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Landscape Controls of Hydrologic Function and Phosphorus Dynamics in two Pond-Wetland Complexes on the Mixedwood Boreal Plain

by

Jenny-Marie Ferone

A thesis submitted to the Faculty of Graduate Studies and Research in partial fulfilment
of the requirements for the degree of Master of Science

in

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The undersigned certify that they have read, and recommend to the Faculty of Graduate Studies and Research for acceptance, a thesis entitled **Landscape Controls of Hydrologic Function and Phosphorous Dynamics in Two Pond-Wetland Complexes on the Mixedwood Boreal Plain** submitted by **Jenny-Marie Ferone** in partial fulfilment of the requirements for the degree of **Master of Science** in Environmental Biology and Ecology.

Dr. K. J. Devito

Dr. S. Bayley

Dr. B. Rostron

Date April 26/2001

Abstract

The dominant hydrologic and phosphorus (P) fluxes were measured in two pond-peatland complexes in the Boreal Plain of Northern Alberta: one moraine pond-peatland (topographic high) and one clay plain pond-peatland (topographic low). During 1999-2000, both locations were groundwater recharge zones to underlying flow systems. At both pond-peatlands, hydrometric, geochemical and isotopic measurements determined that precipitation and evaporation dominated the water balance, and local groundwater fluxes were seasonally variable. The periphery of the moraine pond exhibited local groundwater flow reversals: recharge during dry periods, discharge during wet periods. The clay plain complex was a groundwater flow-through system for most of the study, but reversed to discharge during high rainfall (spring 2000). Although [P] were high in surface and groundwater of both complexes ([TDP] = 30-3000 μgl^{-1}), concentrations were consistently greater at the clay plain. Groundwater [P] was most strongly correlated to low DO, mid-range pH, and high water table. Shallow groundwater accounted for ~50 % of TDP and SRP loading to ponds, and groundwater flow reversals influenced pond [P]. Therefore, shallow groundwater is a small flux in the water balance, but an important control on surface water chemistry. Complex groundwater-phosphorus interactions may have important implications for forest disturbance in the Boreal Plains.

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Chapter 1: Introduction

1.1 Project Rationale

The role of riparian wetlands in nutrient transport and transformation has generated interest in recent years, due to increasing concern over degrading surface water quality (Brinson 1993, Bedford 1999). Riparian zones have generally been recognised as important "control points" where biogeochemical transformations can influence the extent to which upland processes translate to changes in the chemistry of surface water (Hill 1996, Hedin et al. 1998). Over the last three decades, growing landscape disturbance in North America has prompted the evaluation of hydrologic interfaces, such as riparian wetlands, as buffers to protect aquatic systems from increases in water and nutrient loading (Devito et al. 2000, Prepas et al. 2000). However, the effectiveness of riparian wetlands in regulating water and nutrient transport has been shown to vary in different landscapes (Emmett et al. 1994, Lockaby et al.1999, Devito et al. 2000). Studies have shown that wetlands can have variable biogeochemical functions: nutrient sinks (Serrano et al. 1999), nutrient transformers (Brinson 1993, Devito and Hill 1997), and often nutrient sources to adjacent aquatic systems (Knighton and Stiegler 1981, Raisin et al. 1999). Without an understanding of the dominant controls on water and nutrient exchange between aquatic systems and their riparian areas, the impact of watershed disturbance is difficult to predict.

Large-scale disturbance has the potential to impact wetlands by altering their hydrologic regime (Bedford 1999), however, depending on the dominant flowpaths, wetlands in different landscape settings may experience a wide range of susceptibility to disturbance. Hydrogeologic setting has been shown to be a key control on the hydrologic and biogeochemical function of aquatic systems (LaBaugh et al. 1998, Winter 1999, Hill and Devito 1997, Kratz et al. 1997, Devito et al. 2000). Landscape or hydrogeologic position can determine the relative importance of a wetland's connection to uplands, underlying aquifers, and the atmosphere (Winter and Woo 1990). The dominant flowpaths to and from the wetland will control the temporal variability and magnitude of flow, and therefore residence time and wetland permanence (Roulet 1990, Price 1993). For wetlands in landscapes without integrated surface drainage, connections to groundwater flow systems may become increasingly important (Winter 1989, Winter and Rosenberry 1995), and in some cases, these groundwater connections are related to topographic position (Tóth 1963, Winter 1999). Whether groundwater flowpaths are of predominantly local or regional origin may influence the chemical signature and concentration of solutes imported into the system (Winter 1989, Hayashi et al. 1998). Therefore, in order to predict and extrapolate the response of an individual wetland to a greater area, it is necessary to determine how hydrologic function corresponds to connectivity and position within the landscape. Thus, chapter two of this thesis investigates the dominant, pre-disturbance hydrologic controls on wetland complexes on the Western Boreal Plain of Alberta, and examines how these controls vary with landscape position.

Seasonal and annual patterns of groundwater movement can have implications for the biogeochemical function of wetland systems (Waddington and Roulet 1997, Devito and Hill 1997). Several studies in the prairies have noted that although shallow groundwater seepage represents a small portion of the total inputs to lakes and sloughs, it has an important influence on the surface chemistry of these systems (LaBaugh et al. 1997, Hayashi et al. 1998). Within peatlands, the amplitude and frequency of water table fluctuations may induce large variation in moisture, redox conditions, temperature and pH, resulting in variable solute concentrations within the peat column (Shotyk 1986).

Variable phosphorus (P) dynamics in wetland sediments has often been linked to the redox controls on P solubility (Bayley et al. 1985, Serrano et al.1999, Ann et al. 2000). For example, large water table drawdown resulting in aeration of peat, influences the concentrations of P in surface water (Bayley et al. 1985, Devito and Dillon 1993, Prevost et al. 1999). Under reduced peat conditions and mid range pH. P solubility is enhanced (Ann et al. 2000). and therefore dominant hydrologic flowpaths can strongly influence P retention versus export within a catchment (Raisin et al. 1999). As wetlands and ponds of the Boreal Plains tend to be shallow and phosphorus rich (Vitt et al. 1995. Cooke and Prepas 1998). small increases in P additions to pond or wetland systems could easily shift threshold aquatic communities. negatively affecting habitat suitability and surface water quality (Prepas et al. 2000). Understanding how the hydrologic function of these wetlands influences phosphorus dynamics in pre-disturbance conditions is necessary in order to anticipate and manage for potential landscape alteration. Thus. the third chapter of this thesis examines the linkages between peatland groundwater - P dynamics and pond nutrient status in wetland complexes on the boreal plain.

This study is part of the Hydrology. Ecology and Disturbance (HEAD) wetlands study. which is examining how the hydrologic and ecological function of boreal plain wetland complexes relates to landscape position. Ultimately. HEAD seeks to determine how landscape controls may determine wetland response to surrounding forest disturbance. In the Utikuma region of northern Alberta, wetlands complexes across three landscape settings: a glacial outwash area, a moraine, and a low-lying clay plain have been selected. Initial surveys of wetland complexes have indicated that systems on the clay plain tend to be larger systems with elevated TP and cations concentrations compared to those on the moraine (Devito and Bayley, unpublished data), suggesting that landscape position may influence groundwater transport and solute patterns in surface water. Within the "landscape approach" framework of the HEAD study, this study seeks to characterise the hydrologic and nutrient connections between two riparian peatlands and their adjacent shallow ponds: one on the moraine and one on the clay plain. By determining the role of riparian wetlands in regulating water and nutrient exchange pre-disturbance, the implications of landscape disturbance may be better anticipated.

The first chapter of this thesis investigates the dominant water fluxes of two wetland complexes. Annual water balances and seasonal patterns of groundwater fluxes are examined, and in particular, the role of shallow groundwater reversals in influencing pond function is explored. In the second chapter, the importance for groundwater transport of phosphorus to pond nutrient status is evaluated. The effects of groundwater flow reversals on pond P concentrations is examined and sediment controls of P within the peatlands are addressed. By determining the role of riparian peatlands in exchanging water and nutrients within the shallow pond systems, this study aims to contribute to the conceptualisation of landscape patterns of wetland permanence, water quality, and ultimately productivity within the Utikuma region.

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Chapter 2: Groundwater-surface water interactions in two pond -peatland complexes on the Boreal Plain: The influence of landscape position.

2.1 Introduction

Currently, the western boreal forest (WBF) of north-western Canada is experiencing some of the fastest rates of forest disturbance in North America (AEP 1998). In recent years, forestry, oil and gas, mining, and recreational activities have increased rapidly in the area, resulting in extensive forest removal and road construction (AEP 1998). In the Boreal Plains of northern Alberta, land allocated for industrial development has increased from 11% to over 45% in the last three decades (Vogwill 1978, Global Forest Watch 2000). Despite this accelerated landscape alteration in the region, there is currently limited research on the impact of these activities on aquatic systems.

The Boreal Plain landscape, where general low relief limits surface drainage development, is characterised by numerous isolated ponds and associated peatlands of glacial origin (Vogwill 1978, National Wetlands Working Group 1988). Wetlands cover 20-50% of the Boreal Plains and fens and bogs are the dominant wetland types (Kuhry et al. 1993, Vitt et al. 1995). Large, extensive bogs and fens typically develop in large flat basins, while shallow pond-peatland complexes frequently develop in small basins (National Wetlands Working Group 1988). Unlike wetlands in other boreal regions of Canada, wetlands of the Boreal Plains have been shown to be nutrient rich (Vitt et al. 1995) and productive (Thormann and Bayley 1997). These conditions provide optimal habitat for many water birds, and the WBF represents one of the most important waterfowl habitats in North America (Ducks Unlimited 1998). In order to protect and effectively manage this wetland habitat, the hydrologic and nutrient function of shallow ponds and their surrounding peatlands needs to be understood.

Large-scale disturbance has the potential to impact lakes and wetlands by altering their hydrologic regime (Bedford 1999). However, wetlands in different landscape settings may experience a wide range of susceptibility to disturbance, depending on dominant their hydrologic flowpaths (or connections) (Devito et al. 2000). Hydrogeologic setting has been shown to represent a key control on a wetland's hydrologic and biogeochemical function by controlling the hydrologic connections to uplands, underlying aquifers, and the atmosphere (Winter 1989, Devito and Hill 1997, Kratz et al. 1997, LaBaugh et al. 1998). Further, the dominant flowpaths to the wetland will control the timing and magnitude of flow inputs, degree of interaction with the local sediments, and the chemistry of source waters (Roulet 1990, Brinson 1993, Hill and Devito 1997). For wetlands in landscapes lacking well-integrated surface drainage, connections to groundwater flow systems may become increasingly important (Winter 1989, Winter and Rosenberry 1995). Studies of prairie wetlands (sloughs or potholes) have shown that a connection to larger / intermediate groundwater flow systems versus smaller / local flow systems may increase the stability of flow inputs, the concentration of solutes and also influence the dominant forms of chemical species imported into the wetland (Winter 1989, LaBaugh et al. 1998). Differences among wetland-groundwater linkages may control similar processes in the wetlands of Boreal Plain.

Variation in the frequency and quantity of flow to a system may also influence internal aspects of a wetland's hydrologic function. Water storage, water table fluctuation and hydraulic gradients are determined by the dominant water inputs, and in turn, influence flow patterns within the wetland, and connections to the surrounding uplands (Roulet 1990, Devito and Hill 1996). Dynamic flow conditions can have important implications for chemical transport and biogeochemical transformations (Brinson 1993, LaBaugh et al. 1997, Devito and Hill 1997, Hayashi et al. 1998b, Hedin et al. 1998).

Studies in the interior plains of North America have examined relationships between wetland, pond and lake topographic position and function in the context of groundwater flow systems (Tóth 1963, Winter 1989, Winter and Rosenberry 1995, van der Kamp and Hayashi 1998). In several cases, wetlands situated in high topographic areas were found to be groundwater recharge systems, while those situated in low lying areas were more permanent and represented areas of groundwater discharge (Winter and Rosenberry 1995. LaBaugh et al. 1998). Those situated in intermediate positions often reflected flow through conditions (Winter 1989). Several studies have shown that that although groundwater represented a small portion of the overall water balance. the groundwater patterns observed were extremely dynamic. In these sloughs, reversals in groundwater flow direction occurred between open water and the surrounding upland, initiated by the evapotranspiration demand of phreatic plants (ie. willows) at the upland edge (Meyboom, 1966, Hayashi et al. 1998a, van der Kamp and Hayashi 1998). In other cases, reversals were initiated by bank storage which resulted from differential melt rates of the snow accumulated in the pond depression and the frozen surface soil (Winter and Rosenberry 1995. Winter and Rosenberry 1998).

In the boreal climatic region, peat commonly develops at the edges of shallow ponds and lakes, forming riparian peatlands (National Wetlands Working Group 1988).

The high permeability of the peat in these systems suggests that physical processes differing from those in prairie sloughs may determine exchange between open water and the surrounding landscape. While peatlands tend to generate their own local flow cells (Reeve et al. 2000), they are not necessarily independent of the underlying landscape. Devito and Hill (1997) determined that differences in till depth underlying small peatlands in the Canadian Shield had influences on which systems could sustain groundwater flow and which would react to evapotranspiration demands. Studies in Eastern boreal regions have documented dynamic groundwater flow reversals in peatlands connected to (Siegel and Glaser 1987. Romanowicz et al. 1993) and isolated from the underlying flow systems (Devito et al. 1997, Waddington and Roulet 1997. Fraser et al. 2001).

Recently, the hydrological connections between larger Alberta boreal lakes and their surroundings have been investigated (Shaw et al. 1990, Evans et al. 2000, Devito et al. 2000). To date, studies of wetland hydrology in the Alberta boreal region have been primarily limited to peatland forestry ie. the effects of ditching and drainage on substrate water content (Swanson and Rothwell 1989, Hillman 1992, Rothwell et al. 1996). Some Boreal Plain wetland studies have related water table fluctuations to wetland water chemistry (Vitt et al. 1995. Halsey et al. 1997. Thormann and Bayley 1998). However. few of these wetland studies have examined how surface and subsurface flow connect in boreal wetland complexes, peatland – pond interactions, or studied the wetland complexes' linkages to its hydrogeologic setting. As threats to Boreal Plain's ecological integrity and wetland habitat suitability increase, a thorough understanding of how the hydrologic function of Boreal Plain wetlands relates to the surrounding landscape may hold important implications for adaptive landuse planning and aquatic system management.

The overall objective of this chapter is to investigate the interactions of groundwater and surface water in undisturbed pond-peatland complexes, and determine how these interactions may relate to landscape position. Herein "landscape position" is defined as topographic setting: a topographic high area, a moraine and a topographic low area, a clay plain setting represent contrasting landscape positions.

<u>Objectives:</u>

1) To quantify and compare the dominant fluxes of the annual water balance of two Boreal Plain wetland complexes in contrasting topographic positions.

H1: At the regional scale, topographic high moraines will function as groundwater recharge areas and the low-lying clay plain as a discharge zone, therefore the wetland complexes should demonstrate a recharging groundwater function at the topographic high and a discharging function at the topographic low.

H2: The importance of groundwater inputs from a larger (intermediate) flow system to the wetland complex water balance should increase relative to local groundwater and surface inputs as wetland topographic position shifts from high to low.

2) To determine the importance of seasonal variation in the shallow groundwater – pond linkages in two wetland complexes in contrasting topographic positions.

2.1 To characterise the seasonal patterns of shallow pond hydroperiod and describe how they differ with topographic position.

H3: The shallow pond in the low topographic position should be less variable in pond stage due to continuous groundwater input from a larger flow system. The moraine system should be more responsive to atmospheric fluxes.

2.2 To determine whether groundwater flow reversals between pond and surrounding peatland occur in the wetland complexes, and if the pattern of the reversal varies with topographic position.

H4: The wetland complex in the topographic low position should be less prone to reversals in hydraulic gradient and groundwater flow direction than the moraine wetland complex, owing to continuous groundwater input from a larger flow system.

2.2 Site Description

Regional:

The two study wetlands are located in the Mixedwood Boreal Plains Ecozone of northern Alberta, at the transition between the Mid and High Continental Boreal

Subregion (National Wetlands Working Group 1988) (Figure 2-1a). These wetland complexes were selected from two of the three geomorphic zones in the area to represent endpoints in topographic position. The wetlands also represent two of the 24 wetlands that form the Utikuma Region transect for the Hydrology, Ecology and Disturbance of Boreal Wetlands (HEAD) study. The low relief region is characterised by rolling to undulating moraines (primarily hummocky disintegration moraine), glacial outwash areas, and level clay plains (Tóth 1978, Vogwill 1978, Mitchell and Prepas 1990). The major surficial unit is glacial till, which ranges from 20 to 240 m in thickness (Ceroici 1979). These unconsolidated deposits overlie the Smoky Group shale unit of the Upper Cretaceous period (Vogwill 1978, Ceroici 1979). Glacial drift represents the primary aquifer for surface waters (Tóth 1978, Vogwill 1978), and therefore hummocky moraine upland areas represent important recharge zones (Vogwill 1978, Ceroici 1979). Surface drainage diverges in this region but eventually drains into the Peace Basin: streams in the SE portion of the study area connect with the Wabasca tributary, and streams in the NW section connect to the Smoky tributary (Vogwill 1978). Generally, the vegetation consists of aspen *(Populus tremuloides)*, balsam poplar (*Populus balsamifera*) and white spruce (*Picea glauca*) forests in the upland, while black spruce (*Picea mariana*) dominates peatlands in poorly drained areas (National Wetlands Working Group 1988). Wetlands cover 25 – 50% of this region and include blanket peatlands (ie. horizontal fens), basin peatlands, and pond-peatland complexes (National Wetlands Working Group 1988).

Summer (July) and winter (January) long-term mean temperatures for the area are 15.7 °C and –14.6 °C, respectively (Environment Canada 1997). Annual precipitation

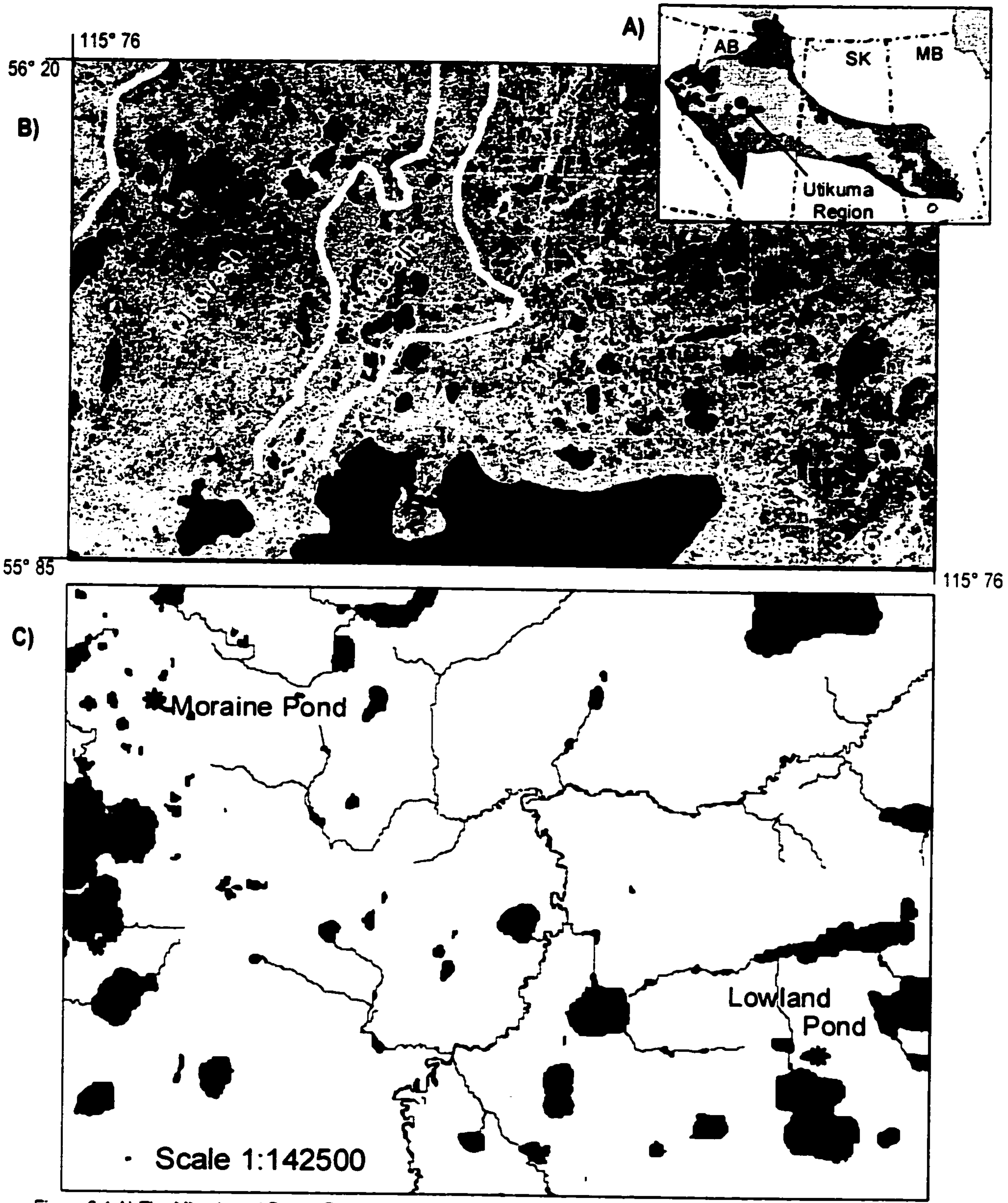

Figure 2-1 A) The Mixedwood Boreal Plains located within the Canadian interior plains with the Utikuma study area identified in Alberta. B) The three landscape settings within the Utikuma study area: Outwash, Moraine, and Clay plain. The box (white dash) indicates the area enlarged in C. C) The moraine (56° 07' 34 N; 115° 46' 99 W) and clay plain (55° 98' 25 N; 115° 19' 36 W) study wetland complexes located among the many boreal ponds and wetlands. The distance between the two sites is approximately 15km.

(P_r) and evaporation (E) in the region are roughly in balance: long-term P_r is 515mm and long-term E values range from 517 (Thornthwaite estimation) to 567mm (Penman estimation) (Environment Canada 1997). Runoff is typically less than 100mm yr^{-1} (see Appendix A) (Hydrological Atlas of Canada 1978). Typically, 50-60% of annual precipitation occurs from June to August, followed by dry autumn months (Environment Canada 1997). The winter snow pack is typically less than 100mm yr^{-1} snow water equivalent (SWE), representing less than 25% of the total annual precipitation (Environment Canada 1997).

Study Sites:

Two wetland complexes were selected from two of the three geomorphic zones in the area: one on the topographic high moraine zone (56° 07'34 N; 115°46'99 W), and one in the topographic low zone of the region, the clay till plain (55° 98'25 N; 115°19'36 W) (Figure 2-1b and 2-1c). The lowland site is approximately 20m lower in elevation than the moraine site. The depressions (clay basins) containing the wetlands tend to be larger on the plain than in the moraine area, but both sites consist of a shallow pond (< 1 m depth) surrounded by peatland (bog, treed fen and thicket swamp) and aspen dominated upland areas (Figure 2-2). Both complexes are depression wetlands within clay till basins. The moraine pond-peatland complex is irregular in shape and is surrounded by hillslopes up to 7 m in height. The lowland pond and wetland are larger and regular in shape, and relief within the catchment is less than 3 m. The moraine catchment is 17.4 ha, of which the pond, wetland, and upland area constitute 8%, 32%,

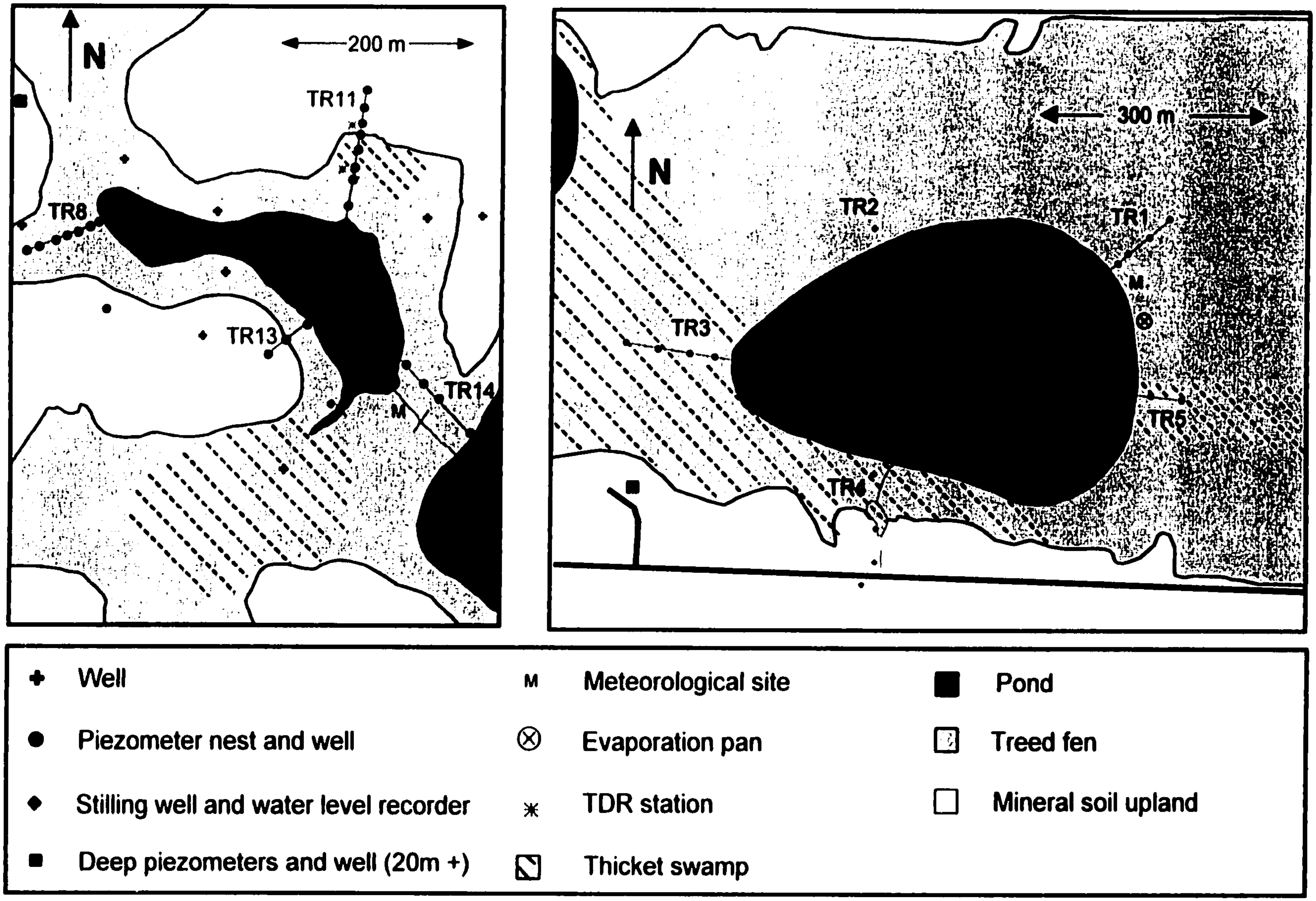

Figure 2-2. Study site maps for the topographic high (moraine, 56° 07' 34 N; 115° 46' 99 W) and lowland (clay plain, 55° 98' 25 N; 115° 19' 36 W) wetland complexes. Both sites consist of a shallow pond (< 1m depth) surrounded by peatland (treed bog/ fen and thicket swamp) and aspen dominated upland areas. Transects of piezometers and wells were installed to monitor interactions at wetland- pond interface (indicated by TR #).

and 60% of the catchment area respectively. The lowland catchment is 144.2 ha of which the pond, wetland, and upland area represent 8%, 41%, and 51% of the area.

The top 30-50 cm of the upland hillslopes at both complexes consists of a sandy silt loam (luvisol) (Figure 2-3). Beneath this, the hillslopes are characterised by oxidised clay till to a depth of 5 – 8 m, with grey unoxidised till underneath. The treed fen areas at both sites consist of fibric peat in the top 30 - 40 cm, mesic peat to a depth of approximately 1.5 m, overlying mesic-humified peat to a depth of up to 3.5 m. At the moraine site, the thicket swamp portion of the peatland has dark brown mesic peat to a depth of approximately 0.5 -1 m overlying clay till. In contrast, the peat in the thicket swamp in the lowland site extends to a depth of 6 m by the pond edge, but is less than 2.5 m throughout most of the wetland (Figure 2-4). The top 1 m is mesic peat with a dark brown to black humified peat beneath. . The transition from peat to till is marked by a ~ 10 cm silty-clay layer. The clay till underlying these wetland systems occasionally contains thin (< 20cm thick) sandy silt lenses, yet they appear to be few and discontinuous and likely do not represent major flowpaths to/from the pond. Similarly, occasional sandy silt layers in the oxidised till of the hillslopes appeared to be discontinuous.

The moraine wetland has two ephemeral surface channels that connect with the pond. During late spring and early summer, water collects in a small inflow channel originating in the thicket swamp area, to the south of the pond (Figure 2-2). The second is a beaver channel that was dug through the peatland within the last 10 years (based on 1990 airphotos) that connects the moraine pond to an adjacent pond ~120 m to the SE (Figure 2-2). During this study the channel was blocked with a sheet metal/plywood dam

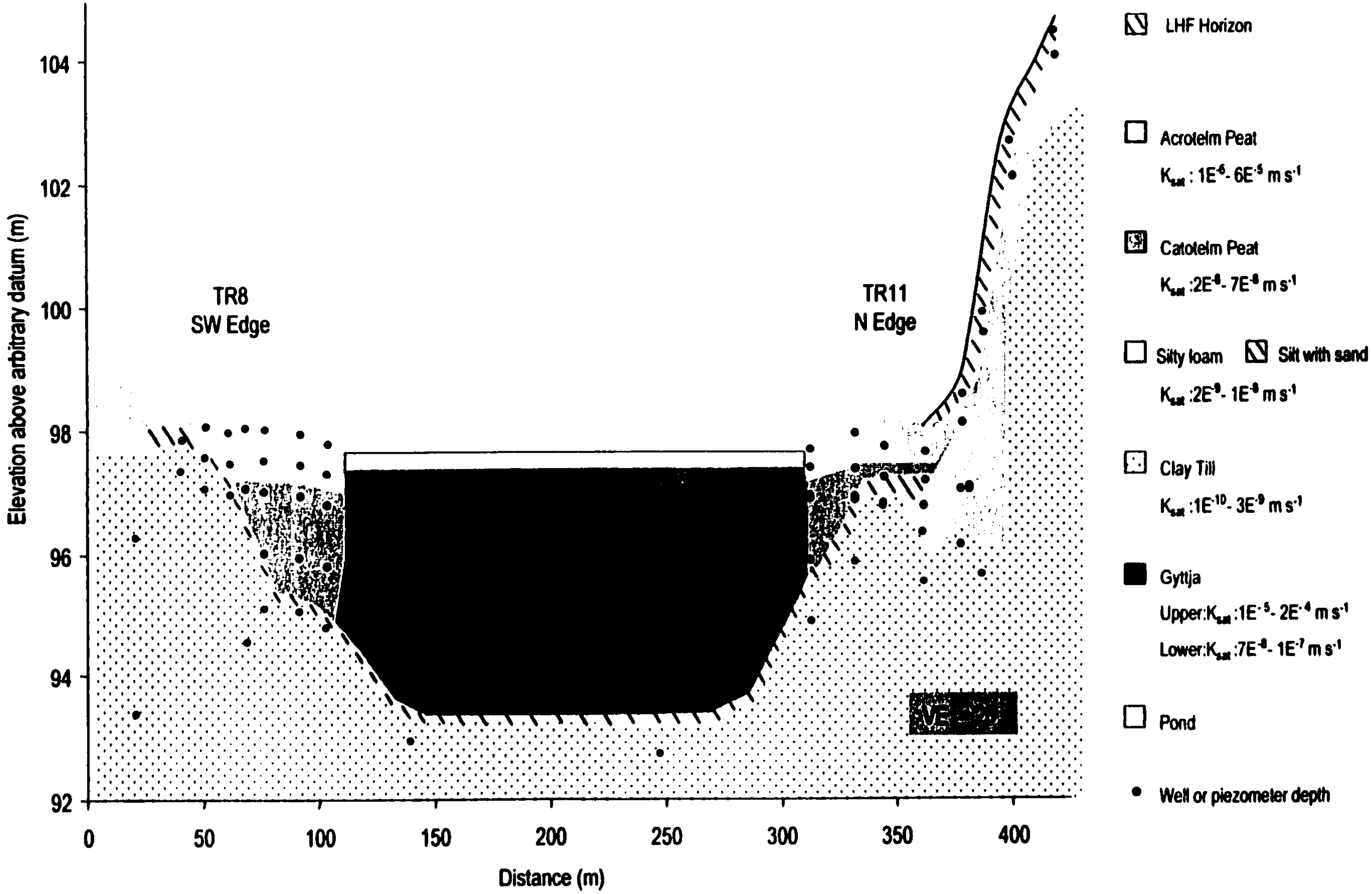

Figure 2 - 3. Cross section of the Moraine wetland complex (SW to N) incorporating transect # 8 and transect # 11. Lithology, hydraulic conductivities and piezometer/well openings (dots) are identified. The dashed line separates the upper and lower gyttja.

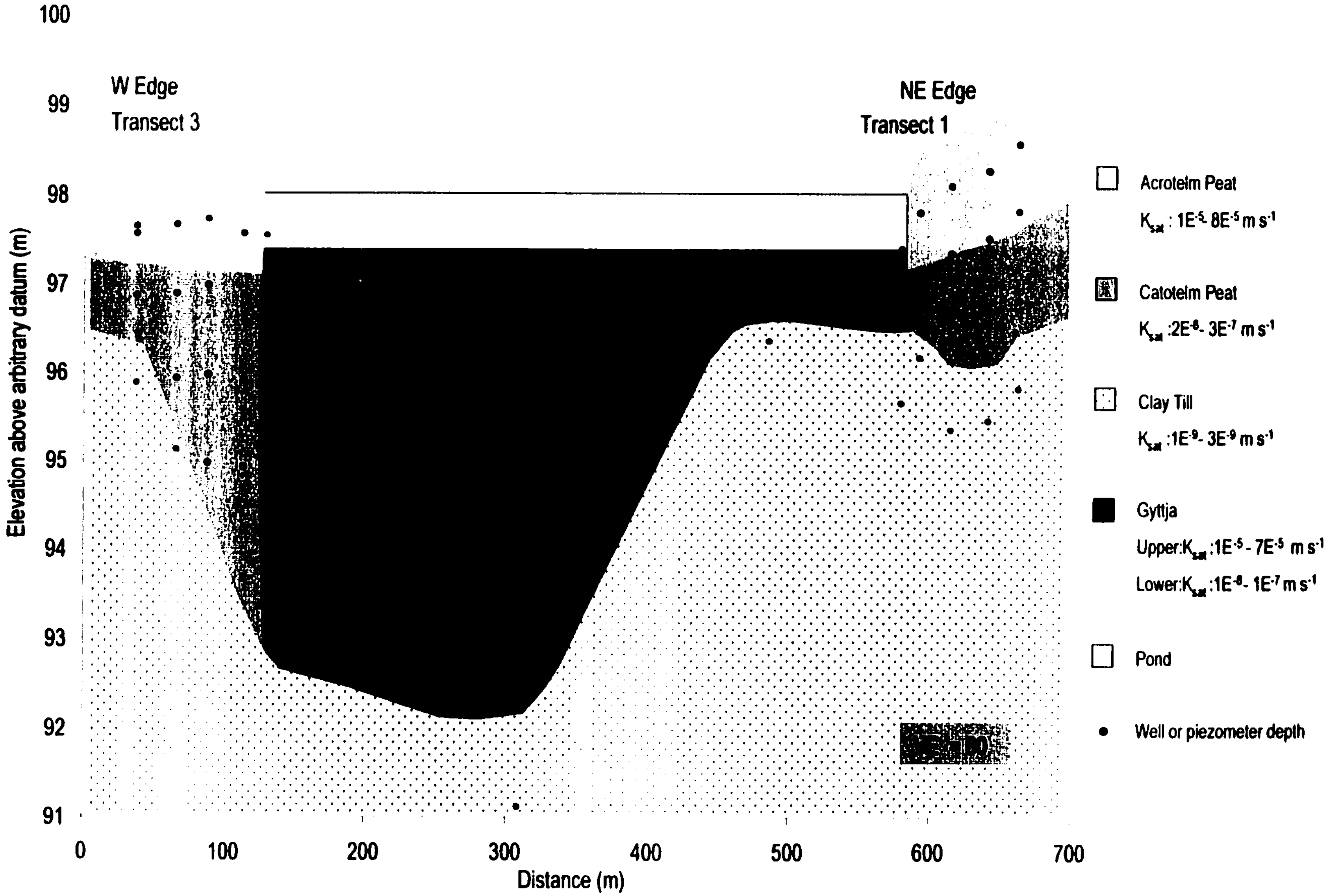

Figure 2 - 4. Cross section of the Lowland wetland complex (W to NE) incorporating transect # 3 and transect # 1. Lithology, hydraulic conductivities and piezometer/well openings (dots) are identified. The dashed line separates the upper and lower gyttja.

and sealed with bentonite clay, to maintain the original hydrologic connections of the study pond. The lowland wetland has three ephemeral inflows that only exist during very high flow periods. Of these three, only the west inflow is a distinct channel.

The vegetation of the treed fen areas are dominated by black spruce, with some larch (*Larix laricina*), and an understory of leatherleaf (*Chamaedaphne calyculata*), Labrador tea (*Ledum groenlandicum*) and peat mosses (*Sphagnum* spp). The thicket swamp areas are dominated by willow (*Salix* spp.), birch (*Betula* spp.), alder (*Alnus* spp.), sedges (*Carex* spp.) and grasses. Some marsh vegetation (cattails (*Typha latifolia*) and marsh ragwort (*Senecio congestus*)) exists on the southern pond edge of the lowland site. During the growing season, submergent macrophyte growth is typical. The moraine pond bottom is almost 100% covered with coontail (*Ceratophyllum demersum*), and common duckweed (*Lemna minor*) grows on the surface. The lowland pond macrophyte communities consist of pondweed (*Potamogetan richardsoni* and *Potamogetan zosteriformis*), coontail (*Ceratophyllum demersum)*, and milfoil (*Myriophyllum exalbescens*.) (Menchenton 2001). Ivy leaved duckweed (*Lemna triculosa*) form thick surface mats throughout July and August at the lowland pond.

2.3 Methods

2.3.1. Catchment Surface and Subsurface Characteristics

Catchment areas were determined from air photos, topographic maps, and topographic data from surveys conducted in October 1999, April 2000, and June 2000. Catchment, peatland, upland, and pond areas and perimeters were calculated using MapInfo GIS software.

Lithology was determined for upland, peatlands, and pond sediments by hand coring at both sites (n = 179 cores) (Figures 2-3 and 2-4). Further, three soil pits were dug in the upland areas of the moraine site for verification of the soil profile. Bail tests were conducted at all piezometers and were used to calculate saturated hydraulic conductivities (K_{sat}), for the till (n = 34), upper mesic peat (acrotelm) (n = 54), lower mesic-humic peat (catotelm) (n = 31) (after Hvorslev 1951).

2.3.2 Atmospheric Fluxes

Meteorological Conditions:

Meteorological data was collected from towers installed on the downwind side of the pond. At each tower, air temperature and relative humidity were measured with External RH/Temperature Loggers (Onset H8 Pro Series). Wind speed and direction were measured with anemometers and vanes (Young Wind Sentry) at the standard 2 m above the wetland surface (Dingman 1994). Surface water temperature in the ponds and in the evaporation pans were measured in the top 3 cm from the surface with temperature loggers (Onset H8 Series). In May 1999, a tower was installed at the moraine site, while only precipitation and temperature were monitored directly at the lowland site. In early April 2000, a tower was installed at the lowland site.

