3X3 m		NE	SE	SW	NW
Labrador tea	*Ledum groenlandicum*	25			30
Black spruce	*Picea mariana*	3	1	1	
Leatherleaf	*Chamaedaphne calyculata*	4	5	16	
Mountain Holly	*Nemopanthus mucronata*				10
Willow	*Salix spp*		40	20	

Table 30.
Vegetation survey Bete Grise dune tree data

Trees BG8 Dune & swale		NE			SE			SW			NW			**st per ha**
Common name	Latin name	#	DBH	H	#	DBH	H	#	DBH	H	#	DBH	H	
Tamarack	*Larix laricina*	2	<5	1.5 2	6	< 5 6 < 5	2 9 3	15	6 5 11 8	5 6 10 8	1	7	4	**240**
Black spruce	*Picea mariana*	18	<5 13 10 13 12	1.5 8 6 9 10	20	< 5 12 7 14 < 5	3 11 13 10 15	7	7 9 < 5	5 9 3	10	12 9	10 7	**550**
Willow	*Salix spp*	2	<5	5				1	< 5	2				**30**
Paper birch	*Betula papyri-fera*	1	10	9	1	< 5	6	1	9	9	1	< 5	3	**40**
White pine	*Pinus strobus*	1	28	16	6	< 5 6 < 5 < 5	1.5 2 4 1.5	1	6	4	3	29 22 30	12 10 11	**110**
Red maple	*Acer rubrum*	2	<5 <5	3 2										**20**
Mountain Holly	*Nemo-panthus mucronata*	8	<5	2 2 1.5	3	< 5	2 1.5	9	< 5	2				**110**

Table 30 (continued)

Trees BG8 Dune & swale		NE			SE			SW			NW			**st per ha**
Common name	Latin name	#	DBH	H	#	DBH	H	#	DBH	H	#	DBH	H	
Dwarf Birch	*Betula nana*				3	< 5	3 2							**30**
Serviceberry	*Amelanchier spp*				1	< 5	2	1	< 5	2				**20**

Table 31.
Vegetation survey Pequaming open fen

Pequaming PQ2 open fen 1x1 m		Cover class			
Common name	Latin name	NE	SE	SW	NW
Surface water		25	30	1-5	20
Bryophytes		60	60	65	
Bog-rosemary	*Andromeda polifolia*	25	5-10	10-15	10-15
Leatherleaf	*Chamaedaphne calyculata*	5-10	1-5	5-10	
Cranberry	*Vaccinium oxycoccus*	1-5	1-5	1-5	
Bog Golden rod	*Solidago uliginosa*	5-10	1-5	10-15	1-5
Pitcher plant	*Sarracenia purpurea*	1-5	1-5	15-20	
Violet	*Viola spp.*	10-15			
Willow herb	*Epilobium palustre*	<1			
Marsh timothy	*Muhlenbergia glomerata*	<1			
Horsetail	*Equisetum spp*	<1		1-5	30
Wiresedge	*Carex lasiocarpa*	75	40	65	60
Spikerush	*Eleocharis spp*	1-5			
Bulrush	*Scripus spp*	1-5	1-5	1-5	
Royal fern	*Osmunda regalis*		10-15	10-15	
Tamarack	*Larix laricina*		15		
Red maple	*Acer rubrum*			<1	
Chokeberry	*Aronia melanocarpa*			1-5	
Northern white cedar	*Thuja occidentalis*			40	
Mountain Holly	*Nemopanthis mucronata*				15
Bog bean	*Menyanthes trifoliata*				<1
Bog birch	*Betula pumila*				<1
3X3 m		NE	SE	SW	NW
Tamarack	*Larix laricina*	1-5	1-5	<1	1-5
Northern white cedar	*Thuja occidentalis*	10-15	5-10	1-5	5-10
Sweetgale	*Myrica gale*	25		10-15	
Black spruce	*Picea mariana*	1-5			
Black Chokeberry	*Aronia melanocarpa*				<1
Willow	*Salix spp*				<1

