UNIVERSITY OF CALGARY

Solute Pathways in Surface and Subsurface Waters of Wetland S109, St. Denis, Saskatchewan.

by

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ABSTRACT

A bromide tracer was introduced to the central pond of slough 109 at St. Denis, Saskatchewan in April 1999. For the next two years bromide distribution in surface water and groundwater, and groundwater flow directions were investigated in order to delineate subsurface solute pathways and to characterize chemical evolution of the pond.

Water samples from piezometers and pond water, and pore water extracts from soil samples reveal that bromide mostly stays within the top metre of sediment beneath the pond and concentrates under the pond edges. Upon infiltration, water and solute from the pond take a shallow, lateral path toward pond edges, along the principal directions of groundwater flow, and follows near-surface, high-permeability soil horizons. This movement is driven by root uptake by trees and marginal pond vegetation.

During the spring and summer of 1999, bromide levels in the pond decreased as water level decreased due to the occurrence of heavy rains in June and July. Mass balance calculations used to model the daily change in pond concentration due to precipitation and evaporation were fit to measured bromide concentrations using the method of least squares. Optimal agreement of the data is achieved using an assumed width of 12.6 m for the vegetation margin, the area of which represents the contribution of evapotranspiration to pond water loss. This value very close to the actual width of the willow ring measured in the field.

In the spring of 2000, bromide was again detected in pond water due to diffusion of accumulated bromide from shallow levels in the bottom sediments. Mass balance calculations show that this bromide entered the pond through mixing with pore water from the top 0.4-0.5 m of soil, which corresponds to the soil's A-horizon.

All 24 kg of bromide introduced to the pond in spring of 1999 could be accounted for in pond water, vegetation, and in soil to a depth of 3 m through July 2000. Even though root uptake of groundwater drives subsurface flow and solute transport, less than a kilogram of this

bromide was incorporated into plant tissues through root uptake.

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CHAPTER 1

INTRODUCTION

1.1 Introduction to Topic and Previous Work

The undulating terrain of the Northern prairies is dotted with millions of small wetlands. Commonly referred to as "sloughs", these wetlands often occur as closed catchments without significant or sustained surface water inflow or outflow. They therefore act as "independent hydrologic systems" and prove to be favourable sites for the study of water and solute transfer (Hayashi, 1998a).

Prairie wetlands form where water collects in depressions on the landscape. Sloughs in low-lying areas are generally fed by groundwater inflow while sloughs situated on uplands typically recharge groundwater, and often contain water for only part of the year (Lissey, 1968; Hayashi, 1996). Recharge sloughs on uplands most often occur by collection of spring snowmelt and snowmelt runoff in topographic depressions (Willis et al., 1961; Lissey, 1971).

The hydrology and water quality of these wetlands are heavily influenced by the exchange of water and chemical constituents with surrounding uplands (Hayashi et. al., 1998b). Consequently, the existence and fate of these wetlands is of importance to the practice of agriculture on adjacent farmland, since movement and accumulation of solutes can affect salinity and nutrient content of nearby soils. Farming is the predominant land-use activity in the prairie region, with the principal crops being wheat, canola, barley and oats (Donald et. al., 1999). To maximize yields, various herbicides, insecticides, and fertilizers are applied to croplands in spring and summer. These chemicals often end up in sloughs by aerial application and runoff (Donald et. al., 1999).

Prairie sloughs are also homes and breeding grounds for many types of plants, insects, and waterfowl. Thus, the residence and eventual fate of chemical constituents from natural or anthropogenic sources in wetlands is also important to the ecology of the region. With the extensive use of farm chemicals on the prairies, the danger of levels that these chemicals reach in ponds has become a concern. Donald et al. (1999) found during a 6-year study that in mid-summer, 9-24% of wetlands in southern Saskatchewan contained levels of pesticides that exceeded ecotoxicological guidelines.

It is for these reasons that, in the last 35 years, attempts have been made to better understand the role wetlands play in the physical and chemical hydrology of the prairies. Lissey (1968, 1971) proposed that most groundwater recharge and discharge in the prairie environment takes place in land-surface depressions that are commonly occupied by wetlands, and coined the term "depression-focussed recharge". In a pioneering study, Meyboom (1966) described seasonal groundwater flow patterns in a recharge slough and showed that root uptake by trees at slough margins drives infiltration and lateral groundwater flow from sloughs in summer. Millar (1971) studied rates of infiltration and water loss in sloughs, and established the existence of a direct relationship between rates of water loss and pond perimeter-area ratios. This finding further supports the notion that evapotranspiration at slough margins is a major factor affecting water loss in sloughs. Mills and Zwarich (1986) and Woo and Rowsell (1993) looked at the effects of such factors as precipitation, evapotranspiration, and snowmelt, on the local and regional flow systems in the vicinity of sloughs. Rosenberry and Winter (1997) observed a "water table trough" adjacent to wetlands that forms as a result of evapotranspiration at the slough margins.

Very few of these early works integrated both hydrology and chemical evolution of wetlands, however. Lebaugh et al. (1987) was one of the first to relate wetland water chemistry to hydrologic processes. This work showed that water table highs did not always occur beneath land surface highs, and that significant differences exist in the chemical composition of nearby wetlands depending on whether they are in recharge or discharge zones. Miller et al. (1985) studied soils around recharge sloughs in central Saskatchewan and discovered varying chemical characteristics from different areas of a catchment related to localized discharge, recharge, and lateral flow.

Zebarth et al. (1989) observed shallow, lateral groundwater flow from sloughs, and demonstrated the influence of lithology on these flow patterns. They, as well as Steinwand and Richardson (1989) also observed salt accumulations at wetland edges that appear to be the result of evapotranspiration. Hayashi et al. (1998b) described a cycling of chloride between slough and upland and also demonstrated that infiltrating water transports solutes laterally to uplands. These solutes were found to accumulate near the surface due to evapotranspiration, and snowmelt runoff in the following spring was observed to return some of these solutes back to the slough.

Solute accumulations have been observed at slough margins, but little is known of the pathways taken by solutes to where they concentrate or the hydrologic and lithologic controls affecting their transport. The study described herein is a more detailed examination of the cycling of salts between sloughs and slough margins.

1.2 Purpose and Objectives

As stated previously, little is known of transport pathways of solutes that cycle between wetland ponds and margins, however previous work can provide some ideas. Zebarth et. al. (1989) observed high permeability deposits at the soil surface in sloughs, along which lateral flow may be preferentially focussed. Meanwhile, Hayashi et. al. (1998a), Miller et al. (1985) and others described fractures and sand lenses in shallow, oxidized tills, which could provide deeper and more tortuous flowpaths.

The current study describes an attempt to delineate pathways and accumulations of solutes as they cycle between surface water and groundwater in a typical recharge slough and surrounding upland. To investigate these phenomena, a bromide tracer was released into the central pond in early spring of 1999. Bromide was chosen as the tracer since it is considered conservative, in that it is largely non-reactive and does not readily sorb to soil particles, and it occurs in nature at very low levels, unlike other commonly-used conservative tracers such as chloride (Flury and Papritz, 1993).

The main objectives of the experiment were 1. to study the change in bromide concentration in pond water from early spring to dry-up in late summer and relate this change to water losses and gains due to evaporation, infiltration, and precipitation, 2. to observe where the applied bromide accumulates in the subsurface soil water, and 3. to relate the observed bromide distribution in soil to groundwater flow and lithological patterns and determine the principal migration pathways followed by the tracer. In doing so, the total mass of all applied bromide in surface water, groundwater, and vegetation will be accounted for by means of a mass balance.

Here, we look only at prairie wetlands, but methods and findings can be applied to such topics as the effects of marginal vegetation on the water quality and baseflow of streams (Hill, 1996; Constantz, 1998), near-shore recharge at lakes in karst terrains (Lee, 2000), and localised and seasonal recharge and discharge in boreal wetlands (Siegel, 1988). Also, by characterizing the migration and behaviour of the conservative bromide tracer in groundwater, one can use these results to predict that of other, non-conservative chemical species, such as halogenated organics or nitrates in pesticides and fertilizers provided sorption to soil particles and chemical reactivity of these species in the subsurface are accounted for. Conversely, by comparing the behaviour of conservative species to that of non-conservative species, a better understanding of the sorption and reactive properties of such contaminants can be obtained as well.

CHAPTER 2

MATERIALS AND METHODS

2.1 Field Site

The experiment was carried out at slough 109 located in the St. Denis National Wildlife Area (106°06' W, 52°02' N), approximately 40 km east of Saskatoon, Saskatchewan (Figure 2.1). It has been previously studied by Miller et al. (1985), and by Hayashi et al. (1998a,b), and is therefore, well-equipped with a network of piezometers, wells, and other field instrumentation. Slough 109 and several other, similar wetlands are situated in a cultivated field of about 1 km^2 area which lies on a regional high about 10-15 m above the floor of a surrounding valley. The area has a hummocky topography and is underlain by a clayey glacial till. The till is oxidized to a depth of about 5 m and is underlain by grey unoxidized till. Thin, discontinuous sand lenses are scattered throughout. A continuous clay layer occurs at about 8 m depth, and a sand aquifer lies at a depth of about 25 m (Hayashi et al. 1998, Figure 2.2).

Crops on the surrounding field consisted of wheat in 1999, and peas and lentils in 2000. Swamp smartweed (*Polygonum coccineum Muhl.*), cow parsnip (*Heracleum lanatum Michx.*), sedge (*Carex Athrodes*) and grasses grew in and around the central pond over both summers, and grew to heights of 1.5 m. Willow (*Salix amygdaloides*), aspen (*Populus tremuloides*), and poplar (*Populus balsamifera*) grow along the slough margins forming a typical "willow ring" (Meyboom, 1966). The willow ring is about 10 m wide in most areas, but an area of mainly aspen on the east side is about 20 m wide. Willows on the north and west sides were not much higher than about 3 m. Aspen and poplar ranged in height from 5 to 8 m.

The yearly average temperature in this area of Saskatchewan is 2 °C with means of

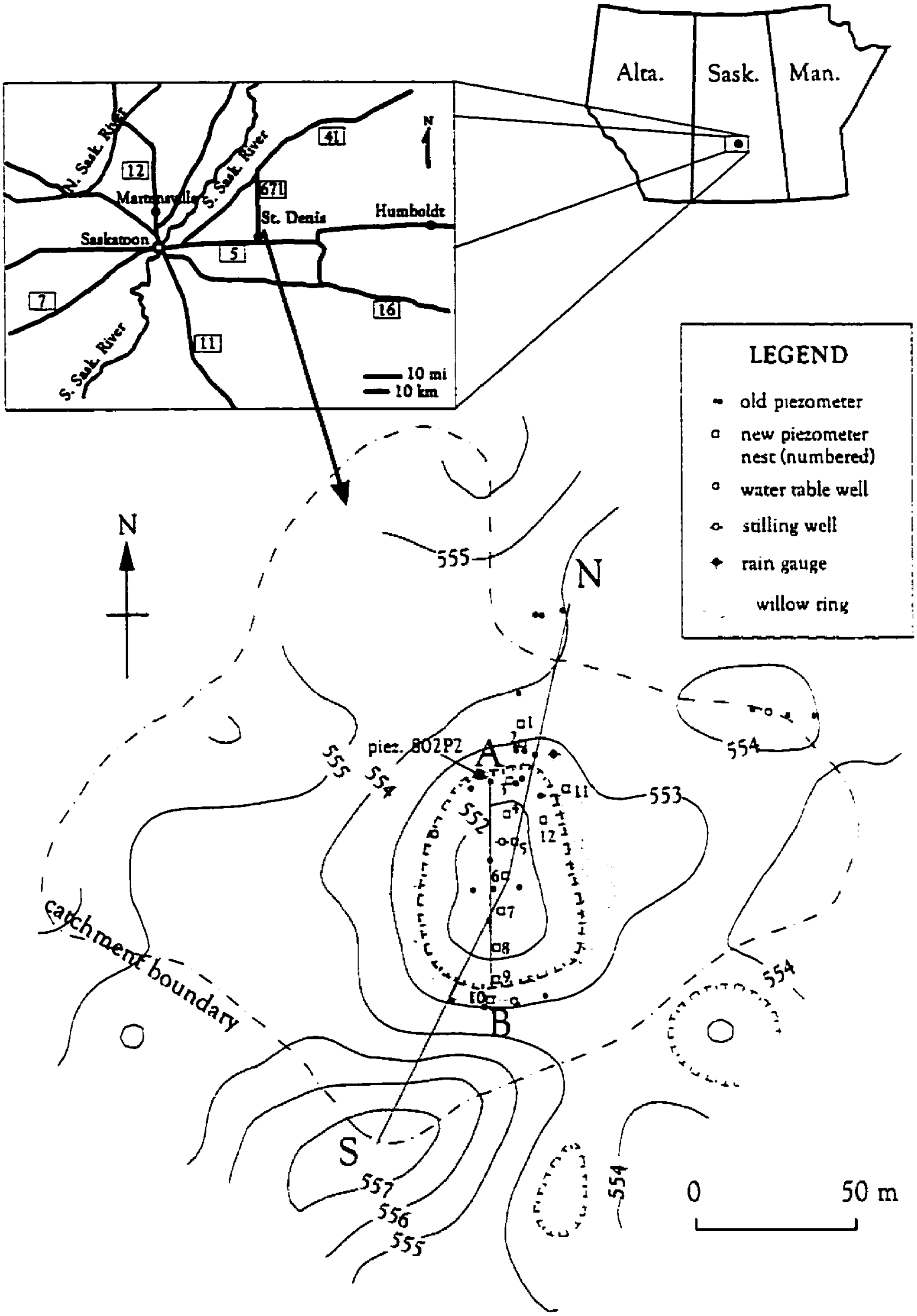

Figure 2.1 Map showing location, topography, and instrumentation of the study area (Modified from Hayashi et al. (1998a).

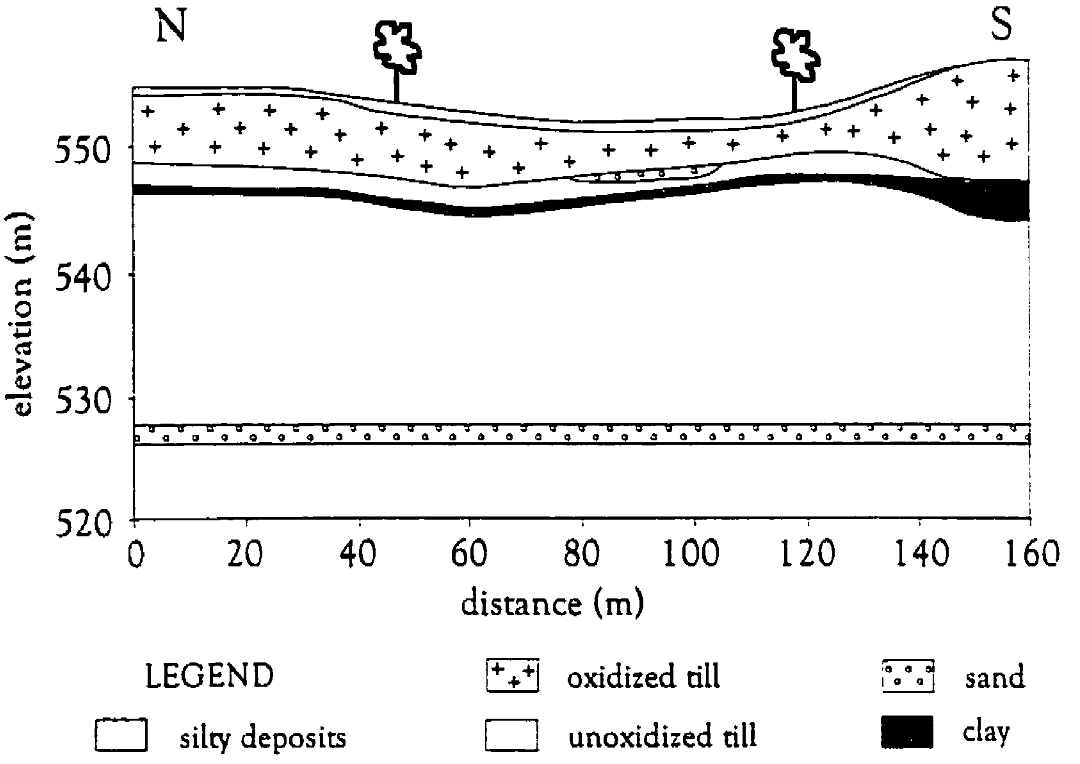

Figure 2.2 Geological cross-section along transect N-S from figure 2.1. (Modified from Hayashi et al. (1998a).

-19°C in January, and 18°C in July (Atmospheric Environment Service, 1997, 2000, Hayashi et al., 1998a). The mean annual precipitation is 360 mm, with about 280 mm occurring as rainfall in spring, summer, and fall. However, over the last 30 years, annual precipitation has ranged between less than 300, to over 400 mm (AES, 1997; Hayashi et al, 1998a). The year 1999 was characterized by relatively wet conditions, with 355 mm of rainfall occurring between April 7 and November 3. Of this, 276 mm fell between April 28 (introduction of the tracer) and August 9 (dry-up of the pond). Annual lake evaporation in this area is approximately 700 mm (Morton, 1983, Hayashi et al., 1998a).

Variation in climatic conditions is one of the major factors controlling pond conditions. Over the last 30-35 years, maximum yearly pond water levels have ranged between 0 and 1.3 m depth (Millar et al, 1998, Hayashi et al., 1998a). In 1999, the pond reached a maximum depth of about 52 cm in spring, and the pond was only 37 cm deep at its highest level in 2000.

Here, several different terms will be used to refer to different areas in and around slough 109. The term "pond" will be in reference to the open water area in the depression, while "wetland" refers to the depression itself and the surrounding willow ring. The term "catchment" will be used for the entire area within the surrounding drainage divide (figure 2.1). The total area of the catchment is approximately 24,000 m^2 (Hayashi et al., 1998a).

2.2 Piezometer Installation

In October of 1998, when the pond bottom was dry, 12 piezometer nests were installed along north-south, and northeast-southwest transects through the middle of the catchment. The nests along each transect were spaced roughly 10 m apart. Each nest contained at least 3 stainless steel piezometers with intakes at 1, 1.5 and 2 m below surface respectively, with the exception of nest #7 (Figure 2.1) at which a piezometer could not be installed to 2 m depth due to the presence of an apparently large boulder. Nests located in and around the pond and enclosed by the willow ring each included a bundle of 3 mini-piezometers with depths of 20, 40 and 60 cm. Odd-numbered nests along each transect included a piezometer of 3 m depth installed in augered holes of 6 cm (nests#5, 7, 9), or 10 cm (nests#1, 3, 11) diameter.

Mini-piezometers consisted of segments of 0.43 cm I.D. (0.17") polyethylene tubing bundled and tied to an aluminum rod. Each mini-piezometer bundle was placed in a hole made with a small soil core hand sampler, and backfilled with soil to the ground surface. The portion of the bundles sticking up above surface was encased in a 3.8 cm (1.5") PVC pipe and cap. Figure 2.3 is a schematic diagram of a piezometer nest containing all types of piezometers installed.

The three steel piezometers in each nest consisted of 0.92 cm I.D. (0.364") stainless steel tubes that were simply pushed and pounded into the clayey till to their respective depths. This was done with the aid of a pointy-tipped brass insert that was placed at the leading end of the piezometer tube to prevent soil from entering. The shaft of the insert was cylindrical with a diameter of 0.7 cm so it could fit easily into the tube and to prevent it from becoming stuck and permanently blocking the tube opening. The cone-shaped tip was therefore made with a base diameter of 1.7 cm, just slightly larger than the outside diameter of the piezometer tube (1.4 cm), to ensure soil would not enter as the shaft shifted slightly. When the tube was inserted to the desired depth, a small quantity of sand was poured into the open end, and the tube then was pulled up 10 cm. This left a small sandpack underneath the bottom end, and above the brass insert, which was left behind in the clay below. Measurements of the distance from the top of casing down to the sand pack when the piezometers were dry verified that all or most of the sand left the tube and filled the void.

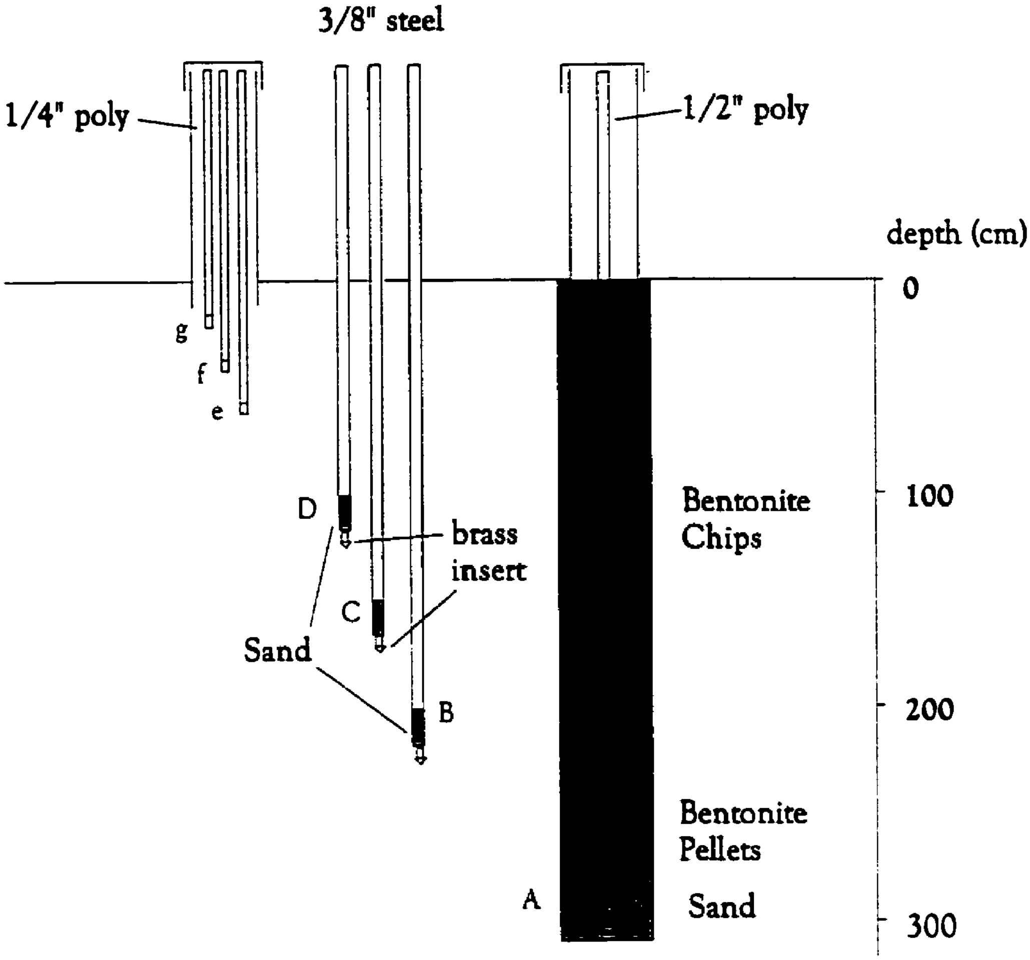

Figure 2.3 Schematic diagram showing the various types of piezometers installed in new piezometer nests.