Precipitation:

At each site, rainfall was continuously measured with a tipping bucket gauge (Jarek Model #4025). In addition, a bulk rain gauge was installed on the opposite side of each wetland for comparison of on-site spatial variability. Gauges were installed at approximately 50 cm above the peat surface. Long-term summer rainfall (April – Oct only) collected from three nearby fire towers (Gift Lake, Whitefish, Enildo), and long-term climate data (full year) for the Utikuma-Red Earth region (Environment Canada 1997) were used for comparison of long-term trends.

Three snow surveys were conducted between January 20 and March 18, 2000 to characterise snow characteristics, patterns of distribution, and snow water equivalent. Sampling transects were selected to represent upland, peatland, and pond surface areas, as well as aspect. Snowpack depth and snow core density was converted to snow water equivalent (SWE) (Dingman 1994). In addition, snow tables were installed in 3 locations at the moraine complex to monitor changes in snowpack depth over the season. SWE values used in the water balance represent net values (snowfall – sublimation).

Evaporation/ Evapotranspiration Calculations:

Pond evaporation was estimated using two methods: an evaporation pan and a mass transfer (aerodynamic) model. Evaporation pans were standard Class A size (1.22m diameter by 25.4 cm depth) and were installed on a mudflat (moraine) and pond shore (lowland) on the downwind side of each pond, within 20 m of the met-station. During the 1999 season an evaporation pan was installed at the moraine site, and evaporation was measured daily at noon using a high precision micrometer hook gauge. In April 2000, a second pan was installed at the lowland site and pans were equipped with automated water level recorders. Evaporation estimates measured at the two sites agreed in 2000 (Figure 2-5), therefore the 1999 E values for the moraine site were adjusted for the lowland site using the regression relationship for 2000 values. E values were not

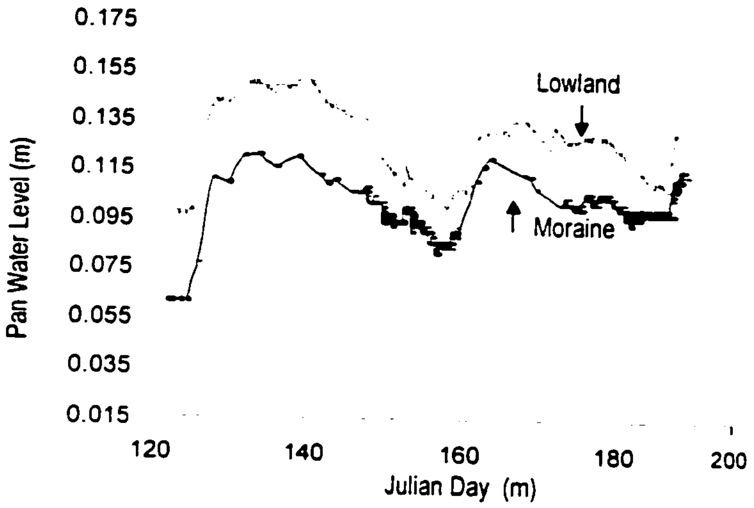

Figure 2-5. Water level fluctuations in the evaporation pans at the moraine and lowland sites indicate that evaporation rates were almost identical at the two sites during spring 2000.

adjusted by a pan coefficient, due to the similar temperature and depth conditions between the pans and ponds (see Appendix B).

For Pan E estimates, changes in pan water level (measured to the nearest mm) represent the net atmospheric evaporation (E) for a given time period (Δt) (Dingman 1994):

$$E = P_r - (V_2 - V_1), \tag{2-1}$$

where Pr is precipitation, and V_1 and V_2 are the storage values at the beginning and end of Δt. The mass transfer model for evaporation incorporates turbulent transport and vapour gradients and is described by (after Dingman 1994):

$$E = K_E \bullet v_a (e_s - e_a) \tag{2-2}$$

Where v_a is windpeed, and e_s and e_a are the vapour pressures for the evaporating surface and overlying air, respectively. K_E is the mass transfer coefficient describing the vertical turbulent transport of water vapour.

$$K_E = (D_{wv} \bullet 0.622 p_a \bullet k^2) / (D_m \bullet P p_w \bullet (\ln[(z_m - z_d)/z_o])^2) \tag{2-3}$$

where D_{wv} and D_m are the diffusivities for water vapour and momentum (D_{wv} / D_m assumed to = 1), p_a is air density (.00122g cm^{-3}), k = 0.4, Pr is atmospheric pressure (mb), p_w is water density, z_m is height of windspeed, z_d is zero plane displacement (assumed to be zero over pond water), z_o is roughness height and is assumed to be 0.023 for ponds and lakes (Dingman 1994).

E values calculated from pan and mass transfer measurements were compared to monthly potential evapotranspiration (PET) was calculated using Thornthwaite's temperature based model:

$$PET_{month} = 0.409[e_{sat}(T_a)] \qquad (2\text{-}4)$$

where e_{sat} is the saturated vapour pressure for the given average monthly T_a (Dingman 1994).

2.3.3 Surface Fluxes

At both ponds, stilling wells with automated recorders and staff gauges were installed for continuous measurements of pond water levels and surface storage change. The beaver channel at the SE edge of the moraine pond connects to an adjacent pond during wet periods. In May 1999, automated water level recorders (float potentiometers) and staff gauges were installed at either end of the SE channel (Figure 2-2), and a pygmy flow meter was used to measure surface velocity. However, as the slope of the channel bed is close to level, water movement was too slow to measure and the direction switched depending on current wind direction. By July 1999, the channel was a series of disconnected pools, and therefore the influence of exchange through the surface channel was minimal on the pond water balance (July 1 1999 - June 31, 2000). In the first week of April 2000, prior to ice off and peat thaw, a sheet metal and plywood dam sealed with bentonite clay was installed midway up the SE channel to prevent surface exchange between the two ponds during high flow conditions. At the SW inflow from the south thicket swamp, a 90° V notch weir with automated water level recorder was installed in early June 1999.

At the three small inflow channels in the lowland complex, wells and staff gauges were installed to monitor water levels during high flow conditions. At the largest of the three (west channel) the "bucket / stopwatch" method was used during the days that flow was measurable. Sheet flow was estimated for the lowland thicket swamp area for the 10 days (June 2000) that the water table raised slightly above the surface, filling the hollows. Sheet flow was calculated using a general laminar flow equation (Dingman 1994):

$$U_{uo} = aY^{m}, \tag{2-5}$$

Where U_{uo} is average overland flow velocity. Y is water depth in hollows. m describes flow conditions (ie. porous-media vs. open channel) and is assumed to be ½ (Dingman 1994), and a is calculated from the laminar flow analogue to the Chézy equation:

$$a = (\gamma_w/3\mu)\tan\beta_s, \tag{2-6}$$

where γ_w is the weight density of water. μ is the dynamic viscosity of water, and β_s is the flow path angle. Discharge was determined by multiplying this velocity by surface water depth (Y) and the perimeter of shoreline contributing to overland flow.

2.3.4 Groundwater Fluxes

Field Methods:

Transects of piezometers and wells were installed to monitor groundwater flow patterns at the pond - wetland interface. Four transects (#8,#11,#13,#14) of wells and piezometers surround the moraine pond, and four transects (#1,#3,#4,#5) surround the lowland system (Figure 2-2). The location of these transects were selected to monitor groundwater flow paths from the uplands through the wetlands to the ponds. In addition, individual wells and piezometers were installed in various locations around the wetland to capture spatial variability in flow patterns (Figure 2-2). Water table wells were constructed with 3.8 cm diameter perforated ABS pipe and installed to depths ranging from 1.5 to 5 m in depth. Piezometers were constructed of 1.9 cm PVC pipe that was slotted only at the bottom 20 cm. Piezometer lengths ranged from 0.5 m to 5 m, spanning the depth of peat deposits and also measuring fluxes in the underlying clay till. One nest of deep wells (up to 30 m depth) was installed in the upland areas of each site to monitor upland water table patterns and to determine each wetland's connection to the underlying larger groundwater flow system.

Darcy Calculations:

Flownets were drawn by hand for several dates (incorporating seasonal wet-dry conditions) for all transects. As determined from the bail tests, there was greater than 2 orders of magnitude (often 3 to 4 orders of magnitude) difference in K_{sat} between the peat and underlying clay till, therefore these were treated as separate flow systems. Vertical recharge rates into the clay till aquiclude layer were determined by multiplying the difference between pond head and hydraulic head in the underlying clay till by the K_{sat} value.

The peat was divided into an upper fibric-mesic peat (acrotelm) and a well-decomposed lower layer (catotelm), as determined from cores across the catchment of the two wetland-complexes. The transition between these layers ranged from 1 to 1.5 m in different zones of the wetlands (ie. fen vs. thicket swamp), but was consistent within a zone. The upper peat had horizontal hydraulic conductivities that ranged from 10^{-5} m s^{-1} to 10^{-6} m s^{-1} ($n = 54$ for mesic peat piezometers), while the lower catotelm peat conductivities ranged from 10^{-8} m s^{-1} to 10^{-9} m s^{-1} ($n = 31$ mesic-humic piezometers). Due to these differences in K_{sat} values, the 2 peat layers were treated as two separate flow systems. Horizontal flow through the catotelm was negligible at this time scale (< 0.05 mm yr^{-1}).

Shallow groundwater exchange between the peatland acrotelm and pond was calculated using Darcy's Equation (Freeze and Cherry 1979):

$$Q = - K_{sat} \bullet A \bullet dh/dl \qquad (2\text{-}7)$$

where K_{sat} is the saturated horizontal hydraulic conductivity (m s^{-1}), A is the cross sectional area of flow (m^2), and dh/dl is the hydraulic gradient (dimensionless). In these calculations the acrotelm was assumed to be isotropic as no change in the peat characteristics were apparent within this zone, and therefore horizontal hydraulic conductivities (K_h) were used in calculations. Area (A) was calculated based on the distance between the water table (just prior to the seepage face) and the acrotelm to catotelm transition.

At transects with water table wells only (TR#2, TR#4 at the lowland site) (Figure 2-2), groundwater flow was calculated using a Dupuit-Forchheimer approximation. Flownets from other transects indicated that groundwater flow was horizontal at the peatland - pond interface, therefore the application of a Dupuit-Forchheimer approximation seemed appropriate owing to the similar lithologies among transects. Continuous water level recorders installed at both ponds and on 4 of the 8 transects allowed for continuous groundwater measurements to be calculated for half of the transects. At the remaining transects total flux was calculated based on manual measurements which ranged infrequency from daily (spring melt and wet summer periods) to twice weekly during the driest periods (71 sample dates total). However water levels were measured only twice between the end of November and February (and were frozen). and four times in March (still mostly frozen). The four transects at each wetland complex were used to represent flow conditions for designated lengths of the shoreline (measured from airphotos). based on peat properties, depth to clay till. and vegetation. The fluxes from these four zones at each pond were then summed to give a total groundwater flux value for each pond.

Error for groundwater flux was estimated by calculating minimum and maximum fluxes: this involved adding +/- 1 standard deviation to the mean K_{sat} of the transect. adding +/- 10cm to the transition depth from acrotelm-catotelm estimate (for A). and +/- 0.5 cm to surveyed elevation of water table wells.

Isotope Calculations:

Using ^{18}O signatures, groundwater seepage was calculated after Krabbenhoft et al. (1990) and Walker and Krabbenhoft (1998):

$$G_i = [P(\delta_L - \delta_P) + E(\delta_E - \delta_L)] / (\delta_{Gi} - \delta_L), \qquad (2\text{-}8)$$

in which δ with subscript is the isotopic composition of each water balance component (L= pond water, P= precipitation, Gi= shallow groundwater inputs and E = evaporation). δ_E was calculated indirectly by Krabbenhoft et al.'s (1990) equation:

$$\delta_E = (\alpha{*}\delta_L - h\delta_A - \varepsilon)/(1 - h + 10^{-3}\Delta\varepsilon), \qquad (2\text{–}9)$$

where h is the relative humidity, and δ_A is the isotopic signature of atmospheric moisture. α* is the equilibrium isotope fractionation factor. Δε is the diffusion controlled or kinetic fractionation factor expressed per mil and is calculated by:

$$\Delta\varepsilon = K(1-h), \qquad (2\text{-}10)$$

where $K(^{18}O) = 14.3$ (Krabbenhoft et al. 1990). The term ε is the total fractionation factor (per mil) and is calculated from:

$$\varepsilon = 1000(1-\alpha{*}) + \Delta\varepsilon. \qquad (3\text{–}11)$$

Since δ_A was not sampled directly, it was approximated as a theoretical vapour in equilibrium with precipitation (Krabbenhoft et al. 1990, LaBaugh et al. 1997). This was calculated using:

$$R_v = \alpha * R_l, \qquad (2\text{-}12)$$

where Rv is the ^{18}O value for vapour and R_l is the ^{18}O signature for precipitation (Kendall and Caldwell 1998).

2.3.5 Pond Volume and Seasonal Pond Storage (ΔV)

Continuous estimates of pond storage change were determined from 30 min interval measurements of pond stage (storage change in mm) and pond bathymetry. For accurate bathymetry, the pond areas and shoreline lengths were determined using MapInfo GIS software and enlarged airphotos (originally 1: 40 000). The bathymetry of each pond was determined by measuring water depth to gyttja along perpendicular transects across the ponds. As pond stage measurements were frequent and spatial variability around the ponds was tested, and as the bathymetry was relatively regular at both ponds, error associated with these calculations was assessed to be less than 5% (Winter 1981).

2.3.6 Water Chemistry

All precipitation, surface water and groundwater was sampled on a monthly basis for pH, electrical conductivity (EC), dissolved oxygen (DO), major cations (Ca^{2+}, Mg^{2+}, Na^+, K^+), anions (Cl^-, SO_4^{2-}), dissolved organic carbon (DOC), and stable isotopes (oxygen-18 (^{18}O), deuterium (D)). In addition, precipitation, surface water and a subset of piezometers (ie. peatland edge nests and upland - peatland transition nests) were sampled biweekly to daily during high flow periods (snowmelt and storms). Other major ions (eg. HCO_3^-, CO_3^{2-}) were sampled from surface water monthly for the HEAD project, and were also used in this study.

During groundwater sampling, all piezometers were bailed within 24 h of sampling. Piezometers in clay till required up to a month to recharge and were not bailed prior to sampling. However, tests conducted on piezometers in higher permeability mineral soil showed that chemical concentration differences were typically less than 10% "before" and "after" purging

E.C., pH, DO, and water temperature (T_s) were measured on site using field meters (YSI 85 for DO/temp/EC, VWR for pH). Groundwater measurements of DO and T_s were obtained using 150 ml syringes to withdraw water from piezometers without introducing mixing/turbulence. Surface water profiles for DO and T_s were measured seasonally, at 10cm intervals from pond surface to pond bottom.

Water sampled for other chemical analyses (ie. cations, anions, DOC, isotopes) was collected with pre-rinsed tubing and bottles, and was filtered within 24 h (except isotopes). DOC samples were filtered through 0.45 μm Millipore paper, acidified with 2N HCl and stored at 4°C until analysis. Cation and anion samples were filtered through Gelman GF/C paper and stored at 4°C until analysis. Cation samples were acidified with two drops of (50%) HNO_3. Isotopes were poured unfiltered into airtight scintillation vials while in the field.

DOC was analysed by the Total Organic Carbon (TOC) /Combustion Infrared Method (Greenberg et al. 1992) using an Ionics Model 1505 Programmable Carbon analyzer. DOC analyses were completed at the University of Alberta Limnology Laboratory. Cations were analysed by atomic absorption spectrometry (Perkins Elmer model 503) at the Earth and Atmospheric Sciences High Volume Laboratory of the University of Alberta.

The $\delta^{18}O$ isotope analysis of water samples was completed at the Stable Isotopes Laboratory at the University of Calgary. The $^{18}O/^{16}O$ ratio of isotopic activities was determined according to CO_2 - H_2O equilibration technique (Epstein 1953, O'Neil et al.1975). Accuracy and precision of lab analysis are reported to be generally better than +/-0.2 $^0/_{00}$ (1 Standard deviation based on n = 50 samples).

2.3.7 Budget Calculations

Hydrologic measurements were made from May 1999 through August 2000, incorporating the hydrologic year, July 1, 1999 to June 30, 2000. This year was chosen to correspond most closely to peat thaw in the wetland complexes, and signifies the beginning of the summer season. Three month seasons were divided within the hydrologic year as follows: Summer: July – September 1999; Autumn: October 1999 – December 2000; Winter: January – March 2000; and Spring: April – July 2000. The intervals were selected to correspond with regional indicators such as the boreal growing season (summer), snowfall period (winter), and peat thaw (spring), as well as instrumentation dates. While the autumn is actually shorter than three months, no major water fluxes occurred during October - December, and therefore grouping these months seemed appropriate.

All hydrologic fluxes to and from the ponds were measured for the water balance and calcium budgets. Water and calcium (Ca^{2+}), annual and seasonal budgets were constructed using continuous water flux measurements. Calcium sampling ranged from monthly to daily (during wet events). Hydrologic budgets were calculated using:

$$\pm r = P_r + S_i + G_i - E - G_o - D_o - \Delta V, \qquad (2\text{-}13)$$

(Wentz et al. 1995, LaBaugh et al. 1997) where ΔV is the change in pond volume, P_r is precipitation, S_i is surface flow inputs, G_i is shallow groundwater inputs, E is evaporation, G_o is shallow groundwater outputs, D_o is deep vertical groundwater seepage out through the pond bottom, and r is the residual reflecting uncertainties in flux measurement. In the water balance, a positive r indicates overestimation of water inputs (or underestimation of outputs).

For calcium fluxes, since S_i is essentially negligible and evaporation does not remove solutes, calcium budgets were calculated using:

$$\Delta(VC_l) = P_r(C_{pr}) + G_i(C_{gi}) - G_o(C_{go}) - D_o(C_{go}) \pm r \qquad (2\text{-}14)$$

where C subscript designates the concentrations associated with the different water balance components (l indicates pond). In the calcium budget, the residual term, r, encompasses both reaction within the pond that might either remove (- r) or add (+ r) to the pond mass storage, and also any error in calculation (Wentz et al. 1995). In contrast to the water balance, r was calculated as the change in storage minus the difference between inputs and outputs (water balance was inputs and output difference minus storage change), in order for positive and negative r components to reflect biogeochemical processes.

Calculation intervals for weighting the chemical mass of inputs were defined by the dates midway between sampiing (LaBaugh et al. 1997). The chemical mass in the ponds was determined by multiplying the volume of the pond by the mean surface concentration (n = 2 per sampling date). Groundwater Ca^{2+} mass input was calculated by multiplying concentrations in littoral piezometers by the volume of seepage for each corresponding shoreline segment, and then summing the mass for the four segments. Chemical mass loss due to seepage from the pond was determined by multiplying the concentration of the pond by the water flux out of the pond. Bulk deposition mass (P_rC_{pr}) was the concentration at that sampling date multiplied by the precipitation volume for the weighted interval. In both the water and calcium budgets, % retention was calculated as the residual divided by the total inputs, multiplied by 100.

2.4 Results

2.4.1 Regional Landscape Patterns

Regional Lithology and Vertical Recharge Rates:

For the HEAD study, deep well and piezometer nests were installed at 7 locations between 1998 and 1999. One of these nests (P4) was installed in the upland adjacent to the moraine wetland complex and one was installed next to the clay-plain wetland complex (P5) (Figure 2-2). During installation, lithology data was collected from the cores. The upland adjacent to the moraine site (approximately 4 m above wetland level) was underlain with 5 m of oxidised clay till, under which unoxidised clay till was sampled for 14 m. At three depths, the till was interrupted by thin sandy lenses: 5 m, 10 m, and 15 m, Hydrogeologic maps indicated that unoxidised till extended for 60 m, and showed evidence of two deeper, extensive lenses (ie. below 30 m) (Vogwill 1978, Ceroici 1979).

In the upland adjacent to the clay plain site, (approximately 1 – 1.5 m above the wetland level), core data indicated the clay till was oxidised to a depth of 5 - 6 m, with unoxidised till sampled for 21 m below this. All sandy silt lenses found within the upland cores were less than 0.5 m in width and it is not known how continuous they were. Shallow cores taken in between the upland deep well nests and the wetlands, and throughout the wetlands did not show evidence of continuous sandy lenses, although small pockets of sandy silt were occasionally located. Shale bedrock lies at approximately 80m below the surface (Vogwill 1978).

Hydraulic gradients in the deep piezometers of both upland areas indicated recharge conditions. Gradients through the till at the moraine complex were larger than gradients at the lowland complex (0.18 - 0.29 vs. 0.09 - 0.1). Based upon these gradients and hydraulic conductivities at these two nests, estimates of vertical recharge ranged from 10 - 15 mm yr^{-1} at the moraine site to 5 mm yr^{-1} at the clay plain.

2.4.2 Dominant Fluxes

Annual Water Balance, Calcium and ^{18}O Budgets:

Over the hydrologic year, total outputs were greater than total inputs at both wetland complexes, and water levels showed a net decrease in elevation (Table 2-1).

Table 2-1. Water balance at the moraine (A) and lowland (B) ponds from July 1, 1999 to June 31, 2000. Fluxes are measured in mm, and the balance is measured as a percentage of total inputs. A positive residual indicates and overestimation of inputs (or underestimation of outputs). * indicates E = 0 since net precipitation (P-E), determined from the SWE of the snow pack was used during the winter season.

A) Moraine Site

	Inputs (mm)				Outputs (mm)				d Storage (mm)		Balance	
	Precipitation **P**	Surface **Si**	Groundwater **Gi**	Total In **I**	Evaporation **E**	Shallow Groundwater **Go**	Deep Groundwater **D**	Total Out **O**	**I-O**	d Volume **dV**	Residual **r**	% of Input **%**
Summer	117	0	20	138	217	3	< 1	220	-82	-143	61	44
Autumn	10	0	1	11	19	6	< 1	25	-15	-25	10	90
Winter	34	0	0	34	0*	1	< 1	1	34	40	-6	-18
Spring	188	0	36	224	157	4	< 1	161	63	102	-38	-17
Annual	344	0	58	402	394	13	1	409	-7	-26	19	5

B) Lowland Site

	Inputs (mm)				Outputs (mm)				d Storage (mm)		Balance	
	Precipitation **P**	Surface **Si**	Groundwater **Gi**	Total In **I**	Evaporation **E**	Shallow Groundwater **Go**	Deep Groundwater **D**	Total Out **O**	**I-O**	d Volume **dV**	Residual **r**	% of Input **%**
Summer	110	0	5	115	245	11	< 1	256	-140	-115	-25	-22
Autumn	11	0	0.4	11	20	3	< 1	24	-12	-28	16	137
Winter	36	0	0	36	0*	0	< 1	0	36	-28	64	176
Spring	190	3	17	210	173	1	< 1	174	36	27	9	4
Annual	347	3	22	372	438	15	1	454	-82	-144	62	17

Precipitation was the dominant input at both the moraine and lowland complexes (86% and 93% respectively), while evaporation represented the dominant output (96% for both pond systems). Shallow groundwater fluxes were small for both systems, yet they were proportionately smaller for the lowland system due to its larger pond area: shoreline ratio. Shallow groundwater inputs ranged from 14% (58 mm) – 6% (22 mm) of the total input for the moraine and lowland systems, while shallow groundwater output was 3% of total outputs for both systems. Vertical recharge out through the pond bottom was negligible for the two sites (< 1mm yr^{-1} loss from pond). Surface flow fluxes were much smaller than expected. Surface fluxes were negligible at the moraine complex, although during wet events, the weir in the SW inflow channel came close to flowing. At the lowland complex, the total surface inputs, including ephemeral sheet flow and inputs through the small inflow channels, was estimated to be 3mm yr^{-1} (< 1% of budget).

Using the hydrologic fluxes described above, the moraine balanced within 5% of total inputs, while the lowland balance closed within 17%. These residuals fall within the error of the instrumentation and approaches used for measurement. On an annual basis, precipitation estimates were assumed to be accurate within +/- 10%, based upon comparison between the two sampling methods. Evaporation estimates using the described techniques are expected to be correct within +/- 15% monthly, and 5 - 10% annually (Winter 1981). Errors in estimating pond storage were assessed to be less than 5% monthly (see methods section). Groundwater estimates using hydrometric measurements were estimated to be accurate within +/- 70% (see methods section).

Owing to the large uncertainties associated with hydrologic measurements (groundwater in particular) (Winter 1981, LaBaugh 1997), water fluxes were also quantified using a calcium and ^{18}O balance. As calcium concentrations were relatively high in these wetland complexes (Mitsch and Gosselink 1993, Vitt et al. 1995), it was assumed that Ca^{2+} was conservative, because removal or additions due to weathering or vegetation uptake would represent a small percentage of the total Ca^{2+}. Furthermore, annual Ca^{2+} uptake by peatland plants tends to occur in the zone above the water table (Damman 1978), and therefore the process should not affect Ca^{2+} exchange between shallow groundwater and pond water. The strong correlation between Ca^{2+} and Mg^{2+} ($R^2 = .89$, F value < 0.0001) (Figure 2-6) indicates that the 2 solutes are conservative within these systems, therefore the difference between pond inputs and outputs of Ca^{2+} should equal the change in Ca^{2+} mass in the ponds (LaBaugh 1997). At the moraine site, the budget balanced within 10%, with a residual (R = change in mass – (inputs -outputs)) of 130.1 mg m^{-2} (Figure 2-7). The lowland budget balanced within 13%, with a residual of -155 mg m^{-2}. These values are close to the residuals of the water balance, and support hydrometric estimates.

Using ^{18}O isotopes for groundwater seepage estimates provides an independent comparison to hydrometric estimates, since no actual groundwater measurement is necessary for the calculation (Krabbenhoft 1994). Annual groundwater input was determined using equation (2-8), and was found to be 40.3 m^3 (3 mm) and 2897.8 m^3 (26 mm) for the moraine and lowland complexes respectively. Groundwater seepage estimates determined by flownet calculations and isotope calculations were similar (Figure 2-8), though the moraine seepage estimates were slightly smaller. Uncertainties associated with the ^{18}O balance are generally related to the $^{18}O_E$ term, a signature which is not directly measured (Krabbenhoft 1994, LaBaugh 1997), however, studies have

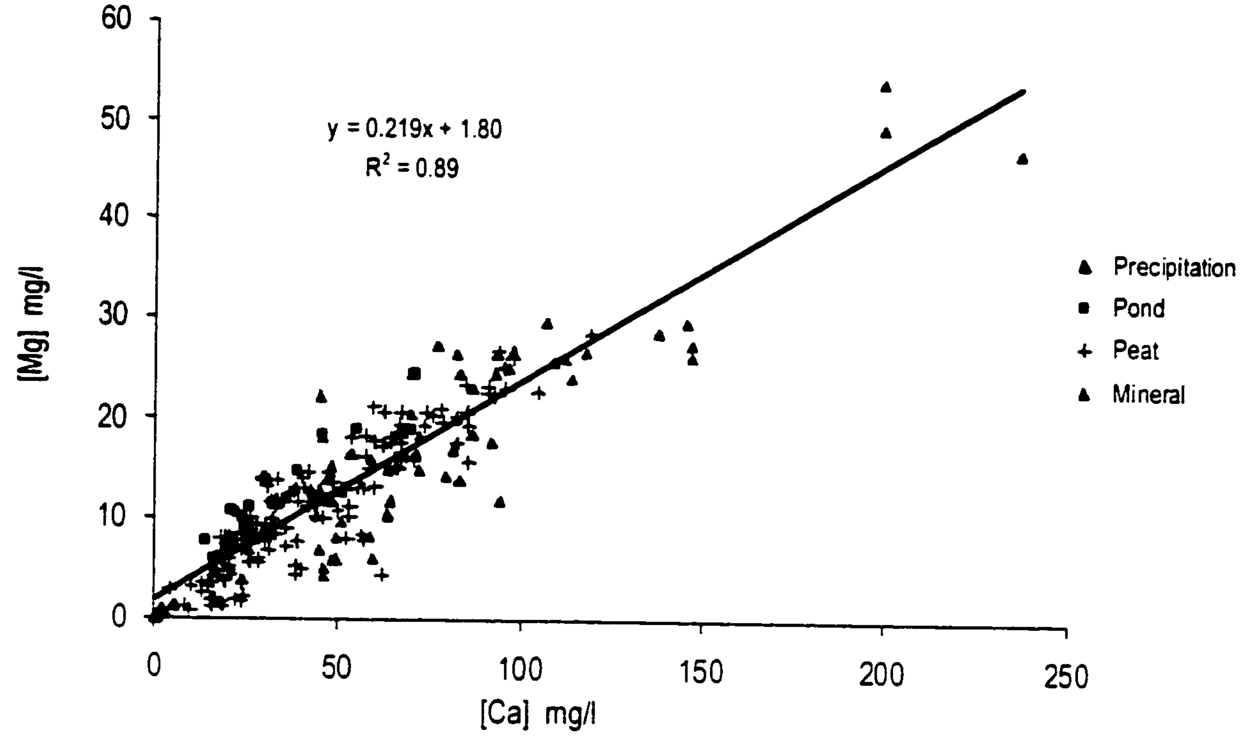

Figure 2-6. The relationship between [Mg] and [Ca] for all water sources in both wetland complexes. The F value of the relationship is <.0001, indicating that the solutes are conservative within the systems.

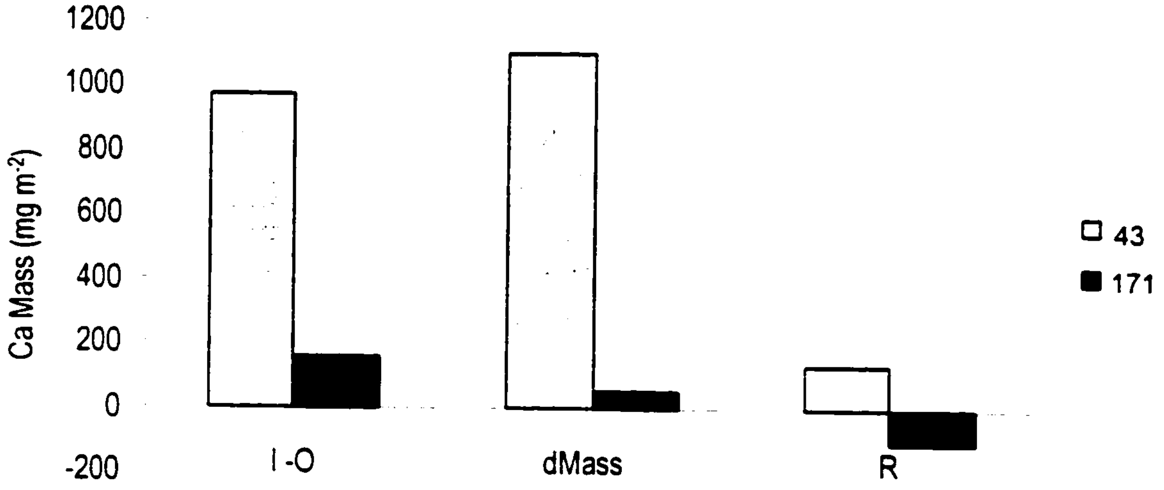

Figure 2-7. Calcium mass balance (mg m^{-2}) for the moraine and lowland complexes. The residual (R) is the difference between the pond change in mass (dMass) and inputs minus outputs (I-O).

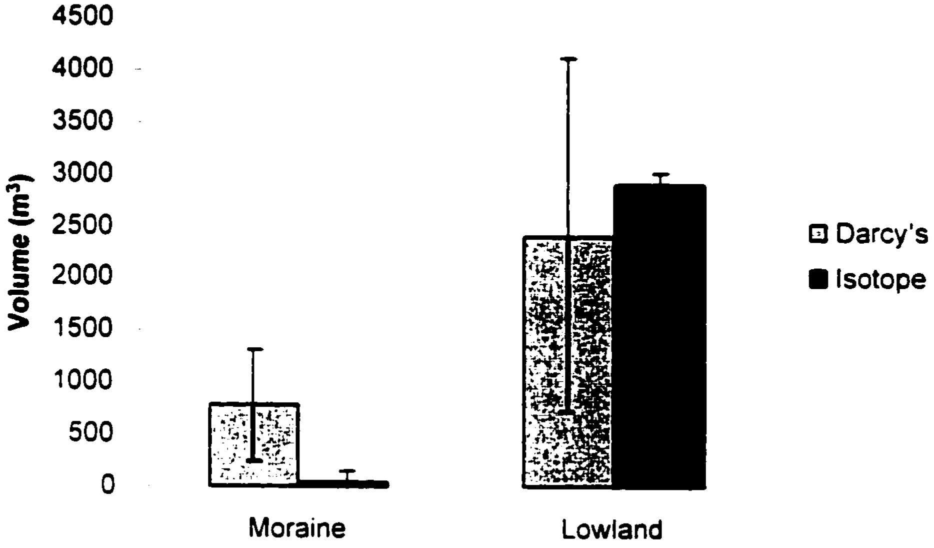

Figure 2-8. Annual shallow groundwater input estimates as calculated by Darcy's equation and $\delta^{18}O$ isotope calculations .

shown that this uncertainty is small for most of the year (Krabbenhoft 1990). Using these independent estimates of groundwater, the annual water balance still closes within 10% for the moraine site and 18% for the lowland site, providing further confidence in our groundwater estimates.

Atmospheric Fluxes:

The annual precipitation (P_r), 344 mm at the moraine site (86% of total inputs) and 347 mm at the lowland site (93% of total inputs), were lower than the long-term climate normals of approximately 450-500 mm yr^{-1} (Environment Canada 1997). The highest precipitation in 1999 occurred during the usual late spring-early summer rains (Figure 2-9 and Figure 2-10), but the inputs were only 59 - 67% of the normal seasonal flux (Figure 2-11). Following a dry autumn and winter (1999), the average SWE of the 2000 spring snowpack was 48.7 mm and 43.8 mm at moraine and lowland site respectively. Due to the very low peatland water table before freeze up, melting snow infiltrated quickly during spring melt (March 27 – April 16), and no measurable surface runoff to the ponds occurred. Direct snowmelt contributions to pond storage were 34.3 mm and 33.7 mm at moraine and lowland site, respectively, from the snowpack on the pond surface (Table 2-1).

These extremely dry conditions were followed by high rainfall in May 2000. Precipitation during this month (81.5 mm) was almost twice the long-term average (41-46 mm)(Figure 2-11). The majority of this precipitation occurred during May 4th -May 8th, 2000, initiating the largest increase in water table height and pond water level measured during the study period. Measured precipitation for the rest of 2000 were

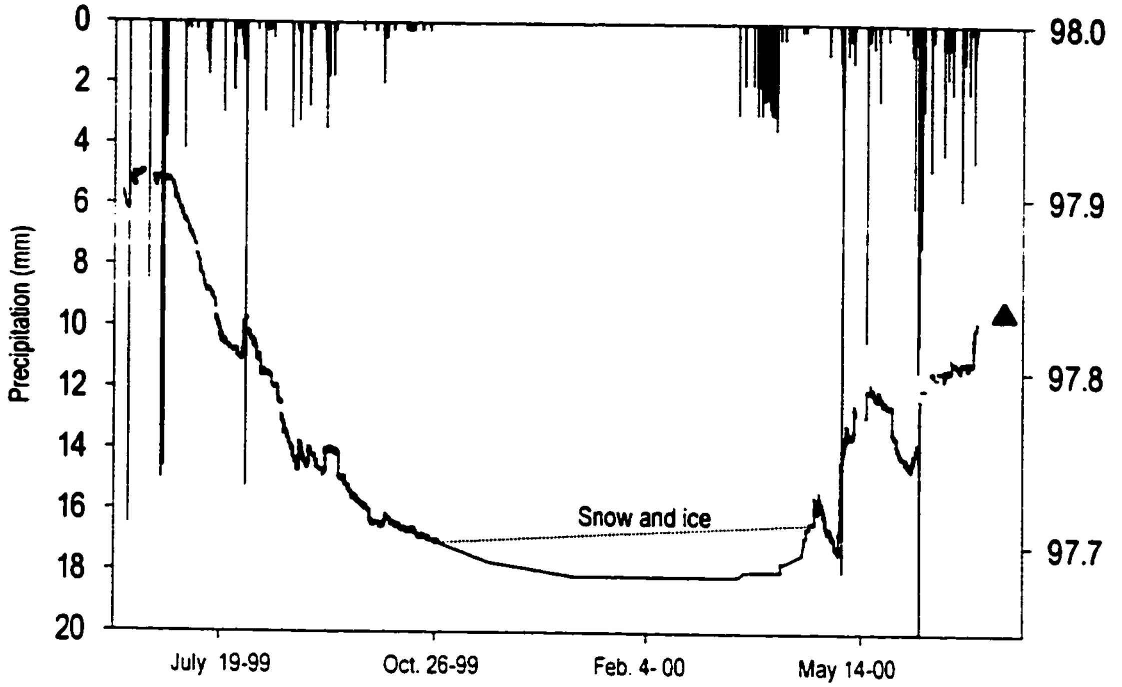

Figure 2-9. Moraine pond hydrograph (m) and precipitation (mm) from May 1999 to July 2000. Snowmelt occurs during March 27- April 15, 2000. ▲ represents the pond water level 50 days after the end of the study year (ie. Aug 28'00).

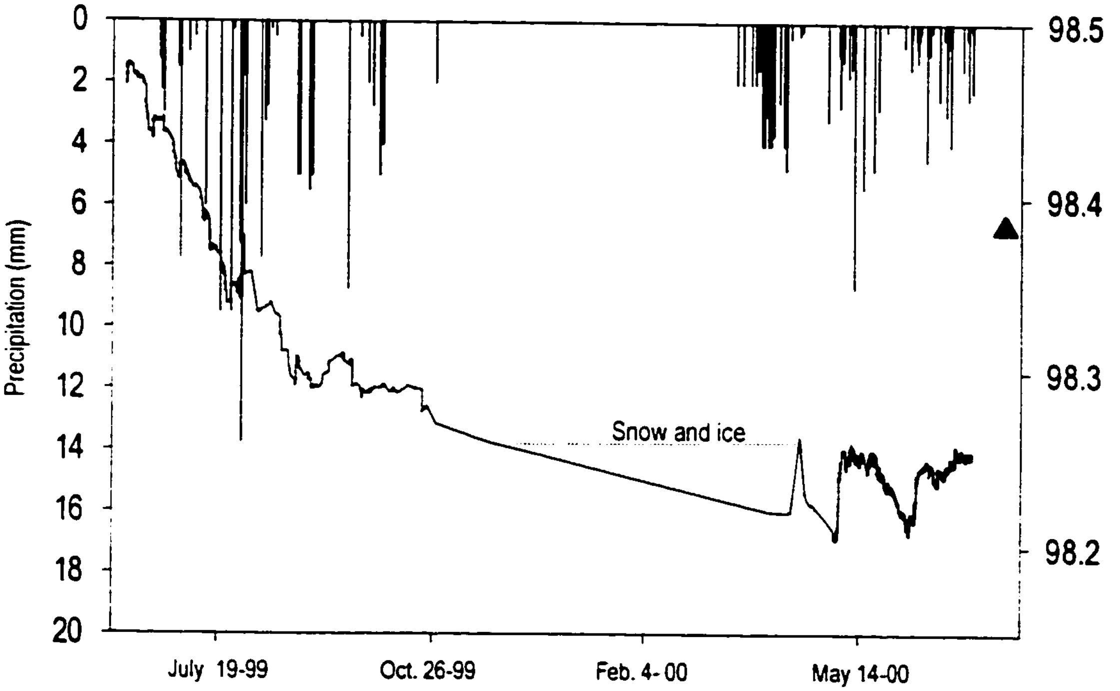

Figure 2-10. Lowland pond hydrograph (m) and precipitation (mm) from May 1999 to July 2000. Snowmelt occurs during March 27- April 15, 2000. ▲ represents the pond water level 50 days after the end of the study year (ie.Aug. 28'00).