Table 32.
Vegetation survey Pequaming open fen tree data

Trees PQ2 Open fen		NE			SE			SW			NW			
Common name	Latin name	#	DBH	H	#	DBH	H	#	DBH	H	#	DBH	H	**st per ha**
Northern white cedar	*Thuja occidentalis*	1	<5	1.5	1	<5	2	1	<5	1.5	1	<5	1.5	**40**
Tamarack	*Larix laricina*	1	<5	1.5	2	<5	1.5	2	<5	1.5	1	<5	1.5	**60**
							2			1.5				
Paper birch	*Betula papyrifera*	1	<5	1.5										**10**

Table 33.
Vegetation survey Pequaming transition zone

Pequaming PQ5 transition 1x1 m		Cover class			
Common name	Latin name	NE	SE	SW	NW
Hairy sedge	*Carex lacustris*			5	1-5
Bristlystalked sedge	*Carex leptalea*			20	1-5
Horsetail	*Equisetum spp*	5-10	30	40-50	40
Labrador tea	*Ledum groenlandicum*	10	15-20	15-20	1-5
Three-leaf Solomon's-seal	*Maianthemum trifolium*	1			
Few seeded sedge	*Carex trisperma*	5-10	1	1-5	
Bryophytes		85	90	100	80
Royal fern	*Osmunda regalis*	25-30			25
Starflower	*Trientalis borealis*	<1	1-5	<1	
Northern white cedar	*Thuja occidentalis*	1	1-5		10-15
White turtlehead	*Chleone glabra*	1-5		<1	
Small cranberry	*Vaccinium oxycoccus*	<1		5-10	<1
Michaux's sedge	*Carex michaux*	1-5			
Liverleaf wintergreen	*Pyrola asarifolia*	<1	10-15		5-10
Tag alder	*Alnus incana*		1	5-10	
Bluejoint	*Calamagrostis canadensis*		1	1-5	30
Sedge (orange roots)	*Carex limosa*			1-5	
Canada mayflower	*Maianthemum canadense*				1-5
3X3 m		NE	SE	SW	NW
Tag alder	*Alnus incana*	5-15	1-5	15	1-5
Northern white cedar	*Thuja occidentalis*	5-10	1-5	25-30	5-10
Labrador tea	*Ledum groenlandicum*	1-5	5-10	1-5	1-5
Mountain Holly	*Ilex mucronata*		1-5	<1	
Leatherleaf	*Chamaedaphne calyculata*			1-5	
Tamarack	*Larix laricina*			<1	

Table 34.
Vegetation survey Pequaming transition zone tree data

Trees PQ5 transition		NE			SE			SW			NW			**st per ha**
Common name	Latin name	#	DBH	H	#	DBH	H	#	DBH	H	#	DBH	H	
Tag alder	*Alnus incana*	57	5	7	20	<5	2	67	<5	2	40	<5	2	**1840**
			<5	4			3			2			2	
			<5	4		5	5			1.5			1.5	
			<5	2			2			2			2	
			<5	3			3			3			1.5	
Northern white cedar	*Thuja occidentalis*	61	<5	3	67	<5	1.5	76	6	4	94	9	5	**2980**
			7	5		29	12		8	4		12	8	
			17	11		<5	3		10	5		8	7	
			17	12		6	5		<5	1.5		<5	1.5	
			31	13					12	5		7	6	
Winter-berry	*Ilex verticillata*	41	<5	2.5	11	<5	3	3	<5	1.5	14	<5	2	**690**
				1.5									1.5	
				3									1.5	
				1.5									1.5	
				2									2.5	
Balsam fir	*Abies balsamea*	26	<5	1.5	39	<5	3							**650**
			2.5	4		6	7							
			4	4		<5	1.5							
			<5	1.5			2							
			<5	2		13	10							
Mountain holly	*Nemopanthus mucronata*	1	<5	1.5	1	<5	4				1	<5	1.5	**30**
Ash	*Fraxinus spp*	6	<5	1.5										**60**
				1.5										
				3										
			5	5										
			<5	4										
Paper birch	*Betula papyrifera*				1	<5	5							**10**
Black spruce	*Picea mariana*	1	6	6	3	<5	3							**40**
						6	7							
						10	12							