The deepest piezometers were constructed from 4 m-long, 1.3 cm (1/2") polyethylene tubes with 1.6 cm diameter slotted screens fitted over one end, also of polyethylene. These tubes were placed in 3 m deep augered holes, which were filled from the bottom up with a sand pack, bentonite pellets, and bentonite chips. The top 1 m of each tube, which sticks up above ground surface was encased with a 5.1 cm (2") PVC pipe and plastic cap.

The elevations of piezometer casings with respect to sea level were determined for all piezometers used in the study. A level survey of casing tops was conducted in the summer of both 1999 and 2000 to prevent measurement errors due to frost heaving during the spring. Piezometer 802P1, one of Miller's (1983) series of piezometers located at the north end of the pond, was used as the elevation benchmark, since it is one of the deeper wells, and it has been found to be a stable benchmark in past surveys (Garth van der Kamp, personal communication). In comparing elevations determined in 1999 and 2000, some movement of piezometers was observed to have occurred between field seasons, with casing elevations increasing slightly in most cases. Piezometers located on the wetland edges and the upland moved only a few millimetres at most, while some of those in the middle of the pond moved as much as 4 cm. Similar movement of piezometers has also been observed elsewhere (Conly and van der Kamp, in press).

The possibility of contamination from trace bromide in bentonite seals was investigated. Soil extracts were used to determine bromide concentrations for bentonite pellets and chips from the same manufacturers as those used for piezometer installation. Bentonite product was added to deionized water in a 1:5 mass ratio using a method similar to that of Remenda and Van der Kamp (1997). Samples were shaken and centrifuged, and supernatent was collected for IC analysis following the procedure described in section 2.5 below. None of the bentonite products were found to contain detectable levels of bromide, although there was significant amounts of chloride. An extract from one sample contained about 30 mg/L chloride.

Slug tests (Hvorslev, 1951; Freeze and Cherry, 1979) were performed on most of the newly-installed piezometers to test their reliability and lag times. Basic time lags and hydraulic conductivities calculated from these tests, as well as specifications for these and other piezometers and wells installed by Miller (1983) and Hayashi (1996) are given in Appendix A. Note that slug test results are not available for many of the new piezometers, since a lot of them contained water for little or no time during the 2 years of the experiment. Also, some others took longer than the weekly measuring period to recover significantly.

2.3 Introduction of Tracer

The tracer was applied to the central pond on April 28, 1999, after snowmelt was completely finished and the pond level began dropping. Portions of approximately 4 kg of technical grade sodium bromide (Van Waters and Rogers, Ltd) were each mixed with slough water in 20 L polyethylene jugs. To achieve an even application of tracer, the jugs were emptied through a spigot from the back of a small boat, as the boat was being paddled around the pond. This was repeated 10 times, thus introducing 40 ± 0.5 kg of sodium bromide (24 kg of bromide ion) to the pond and increasing the concentration of pond water to almost 100 mg/L bromide.

2.4 Water Sampling

Surface water was sampled at five locations in the pond; at the pond centre, and at each of the north, south, east, and west corners, about 2 m from the water edge. Samples taken within an hour of tracer application ranged in concentration from 50 to 150 mg/L bromide, but samples from 2 days later all measured close to the expected concentration of 100 mg/L, showing that the pond was well-mixed. A small boat was used to access each sampling location to minimize disturbance of the bottom sediments. Sampling was done at these locations until July 1999, after which the pond area was too small to make it practical. Sampling was done only at the pond centre after this. At each location, a 60 ml polyethylene bottle was submerged, filled to the top, capped, and labelled.

Water in piezometers was sampled by suction from the piezometer bottom through a 0.64 cm (1/4") polyethylene tube using a small syringe. Mini-piezometers were sampled in a similar fashion, with the syringe being connected directly to each 0.64 cm (1/4") piezometer casing. After complete removal of water from a piezometer, the syringe and sampling tube were emptied into a 30 ml bottle, which was then capped and labelled. The low hydraulic conductivity of the till, and the resultant slow response of many of the piezometers, made purging of piezometers impractical. Analysis of pre- and post-purged samples collected from 2 of the faster-responding piezometers (the mini-piezometers in nests #4 and #7 with intakes at 20 cm) showed that bromide concentration before and after purging were not significantly different. Pond and piezometer water were sampled on a monthly and sometimes weekly basis in spring and summer of 1999 and 2000, when water was available. All water samples were syringe-filtered through .45 μm cellulose nitrate membranes and stored at 4°C for several days to weeks. Selected samples were chosen to be analysed for bromide and chloride by ion chromatography (IC). Between sampling periods, sampling syringes and tubing were rinsed with deionized water to prevent contamination from previous sampling episodes.

2.5 Soil Sampling and Pore Water Extraction

Soil samples from various depths were collected from above the water table in October

1999, from holes located at the mid-points between successive pairs of nests along the 98-series piezometer transects. There were additional holes augered alongside selected piezometers and at several new locations spaced 10 m along a transect extending to the southwest of nest #5. The samples were recovered slightly disturbed from 10 cm depth intervals using 6 cm-diameter hand augers. All of the holes from which samples were obtained were filled to the surface with bentonite chips. Samples were sealed in plastic bags, and stored at 4°C for several days to weeks before pore water was extracted for analysis.

Approximately 50 g of each sample was oven-dried for 24 h at 105°C and weighed to determine gravimetric water content. About 100 g of wet sample was then placed in a 250 ml polyethylene bottle, and deionized water was added to dilute the estimated quantity of pore water by a factor of 5. After addition of water, samples were placed on a mechanical wrist-action shaker and shaken vigorously for 4 h. Shaken samples were centrifuged at 7000 rpm for 1/2 h, and supernatent was collected in small sample vials. The procedure for pore-water extraction was based on a method described by Rhoades (1982), and the 4 h shaking time was the same as used by Hayashi et al. (1998b) for till samples from the same area. Supernatent was syringe-filtered through .45 μm cellulose nitrate membranes and analysed for bromide and chloride by IC.

2.6 Vegetation Sampling and Chemical Analysis

Different types of vegetation were present in different areas of slough 109 and its catchment in the summer of 1999. The pond was overgrown by mostly swamp smartweed to the northeast, and a mixture of smartweed, sedge, and cow parsnip to the southwest. Sedge predominated over a small area in the centre of the pond. The surrounding tree ring consisted of mostly willow and poplar to the north and west, and mostly aspen with some poplar to the south and east. Outside the trees was wheat field except for a patch of thin grass on the north side where several piezometers and other instrumentation were located. These different areas defined vegetation "zones" which provided the basis for the choice of locations sampled in early September 1999 (Figure 2.4).

Vegetation was sampled inside a 1 m^2 wooden frame placed at the approximate mid-point of each vegetation "zone" along N-S and E-W transects that intersected the middle of the catchment (Figure 2.1). All emergent plant material within the frame area was cut using garden shears and bagged (Figure 2.5). Only above-ground portions of vegetation were obtained, since sampling root systems was, in some cases, impossible (i.e. for trees), and such sampling would cause too much disruption of the sediments on the pond bottom. It is believed that very little bromide would be unaccounted for because of this, since root systems typically make up less than 10% of the dry mass of such plants, and most solutes that are incorporated into plants by root uptake end up in leaves and stems (Karcher, 1995).

It was deemed impractical to collect entire trees from the tree ring, so total biomass was estimated in two steps. First, the volume of a tree trunk was calculated by taking it to be a cylinder with a diameter that is the square root mean of the end diameters (top diameter taken to be zero) after Moore and Chapman (1986). Secondly, average-sized branches were taken from each tree within the sampling area, and their masses were multiplied by the number of branches present. The mass of the trunk was determined from a density estimate derived from the mass of a small, cylindrical segment of the branch sample.

The fresh plant material was stored for several weeks in a freezer at -10°C. The samples were subsequently thawed, weighed, rinsed with deionized water, and then oven-dried at 70°C for 24 h and reweighed. The dried material was broken down by hand and passed through a 1 cm mesh. Each sample was then split to obtain small subsamples which were processed through a Whiley mill with a 1 mm mesh, to form a fine powder. Other dry

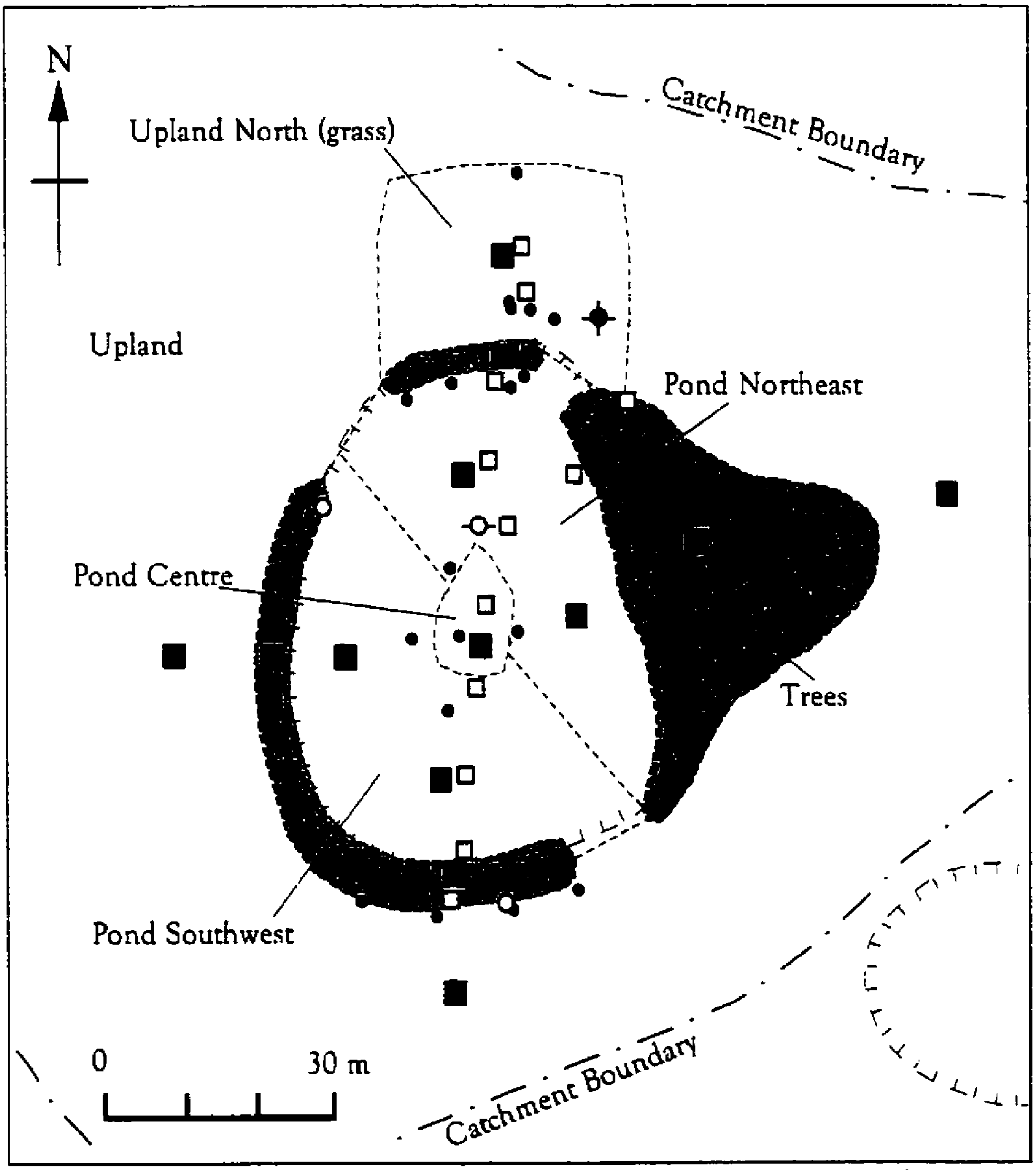

Figure 2.4 Map showing areas of distinct plant types (dashed boundaries) and vegetation sampling locations (black squares).

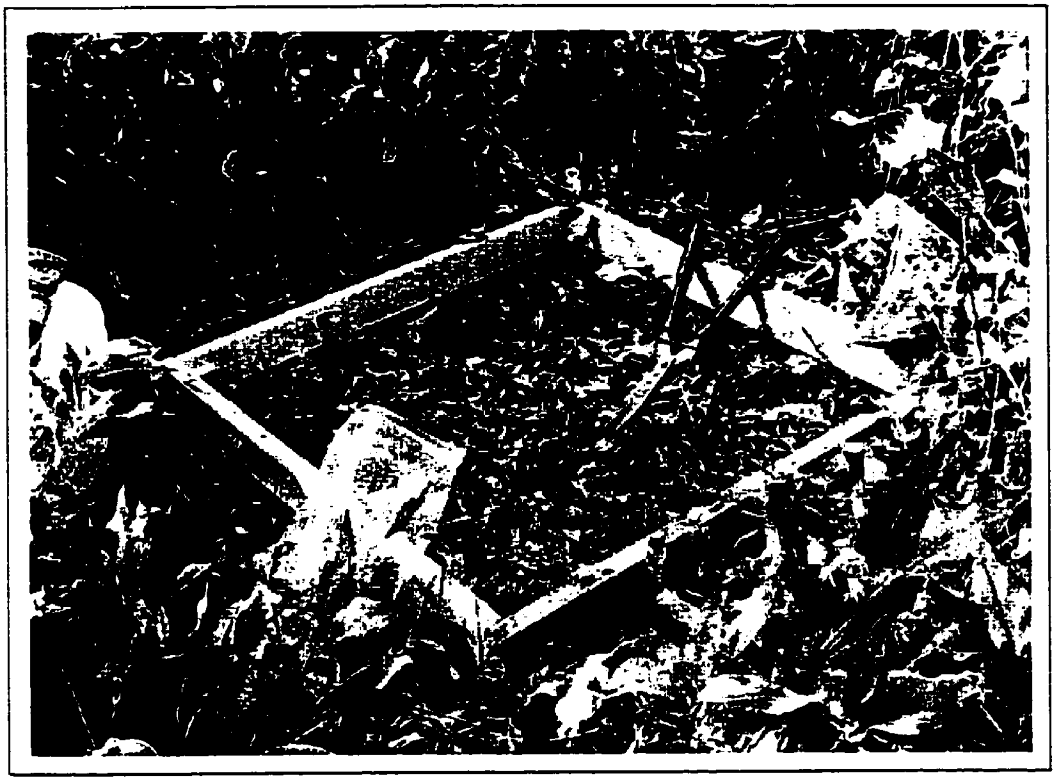

Figure 2.5 Vegetation sampling apparatus.

subsamples were weighed and oven-dried again at 105°C to determine water content of the plant tissues. The reason for the initial lower-temperature drying was to avoid any volatilization of chemical species present in the plant material being analysed (Walinga et al., 1995).

To prepare the samples for chemical analysis, 1 g of each milled sample was placed in a 100 ml flask and 50 ml of deionized water was added. The powder suspensions were shaken for 1/2 hr, and passed twice through a filter paper following the "Extraction with water" procedure for chloride described by Walinga et al. (1995). Filtrate was collected in small vials, and was later filtered again through a .45 μm membrane and a porcelain filter treated with acetonitrile in preparation for IC analysis.

2.7 Precipitation and Water Level Measurements

Pond water levels were measured using a pressure transducer placed at the bottom of a 3.8 cm diameter stilling well located near the middle of slough 109. Levels were recorded every half hour by a data logger. Manual measurements were obtained monthly and sometimes weekly by measuring the height of a central metal stake, of known elevation, above the pond water level.

Water levels in piezometers were obtained by measuring down to the water from the tops of the piezometer casings with a dropline. The elevations of piezometer casings are all known.

Precipitation was measured with a tipping-bucket rain gauge between April 7 and November 3, 1999, and between March 16 and July 28, 2000. Tipping bucket measurements were recorded every half hour by a data logger. Winter precipitation was measured at Saskatoon airport (Atmospheric Environment Service, 1997, 2000).

2.8 Water Balance

Daily mass balance of bromide in the pond was calculated to model the change in pond concentration due to the change of water volume from infiltration, evaporation, and precipitation. The water balance and changes in bromide concentrations were calculated for each day of the experiment. The water balance for the pond was calculated using the relation:

$$\frac{dz}{dt} = P + R - E - I \qquad (1)$$

where z is pond water depth, P is precipitation, E is open water evaporation, and I represents infiltration or all water that is lost by seepage into the ground (all in units of $L\ t^{-1}$). Runoff, R ($L\ t^{-1}$), was not measured directly, but was estimated daily from the difference between pond level rise (if any) and precipitation. For most days, this value was only a fraction of a millimetre and often negative, and was just assumed to be zero. Pond water volume and open water area were calculated daily from pond depth using the volume-depth (V-z) and area-depth (A-z) functions determined for S109 by Hayashi and Van der Kamp (2000). They are given as follows:

$$A = 3180z^{1.24} \qquad (2)$$

$$V = 1420z^{2.24} \qquad (3).$$

Since daily change in pond depth is small compared to the total depth, the daily change in pond water volume can be given by

$$\frac{dV}{dt} = A(P + R - E - I) \qquad (4)$$

where A equals the open water area of the pond. The daily change in bromide mass in the pond is therefore given by the following expression from Hayashi et al, (1998b), assuming negligible diffusion or vegetative uptake:

$$V\frac{dC}{dt} + C\frac{dV}{dt} = A(C_pP + C_RR - CI). \qquad (5)$$

In Eq. (5), C is pond concentration and C_p is average concentration in precipitation, which herein is taken to be 0.01 mg/L (Flury and Papritz, 1993). Runoff was not analysed for bromide, nor was it sampled on a regular basis, so concentration in runoff, C_R was assumed equal to C_P. Precipitation, which contains essentially no bromide, acts to dilute pond water, while evaporation concentrates bromide in pond water, and infiltration does not change concentration. Substituting Eq. (4) into Eq. (5), the daily change in bromide concentration was determined, as by Nir (1973), as follows:

$$\frac{dC}{dt} = \frac{A(C_pP + C_RR)}{V} - \frac{CA(P + R - E)}{V} \qquad (6)$$

The change in bromide concentration calculated from Eq. (6) could then be compared to the actual change observed in pond water samples. A difference between the two would be indicative of other processes affecting the bromide concentration that were unaccounted for in the mass balance.

CHAPTER 3

ANALYSIS AND RESULTS

The following describes the changes in concentration of bromide in pond water, groundwater, and vegetation and how they relate to such processes as precipitation, infiltration, and evapotranspiration. In 1999, distributions of solute in ground and surface water were the main focus, while in 2000, diffusion of solute from sediment into newly-ponded snowmelt water was investigated as well. In these sections, each year of the study will be dealt with separately.

3.1 Calendar Year 1999

3.1.1 Surface Water

In 1999, the water depth in slough 109 reached a peak of 52 cm after snowmelt was complete in mid-April. This translates into a pond water volume of 274 m^3 and a runoff equivalent of about 11 mm over the area of the catchment. After this, the pond level began to drop steadily, and the bromide tracer was introduced on April 28, 1999, when the pond depth was at about 45 cm. Before introduction of the tracer, pond bromide levels measured below detection limits of the IC. The release of the tracer increased the bromide concentration of the pond to 98 mg/L. The concentration increased slightly in May to just over 100 mg/L as precipitation levels were low and water was being lost from the slough by evaporation and infiltration. Through June and July, heavy rains and runoff slowed the rate of pond level decline, and caused the pond bromide concentration to drop as well (Figure 3.1). For most rain events, there was no significant amount of runoff, but there were several times, during the

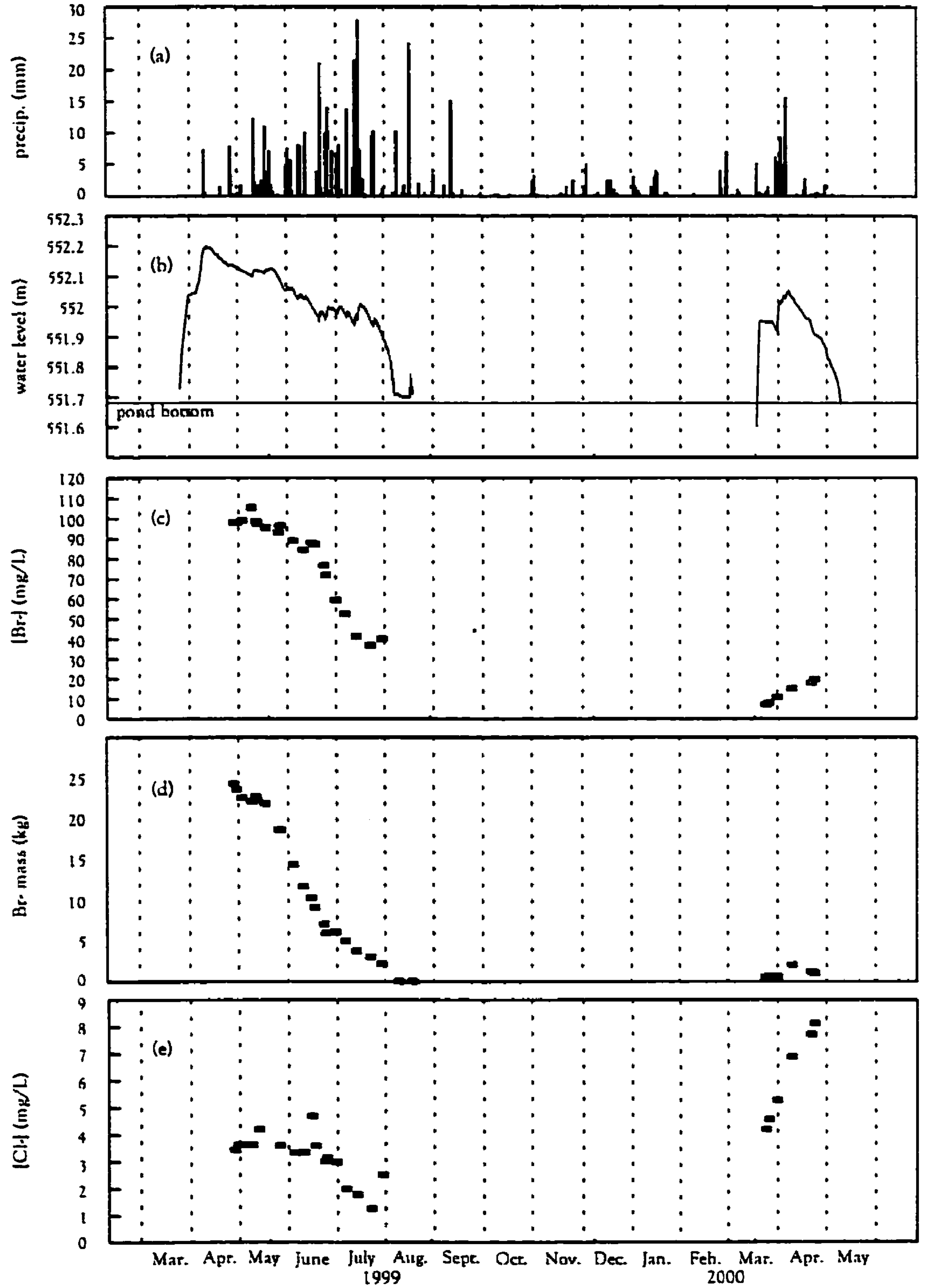

Figure 3.1 Time series plots of (a) precipitation, (b) pond water level, (c) pond bromide concentration, (d) pond bromide mass, and (e) pond chloride concentrations (after Hayashi et al., 1998b).

really heavy rain events, that a rise in pond level was as much as 10 mm more than the amount contributed by precipitation (Figure 3.2). After conditions became drier in late July, the remaining water in the pond disappeared over a period of about 2 weeks. The pond was completely dry by August 9 except for some small puddles at the centre that were sustained through mid-August by a few more heavy rain events.