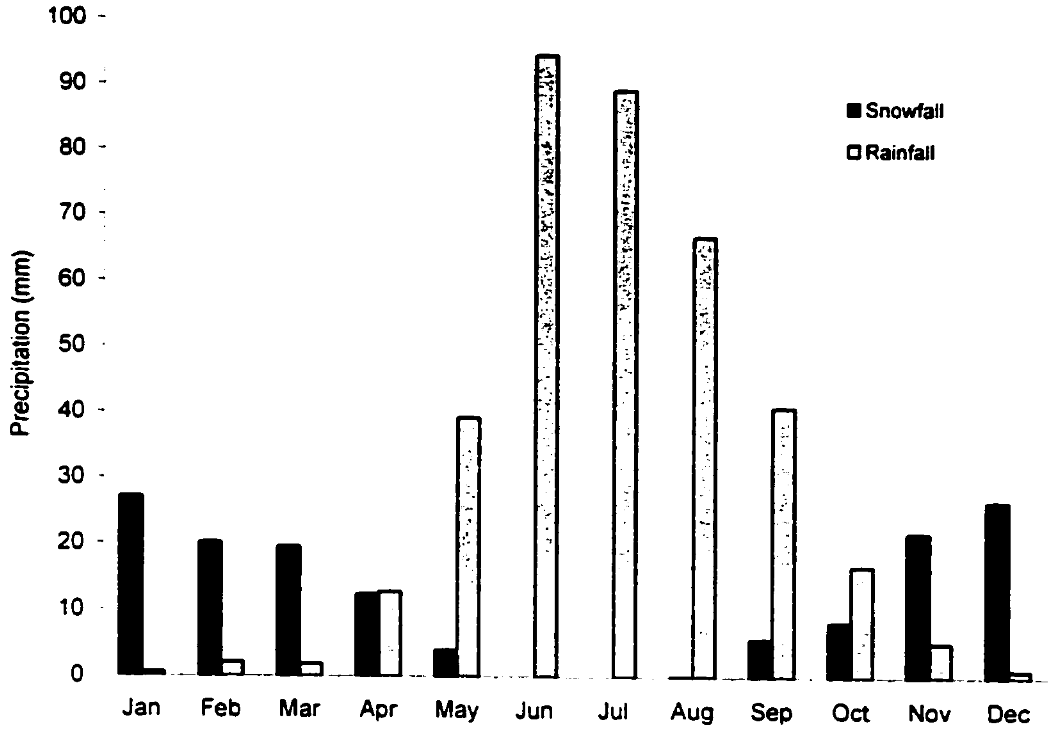

Figure 2-11. Longterm precipitation records for the Red Earth-Utikuma Area (1967-1990). The majority of precipitation falls as rain during the summer months. Source: Environment Canada 1997.

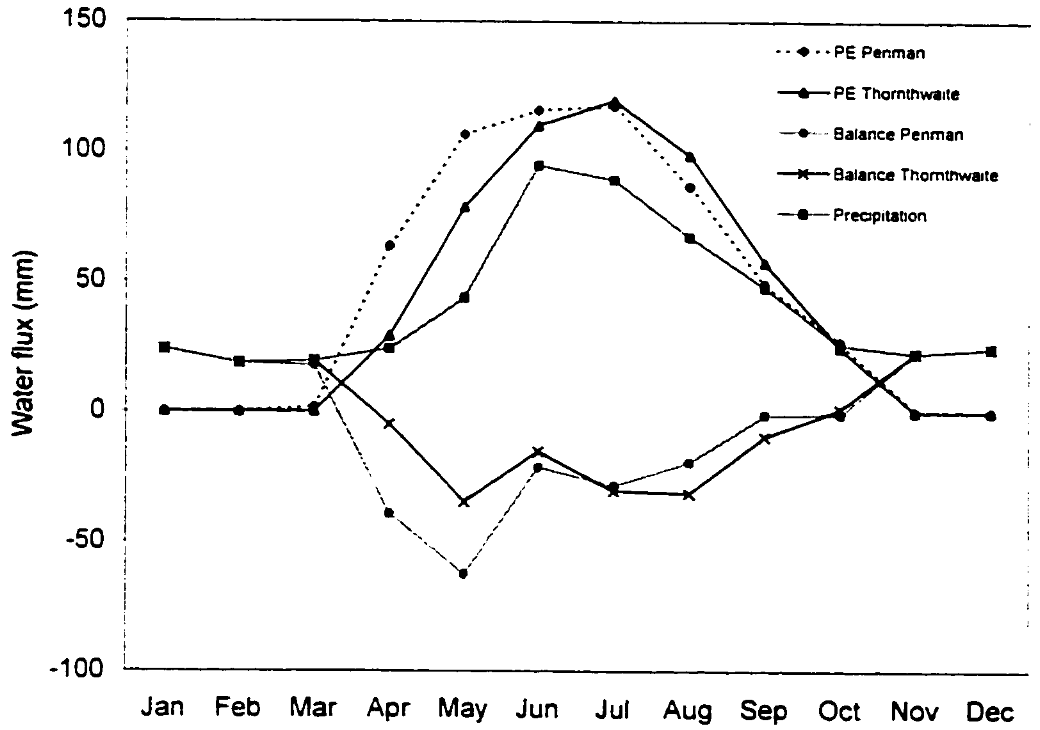

Figure 2-12: Longterm precipitation, PE (as Penman and Thornthwaite), and balance (P-E) records for the Red Earth-Utikuma Area (1967-1990). Source: Environment Canada 1997.

similar to the long-term averages. As a result, the study period appears to have captured a range of flow conditions: drier than normal conditions in 1999, wetter than normal conditions in May, normal conditions during spring 2000 (see Appendix A for runoff records).

Pond evaporation was calculated by two independent methods and compared to Thornthwaite potential evapotranspiration (PET) calculations (Table 2-2). Annual E values calculated using the mass transfer model were much lower than the evaporation pan values at both sites (46% lower). Due to the concerns of underestimation with the mass transfer model, and because of the similar temperature patterns of the pan and pond, pan E estimates were used in the calculation of the annual water balance (Appendix B). Using pan values, the moraine pond E was 394 mm yr^{-1} and the lowland pond was 438 mm yr^{-1}.

ET values calculated by the Thornthwaite method closely approximated pan E values (less than 4% difference for both ponds) (Table 2-2). Since values do not include winter sublimation (ie. net SWE of snowpack used in balance) which could represent 0 to 60 mm during this period (depending on method of calculation, see Figure 2-12), total annual E may actually be higher. If sublimation estimates are included, these locally measured values are slightly lower than the 30-year average 515 - 570 mm of ET for the region (Figure 2-12).

Table 2- 2. Monthly evaporation for the moraine and lowland ponds calculated by three methods. Winter values are not included since precipitation during this period (SWE) is presented as a net value (precipitation minus evaporation).

Date		Moraine			Lowland		
		Mass Transfer	Pan	Thornthwaite	Mass Transfer	Pan	Thornthwaite
		E (mm)	E (mm)	PET (mm)	E (mm)	E (mm)	PET (mm)
Jun	1999	38	75	71	--	83	71
Jul	1999	37	119	70	--	131	70
Aug	1999	20	89	75	--	98	75
Sep	1999	19	28	66	--	31	66
Oct	1999	10	11	33	--	12	33
Nov	1999	n.d.	8	19	--	8	19
Dec	1999	n.d.	n.d.	17	--	n.d.	17
Jan	2000	n.d.	n.d.	9	--	n.d.	9
Feb	2000	n.d.	n.d.	14	--	n.d.	14
Mar	2000	n.d.	n.d.	22	--	n.d.	22
Apr	2000	14	27	32	14	30	32
May	2000	28	73	42	29	69	43
Jun	2000	49	41	71	26	59	72
Jul 1 99 - Jun 1 00:		**183**	**394**	**420**	**84**	**438**	**426**

2.4.3 Seasonal Groundwater Flow Patterns

Upland Water Table Patterns:

Upland water table patterns in the deep well nests (P4 at the moraine, P5 at lowland) of both sites showed large seasonal fluctuations (Figure 2-13a and b), however, the amplitude of fluctuations was greater at the moraine site than at the lowland site (ie. 2.5 m vs. 1.5 m). Figure 2-13 shows that between September 1999 and May 2000, the water table in both uplands was below the pond surfaces (and peatland water table). Before and after this period the moraine upland water table was higher than the adjacent pond (and peatland water table). Although the deep well at the lowland was not installed until October 1999, the water table pattern is likely similar to that of the moraine during the summer 1999. The timing of the upland water table patterns corresponds to the same seasonal patterns as the pond surfaces, suggesting that P_r and ET are important fluxes to these hillslopes. However, well records at the base of some upland hummocks (ie. transition between upland and peatland) at the moraine site indicate that the water table was continuously below pond level, thus it appears that upland and wetland complex water table patterns were disconnected.

Seasonal Pond Hydroperiod:

Pond stage at both sites responded seasonally to changes in P_r and E. During the hydrologic year, the maximum range of pond level fluctuation at both sites was very similar: 22 cm at the moraine pond vs. 21 cm at the lowland pond (Figures 2-9 and 2-10). Pond water level was extremely responsive to individual rainfall events, with water table

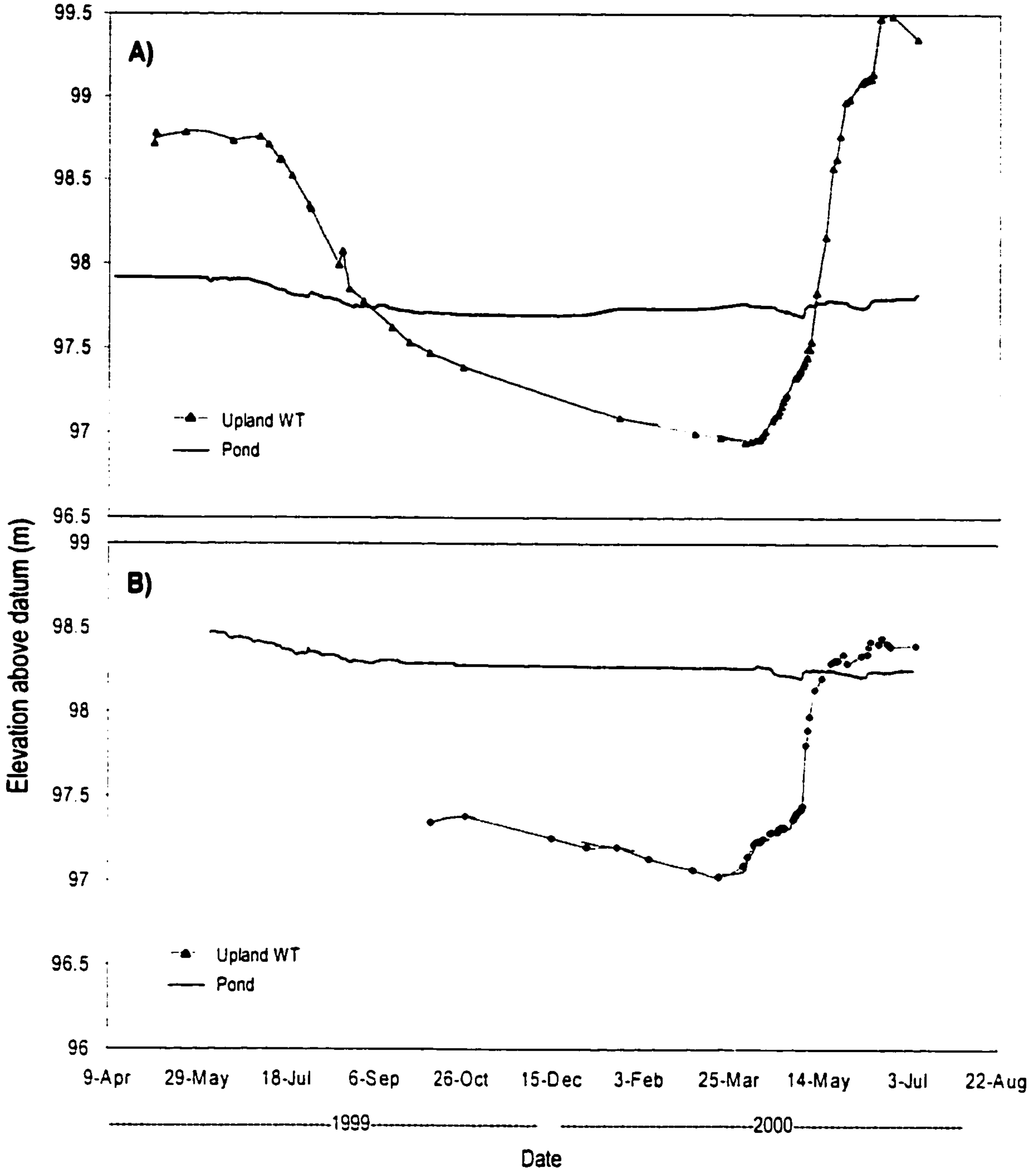

Figure 2-13 a and b. Upland water table fluctuations vs. pond stage at the moraine site (a) and lowland site (b). Moraine upland WT fluctuations are larger than at the lowland site.

rises generally similar to precipitation inputs. In response to the low precipitation in the summer of 1999, the pond stage dropped rapidly by early April 2000.

However, the timing of seasonal pond water level responses, and the magnitude of response to individual events differed between the sites. During the summer and fall of 1999, the moraine pond hydrograph showed a more rapid decline than that of the lowland (22 cm vs. 15 cm), as well as a sharper increase during the spring of 2000 (10 cm vs. 3 cm). During rain events in May and June 2000, the moraine pond level appeared to rise beyond the amount added by precipitation. For example, the moraine pond level rose 71 mm in response to a 57 mm event, and 55 mm in response to a 41 mm event, during this time, suggesting that groundwater seepage contributed to pond stage. Following similar events in May and June 2000 at the clay plain, the lowland pond level appeared to rise only in direct response to precipitation inputs. However increases in pond stage continued for longer periods, suggesting slower seepage inputs than at the moraine. Measurements of pond stage 50 days after the end of the hydrologic year showed that the moraine pond level had increases by 2 cm since July 1, 2000, while the lowland pond stage had increased by 13 cm (Figures 2-9 and 2-10). Therefore, overall seasonal increases or decreases in storage were attenuated at the lowland site.

Seasonal Peatland Groundwater Dynamics:

At both wetland complexes, the peatland water table tracked the seasonal patterns of the pond. The amplitude of peatland water table fluctuation ranged from less than half a metre in wells adjacent to the ponds, to over a metre in peatland areas furthest from the ponds. Generally, the moraine peatland water table fluctuations were uniform around the pond, while at the lowland site, the inflow edge showed greater fluctuation than the outflow edge.

Hydrographs of the moraine pond level and peatland water table show that seasonal reversals in groundwater flow direction occurred (Figure 2-14). Peatland wells at all edges of the moraine complex indicated that the peatland water table responded to high rates of ET and low P_r throughout the late summer and fall, and dropped below the pond level by September 1999 (Figure 2-14). During this dry period, shallow groundwater flow was directed away from the pond, through the riparian peatlands and towards the surrounding uplands, as demonstrated by transects 8 and 11 (Figure 2-15a and 16a). This pattern occurred uniformly on all sides of the pond, and the pond functioned entirely as a recharge system. This flow direction was sustained until May 2000, when a 40 mm rain event raised peatland water levels above the pond level (Figure 2-14). After this rain event, water table mounds formed at the peat domes and directed flow both towards the pond (pond discharge) and away from the pond towards the upland (Figure 2-15b and Figure 2-16b). During this wetter period, the entire littoral edge of the peatland discharged towards the pond. In parts of the peatland (i.e. transect #8), with continued precipitation the water table mounds expanded back towards the uplands (Figure 2-16b).

Hydrographs of the lowland pond level and peatland water table also demonstrated seasonal reversals in groundwater flow direction, but temporal and spatial patterns differ from those of the moraine (Figure 2-17). The peatland water table on the east edge was almost permanently above the pond (TR #1), indicating a continuous input throughout dry and wet periods. Water table elevation on the north and south side of the

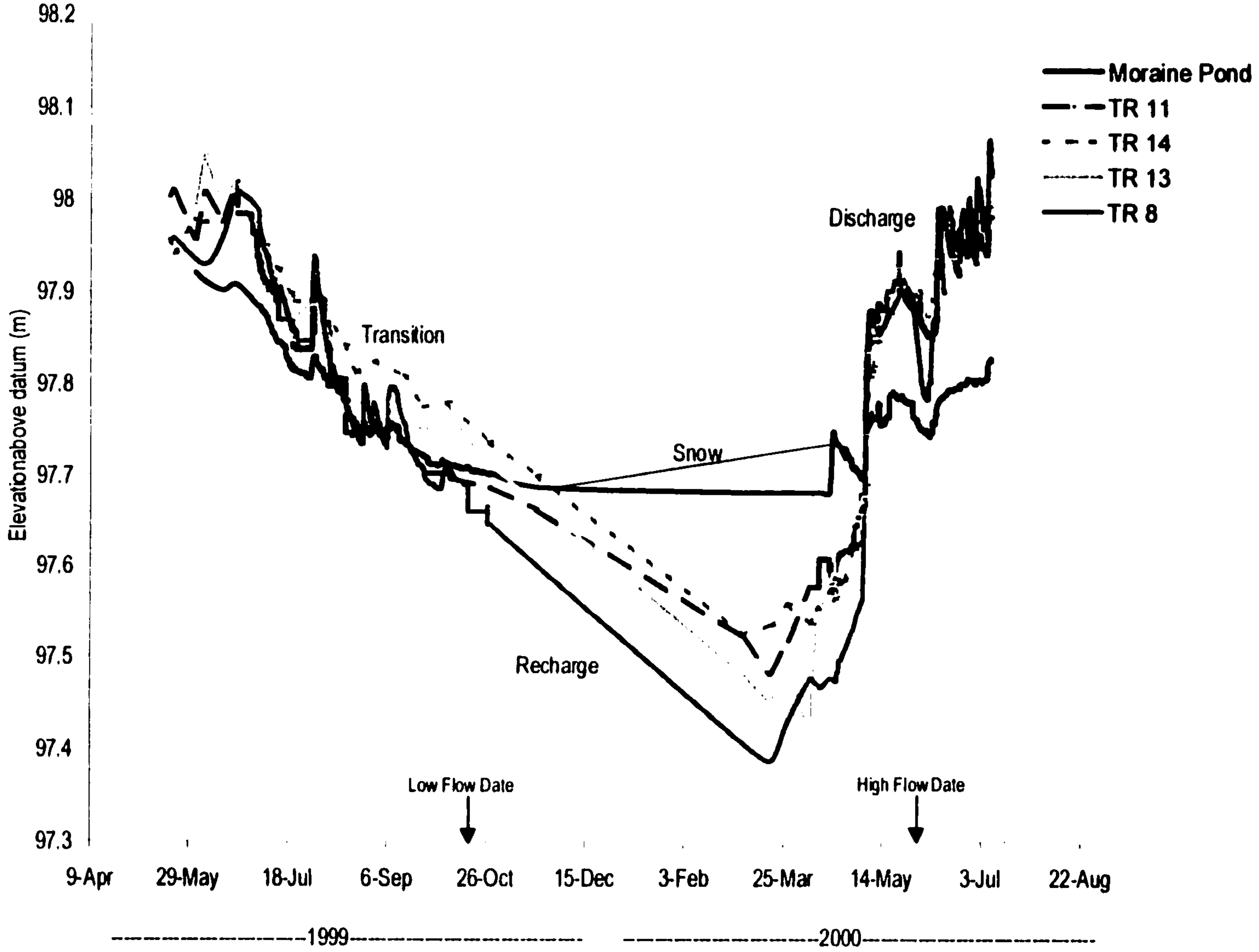

Figure 2-14. Hydrographs of the pond and peatland edge water table at the moraine wetland complex. The system switches between discharge to the pond and recharge from pond on all sides (TR# 11,14,13, 8 shown). Dates for flow diagrams (figures 2-15 amd 2-16) are indicated along X-axis.

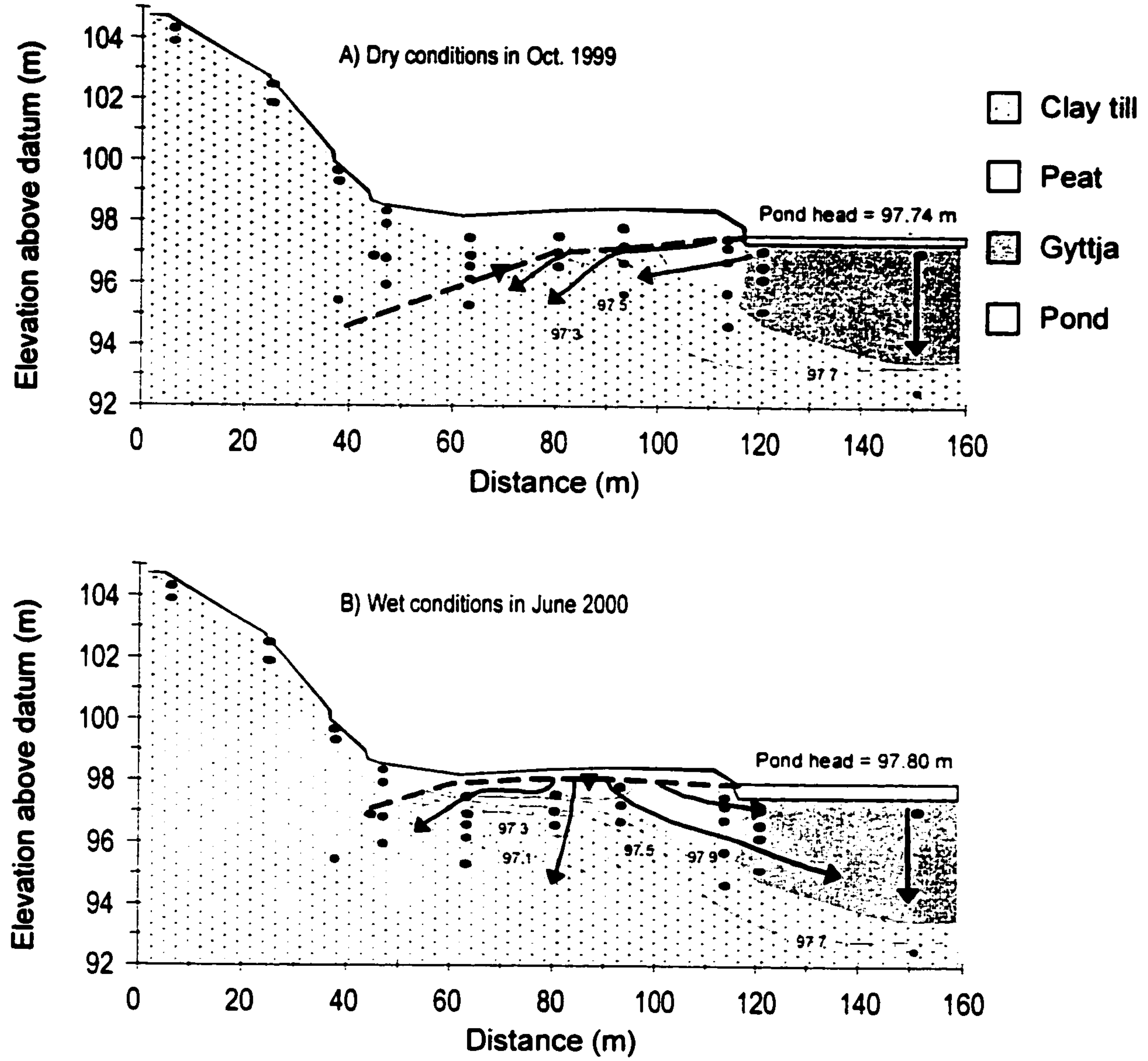

Figure 2-15. Flow diagrams for dry conditions (A) and wet conditions (B) at the hillslope transect (TR#11) Of the moraine wetland complex. The water table mound in (B) directs flow toward the pond and toward the hillslope during high flow.

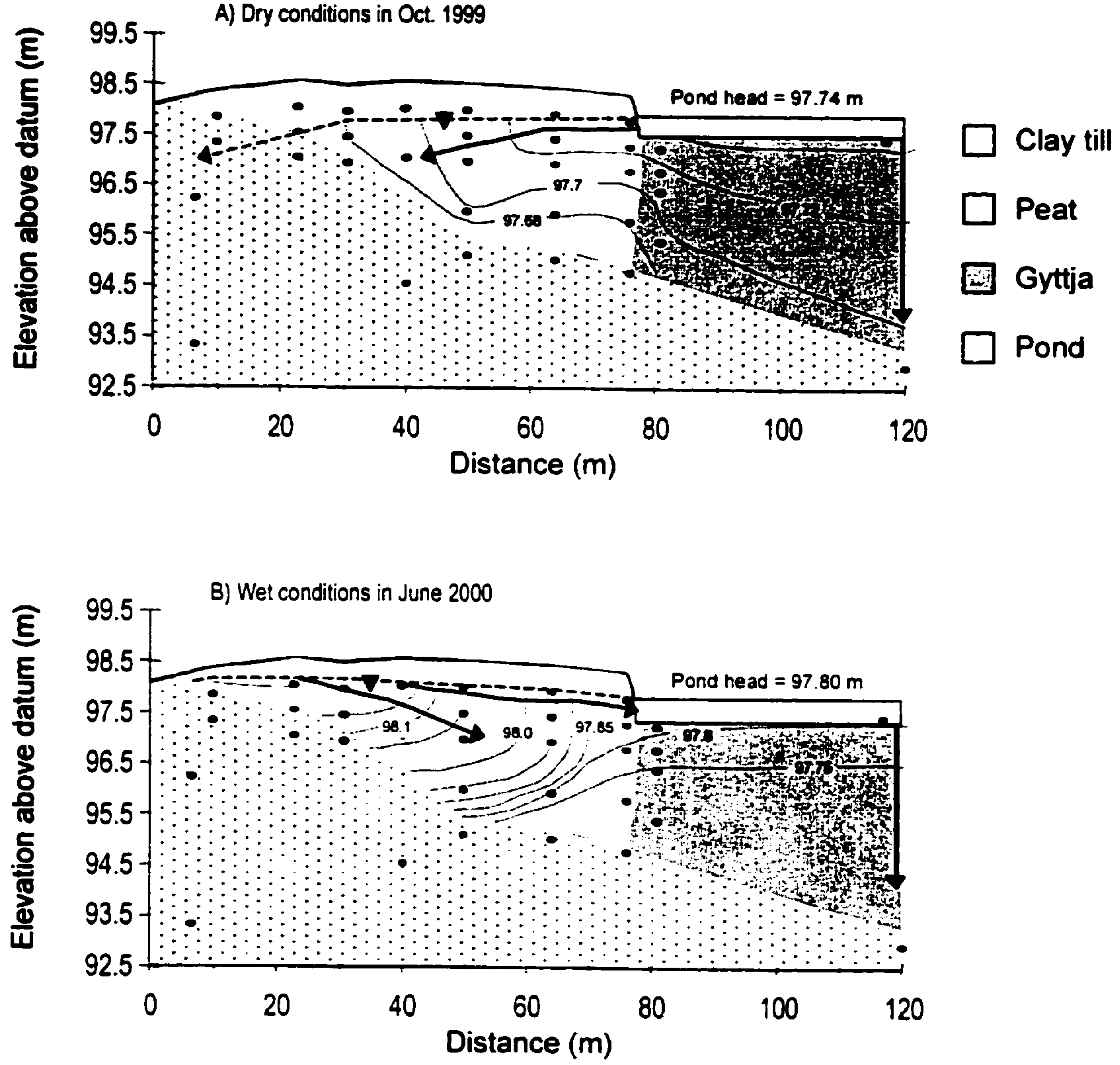

Figure 2-16. Flow diagrams for dry conditions (A) and wet conditions (B) at the SW transect (TR#8) of the moraine wetland complex. The water table mound in (B) directs flow toward the pond during high flow.

pond (perpendicular to the major axis of flow) switched between lower than pond during dry periods and above the pond during high flow periods. On the west side of the pond (TR#3) the peatland water table was lower than the pond for 10 months of the hydrologic year (Figure 2-17). Therefore, during the majority of the year, a "flow through" system existed, with an inflow along the northeast edge and outflow along the west edge (Figure 2-18a and Figure 2-19a). During the high rainfall in May 2000, flow through the upper peat at the inflow increased (Figure 2-18b). Additionally, water table mounds developed on the outflow edges of the peatland (transects 2,3, and 4), directing flow back towards the pond, producing discharge conditions on all pond edges (Figure 2-19b).

In both high flow and low flow conditions, the hydraulic gradients between the pond and peatland were low at both sites. At the moraine peatland, gradients ranged from +0.018 to -0.017, while at the lowland, gradients at the lowland site ranged from +0.026 to -0.01. These gradients are within the expected range for peatlands (Brooks 1992).

Monthly Shallow Groundwater Fluxes:

Variable groundwater flow conditions at both complexes produced seasonal variability in net groundwater function. At the moraine site, although the net annual flux was toward the pond, during the period of late September 1999 to early May 2000, the net groundwater flux was out of the pond (Figure 2-20a). At the lowland site, the pond functioned as net recharge system for a longer period (beginning of August 1999 to early May 2000) and the resulting annual net flux was low (Figure 2-20b). While the moraine site switched between recharge and discharge uniformly around the pond, the lowland

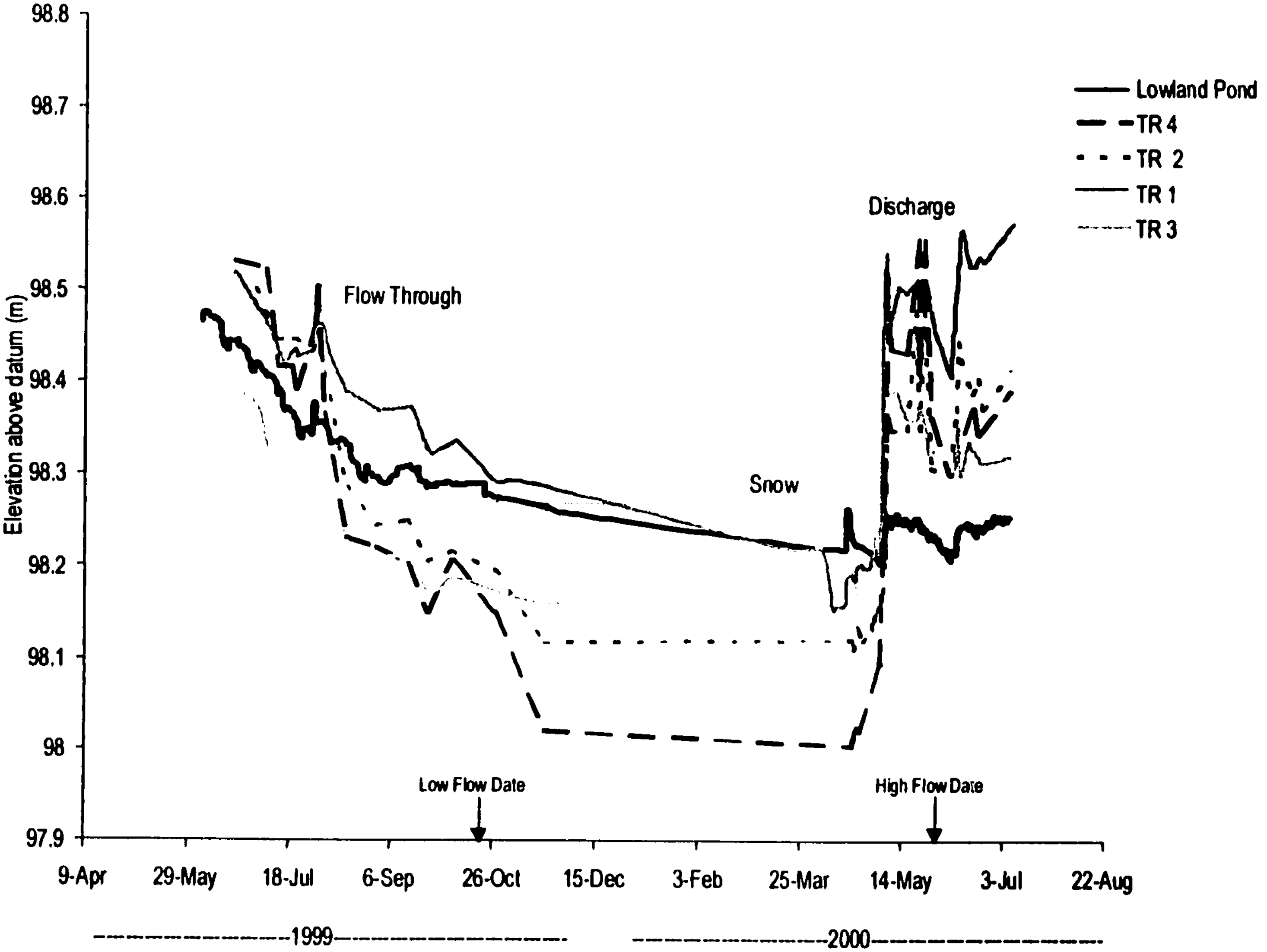

Figure 2-17. Hydrographs of the pond and peatland edge water table at the lowland wetland complex. The system is a flow through system for most of the study period but switches to a discharge system in May 2000. Dates for flow diagrams (figures 2-18 and 2-19) are indicated along X-axis.

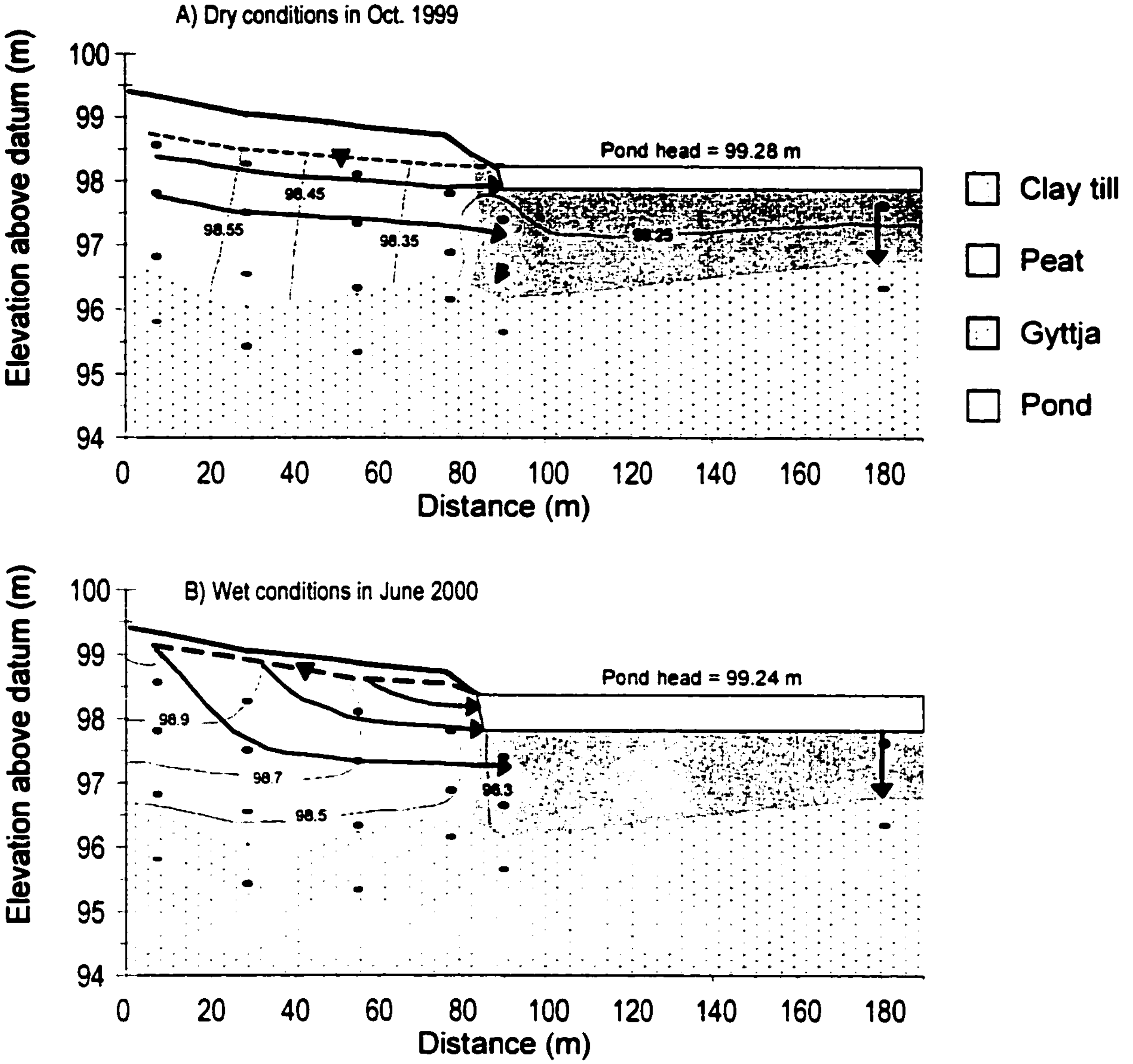

Figure 2-18. Flow diagrams for dry conditions (A) and wet conditions (B) at the inflow transect (TR# 1) of the lowland wetland complex. The elevated water table in (B) increases flow through the acrotelm toward the pond during high flow.

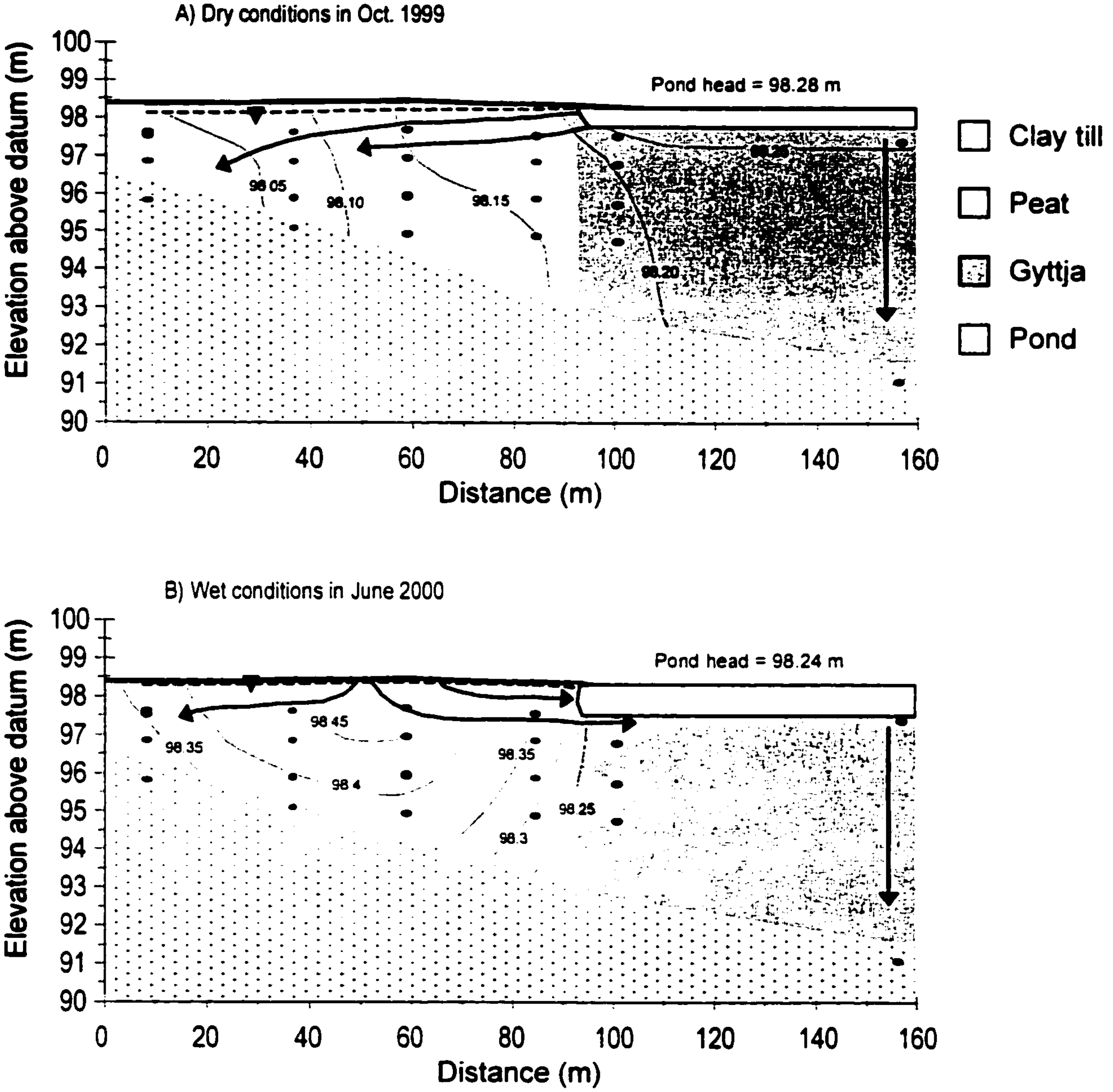

Figure 2-19. Flow diagrams for dry conditions (A) and wet conditions (B) at the outflow transect (TR#3) of the lowland wetland complex. The water table mound in (B) directs flow back toward the pond during high flow.