Table 35.
Vegetation survey Pequaming upland

Pequaming upland 1x1 m		Cover class			
Common name	Latin name	NE	SE	SW	NW
labrador tea	*Ledum groenlandicum*	7	1-5		1-5
Creeping snowberry	*Gaultheria hispidula*	5	<1	1-5	
Cinnamon fern	*Osmunda cinnamomea*			30	
Lowbush blueberry	*Vaccinium angustifolium*			1-5	
Starflower	*Trientalis borealis*	1-5	1-5		
Mayflower	*Epigaea repens*	1-5	5-10		
Bryophytes		85	25	10-15	35
Twinflower	*Linnaea borealis*	1-5			
Horsetail	*Equisetum ssp*	1			1-5
Fowl manna grass	*Glyceria striata*	1-5		25	1-5
Northern white cedar	*Thuja occidentalis*	20	10-15	1-5	40
Red maple	*Acer rubrum*	< 1			
Clubmoss	*Lycopodium spp*	< 1	< 1	1-5	
Three-seeded sedge	*Carex trisperma*	30	1-5	5-10	5-10
Balsam fir	*Abies balsamea*	5-10	1-5	1-5	
Marsh marygold	*Caltha palustris*				<1
White turtlehead	*Chleone glabra*				<1
Royal fern	*Osmunda regalis*				10-15
Three-leaf goldthread	*Coptis trifolia*		<1	<1	
Wintergreen	*Gaultheria*		1-5		
Michaux's sedge	*Carex michauxiana*			5-10	
3x3 m		NE	SE	SW	NW
Mountain Holly	*Nemopanthis mucronata*	5			<1
Northern white cedar	*Thuja occidentalis*	5-25	25		75
Balsam fir	*Abies balsamea*	50		50	5-10
Green Ash	*Fraxinus Pennsylvanica*	<1			
Tag alder	*Alnus incana*	1-5			1-5
Mountain Holly	*Ilex mucronata*	5-10		1	<5
Red maple	*Acer rubrum*				<1
Labrador tea	*Ledum groenlandicum*		1-5	1	<1

Table 36.
Vegetation survey Pequaming upland tree data

Trees PQ Upland		NE			SE			SW			NW			
Common name	Latin name	#	DBH	H	#	DBH	H	#	DBH	H	#	DBH	H	**st per ha**
Northern white cedar	*Thuja occidentalis*	55	6 7 12 7 6 8 10 7	4 4 6 5 5 4 6 5	76	6 11 11 6 7	4 4 6 3 5	97	11 <5 8 22	8 2 6 13	67	21 9 13 <5 14	12 6 11 2 9	**2950**
Tag alder	*Alnus incana*	28	<5	2 3 1.5 2 3	19	<5	2 2 2 3 2	34	<5	5 6 6 5 7	50	<5 <5 <5 7 <5	5 3 2 8 4	**1310**
Black spruce	*Picea mariana*	5	8 9 11 11 14	14 9 10 11 15	3	12 7 8	15 6 10	1	23	14				**90**
Mountain Holly	*Ilex mucronata*	22	<5	2 2 2 1.5 2	30	<5	2 2 2 2 2	19	<5	2 1.5 2 1.5 3	41	<5	2 3 2 2 2	**1120**
Tamarack	*Larix laricina*	6	6 6 17 9 21 12	7 6 10 8 10 7	13	8 8 7 14 7	9 8 7 10 7							**190**

Table 36 (continued)

Trees PQ Upland		NE			SE			SW			NW			
Common name	Latin name	#	DBH	H	#	DBH	H	#	DBH	H	#	DBH	H	**st per ha**
Balsam fir	*Abies balsamea*							34	<5	4 3 1.5 2 3	18	<5	3 3 2 3 2	**520**
Ash	*Fraxinus spp*										4	<5	1.5 3 5 6	**40**
Paper birch	*Betula papyrifera*										2	18 15	12 10	**20**