An attempt was made to characterize the change in pond bromide concentration based on the operation of evaporation, precipitation, and infiltration. There was no reliable independent measure of evaporation or infiltration, but total water loss from the slough can be estimated from Eq. (1) on most days when runoff is negligible. Rough estimates of evaporation, E, were determined for time periods between evaporation pan measurements, but these were highly variable, with estimates ranging from 1.1 mm/d to 7.2 mm/d, with no clear seasonal patterns. This was probably due to shifting of the pan on the muddy pond bottom, and introduction of foreign objects into the pan (frogs, wind-blown leaves, etc.). The average evaporation rate, determined from pan measurements from May 26 to August 9, was about 3.3 mm/d.

Attempts were also made to estimate infiltration, I. First, I was calculated from Darcy's Law using hydraulic gradients measured in piezometers, and hydraulic conductivities determined from slug tests. The variable recovery behaviour of these piezometers, as well as subsurface heterogenieties gave values determined by this method a high level of uncertainty, however. Infiltration was also calculated using Eq. (5) for the period mid-June to mid-July when the pond level was somewhat constant. This, like the other methods, provides a constant, average value for I, which is not necessarily representative of the true conditions on a daily basis. This is because of differences in air temperatures and transpiration activity of vegetation, both daily, and between spring and summer. Both methods of estimating I were fairly consistent however, yielding values of approximately 5 mm/d.

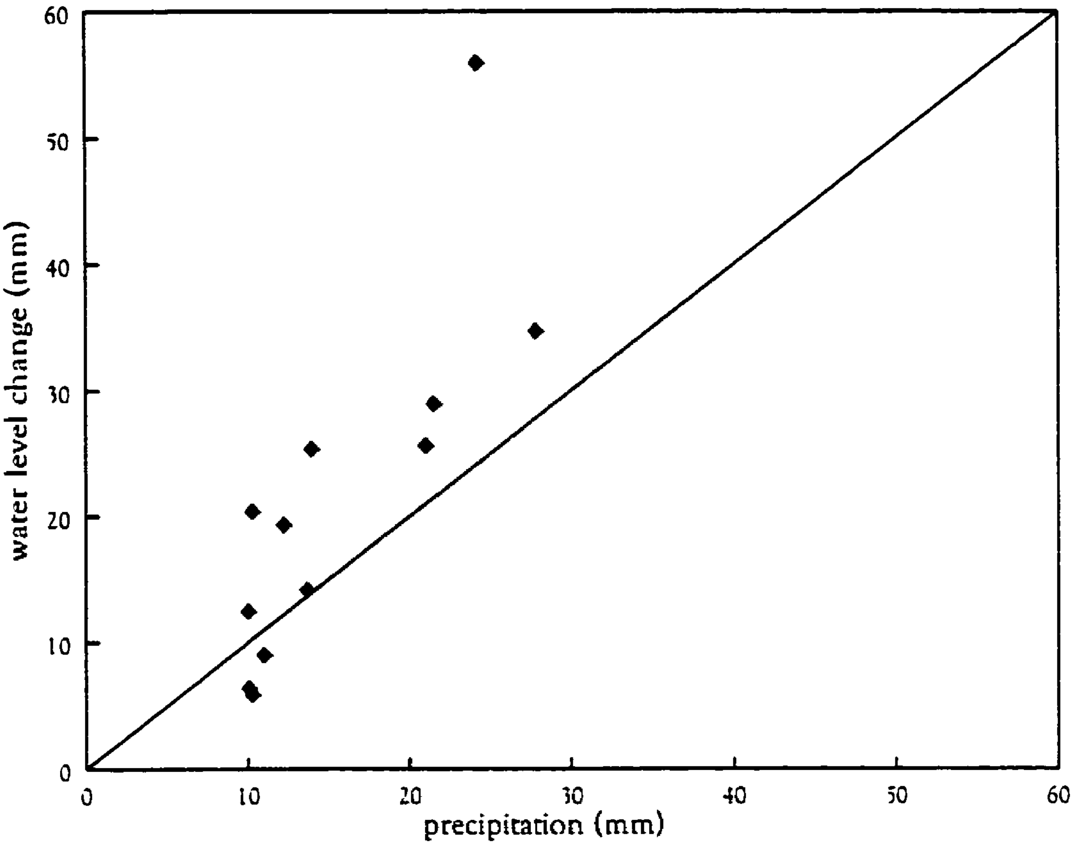

Figure 3.2 Pond level change versus precipitation for heavy rain events, 1999. The straight line represents equality of the two.

To obtain reasonable, separate values of these parameters on a daily basis, estimates of the ratio of infiltration to total water loss (f) were used. This ratio is expressed as follows:

$$f = \frac{I}{E + I} \qquad (7).$$

First, constant values of f were used over the course of the experiment, and values of E and I derived from them were applied to Eq. (5) for each day. Figure 3.3 shows that measured concentrations fit calculated values more closely for lower values of f in spring, and higher values of f in summer when the pond was smaller. The best-fitting value of f increased from about 0.6 in May, to over 0.7 in late July when the area of the pond was smaller.

Millar (1971) established a linear correlation between water loss and pond perimeter-area ratio (p/A), and his results can be reinterpreted as follows (Garth van der Kamp, personal communication):

$$A\frac{dz}{dt} = AE + wpE \qquad (8).$$

As shown in Eq. (8), pond water volume loss is taken as the sum of evaporation from the pond surface area (A), and pond water infiltration which results from evapotranspiration (assumed to operate at the same rate, E, as evaporation) from the area of the marginal vegetation zone of width, w (wp). Since the pond is nearly circular in shape, the area of the pond margin is slightly underestimated by this. As the pond decreases in size in late summer, and the size of the pond margin and its contribution to water loss becomes relatively large, the error in the pond margin area will create an increasingly significant error in the determination of relative contribution of infiltration to the total loss (f). A much more accurate means of determining f would result from a better model for the shape of the pond margin. Eq. (8) can

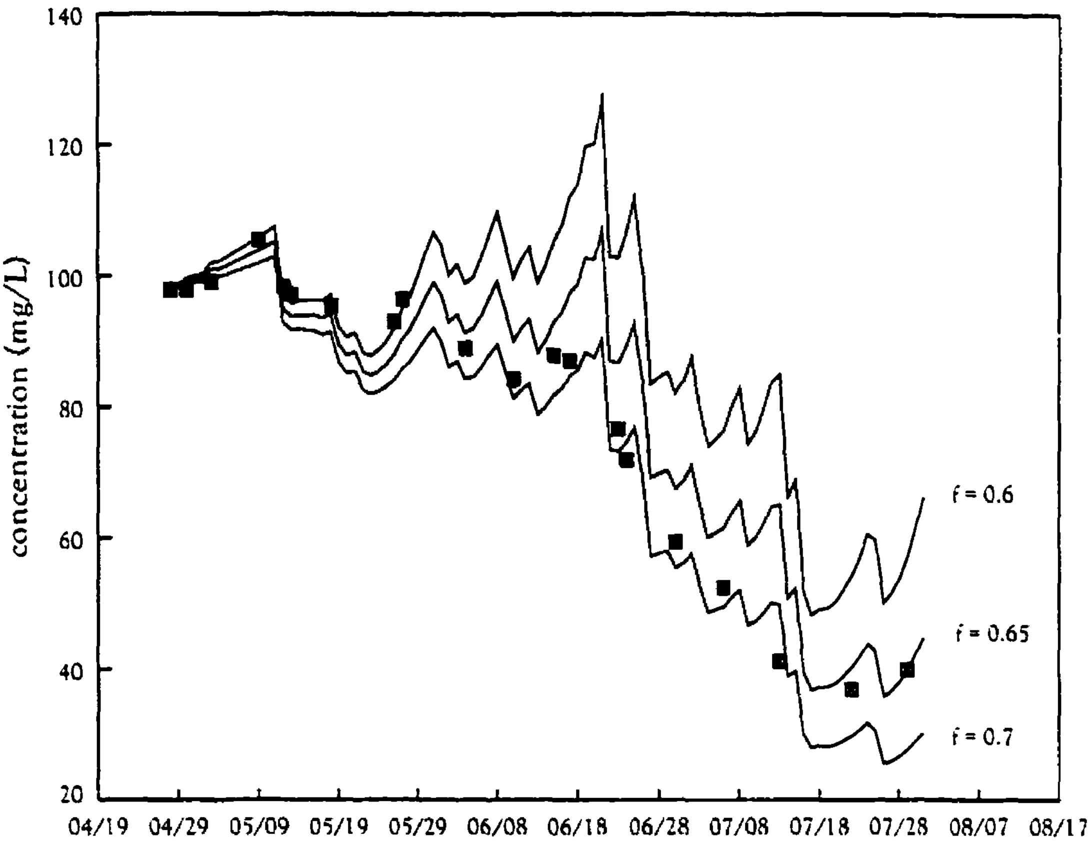

Figure 3.3 Calculated change in pond bromide concentration in 1999, for constant values of f. Symbols indicate actual concentrations of pond samples.

therefore be rewritten more generally as:

$$A\frac{dz}{dt} = AE + A_{margin}E \qquad (9).$$

Noting that I is infiltration beneath the pond area, and assuming that most infiltration is the result of transpiration of marginal vegetation,

$$f = \frac{I}{E + I} = \frac{\frac{A_{margin}E}{A}}{E + \frac{A_{margin}}{A}E} = \frac{A_{margin}}{A + A_{margin}} \qquad (10).$$

Taking the area of the pond as that of a circle with radius, r, and the marginal zone as a concentric ring of width, w gives:

$$f = \frac{A_{margin}}{A + A_{margin}} = \frac{\Pi[(r + w)^2 - r^2]}{\Pi r^2 + \Pi[(r + w)^2 - r^2]} \qquad (11)$$

which reduces to:

$$f = \frac{\frac{p}{A}w + \frac{\Pi w^2}{A}}{1 + \frac{p}{A}w + \frac{\Pi w^2}{A}} \qquad (12).$$

Since A and p could be estimated daily from Eq. (2), assuming a circular pond, daily values of f could therefore be obtained from an estimate of w, the width of the marginal vegetation zone. Pond bromide concentrations were calculated daily by applying the values of E and I, obtained by the new estimates of f, to Eq. (6). These calculated concentrations were then fit more closely to the actual measurements by recalculation of w by the method of least squares (Figure 3.4). Optimal fit of the data was achieved for a width of 12.6 m, which falls very close to the average measured width of the willow ring measured in the field (13 m).

3.1.2 Groundwater

Groundwater flow in the near-surface sediments beneath the pond was downward and laterally divergent toward pond edges through most of the spring and summer, except a "flow-through" condition (Lebaugh et al., 1987) might have existed for a brief period in early spring when the water table and hydraulic heads were relatively high to the south of the pond (Figure 3.5a). In summer, as trees in the surrounding willow ring began to transpire more actively, a "water table trough" (Rosenberry and Winter, 1997) and hydraulic head lows occurred beneath the tree ring (Figure 3.5b). As implied in the previous section, this condition increased infiltration rates and accelerated the lowering of the level of the nearby pond. By late summer, the water table beneath the pond had dropped to below the level of the water table under the upland. This caused the principal flow directions to reverse towards the pond centre from beneath the surrounding upland, in a manner similar to that described by Meyboom (1966) (Figure 3.5c).

In the spring of 1999, bromide began to be detected in piezometers, and in some of the deeper piezometers, bromide was present much earlier than expected considering the low hydraulic conductivity of the till. By mid-May, bromide was appearing in piezometers at depths of 2 m in piezometer nests #6 and #8 (Figure 3.6a). This likely was the result of pond water following preferential pathways, either along the stainless steel piezometer casings, or some

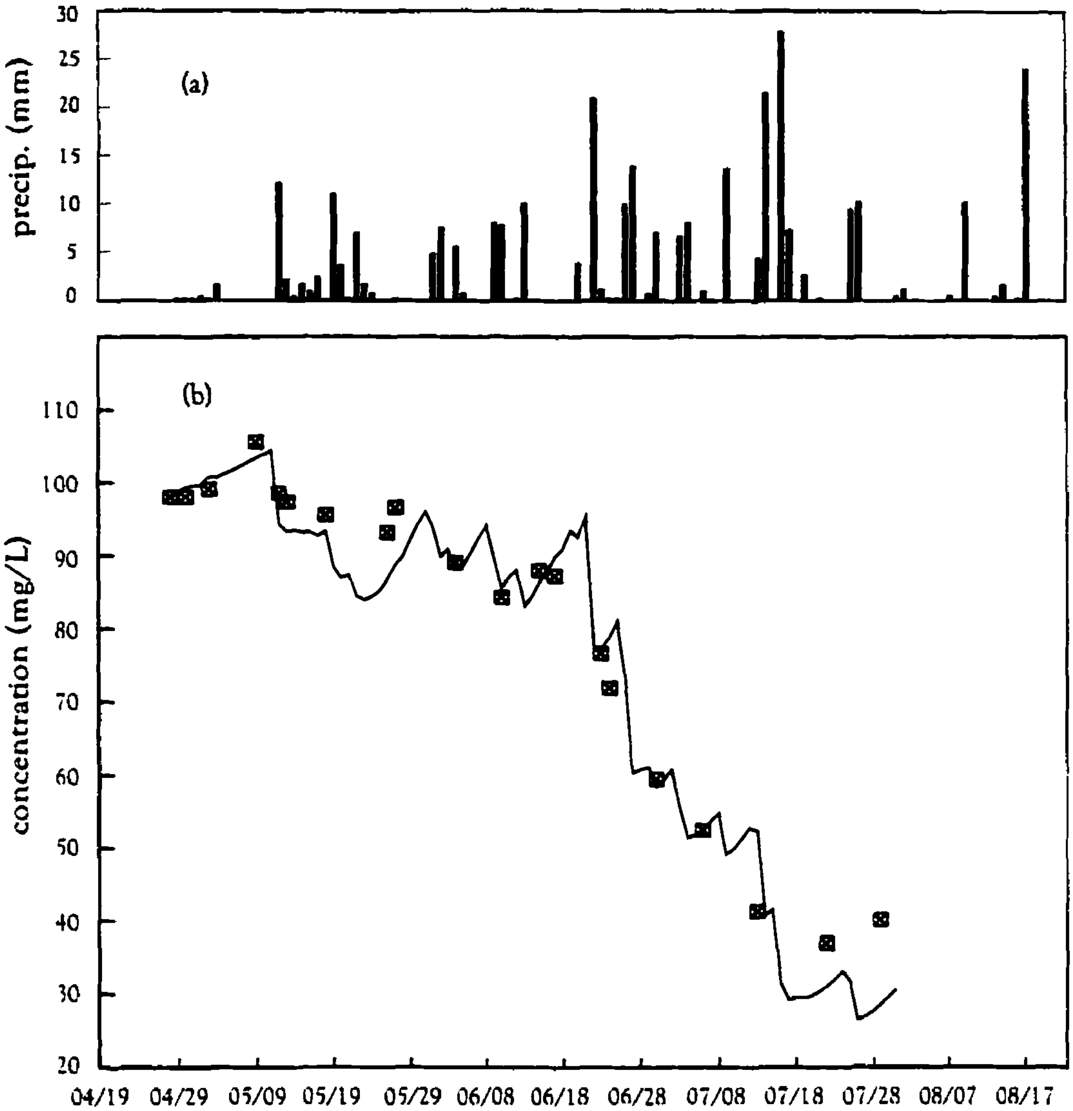

Figure 3.4 Change in pond bromide concentration in 1999. (a) Daily precipitation (b) Measured and calculated bromide concentrations.

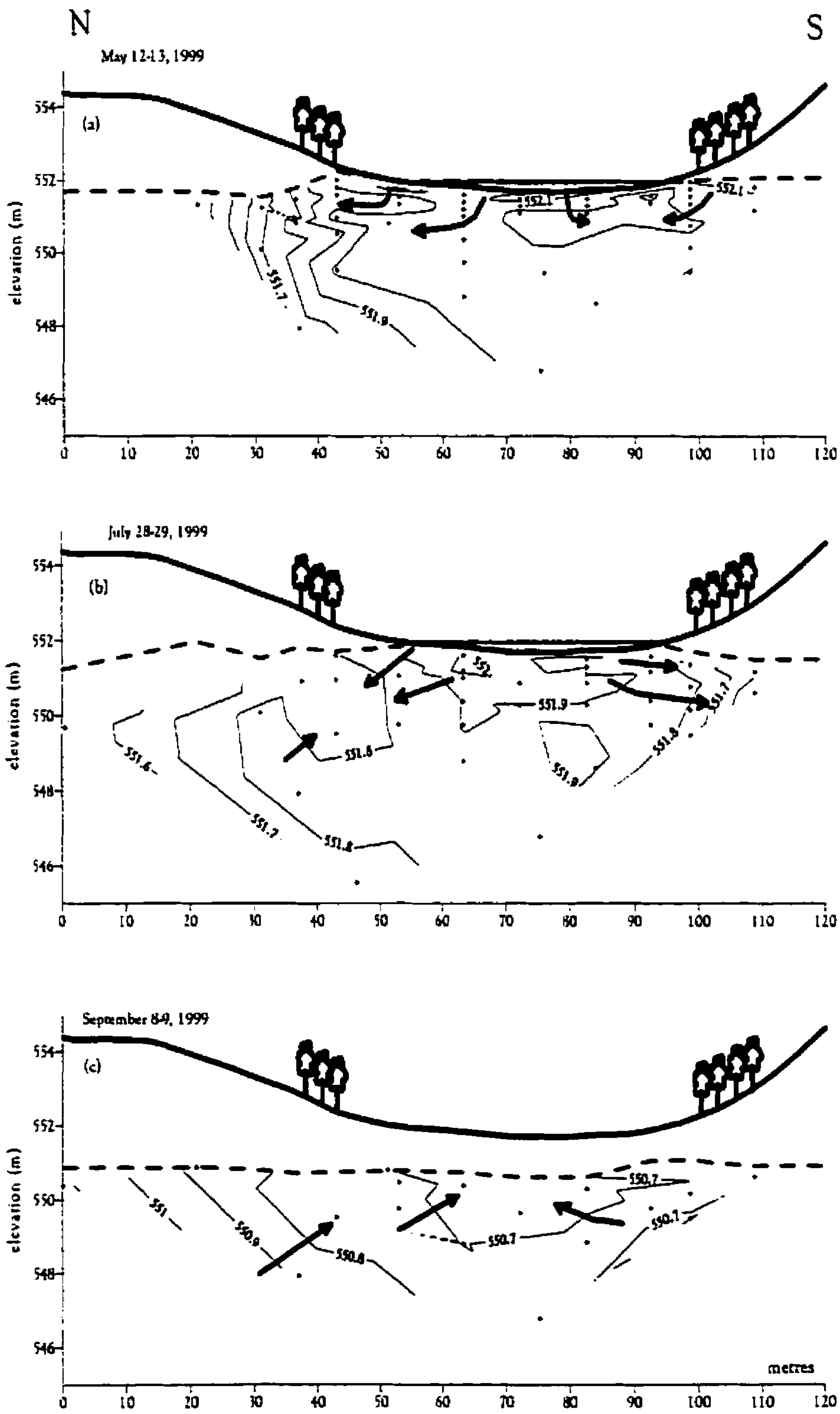

Figure 3.5 Hydraulic head distribution and inferred directions of groundwater flow. Contour interval = 0.1 m. Dashed line indicates the position of the water table.

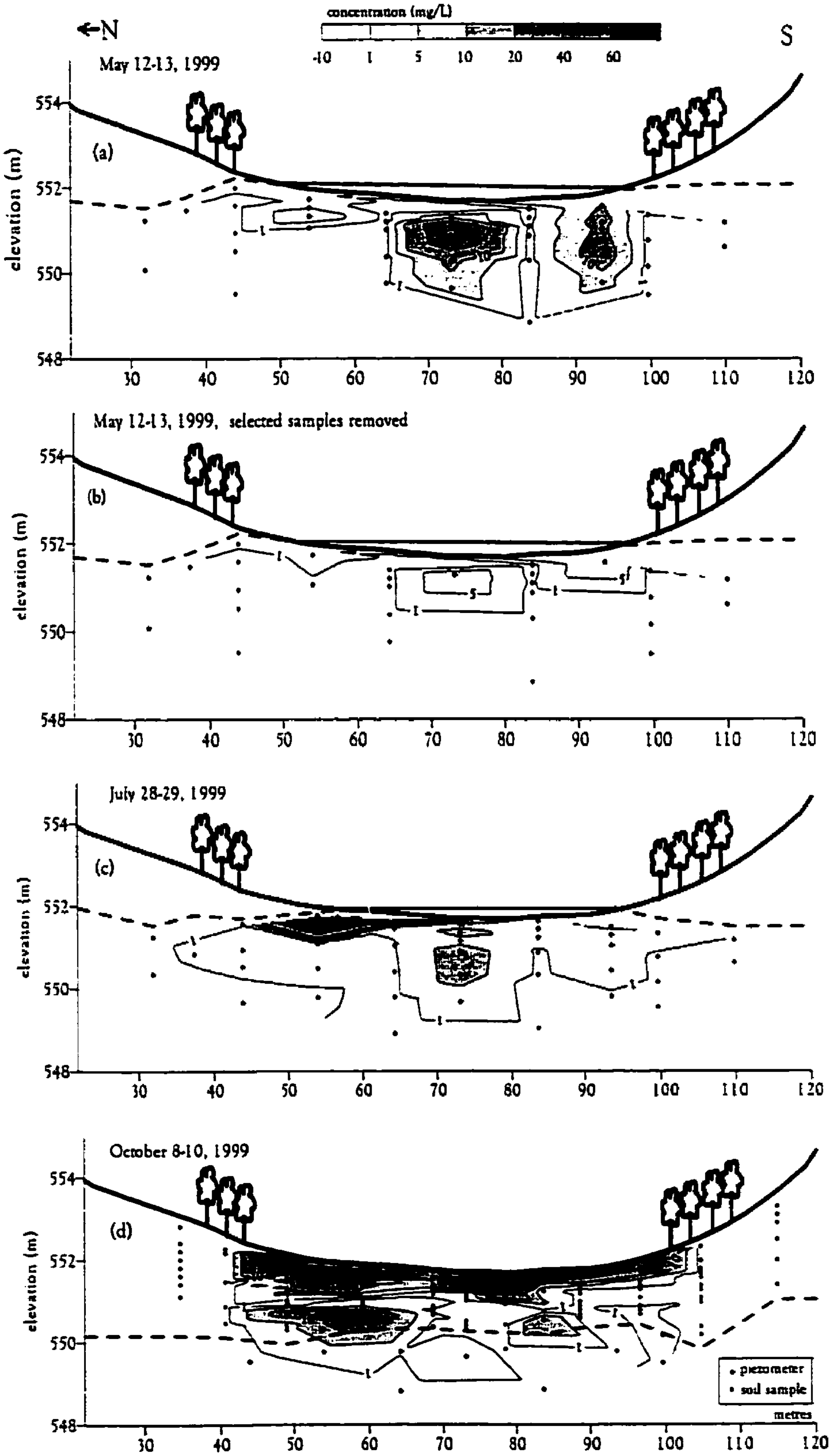

Figure 3.6 Subsurface bromide distribution, 1999.

natural features such as fractures or roots. To test this idea, a simple mass balance was calculated for the sediments beneath the catchment. The sediments were divided into zones at different distances from the centre of the slough as shown in figure 3.7. Bromide mass in each zone was determined by the expression

$$m = \theta_v C_{avg} V_{zone} \qquad (13)$$

where θ_v is an estimate of average volumetric water content (Here, we use $\theta_v = 0.4$), C_{avg} is the average bromide concentration in the zone, and V_{zone} is the estimated volume of the zone. The volume of the central zone is calculated taking the slough to be approximately a circular shape, using

$$V = \pi r^2 z \qquad (14)$$

with r being the horizontal distance from the edge of the zone to the pond centre, and z is the depth interval in the soil profile. The mass in the zone that includes the pond edges would be determined by a similar method, except this zone would be in the shape of a "doughnut" with the central zone volume removed.