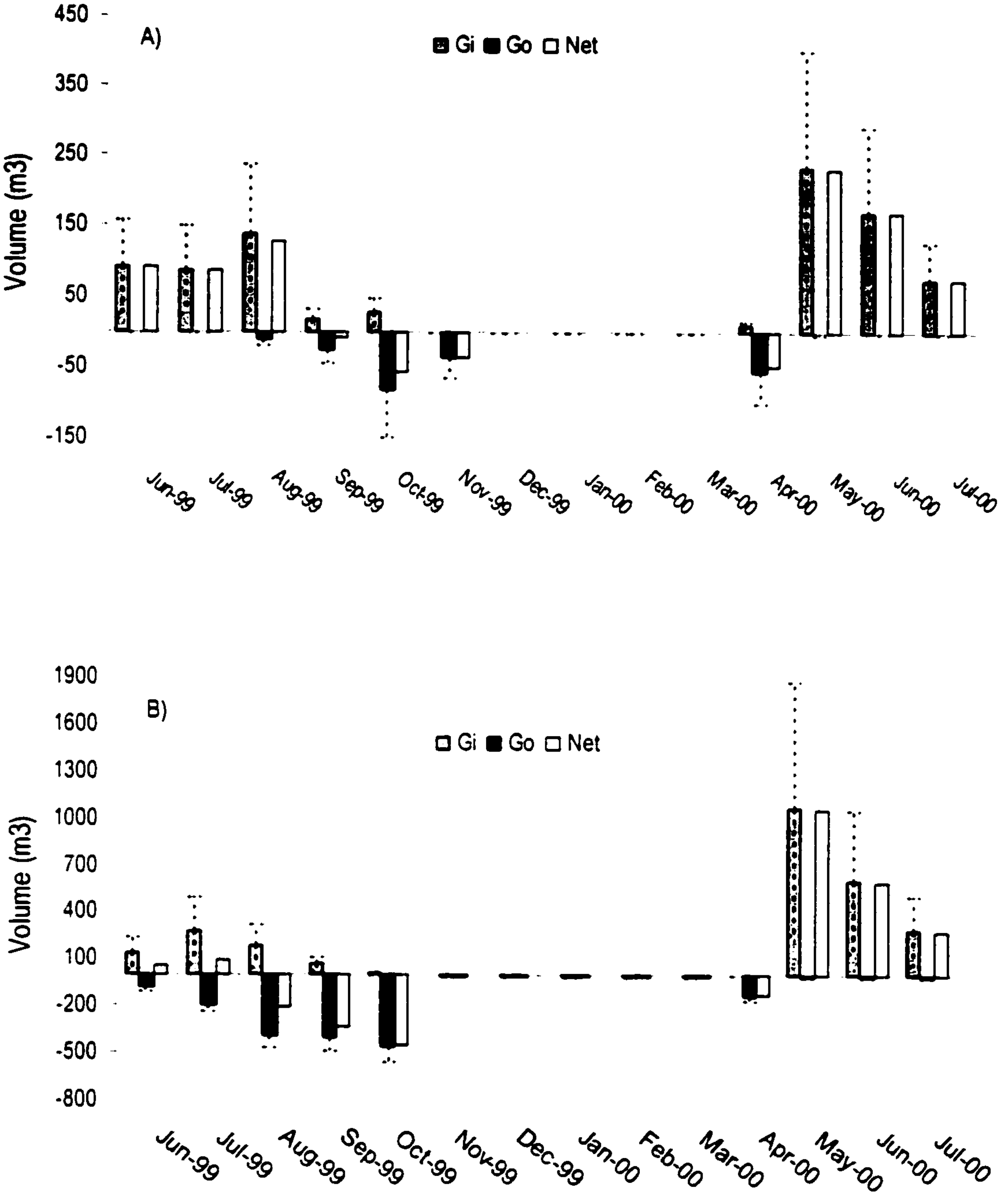

Figure 2-20 a and b. Monthly shallow groundwater fluxes: inputs (Gi), outputs (Go), and net flux (Gi - Go) at the moraine (A) and lowland (B) sites.

system functioned as a flow through system (June 1999 to May 2000), with concurrent groundwater inputs and outputs.

As a result of changing flow direction, large variation was observed in the magnitude of the groundwater fluxes at the two sites. During the highest flow periods (ie. May 2000), the moraine site received a total shallow groundwater input of 5.7 x 10^{-2} m^3d^{-1} while the lowland pond receives 1.2 x 10^{-1} m^3d^{-1}. During the low flow period (October 1999), the moraine pond lost up to 1.4 x 10^{-2} m^3d^{-1}, and the lowland pond lost up to 5 x 10^{-2} m^3d^{-1} of groundwater. The low estimates of winter groundwater movement occur because the ponds were completely frozen from the end of November 1999 to April 7, 2000 (Figure 2-20 a and b). Therefore, although the hydraulic gradients were directed away from the pond edge at the moraine site and as a flow through gradient at the lowland pond, it was assumed no water moved from the ponds. By April 18 surface ice at the pond edges had melted and groundwater exchange between pond and peatland resumed.

Groundwater and Pond Geochemistry:

Analysis of the interaction between pond water and shallow groundwater was conducted using DOC and Ca^{2+} end member plots (Figure 2-21 and Figure 2-22). By plotting source waters by these solutes, the dominant contributions to pond water can be evaluated. Precipitation has a dilute signature and represents an end member more dilute than surface water. Deeper mineral groundwater, a second potential source, is characterised by elevated Ca^{2+} and low DOC. The gyttja reflects intermediate calcium levels, but much higher DOC levels than the mineral groundwater. Finally the mesic peat

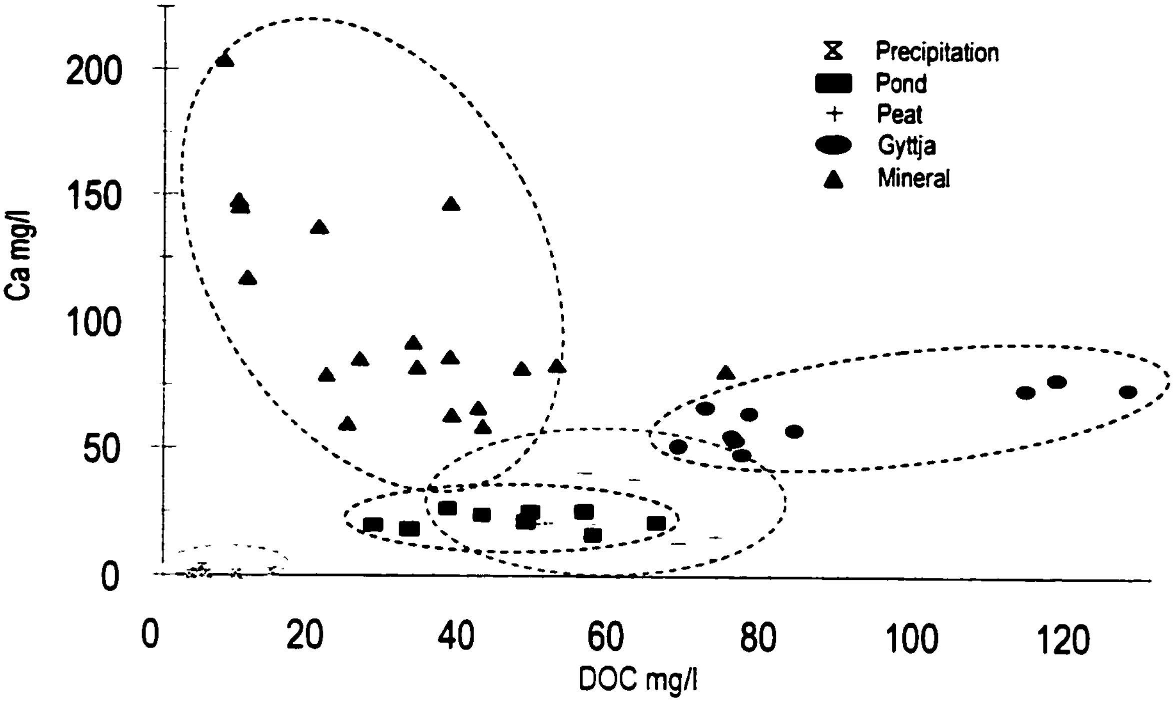

Figure 2 -21. Moraine complex geochemical signatures of precipitation, pond water, shallow peat groundwater, mineral groundwater and gyttja porewater. Pond water most strongly reflects peat signature.

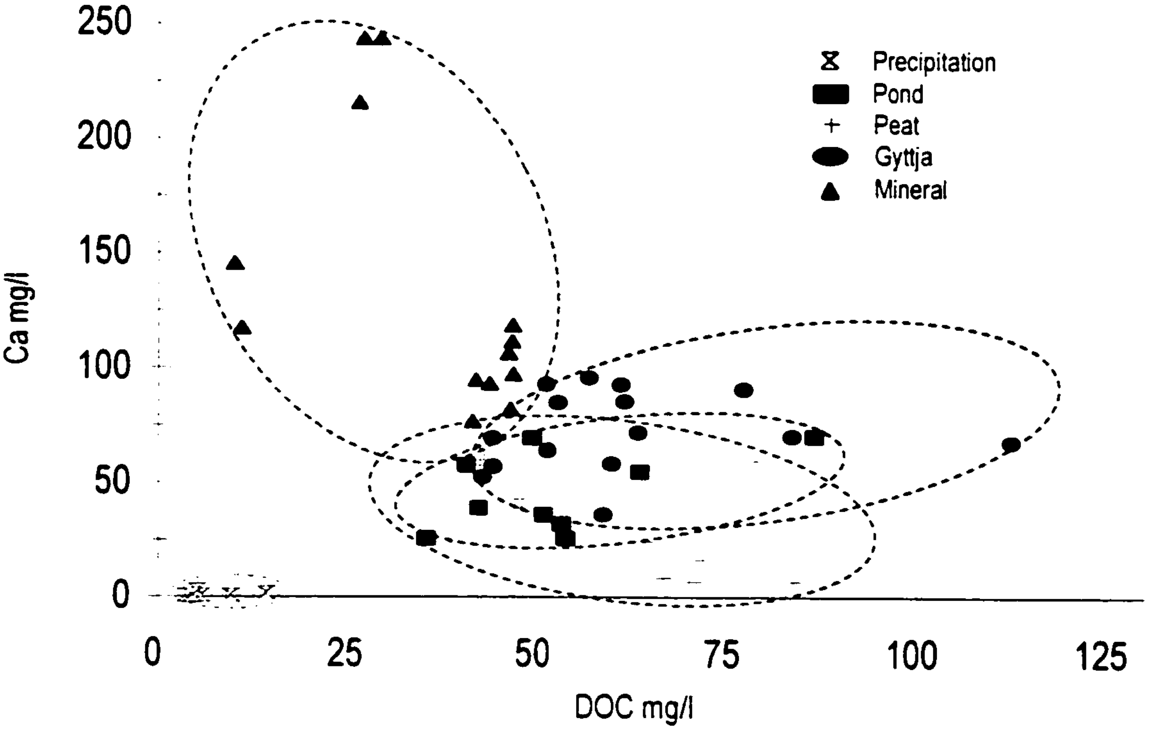

Figure 2-22. Lowland complex geochemical signatures of precipitation, pond water, shallow peat groundwater, mineral groundwater and gyttja porewater. Overall Ca concentrations are higher than the moraine site.

porewater, which reflects precipitation inputs, interaction with mineral waters as well as organic matter decomposition is characterised by intermediate DOC and Ca^{2+} concentrations. Although precipitation dominates the hydrologic inputs to the ponds, the pond signature at both sites exhibits higher levels of both DOC and Ca^{2+} than can be attributed to an atmospheric source. The moraine pond water appears to reflect the signature of mesic peat signature, suggesting lateral groundwater seepage is a more important control on pond chemistry than mineral upland sources. The lowland pond water has a signature that reflects mesic peat water sources and potentially, interaction with underlying gyttja.

In general, solute concentrations were higher at the lowland site. Calcium values in the pond water ranged from 20-30 mg l^{-1} at the moraine site compared to 25 - 75 mg l^{-1} at the lowland site. Moraine pond HCO_3^- concentrations ranged from 38.3 – 42.66 mg l^{-1}, but were much greater at the lowland site, where they ranged from 158.2 – 183.9 mg l^{-1} (Devito and Bayley, unpublished data). Conductivity values ranged from 66 – 151 μS cm^{-1} in moraine pond water, and again were almost twice as high at the lowland site (192 – 370 μS cm^{-1}). In contrast, DOC concentrations appeared to be quite similar (moraine: 25 - 65 mg l^{-1}; lowland: 30 - 80 mg l^{-1}).

As the end-member solute concentrations (mineral soils and precipitation) are similar at both ponds, differences in pond water concentrations are likely due to differences in the peat solute levels (Figure 2-21 mesic peat signature vs. Figure 2-22). Water residence time is similar in the two ponds (moraine: 1.2 yr. vs. lowland: 1.7 yr.), thus elevated solute levels in the lowland pond can not be simply attributed to higher evapo-concentration (Wentz et al. 1995, LaBaugh et al. 1997).

2.5 Discussion

2.5.1. Regional Scale Processes: The Moraine vs. the Clay Plain Setting

Regional Groundwater Flow System:

At the regional scale, both the moraine and clay plain areas demonstrated groundwater recharge over the study period. Vertical hydraulic gradients were slightly greater at the moraine site, however, the low hydraulic conductivity of the surface clay tills limited interaction with regional groundwater in both landscape positions. In the upland areas adjacent to the wetland complexes, vertical recharge rates through the till layers (>10 m depth) were estimated to range between 5 mm yr^{-1} at the lowland to 10 - 15 mm yr^{-1} at the moraine site. Although a small flux, these values suggest that recharge is slightly greater in the moraine area. Recharge through hummocky moraine areas is considered important for surface drift aquifers in the greater Utikuma region (Vogwill 1978). Vertical recharge through the clay till underlying the ponds was lower than in the uplands, and estimated to be less than 1 mm yr^{-1} at both ponds. This suggests that unlike many sloughs in the prairies, these ponds are not locations of "focused recharge" (see Lissey 1971). Generally, both upland and pond recharge rates fall within the range found by several other prairie studies of recharge through till (1- 45 mm yr^{-1}) (Hendry 1982, Horgan 1994, Hayashi et al. 1998).

The fact that the clay plain site did not show regional groundwater discharge may suggest that the study site is not situated at the terminus of the groundwater flow system. Although the lowland site is 15 - 20 m below the top of the moraine area, it is not the lowest topographic point in the greater Utikuma area, and therefore it is possible a regional discharge zone is located at a lower landscape position outside of the study area.

Artesian springs occur within 10 km of the lowland pond, and nearby flowing wells have been reported (Ceroici 1979), suggesting that the area does receive some regional discharge. However, it appears the presence of the >10 m clay till confining layer serves to isolate the surface hydrology from the underlying flow systems, and reduces the importance of regional flow to wetland hydrology. Vogwill (1978) noted that regional discharge zones in the area are effectively masked by this thick till drift. This suggests that, within areas characterised by low permeability clay till, the groundwater function of many wetlands located in topographic low areas will be dominated by local (or shorter) flow systems. For this reason, regional flow patterns at discharge positions may have little effect on surface wetland hydrology over a seasonal time scale.

2.5.2 Local Scale Processes: The Moraine vs. Lowland Wetland Complex

Dominant Fluxes - Water Balance:

Independent of topographic position, the dominant fluxes in these boreal wetland systems were atmospheric inputs and outputs. During the study, adjacent hillslopes did not generate runoff and surface inputs to the wetland water balance were negligible. Shallow groundwater inflow and outflow represented the most important non-meteoric fluxes for both ponds, yet on an annual basis, these fluxes accounted for a small proportion of the total balance (7 - 14%). Due to the low pond shoreline: area ratio at the lowland site, shallow groundwater represented a smaller input per unit area than at the moraine site, and precipitation a larger relative input. This refutes the initial hypothesis that predicted smaller relative inputs of precipitation and local flow at the low topographic position.

At both locations, the calculated water fluxes closely balanced (5 and 17 %). As groundwater is considered to be the measurement with the largest uncertainties involved (Winter 1981, LaBaugh et al. 1997), a small groundwater component reduces uncertainty involved in the total balance. The budgets showed positive residuals, indicating that uncertainties would likely be due to underestimates of E and/or Go. However, since the E values approximated estimates of annual PET, it is unlikely that these values could be much larger. Error in groundwater measurement was assessed by comparing the results of the hydrometric values to those of the calcium and isotope balances. Fair agreement among these independent estimates suggests that the groundwater fluxes measured are reasonable.

Dominant Fluxes - Atmospheric Fluxes:

The dominance of atmospheric fluxes and poorly integrated surface drainage observed herein are characteristic of most wetlands in the interior plains region of North America (Winter and Woo 1990, Hayashi et al. 1998a, Winter and Rosenberry 1998). However, climatic differences affect the hydrologic function of Boreal Plain wetlands differently from those in the prairie regions. Average precipitation across the prairie regions is slightly lower the western boreal region (long-term boreal = 450 - 500 mm yr^{-1} vs. long-term prairie range = 300 - 450 mm yr^{-1})(National Wetlands Working Group 1988). As well, the cooler temperatures of the Boreal Plains limit the evaporative flux in the summer (ie. long-term boreal E = 500 - 560 mm yr^{-1} vs. long-term prairie E = 560 - 1000+ mm yr^{-1}) resulting in larger open water systems that are less susceptible to seasonal "dry up", typical in wetlands south of the boreal limit (Price 1993, Winter and Rosenberry 1998).

Boreal plain wetlands also differ from peat systems in eastern boreal and temperate regions in terms of the magnitude and timing of precipitation inputs. These continental boreal systems receive ~ 50 - 60% of the precipitation inputs that peatlands in most other parts of Canada receive (National Wetlands Working Group 1988). Furthermore, unlike other peat and prairie systems, a relatively small snowpack, resulting from low snowfall and high sublimation, means that storage is not recharged during snowmelt (National Wetlands Working Group 1988). Based on long-term climate normals, major precipitation event occurs during late spring to summer, when soils are thawed and plant transpiration is high, therefore the likelihood of surface runoff is greatly reduced in these systems. As a result, shallow groundwater represents an important flowpath in these systems, as the primary connection between the ponds and their surroundings.

Although atmospheric fluxes of the water balance were measured with respect to the ponds, the relationship between P_r and E at or across the pond should be similar at the peatland, as well. Open water evaporation has been shown to be similar to PET for short vegetation systems (Dingman 1994). Actual ET in peatlands has been found to range between 98% to 288% of open water evaporation, depending on water table depth and vegetation cover (Boelter and Verry 1977, Koerselman and Beltman 1988, Brooks 1992). As PET was calculated to be within 5% of measured open water evaporation, it is likely that the peatland ET flux was only slightly larger than the measured E in the ponds. As well, interception by trees and shrubs might slightly limit the precipitation input to the peatlands. With potentially less P_r and slightly greater ET, the negative balance could be slightly greater in the peatland than the pond. This potential for greater water loss combined with the specific yield of peat help to produce steep hydraulic gradients between pond and peatland during dry periods.

Upland-Peatland Groundwater Connections:

Despite the large hydraulic gradients produced between uplands and adjacent wetlands, the fact that water table at the peatland and upland hillslopes transition remained below the pond, indicate there was little groundwater exchange between the hillslopes and the wetlands. Furthermore, seasonal groundwater flownets indicated that shallow groundwater flow from the peat was often directed beneath the hillslopes.

The large water table fluctuations observed in the uplands are likely due to the "dual porosity" of the clay till (Winter and Rosenberry 1995). Previous work in the prairies has shown that oxidized surface glacial tills often tend to be vertically fractured in the upper layers (Hendry 1982, Winter and Rosenberry 1995) as a result of desiccation during dry climate phases, and disturbance due to glacier movement (van der Kamp and Hayashi 1998). In previous studies, it was found that infiltration prompted rapid vertical water table response, since the infiltrating water followed the fracture orientation. In contrast, horizontal water movement to the pond was found to be very slow, limited by the lower horizontal K values of the clay matrix (Winter and Rosenberry 1995), as observed in the Utikuma area. Other mechanisms have also been attributed to water table configuration in clay. For example, Gerla (1992) and Rosenberry and Winter (1997) noted steep vertical rises in water table as a result of infiltration into the capillary fringe of clay soils. Again, in such cases, the lateral flow was suggested to be limited. As a result of the low permeability surface clay and elevated soil moisture deficits in the Utikuma area, the upland landscape appears to have limited control on wetland hydrology on a seasonal basis, regardless of topographic position.

Seasonal Pond Hydroperiod Patterns:

As isolated systems, neither pond received continuous inputs of regional groundwater, and therefore seasonal water level fluctuations occurred in response to atmospheric fluxes at both sites. In this respect, Boreal Plains functioned similarly to prairie sloughs in low permeability till areas, where surface storage is greatly dependent on exchange of water with the atmosphere (Winter and Rosenberry 1998). However, although the hypothesised connection to a larger flow system didn't influence either pond, small differences in seasonal amplitude and period of pond fluctuations did exist. Most notably, seasonal increases and decreases in surface storage were attenuated at the lowland site compared to the moraine site. These hydroperiod patterns appeared to be controlled primarily by two catchment characteristics: effective peatland storage in the local drainage basin (ie. flowpath length) and pond shoreline: area ratio.

During the study, the mineral uplands generated very little runoff, thus contributing area to the ponds consisted exclusively of peatland. The potential for peatland discharge from the peatland to the pond is influenced by the total peatland storage, but is also limited by the connectivity of the peatland to the pond. Peatland storage generally has generally been considered to be a function of peatland size (Boelter and Verry 1977, Brooks 1992), which suggests that continuous inflow at the lowland site might be a function of the slightly larger peatland (relative to pond size). Perhaps more important is connectivity between pond and peatland. If peatland areas within the catchment do not directly connect to the pond, the storage may not affect pond discharge. If so, the total groundwater reaching the ponds might be determined by the flowpath length of the immediately, adjacent riparian peatland, which represents an effective (or useful) storage. The moraine complex is an irregular, isolated basin where the majority of the peatland is not directly connected to the pond (Figure 2-2), therefore flowpaths influencing pond hydroperiod originate from a small percentage of the peatland in the catchment. In contrast, glacial activity in the clay plain setting resulted in larger, connected basins and therefore, expansive peatland systems. Thus, longer shallow groundwater flowpaths to the pond are generated in the lowland basin, which represent larger effective storage for discharge to the pond. As observed during the study, this larger groundwater connection sustains constant inflow to the pond. By preventing reversals to pond recharge conditions, surface storage is conserved. While the influence of this shallow groundwater connection might not be as large as a regional groundwater source, it appeared to have moderating effects on pond hydroperiod. Furthermore, if patterns of peatland storage and connectivity are related to topographic position, then landscape position may have importance for pond permanence.

Pond shoreline: area ratio is a second catchment characteristic that controls the rate of groundwater supply to the pond. Since rates of groundwater exchange are low in these pond-wetland complexes, the seepage area (as shoreline length) relative to the pond volume is an important control on the magnitude of shallow groundwater fluxes. It follows then that pond shoreline: area (and/or shoreline: volume) influences pond hydroperiod by limiting the extent of groundwater exchange with the pond (Price 1993, Hayashi and Van der Kamp 2000). On account of it's smaller size and increased pond shoreline: area ratio, the moraine pond level appeared to drop and rise quickly in response to the autumn and spring groundwater flow reversals. In contrast, a smaller pond shoreline: area ratio at the lowland complex decreased the relative groundwater exchange between the pond and riparian peatland, and as a result, the lowland system showed a slower rate of pond water level decline throughout the autumn given the same E demands as the moraine site. Similarly, due to this low ratio, the larger lowland pond responded more slowly to the high flow recharge events.

These catchment controls on hydroperiod may have implications for pond permanence during drought. For example, during a drought in North Dakota, almost all sloughs located in high or intermediate topographic positions dried during the first year (Winter and Rosenberry 1998). Those situated in low topographic positions that received even small groundwater inputs persisted for 2 to 4 years. While the source of shallow groundwater in the Boreal Plain systems originates in adjacent peat, large storage in the lowland peatland may serve a similar function of sustaining input to surface water during drought conditions. Furthermore, if persistent dry conditions drove both systems to be completely recharge systems, due to the greater pond shoreline: area ratio at the moraine complex, groundwater recharge would be faster, and the moraine system would likely dry more quickly. Studies conducted in the northern prairies have employed a shoreline: volume indicator to predict prairie slough resistance to seasonal drying (Millar 1971, Price 1993), and determined that those with the largest ratios recharged water more rapidly, and tended to be ephemeral or semi-permanent systems. In a survey of parkland

and prairie sloughs, Price (1993) found that sloughs with ratios of less than 0.1 m m^{-3} tended to be permanent and only dried completely less than 1% of the time. As well, these larger sloughs were generally located in the northern parkland. Using this index, the Boreal Plains complexes rank within the "permanent wetland" category (moraine = 0.093 m m^{-3}, lowland = 0.015 m m^{-3}), nonetheless, after prolonged drought conditions, the moraine pond would be more susceptible to drying than the lowland.

As large peatland storage (relative to pond size) appears to sustain shallow groundwater inflow to the pond, and since increased shoreline: area ratio appears to increase exchange of groundwater between peatland and pond (ie. both inflow and outflow), the combination of these characteristics may determine the hydroperiod for any individual, isolated peatland-pond complex within this low relief setting (Figure 2-23). Determining how these catchment characteristics may correlate to landscape setting could prove useful in predicting pond permanence, but requires further study.

Seasonal Shallow Groundwater Reversals:

As hypothesised, the two complexes differed in their susceptibility to flow reversals, and reversals showed differences in spatial extent across pond-wetland complexes. However, as neither wetland complex was connected to a larger groundwater flow system, these dynamic flow conditions only involved local peatland flow cells. The peatland surrounding the moraine pond switched almost uniformly between recharge during dry periods and discharge to ponds during the wet periods. All edges of the moraine peatland responded similarly during the event, with the exception of a slight lag

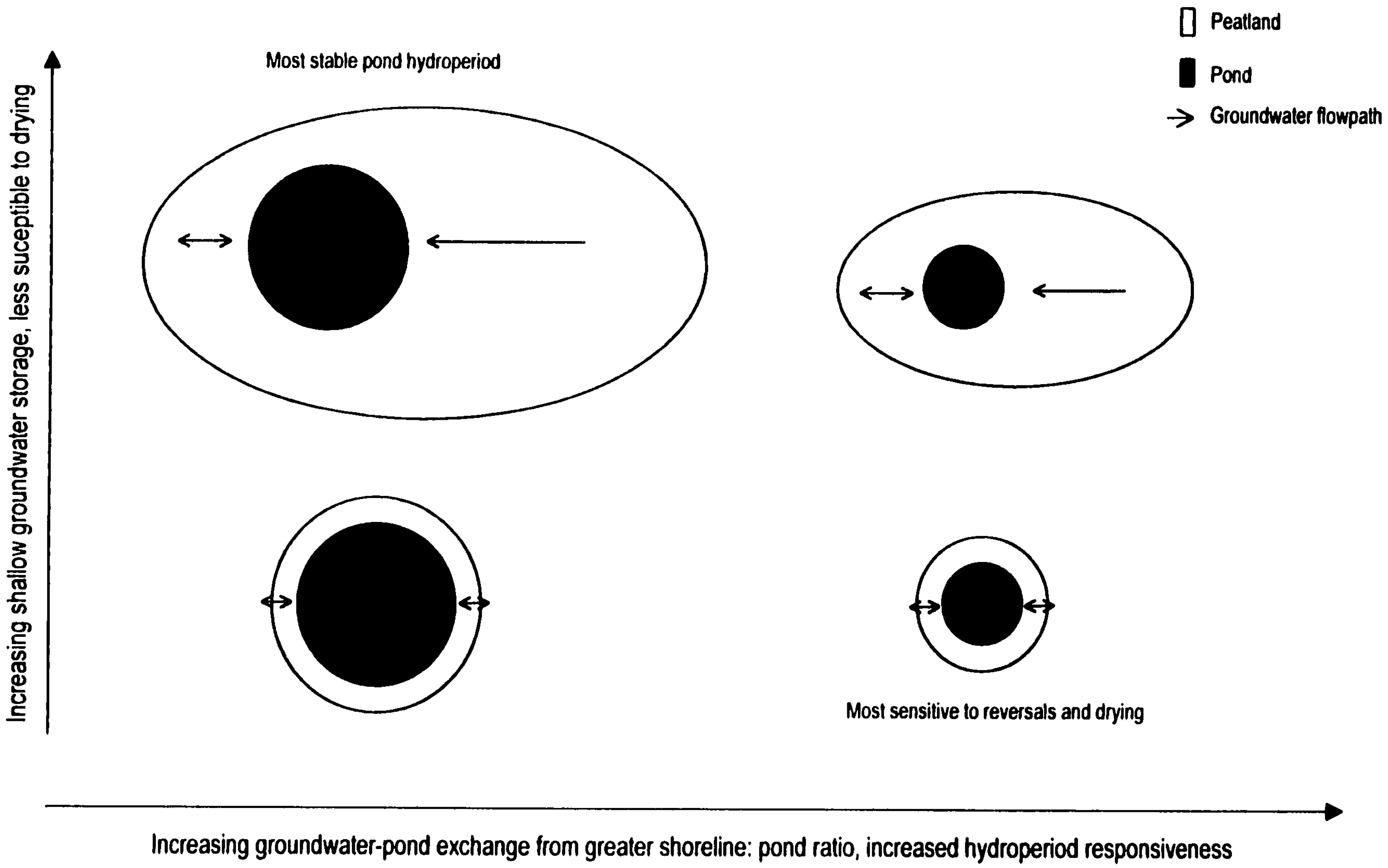

Figure 2-23. The interacting effects of peatland storage (ie. groundwater flowpath length) vs. pond shoreline: area ratio (extent of exchange between pond and peatland) on pond hydroperiod.

in response on the SE edge. With continued precipitation inputs at the moraine site, some water table mounds extended back towards the upland and large sections of the riparian peatland contributed shallow groundwater flow to the pond. The occurrence of reversals in both 1999 and 2000 suggest that groundwater flow conditions are dynamic and seasonally variable at the moraine site.

In contrast, the lowland system functioned predominately as a flow through system for most of the study period, with flow reversals limited to the S and N sides, perpendicular to the major axis of flow. The Northeast edge of the pond served continuously as an inflow to the pond throughout the study, while the west shoreline functioned as an outflow for the majority of the year. However, after the heavy rains in May and June 2000, the formation of a water table mound caused flow along this outflow transect to reverse. This mound created a hydraulic dam, preventing the outflow of groundwater away from the lowland wetland complex. The persistence of this mound beyond May and June 2000 is unknown, but could have important implications for summer water and nutrient transport (see next chapter). The high spatial variability in groundwater flow conditions suggests that high-density sampling is required to capture the range of groundwater – surface water interactions at the lowland site. A single piezometer transect between the wetland and the pond would provide limited flow information.

Reversals in hydraulic gradient and groundwater flow direction have been documented in peatlands (Siegel and Glaser 1987, Devito et al. 1997, Waddington and Roulet 1997, Fraser et al. 2001), and prairie slough wetlands (Meyboom 1966, Winter 1989, Winter and Rosenberry 1995, LaBaugh et al. 1998, Hayashi et al. 1998a, van der

Kamp and Hayashi 1998). However the temporal and spatial patterns of reversals in the Boreal Plain are controlled by different driving mechanisms. In prairie sloughs of southern Canada and the northern United States, reversals occurred in response to both ET demands in the mineral rich phreatic (riparian) zone during summer (Meyboom 1966, van der Kamp and Hayashi 1998), and bank storage during spring melt (Winter and Rosenberry 1995). In both circumstances, the prairie reversals were driven by local groundwater interactions between the pond and surrounding upland. In large eastern peatlands, flow reversals have occurred in response to seasonal changes in local and regional groundwater flow interactions resulting from drought (Siegel and Glaser 1987. Romanowicz et al. 1993). In eastern peatlands isolated from regional groundwater, flow reversals were shown to result from water deficits at the peatland surface, in response to ET alone (Devito et al. 1997. Waddington and Roulet 1997. Fraser et al. 2001).

In Boreal Plain peatlands. reversals were initiated by variable hydraulic gradients with adjacent ponds, and occurred most dramatically in response to large rainfall events. rather than drought conditions. The specific yield of peat determined the peatland water table height for a given water volume, and water table configuration responded dramatically to P_r or E fluxes to produce positive or negative gradients towards the pond. During the transition from dryer to wetter periods, the formation of water table mounds at the peat domes served to initiate positive gradients towards the pond.

These dynamic patterns of recharge and discharge at both wetland complexes are similar to patterns in other peatland systems. The presence of peat domes within a low regional gradient , promotes local flow cells and lateral flow reversals (Reeve et al. 2000). However, the flow patterns in the Utikuma wetland complexes are also similar to those observed in the prairie regions in that the flow reversal involves a horizontal flow path between surface pond water and the surrounding riparian soils. However, because of the boreal climate, Boreal Plain systems are forested and develop peat deposits (National Wetlands Working Group 1988), both of which modify the timing and magnitude of groundwater fluxes. The high permeability of the peat permits rapid water movement in response to daily changes in atmospheric conditions. Therefore, the groundwater fluxes in these systems are extremely dynamic and can transport water to or from the open water at higher rates than observed at many mineral wetlands of the interior plains.

2.5.3 Long-term Influence of Topographic Position

Although the groundwater patterns observed during this short-term study suggest little connection between the wetland complexes and their surrounding landscape, there is some evidence that landscape position may influence wetland function over longer time scale. The lowland complex is typical of wetlands on the clay plain in that it is a large peatland basin that contains a larger pond. While larger, permanent ponds and wetlands are often associated with regional groundwater discharge in drier prairie regions (Winter and Woo 1990, Winter 1999), differences in regional recharge rates related to landscape position could also contribute to differences in wetland volume. The greater recharge rates, deeper water table and larger water table fluctuations suggest that the moraine setting is a more important recharge area than the clay plain (Freeze and Cherry 1979). While regional recharge rates did not influence the wetland complex water balances over the study period, on a longer time scale they could hold importance for wetland storage. If so, the higher recharge rates at the moraine setting would result in deceased surface storage, and the larger lowland wetlands and higher water tables could reflect long-term patterns of groundwater "flow through" at the clay plain glacial drift.

Additionally, a difference in solute concentrations between the two wetland complexes suggests differences in groundwater flow regimes (Winter 1989). The moraine pond was generally more dilute, while the higher levels of calcium in the lowland pond suggest a connection to a longer (or deeper) groundwater flowpath. Since the lowland complex has continuous groundwater input, high pond concentrations could simply reflect its continuous Ca^{2+} source, whereas the moraine receives intermittent seasonal pulses of Ca^{2+} during high flow conditions. However, the peatland groundwater calcium concentrations in the lowland system are also higher than those of the moraine, suggesting more interaction with the surrounding and underlying Ca^{2+} rich, clay till. Elevated levels could possibly reflect long-term diffusion patterns from the underlying clay, or perhaps could be due to past prolonged wet periods, when positive pressure developed in the groundwater underlying the wetland and resulted in slow upward discharge through the peats. In either case, the difference in solute concentrations between the systems implies that topographic position may play a role in controlling wetland hydrology over a longer time scale.

2.6 Conclusion

The conclusions of the study are as follows:

Objective 1:

H1: A change from groundwater recharge to discharge conditions with a decrease in topographic position was not observed during the study. Two scales of flow appeared to determine the hydrologic function of pond-peatland complexes in the Utikuma area. At a regional scale, both wetland complexes demonstrated recharge over the study period. Slight differences in the vertical gradients between the two sites suggest topographic position may influence recharge rates, but the low conductivity tills limit water movement at both locations. The lowland site may not have reflected regional discharge conditions for two reasons. The lowland complex did not represent the lowest topographic point in the region, and possibly is situated above the discharge zone of the system. Secondly, the presence of a 10 m clay till confining layer appeared to isolate the surface from the underlying flow systems.

As a result of this confining layer, a second scale of hydrological processes was observed at the wetland complexes. These local flow systems were very dynamic and reversed between patterns of groundwater recharge and discharge at both the topographic high and topographic low sites. Therefore, the hypothesis that wetland recharge and discharge function was controlled by topographic position was not supported. This suggests that the development of such large-scale groundwater flow systems is limited by the lithology of the Mixedwood Boreal Plains.

H2: A shift from local flow (surface water and shallow groundwater) and atmospheric fluxes dominating the water balance towards increasingly large regional groundwater inputs was not observed with the change from high to low topographic position. At both wetland systems atmospheric fluxes (P_r and E) dominated, while shallow (local) groundwater represented the most important non-meteoric water source. In fact, due to the smaller pond shoreline: area ratio in the lowland area, shallow groundwater represented a smaller proportion of the annual water balance, and P_r and E had relatively greater importance than at the moraine site. These findings reflect fluxes during a relatively dry year, and the relative importance of non-meteoric contributions at both sites might increase under wetter periods.

Objective 2:

H3: Seasonal hydroperiod patterns differed between the two wetland complexes. However the differences in water level patterns appeared to be due to differences in storage and shoreline: area relationships rather than connection to a regional groundwater system.

The response of the pond surface to seasonal events also differed between complexes. Pond surface levels in the moraine and lowland systems responded similarly to the precipitation events, but overall increases or decreases in storage were attenuated at the lowland site. Due to its smaller surface water storage and its smaller shoreline: area ratio, the moraine pond level decreased and increased quickly in response to the autumn and spring groundwater flow reversals. The position of the lowland pond within a larger peatland basin provides greater basin storage and prolonged groundwater "flow through" conditions. As a result, the lowland system showed a slower pond water level decline throughout the autumn. Likewise, in the spring, the larger lowland pond took longer to respond to recharge events. Therefore, although the hydroperiods did vary between the complexes, the locally driven mechanisms differed from those hypothesized.

H4: Landscape position influenced the sensitivity of the wetland complexes to groundwater flow reversals, however the differences were not dramatic. Although the water balance at each site was dominated by atmospheric exchange, both complexes demonstrated seasonally dynamic shallow groundwater flow patterns. Both wetland systems experienced dynamic reversals between locally recharging and discharging conditions, however some differences between the high and lowland system were apparent. The moraine peatland showed a uniform pattern of groundwater flow at all pond edges, switching between recharge and discharge to the pond in response to hydraulic gradient changes. The lowland peatland functioned primarily as a flow though system with smaller hydraulic gradients along the major flow lines, making it less susceptible to seasonal reversals. However, rapid peatland water table responses during the extended high flow conditions induced a groundwater flow reversal on the outflow edge during the spring 2000, and along the N and S sides of the wetland. Since neither system appeared to be influenced by underlying larger groundwater flow system, or adjacent hillslopes, these seasonal reversals were locally driven, and differences were a function of wetland storage and basin morphometry.