Table 37.
Vegetation survey Lightfoot Bay open fen

Lightfoot Bay LB2 open fen 1x1 m		Cover class			
Common name	Latin name	NE	SE	SW	NW
Bog-rosemary	*Andromeda polifolia*	1	2		1
Narrow-panicle rush	*Juncus brevicaudatus*	60	25	35	40
Bryophytes		35	25	20	45
Violet	*Viola spp*	2	2		
Small cranberry	*Vaccinium oxycoccus*	2	5	4	1
Horsetail	*Equisetum ssp*	1	1		3
Spiked muhly	*Muhlenbergia glomerata*	5	15		4
Sweet Gale	*Myrica gale*	15	4		6
American Winterberry	*Ilex verticillata*	1			
Black Chokeberry	*Aronia melanocarpa*	1			5
Bog golden rod	*Solidago uliginosa*	1	2	4	5
Pitcher plant	*Sarracenia purpurea*	2	25	10	10
Bog bean	*Menyanthes trifoliata*		1	3	
Royal fern	*Osmunda regalis*				
Clubmoss	*Lycopodium spp*		1		
Red maple	*Acer rubrum*		1		
Ash	*Fraxinus ssp*			1	
Northern white cedar	*Thuja occidentalis*				15
Softleaf sedge	*Carex disperma*				3
3X3 m		NE	SE	SW	NW
Northern white cedar saplings	220 / ha				

Table 38.
Vegetation survey Lightfoot Bay transition zone

Lightfoot Bay LB5 transition 1x1m		Cover class			
Common name	Latin name	NE	SE	SW	NW
Sweet Gale	*Myrica gale*	15	3	10	5
Tag alder	*Alnus incana*	7			
Leatherleaf	*Chamaedaphne calyculata*	15	10	25	
Bog-rosemary	*Andromeda polifolia*	7	3	25	
Bryophytes		100	5	50	
Starflower	*Trientalis borealis*	3			2
Dwarf raspberry	*Rubus pubescens*	15	5	2	10
Swamp rose	*Rosa palustris*	7		25	
Bog bean	*Menyanthes trifoliata*	10		1	
Pitcher plant	*Sarracenia purpurea*	5			
Slender sedge	*Carex lasiocarpa*	15	5	40	15
Horsetail	*Equisetum ssp*	10	<1	2	5
Spikerush	*Eleocharis ssp*	5			
Small cranberry	*Vaccinium oxycoccus*	3	4	15	10
Black chokeberry	*Aronia melanocarpa*	1			1
Bluejoint	*Calamagrostis canadensis*	3			
Willow	*Salix spp*	1	<1		
Royal fern	*Osmunda regalis*	10	75		40
Labrador tea	*Ledum groenlandicum*		2		7
Sedge	*Carex ssp*		15		
Northern bugleweed	*Lycopus uniflorus*			8	
Red maple	*Acer rubrum*			1	4
Bog-laurel	*Kalmia polifolia*				1
3X3 m		NE	SE	SW	NW
Sweet Gale	*Myrica gale*	90	80	95	30
Tag alder	*Alnus incana*	10	2	5	7
American Winterberry	*Ilex verticillata*	50	15		30
Mountain Holly	*Nemopanthus mucronata*	10	15	15	
Black Chokeberry	*Aronia melanocarpa*	1	<5	5	
Leatherleaf	*Chamaedaphne calyculata*		5-10	20	25
Bog-rosemary	*Andromeda polifolia*		1		5
Red maple	*Acer rubrum*			1	
Labrador tea	*Ledum groenlandicum*			1	<5
Willow	*Salix spp*			1	
Serviceberry	*Amelanchier sp*				<1