With concentrations of samples from the problematic piezometers included in the calculation, total bromide mass in sediments was found to be about 36 kg, much more than the 24 kg that was originally applied (Table 3.1). With the unreasonably high concentrations from these deep piezometers removed (Figure 3.6b), the mass balance yielded a slightly high, but more reasonable mass of about 26 kg of bromide (Table 3.2). This provides further evidence that these high concentrations at depth were only representative of very discrete zones. These could have been natural features such as fractures in the till or decayed root systems. They could also have simply been conduits formed along the casings of the stainless steel piezometers, either due to frost action, or unfilled annular space between the piezometer

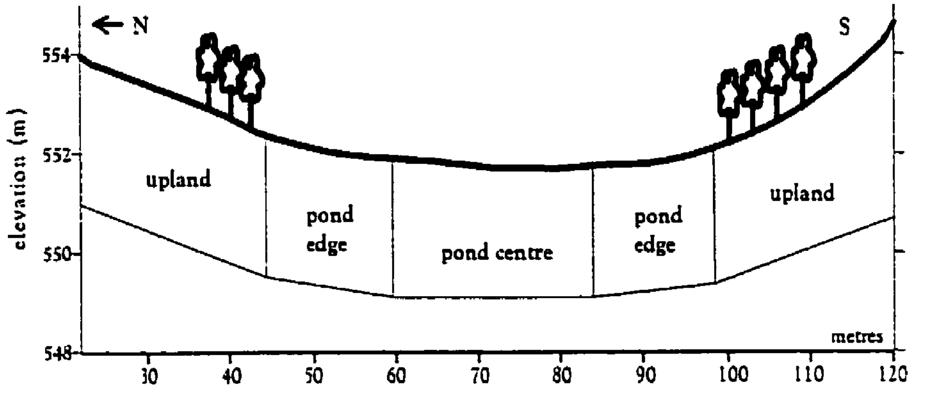

Figure 3.7 Soil zone divisions used in mass balance calculations.

Table 3.1 Summary of groundwater bromide mass balance, May 1999.

depth interval (m)	Centre [Br-] (mg/L)	(V of interval = 19.6m³) [Br-] (kg/m^3)	mass (kg)	Edge [Br-] (mg/L)	(V of interval = 75.4m³) [Br-] (kg/m^3)	mass (kg)	Upland [Br-] (mg/L)	(V of interval = 219m³) [Br-] (kg/m^3)	mass (kg)
0-0.1	0.73	0.00073	0.014	5.97	0.0060	0.45	0	0	0
0.1-0.2	0.73	0.00073	0.014	5.97	0.0060	0.45	0	0	0
0.2-0.3	2.58	0.0026	0.051	6.74	0.0067	0.51	1.39	0.0014	0.30
0.3-0.4	3.20	0.0032	0.063	4.62	0.0046	0.35	1.39	0.0014	0.30
0.4-0.5	7.47	0.0075	0.15	9.95	0.0100	0.75	1.39	0.0014	0.30
0.5-0.6	11.74	0.012	0.23	11.19	0.011	0.84	0	0	0
0.6-0.7	11.74	0.012	0.23	11.19	0.011	0.84	0	0	0
0.7-0.8	0	0	0	0	0	0	0	0	0
0.8-0.9	10.77	0.011	0.21	6.16	0.0062	0.46	0.44	0.00044	0.097
0.9-1.0	10.77	0.011	0.21	6.16	0.0062	0.46	0.44	0.00044	0.097
1.0-1.1	10.77	0.011	0.21	6.16	0.0062	0.46	0.44	0.00044	0.097
1.1-1.2	0	0	0	0	0	0	0	0	0
1.2-1.3	0	0	0	0	0	0	0	0	0
1.3-1.4	4.28	0.0043	0.084	14.2	0.014	1.07	0.52	0.00052	0.11
1.4-1.5	4.28	0.0043	0.084	14.2	0.014	1.07	0.52	0.00052	0.11
1.5-1.6	4.28	0.0043	0.084	14.2	0.014	1.07	0.52	0.00052	0.11
1.6-1.7	0	0	0	0	0	0	0	0	0
1.7-1.8	0	0	0	0	0	0	0	0	0
1.8-1.9	4.17	0.0042	0.082	6.96	0.0070	0.52	0.66	0.00066	0.15
1.9-2.0	4.17	0.0042	0.082	6.96	0.0070	0.52	0.66	0.00066	0.15
2.0-2.1	4.17	0.0042	0.082	6.96	0.0070	0.52	0.66	0.00066	0.15
2.1-2.2	0	0	0	0	0	0	0	0	0
2.2-2.3	0	0	0	0	0	0	0	0	0
2.3-2.4	0	0	0	0	0	0	0	0	0
2.4-2.5	0	0	0	0	0	0	0	0	0
2.5-2.6	0	0	0	0	0	0	0	0	0
2.6-2.7	0	0	0	0	0	0	0	0	0
2.7-2.8	0	0	0	0	0	0	0	0	0
2.8-2.9	0.43	0.00043	0.0084	0	0	0	0.56	0.00056	0.12
2.9-3.0	0.43	0.00043	0.0084	0	0	0	0.56	0.00056	0.12
3.0-3.1	0.43	0.00043	0.0034	0	0	0	0.56	0.00056	0.12
3.1-3.2	0	0	0	0	0	0	0	0	0
		zone total =	1.91		zone total =	10.37		zone total =	2.35

soil total >	14.63
pond >	22.04
total >	36.67

Table 3.2 Summary of groundwater bromide mass balance with suspect concentrations removed, May 1999

depth interval (m)	Centre [Br-] (mg/L)	(V of interval = 19.6 m³) [Br-] (kg/m^3)	mass (kg)	Edge [Br-] (mg/L)	(V of interval = 75.4 m³) [Br-] (kg/m^3)	mass (kg)	Upland [Br-] (mg/L)	(V of interval = 219 m³) [Br-] (kg/m^3)	mass (kg)
0-0.1	0.73	0.00073	0.014	6.74	0.0067	0.51	0	0	0
0.1-0.2	0.73	0.00073	0.014	6.74	0.0067	0.51	0	0	0
0.2-0.3	2.58	0.0026	0.051	6.74	0.0067	0.51	1.39	0.0014	0.30
0.3-0.4	3.20	0.0032	0.063	0	0	0	1.39	0.0014	0.30
0.4-0.5	2.04	0.0020	0.040	0	0	0	1.39	0.0014	0.30
0.5-0.6	0.31	0.00031	0.0061	0	0	0	0	0	0
0.6-0.7	0.31	0.00031	0.0061	0	0	0	0	0	0
0.7-0.8	0	0	0	0	0	0	0	0	0
0.8-0.9	0.70	0.00070	0.014	0.81	0.00081	0.061	0.44	0.00044	0.097
0.9-1.0	0.70	0.00070	0.014	0.81	0.00081	0.061	0.44	0.00044	0.097
1.0-1.1	0.70	0.00070	0.014	0.81	0.00081	0.061	0.44	0.00044	0.097
1.1-1.2	0	0	0	0	0	0	0	0	0
1.2-1.3	0	0	0	0	0	0	0	0	0
1.3-1.4	0.68	0.00068	0.013	0	0	0	0.52	0.00052	0.11
1.4-1.5	0.68	0.00068	0.013	0	0	0	0.52	0.00052	0.11
1.5-1.6	0.68	0.00068	0.013	0	0	0	0.52	0.00052	0.11
1.6-1.7	0	0	0	0	0	0	0	0	0
1.7-1.8	0	0	0	0	0	0	0	0	0
1.8-1.9	0.38	0.00038	0.0075	0	0	0	0.66	0.00066	0.15
1.9-2.0	0.38	0.00038	0.0075	0	0	0	0.66	0.00066	0.15
2.0-2.1	0.38	0.00038	0.0075	0	0	0	0.66	0.00066	0.15
2.1-2.2	0	0	0	0	0	0	0	0	0
2.2-2.3	0	0	0	0	0	0	0	0	0
2.3-2.4	0	0	0	0	0	0	0	0	0
2.4-2.5	0	0	0	0	0	0	0	0	0
2.5-2.6	0	0	0	0	0	0	0	0	0
2.6-2.7	0	0	0	0	0	0	0	0	0
2.7-2.8	0	0	0	0	0	0	0	0	0
2.8-2.9	0.43	0.00043	0.0084	0	0	0	0.56	0.00056	0.12
2.9-3.0	0.43	0.00043	0.0084	0	0	0	0.56	0.00056	0.12
3.0-3.1	0.43	0.00043	0.0084	0	0	0	0.56	0.00056	0.12
3.1-3.2	0	0	0	0	0	0	0	0	0
		zone total =	0.32		zone total =	1.71		zone total =	2.35

soil total >	4.38
pond >	22.04
total >	26.42

casings and the surrounding sediment caused by the slightly larger diameter of the insertion cones described in chapter 2. Relatively high concentrations continued to be observed in these particular piezometers throughout the summer (Figure 3.6c).

Since there were such uncertainties as to how representative piezometer samples were of the bromide content of sediments, soil samples were collected from beneath the wetland on October 8-10. Samples were collected, using a hand auger, from the top 1.5-2 m of sediment, which at this time was above the water table. Figure 3.6d shows that from analysis of these samples, most of the bromide was found to have been concentrated immediately beneath the pond and the pond edges. Very little bromide was found below 1 m depth beneath the pond centre, and little to no bromide was detected in samples from underneath or outside the willow ring. Also, some bromide was found to have penetrated to a depth of about 2 m below the pond edges. A mass balance for the October soil data, using equations 10 and 11 verified that all 24 kg of bromide could be accounted for in the shallow sediments under the pond and pond edges (Table 3.3).

3.1.3 Vegetation

Chemical analyses of vegetation samples revealed that measurable, and in some cases, considerable weight percentage of bromide had been incorporated into plant tissues of pond vegetation. In a sample from the pond centre, 10.5 mg of bromide was detected per gram of dry sample. This translates into a concentration of over 3000 mg/L inside the living plant at a water content of 70% by mass (determined from drying the sample). Karcher (1995) demonstrates that such a weight percent of assimilated solute is common in such plants. Also, bromide in pond vegetation only accounted for a total mass of about 0.6 kg, since pond plants make up only a very small dry mass (Table 3.4). There is much higher quantity of plant

Table 3.3 Summary of soil water bromide mass balance, October 1999.

depth interval (m)	Centre (V of interval = 19.6m³) [Br-] (mg/L)	[Br-] (kg/m^3)	mass (kg)	Edge (V of interval = 75.4m³) [Br-] (mg/L)	[Br-] (kg/m^3)	mass (kg)	Upland (V of interval = 219m³) [Br-] (mg/L)	[Br-] (kg/m^3)	mass (kg)
0-0.1	59.01	0.059	1.16	79.74	0.080	6.01	0	0	0
0.1-0.2	47.11	0.047	0.93	45.25	0.045	3.41	0.02	0.00002	0.0052
0.2-0.3	39.66	0.040	0.78	45.25	0.045	3.41	0.34	0.00034	0.075
0.3-0.4	24.29	0.024	0.48	26.86	0.027	2.03	0.28	0.00028	0.061
0.4-0.5	15.56	0.016	0.31	3.54	0.0035	0.27	0.37	0.00037	0.080
0.5-0.6	12.38	0.012	0.24	3.54	0.0035	0.27	0.07	0.00007	0.016
0.6-0.7	2.91	0.0029	0.057	3.74	0.0037	0.28	0.06	0.00006	0.014
0.7-0.8	1.15	0.0011	0.023	1.46	0.0015	0.11	0.06	0.00006	0.013
0.8-0.9	2.21	0.0022	0.043	1.14	0.0011	0.086	0.05	0.00005	0.012
0.9-1.0	2.19	0.0022	0.043	1.33	0.0013	0.100	0.04	0.00004	0.0086
1.0-1.1	1.17	0.0012	0.023	1.66	0.0017	0.13	0.06	0.00006	0.012
1.1-1.2	2.12	0.0021	0.042	3.10	0.0031	0.23	0.06	0.00006	0.012
1.2-1.3	2.54	0.0025	0.050	3.45	0.0034	0.26	0.04	0.00004	0.0085
1.3-1.4	1.92	0.0019	0.038	6.16	0.0062	0.46	0.01	0.00001	0.0029
1.4-1.5	0.13	0.00013	0.0026	7.75	0.0077	0.58	0.01	0.00001	0.0029
1.5-1.6	0.20	0.00020	0.0038	14.03	0.014	1.06	0.01	0.00001	0.0029
1.6-1.7	0	0	0	2.22	0.0022	0.17	0.02	0.00002	0.0039
1.7-1.8	0	0	0	2.75	0.0028	0.21	0.02	0.00002	0.0039
1.8-1.9	1.53	0.0015	0.030	1.74	0.0017	0.13	0.97	0.00097	0.21
1.9-2.0	1.53	0.0015	0.030	1.85	0.0019	0.14	0.50	0.00050	0.11
2.0-2.1	2.3	0.0023	0.045	1.66	0.0017	0.13	0.50	0.00050	0.11
2.1-2.2	0	0	0	0	0	0	0.04	0.00004	0.0084
2.2-2.3	0	0	0	0	0	0	0.04	0.00004	0.0084
2.3-2.4	0	0	0	0	0	0	0	0	0
2.4-2.5	0	0	0	0	0	0	0	0	0
2.5-2.6	0	0	0	0	0	0	0	0	0
2.6-2.7	0	0	0	0	0	0	0	0	0
2.7-2.8	0	0	0	0	0	0	0	0	0
2.8-2.9	0.73	0.00073	0.014	0	0	0	1.02	0.0010	0.22
2.9-3.0	0.73	0.00073	0.014	0	0	0	1.02	0.0010	0.22
3.0-3.1	0.73	0.00073	0.014	0	0	0	1.02	0.0010	0.22
3.1-3.2	0	0	0	0	0	0	0	0	0
		zone total =	4.36		zone total =	19.47		zone total =	1.45

soil total > 25.28

Table 3.4 Summary of vegetation sample bromide analysis.

Location	Zone	Vegetation	dry mass sample (g)	water added (mL)	[Br-] of extract (mg/L)	mass of Br (mg) per g sample	dry mass (g) per sq. m	zone area (sq. m)	Br mass (kg)
Pond	Centre	sedge, smartweed	1.004	50.10	210.55	10.50	89.48	79	0.037
	North	smartweed	0.999	50.00	1.61	0.08	461.34	680	0.025
	South	cow parsnip, sedge, smartweed	0.999	50.00	42.00	2.10	265.76	680	0.390
	East	smartweed	1.000	50.20	0.35	0.02	354.64	680	0.004
	West	cow parsnip, sedge, smartweed	1.010	50.00	1.87	0.09	329.49	680	0.021
Upland	North	grass	1.004	50.20	1.02	0.05	96.86	400	0.002
	South	wheat	1.000	50.10	0.00	0.00	367.35	2087	0.000
	East	wheat	1.004	50.00	3.65	0.18	464.78	2087	0.176
	West	wheat	0.999	50.10	0.00	0.00	699.02	2087	0.000
Trees	North	willow	1.035	50.00	0.00	0.00	57126.00	752	0.000
	South	aspen, poplar, willow	1.003	50.00	1.57	0.08	3688.00	752	0.217
	East	aspen, poplar	1.007	50.10	0.00	0.00	10394.00	752	0.000
	West	willow, poplar	0.999	50.00	0.00	0.00	5234.00	752	0.000
								Total >	0.872

biomass in trees, however, bromide was undetected in 3 of the 4 samples from the willow ring. Also, little to no bromide was found in upland vegetation. In total, less than 1 kg of the applied bromide was detected in vegetation.

3.2 Calendar Year 2000

3.2.1 Surface Water

A combination of very little winter snow cover and unusually warm temperatures in early March resulted in the central pond of S109 to be very small and short-lived in 2000. The pond reached a maximum depth of about 37 cm in late March after a quick snowmelt, giving it a volume of about 153 m^3 (runoff equivalent = 6.4 mm). By early May, the pond had become completely dry (Figure 3.1).

In late April, a survey of frost depth was conducted along transect A-B (Figure 2.1). Depth was measured using a crude metal probe which could be inserted to a maximum depth of 65 cm into the soil. The ground in slough 109 was found to be frozen right to the surface except for immediately beneath the pond (figure 3.8). This was probably the result of the absence of insolating snow cover during the previous winter.

Even though the new pond water came from snowmelt, which is known to contain no significant amount of bromide, bromide did appear in measurable quantity in the pond again in 2000. With little rainfall during this period, the bromide concentration increased from about 7 mg/L in March to 20 mg/L in late April. The bromide-chloride ratio in the pond also increased during this period, even after the pond level began to decline. Bromide mass increased as well, even during a pond level drop in late March (Figure 3.9). This shows that

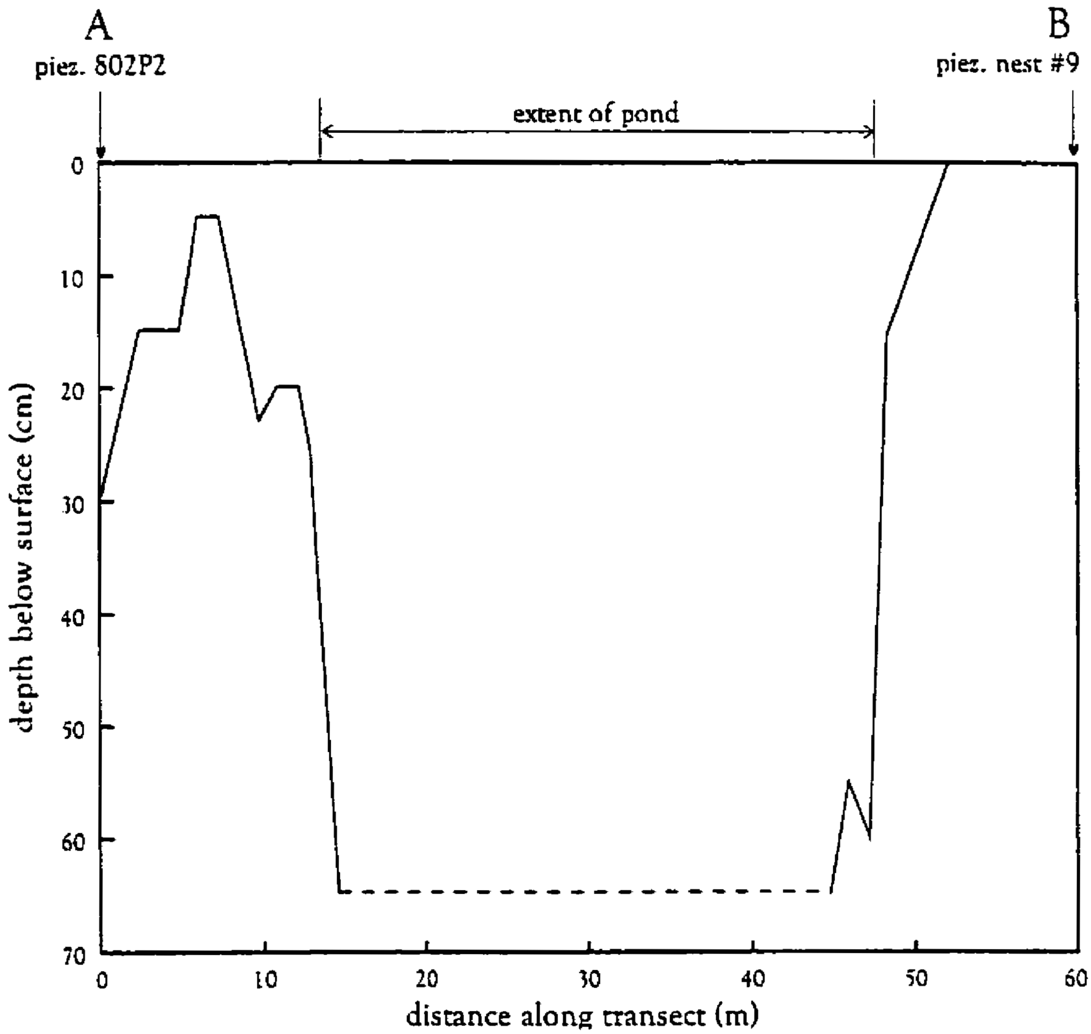

Figure 3.8 Frost depth beneath the pond and pond edges, April 20, 2000.