The geochemical signature of the ponds reflects the importance of this seasonal linkage between shallow groundwater and the ponds. In both systems, pond surface water chemistry appears to reflect the peatland porewater signature, indicating that although precipitation controls the amount of pond water available, shallow groundwater flowpaths dominate pond chemistry. The elevated solute concentration in the lowland pond might reflect continuous, longer flowpaths to the pond, while the more dilute moraine pond receives intermittent pulses of shallow groundwater. The differences in peatland geochemistry indicate that landscape position may play a role in influencing the wetland environment on a longer time scale. These patterns indicate that peatland to pond interactions are dynamic and need to be understood in order to predict boreal pond water quality and ecological function.

Finally, the extremely dynamic patterns observed in this study suggest that high frequency measurements are necessary in order to capture the complex flowpaths that may occur in these systems. Sampling only a few times a year could provide a very misleading picture of dominant pathways, and could result in erroneous calculations in water balances and chemical transport.

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Chapter 3: The role of seasonal groundwater patterns on the phosphorus dynamics of two Boreal Plain wetland complexes in contrasting landscape positions.

3.1 Introduction:

Recent accelerated rates of industrial development in northern Alberta have lead to extensive forest disturbance (AEP 1998, Global Forest Watch 2000). In some ecosystems, forest removal and landuse conversion has been linked to increased nutrient loading to adjacent aquatic systems (Knighton and Steigler 1981, Cooke and Prepas 1998, Lockaby et al. 1999). Depending on the dominant flowpaths to a pond or lake, landscape disturbance may alter the timing and magnitude of hydrologic inputs, thereby altering nutrient pathways and transport to adjacent lakes and wetlands (Evans et al. 2000, Devito et al. 2000). Wetlands and lakes of the Boreal Plains ecoregion of the Western Boreal Forest (WBF) may be particularly sensitive to changes in nutrient loading, because they are shallow and phosphorus rich (Vitt et al. 1995, Cooke and Prepas 1998). Small increases in P to ponds or wetland complexes can shift threshold communities, negatively affecting habitat suitability and water quality (Prepas et al. 2000). While managers have sought to protect aquatic systems from watershed disturbance by leaving riparian forested zones or wetlands, the effectiveness of such buffers in different landscapes has been questioned (Emmett et al. 1994, Devito et al. 2000). Without an understanding of the dominant pathways for water and nutrient exchange between water bodies and their riparian areas, the impact of watershed activities is difficult to predict. This chapter examines the patterns of phosphorus transport and exchange between two shallow ponds and their surrounding riparian peatland areas in the Mixedwood Boreal Plain of Northern Alberta.

Wetlands cover 20-50 % of the Boreal Plain region, and fens and bogs are the dominant wetland types (National Wetlands Working Group 1988, Kuhry et al. 1993, Vitt et al. 1995). While extensive flat bogs and horizontal fens are prone to develop in large flat basins (National Wetlands Working Group 1988), the Boreal Plains landscape is also characterised by numerous small, isolated wetlands and ponds of glacial origin (Vogwill 1978). In the Utikuma region, wetland-pond complexes develop in small basins, and commonly support diverse wetland types; (ie. shallow ponds are surrounded by a combination of open and treed bog/fen, thicket swamp and shoreline marsh (Bayley and Devito, unpublished data). Unlike wetlands in other boreal regions, wetlands at the southern edge of the Boreal Plains have been shown to be nutrient rich and productive (Vitt et al. 1995, Thormann and Bayley 1997). These conditions provide optimal wetland habitat for many water birds, and the WBF represents one of the most important waterfowl habitats in North America (Ducks Unlimited 1998). In order to protect and effectively manage this wetland habitat, the hydrologic controls on nutrient dynamics of shallow ponds and their surrounding peatlands needs to be understood.

Not all wetland complexes will respond similarly to watershed disturbance (Bedford 1999, Lockaby et al.1999). Landscape or hydrogeologic position can determine the relative importance of an upland-wetland connection, as well as connectivity to underlying aquifers, and the atmosphere (Devito and Hill 1996). The dominant linkages to the wetland will control the timing and magnitude of groundwater and surface water flow inputs, degree of interaction with the underlying sediments, and the chemistry of source waters (Roulet 1990, Brinson 1993, Hill and Devito 1997). Size of a groundwater flow system (ie. local vs. intermediate or regional) will influence the concentration of solutes and the dominant forms of chemical species imported into wetlands (Winter 1989, Hayashi et al. 1998). Studies have shown that wetlands receiving groundwater from a larger flow system will reflect the geochemistry of longer flow paths (e.g. increased salinity) (Freeze and Cherry 1979) and the underlying geologic material (e.g. glacial tills) (LaBaugh et al. 1998). In contrast, wetlands influenced by local groundwater flow reflect shorter flowpaths (lower salinity) and near surface chemistry (Winter 1989, LaBaugh et al. 1998). Wetlands, for which the majority of their water enters as precipitation, typically have more dilute chemical signatures (Winter 1989).

In the Western Boreal Plains, the poor surface water drainage suggests that groundwater connections may be an important minerotrophic water source to wetland complexes (Chapter 2), and seasonal and annual changes of groundwater flow may have implications for wetland biogeochemistry. Several studies in the Interior Plains have shown that although shallow groundwater seepage represents a small portion of the total inputs in several lakes and wetlands, it has an important influence on the surface chemistry of the systems (Shaw et al. 1990, Wentz et al. 1995, LaBaugh et al. 1997, Hayashi et al. 1998). Additionally, variable water levels and groundwater flow direction in wetlands can have important implications for redox conditions, elemental transformations and ultimately transport (Hill and Devito 1997, Waddington and Roulet 1997).

The nutrient and hydrological connections between large Alberta boreal lakes and their surroundings have been studied (Shaw et al. 1990, Evans et al. 2000, Devito et al. 2000). However, to date, studies of nutrient-hydrologic interactions between shallow ponds and wetlands of the Alberta boreal region are limited. Some wetland studies have related water table fluctuations to wetland water chemistry (Vitt et al. 1995, Halsey et al. 1997, Thormann et al. 1998), but few of these have examined shallow pond systems, how surface and subsurface flow connect in boreal wetland complexes, or examined how these linkages translate to nutrient transport. Recently, a study investigating how the hydrologic and ecological functioning of Boreal Plain wetlands (Hydrology, Ecology and Disturbance of boreal wetlands (HEAD) study) was initiated. Initial surveys have shown a trend of increasing salinity and phosphorus in surface water, with a shift from topographically high moraine areas to topographically low clay plain areas, suggesting that landscape position may influence groundwater nutrient transport. Within the framework of the HEAD project, this study examines the role of riparian peatlands in generating and/or influencing phosphorus transport to shallow pond systems in the Boreal Plain. By examining wetland complexes in two contrasting landscape positions (moraine and clay plain), this study attempts to incorporate a range of wetland groundwater flow patterns and nutrient dynamics.

Objectives:

The objectives of this study are to investigate the relationships between hydrologic flowpath, hydroperiod and phosphorus dynamics in pond and riparian peatlands:

1) To determine the importance of groundwater transport to the annual phosphorus balance of two boreal wetland complexes in contrasting landscape positions.

H1: The lowland wetland complex should receive groundwater inputs from a larger flow system and reflect elevated phosphorus concentrations of the underlying glacial drift. The moraine pond should reflect the lower phosphorus conditions of shallow groundwater flowpaths that have limited interaction with the P rich drift. .

2) To examine the effect of groundwater flow reversals on phosphorus exchange patterns at two shallow ponds and in their adjacent riparian peatlands, and to determine the extent (timing and magnitude) of reversals relative to landscape position.

H2: Peatland groundwater flow reversals have large control on seasonal P concentrations in the ponds.

H3: Flow reversals are more likely to occur at the moraine system. therefore, moraine pond water should show seasonal pulses of P that reflect the reversing flow conditions. The lowland site should not reflect these same seasonal patterns.

3) To examine how water table fluctuations affect redox conditions and peatland porewater P concentrations in the two wetland complexes.

H4: The water table at the lowland site should be higher and less variable than the water table at the moraine site, and peatland areas at the lowland site should show more reduced conditions and higher porewater phosphorus concentrations than found at the moraine site.

3.2 Site Description

General Region:

The two study wetlands are located in the Mixedwood Boreal Plains Ecozone of northern Alberta, at the transition between the Mid and High Continental Boreal Subregion (National Wetlands Working Group 1988) (Figure 3-1a). These pond-wetland complexes were selected from 24 wetlands that form the Utikuma Region transect of the Hydrology, Ecosystem, and Disturbance of Boreal Wetland Study (HEAD). The study area is characterised by low relief of rolling to undulating moraines, glacial outwash areas, and level lacustrine plains (Tóth 1978, Vogwill 1978, Mitchell and Prepas 1990). The major surficial unit is glacial till, which ranges from 20 to 240 m in thickness (Ceroici 1979). These unconsolidated deposits overlie the Smoky Group shale unit of the Upper Cretaceous period (Vogwill 1978, Ceroici 1979). Glacial drift represents the primary aquifer for surface waters (Tóth 1978, Vogwill 1978), and therefore moraine uplands represent recharge zones for the area (Vogwill 1978, Ceroici 1979). Surface drainage diverges in this region but eventually drains into the Peace Basin: streams in the SE portion of the Utikuma study area connect with the Wabasca tributary, and streams in the NW section connect to the Smoky tributary (Vogwill 1978). Generally, the canopy vegetation consists of aspen *(Populus tremuloides)*, balsam poplar (*Populus balsamifera*)

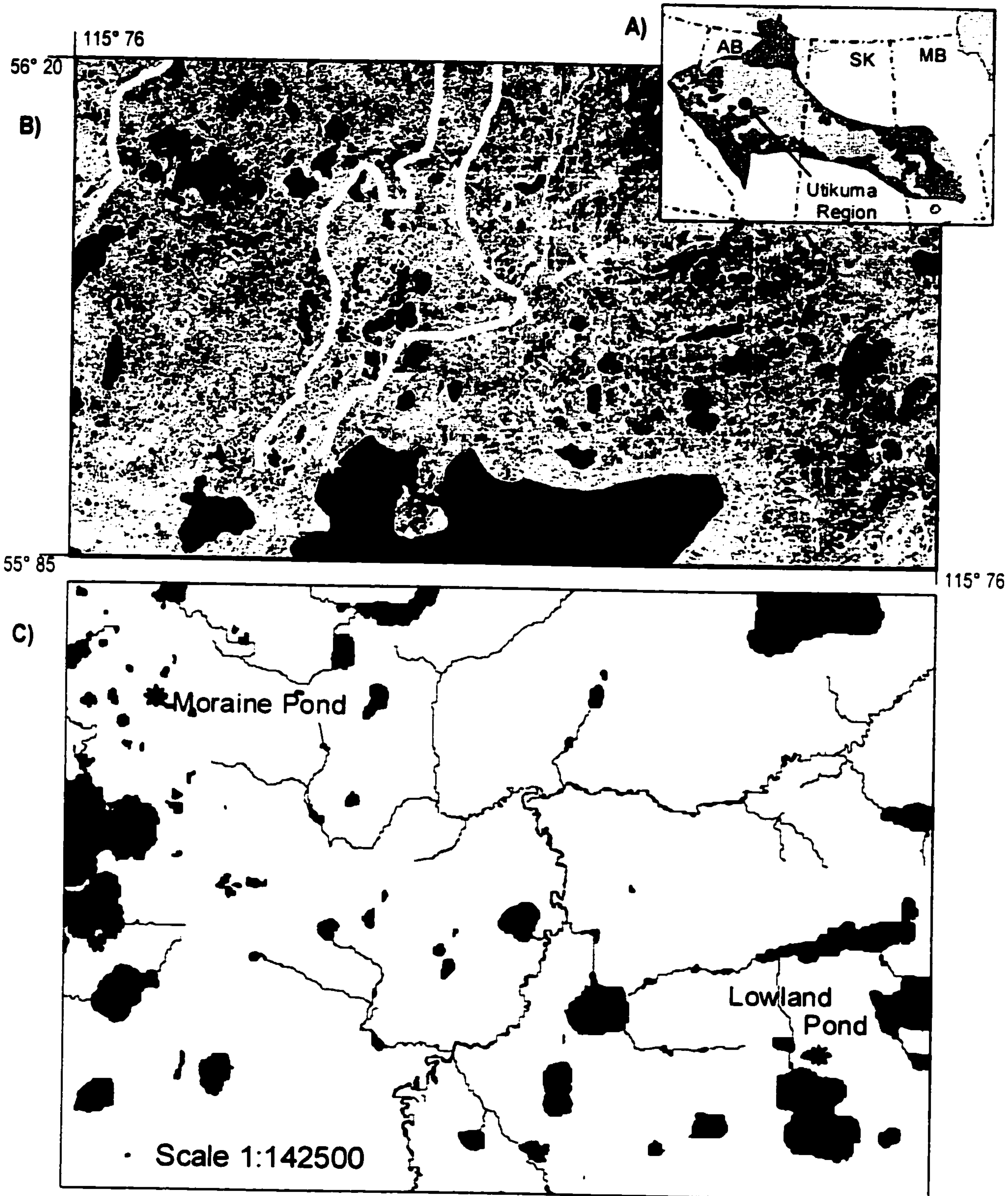

Figure 3-1 A) The Mixedwood Boreal Plains located within the Canadian interior plains with the Utikuma study area identified in Alberta. B) The three landscape settings within the Utikuma study area: Outwash, Moraine, and Clay plain. The box (white dash) indicates the area enlarged in C. C) The moraine (56° 07' 34 N; 115° 46' 99 W) and clay plain (55° 98' 25 N; 115° 19' 36 W) study wetland complexes located among the many boreal ponds and wetlands. The distance between the two sites is approximately 15km.

and white spruce (*Picea glauca*) forests in uplands, and black spruce (*Picea mariana*) dominates peatlands in poorly drained (National Wetlands Working Group 1988). Wetlands cover 25 – 50% of this region and include large expansive peatlands (ie. horizontal fens), basin bogs and fens, shoreline marsh and pond-peatland complexes (National Wetlands Working Group 1988).

Summer (July) and winter (January) mean temperatures for the area are 15.7°C and –14.6°C (Environment Canada 1998). Annual precipitation (P_r) and evaporation (E) in the region are roughly in balance: long-term P_r is 515 mm yr^{-1} and long-term E values range from 517 yr^{-1} (Thornthwaite estimation) to 567 mm yr^{-1} (Penman estimation) (Environment Canada 1997). Runoff is typically less than 100 mm yr^{-1} (see Appendix A)(Environment Canada 1987). Typically, 50-60% of annual precipitation occurs from June to August, followed by dry autumn months (Environment Canada 1997). Winter snow pack is typically less than 100 mm yr^{-1} snow water equivalent (SWE), representing less than 25% of total annual precipitation (Environment Canada 1997).

Study Sites:

Two wetland complexes were selected from two of the three geomorphologic zones in the area: one is located in the moraine area (topographic high: 56° 07'34 N; 115°46'99 W), and the other in the topographic low of the region, on the clay till plain (55° 98'25 N; 115°19'36 W) (Figure 3-1b and 3-1c). Change in elevation between the two sites is approximately 20 m. The depressions (clay basins) containing wetlands tend to be larger on the plain than in the moraine area, but both sites consist of a shallow pond

(< 1 m depth) surrounded by peatland (both treed bog/fen and thicket swamp) and aspen dominated upland areas (Figure 3-2).

Both complexes are depression wetlands within clay till basins. The moraine pond-peatland complex is irregular in shape and is surrounded by hillslopes up to 7 m in height. The lowland pond and wetlands are larger and regular in shape, and relief within the catchment is less than 3 m. The moraine catchment is 17.4 ha, of which the pond, wetland, and upland area constitute 8%, 60%, and 32% of the catchment area respectively. The lowland catchment is 144.2 ha of which the pond, wetland, and upland area represent 8 %, 51 % and 41% of the area.

The upper top 30-50 cm of the upland hillslopes at both complexes consists of a sandy silt loam (luvisol) (Figure 3-3). Beneath this, the hillslopes are characterised by oxidised beige clay till to a depth of 5 - 8 m, with grey unoxidised till underneath. The treed fen areas at both sites consist of fibric peat in the upper 30 - 40 cm, and mesic peat to a depth of approximately 1.5 m, which overlies mesic-humified peat to a depth of up to 3.5 m. At the moraine site, the thicket swamp portion of the peatland has dark brown mesic peat to a depth of approximately 0.5 - 1 m overlying clay till. In contrast, the thicket swamp in the lowland site extends to a depth of 6 m at the pond edge, but is less than 2.5 m depth throughout most of the wetland (Figure 3-4). The upper 1 m of the thicket swamp is mesic peat with a dark brown to black humified peat beneath. The transition from peat to till is marked by a ~ 10 cm silty-clay layer. Herein, upper peat refers to the upper mesic layer (acrotelm), and lower peat refers to the underlying mesic-humic lower layer.

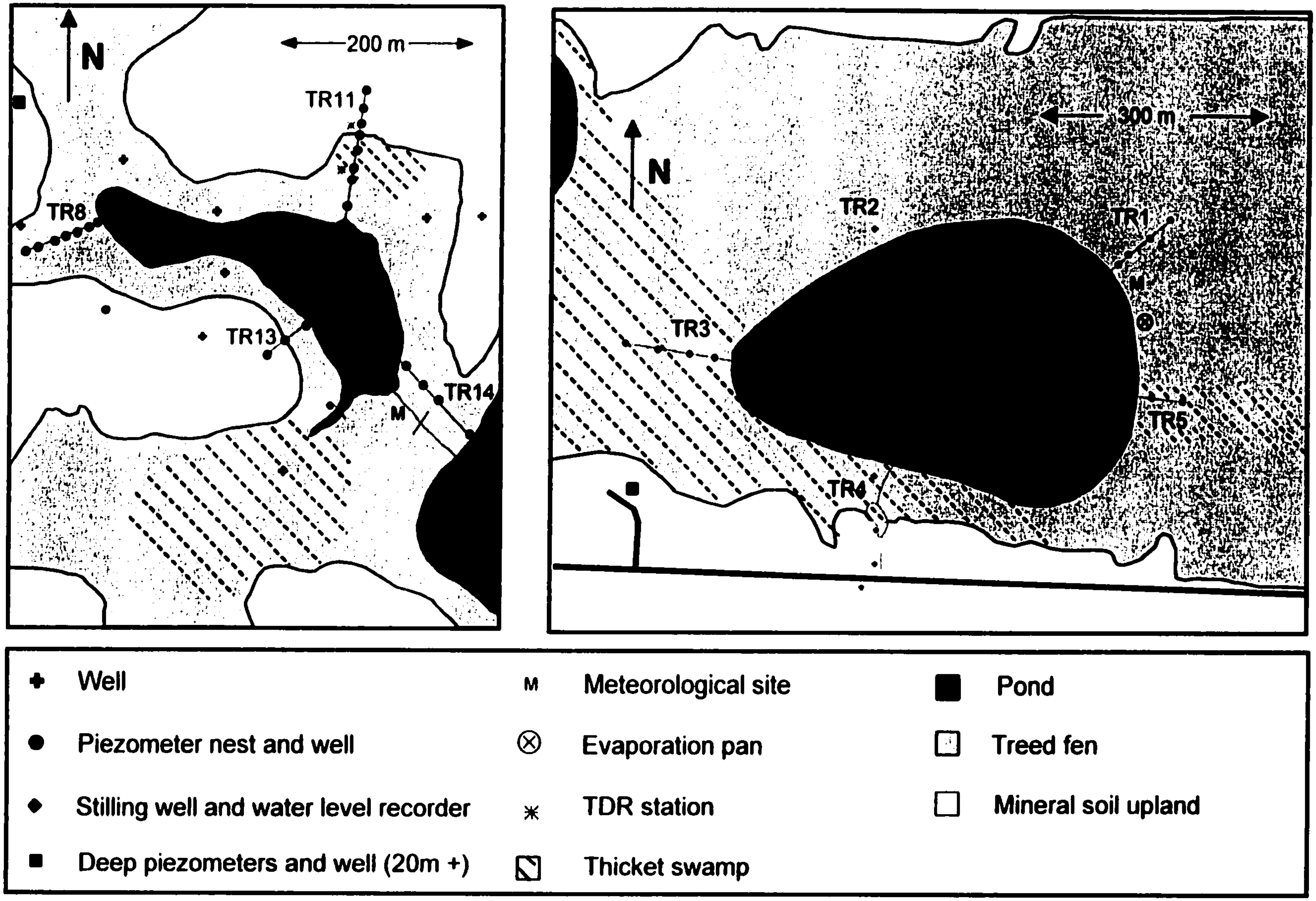

Figure 3-2. Study site maps for the topographic high (moraine, 56° 07' 34 N; 115° 46' 99 W) and lowland (clay plain, 55° 98' 25 N; 115° 19' 36 W) wetland complexes. Both sites consist of a shallow pond (< 1m depth) surrounded by peatland (treed bog/fen and thicket swamp) and aspen dominated upland areas. Transects of piezometers and wells were installed to monitor interactions at wetland- pond interface (indicated by TR #).

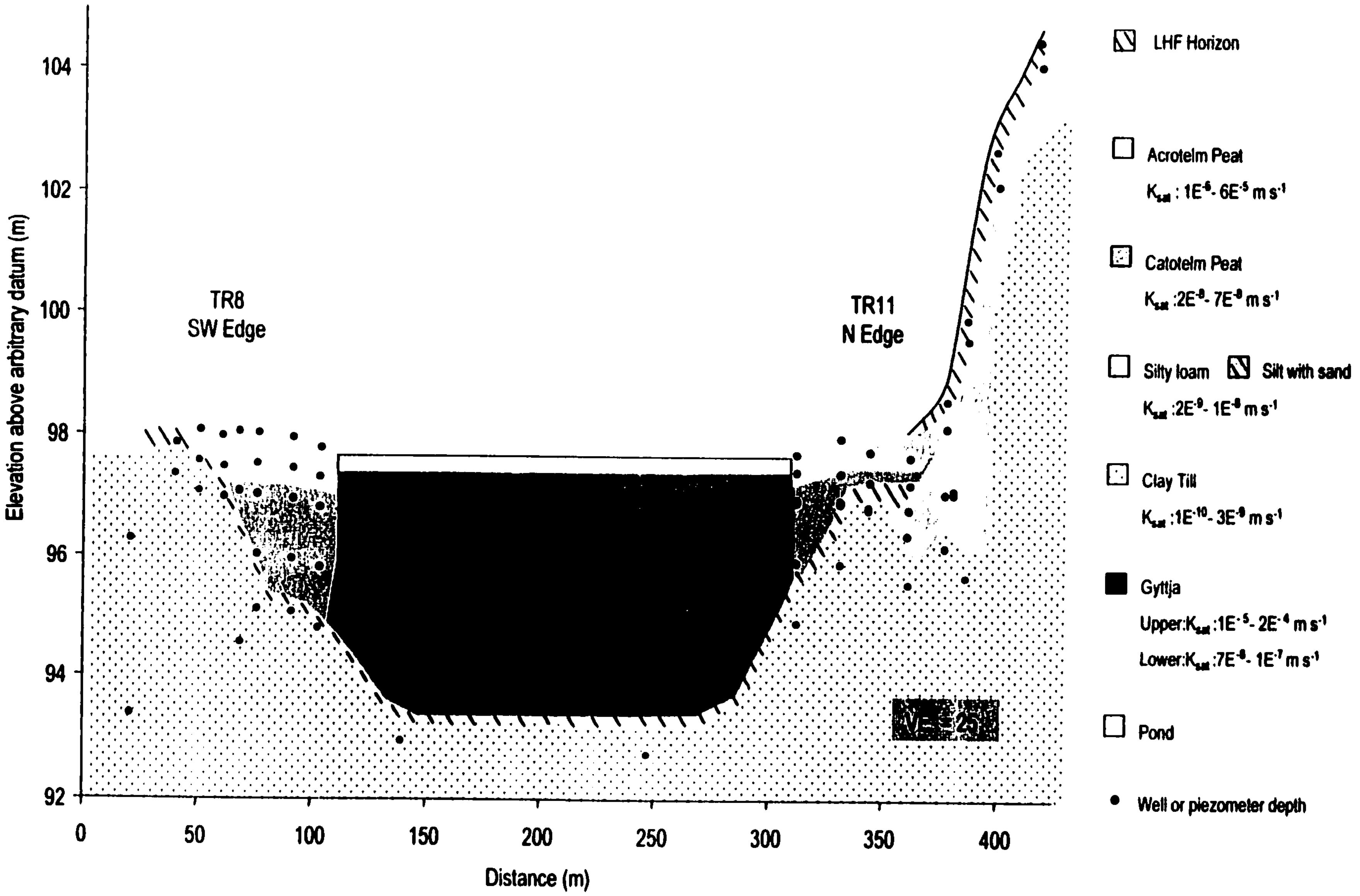

Figure 3 - 3. Cross section of the Moraine wetland complex (SW to N) incorporating transect # 8 and transect #11. Lithology, hydraulic conductivities and piezometer/well openings (dots) are identified. The dashed line separates the upper and lower gyttja.

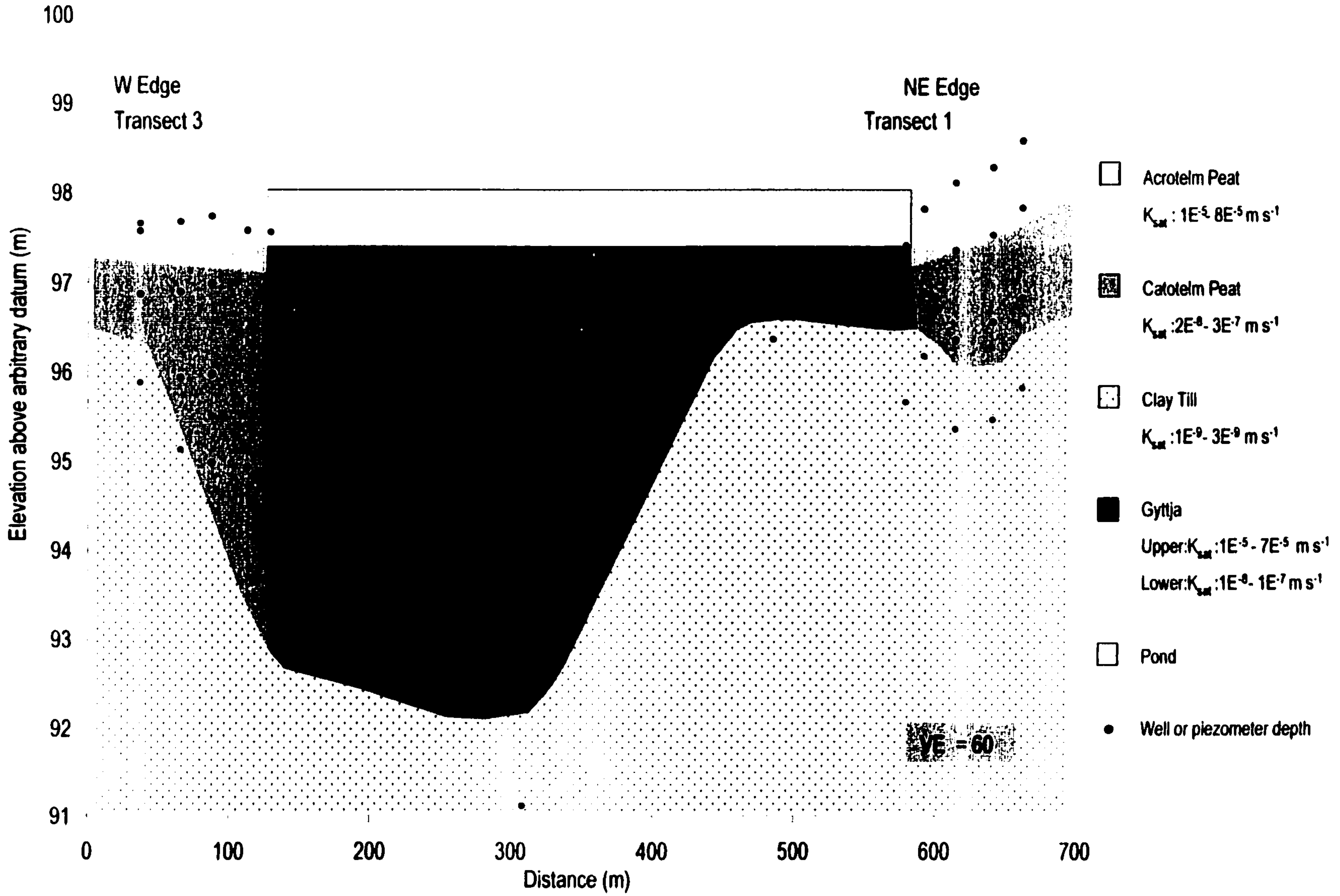

Figure 3 - 4. Cross section of the Lowland wetland complex (W to NE) incorporating transect # 3 and transect # 1. Lithology, hydraulic conductivities and piezometer/well openings (dots) are identified. The dashed line separates the upper and lower gyttja.

The vegetation of the treed bog/fen areas are dominated by black spruce, with some larch (*Larix laricina*), and an understory of leatherleaf (*Chamaedaphne calyculata*), Labrador tea (*Ledum groenlandicum*) and peat mosses (*Sphagnum* spp). The thicket swamp areas are dominated by willow (*Salix* spp.), birch (*Betula* spp.), alder (*Alnus* spp.), sedges (*Carex* spp.) and grasses. Some marsh vegetation (cattails (*Typha latifolia*) and marsh ragwort (*Senecio congestus*)) exists on the southern pond edge of the lowland site. During the growing season, submergent macrophyte growth is typical. The moraine pond bottom is almost 100% covered with coontail (*Ceratophyllum demersum*), and common duckweed (*Lemna minor*) grows on the surface. The lowland pond macrophyte communities consist of pondweed (*Potamogetan richardsoni* and *Potamogetan zosteriformis*), coontail (*Ceratophyllum demersum)*, and milfoil (*Myriophyllum exalbescens*) (Menchenton 2001). Ivy leaved duckweed (*Lemna triculosa*) form thick surface mats throughout July and August at the lowland pond.

While the hydrology of these wetlands was found to be dominated by atmospheric fluxes, the hydroperiod and shallow groundwater flow patterns were found to be seasonally dynamic (Chapter 2). The hydrology of these systems is described in detail in Chapter 2.

3.3 Methods

3.3.1 Catchment Surface and Subsurface Characteristics

Catchment areas were determined from air photos, topographic maps, and topographic data from surveys conducted in October 1999, April 2000, and June 2000.

Catchment, peatland, upland, and pond areas and perimeters were calculated using MapInfo GIS software. Methods for determining lithology for upland, peatlands, and pond sediments are described in Chapter 2 (Figures 3-3 and 3-4).

3.3.2 Hydrologic Fluxes

Measurement of hydrologic variables was made from May 1999 through August 2000, with the hydrologic year spanning July 1, 1999 to June 30, 2000, and methods are described in detail in Chapter 2. Briefly, all hydrologic fluxes were measured by a combination of hydrometric, geochemical and isotopic techniques. Automated equipment and manual sampling ensured that fluxes were measured between 30 min intervals (continuous monitoring of peatland water table and pond water levels, precipitation and evaporation) to at least twice weekly (piezometer measurements, total = 71).

3.3.3 Water Chemistry

Precipitation, surface water and groundwater was sampled on a monthly basis for nutrients: total phosphorus (TP), total dissolved phosphorus (TDP), soluble reactive phosphorus (SRP), ammonium (NH_4^+) and nitrate (NO_3^-; as well as for pH, electrical conductivity (EC), dissolved oxygen (DO), major cations (Ca^{2+}, Mg^{2+}, Na^+, K^+), and dissolved organic carbon (DOC). In addition, precipitation, surface water and a subset of piezometers (ie. peatland edge nests and upland- peatland transition nests) were sampled biweekly to daily during high flow periods (snowmelt and storms). Other major ions (eg.

HCO_3^-, CO_3^{2-}) were sampled from surface water monthly for the HEAD project, and were also used in this study.

During groundwater sampling, all piezometers were bailed within 24 h of sampling. Piezometers in clay till required up to a month to recharge and were not bailed prior to sampling. However, tests conducted on piezometers in higher permeability mineral soil showed that chemical concentration differences were typically less than 10% "before" and "after" purging.

E.C., pH, DO, and water temperature (Ts) were measured on site using field meters (YSI 85 for DO/temp/EC, VWR for pH). Groundwater measurements of DO and Ts were obtained using 150 ml syringes to withdraw water from piezometers without introducing mixing/turbulence. Surface water profiles for DO and Ts in the ponds were measured seasonally at 10 cm intervals from pond surface to pond bottom.

Water sampled for all other chemical analyses were collected with pre-rinsed tubing and bottles, and was filtered within 24 h (except TP). TDP, SRP, NH4+, NO3-, and DOC samples were filtered through 0.45 μm Millipore™ paper. If not analysed immediately, P and N samples were frozen after filtering. DOC was acidified and stored at 4 °C until analysis. TP was filtered through a course sieve to remove large organic particles, and stored at 4 °C until analysed. Cation and anion samples were filtered through Gelman™ GF/C paper and stored at 4 °C until analysis. Cation samples were acidified with 2 drops of nitric acid (50% HNO_3)

SRP was analysed within 24 h, except for May 4 - 8, and June 7-11, 2000 samples, which were immediately frozen after filtering and analysed within the month. Tests done within the lab and others comparing the results of frozen vs. non-frozen SRP methods, found no difference. SRP was analysed according to the method of Murphy and Riley (1962). TP and TDP were digested and analysed after Menzel and Corwin (1965) as modified by Prepas and Rigler (1982), within 1 day to 1 month of sampling. NH_4^+ and NO_3^- were analysed using a Technicon TM Autoanalyzer II (Technicon 1977). DOC was analysed by the Total Organic Carbon (TOC) /Combustion Infrared Method (Greenberg et al. 1992) using an Ionics Model 1505 Programmable Carbon analyzer. Phosphorus, nitrogen and DOC analyses were completed at the University of Alberta Limnology Laboratory. Cations were analysed by atomic absorption spectrometry (Perkins Elmer model 503) at the Earth and Atmospheric Sciences High Volume Laboratory of the University of Alberta.

3.3.4 Soil Nutrient Analysis

Soil cores for extractable nutrient pools and adsorption/desorption tests were collected at various depths within the peatlands and adjacent hillslopes using a 10cm bulb core for surface samples. or a Russian or Bucket auger for depths below the surface. Samples were kept in Ziploc © bags at 4° C until analysed.

For extractable pools of phosphorus, samples were collected along transects in representative areas of the wetland complexes, based upon visual differences in sediment characteristics. These representative zones included: treed fen peat (mesic), thicket swamp peat (humic). hillslope mineral soils (mineral). and littoral pond sediment (gyttja). In each of these zones. cores were collected at the following depths: 0-10 cm (surface) (7 cores). 50 - 60 cm (water table zone) (3 cores). and at the 10cm above the transition from peat to underlying mineral soils (varied with locations within the wetlands) (1 core). At the hillslope transect, the deep core was taken at 1 m, representing the transition from clay loam to clay till. Soils were analysed within 48 h of collection. For each core, subsamples of 5 g dry soil weight were shaken with 50 ml of deionized-distilled water for 1h. Extracts were gravity filtered through pre-washed (with distilled water) Fisherbrand 1 μm filter paper and frozen until analysis. Extracts were analysed according to the P methods described in the preceding section.

For adsorption experiments, sampling locations and procedures were similar to those described for extractable pools. Additional cores were collected at four locations from the clay till underlying the mesic and humic peat. Techniques for analysis were according to Hill (1982) and Lyons et al. (1998) with some modifications. Briefly, sediment samples were dried for 72 h and then subsampled for 5 g dry weight. Subsamples were placed in 50 ml of five of the following solutions of P concentrations (KH_2PO_4): 0 mg l^{-1}, 0.05 mg l^{-1}, 0.1 mg l^{-1}, 0.2 mg l^{-1}, 0.5 mg l^{-1}, 1mg l^{-1}, 2 mg l^{-1}, 5 mg l^{-1}, 10 mg l^{-1}. P solutions were not adjusted with 0.01M $CaCl_2$, as is often done in studies of plant available P, in order to evaluate the potential for P release directly into runoff (or groundwater) (Hill 1982, Hooda et al. 2000). Gyttja and humified peat were tested with low to medium concentrations (0 – 2 mg l^{-1}). Mesic and hillslope LFH samples spanned slightly higher concentrations (0 – 5 mg l^{-1}). Mineral soil samples, known to adsorb high quantities of P, were treated with the widest range of concentrations (0 – 10 mg l^{-1}). All solutions were shaken at 100 rpm for 24 h, and then gravity filtered using Whatman No. 42 paper. Cloudy filtered solutions (ie. from the fine clay samples) were centrifuged for 10 min to remove any remaining particles. Samples were immediately analysed for orthophosphate (SRP) according to the techniques described above.

Equilibrium phosphorus concentrations (EPC values), the dissolved phosphorus concentration at which there is neither adsorption or desorption by the sediments (Hill 1982, Lyons et al. 1998), were evaluated from P adsorption curves by plotting the amount of P sorbed (mg P kg^{-1} dry soil) vs. the final P concentrations in solution after shaking (Hill 1982). The P buffering capacity of these sediments were calculated from a P sorption index:

$$\text{Index} = X / \log_{10} C , \qquad (3\text{-}1)$$

after Hill (1982) and (Axt and Walbridge 1999), where X is the P (in $\mu g\ g^{-1}$ sediment), adsorbed from an initial concentration of 2000 $\mu g\ P\ l^{-1}$, and C is the final P concentration ($\mu g\ P\ l^{-1}$) in solution after shaking.

3.3.5 Phosphorus Budgets

For SRP and TDP budget calculations, the hydrologic year incorporated measurements between July1, 1999 to June 30, 2000. The seasonal intervals each represented 3 months and were divided within the hydrologic year as follows:

Summer: July 1999- September 1999; Autumn: October 1999- December 2000; Winter: January 2000 – March, 2000; and Spring: April 2000 – June, 2000. These intervals were selected to correspond with regional indicators such as the boreal growing season (summer), snowfall period (winter), and peat thaw (spring).

Fluxes for the TDP and SRP budgets were measured with respect to the ponds. Annual and seasonal budgets were constructed using continuous water flux measurements (chapter 1). Budgets were calculated after Wentz et al. (1995):

$$\Delta(VC_l) = P_r(C_{pr}) + G_i(C_{gi}) + S_i(C_{si}) - G_o(C_{go}) - D_o(C_{go}) \pm r\ , \qquad (3\text{-}1)$$

where C subscript designates the P concentrations associated with the different water balance components. The water fluxes are as follows: P_r is precipitation, G_i is shallow groundwater inputs, S_i is surface water inputs, G_o is shallow groundwater outputs, D_o is deep vertical groundwater seepage out through the pond bottom, l is pond water, ΔV is the change in pond volume and r is the residual reflecting uncertainties in flux measurement (Wentz et al. 1995, LaBaugh et al. 1997). In the budget, the positive residual term, (r), includes both reaction within the pond that might either remove (-r) or add (+r) to the pond mass storage, and also any error in calculation (Wentz et al. 1995).