Table 39.
Vegetation survey Lightfoot Bay transition zone tree data

Trees LB5 transition		NE			SE			SW			NW			**st per ha**
Common name	Latin name	#	DBH	H	#	DBH	H	#	DBH	H	#	DBH	H	
Black spruce	*Picea mariana*	4	5	3	3	7	4.5	1	<5	2	7	<5	2	**150**
			5	2		<5	1.5						1.5	
			<5	1.5									3	
			<5	1.5									2	
												5	4	
Tamarack	*Larix laricina*	28	6	4	30	<5	2	24	<5	2.5	29	7	4	**1110**
			4	4		<5	2		6	3.5		<5	2.5	
			7	4		6	2.5		5.5	3		6	4	
			6	4		7	5		<5	2		6	3	
			<5	2		<5	3		5	3		7	5	
Northern white cedar	*Thuja occidentalis*	17	15	5	9	6	3	4	6	3	18	7	4	**480**
			8	4		11	6		6	4		<5	3	
			11	5		11	5		10	5		7	4	
			8	4		7	5		9	5		6	3	
						8	4							
Tag alder	*Alnus incana*	5	<5	2							1	<5	2	**60**
Red maple	*Acer rubrum*	3	<5	4	4	<5	2	1	<5	4	7	<5	2	**150**
				2			3						1.5	
				2			2						5.5	
						5	5						2	
						<5	2							
White pine	*Pinus strobus*	1	<5	2	1	8.5	6	1	11	6.5				**30**
Red osier dogwood	*Cornus sericea*	3	<5	2							2	<5	2	**50**

Table 39 (continued)

Trees LB5 transition		NE			SE			SW			NW			st per ha
Common name	Latin name	#	DBH	H	#	DBH	H	#	DBH	H	#	DBH	H	
Serviceberry	*Amelanchier spp*	1	<5	1.5										**10**
Black chokeberry	*Aronia melanocarpa*										1	<5	1.5	**10**
Mountain Holly	*Nemopanthis mucronata*										1	<5	1.5	**10**
Sweet gale	*Myrica gale*										1	<5	1.5	**10**
American winterberry	*Ilex verticillata*										2	<5	2	**20**

Table 40.
Vegetation survey Lightfoot Bay upland

LB upland 1x1m		Cover class			
Common name	Latin name	NE	SE	SW	NW
Bryophytes		100	25	20	60
Royal fern	Osmunda regalis	25			30
Black spruce	Picea mariana	5-10			
Red maple	Acer rubrum	5	30	10	2
Brownish sedge	Carex brunnescens	15			15
Starflower	Trientalis borealis	5			5
Three-leaf goldthread	Coptis trifolia	2	6		
Bunchberry dogwood	Cornus canadensis	7	10		
Yellow birch	Betula alleghaniensis	7	2	5	
Blue bead lily	Clintonia borealis	1	2	5	
Trailing arbutus	Epigaea repens		1		
Wood sorrel	Oxalis spp		<1		
Creeping snowberry	Gaultheria hispidula		<1		
Eastern Hemlock	Tsuga canadensis	1	<1	3	
Clubmoss	Lycopodium spp			3	
American Winterberry	Ilex verticillata		4	5	5
Canada Mayflower	Maianthemum canadense		4	5	
3X3 m		NE	SE	SW	NW
Black spruce	Picea mariana	7			5
Yellow birch	Betula alleghaniensis	10	5	5	5
American Winterberry	Ilex verticillata	3			30
Common bilberry	Vaccinium myrtillus			5	
Eastern Hemlock	Tsuga canadensis	15			

Table 41.
Vegetation survey Lightfoot Bay upland tree data

Trees LB upland		NE			SE			SW			NW			**st per ha**
Common name	Latin name	#	DBH	H	#	DBH	H	#	DBH	H	#	DBH	H	
Northern white cedar	*Thuja occidentalis*	26	29	12	7	16	8	21	13	9	39	16	11	**930**
			32	13		43	14		7	4		12	11	
			24	10		17	11		33	13		27	12	
			16	8					38	14		10	8	
									8	9		5	4	
												9	8	
Black spruce	*Picea mariana*	1	32	16							1	33	13	**20**
Eastern hemlock	*Tsuga canadensis*	1	32	15	4	19	13							**50**
						30	16							
						6	4							
						11	9							
Yellow birch	*Betula alleghaniensis*	1	27	14	3	38	16	2	25	13				**60**
						23	14		33	14				
						9	10							
Balsam fir	*Abies balsamea*				1	18	14	2	17	12	2	10	13	**50**
									24	14		16	15	
Red maple	*Acer rubrum*				3	18	13	1	30	14				**40**
						27	20							
						24	16							