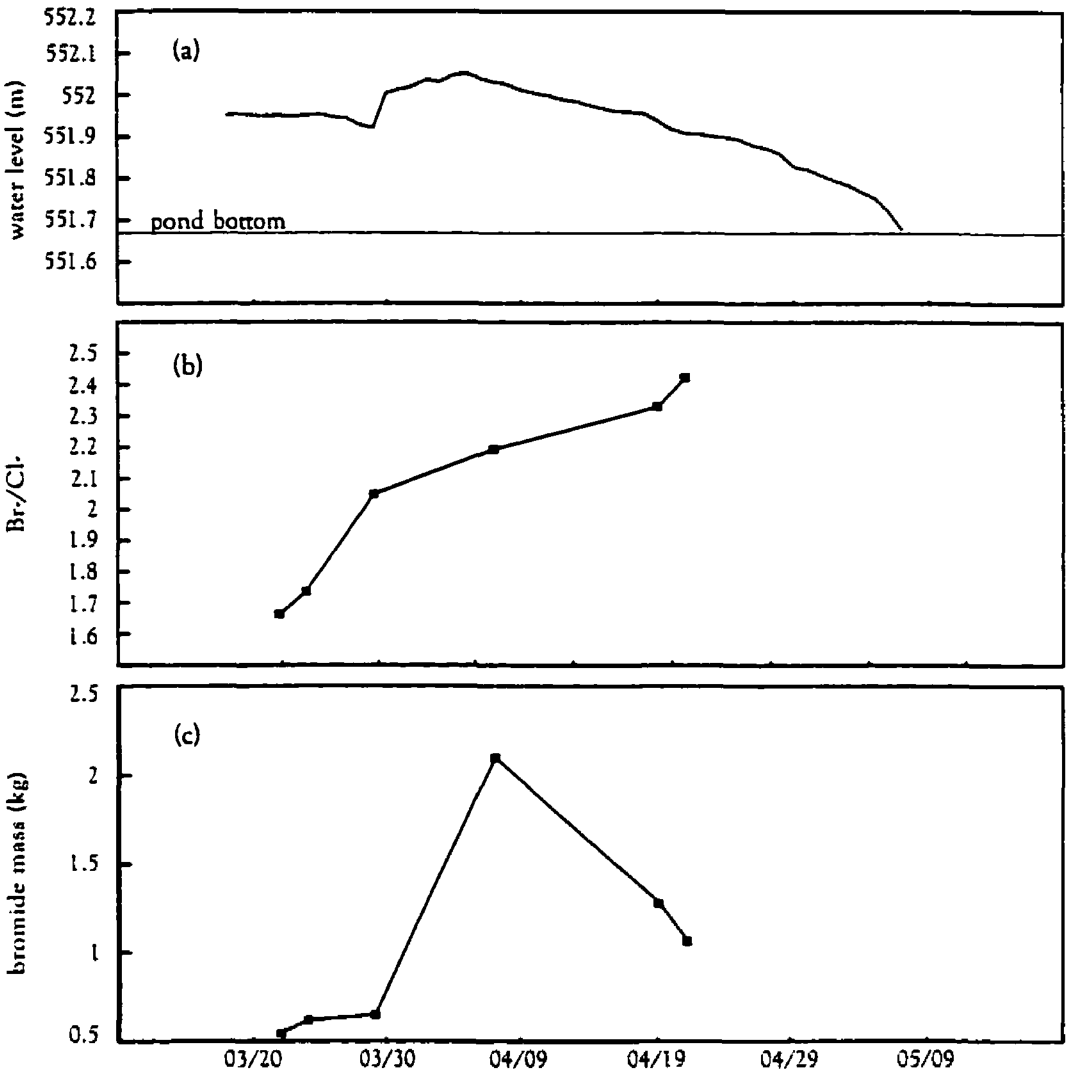

Figure 3.9 Time series plots of (a) pond water level, (b) pond bromide-chloride ratio, and (c) pond bromide mass, spring 2000.

bromide was physically entering the pond somehow. It could not have been in runoff or precipitation since bromide levels continued to increase after snowmelt was complete, and the amount of bromide in precipitation is negligible. As will be discussed later, this bromide would have had to come from pond sediments, where bromide had accumulated in the previous year.

3.2.2 Groundwater

Similar patterns of lateral, divergent groundwater flow to those observed in spring and summer 1999 were also occurring beneath S109 in 2000 (Figure 3.10). In April, the water table was low, and steep hydraulic gradients existed between the pond and upland because soils adjacent to the pond were still frozen (Figure 3.10a). In May, the water table beneath the upland to the south of the pond was at about the same level as the pond, so a flow-through condition might have existed for a brief period (Figure 3.10b). Since the pond was smaller in open water area, and was dry by early May, the water table had declined to 1.5-2.0 m below surface and groundwater flow reversal toward the pond centre had occurred by late July (Figure 3.10d).

Again in 2000, water in piezometers from particular nests contained high concentrations of bromide, while other, nearby ones did not. Despite this, most bromide was still concentrated near the surface (Figure 3.11a,b,c). A final set of soil samples collected in July 2000 showed bromide to be more concentrated and reaching deeper levels beneath the pond edges, with very little detected beneath the pond centre, even near the surface (Figure 3.11d). Little to no bromide was detected in soil water extracts from outside the willow ring, and again, almost all of the original 24 kg of bromide was accounted for in mass balance calculations (Table 3.5).

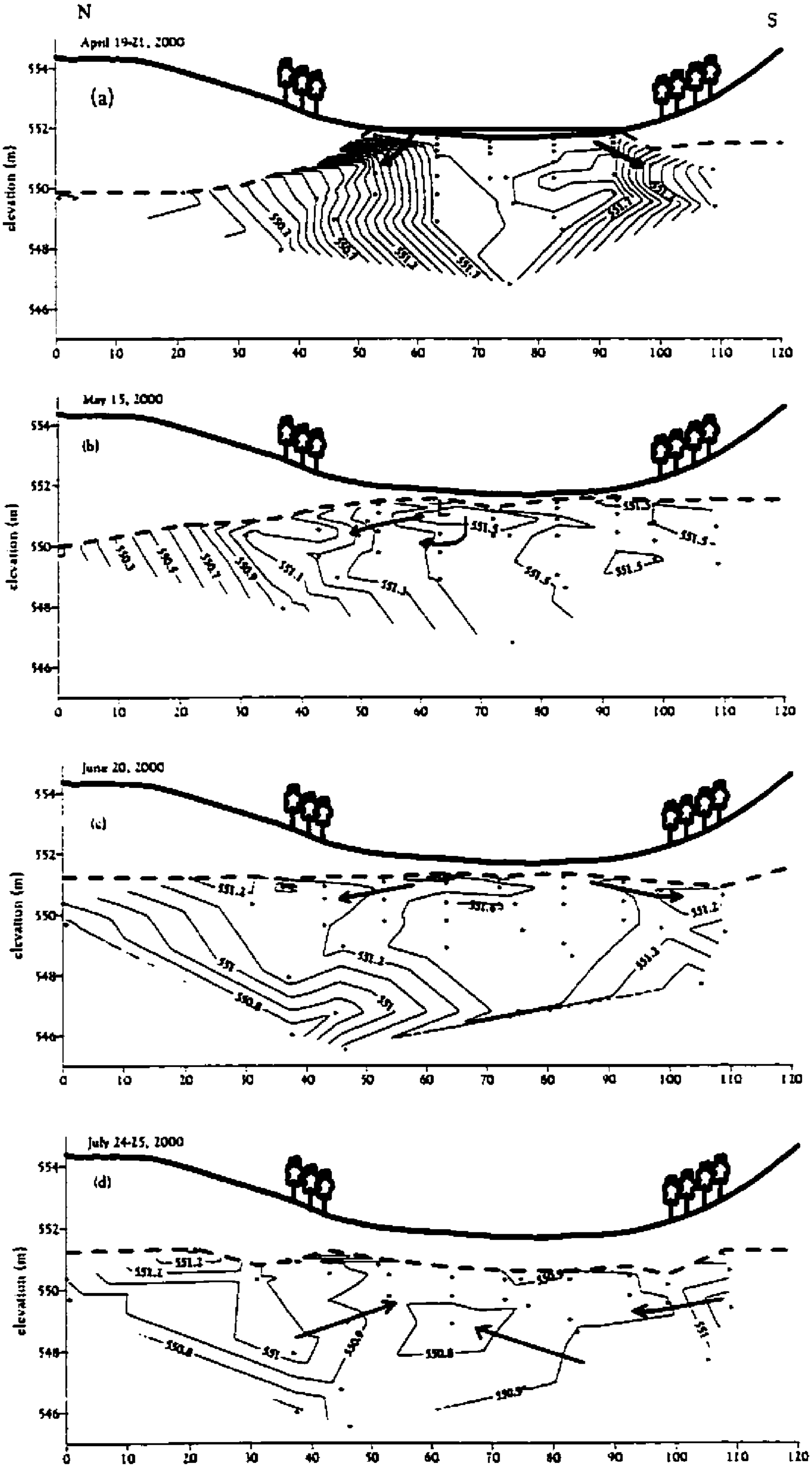

Figure 3.10 Hydraulic head distribution and inferred groundwater flow directions, 2000.

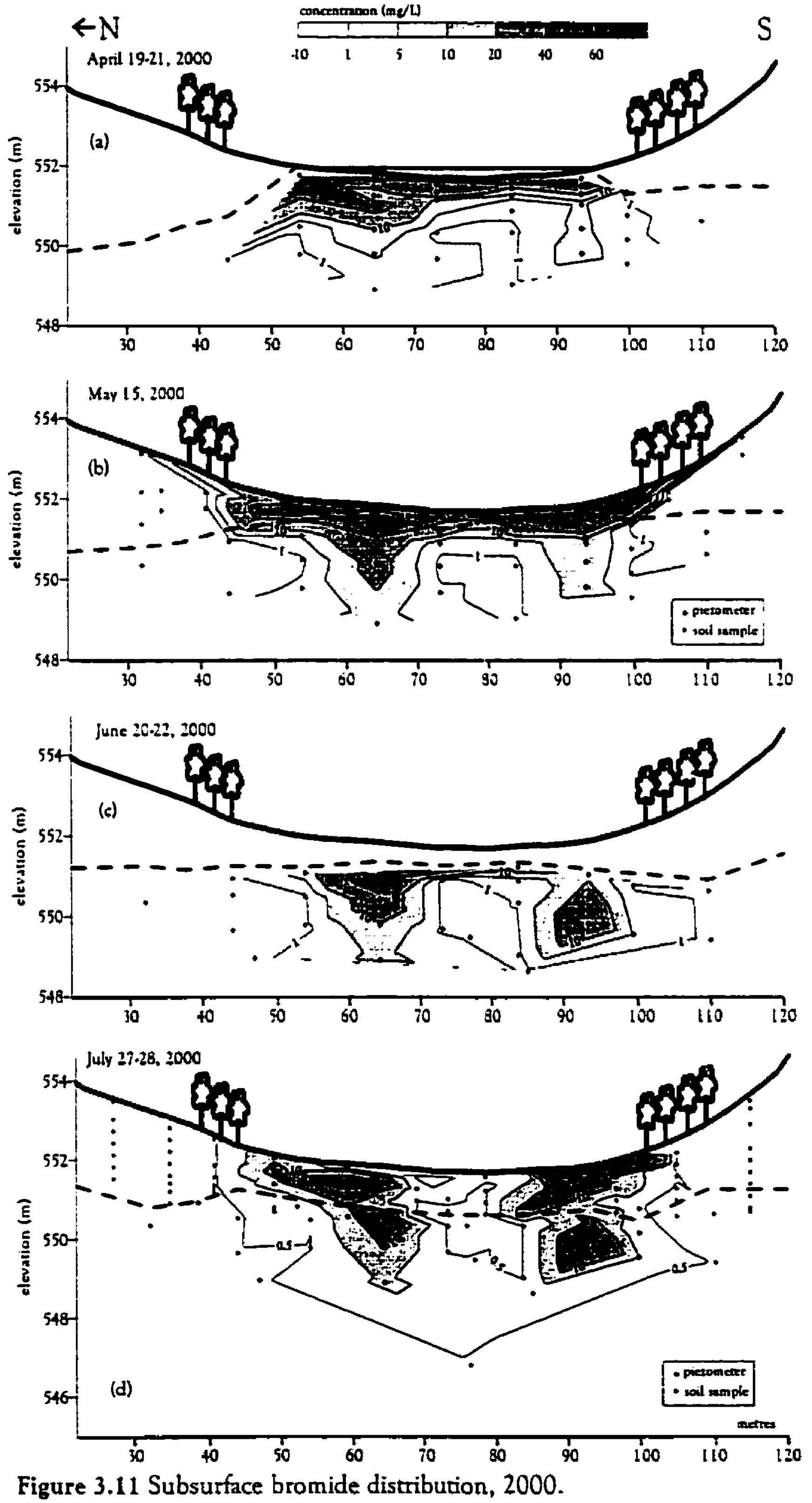

Figure 3.11 Subsurface bromide distribution, 2000.

Table 3.5 Summary of soil water bromide mass balance, July 2000.

depth	Centre (V of interval = 19.6m³)			Edge (V of interval = 75.4m³)			Upland (V of interval = 219m³)		
intrerval (m)	[Br-] (mg/L)	[Br-] (kg/m^3)	mass (kg)	[Br-] (mg/L)	[Br-] (kg/m^3)	mass (kg)	[Br-] (mg/L)	[Br-] (kg/m^3)	mass (kg)
0-0.1	1.21	0.0012	0.024	32.93	0.033	2.48	0.05	0.00005	0.012
0.1-0.2	0.96	0.00096	0.019	32.93	0.033	2.48	0.07	0.00007	0.016
0.2-0.3	0.96	0.00096	0.019	32.93	0.033	2.48	0.09	0.00009	0.019
0.3-0.4	0.27	0.00027	0.0053	17.45	0.017	1.32	0.10	0.00010	0.022
0.4-0.5	1.57	0.0016	0.031	17.45	0.017	1.32	0.14	0.00014	0.030
0.5-0.6	1.57	0.0016	0.031	17.45	0.017	1.32	0.14	0.00014	0.031
0.6-0.7	1.37	0.0014	0.027	11.64	0.012	0.88	0.12	0.00012	0.026
0.7-0.8	0.52	0.00052	0.010	11.64	0.012	0.88	0.25	0.00025	0.055
0.8-0.9	3.47	0.0035	0.068	11.64	0.012	0.88	0.25	0.00025	0.055
0.9-1.0	3.28	0.0033	0.064	6.24	0.0062	0.47	0.42	0.00042	0.092
1.0-1.1	3.21	0.0032	0.063	6.24	0.0062	0.47	0.24	0.00024	0.052
1.1-1.2	0.17	0.00017	0.0034	6.24	0.0062	0.47	0.24	0.00024	0.052
1.2-1.3	0.23	0.00023	0.0044	6.18	0.0062	0.47	0.15	0.00015	0.032
1.3-1.4	6.12	0.0061	0.12	6.29	0.0063	0.47	0.20	0.00020	0.044
1.4-1.5	6.12	0.0061	0.12	6.29	0.0063	0.47	0.20	0.00020	0.044
1.5-1.6	6.12	0.0061	0.12	6.40	0.0064	0.48	0.22	0.00022	0.047
1.6-1.7	0	0	0	0	0	0	0.11	0.00011	0.023
1.7-1.8	0	0	0	0	0	0	0.16	0.00016	0.035
1.8-1.9	5.44	0.0054	0.11	10.32	0.010	0.78	0.32	0.00032	0.070
1.9-2.0	5.44	0.0054	0.11	10.32	0.010	0.78	0.32	0.00032	0.070
2.0-2.1	5.44	0.0054	0.11	10.32	0.010	0.78	0.37	0.00037	0.082
2.1-2.2	0	0	0	0	0	0	0.20	0.00020	0.043
2.2-2.3	0	0	0	0	0	0	0.19	0.00019	0.043
2.3-2.4	0	0	0	0	0	0	0.30	0.00030	0.066
2.4-2.5	0	0	0	0	0	0	0.23	0.00023	0.051
2.5-2.6	0	0	0	0	0	0	0.23	0.00023	0.051
2.6-2.7	0	0	0	0	0	0	0.23	0.00023	0.051
2.7-2.8	0	0	0	0	0	0	0.23	0.00023	0.051
2.8-2.9	3.08	0.0031	0.060	0	0	0	1.05	0.0010	0.23
2.9-3.0	3.08	0.0031	0.060	0	0	0	1.05	0.0010	0.23
3.0-3.1	3.08	0.0031	0.060	0	0	0	1.46	0.0015	0.32
3.1-3.2	0	0	0	0	0	0	1	0.001	0.22
		zone total =	1.23		zone total =	19.67		zone total =	2.26

soil total > 23.16

CHAPTER 4

DISCUSSION/IMPLICATIONS

4.1 Calendar Year 1999

In a normal year in Saskatchewan, potential evaporation exceeds precipitation, and therefore solute concentrations in ponds normally increase through the spring and summer, as they did in slough 109 in 1993-1996 (Hayashi et al., 1998b). In 1999 however, due to high levels of precipitation, the bromide concentration of S109 dropped as pond level dropped. As described in the previous chapter, concentrations derived from daily mass balance calculations closely fit the measured data when the marginal vegetation zone is assumed to have a width of about 12.6 m, very close to the average width of the willow ring measured in the field.

When the same analysis is done for chloride using the same value of w, the data follows a very similar trend, but calculated concentrations fall slightly below measured values (figure 4.1). One possible reason for this could be underestimation of chloride in runoff, C_R. In the mass balance, C_R is taken to be 0.04 mg/L, the same as the assumed concentration in precipitation (Hayashi et al., 1998b). Runoff samples collected from the upland in the spring of 1999 have concentrations averaging 1.55 mg/L. Using $C_R = C_P$, fitting the data to the measured values by the least squares difference method, yields a width of 9.84 m. When C_R is set to 1.55 mg/L, the analysis results in a width of 11.3 m, much closer to the width of 12.6 m calculated using bromide levels. The remaining difference between the chloride and bromide results could be because the amount of runoff was underestimated. Runoff was not measured directly, so it was estimated from the difference between water level rise during a rain event, and the measured quantity of precipitation. This, however, neglects the losses from the pond due to infiltration and evaporation during each of these days. Such losses would also

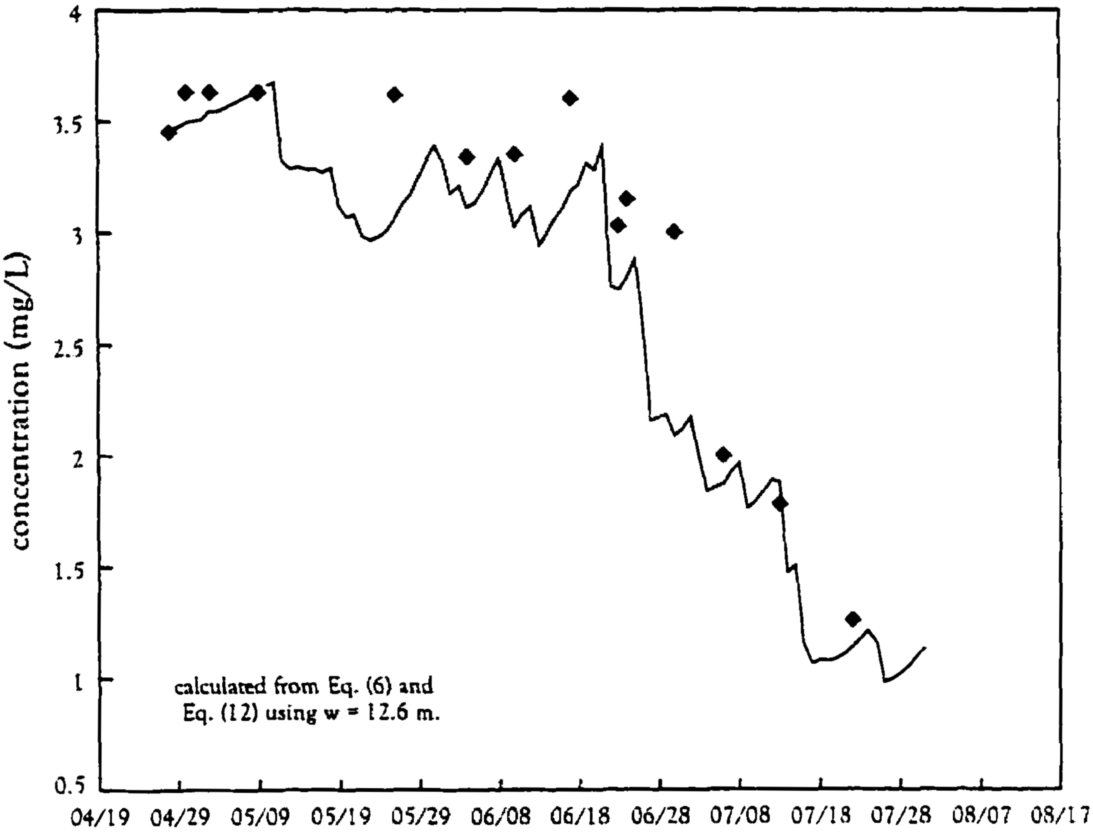

Figure 4.1 Fit of calculated to measured chloride concentrations in pond water, 1999.

have to be made up by an equal amount of runoff to account for the water level rise observed. An underestimation of runoff would fail to account for a small amount of chloride entering the pond, thereby keeping the calculated concentrations slightly lower than measured values, and effectively lowering the value of w determined from the analysis.

In other years, the same mass balance calculations to model pond chemical evolution could be applied to detect anomalies caused by other processes. For instance, diffusion of solute from sediments into the pond in spring would likely cause predicted pond concentrations to be slightly less than the actual.

The close correlation of calculated w and the measured width of the marginal vegetation zone supports the idea of shoreline-related water loss driven by marginal vegetation discussed in early work by Meyboom (1966) and Millar (1971). As the size of the slough decreased in summer, the f value, and therefore the relative importance of infiltration compared to open water evaporation became greater. The distribution of bromide in the soil beneath the pond also supports this. With bromide restricted to mainly the top metre of sediment beneath the pond centre, and further bromide accumulation and concentration at the pond edges, it can therefore be inferred that after infiltration, bromide followed a shortest-possible, shallow path to the slough margins. Hayashi et al. (1998a) also showed a relative increase of soil hydraulic conductivity with closer proximity to the surface. Due to the lack of reliability of most of the new piezometers, however, it was impossible to show as clear a trend for the top 3 m, but each individual piezometer type does appear to exhibit a roughly negative correlation between intake depth and soil hydraulic conductivity (Figure 4.2).