Calculation intervals for weighting the chemical mass of inputs were defined by the dates midway between sampling (LaBaugh et al. 1997). The chemical mass in the ponds was determined by multiplying the volume of the pond by the mean surface concentration ($n = 2$ per sampling date). Groundwater TDP and SRP mass input was calculated by multiplying concentrations in littoral piezometers by the volume of seepage for each corresponding shoreline segment, and then summing the mass for the four segments. Chemical mass loss due to seepage from the pond was determined by multiplying the concentration of the pond by the water flux out of the pond. Bulk deposition mass (precipitation) was determined as the concentration on a sampling date multiplied by the precipitation volume for the weighted interval. In both the TDP and SRP budgets, % retention was calculated as the residual divided by the total inputs, multiplied by 100.

3.3.6 Statistical Analysis

To examine how the physico-chemical properties of the peatlands might affect phosphorus concentrations in the pore water, Pearson correlation coefficients were tested (SPSS 1999). For each site, correlation coefficients were used to determine linear relationships between phosphorus concentrations (TDP and SRP), and other water parameters: sample depth, water table depth below surface, DO, pH, and EC. TDP and SRP data were log transformed for linear correlation with DO. For correlations between water table and other variables, only porewater samples from piezometers within the water table zone were used (e.g. usually 0.5 – 1.0 m depth, varying with season). Probabilities were adjusted with Bonferroni tests, and considered significant at $\alpha = 0.05$. All correlations and descriptive statistics (e.g. sample means, medians, standard deviations (SD) etc. were calculated using Systat version 9.0.

3.4 Results

3.4.1 Annual Phosphorus Budgets

On an annual basis, total P inputs greatly exceeded outputs in both the moraine and lowland pond, resulting in a large increase in mass of P in standing pond water (Table 3-1). The annual change in mass storage in the moraine pond indicated a small increase in TDP relative to measured inputs and outputs (r = +33 %) (Table 3-1), while the change in SRP pond storage roughly equalled the difference between inputs and outputs, with budget residuals within the hydrologic budget errors (r = 10%). Changes in mass at the lowland pond were 2-5 times less than the difference between inputs and outputs of TDP and SRP, resulting in large retention (-37% and –71%, respectively).

Table 3-1. Annual TDP and SRP (mg m^{-2}) budgets for the moraine and lowland ponds. A positive residual indicates P addition to pond water, whereas a negative indicates P removal from pond water.

	Inputs (mg m^{-2})				Outputs (mg m^{-2})			d Storage (mg m^{-2})		Balance	
	Atmospheric	**Surface**	**Shallow GW**	**Total In**	**Shallow GW**	**Deep GW**	**Total Out**	**Inputs - Outputs**	**Change Pond Mass**	**Residual**	**% of Input**
	P	Si	Gi	I	Go	Do	O	(I-O)	dMass	r (mg m^{-2})	%
Moraine:											
TDP	7.9	0.0	7.6	15.5	1.6	0.1	1.7	13.7	18.9	5.2	33
SRP	5.5	0.0	7.3	12.8	0.4	0.03	0.4	12.4	13.7	1.3	10
Lowland:											
TDP	9.1	0.2	9.5	18.9	3.4	0.3	3.7	15.2	8.1	-7.1	-37
SRP	6.9	0.1	5.5	12.5	1.7	0.2	1.9	10.6	1.7	-8.9	-71

The calcium budget shown in Chapter 2 indicated that a conservative element should balance roughly ~ 10 - 13%. The fact that the phosphorus residuals ranged between 37% to -71% suggests that there are likely internal processes (e.g. biotic uptake and release, sediment immobilization and release etc.) leading to a wide range of P variability in pond concentrations.

Groundwater transport of both TDP and SRP were important to the annual P budgets of both systems (Table 3-1). At the lowland site, due to it's lower ratio of pond shoreline: area, the annual groundwater inputs of water were lower per pond area (Chapter 2). In contrast, the nutrient budgets indicate that the total TDP transported via shallow groundwater to the lowland complex was slightly larger (per pond area) to that transported to the moraine (9.5 vs. 7.6 mg m^{-2}). The reverse was true for SRP fluxes (5.5 vs. 7.3 mg m^{-2}) (Table 3-1). At the moraine site, G_i accounted for 49% and 57% of TDP and SRP inputs, respectively. Shallow groundwater out (G_o) represented 91% (TDP) and 88% (SRP) of the external P outputs, although absolute amounts of G_o were 5-times less than G_i. At the lowland site, approximately 51% of the annual TDP and 44% of the SRP of the P was transported to the pond via shallow groundwater flow, while approximately 90% of the outputs of both P forms were accounted for by Go. The hydrologic results indicated that precipitation represents approximately 86-93% of the water inputs to the ponds (Chapter 2). In contrast, nutrient balances indicate that atmospheric fluxes contribute approximately half the annual P at both wetland complexes (Table 3-1). Surface inputs of TDP and SRP represented 1% of total P inputs to the lowland pond, while it was zero for the moraine site. Outputs of TDP and SRP from the ponds via deep vertical groundwater fluxes (D_o) ranged from 7 to 10%. No regional groundwater input of water or P occurred.

Total SRP inputs were similar to TDP concentrations (66 - 82% of TDP values) at both systems, suggesting that dissolved P in groundwater and precipitation was dominated by the inorganic fraction of P species. SRP represented a smaller component of the P outputs (23 - 51% of TDP values), indicating preferential retention of SRP within the pond.

3.4.2 Seasonal Phosphorus Fluxes

Seasonally, groundwater flow conditions were dynamic and influenced the relative magnitude of P inputs among the water fluxes. Generally, highest net P inputs occurred during summer 1999 and spring 2000 at the moraine, and during the spring 2000 at the lowland site, reflecting both elevated precipitation and shallow groundwater inputs (Figures 3-5 to 3-8). Throughout the year, the moraine pond received almost equal inputs of TDP through precipitation and groundwater (ie. summer: 2.2 mg m^{-2} vs. 2.6 mg m^{-2} respectively, spring: 4.6 mg m^{-2} vs. 4.5 mg m^{-2}, respectively), but groundwater SRP input was slightly higher than precipitation SRP (Figures 3-5 and 3-7). At the lowland site, groundwater TDP inputs were slightly less than precipitation inputs throughout most of the year, but increased beyond precipitation inputs during the spring (April- July precipitation = 5.8 mg m^{-2}, groundwater = 7.0 mg m^{-2}), coinciding with the flow reversal along the outflow zones (Figure 3-6) (chapter 2). SRP inputs followed the same general trend, but groundwater SRP inputs were very low during the summer 1999 (Figures 3-6 and 3-7).

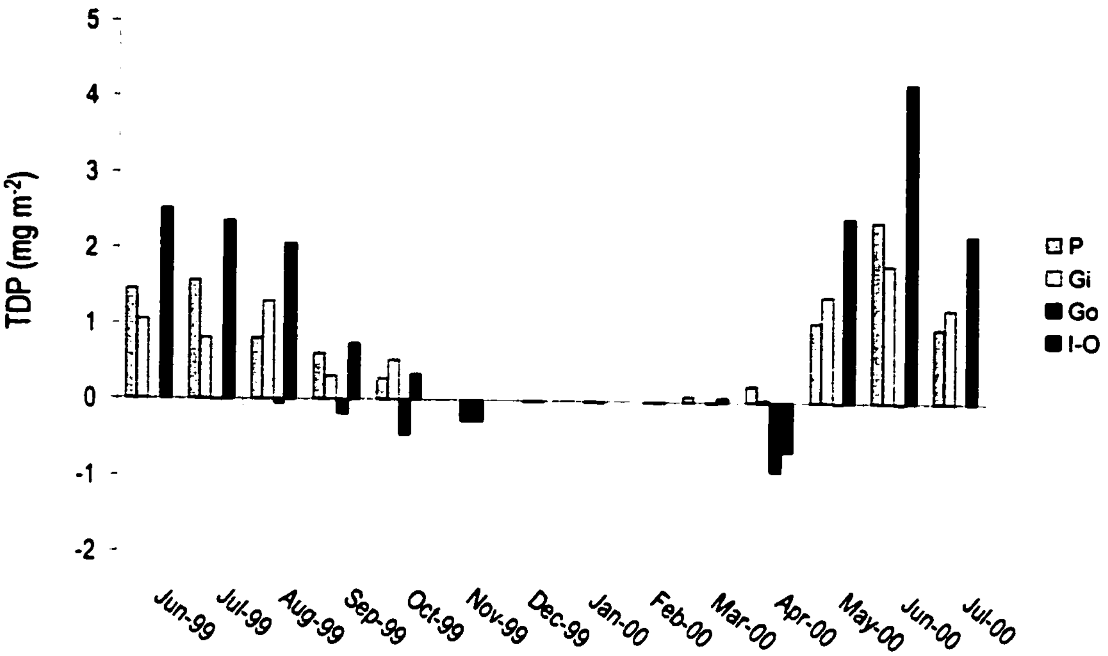

Figure 3-5. Moraine pond monthly TDP fluxes (mg m^{-2}) and budgets. The pond is frozen December 1999 to March 2000. Snowmelt occurs in March 2000. The June 1999 values were not included in the annual P budget, but are shown for seasonal trends. July- 00 represents only July 1-7. Pr= precipitation P, Gi = shallow groundwater inputs of P, Go = shallow groundwater outputs of P, I-O = net inputs.

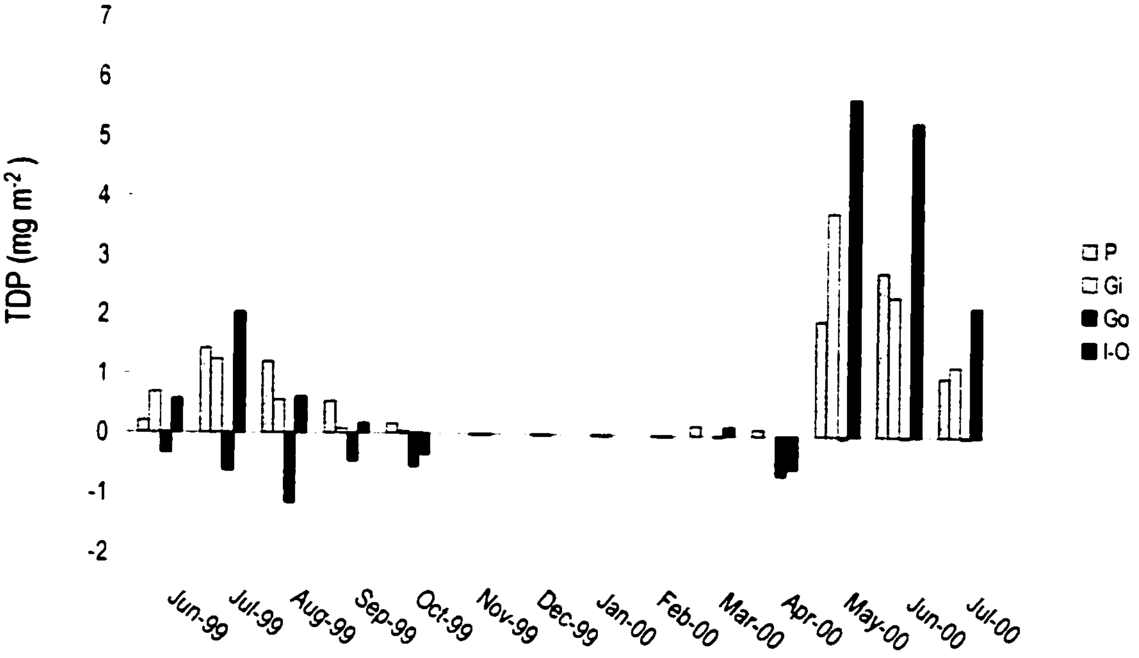

Figure 3-6. Lowland pond monthly TDP fluxes (mg m^{-2}) and budgets. The pond is frozen December 1999 to March 2000. Snowmelt occurs in March 2000. The June 1999 values were not included in the annual P budget, but are shown for seasonal trends. July- 00 represents only July 1-7. Pr= precipitation P, Gi = shallow groundwater inputs of P, Go = shallow groundwater outputs of P, I-O = net inputs.

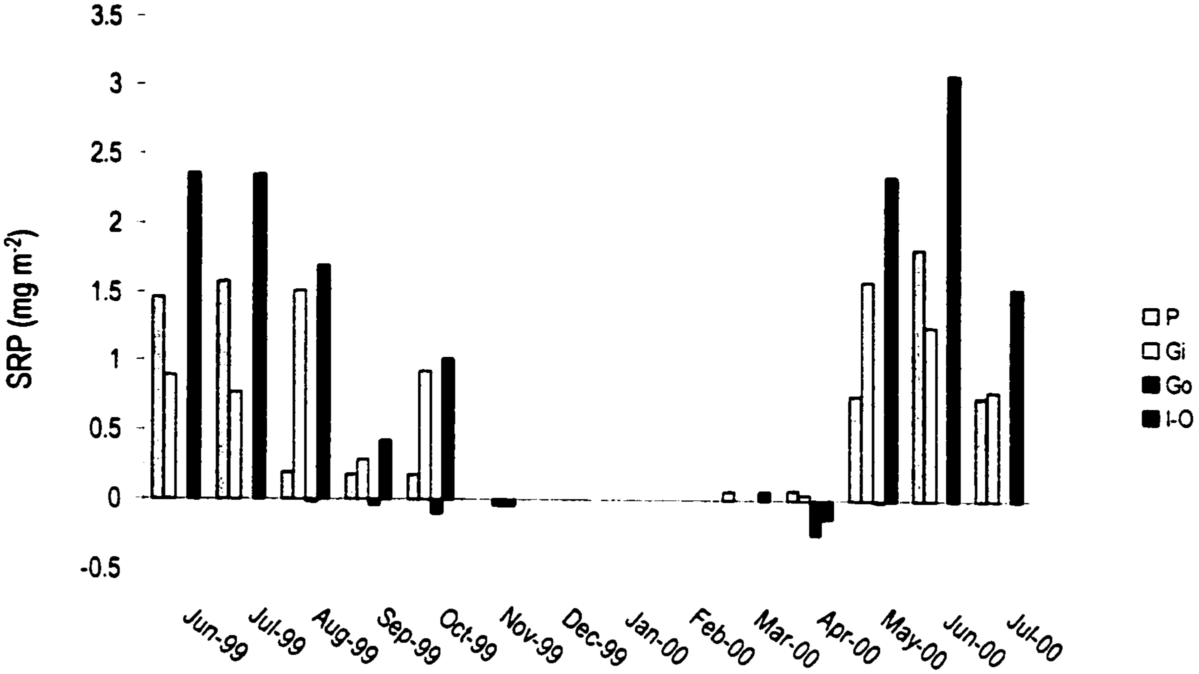

Figure 3-7. Moraine pond monthly SRP fluxes (mg m^{-2}) and budget. The pond is frozen December 1999 to March 2000. Snowmelt occurs in March 2000. The June 1999 values were not included in annual P budget, but are shown for seasonal trends. July- 00 represents only July 1-7. Pr= precipitation P, Gi = shallow groundwater inputs of P, Go = shallow groundwater outputs of P, I-O = net inputs.

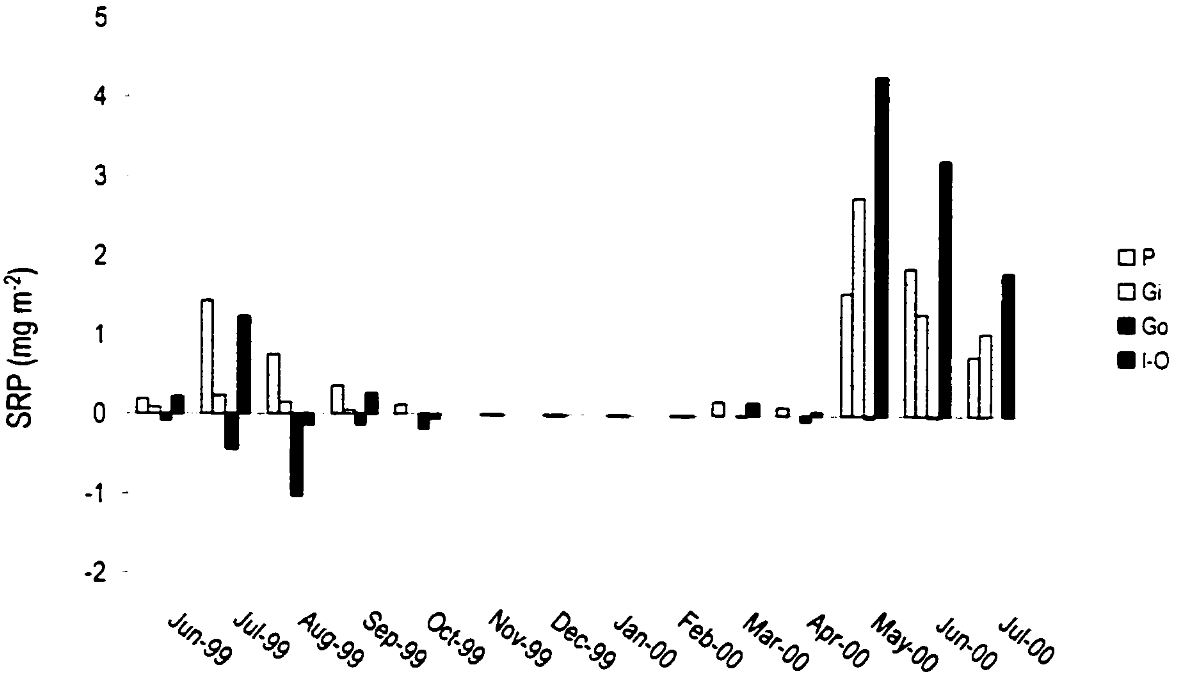

Figure 3-8. Lowland pond monthly SRP fluxes (mg m^{-2}). The pond is frozen December 1999 to March 2000. Snowmelt occurs in March 2000. The June 1999 vales were not included in annual P budget, but are shown for seasonal trends. July- 00 represents only July 1-7. Pr= precipitation P, Gi = shallow groundwater inputs of P, Go = shallow groundwater outputs of P, I-O = net inputs.

Largest net P outputs at both sites coincided with groundwater flow reversals during the fall and winter months (Figures 3-5 to 3-8) (Chapter 2). At the moraine site, groundwater output of phosphorus occurred during this reversal period only, while the groundwater flow through lowland pond demonstrated P outputs via groundwater throughout most of the year (Figures 3-5 to 3-8).

Seasonal differences in the ratios of pond water Ca:TDP and Ca:SRP at both ponds indicated that the variability in surface P concentrations is not solely a function of variable flow conditions (Figure 3-9 and Figure 3-10), since Ca^{2+} variations reflect hydrologic flowpath. The lowest ratios at both sites were observed during winter (moraine Ca:TDP = 32, Lowland Ca:TDP = 62), which suggests internal P additions to the pond that are independent of hydrology. The highest ratios at the moraine site, 277 (Ca:TDP in μmol l^{-1}) and 941 (Ca:SRP in μmol l^{-1}), were observed during summer, indicating P removal from the water column. At the lowland site, the summer ratio was high, but the autumn ratio was slightly greater (Figures 3-9 and 3-10). At both sites, spring ratios reflected intermediate to high levels: Ca:TDP ranged from 106 - 242, and Ca:SRP ranged from 308 - 497. The seasonal trend of Ca:P appeared to be the same for TDP and SRP, but since SRP values were less than TDP, the ratios with SRP were 1- 4 times large.

3.4.3 Influence of Groundwater Flow Patterns on Phosphorus Transport

Groundwater TDP Concentrations:

The seasonal median and range of TDP concentration of pond and porewater of various organic and mineral substrates are shown in Figure 3-11 to illustrate the spatial

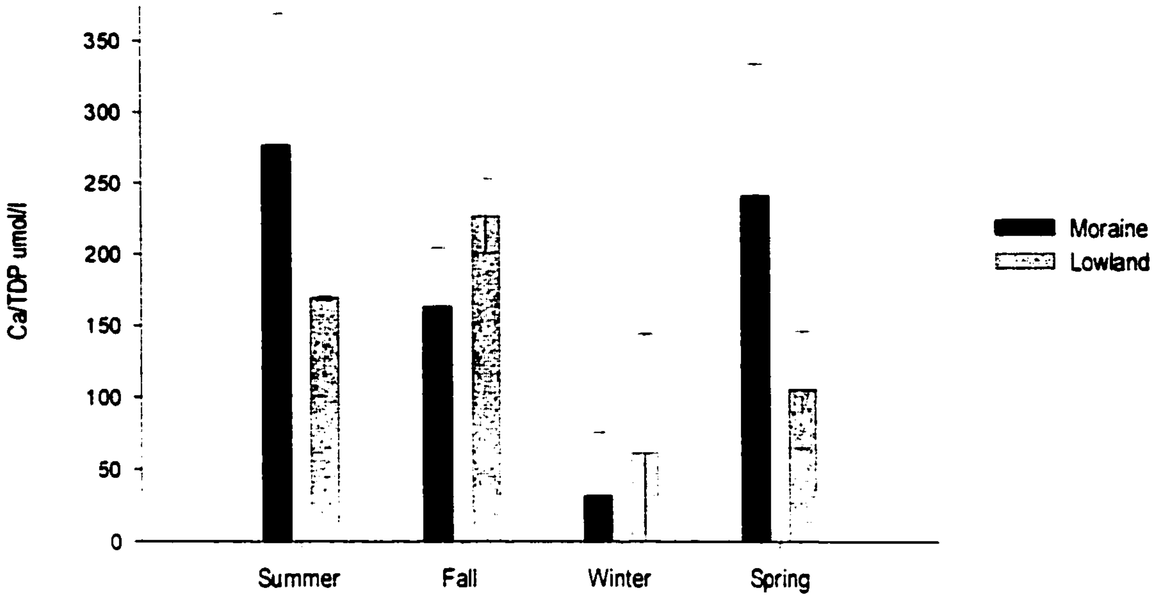

Figure 3-9. Seasonal patterns of Ca:TDP (umol l^{-1}) in the surface water of the Moraine and Lowland Complexes. The high ratios indicate internal P retention, low ratios indicate P release.

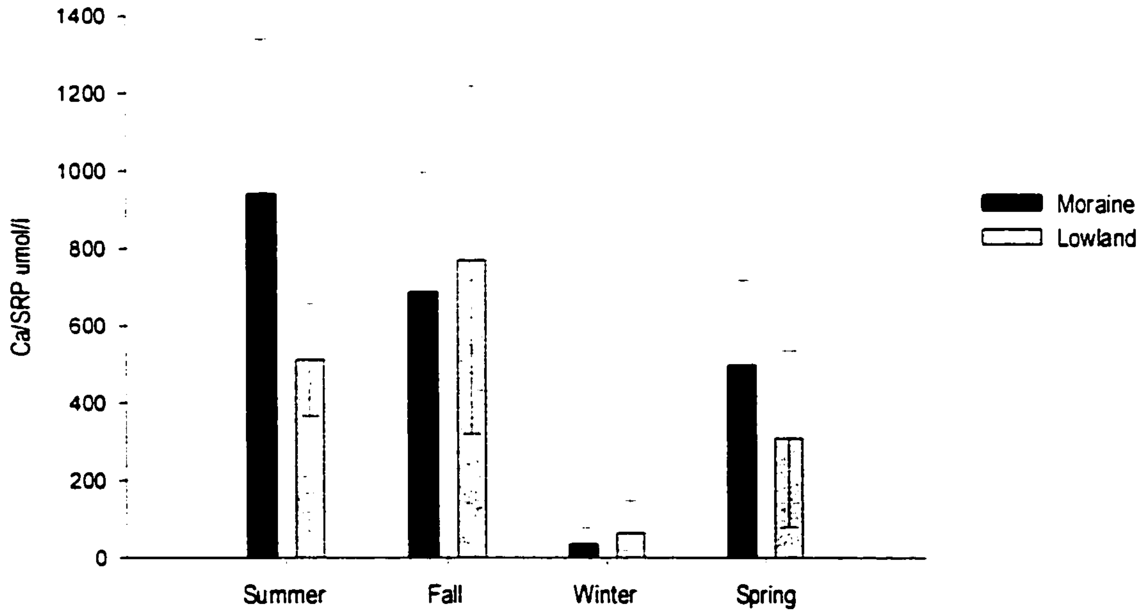

Figure 3-10. Seasonal patterns of Ca:SRP (umol l^{-1}) in the surface water of the Moraine and Lowland Complexes. The high ratios indicate internal P retention, low ratios indicate P release.

and temporal variability of potential source water to the pond. The distribution of porewater [TDP] for representative water table configurations and groundwater flow directions (wet / dry), are presented in Figure 3-12 to 3-15. Precipitation had the lowest TDP concentrations, with a median value of 35 μg l^{-1}. Pond water TDP concentrations ranged from 27 to 880 μg l^{-1}, with the lowland pond TDP levels consistently higher than the moraine pond (Figure 3-11). Groundwater samples from oxidised till (in the hillslopes) and unoxidised till (underlying the peatland and pond gyttja) had the lowest groundwater TDP concentrations, at 64 and 73 μg l^{-1} respectively (Figure 3-11). Groundwater from these areas does not discharge directly into the ponds (Figures 3-12 to 3-15), and since it was a dry period, the hillslopes did not directly connect with the peatlands either (e.g. Figure 3-12a) (Chapter 2). Therefore, during dry conditions, groundwater from the till is not an important source of P to the ponds. Median pore water concentrations for the upland LFH (i.e. Litter/ Fibric /Humic organic layer at surface) were high (460 μg l^{-1}) (Figure 3-11), but as minimal runoff occurred through this layer during the study, very little LFH porewater would have come into contact with peat or reached the pond (Figure 3-12). The upper mesic and lower peat and gyttja were in closest proximity to the pond water, and analysis of groundwater flow patterns determined that these zones had the most hydrologic interaction with the pond (Chapter 2). The mesic peat TDP values were similar to the pond median concentrations, but were less variable with values ranging between 57 and 184 μg l^{-1} (Figure 3-11). The highest TDP concentrations were observed in the lower peat and gyttja (Figure 3-11), with most elevated TDP located at the pond-peatland edge (Figures 3-12 to 3-15). There were differences in TDP concentrations between the peatland zones of the two ponds

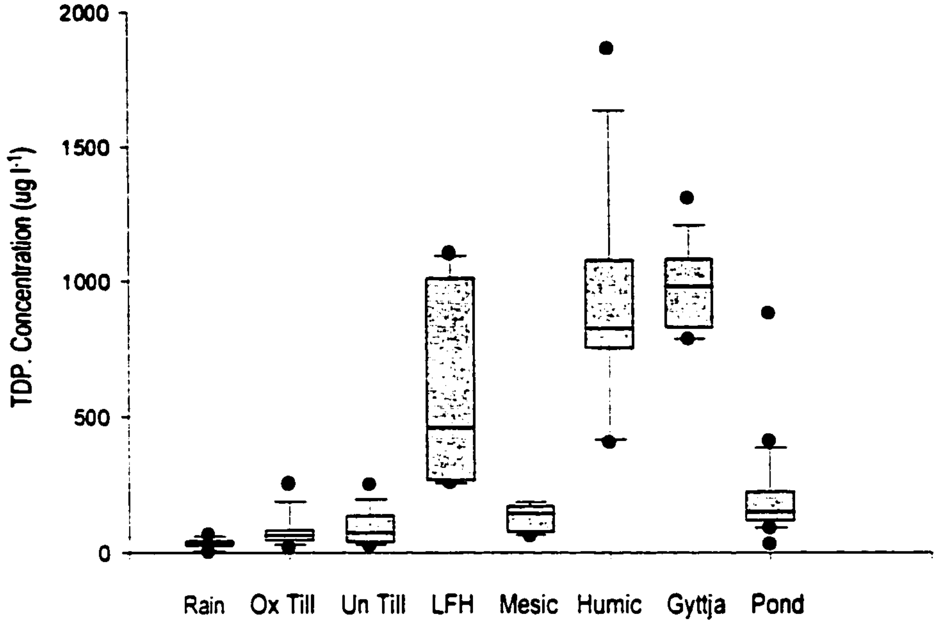

Figure 3-11. TDP (ug l^{-1}) concentrations in rain, pond and porewater of the various sediments of the moraine and lowland wetland complexes. Boxes include 50% of the values and whiskers include 90% of values. Each plot includes medians of 11- 20 sampling dates, and each sampling date represents the median value of 16-32 locations per sediment type. The LFH plot represents the medians of the 5 sampling dates that surface water passed through this layer. Rain sampling dates represent medians of two locations and pond dates represent medians of 4 locations. Ox Till = oxidised till, Un Till = unoxidised till, Mesic = upper peat, Humic = lower peat, Pond = pond surface.

(Figures 3-12 to 3-15); peat porewater TDP tends to be greater at the lowland site than the moraine. SRP concentrations were generally 66-82% of TDP values (not shown).

Groundwater Flow Reversals:

With the highest P concentrations at the littoral edge of the peatland, changes in direction of groundwater flow had implications for seasonal P transport to the pond. At the moraine site, the direction of groundwater exchange between the pond and the surrounding peatland was uniform around the pond (Chapter 2), and the high P concentrations at the littoral zone were similar in size and concentration on all sides of the pond (Figures 3-12 and 3-13). Between September 1999 and late April 2000, groundwater flowed away from the pond into the littoral edges, and therefore, P rich groundwater did not influence pond P mass (Figures 3-12a and 3-13a). During high flow, groundwater movement and P transport was toward the pond, passing through high P concentration peat and gyttja zones (100 – 500 $\mu g\ l^{-1}$ in the upper flow zone) at the littoral peatland edge (Figures 3-12a and 3-13b).

At the lowland site, due to the larger peatland storage (Chapter 2), the inflow transect continuously discharged water and P to the pond (Figure 3-14). Since peat and gyttja pore water concentrations were greater at the lowland site (from 500 to 2500 $\mu g\ l^{-1}$ in the upper flow zone: Figures 3-14 and 3-15) groundwater reaching the pond transported P even during dry periods when water fluxes were small. The recharging edge of the pond (west side) transported P out of the pond for most of the year (Figure 3-15a). However, during the wet conditions of the spring of 2000, the formation of mounds along this edge (Chapter 2), reversed groundwater flow direction and the direction of P

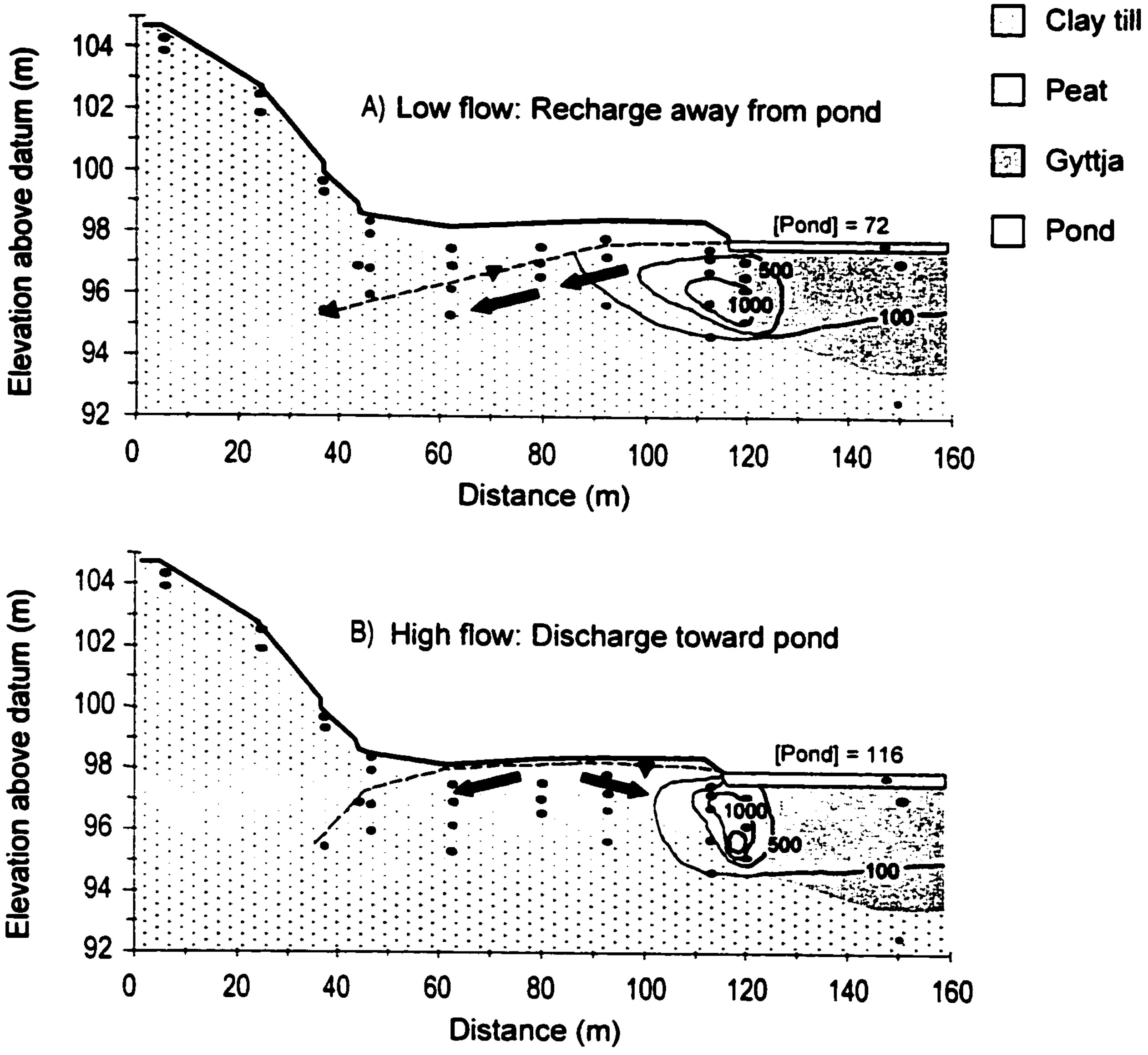

Figure 3 -12 . TDP concentrations (ug/l) in the peatland porewater and pond surface during low (A) and high flow periods (B) at TR # 11 of the moraine site. During low flow (ie. Oct 1999), pond water recharged into the hillslopes. During high flow, (ie. June 2000) P rich groundwater was transported from the peatland edge into the pond. Arrow denotes groundwater flow direction.

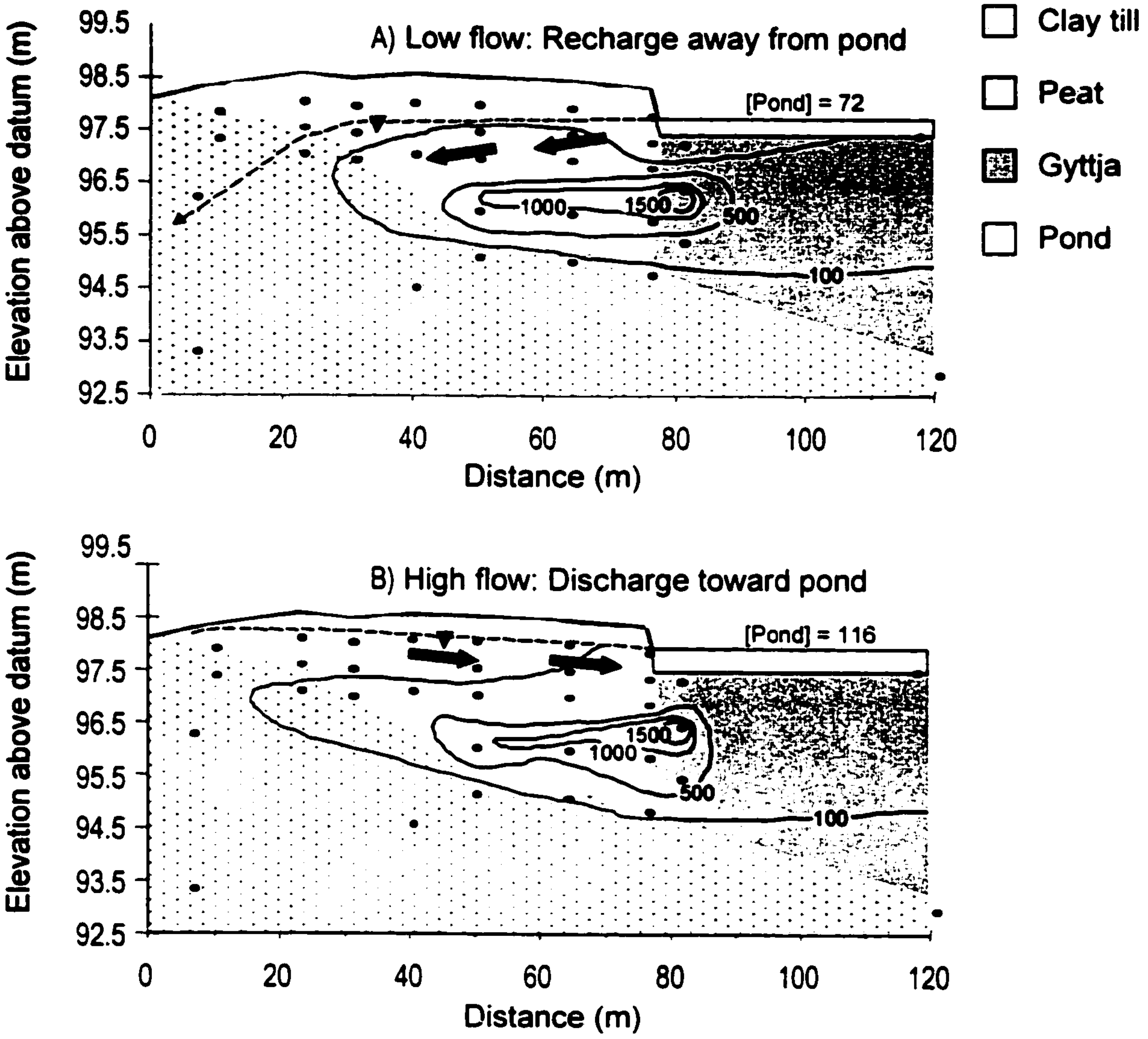

Figure 3 -13. TDP concentrations (ug/l) in the peatland porewater and pond surface during low (A) and high flow periods (B) at TR# 8 of the moraine site. During low flow (ie. Oct. 1999), pond water recharged into the hillslopes. During high flow, (ie. June 2000) P rich groundwater was transported from the peatland edge into the pond. Arrow denotes groundwater flow direction.

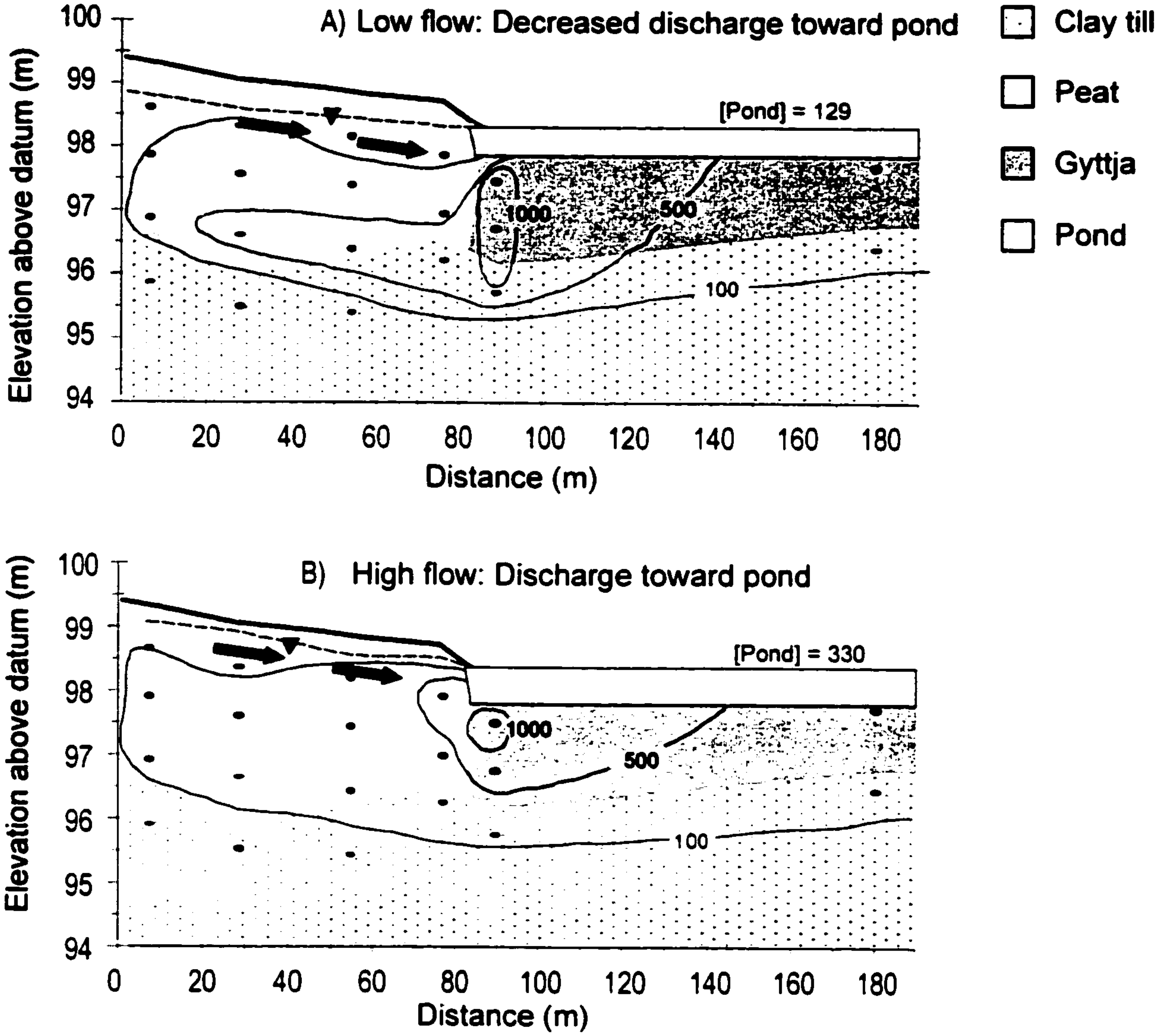

Figure 3 -14. TDP concentrations (ug/l) in the peatland porewater and pond surface during low (A) and high flow periods (B) at TR# 1 of the lowland site. During low flow (ie. Oct. 1999), pond water discharged into the pond, but the flux was small. During high flow, (ie. June 2000) large fluxes of P rich groundwater was transported from the peatland edge into the pond. Arrow denotes groundwater flow direction.

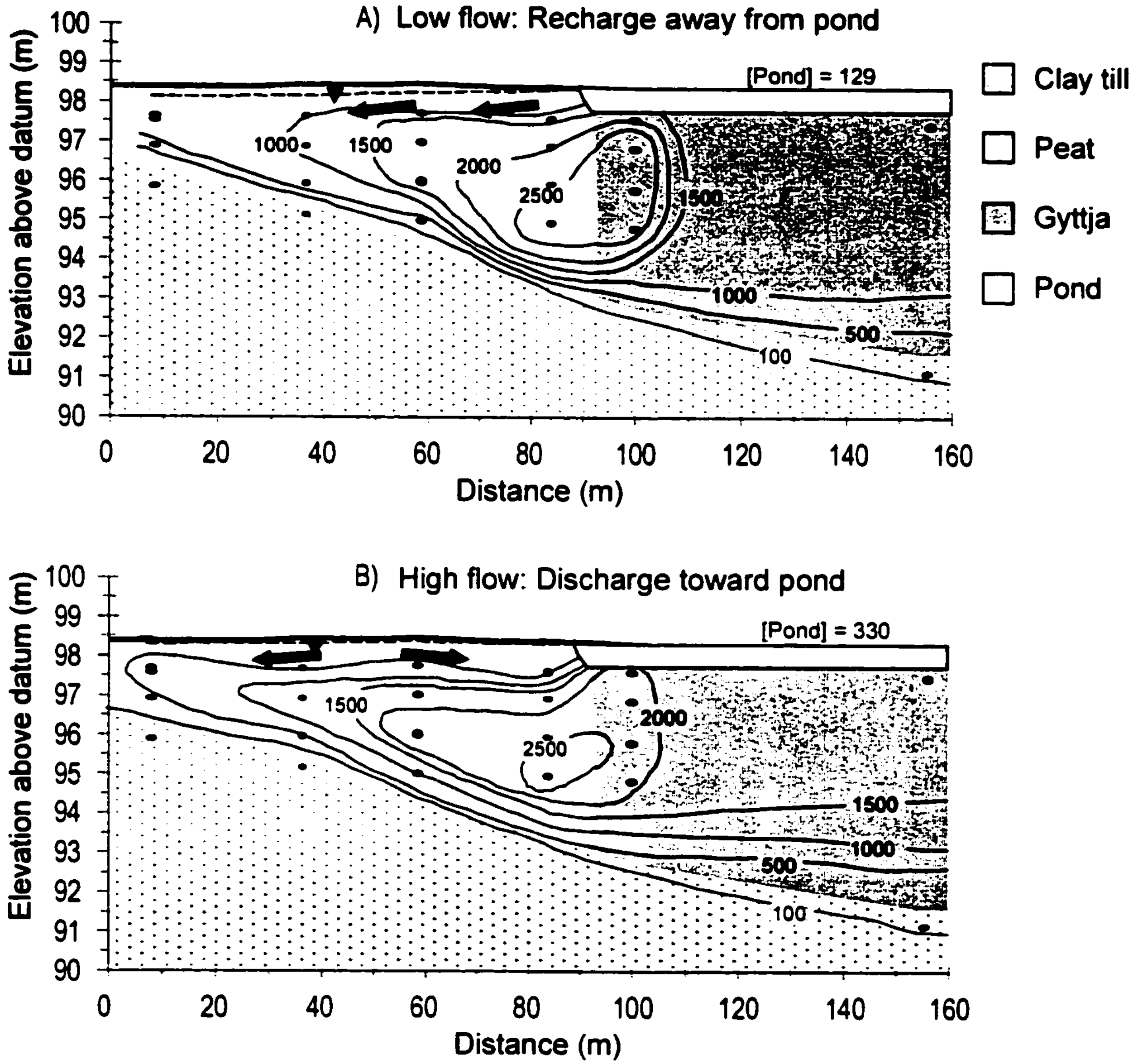

Figure 3 -15. TDP concentrations (ug/l) in the peatland porewater and pond surface during low (A) and high flow periods (B) at TR# 3 of the lowland site. During low flow (ie. Oct.-1999), pond water recharged into the hillslopes. During high flow, (ie. June 2000) P rich groundwater was transported from the peatland edge into the pond. Arrow denotes groundwater flow direction.

transport. Groundwater P values were very high on the outflow peatland side of the pond (TDP values up to 3000 μg l^{-1}), therefore small groundwater fluxes transported large masses of P to the pond during this time (Figure 3-15b).

Pond phosphorus concentrations were extremely variable at both sites, but during high flow conditions, groundwater flow direction appeared to influence P concentrations in both ponds. Peaks in TDP and SRP concentrations generally corresponded to wet periods (noted as increase in pond stage) (Figures 3-16 and 3-17). In particular, the highest pulses of P corresponded to the rising limb of each high flow event. During such events, steep hydraulic gradients developed through the P rich littoral zone toward the ponds (Chapter 2), and P flushing appeared to be high. Since the majority of the water entering the pond during rain events is dilute precipitation, P concentration would be expected to decrease during this period. The fact that P increases with pond water level suggests that P rich pulses of shallow groundwater occurring during these periods strongly influences pond chemistry. The influence of shallow groundwater flow on pond chemistry is also reflected by DOC concentrations in pond water (Figure 3-18). DOC also peaks during high flow periods, indicating that a shallow flowpath through adjacent peat represents an important vector for seasonal solute transport.

During dry periods, P and DOC transport patterns were not as marked in pond water concentrations. However, as groundwater P fluxes were smaller during these periods (Figures 3-7 to 3-10), other hydrologic (ie. evaporation) or internal controls may be more important for pond concentrations. Overall, the ponds demonstrated equally variable concentrations of P relative to mean annual concentrations (Figure 3-19).

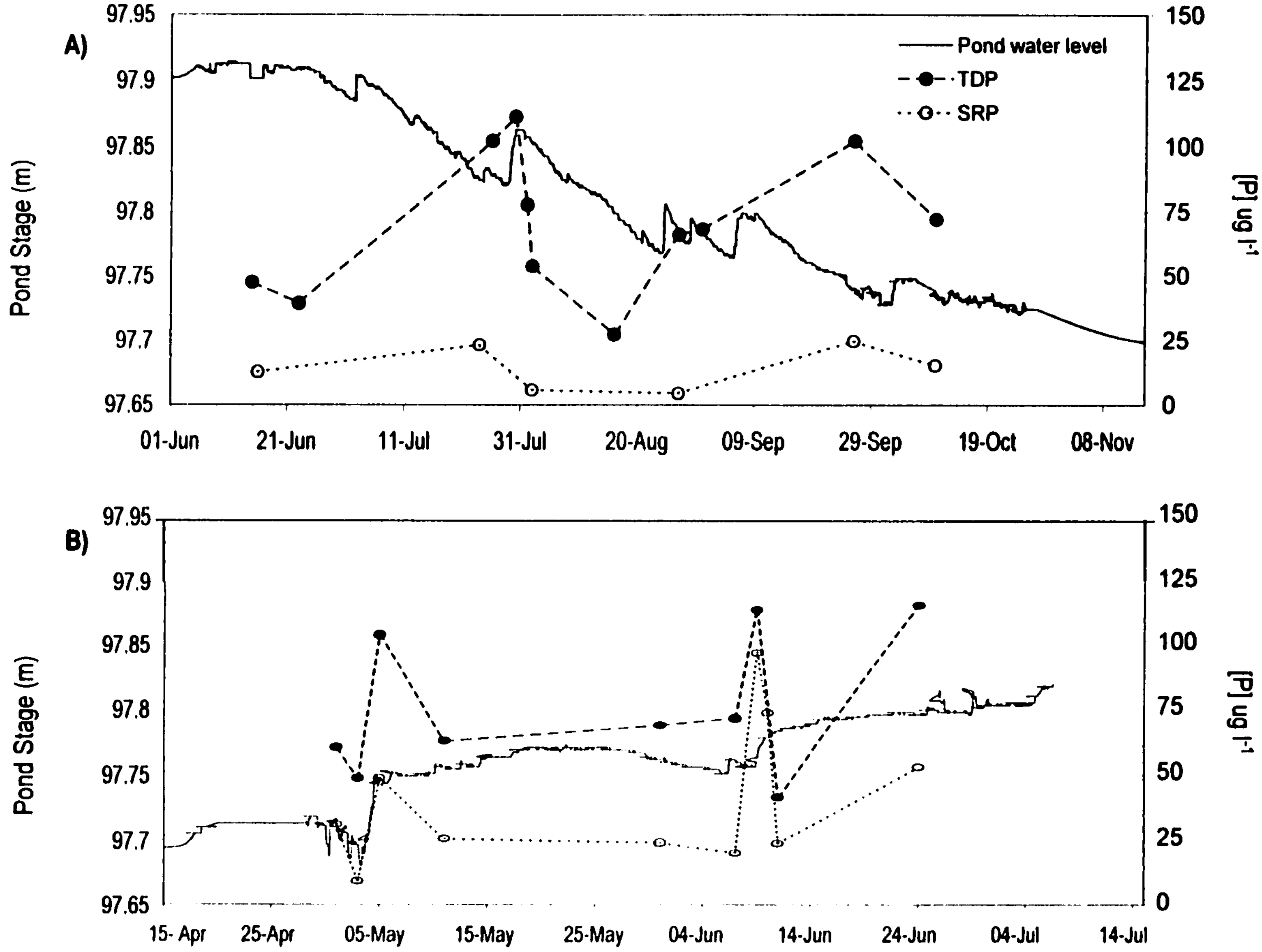

Figure 3-16. Moraine pond TDP and SRP concentrations (μg l^{-1}) and pond water level fluctuations during the summer-fall 1999 (A) and during the spring 2000 (B). In general, increased [P] values follow initial peaks in pond stage.

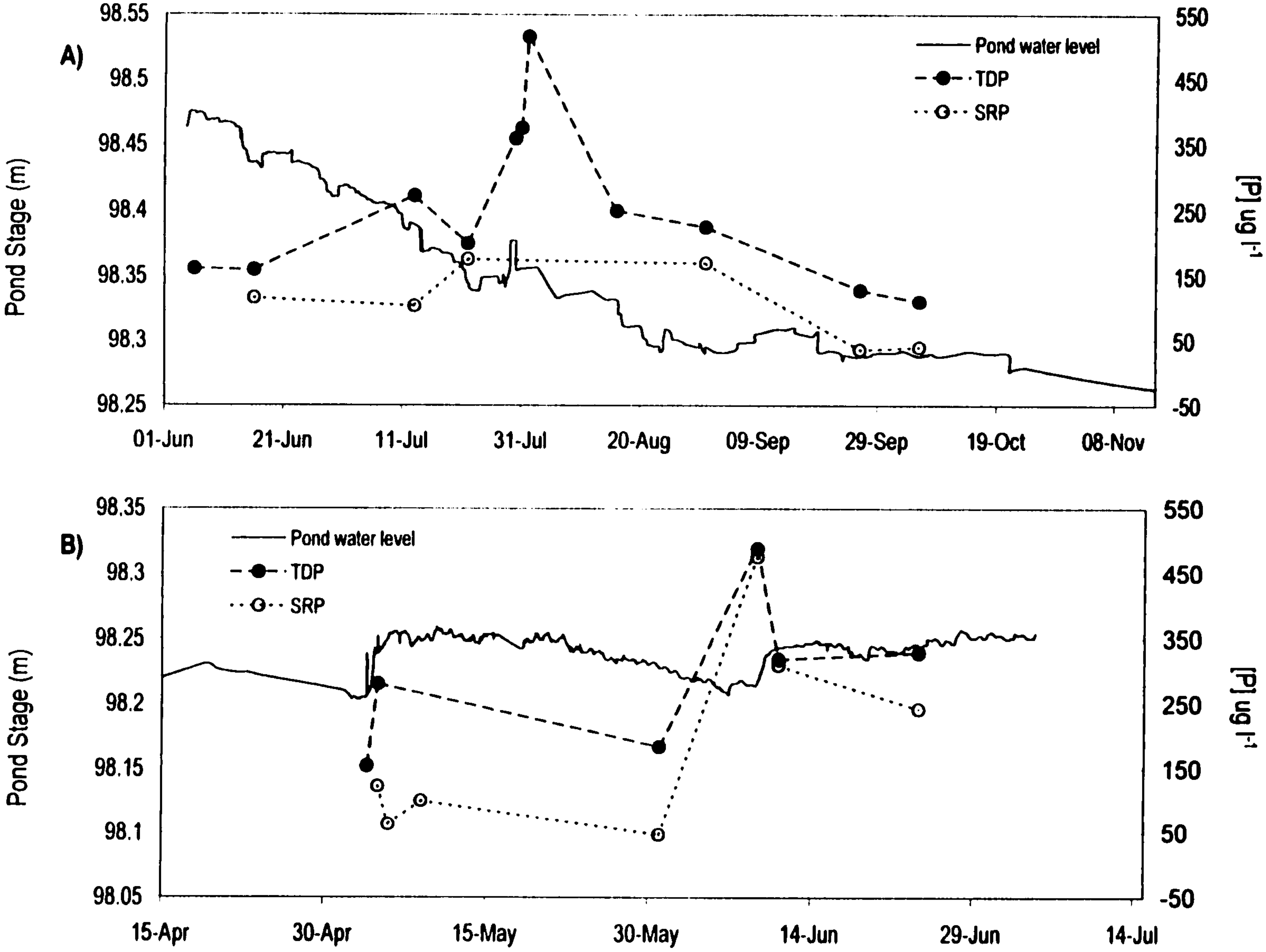

Figure 3-17. Lowland pond TDP and SRP concentrations (μg l^{-1}) and pond water level fluctuations during the summer-fall 1999 (A) and during the spring 2000 (B). In general, increased [P] values follow initial peaks in pond stage.

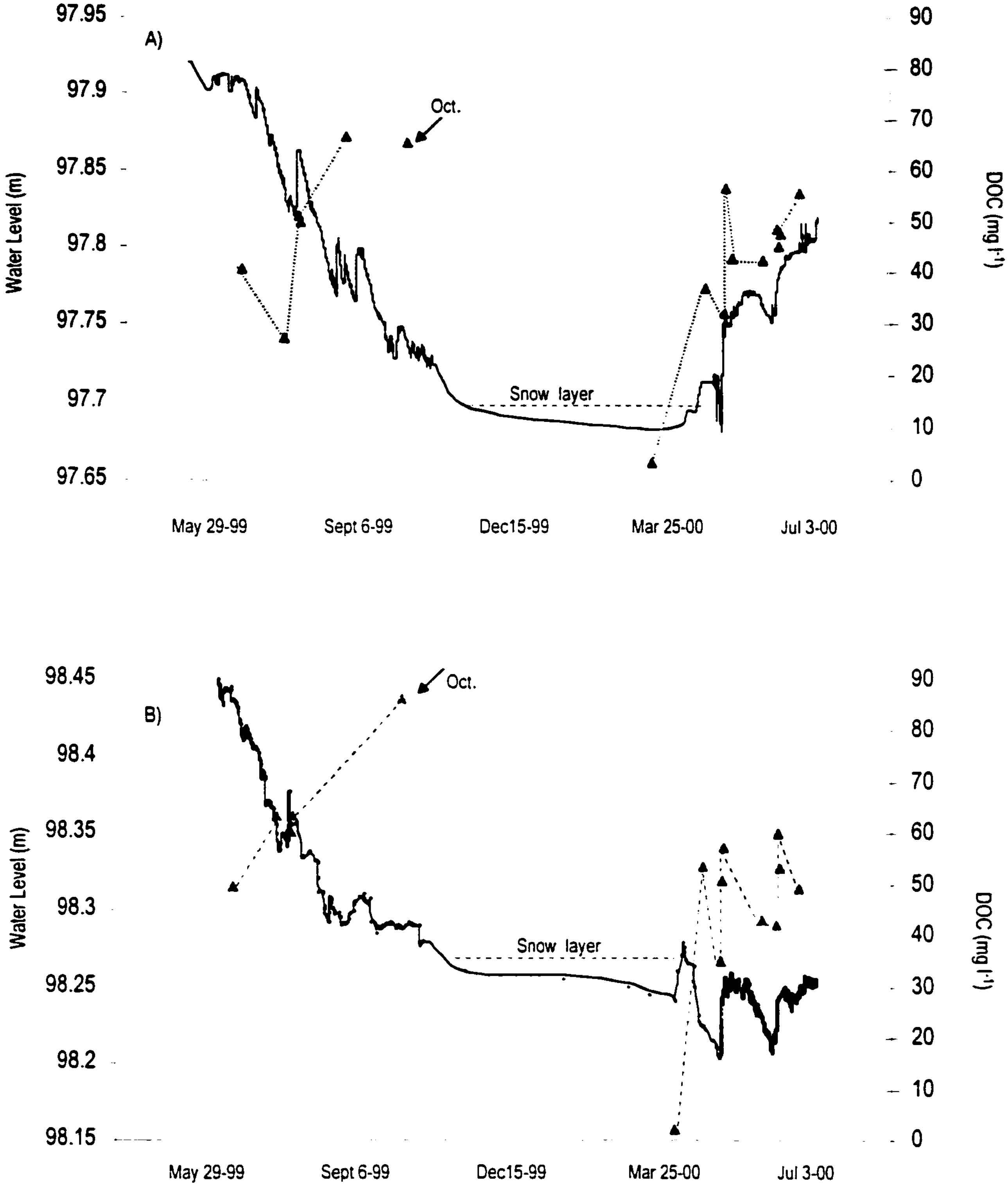

Figure 3-18. Moraine and Lowland pond DOC concentrations (mg l^{-1}) in response to pond water level fluctuations. Generally, increased DOC values follow water pulses to ponds. The high Oct. DOC value coincides with a prolonged dry period where evaporation resulted in concentrated solutes.

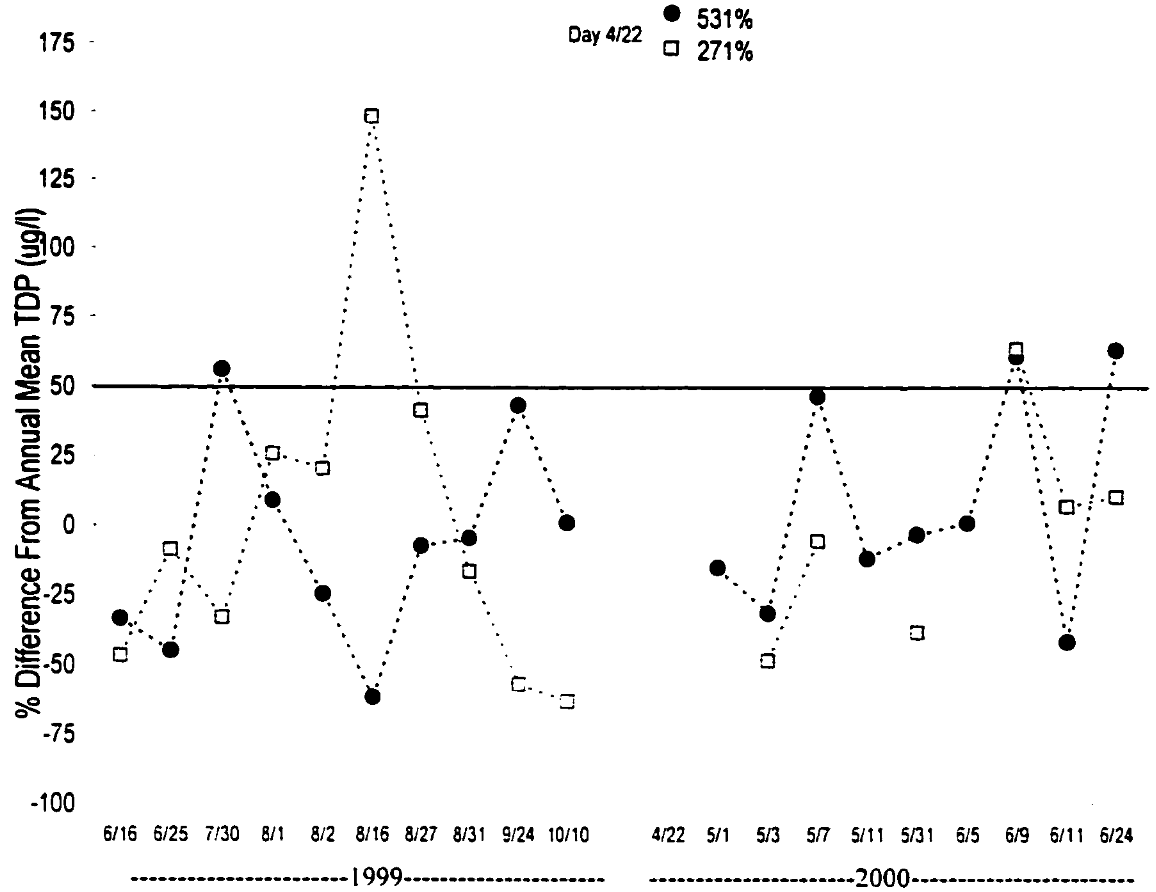

Figure 3-19. Seasonal variability of pond surface TDP (ug l^{-1}) at the moraine and lowland complex. Values represent % difference than annual mean [TDP]. April 22, 2000 values following ice off were extremely high concentrations at both ponds.

3.4.4 Redox controls on peatland groundwater P concentrations

The direct and indirect effects of peatland water table on phosphorus levels in porewater are evaluated in Table 3-2. While the linear model does not explain the variance between water table depth and [P] at each sites by itself (Table 3-2), when the sites were combined to capture the range of water table fluctuations, correlation coefficients indicated that there is a negative relationship between distance of water table beneath ground surface and TDP ($r = -.475$, $p < 0.05$) and SRP concentration ($r = -0.498$, $p < 0.05$). Within the individual sites, water table correlated with factors that likely influence redox conditions. For example, at both the moraine and the lowland site, depth of water table below surface correlated with pH (moraine $r = -0.353$, $p < 0.05$; lowland $r = -0.453$, $p < 0.05$) and DO (lowland $r = 0.380$, $p < 0.05$), suggesting that a lower water table results in decreased pH and increased DO in peatland porewater (Table 3-2). Additionally, significant correlations between DO and logTDP (moraine $r = -0.243$, $p < 0.05$; lowland $r = -0.273$, $p < 0.05$) and log SRP (moraine $r = -0.258$, $p < 0.05$; lowland $r = -0.330$, $p < 0.05$), suggest that an inverse relationship between oxygen levels and phosphorus concentrations exists within the peatland porewater. The same effect is seen with between P and pH (Table 3-2). Finally, Pearson coefficients showed significant negative correlations between depth and TDP and SRP concentrations (Table 3-2). Peat depth represents a comprehensive variable that likely reflects degree of peat humification as well as pH, and DO conditions.

Water table position does not influence P concentrations directly, however, changes in redox owing to water table dynamics through altering the redox conditions of the sediments it may indirectly influence P levels in pore water. Figures 3-20 and 3-21

Table 3-2. Pearson correlation coefficients for linear relationships among porewater variables: Depth (within peat only), water table distance beneath surface, DO, pH, COND, [TDP], and [SRP]. * indicates significant relationship at $p < 0.05$. Phosphorous correlations with DO are LogTDP, Log SRP.

Moraine:

	Depth	WT	DO	pH	COND
WT					
DO	-0.458*	0.110			
pH	0.080	-0.353*	0.386*		
COND	0.426*	0.114	-0.063	0.448*	
TDP	0.623*	-0.036	-0.243*	0.217*	0.209*
SRP	0.586*	-0.228	-0.258*	0.177*	0.213*

Lowland:

	Depth	WT	DO	pH	COND
WT					
DO	-0.498*	0.380			
pH	0.051	-0.485*	0.089		
COND	0.575*	0.466	-0.204	0.487*	
TDP	0.584*	-0.316	-0.273*	0.255*	0.262*
SRP	0.608*	-0.220	-0.330*	0.268*	0.248*

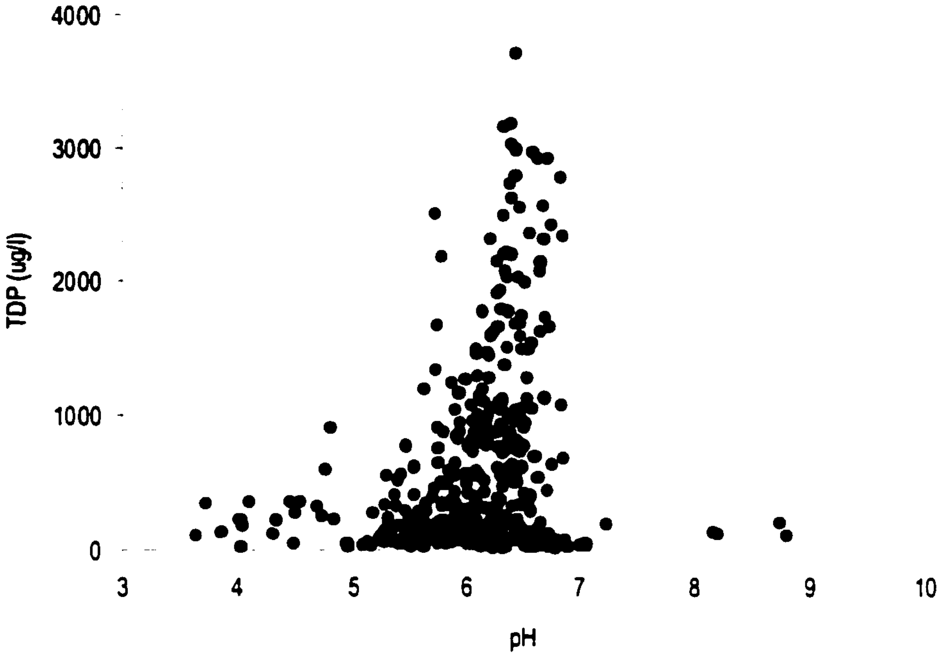

Figure 3-20. The relationship between surface water and groundwater pH and P solubility at the moraine and lowland complexes. TDP values greater than 1000 ug l^{-1} fall within 5.5 < pH < 7.

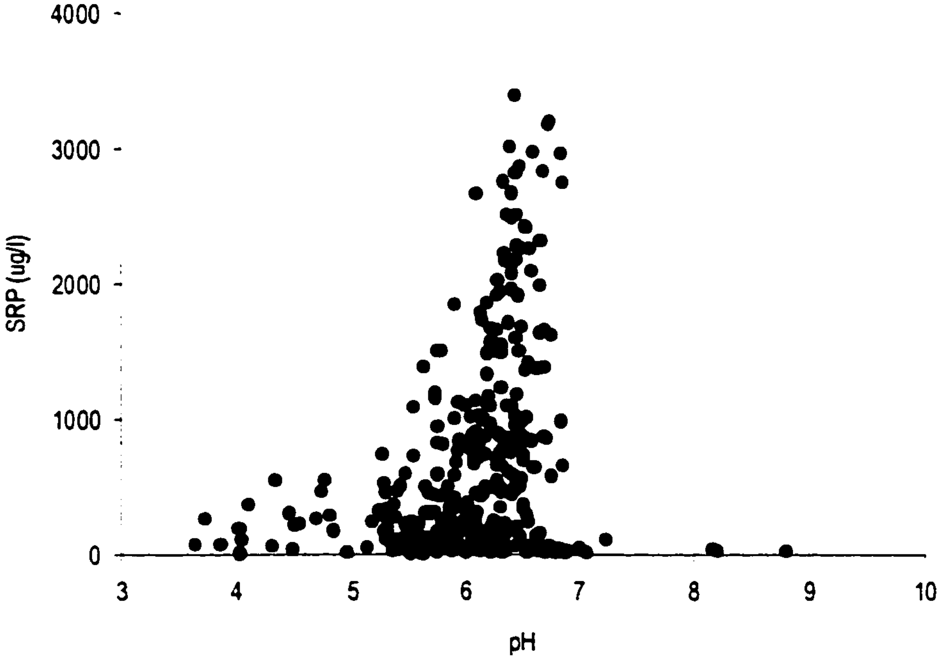

Figure 3-21. The relationship between surface water and groundwater pH and P solubility at the moraine and lowland complexes. SRP values greater than 1000 ug l^{-1} fall within 5.5 < pH < 7.

show that TDP and SRP concentrations in groundwater and surface water exceed 1000 μg P l^{-1} only when pH is between 5.5 and 7. Additionally, such levels were only observed where DO was less than 2 mg l^{-1} (Figures 3-22 and 3-23). Both indicators suggest reduced conditions are necessary for high P solubility. Figures 3-24 to 3-26 show the range of pH, DO and NH_4^+ concentrations observed throughout the two wetland complexes over the study. The range of pH distribution throughout the wetland complexes was not extremely variable, and most peats showed pH in the 6 - 7 range (Figure 3-24). DO values were generally less than 1 mg l^{-1} throughout the lower mesic-humic peat, and were slightly higher in the upper mesic peat (1-3 mg l^{-1})(Figure 3-25). Additionally, the elevated NH_4^+ concentrations (reduced N) which characterise both peatlands supports the hypothesis that P solubility is related to redox conditions (Figure 3-26).

3.4.5 Sediment Controls on Peatland Groundwater P concentrations

The extractable P pools, EPC values and sorption indices for different substrates are presented in Table 3-3, and show how differences in substrate type may influence phosphorus in groundwater. In contrast to the high [TDP] concentrations in the porewater of the lower peat and gyttja, extractable P pools from the lower humic peat and gyttja were found to be very low. As well, aerobic adsorption tests suggest that these wetland sediment types will adsorb phosphorus to high levels. Equilibrium phosphorus concentrations (EPC values) were found to range from 30-60 μg l^{-1} for gyttja and humic peat (Table 3-3). However, the mesic peat at and above the water table zone had higher extractable P and demonstrated desorption up to 1400 μg l^{-1}, suggesting that even in

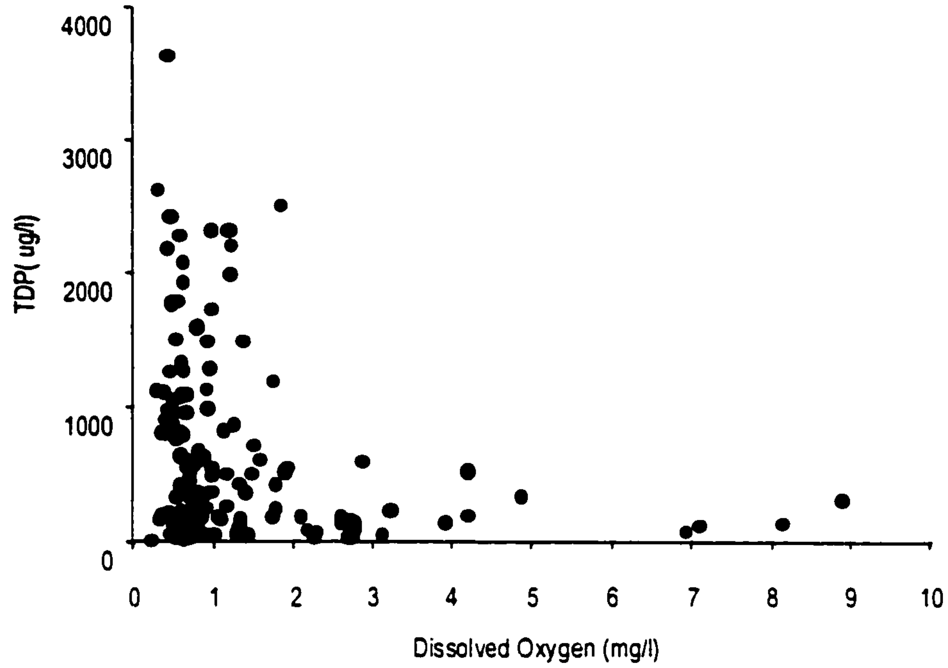

Figure 3-22. The relationship between surface water and groundwater DO and P solubility at the Moraine and Lowland complexes. TDP values greater than 1000 ug l^{-1} fall within 0< DO < 2 mg/l.

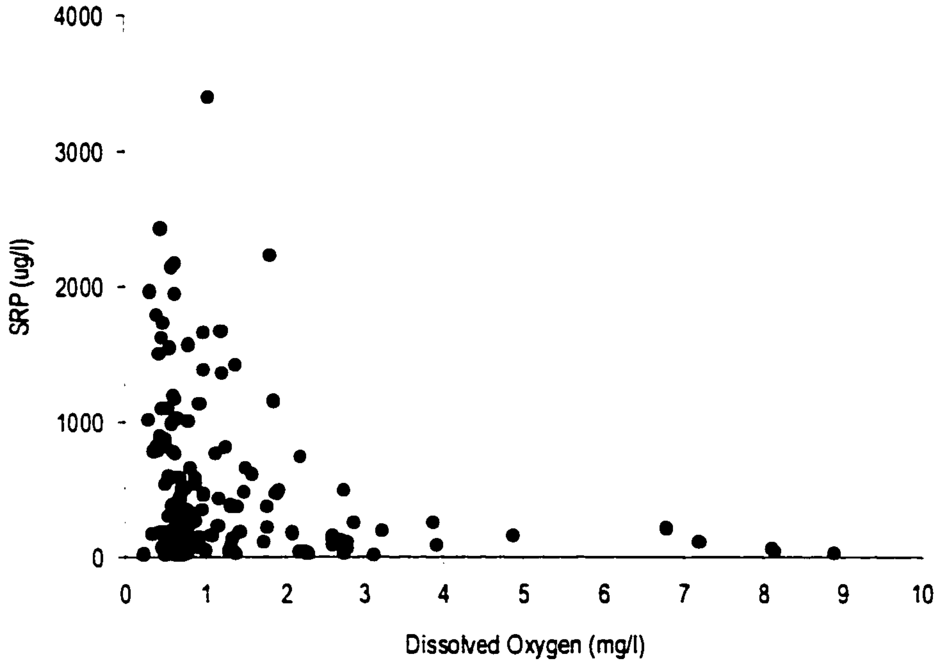

Figure 3-23. The relationship between surface water and groundwater DO and P solubility at the Moraine and Lowland complexes. SRP values greater than 1000 ug l^{-1} fall within 0< DO < 2 mg/l.

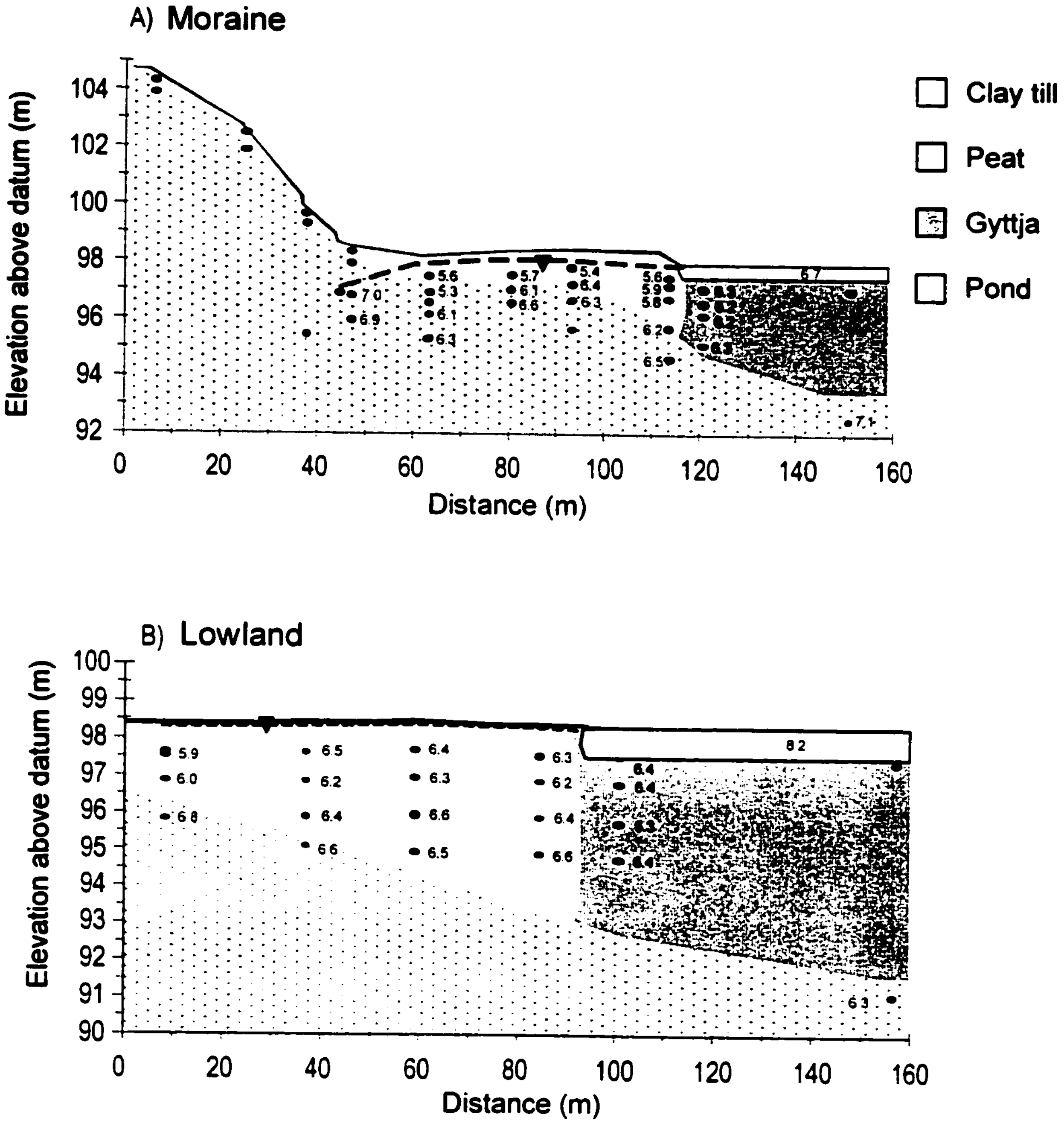

Figure 3 - 24. Range of pH found at the moraine (A) and lowland (B) wetland complexes. Dates are from June 2000. Values did not vary greatly over the seasons.