With this, one would expect that pond and marginal vegetation would incorporate some bromide into plant vascular systems. Very little bromide mass, however was found to reside in the plant tissues. Flury and Papritz (1993) say that bromide is very readily taken up through the root systems of plants. Also, some pond vegetation extracts were found to have

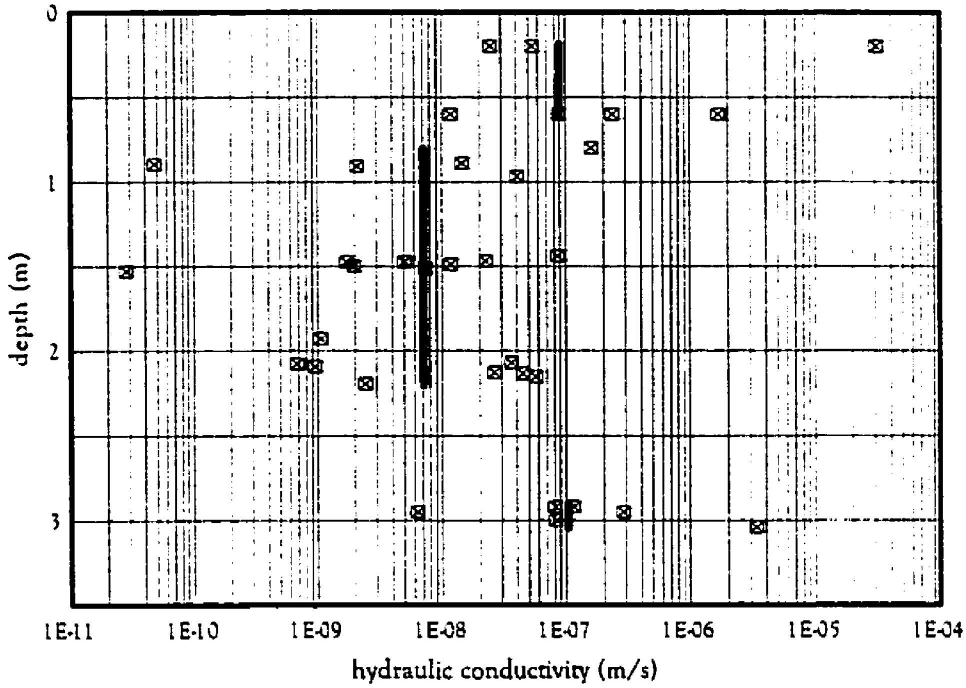

Figure 4.2 Soil hydraulic conductivity versus depth for new piezometers. Bars represent depth ranges and median values for each piezometer type.

very high concentrations of bromide. However, as shown in the previous chapter, pond vegetation only makes up less than 500 g of dry mass per square metre, with bromide tracer accounting for only a very miniscule portion of this dry mass. Meanwhile, trees in the willow ring, although they make up a much larger portion of the dry mass of vegetation in the catchment, they yielded very low bromide concentrations and therefore very low masses of bromide. This may be because the root systems of the large, mature trees in the willow ring run too deep to intercept water directly from the pond and therefore any of the applied bromide. Such was the case as found in a study of isotopes in streamside trees in Utah by Dawson and Ehleringer (1991). By drawing down the water table beneath the willow ring, however, the trees still largely control the flow of groundwater and the accumulation of solutes in the adjacent soils. Bromide levels were measurable in the willow ring sample from the south end of the slough, however, this is probably due to the occurrence of a few very young trees with less developed root systems in this particular sample (The sample included 3 small trees which were less than a metre in height).

4.2 Calendar Year 2000

The question remains as to the means by which bromide reappeared in the pond in the second year of the experiment. It is unlikely that very much of it was simply sitting at the ground surface, since rainfall, including a couple of heavy rain events in August and September 1999 would have caused most of this bromide to seep beneath the surface. Also there was not likely to have been any significant amount of groundwater inflow at any time in March and April 2000, and except for immediately below the open water area of the pond, the ground was frozen right to the surface. It is therefore likely that most of the bromide was incorporated into pond water by diffusive mixing with the sediments directly beneath the pond.

The increase in the amount of bromide in the pond from mid-March to late April 2000, indicates that diffusion may be the cause for this. Concentrations increased during this period, but so did bromide-chloride ratio, and bromide mass, even after snowmelt had ended and the pond level began dropping. This means that bromide had to have been physically entering the pond, not just being picked up from the surface and concentrated as the pond level dropped.

A mass balance was calculated to estimate a depth to which the diffusion was taking effect. The pond chemistry was changing to match that of the soil to a depth to which it could readily mix. (Figure 4.3) shows the distribution of bromide and chloride mass with soil depth beneath the pond and pond edges. The bromide-chloride ratio in the pond was about 2.2 in early April, when the pond was at its maximum size. Visual inspection of figure 4.3 shows that this ratio is observed between the cumulative masses of bromide and chloride in the top 0.4-0.5 m of sediment. Assuming that the pond had achieved chemical equilibrium with the near-surface soil water, and that all bromide originated from the soil, a bromide-chloride ratio of 2.2 should be obtained from

$$\frac{Br^-}{Cl^-} = \frac{\text{mass of bromide in soil}}{\text{mass of chloride in runoff} + \text{mass of chloride in soil}} \tag{15}$$

for the depth to which the shallow mixing zone occurs. The masses of bromide and chloride in soil are calculated from the product of average pore water concentrations determined from October 1999 soil samples, and the estimated initial pore water volume (assuming volumetric water content of 0.4). Both of these quantities are functions of depth in the soil profile. Since runoff was not directly sampled in 2000, the mass of chloride in runoff was taken as the product of total runoff volume (the sum of estimated volume of runoff infiltrated into soil, $V_{infiltrated}$, and volume of water in the pond, V_{pond}) and the chloride concentration of runoff

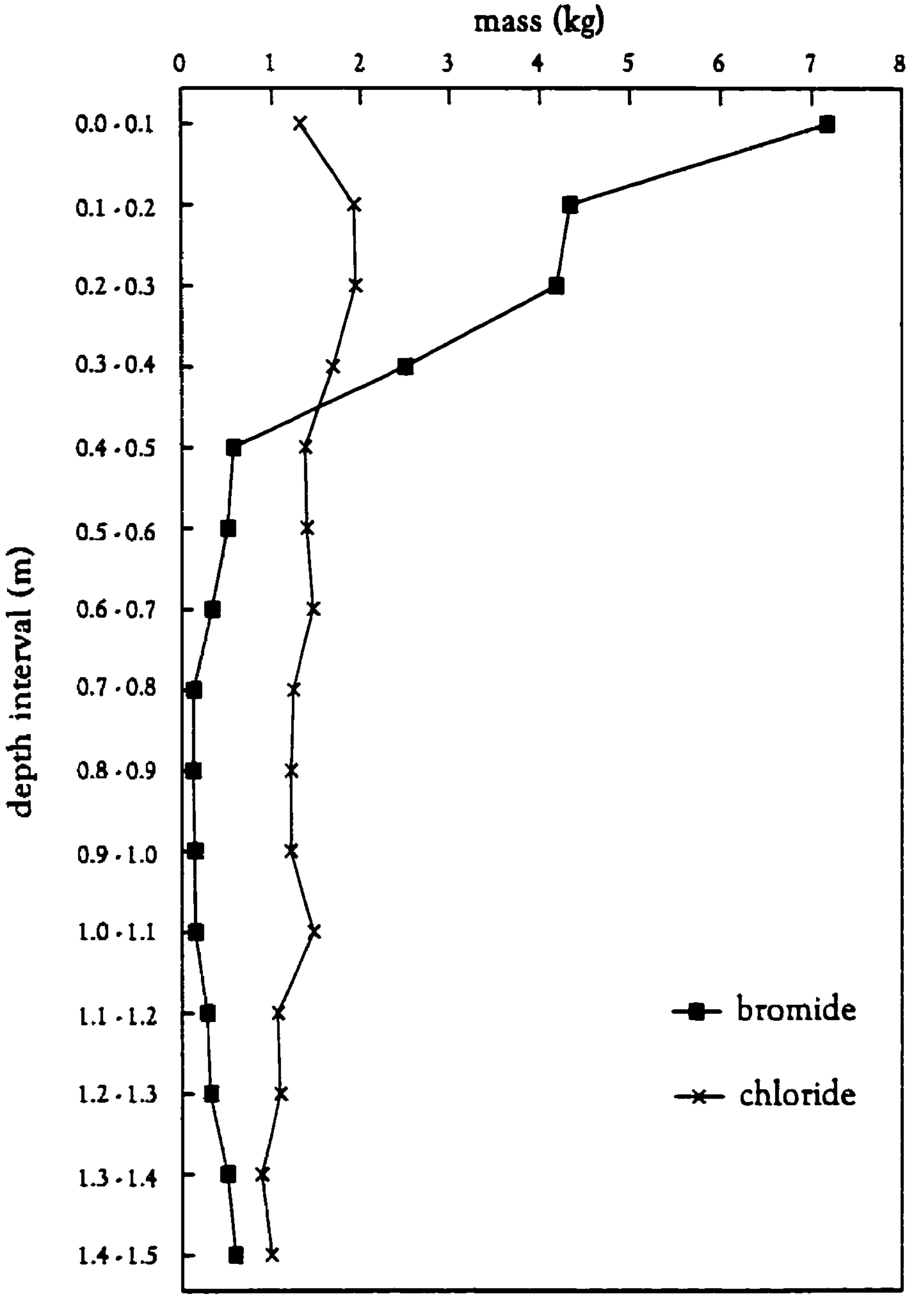

Figure 4.3 Distribution of bromide and chloride mass with depth beneath the pond and pond edges, October, 1999.

estimated from analyses of samples from small, temporary meltwater ponds on the upland (C_{runoff} = 3.08 mg/L). Therefore, Eq. (15) can be rewritten as:

$$\frac{Br^-}{Cl^-} = \frac{C_{Br-soil}V_{soil}}{(V_{infiltrated} + V_{pond})C_{Cl-runoff} + C_{Cl-soil}V_{soil}} \qquad (16)$$

Figure 4.4 is a plot of the different bromide-chloride ratios calculated for different estimates of infiltrated runoff ($V_{infiltrated}$) and different depths in the soil. The figure shows that diffusive mixing was actually taking place between the pond and the soil to a depth of between 0.4 and 0.5 m. This would help in explaining the bromide accumulation at shallow depth as shown in the previous chapter. Also, this depth corresponds to the soil's A-horizon which consists of organic-rich, peaty soil, which would have a much higher permeability than the underlying, more clayey B-horizon (Darryl Cerkowniak, Unpublished data, Figure 4.5). Some Guelph permeameter measurements from depths of 20-40 cm in and around slough 109 show that hydraulic conductivities in the A-horizon are very high, with values of close to 10^{-4} m/s (Bret Parlee, unpublished data). Iron-oxide staining observed in soil samples from the transition between the A and B horizons also provides evidence of leaching and focussed groundwater flow at these levels. It is along this shallow, high-conductivity horizon that bromide-spiked water would have followed a lateral path toward the pond edges.

4.3 Conceptual Model

In 1993-1996, Hayashi et al. (1998) observed a cycling of chloride between slough 109 and the surrounding upland, as well as accumulation of chloride in soil beneath the upland.

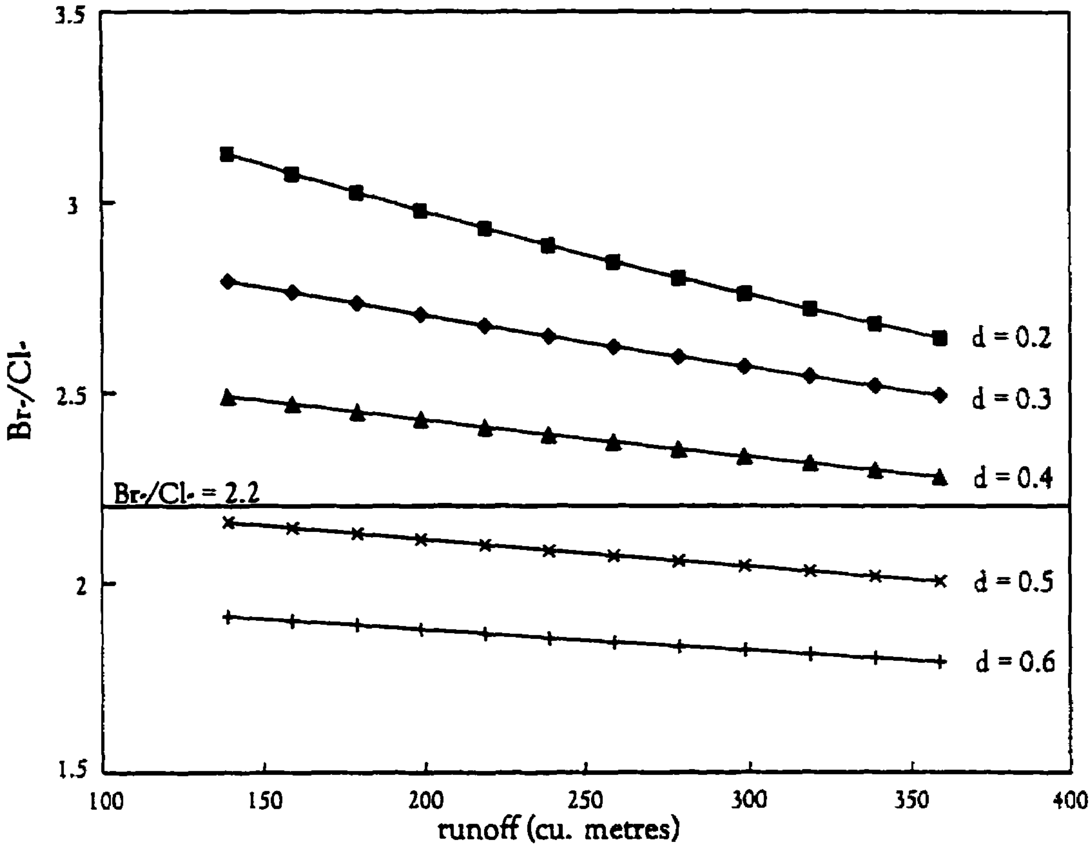

Figure 4.4 Soil bromide-chloride ratios calculated for different amounts of runoff and different depths. Horizontal line represents the ratio in the pond at peak water level, April 2000.

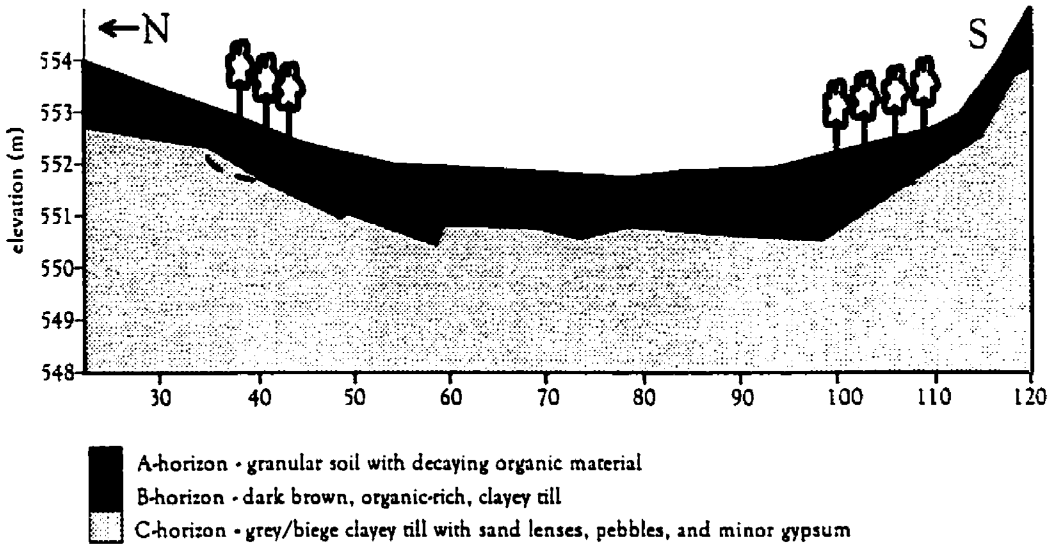

Figure 4.5 Identified soil horizons underlying slough 109. Dashed line brackets a "gleyed zone" that exhibits evidence of leaching.

During the current study, the applied bromide tracer was seen to accumulate in shallow pond sediments and concentrate at slough margins, with little to no bromide found underneath the willow ring or the upland. Analyses of soil and piezometer samples suggest that upon infiltration, the bromide-spiked pond water mostly took a shallow path through the top 0.5 m of sediment toward the pond edges. This flow appears to be mainly driven by marginal pond vegetation and a willow ring surrounding the wetland. The pond vegetation readily takes up bromide through its roots and concentrates it in this shallow soil zone beneath the pond and pond edges (Figure 4.6a). The root systems of trees in the willow ring likely reach too deep to directly take up pond water, however, they do form a water table trough beneath the trees, preventing flow and solute transport from the shallow soil zone beneath the slough to the upland. They also maintain the divergent flow pattern observed beneath the slough in spring and summer.

In the second year of the experiment, some of the bromide concentrated in soils was observed to diffuse back into the new, dilute meltwater in the pond. This bromide made it back into the sediment upon infiltration, and again accumulated at the pond edges due to evapotranspiration (Figure 4.6b). Deep, persistent frost in spring, and root uptake by willows in summer kept water tables sufficiently low to prevent bromide from migrating to the upland. If such conditions continue to exist in subsequent years, it seems likely that most of the applied bromide will remain concentrated in shallow pond sediments. Higher pond levels and water tables such as those observed in 1993-1996 (Hayashi et al., 1998) may allow some bromide to migrate toward the upland in spring when trees are not yet actively transpiring (Figure 4.6c).

As shown in Chapter 3, some bromide was found to have concentrated at depths of 1.5 - 2.0 m in isolated "pockets" beneath the pond edges in 1999 and 2000. These concentrations are likely the result of bromide that followed preferential pathways through the

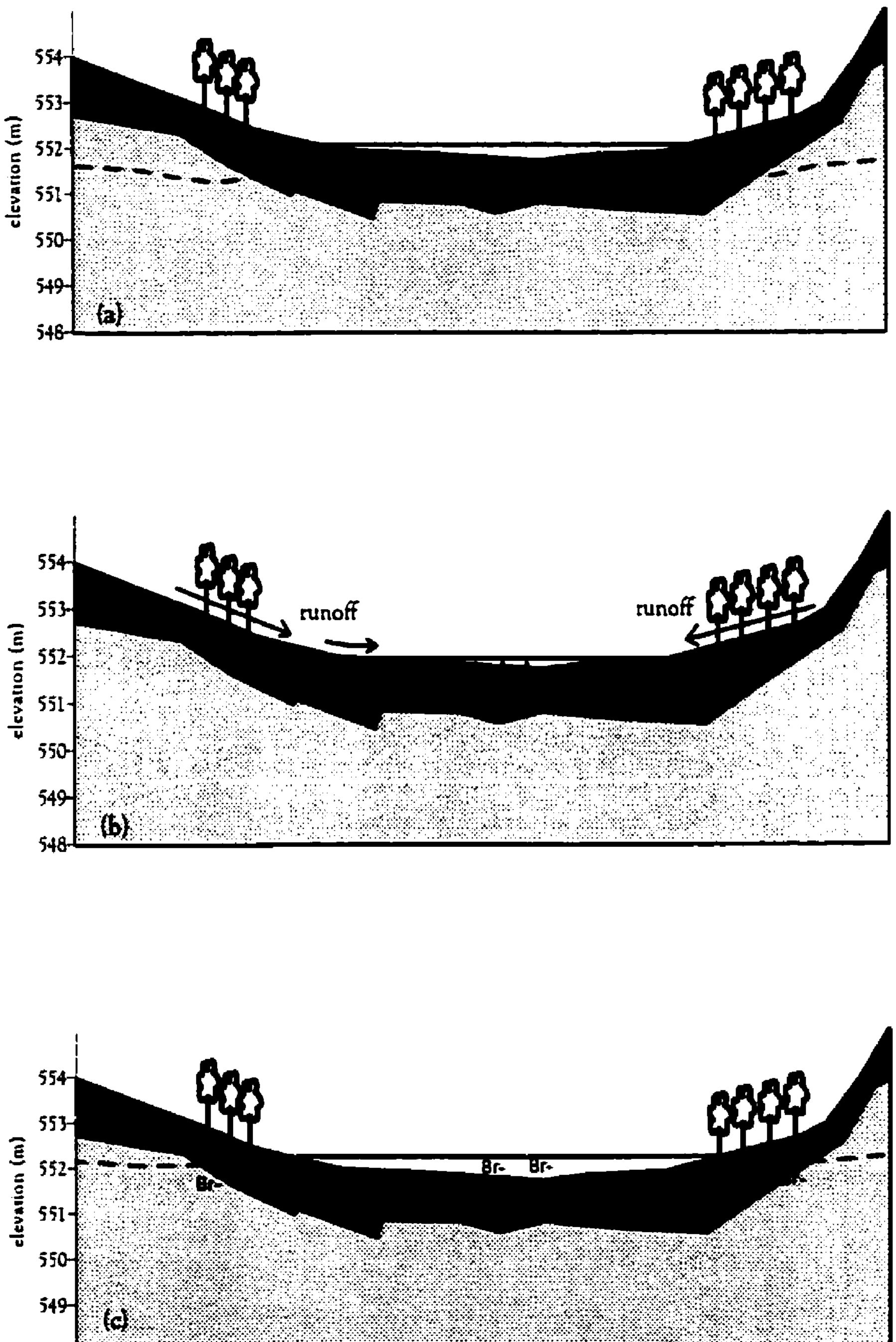

Figure 4.6 Inferred solute pathways. (a) Lateral flow along shallow levels in soil toward pond edges. (b) Diffusive mixing of solute in soil with dilute pond water in spring. (c) Possible transport of bromide to the upland during periods of high water tables in spring.

B-horizon. This bromide occurs at the approximate depth of the transition between the B and C horizons where the till appears to have a slightly higher gravel and sand content, and contains some evidence of minor leaching.

CHAPTER 5

CONCLUSIONS

5.1 Summary

In 1999, the bromide concentration in pond water in slough 109 decreased as water level decreased due to high levels of precipitation in June and July. A mathematical relationship was developed to predict the ratio of infiltration to total water loss (f), from the pond perimeter to area ratio. This relationship can possibly be used to predict pond chemical evolution in other years, and detect anomalies caused by such things as diffusion from underlying soil.

The reappearance of significant quantity of bromide in the pond in the spring of 2000 was evidence that bromide from soil was mixing into the fresh snowmelt water in the pond. The increase of bromide mass in the pond, even after the pond level began to decline, confirms this. Mass balance calculations show that bromide was being transferred to the pond from a 0.5 m-deep mixing zone, which appears to correspond to the A-horizon of underlying soil.

Snowmelt runoff collected in the pond in spring and created a water table mound. Marginal vegetation and root uptake of trees in a surrounding willow ring drove groundwater flow that diverged outward from the pond centre. Root uptake by trees created a "water table trough" beneath the willow ring. Eventual dry-up of the pond, and dissipation of the water table mound resulted in a reversal of groundwater flow toward the pond centre in September 1999 and July 2000.

Bromide applied to the pond in spring 1999 was found to accumulate at shallow levels in the soil beneath the pond and pond edges. After 2 years, most of the bromide had become concentrated beneath the pond edges by evapotranspiration at the pond margins. The scarcity of bromide at levels deeper than 0.5-1 m beneath the middle of the pond suggests that upon infiltration, the solute migrated toward the slough margins along a shallow path. The major pathway was likely located in the high-permeability A-horizon in the top 0.5 m of sediment.

Although groundwater flow and solute movement and accumulation was largely controlled by vegetation, only about 900 g of bromide was estimated to have been taken up by vegetation in the catchment in 1999. Almost all of this bromide was found to reside in pond vegetation.

Frost and evapotranspiration caused low water tables below the willow ring that prevented bromide from migrating to the upland. In both years, almost all 24 kg of bromide introduced to the system could be accounted for in soil water and vegetation from the pond and pond edges.

5.2 Future Work

Results presented here lead to more questions and detailed study of chemical evolution and solute distribution in S109 and other sloughs. Low water levels and quick dry-up of the pond in 2000 did not allow rigorous study of diffusion processes that were observed. Seepage meters placed on the pond bottom could be used to directly measure diffusion rates. Also, more rigorous sampling and measurement of runoff would improve water and solute mass balances.

Stable isotopes could be used to model chemical evolution of the pond and results could be compared to those obtained using the solute tracers. Nonconservative tracers could be used and their movement and distribution in groundwater could be compared to that of bromide and chloride. Introduction of a dye tracer and excavation of the pond bottom could eventually be conducted to confirm the inferred groundwater flow and chemical transport pathways. Continued groundwater and surface water sampling in and around wetland S109 may eventually reveal the long-term fate of the bromide tracer introduced in this experiment.

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APPENDIX A

Specifications of Piezometers and Wells

Table A1 contains piezometer dimensions, top of casing elevations, and response data for all 98-, 94-, 93-, and 80- series piezometers from which measurements were taken. All measurements are in metres unless otherwise indicated.

Table A1 Piezometer Specifications

nest # (fig. 2.1)	ID	Mean Depth	Casing Length	Casing Stick-up	Casing Diameter	Bore hole Diameter	Screen Length	Sand Pack Length	TOC elevation	K-sat (m/s)	Time Lag (h.)
5	9801A	3.04	4	1.03	0.0127	0.0635		0.195	552.873	3.3E-06	0.02
	9801B	2.128	3.048	0.97	0.00924	0.0137		0.1	552.84	2.6E-08	3.0
	9801C	1.514	2.438	0.974	0.00924	0.0137		0.1	552.845	7.4E-09	10.8
	9801D	0.894	1.829	0.985	0.00924	0.0137		0.1	552.87	4.8E-11	1660
	9801e	0.6	1.6	0.92	0.00636	0.00792	0.05		552.773		
	9801f	0.4	1.4	0.92	0.00636	0.00792	0.05		552.774	3.0E-09	<24
	9801g	0.2	1.2	0.9	0.00636	0.00792	0.05		552.769	5.9E-10	<120
7	9802A	2.92	4	0.977	0.0127	0.0635		0.25	552.804	8.2E-08	0.6
	9802C	1.499	2.438	0.989	0.00924	0.0137		0.1	552.775	2.0E-09	40.3
	9802D	0.967	1.829	0.912	0.00924	0.0137		0.1	552.71	4.1E-08	2
	9802e	0.6	1.6	0.823	0.00636	0.00792	0.05		552.662	1.7E-06	0.04
	9802f	0.4	1.4	0.824	0.00636	0.00792	0.05		552.666	3.0E-09	<24
	9802g	0.2	1.2	0.824	0.00636	0.00792	0.05		552.666	3.0E-09	<24
3	9803A	2.92	4	0.96	0.0127	0.102		0.18	553.442	1.1E-07	0.3
	9803B	1.928	3.048	1.17	0.00924	0.0137		0.1	553.575	1.1E-09	75.3
	9803C	1.438	2.438	1.05	0.00924	0.0137		0.1	553.38	8.6E-08	0.9
	9803D	0.799	1.829	1.08	0.00952	0.0137		0.1	553.395	1.6E-07	0.5
	9803e	0.6	1.6	0.9	0.00636	0.00792	0.05		553.332		
	9803f	0.4	1.4	0.908	0.00636	0.00792	0.05		553.336		
	9803g	0.2	1.2	0.908	0.00636	0.00792	0.05		553.342		
9	9804A	2.95	4	1.263	0.0127	0.0635		0.65	553.44	2.9E-07	0.09
	9804B	2.078	3.048	1.02	0.00924	0.0137		0.1	553.21	6.8E-10	117
	9804C	1.468	2.438	1.02	0.00924	0.0137		0.1	553.21	2.2E-08	3.5
	9804D	0.883	1.829	0.996	0.00924	0.0137		0.1	553.18		
	9804e	0.6	1.6	0.902	0.00636	0.00792	0.05		553.103		
	9804f	0.4	1.4	0.902	0.00636	0.00792	0.05		553.105	5.9E-10	<120
	9804g	0.2	1.2	0.904	0.00636	0.00792	0.05		553.108		
11	9805A	2.95	4	0.83	0.0127	0.102		0.21	553.725	6.3E-09	6
	9805B	2.08	3.048	1.018	0.00924	0.0137		0.1	553.96		
	9805C	1.423	2.438	1.065	0.00924	0.0137		0.1	554.09		
	9805D	1.016	1.829	0.863	0.00924	0.0137		0.1	553.82		
1	9806A	3	4	0.867	0.0127	0.102		0.25	554.091	8.2E-08	0.4
	9806B	2.087	3.048	1.011	0.00924	0.0137		0.1	554.3		
	9806C	1.471	2.438	1.017	0.00924	0.0137		0.1	554.24		
	9806D	0.89	1.829	0.989	0.00924	0.0137		0.1	554.29		
2	9807B	2.12	3.048	0.978	0.00924	0.0137		0.1	553.88	6.6E-10	<120
	9807C	1.455	2.438	1.033	0.00924	0.0137		0.1	553.93	6.6E-10	<120
	9807D	0.843	1.829	1.036	0.00924	0.0137		0.1	553.915		
4	9808B	2.193	3.048	0.905	0.00924	0.0137		0.1	552.83	2.4E-09	32.7
	9808C	1.53	2.438	0.958	0.00924	0.0137		0.1	552.925	2.8E-11	2817
	9808D	0.906	1.829	0.973	0.00924	0.0137		0.1	552.91	2.1E-09	38.1
	9808e	0.6	1.6	0.899	0.00636	0.00792	0.05		552.865	2.4E-07	0.3
	9808f	0.4	1.4	0.902	0.00636	0.00792	0.05		552.869	5.9E-10	<120
	9808g	0.2	1.2	0.9	0.00636	0.00792	0.05		552.865	3.1E-05	0.002
12	9809B	2.071	3.048	1.027	0.00924	0.0137		0.1	553.08	3.6E-08	2.2
	9809C	1.474	2.438	1.014	0.00924	0.0137		0.1	553.085	1.7E-09	46.1
	9809D	0.892	1.829	0.987	0.00924	0.0137		0.1	553.055		
	9809e	0.6	1.6	0.9	0.00636	0.00792	0.05		552.969	5.9E-10	<120
	9809f	0.4	1.4	0.908	0.00636	0.00792	0.05		552.974	3.0E-09	<24
	9809g	0.2	1.2	0.889	0.00636	0.00792	0.05		552.964	3.0E-09	<24
6	9810B	2.153	3.048	0.945	0.00924	0.0137		0.1	552.725	5.7E-08	1.4
	9810C	1.475	2.438	1.013	0.00924	0.0137		0.1	552.77	5.0E-09	15.9
	9810D	0.889	1.829	0.99	0.00924	0.0137		0.1	552.725	1.5E-08	5.5
	9810e	0.6	1.6	0.903	0.00636	0.00792	0.05		552.656	1.2E-08	6.0
	9810f	0.4	1.4	0.903	0.00636	0.00792	0.05		552.655	3.0E-09	<24
	9810g	0.2	1.2	0.89	0.00636	0.00792	0.05		552.644	5.4E-08	1.3
8	9811B	2.132	3.048	0.966	0.00924	0.0137		0.1	552.86	4.5E-08	1.8
	9811C	1.488	2.438	1	0.00924	0.0137		0.1	552.88	1.2E-08	7
	9811D	0.915	1.829	0.964	0.00924	0.0137		0.1	552.875		
	9811e	0.6	1.6	0.813	0.00636	0.00792	0.05		552.718	8.9E-08	0.8
	9811f	0.4	1.4	0.814	0.00636	0.00792	0.05		552.717		
	9811g	0.2	1.2	0.813	0.00636	0.00792	0.05		552.722	2.5E-08	2.9

Table A1 Continued

nest # (fig. 2.1)	ID	Mean Depth	Casing Length	Casing Stick-up	Casing Diameter	Bore hole Diameter	Screen Length	Sand Pack Length	TOC elevation	K-sat (m/s)	Time Lag (h.)
10	9812B	2.093	3.048	1.005	0.00924	0.0137		0.1	553.68	9.5E-10	83.9
	9812C	1.531	2.438	0.957	0.00924	0.0137		0.1	553.62		
	9812D	0.882	1.829	0.997	0.00924	0.0137		0.1	553.66	6.6E-11	<1200
	801P1*	5	7.29	1.67	0.032	0.15	0.46	1.17	553.485	1.6E-06	0.05
	801P2*	3.1	5.2	1.65	0.032	0.15	0.4	0.96	553.38	1.4E-08	6.01
	801P3*	2.4	4.31	1.59	0.032	0.15	0.38	0.69	553.475	1.8E-07	0.57
	801P4*	1.7	3.42	1.33	0.032	0.15	0.43	0.73	553.37	1.8E-07	0.55
	802P1*	6.7	8.67	1.06	0.032	0.15	0.4	1.86	553.3	2.7E-09	36
	802P2*	5.5	6.95	1.09	0.032	0.15	0.4	0.77	553.345	8.0E-11	1200
	802P3*	3.3	4.73	1.03	0.032	0.15	0.45	0.91	553.29	1.6E-07	0.54
	802P4*	1.4	2.89	1.08	0.032	0.15	0.35	0.73	553.295	9.0E-07	0.11
	803P1*	7.6	9.45	1.08	0.032	0.15	0.4	1.62	554.035	2.0E-09	30
	803P2*	5.2	6.61	1.07	0.032	0.15	0.4	0.7	553.981	1.3E-10	780
	803P3*	3.6	5.01	1.04	0.032	0.15	0.4	0.84	554.05	3.5E-07	0.26
	803P4*	1.4	2.88	1.03	0.032	0.15	0.4	0.85	553.974		
	80W1*	wtmw	4.08	1.1	0.032	0.15			553.57		
	80W2*	wtmw	4.61	1.46	0.032	0.15			553.285		
	93W2*	wtmw	2.98	0.85	0.032	0.06			553.785		
	93UP2*	11	12.77	1.09	0.013	0.15	0.6	1.4	553.437	1.2E-09	8.6
	93UP3A*	1.9	3.36	1.09	0.013	0.15	0.2	0.7	553.913	1.2E-06	0.01
	93UP3B*	6.8	8.38	1.09	0.013	0.15	0.2	1.05	553.913	7.0E-11	176
	93UP3C*	10.3	11.94	1.09	0.013	0.15	0.25	1.05	553.913	3.5E-10	35
	93UP4*	4.9	6.92	1.46	0.013	0.15	0.7	1.2	554.293	3.8E-09	53
	93UP6A*	2.3	3.8	1.01	0.013	0.15	0.2	1	555.402		
	93UP6B*	4.7	6.24	1.01	0.013	0.15	0.2	1.05	555.402	2.0E-10	32
	93UP6C*	8.2	9.66	1.01	0.013	0.15	0.25	0.9	555.402	4.5E-10	30
	94W7*	wtmw		0.8	0.041	0.05			554.745		
	94UP8*	2	3.05	0.65	0.027	0.05	0.3	0.9	553.552		
	94UP9*	1.9	3.15	0.75	0.027	0.1	0.3	1	553.612	2.8E-06	
	94UP10*	4	5.45	0.85	0.021	0.1	0.3	1.3	555.23	1.0E-09	
	94SWL1*	sw	3	1.2	0.041	0.06			552.985		

* Specifications from Hayashi (1996)

APPENDIX B

Water Levels in Piezometers and Wells

Table B1 shows water level elevations measured in piezometers and the central pond of slough 109. All measurements are given in metres above a datum plane located at 500 m above mean sea level.

Table B1 Water levels in piezometers and wells

date	piezometer ID 9801A	9801B	9801C	9801D	9801e	9801f	9801g	9802A	9802C	9802D	9802e
03/22/99	49.81	49.86						49.94		50.85	
03/31/99	51.24	51.14	51.17					50.84	50.62		
04/15/99	52.14	52.15	52.12	52.15				51.70	51.50	51.58	
04/19/99											
04/21/99											
04/22/99	52.10							52.10	52.06		
04/23/99											
04/28/99											
05/09/99											
05/12/99	52.07	52.08	52.07	52.09	52.07	52.07	51.63				
05/18/99				51.56	52.07	52.07	52.07	51.62			51.97
07/09/99	51.91	51.91		51.71	52.04		52.01	51.92		51.66	51.87
07/14/99	51.90		51.91			51.90			51.90		51.91
07/26/99	51.89	51.90	51.90	51.94	52.04		52.01	52.01	51.90	51.91	51.90
07/28/99											
08/17/99	51.64	51.64	51.63	51.45	51.90		51.94				
08/18/99								51.62	51.73		
08/19/99											51.54
09/08/99	50.70	50.48						50.74			
09/09/99			50.66						50.67		
04/19/2000	51.86				51.94		51.91	51.92			
04/20/2000			51.88	51.89	51.94	51.95	51.94		51.62	51.91	51.93
04/21/2000		51.86	51.88	51.89					51.74		
05/15/2000	51.41	51.42	51.40	51.61	51.41	51.59		51.50	51.53	51.48	51.54
06/20/2000	51.40	51.38	51.40	51.21	51.48			51.38	51.32	51.36	51.37
07/25/2000	50.73	50.82	50.82					50.89	50.89		

date	piezometer ID 9802f	9802g	9803A	9803B	9803C	9803D	9803e	9803f	9804A	9804B	9804C
03/22/99			49.68						49.89		50.92
03/31/99			50.69	50.58					50.44		
04/15/99	51.26	52.11	51.77	51.27	51.83	51.91	51.83		51.68	51.21	51.15
04/19/99			51.82	51.44	51.88						
04/21/99						51.84					
04/22/99											
04/23/99									51.99		
04/28/99											
05/09/99											
05/12/99			52.02	51.87	52.04	52.03		52.06	52.10	52.06	51.97
05/18/99	52.08	52.07	51.66			51.84	52.00			51.53	
07/09/99		51.93				51.67					51.90
07/14/99		51.91	551.86		51.86	51.84				51.76	51.88
07/26/99	51.90	51.80									
07/28/99			51.73	52.10	51.73	51.80			51.75	51.79	51.84
08/17/99									51.57		
08/18/99				51.16	51.36					51.17	51.29
08/19/99		51.56									
09/08/99			50.70	50.82					50.67	50.79	50.88
09/09/99											
04/19/2000			50.50						51.51		
04/20/2000	51.93	51.93								51.11	51.16
04/21/2000										51.18	51.20
05/15/2000	51.55		51.22	51.00	51.22				51.49	51.54	51.50
06/20/2000			51.19	51.14	51.16				51.24	51.66	51.18
07/25/2000			50.90	50.96					50.88	50.93	50.96

Table B1 Continued

	piezometer ID										
date	9804D	9804e	9804f	9804g	9805A	9805B	9805C	9806A	9806B	9806C	9807B
03/22/99									51.84		
03/31/99					50.52						
04/15/99					51.18	51.20		50.65			
04/19/99											
04/21/99								50.91			
04/22/99											
04/23/99											
04/28/99											
05/09/99											
05/12/99	52.10		51.82		51.92	51.87	51.95	51.69	51.67		51.85
05/18/99	51.88	52.09	52.10	52.10							51.87
07/09/99	51.86					51.89		51.96	51.98	51.98	
07/14/99	51.84		51.86					52.11		51.96	
07/26/99											
07/28/99	51.74				51.64			51.84			
08/17/99					51.07	51.09		51.26	52.25		
08/18/99	51.50										
08/19/99		51.74									
09/08/99					50.43			50.70			
09/09/99											
04/19/2000					50.55						
04/20/2000											
04/21/2000											
05/15/2000	51.50				51.40	51.39		51.13	51.20		
06/20/2000					51.26	51.24		51.19	51.22		
07/25/2000					50.86			51.02			

	piezometer ID										
date	9807C	9808B	9808C	9808D	9808e	9808f	9808g	9809B	9809C	9809D	9809e
03/22/99								50.09			
03/31/99		51.01		50.99				50.33	50.72		
04/15/99		52.09	52.15	52.08		51.55	51.75	51.60	52.07	51.38	51.43
04/19/99											
04/21/99		52.12	52.20	52.12							
04/22/99											
04/23/99					52.04						
04/28/99							552.13				
05/09/99					52.05						
05/12/99	51.81	51.52		51.63	51.90	51.91	52.10	52.09	52.09	51.68	51.44
05/18/99	51.83	51.53			51.92	52.02	52.16	51.55		51.38	52.10
07/09/99	51.93									51.33	
07/14/99	51.92	51.91									
07/26/99											
07/28/99	52.21	51.82	51.54	51.82				51.85	51.80	51.52	51.81
08/17/99		51.52				51.63			51.42	51.33	51.50
08/18/99					51.51			51.12			
08/19/99			51.14	51.41							
09/08/99		50.73	50.77					50.70	50.69		
09/09/99											
04/19/2000	52.87										
04/20/2000		51.04	51.12	51.19			51.93	50.82	51.09		
04/21/2000								50.89			
05/15/2000		51.34	51.32	51.34	51.35			51.44	51.43	51.28	
06/20/2000		51.26	51.23	51.25				51.17	51.18	51.25	
07/25/2000		50.83	50.87					50.84	50.77		

Table B1 Continued

date	piezometer ID 9809f	9809g	9810B	9810C	9810D	9810e	9810f	9810g	9811B	9811C	9811D
03/22/99			50.02	50.34	50.87				49.88		51.02
03/31/99			50.05	50.58	51.07				50.39		
04/15/99		51.84	50.73	51.93	52.13				51.90	51.84	51.69
04/19/99											
04/21/99						52.15	52.14	52.15			
04/22/99											
04/23/99									52.12		
04/28/99								51.99			
05/09/99			51.43	52.08	52.09	52.01					
05/12/99	51.69	51.88									
05/18/99	52.09	52.13		51.52		51.97	52.05	52.13	51.52		
07/09/99									51.91		51.20
07/14/99			51.39	51.92	51.91				51.89		51.26
07/26/99			51.60	51.90	51.97				51.88	51.89	
07/28/99	51.82	51.82									
08/17/99			51.34	51.50	51.54						
08/18/99								51.63	51.55	51.57	51.98
08/19/99											
09/08/99											
09/09/99			50.63						50.72		51.04
04/19/2000						51.94					
04/20/2000			50.84	51.92	51.35			51.93			
04/21/2000			50.88		51.35		52.00		51.94	51.73	51.76
05/15/2000			51.11	51.47	51.57	51.50			51.50	51.51	51.60
06/20/2000			51.02	51.41	51.21	51.41			51.35	51.35	51.26
07/25/2000			50.86	50.89	50.92				50.89	50.89	

date	piezometer ID 9811e	9811f	9811g	9812B	9812C	9812D
03/22/99						51.81
03/31/99						
04/15/99		51.45	51.62	50.84	51.35	
04/19/99						
04/21/99						
04/22/99						
04/23/99	51.94					
04/28/99			52.14			
05/09/99						
05/12/99				51.82	52.09	52.10
05/18/99	51.70	51.92	51.86		51.83	51.96
07/09/99	51.89		51.93		51.80	51.83
07/14/99	51.91		51.92			
07/26/99	51.90		51.90			
07/28/99				51.52	51.62	
08/17/99				51.35	51.30	
08/18/99	51.57					
08/19/99	51.51					
09/08/99				50.72		
09/09/99						
04/19/2000						
04/20/2000				50.68		
04/21/2000	51.90	51.90	51.90			
05/15/2000	51.49	51.46		51.44		
06/20/2000				51.12		
07/25/2000				50.93		

Table B1 Continued

date	piezometer ID 801P1	801P2	801P3	801P4	802P1	802P2	802P3	802P4	803P1	803P2	803P3	803P4	80W1
03/23/99	49.88				49.69	49.76	49.81			49.86			49.91
03/26/99													
03/31/99													
04/05/99													
04/08/99													
04/15/99													
04/21/99													
04/23/99													
04/28/99													
05/09/99													
05/12/99	52.05												
05/13/99													
05/18/99	52.05	52.06	52.02										
05/26/99													
05/27/99	52.04	52.05	52.03		51.95	51.35			50.49			51.98	
06/09/99	51.97				51.85		51.92	51.88	50.45			51.91	
06/10/99		51.99	51.98										
06/15/99													
06/17/99	51.93				51.77	51.52	51.73	51.72	50.46		51.85	51.85	51.72
06/23/99													
06/24/99													
07/06/99													
07/07/99													
07/09/99	51.91				51.86		51.90	51.82	50.53		51.96	52.00	51.84
07/13/99													
07/14/99	51.90				51.83								
07/22/99													
07/26/99	51.88	51.91											
07/28/99					51.76	51.70	51.73	51.66	50.52	51.67	51.80	51.81	51.80
07/29/99													
08/09/99													
08/17/99									49.93				
08/18/99	51.59	51.64			51.37			51.30					
09/08/99	50.71	50.76			50.77			50.65	49.76				
10/05/99	50.49				50.45					50.57			
10/09/99	50.49												
10/10/99	50.44	50.45	50.43	50.49	50.42	50.80	50.47		49.44	50.53	50.43		50.51
01/27/2000	50.07				50.05					50.10			50.21
02/07/2000	50.04				49.98		50.09			50.07			50.16
03/04/2000	49.89	49.94	49.85	Dry	49.78	49.94	49.90		49.01	49.96	49.95		50.00
03/20/2000	50.24												
03/24/2000	50.24	50.32	50.17	50.29	49.75	49.83	49.88		48.97	49.88	50.01		50.06
03/27/2000	51.66	51.54		51.79	49.86	49.83	49.93		48.99	49.88	50.05		50.17
03/29/2000	51.76	51.77	51.46	51.80	49.86	49.81	49.98		49.00	49.87	50.11		50.25
03/31/2000	51.82	51.83	51.58	51.85	49.93	49.81	50.04		49.02	49.88	50.15		50.34
04/03/2000	51.88	51.90	51.71	51.89	50.05	49.82	50.18		49.08	49.92	50.27		50.50
04/05/2000	51.88	51.90	51.71	51.91	50.15	49.84	50.26		49.14	49.94	50.37		50.73
04/07/2000	51.92			51.95	50.23	49.84	50.34		49.17	49.96	50.49		50.66
04/10/2000	51.92			51.96	50.36	49.87	50.48		49.26	50.01	50.62		50.76
04/13/2000	51.92	51.94	51.89	51.94	50.48	49.89	50.59		49.35	50.07	50.70		50.84
04/14/2000	51.92			51.94	50.51	49.90	50.62		49.38	50.09	50.73		50.88
04/18/2000	51.91	51.94	51.91	51.94	50.64	49.96	50.75		49.49	50.18	50.84		50.98
04/19/2000	51.93	51.93	51.91	51.93	50.66	49.97	50.77	50.85	49.52	50.20	50.87		50.99
04/20/2000													
04/28/2000	51.85			51.85	50.98	50.11	51.07		49.73	50.43	51.23	51.09	51.31
05/05/2000	51.76	51.76	51.76	51.75	51.14	50.25	51.24	51.36	49.90	50.61	51.46	51.40	51.40
05/12/2000	51.56	51.58	51.58	51.55	51.18	50.38	51.27	51.34	50.00	50.76	51.53	51.51	51.40
05/15/2000	51.48	51.51	51.50	51.47	51.19	50.42	51.29	51.35	50.03	50.83	51.55	51.54	51.39
05/17/2000	51.44			51.42					50.04	50.86	51.54	51.51	
05/24/2000	51.37	51.42	51.42	51.37	51.23	50.57	51.28	51.29	50.07	50.96	51.51	51.50	51.34
05/31/2000	51.18	51.22	51.23	51.17	51.16	50.65	51.20	51.19	50.03	51.01	51.44	51.45	51.23
06/20/2000	51.38	51.37	51.38	51.38	51.14	50.81	51.23	51.19	49.99	51.02	51.38	51.45	51.19
07/24/2000	50.89	50.90	50.81	50.92	50.88	50.87	50.94	50.81	50.96	51.21	51.25		51.02
10/26/2000		49.49				49.54	49.34				49.83		