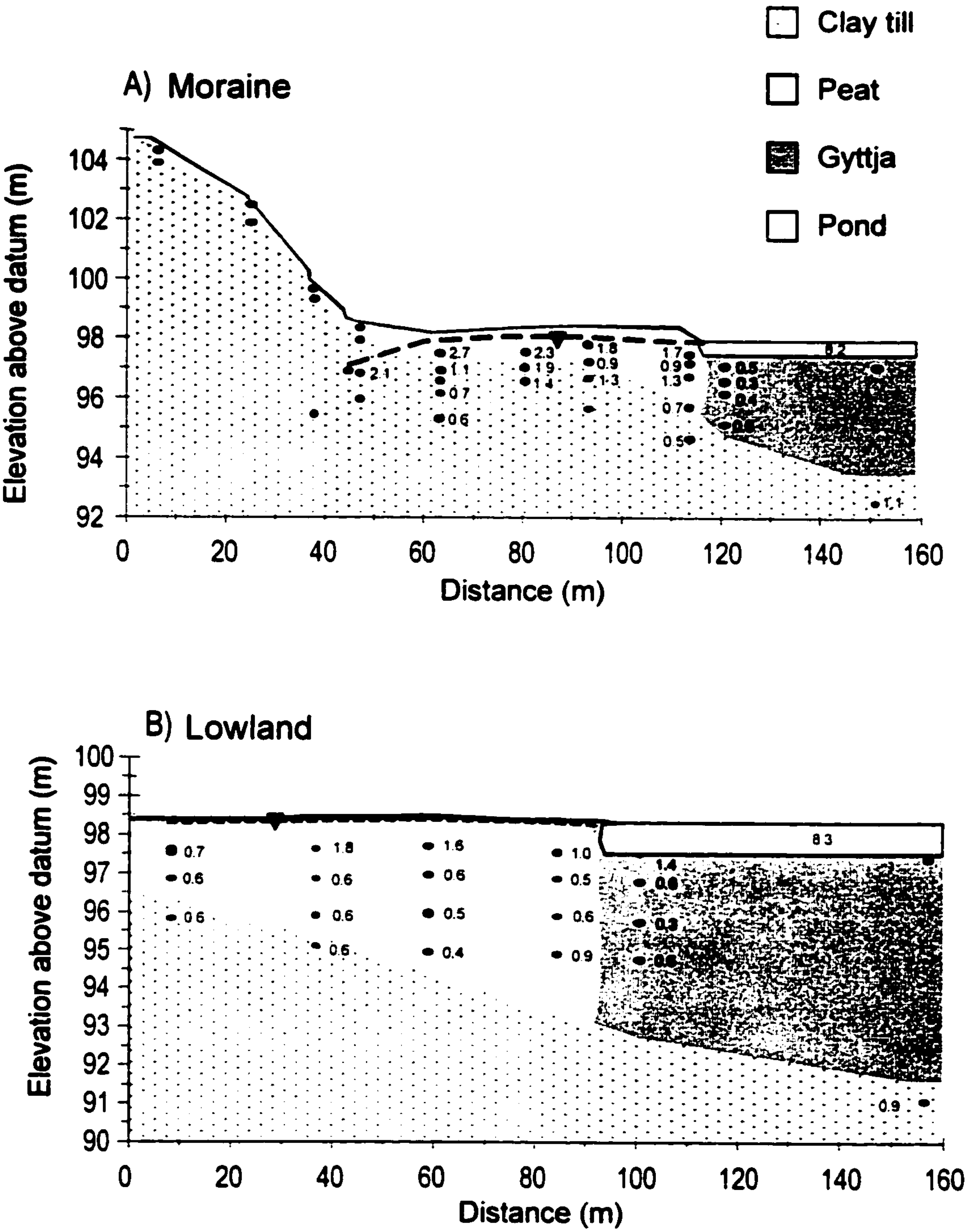

Figure 3-25. Range of DO at the moraine (A) and lowland (B) wetland complexes. Dates shown are from June 2000. Neither groundwater or surface water values varied over the seasons.

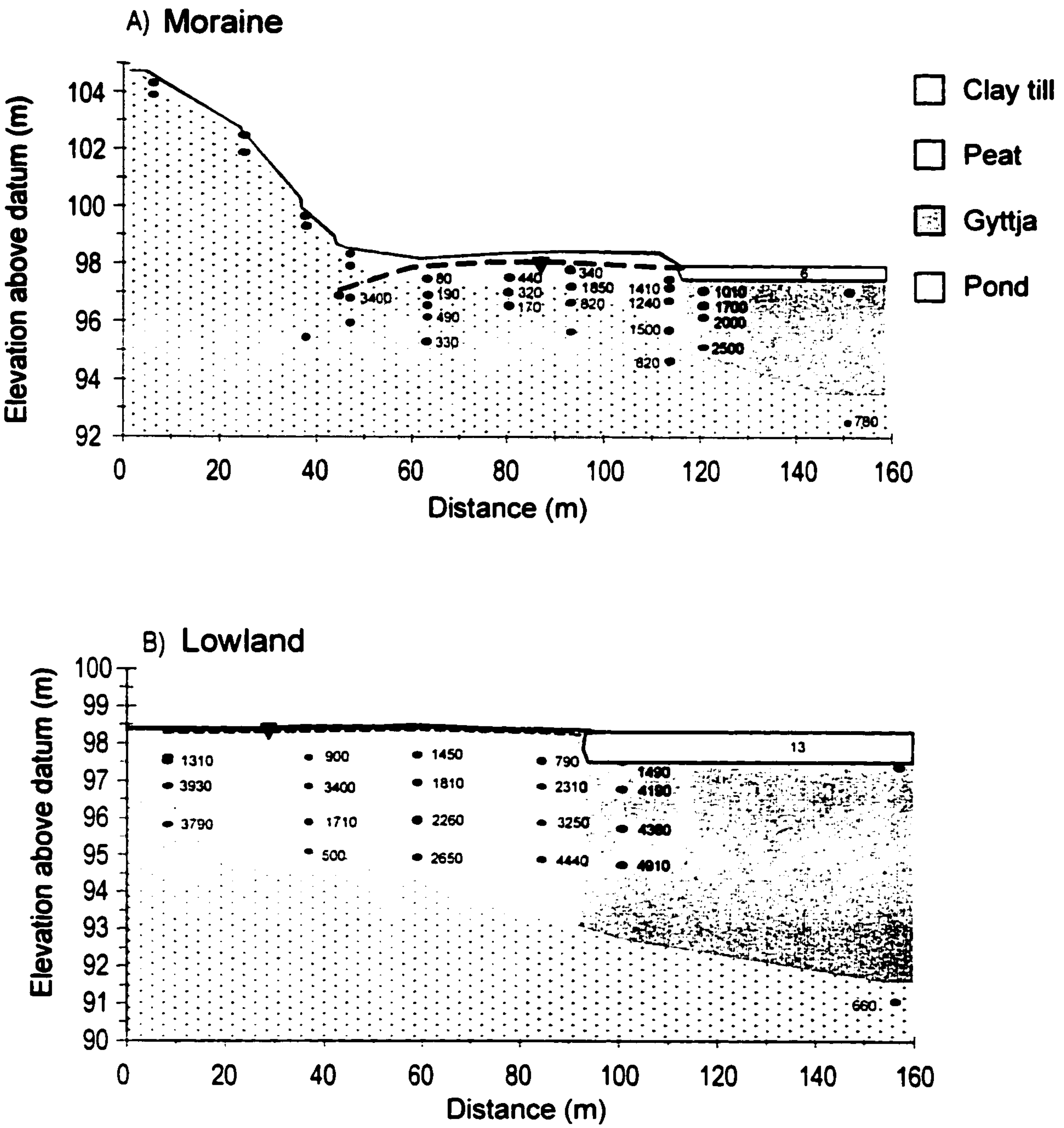

Figure 3 - 26. Range of [NH_4^+] found at the moraine (A) and lowland (B) wetland complexes. Dates are from June 2000. Surface water [NH_4^+] values varied seasonally between 7-70 ug l^{-1}.

Table 3-3. Descriptors of sediment phosphorus levels: extractable P pools (mg P kg^{-1}) and adsorption characteristics (EPC mg l^{-1} and Sorption Index) for the various wetland sediment types. Each sediment value represents the mean, standard deviation (SD), and % CV of 4 to 7 cores.

	SRP mg kg^{-1}			EPC (ug l^{-1})			Sorption Index		
	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV
Mesic Peat	0.6_a	0.9	1.5	1418.8	1603.3	1.1	1.8	6.5	3.6
	0.10_b	0.1	0.5						
Humic Peat	2.6_a	2.8	1.1	35.0	10.0	0.3	8.9	2.4	0.3
	0.07_b	0.1	0.9						
Gyttja	0.03_a	0.0	0.8	27.5	21.3	0.8	14.3	7.0	0.5
Upland LFH	57.10	7.8	0.1	Always desorbed			<< 0	11.5	-0.2
Upland 0-10cm	0.50	0.4	0.8	217.5	279.3	1.3	2.5	1.6	0.6
Deep Till (below peat)	0.10	0.1	0.7	59.5	33.9	0.6	9.0	3.3	0.4

$_a$ signifies surface core (0-10cm)

$_b$ signifies water table zone core (50-60cm) aerobic conditions P will be removed from the upper peat. The upland till and unoxidized till had moderate extractable P and high EPC values (100-200 $\mu g\ l^{-1}$). The LFH had very high extractable P and EPC was greater than 5000 $\mu g\ l^{-1}$.

Sorption indices demonstrated the same pattern. Under aerobic conditions, till, humic peat and gyttja showed indices in the range of 8 - 14, indicating they can buffer additions of P. Mesic peat and hillslope surface soil was shown to buffer less (1.8 – 2.5, Table 3-3). The LFH layer on the hillslope did not buffer P additions at all.

3.5 Discussion

3.5.1 Importance of Groundwater Contributions to the Annual Phosphorus Budget

Precipitation and shallow groundwater originating from adjacent riparian peatlands were the dominant sources of phosphorus to the annual budget of ponds in both topographic positions. However, since the shallow groundwater water flux was much smaller than the precipitation water flux (precipitation inputs were 6 - 13 times greater), even small fluctuations in groundwater exchange appear to strongly affect pond nutrient status. In the Boreal Plains, the limited surface drainage and P rich glacial till (Vogwill 1978, Cooke and Prepas 1998) enhances the potential for groundwater P transport. Therefore, groundwater commonly influences the nutrient status of precipitation dominated lakes and wetlands. In a small, north central Alberta lake where 30% of the annual water input was groundwater, elevated annual SRP loading from groundwater (39 mg m^{-2}) was twice as large as measured TP loading from atmospheric deposition, and 4-5 times greater than surface runoff P loads (Shaw et al. 1990). While groundwater [TDP] and [SRP] in the Utikuma wetland complexes were similar to those found by

Shaw et al. (1990), TDP loading via groundwater to the Utikuma ponds was slightly less, and approximately equal to atmospheric loads (groundwater: 7.6 - 9.5 mg m^{-2} vs. deposition: 7.9 - 9.1 mg m^{-2}). Devito et al. (2000) examined lake position within groundwater flow systems and showed the importance of deep groundwater in moderating inter-annual change in TP loading and lake concentrations on the Boreal Plain. While deep groundwater contributions were important, they also determined that, as in this study, P loading was greatest following high flow when a major source of P originated from peatland systems connected to local groundwater systems. At a precipitation dominated prairie slough, Hayashi et al. (1998) found that the chloride signature of a northern prairie recharge wetland was determined primarily by local groundwater cycling with adjacent uplands. Therefore, while the source of groundwater in the Utikuma wetlands may differ from other studies, the importance of groundwater for solute transport has been noted throughout the interior plains.

Since neither wetland complex was influenced by larger groundwater flow systems, differences in phosphorus loading to the ponds were due to differences in the shallow groundwater P sources. In both the moraine and lowland system, adjacent peatlands represented the origin of shallow groundwater fluxes as well as the highest P source (including littoral gyttja). Therefore, while the lowland pond TDP and SRP concentrations were 2 to 7 times higher than the moraine pond, the differences were not controlled by regional groundwater, as originally hypothesised. Thus, unlike many prairie sloughs, topographic position did not explain the differences in pond surface water solute concentrations (Winter 1989, Winter and Rosenberry 1995).

Differences in phosphorus dynamics between the two sites appeared to be influenced by "within catchment" features. Firstly, P concentrations in peatland groundwater were greater at the lowland site, resulting in greater P inputs for a given groundwater flux. Furthermore, hydrologic results suggested that catchment characteristics, such as peatland storage within the local drainage basin, could influence local flow patterns (Chapter 2). The larger peatland storage in the lowland system produced a constant inflow of P rich groundwater to the pond, even during low flow periods. Therefore, while annual TDP loading via groundwater was only slightly greater at the lowland pond this year (9.6 vs. 7.6 mg m^{-2}), over the long-term, larger P fluxes due to continuous groundwater and increased P concentrations could maintain greater surface P concentrations in the lowland pond, as compared to the moraine pond. The importance of catchment control on ephemeral vs. continuous local groundwater flows on peatland water table regime and chemical outflow has previously been demonstrated in wetlands on the Canadian Shield and in glaciated regions of southern Ontario (Devito and Hill 1997, Hill and Devito 1997).

Finally, the potential for long-term inputs of P must be described within the context of flow conditions (ie. low flow in 1999 and moderate – wet conditions 2000 (Environment Canada 1997). During "normal" years, the lowland pond may typically receive much higher groundwater and P inputs from the large inflow peatland. Previous lake and wetland studies have shown that variable groundwater flow conditions can alter dominant biogeochemical processes over several years (Romanowicz et al. 1993, Wentz et al. 1995, Devito and Hill 1997). For example, Wentz et al. (1995) found that a Wisconsin lake switched from a flow through system to a recharge system over several years in response to annual rainfall patterns. During this time, the dominant biogeochemical controls changed from mineral weathering in inflowing groundwater to sulphate reduction in lake sediments. Therefore, although flow conditions similar to those described herein have occurred in the Utikuma area periodically over the past two decades, much wetter periods occur more frequently (Appendix A). Thus, the P loading observed during this study might represent only a portion of the long-term patterns in pond P storage and water concentrations.

3.5.2 Effect of seasonal groundwater flow reversals on peatland-pond P exchange

Groundwater flow reversals influenced seasonal exchange of P and pond P concentrations. The effects were greatest at the moraine site where, during wet conditions, the moraine peatland reversed uniformly to discharge conditions. The hydraulic mounding around the pond prevented pond outflow losses, resulting in net inputs of P from source areas near the pond edge, and pond P concentrations increased in excess of precipitation inputs. The pulses of DOC and P indicate the rapid groundwater response from the peat and gyttja adjacent to the pond. During dryer periods, the pond reversed to recharge conditions. Due to the low pond stage, the groundwater seepage from the pond was forced to pass through the lower permeability, deeper peat, resulting in a low rate of P transport out of the system. Furthermore, pond water seeping out of the pond passed through the elevated P gyttja, and thus transported P rich water into the adjacent peatland edge. At the moraine site, regular seasonal flow reversals may limit the distance that P is transported in either direction, and thereby influence the formation of regions with elevated P concentration or "hotspots" in the peatland edge-littoral gyttja zone.

Although groundwater flow-through dominated the lowland complex, a groundwater reversal occurred and appeared to influence seasonal P transport and pond concentration, contrary to hypothesis two. During dryer periods, edges of the lowland pond perpendicular to the flow- through became regions of recharge, greatly increasing P losses. During intense wet periods, such as May 2000, flow conditions reversed on the outflow side of the peatland and all areas of the P rich peatland contributed P to the pond. Therefore, flow reversals enhanced P loading by both increasing inflow through P source areas and reducing export.

Groundwater flow reversals observed in these Boreal Plain wetlands are similar to patterns in prairie slough wetlands, where flow reversals influence lateral solute transport between local flow systems and adjacent surface water. For example, transpiration induced reversals between riparian upland and adjacent prairie sloughs have been shown to control solute concentrations in surface water (Hayashi et al. 1998). However, the physical and chemical properties of peat allow for rapid flow responses and variable biogeochemistry, a finding not reported for slough systems.

Studies of groundwater flow in peatlands connected to a regional flow system (Siegel and Glaser 1987, Romanowicz et al.1993) and peatlands isolated from underlying flow systems (Waddington and Roulet 1997, Fraser et al. 2001), have noted the effects of flow reversals on the distributions of solutes within the peat column. Studies in isolated peatlands have observed that flow reversals between wet and dry periods resulted in the translocation of DOC and other solutes to the upper profile of the peat margins

(Waddington and Roulet 1997, Fraser 2001). Simulation modelling by Reeve et al. (2000) predicted that lateral flow reversals should occur in peat mounds where regional gradients were low. In the Boreal Plains wetlands, peat mounds tend to develop near the pond edges, where the wet and dry cycles induce strong gradients with the surface water. Thus, flow reversals associated with these mounds have high potential to enhance nutrient interactions between the peatland and surface water.

3.5.3 Geochemical controls on peatland porewater P concentrations

While porewater P concentrations were generally greater at the lowland site, the controls on these levels appear to be more complex than based simply on differences in regional groundwater inputs. The results suggest that high water table and saturated conditions in the riparian peat create a reduced environment optimal for P solubility. In particular, correlations indicated that low DO and neutral pH favour P release in porewater. In aerobic, non-calcareous soils, P is often retained by Fe, Al and Mn minerals (Ann et al. 2000). If these soils become anaerobic, the reduction of these metal phosphates releases soluble P to interstitial water. In calcareous systems, Ca^{2+} bound P (e.g. apatite) is more strongly controlled by pH rather than Eh (Ann et al. 2000). In most soils, P fixation by mineral complexes is lowest between pH 6 - 7 (Brady and Weil 1999). In a study simulating the variable Eh and pH of organic wetland soils, Ann et al. (2000), found that changing redox potential had the least effect on P release from $CaCO_3$ amended soils rather than those amended with Fe or Al. Therefore, under aerobic conditions iron levels may control the available P, yet under reduced conditions, Ca^{2+} bound P may determine P in porewater (Ann et al. 2000). Complex relationships among

P, Fe and Ca^{2+} might explain the occurrence of very high [P] within the deeper mesic - humic peat in contrast to much lower [P] in the anoxic underlying clay till transition. Furthermore, the presence of high DOC likely increases P solubility in peat. As both humates and P molecules compete for the same metal complex adsorption sites, high levels of organic matter have been found to enhance P levels in solution (Lyons et al. 1998, Brady and Weil 1999).

While the redox conditions within the wetland complexes may promote the ideal environmental conditions for P solubility, the individual geochemistry of the sediments may limit the extent to which P will be bound or released. The results from adsorption tests show that even under aerobic conditions the upper, mesic peat desorbs large amounts of P. This suggests that soluble P is released to the shallow groundwater flow zone, even under the aerobic conditions induced by a fluctuating water table. Although the lower mesic-humified peat, gyttja and till were shown to adsorb P under aerobic conditions, porewater conditions in the peat and gyttja were generally anoxic, and represent large P sources. The larger P adsorption under oxygenated conditions indicates there is a large mineral content in the lower peat soils (Lyons et al. 1998, Axt and Walbridge 1999). Porewater concentrations indicate that Ca^{2+} and Mg^{2+} levels in the lower peat approach the levels in the underlying till, and grab samples have indicated Fe^{2+} levels are high in the lower sediments of both peatlands (up to 1.8 mg l^{-1}).

While difficult to compare directly, the EPC values found in this study are similar to aquatic systems of other regions. EPC values of the mesic peat and upland surface soils fell within the range of the EPC values for moderately well drained and poorly drained forest soils in riparian zones in Rhode Island (Lyons et al. 1998). However the gyttja, humic peat and clay till showed much higher P retention capacity (lower EPC) than the riparian soil study. The EPC values of the gyttja and humic peat were comparable to those of stream sediments in southern Ontario (0.01 to 0.025 mg l^{-1}), but the buffering capacities of those stream sediments was much higher than the wetland sediments (Phosphorus Sorption Index (PSI) = 85 -142 in stream vs. 14 in gyttja) (Hill 1982). EPC and buffering capacity of the oxidised tills and the deep tills below the peat and pond indicate that groundwater from mineral uplands and larger regional flow systems will be buffered to [P] near 40-250 μg l^{-1}. Deep groundwater wells along the hydrogeologic transect throughout greater study region indicate that TDP ranges from 50 –150 μg l^{-1}. Likely, Ca complexes bind the P, and therefore solubility is not as affected by reduced conditions. Therefore, elevated [P] appears to be restricted to the organic sediment in the riparian area (including gyttja) where anoxic processes can influence solubility. The importance of this littoral-riparian interface as a biogeochemically active zone for groundwater flowpaths has been previously noted (Shaw et al. 1990, Hill 1996, Hedin 1998). Shaw et al. (1990) determined that groundwater P concentrations increased eightfold after passing through the P rich near shore sediments of Narrow Lake, AB.

3.5.4 Internal processes influencing pond P storage

While groundwater P is obviously an important input to the pond budget, the residuals in the annual P balances and the Ca/P ratios indicated that internal P cycling is important in boreal wetland complexes. Internal P release was observed during fall and could be related to senescence of pond macrophytes and other growing season biota.

Internal P removal appeared to occur coinciding for growing season demands for available P. Since both wetlands had productive algal communities (moraine mean summer chlorophyll a (chl a) = 26 μg l^{-1}; lowland mean summer chl a = 57.1 μg l^{-1}) and submersed aquatic communities (mean aboveground biomass ranged from 462.1 g m^{-2} (1999) to 704.1 g m^{-2} (2000) in the study area) (Menchenton 2001), there is large potential for seasonal P removal from the water column. The low Ca:P ratio observed during the winter (including the snow melt period) is likely associated with P release from anoxic sediments under the ice (Sondergaard et al. 1999), as the pond melted from the bottom up and pond water was anoxic during this period. At both sites spring Ca:P ratios reflected high flow conditions, prior to peak growing season. During this period both Ca and P should have entered the ponds at equally high levels, but slight P removal could have occurred with early vegetation growth.

Finally, P release from sediments due to molecular diffusion has been reported to be potentially important in shallow lakes with P rich sediments (Shaw and Prepas 1990, Golosov and Ignatieva 1999). Some estimates in boreal Alberta lakes have ranged from 0.04 mg m^{-2} d^{-1} to 1.5 mg m^{-2} d^{-1}, however diffusion of P from anaerobic porewater to aerobic pondwater may be prevented by P sorption onto ferric iron complexes, forming under oxygenated conditions (Shaw and Prepas 1990). In the Utikuma systems, the gyttja adsorbed P (rather than released) under aerobic conditions, indicating that P release from the pond sediments to the water column would be limited during the year. Furthermore, during flow reversals from discharge to recharge conditions, oxygenated surface water was transported into the littoral peatland and gyttja, further limiting anoxic P release. Studies of P release in shallow ponds has indicated that the capacity for sediment P adsorption vs. release was strongly correlated to iron and Fe:P ratio (Jensen et al. 1992, Andersen and Ring 1999). The implications of internal P loading could be important for the annual wetland complex P budget, and requires further investigation.

3.6 Conclusion

The conclusions of the study are as follows:

Objective 1:

H1: Groundwater transport represented an important source of phosphorus in the annual budgets of both wetlands. In the moraine and lowland wetland complexes, groundwater TDP and SRP transport from adjacent peatland areas represented approximately half of the annual external P inputs to the pond surface water. Pond surface water TDP and SRP concentrations were consistently greater at the lowland site than the moraine site, but since as neither system was influenced by the regional groundwater flow system, observed P concentrations were more influenced by differences in shallow groundwater flowpaths and internal P cycling. Variable seasonal Ca:P ratios in the ponds suggest that internal factors (such as P uptake by pond biota, sediment release, molecular diffusion etc.) are an important influence on seasonal P storage, and that internal dynamics need to be further investigated.

Based on the year of study, the hypothesis that groundwater P transport to the lowland site would be greater due to a regional flow connection is refuted. Both systems represented recharge areas, but due to impermeable tills, water and P loss was minimal. In contrast, shallow groundwater contributions appear to play an important role in the annual P budgets of both wetland complexes.

Objective 2:

H2: Seasonal groundwater flow reversals appeared to influence P transport to ponds in both topographic settings. Although TDP and SRP concentrations in peatland groundwater did not vary greatly throughout the year, flow direction controlled P pulses to the pond. During wet periods, the moraine pond received large P inputs from P rich littoral peat, contributed by all sides of the peatland; during drier periods (September to April) P transport was away from the pond, but it was a small flux. As the lowland system functioned as a groundwater flow through system for most of the year, it received constant and large inputs of P rich peatland water during high flow, and lost smaller fluxes of P through groundwater outflow. During low flow, discharge along the inflow transect decreased, and P inputs were reduced. During spring 2000, large inputs of P discharged to the pond from the surrounding P rich peatland. The dynamic pattern of seasonal solute transport also confirmed by DOC pulses to pond water, and emphasises the importance of shallow groundwater flowpaths.

As hypothesised, seasonal pulses of P to the pond appeared to correspond to peatland groundwater flow reversals. While the moraine complex appeared to be more susceptible to gradient reversal, both wetland complexes had flow reversals, and as a result, variable pond P concentrations. However, pond P concentrations were highly variable, and were likely influenced by other processes (ie. evapo-concentration and internal cycling) during dry periods, when groundwater P fluxes were small and away from the pond.

These patterns reflect short-term processes and long-term characteristics may be different. This study occurred during one of the driest periods (1999), and 2000 was moderate to slightly wetter. Dry conditions may have greatly reduced local flow-through at the lowland plain, which might occur during most years. As a result, the high frequency of reversals during this study may not reflect patterns over longer and wetter periods.

Objective 3:

H3: As hypothesised, high water table and saturated sediments appeared to play a role in determining redox conditions within the peatlands, however, the P concentrations in porewater appears to be controlled by a number of factors. The relationships observed among TDP, SRP, water table, DO, and pH suggest that reduced conditions prevail (low DO, mid pH) within the peat and gyttja, and therefore, P solubility is maximised in these two zones. In the upper peat column, mesic peats appear to desorb P even under aerobic conditions, suggesting that high P is available to the flow zone of shallow groundwater. The humic peat, gyttja and till appear to easily adsorb P under aerobic conditions, however, as the peat column was shown to be continuously anaerobic, the humic peats likely released P into pore water. The adsorption capacity of the gyttja suggests pond sediments are not independently releasing P into the oxygenated water column, however P transport to the pond likely occurs due to groundwater advection through this zone. While the data set is limited for these analyses, the adsorption tests also indicate that redox is important in determining the available P for groundwater transport from peat.

Further research is needed to examine the details of P release from peat and pond sediments in order to quantify the importance of internal P loading.

This study has shown that P transport and exchange between peatlands and pond is a result of complex groundwater-surface water interactions. Landscape alteration that affect the connection between peatlands and adjacent ponds could have large impacts on P loading to ponds, and therefore the nutrient status of the wetland complexes, in general. In order to predict responses, further research is needed in years spanning a broader range of long-term climatic conditions. As well, studies examining the geochemical controls on P availability and distribution within the peatland and pond sediments need to be further investigated.

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Chapter 4: General Conclusion

4.1 Implications for Landscape Disturbance

The results of this study describe the hydrologic and nutrient function of two boreal plain wetland complexes during a relatively dry period (see Appendix 2). Therefore it is important to recognise that the processes described here do not necessarily represent hydrologic and biogeochemical function under all conditions. Long-term monitoring of these systems is necessary to determine overall hydrologic function, in order to realistically predict wetland response to landscape disturbance. However, while the results shown here reflect short-term trends, certain patterns of wetland hydrologic and biogeochemical function are evident and might be enhanced under wetter or dryer conditions.

Shallow groundwater represents a small portion of the annual water balance in the Boreal Plain study wetlands, and these fluxes are extremely dynamic and sensitive to changes in atmospheric forcing (ie. P, ET) and flow condition (i.e. wet vs. dry). Reversals in flow direction appear to be a seasonal characteristic of the moraine wetland, and have the potential to occur in the lowland sites. Thus, reversals may explain differences in pond permanence between the moraine and lowland system during dry years. Furthermore, the riparian edge of the peatland areas within both catchments represent a seasonal source of water to the ponds, and do not appear to have a riparian "buffer" role in water interception. Therefore, activity directly or indirectly affecting the riparian peatlands (e.g. cutlines, compaction, ditching and drainage, harvesting) could potentially have larger adverse effects on pond function than activity that affects the hydrologically disconnected uplands. For example, harvesting peatland areas reduce ET demands and increase peatland water tables and timing and length of discharge conditions. As well, studies of forestry practices in nearby peatlands suggest that ditching greatly alters water table configuration (Hillman 1992). Changes in the groundwater freeze-thaw dynamics resulting from peatland drainage have been suggested to lead to increased permafrost development (Swanson and Rothwell 1989). Such alterations to peatland subsurface flow conditions would impact seasonal water exchange with adjacent ponds, and alter pond function.

Riparian peatland-groundwater interactions appear to influence pond chemistry. The littoral peat areas represent a seasonal source of P to adjacent ponds and flow reversals within the peatlands appear to affect seasonal pond phosphorus status. This suggests that even small changes to shallow groundwater fluxes could have a large impact on boreal pond habitat quality. For example, long periods of drought, inducing groundwater flow away from the ponds could potentially limit the necessary supply of nutrients for boreal pond biota. Conversely, very wet conditions could result in excess nutrient loading to the systems through increased and prolonged discharge. Increased P additions could alter aquatic communities and degrade water quality (Prepas et al. 2000). If the mechanisms observed at these two wetland sites apply to other peatland-pond complexes in the region, there may be implications for wetland disturbance and contamination. Less desirable contaminants sequestered in peat soils could also be easily released into pond water through this seasonal pulse, and affect productivity levels and/or habitat quality.

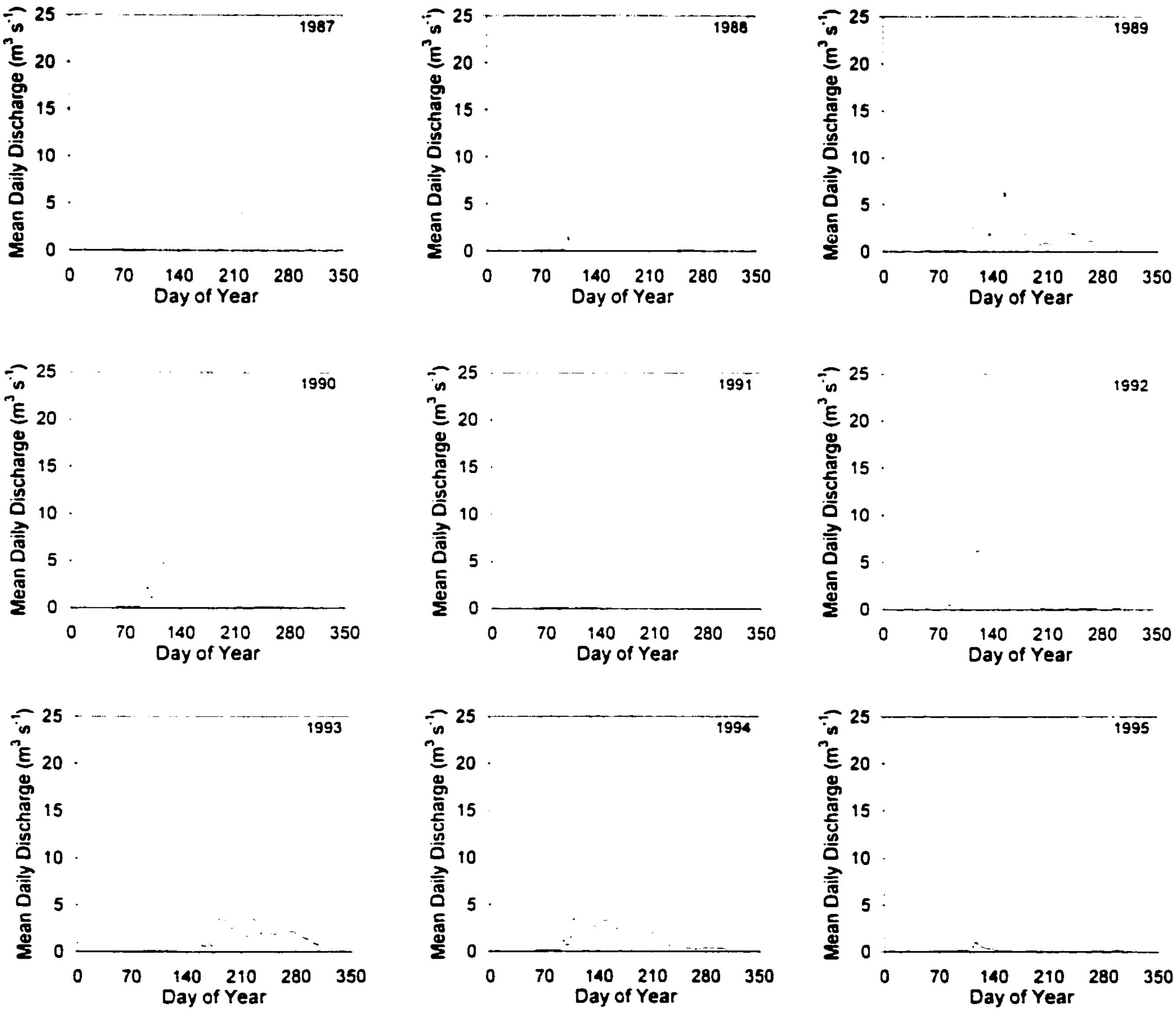
While the importance of protecting the riparian peatland zone in order to preserve pond function is important in both locations, due to differences in shallow groundwater flowpaths, the wetland complexes may differ in susceptibility to greater landscape disturbance. The moraine is a smaller, isolated catchment that demonstrated little interaction with the surrounding mineral hillslopes. In the clay plain area, while the pond is still influenced by local groundwater within the peatlands, the flowpaths appear to be slightly larger, connecting to large, expanses of surrounding peatland. Any activity occurring within these larger peatlands could alter the flow through nature of the wetland complex and the overall ecological function of the system.

Current hypotheses on the impacts of future disturbance are based on short-term information, but it appears that changes to the groundwater- surface water interactions in Boreal Plain wetland complexes could have implications for boreal wetland hydrologic and biogeochemical functioning. Monitoring these trends and experimental manipulations over the next few years within the study area will provide further insights.

Appendix A.

Hydrographs for Red Earth Creek near Red Earth (1987-2000)
Drainage Area = 619 km²

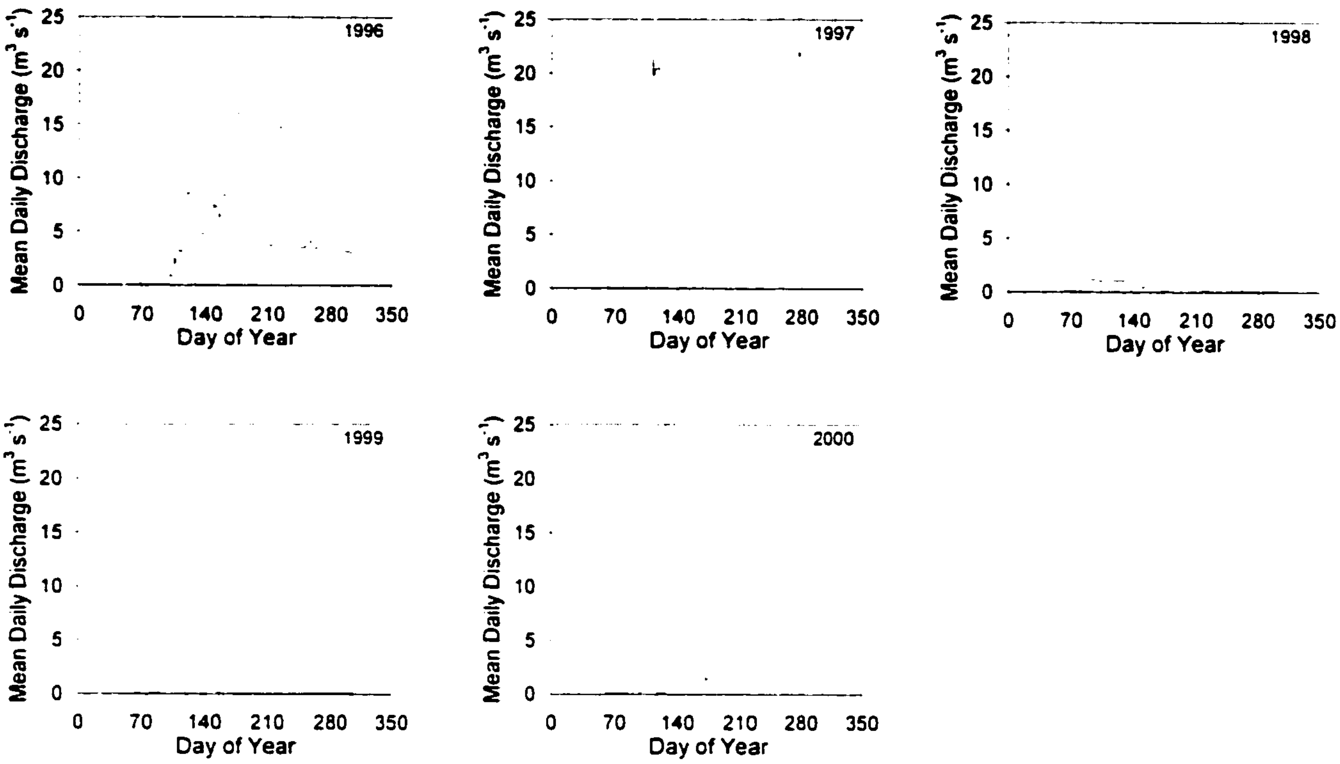
Source - Water Survey of Canada (HYDAT)



Appendix A. continued

Hydrographs for Red Earth Creek near Red Earth (1987-2000)
Drainage Area = 619 km^2

Source - Water Survey of Canada (HYDAT)



Appendix B: Selection of Evaporation Values

Pond evaporation was calculated by two independent methods and compared to Thornthwaite potential evapotranspiration (PET) calculations (Table 2-2). Annual E values calculated using the mass transfer model were much lower than the evaporation pan values at both sites (46% lower). A possible explanation for this could be the dependence of the mass transfer E on turbulent transport (measured as windspeed). The low average wind speed at both sites (Figure 2-23) strongly limits the maximum potential E as calculated by this model (Figure 2-23). However, in systems where pond surface temperatures (Ts) are greater than overlying air temperatures (Ta), free convection may also play a role in water vapour transport from the pond surface, independent of wind speed (Dingman 1994). At Utikuma, the shallow nature of the study ponds resulted in high pond water temperatures that often equalled or exceeded Ta (Figure 2-24), therefore free convection may have been an important factor allowing evaporation to occur in absence of high winds.

The uncertainties generally associated with pan E estimates are due to differences in the dimensions and heat storage capacity between a water body and a pan (Dingman 1994). As both of these factors can lead to an elevated Ts for the pan, correction factors are often applied to adjust for differences (0.7 is commonly used). However, due to the shallow pond depths at both the moraine and lowland site, daily temperature fluctuations in the ponds and the pans were nearly identical (Figure 2-5).

Due to the concerns with potential underestimates with the mass transfer model, and because of the similar temperature patterns of the pan and pond, pan E estimates were used in the calculation of the annual water balance. Using these values, the moraine pond annual E was 394 mm and the lowland pond was 438 mm. ET values calculated by the Thornthwaite method closely approximated pan E values (less than 4% difference for both ponds).