Table B1 Continued

date	80W2	93UP2	93UP3A	93UP3B	93UP3C	93UP4	93UP6B	93UP6C	94W7	94UP8	94UP9	94UP10	S109
						piezometer ID							
03/23/99		47.08		49.32	47.06	49.61	49.76	47.94	49.64			50.02	
03/26/99													51.73
03/31/99													52.04
04/05/99													52.05
04/08/99													52.12
04/15/99													52.16
04/21/99													52.15
04/23/99													52.13
04/28/99													52.13
05/09/99													52.07
05/12/99										51.59			52.08
05/13/99													52.04
05/18/99	52.06									51.70			
05/26/99													52.06
05/27/99	52.05					51.88			51.70	51.79		50.85	52.08
06/09/99						51.82			51.70		51.69	51.21	
06/10/99													51.99
06/15/99													51.96
06/17/99	51.95					51.80			51.76	51.63		51.24	51.99
06/23/99													51.92
06/24/99													51.91
07/06/99													51.92
07/07/99													51.92
07/09/99		47.53				51.90	51.24	48.01	51.95	51.82	51.80	51.36	51.97
07/13/99													51.92
07/14/99									51.97	51.81			51.91
07/22/99													51.91
07/26/99	51.90												51.90
07/28/99			51.76	51.43		51.89	51.52	48.15	51.96		51.66	51.67	51.70
07/29/99													51.86
08/09/99													51.70
08/17/99	51.61												
08/18/99									51.33		51.23		51.69
09/08/99	50.72					50.88			50.87			51.12	51.68
10/05/99		47.41				50.45	50.89	48.15	50.47	50.62		48.72	
10/09/99													
10/10/99		47.44		50.30	47.54		51.46	48.25		50.61			
01/27/2000		47.27				50.00	50.11	48.09	49.95			48.11	
02/07/2000													
03/04/2000	49.97	47.17		49.41	47.13		49.99	48.00		50.61			
03/20/2000	50.32												51.97
03/24/2000	50.18												52.02
03/27/2000	51.92	47.08		49.34	47.05		49.96	47.95		50.62			52.01
03/29/2000	51.91	47.07		49.34	47.04	49.63	49.88	47.93	49.63	50.63		47.95	51.99
03/31/2000	51.95	47.04		49.33	47.02		49.82	47.85		50.62		47.94	52.00
04/03/2000	51.99	47.04		49.37	47.02		49.80	47.84				47.93	52.01
04/05/2000	52.01	47.08		49.40	47.03								52.03
04/07/2000													
04/10/2000													
04/13/2000	51.97	47.03		49.54	47.00								51.97
04/14/2000		47.03		49.56	47.00		49.73	47.81				47.89	51.96
04/18/2000	51.96	47.03		49.67	47.00	50.05	49.78	47.85				47.89	51.95
04/19/2000	51.96	47.05		49.69	46.98	50.07	49.79	47.85	49.86			49.88	51.94
04/20/2000		47.05		49.71	47.00								51.93
04/28/2000		47.06		49.93	47.02								51.85
05/05/2000	51.77	47.14		50.12	47.05	50.58	49.91	47.87	50.24			47.92	51.77
05/12/2000	51.52	47.17		50.35	47.08	50.84	49.93	47.81				47.95	51.68
05/15/2000	51.45	47.18		50.44	47.08	50.94	49.98	47.80	50.70	51.05	51.04	49.97	51.67
05/17/2000													51.67
05/24/2000	51.34	47.24		50.65	47.17	51.14	50.20	47.85	50.95	51.12	51.11	48.32	51.67
05/31/2000	51.15	47.25		50.69	47.18	51.17	50.27	47.77	51.01	51.08	51.07	48.40	51.68
06/20/2000	51.41	47.31	51.21	50.72	47.25	51.16	50.67	47.94	51.20	51.07	51.07	50.80	51.67
07/24/2000	50.86	47.31	51.01	50.68	47.26	51.05	50.85		51.33	50.92	50.89	50.90	51.69
10/26/2000							50.17					50.11	

APPENDIX C

Chemical Analyses of Pond Water and Groundwater

Table C1 contains results of bromide, oxygen-18, deuterium, and major ion analyses of pond water samples. Bromide and chloride numbers are given as averages of concentrations of multiple samples collected on each sampling date.

Table C2 shows bromide concentrations of piezometer samples. Measurements were obtained either by IC or bromide-specific electrode.

Table C3 gives chloride concentrations of piezometer samples. All samples were analysed by IC.

Table C1 Results of chemical and isotopic analyses of pond water.

Date	Br (mg/L)	Ca (mg/L)	Mg (mg/L)	Na (mg/L)	K (mg/L)	Cl (mg/L)	NO3 (mg/L)	SO4 (mg/L)	Alk (mg/L)	delO18 (‰)	delD (‰)
03/31/99		15.4	6.99	1.33	0.24	2.55	22.2	22.1	66.6	-23.4	-178
04/06/99		17.7	9.57	1.42	0.23	2.74	4.15	24.5	81.0	-22.3	-172
04/15/99		21.2	9.25	1.68	0.24	2.65	1.76	29.3	90.9	-20.4	-161
04/28/99	84.1					3.45				-17.2	-147
04/30/99	97.9					3.63					
05/03/99	99.1					3.63				-13.6	-134
05/09/99	105.5					3.63				-8.2	-114
05/12/99	98.4										
05/13/99	97.3	27.8	12.2	29.3	0.28	4.20	<0.05	12.7	138		
05/18/99	95.5					5.19					-127
05/26/99	92.5	27.3	13.1	26.8	0.24	3.88	<0.05	7.34	139	-13.3	-124
05/27/99	96.5					8.30					
06/04/99	89.0	40.1	13.7	27.2	0.27	3.34	<0.05	0.83	217		
06/10/99	84.3					3.35				-11.5	-109
06/15/99	87.9	20.8	13.4	25.4	0.26	4.70	<0.05	3.41	121		-107
06/17/99	87.2					3.60				-10.7	-102
06/23/99	76.7					3.03				-9.6	-92.2
06/24/99	71.9					3.15					-93
06/30/99	59.4					3.00					
07/06/99	52.4					2.00					
07/13/99	41.2					1.78				-10.2	-93.6
07/22/99	36.8					1.26					
07/29/99	40.0					2.52				-10.3	
08/09/99	82.0					7.45				-10.1	-90
08/17/99	57.8					4.71					
03/22/2000	6.97					4.19	<0.08	13.5			
03/24/2000						6.68					
03/29/2000	10.8					5.27	<0.09	17.2			
04/07/2000	15.0					10.9	<0.09	30.9			
04/19/2000	18.0					7.76	<0.09	31.8			
04/21/2000						8.13					

Table C2 Bromide concentrations in groundwater (mg/L).

	piezometer ID											
Date	9801A	9802A	9803A	9804A	9805A	9806A	9801B	9803B	9804B	9805B	9806B	9807B
04/28/99												
05/09/99												
05/12/99			0.73	0.32	0.78	0.87	0.38		0.75	0.93	0.49	
05/13/99		0.43						0.81				
05/18/99		0.73	0.63		0.85				0.88			
05/26/99											0.89	
05/27/99												
06/10/99												
06/17/99		1.90										
06/23/99				1.17								
06/24/99										1.69		1.82
07/07/99	0.20	0.34										
07/09/99						0.26			0.38			
07/14/99						1.20	0.34					
07/22/99												
07/29/99	0.27	0.66	1.84	0.44	0.86	1.58	0.42	0.57	0.47	1.43	1.29	0.70
08/09/99												
08/19/99	0.61		1.36			1.74	0.88	0.69			0.65	
08/20/99		1.36		0.61	1.13				1.56	1.39		
09/08/99							3.45					
09/09/99	1.36	0.88	1.54	1.45	1.13	1.75		1.28	1.56			
10/10/99	0.73	0.73	0.69	1.35	1.28		1.08	1.89	1.89			
04/19/2000			0.18									
04/20/2000	1.42	0.38		1.68			5.54					
04/21/2000					0.87				1.31			
05/17/2000	6.82	0.23	0.10	3.75		0.13			0.57			
06/20/2000				4.77								
06/21/2000	6.36				0.76	0.17	9.77					
06/22/2000		0.27	0.20					0.70				
07/27/2000	5.81		0.21	5.25	0.16	0.17	10.50	0.05	1.01			
07/28/2000		0.35										

	piezometer ID											
Date	9808B	9809B	9810B	9811B	9812B	9801C	9802C	9803C	9804C	9805C	9806C	9807C
04/28/99												
05/09/99	1.17		1.48									
05/12/99		0.26		7.89	0.60	0.68		0.51	0.61			0.74
05/13/99			7.95	6.96			0.68					
05/18/99	2.21			3.46								
05/26/99												
05/27/99			11.3				0.63					
06/10/99			9.23					1.75				
06/17/99						1.18						
06/23/99												
06/24/99			9.31							0.52		
07/07/99				5.27								
07/09/99										0.36		1.54
07/14/99						0.49		0.31			0.19	1.21
07/22/99												
07/29/99	1.28	0.33	2.09	0.49	0.52	0.47	0.52	0.42	0.31			
08/09/99												
08/19/99	1.66					1.74		1.00				
08/20/99		0.94	3.95	1.36	2.69		0.94		1.45			
09/08/99												
09/09/99	1.28	1.97	2.93	1.51	3.67	3.05	3.45					
10/10/99	2.51	1.60	3.52	0.81								
04/19/2000												
04/20/2000	0.33		2.00									
04/21/2000		5.37		7.97	0.17	9.15	0.28		1.42			
05/17/2000	1.53		1.36	7.72	<0.07	12.9	0.26	<0.03	1.36			
06/20/2000			0.39						1.12			
06/21/2000	0.29					16.0						
06/22/2000		4.76		18.3	0.13		1.08	0.26	0.52			
07/27/2000	0.33		0.37		0.15	17.7			0.62			
07/28/2000		5.30		20.3			0.35					

Table C2 Continued

Date	piezometer ID 9808C	9809C	9810C	9811C	9812C	9801D	9802D	9803D	9804D	9808D	9809D	9810D
04/28/99												
05/09/99			0.93	8.54						0.24		1.47
05/12/99		0.12	12.5	14.9	0.21	0.70		0.02	0.87	0.81	0.10	30.9
05/13/99			11.5	14.2			0.70					
05/18/99					0.55	0.73		0.42	0.30			
05/26/99								0.15	0.57			
05/27/99				4.91		0.60						14.3
06/10/99												
06/17/99							1.23	0.94				
06/23/99			10.4						3.62			
06/24/99												11.7
07/07/99											2.02	
07/09/99												
07/14/99								0.34				6.13
07/22/99	0.49											
07/29/99	0.44	0.33	7.45	3.20	0.74	0.86	0.63	1.04	3.60	0.33	10.9	7.74
08/09/99												
08/19/99						1.74				0.94		
08/20/99		1.66	7.69	12.4								8.92
09/08/99												
09/09/99	1.45		11.1	9.25								
10/10/99												
04/19/2000												
04/20/2000	1.27		0.34			25.1	1.59					
04/21/2000		1.59		6.11					0.60			
05/17/2000	0.27		0.23	9.51	<0.2	19.6	1.92		0.67	5.37		1.71
06/20/2000												0.20
06/21/2000	0.58									7.02		
06/22/2000						31.1	2.55					
07/27/2000	0.60		0.31									
07/28/2000		2.96		11.3								

Date	piezometer ID 9811D	9812D	9801e	9802e	9804e	9808e	9810e	9811e	9801f	9802f	9803f	9804f
04/28/99												
05/09/99	1.86					2.79		13.0				
05/12/99	11.5		0.08			9.58	34.6	12.8	0.19	0.07	1.37	
05/13/99				0.54								
05/18/99						3.39	24.4	12.7				31.6
05/26/99		0.44				1.52	16.7					49.8
05/27/99	13.6			0.28				6.89				
06/10/99	8.70											
06/17/99					7.39				0.54	0.97		23.1
06/23/99	6.41							4.82				
06/24/99							10.9					
07/07/99	2.12			0.23				2.03	0.36	0.14		
07/09/99												2.47
07/14/99							3.34		0.98			
07/22/99												
07/29/99	3.45			2.08			3.26	1.94	1.31	1.14		
08/09/99				0.19								
08/19/99			0.37									
08/20/99	4.10			1.02			0.84	2.74				
09/08/99												
09/09/99												
10/10/99												
04/19/2000												
04/20/2000				5.84			8.95		20.8	19.2		
04/21/2000	5.54		9.89					21.8				
05/17/2000	10.4			17.0			14.7	30.8				
06/20/2000				15.6								
06/21/2000												
06/22/2000	8.78											
07/27/2000												
07/28/2000												

Table C2 Continued

Date	piezometer ID: 9808f	9809f	9810f	9811f	9801g	9802g	9804g	9808g	9809g	9810g	9811g	801P1
04/28/99								7.3		26.8	49.4	
05/09/99	17		14.1					4.55			8.3	
05/12/99	4.62	0.83				0.73		2.36	3.97		10.4	
05/13/99			9.33									
05/18/99		1.01				2.94		2.51	5.23			
05/26/99		6.84					60.7		13.7			
05/27/99			4.04		1.06	5.36		4.95				
06/10/99		48.7	4.78	5.66				29.3	86.7			
06/17/99		89.2				9.82			73.9			
06/23/99			4.29					91.7	110	2.6	8.76	
06/24/99		89.2										
07/07/99									57.4			
07/09/99												
07/14/99								64.3				
07/22/99												
07/29/99		49.4	7.23	6.79		3.82		55		2.47		
08/09/99												
08/19/99												
08/20/99												
09/08/99												
09/09/99												
10/10/99												
04/19/2000												
04/20/2000			40.9			57.5		35.6		24.4		
04/21/2000				34.8	44.5						36.01	
05/17/2000												
06/20/2000												
06/21/2000												
06/22/2000												
07/27/2000												0.08
07/28/2000												

Date	piezometer ID: 801P2	801P3	801P4	802P3	802P4	803P3	80UP3A
04/28/99							
05/09/99							
05/12/99							
05/13/99							
05/18/99							
05/26/99							
05/27/99							
06/10/99							
06/17/99							
06/23/99							
06/24/99							
07/07/99							
07/09/99							
07/14/99							
07/22/99							
07/29/99							
08/09/99							
08/19/99							
08/20/99							
09/08/99							
09/09/99							
10/10/99							
04/19/2000							
04/20/2000							
04/21/2000							
05/17/2000							
06/20/2000							
06/21/2000							
06/22/2000	0.54	0.52		0.13		0.13	
07/27/2000	1.35	0.57	0.13	0.1	0.68	0.17	0.07
07/28/2000							

Table C3 Chloride concentrations in groundwater (mg/L).

Date	piezometer ID											
	9801A	9802A	9803A	9804A	9806A	9801B	9804B	9805B	9806B	9808B	9810B	9811B
04/28/99												
05/09/99												
05/12/99												
05/13/99												6.69
05/18/99												
05/26/99												
05/27/99												
06/10/99												
06/23/99												
06/24/99												
07/07/99												
07/09/99												
07/14/99												
07/29/99												
08/09/99												
08/19/99									5.83			
08/20/99								20.9				
04/19/2000			8.81									
04/20/2000	9.99	10.0		7.35						7.46		
04/21/2000												6.05
05/17/2000	7.86	8.58	7.72	7.43	5.26		8.69					3.75
06/20/2000		8.09		7.09							11.6	
06/21/2000	8.11				5.44	8.05				7.56		
06/22/2000			9.12									7.48
07/27/2000												
07/28/2000												

Date	piezometer ID											
	9812B	9801C	9802C	9803C	9804C	9805C	9806C	9807C	9808C	9810C	9811C	9812C
04/28/99												
05/09/99												
05/12/99												
05/13/99											7.94	
05/18/99												
05/26/99												
05/27/99												
06/10/99												
06/23/99												
06/24/99						17.1						
07/07/99												
07/09/99								10.8				
07/14/99							1.52	11.1				
07/29/99												
08/09/99												
08/19/99												
08/20/99												
04/19/2000												
04/20/2000										8.31		
04/21/2000	9.50	10.9	8.41								6.84	
05/17/2000	7.75	11.0	7.97	6.90					6.01	4.95		17.0
06/20/2000												
06/21/2000												
06/22/2000	8.25			7.53	6.70							
07/27/2000												
07/28/2000												

Table C3 Continued

	piezometer ID											
Date	9801D	9804D	9808D	9810D	9811D	9801e	9802e	9810e	9811e	9801f	9802f	9810f
04/28/99												
05/09/99			5.19						9.65			
05/12/99											9.34	
05/13/99							13.2					
05/18/99		16.2										
05/26/99		11.8										
05/27/99					14.9							
06/10/99					10.8							12.4
06/23/99												15.1
06/24/99												
07/07/99							9.74		9.98		12.4	
07/09/99												
07/14/99										17.0		
07/29/99								10.9		21.4		
08/09/99							11.3					
08/19/99						18.8						
08/20/99							12.9	10.8	12.0			
04/19/2000												
04/20/2000							11.5	10.3		13.7	13.0	
04/21/2000		9.69				19.3			10.4			
05/17/2000					5.32		13.7	13.7	10.6			
06/20/2000				7.74			9.56					
06/21/2000			6.69									
06/22/2000	11.9				5.62							
07/27/2000												
07/28/2000												

	piezometer ID											
Date	9811f	9801g	9802g	9808g	9809g	9810g	9811g	801P2	801P3	802P3	803P3	
04/28/99				5.16								
05/09/99												
05/12/99				5.06								
05/13/99												
05/18/99					4.39							
05/26/99												
05/27/99												
06/10/99	9.68											
06/23/99						10.0	8.25					
06/24/99												
07/07/99												
07/09/99												
07/14/99												
07/29/99	10.4		10.3									
08/09/99												
08/19/99												
08/20/99												
04/19/2000												
04/20/2000				14.6		11.0						
04/21/2000	12.4	24.2										
05/17/2000												
06/20/2000												
06/21/2000												
06/22/2000								5.51	12.8	3.10	8.41	
07/27/2000												
07/28/2000												

APPENDIX D

Chemical Analyses of Soil Pore Water Extracts

Table D1 contains bromide and chloride concentrations of pore water extracts from soil samples. For analysis, samples were diluted by approximately a factor of five. Concentrations given here are those obtained by IC for the dilute sample multiplied by the exact dilution factor.

Most location numbers in the table represent the mid-point between 98- series piezometer nests. Location number 02-11, for example, is the mid-point between piezometer nests 9802 and 9811. Non-hyphenated numbers numbers indicate locations next to particular piezometers. Exceptions to this include location 12 which is situated 5 metres south of piezometer nest 9812, and location C, which lies at the mid-point between piezometer nests 9810 and 9802, at what is referred to as the "pond centre".

Table D1 Bromide and chloride concentrations of soil water extracts (mg/L).

Date	Location	Depth Interval (cm)	Br	Cl	Date	Location	Depth Interval (cm)	Br	Cl
10/99	02-11	0-20	79.7	14.3	10/99	06-07	20-30	0.05	16.0
10/99		20-30	23.8	5.26	10/99		60-70	0.05	5.85
10/99		40-50	6.05	10.7	10/99		80-90	0	6.57
10/99		50-60	0.53	5.73	10/99		100-110	0	9.66
10/99		60-70	0	4.62	10/99		120-130	0	8.71
10/99		80-90	0	4.31	10/99		140-150	0	5.19
10/99		90-100	0.10	7.09	10/99		160-170	0	16.5
10/99		100-110	0	0	10/99		190-200	0.05	6.86
10/99		110-120	0.10	4.26	10/99		240-250	0	11.3
10/99		120-130	0	5.27	10/99		260-270	0	10.5
10/99		140-150	41.8	8.47	10/99	C	10-20	119	9.32
10/99	04-12	0-20	0	49.6	10/99		50-60	19.2	2.30
10/99		40-50	0	24.1	10/99		70-80	0	28.0
10/99		60-70	0.05	12.7	10/99		120-130	0	13.0
10/99		70-80	0	15.6	10/99		180-190	0	23.7
10/99		80-90	0.06	14.9	10/99	10	0-20	40.5	13.4
10/99		100-110	0.10	13.5	10/99		40-50	67.7	10.3
10/99		110-120	0	41.6	10/99		50-60	0.42	6.43
10/99		130-140	0	18.7	10/99		60-70	0	10.3
10/99		140-150	0.05	4.43	10/99		70-80	0.05	12.7
10/99		200-210	0	21.1	10/99		120-130	0.78	10.8
10/99		220-230	0	39.4	10/99		130-140	0.00	18.9
10/99	01-10	0-20	17.6	15.0	10/99		140-150	0.39	18.5
10/99		20-30	11.4	16.2	10/99	07-03	30-40	1.11	6.76
10/99		40-50	8.16	21.4	10/99		40-50	0.21	4.94
10/99		50-60	1.73	35.0	10/99		110-120	0	5.16
10/99		60-70	0	25.3	10/99		170-180	0.07	8.87
10/99		90-100	3.10	44.7	10/99		210-220	0.08	13.7
10/99		100-110	0	30.7	10/99	11-04	20-30	21.5	11.5
10/99		110-120	1.59	30.2	10/99		50-60	2.90	46.3
10/99		140-150	0	23.5	10/99		60-70	2.15	5.52
10/99	12	30-40	0.20	7.00	10/99		70-80	0	3.45
10/99		50-60	0	3.13	10/99		90-100	0	5.36
10/99		70-80	0.26	14.7	10/99		110-120	0	5.53
10/99		110-120	0.23	7.54	10/99		120-130	4.24	8.18
10/99		160-170	0	7.46	10/99		130-140	1.47	6.12
10/99		220-230	0	8.25	10/99	08-01	20-30	52.3	6.70
10/99	08	20-30	58.2	0.76	10/99		40-50	0	6.64
10/99	03-08	20-30	36.0	93.8	10/99		50-60	12.3	4.93
10/99		50-60	0	11.7	10/99		80-90	0	15.7
10/99		60-70	7.17	34.5	10/99		90-100	2.75	8.64
10/99		80-90	0	6.59	10/99		100-110	4.11	10.1
10/99		90-100	6.27	25.2	10/99		120-130	17.2	6.89
10/99		110-120	0	27.2	05/2000	01-10	20-30	26.3	
10/99		120-130	0	8.88	05/2000	02-11	20-30	53.4	
10/99		140-150	14.0	8.15	05/2000	03-08	40-50	31.2	
10/99		170-180	2.22	49.8	05/2000	04-12	20-30	0.12	
10/99		180-190	3.28	50.0	05/2000		40-50	0.16	
10/99	02	30-40	9.88	18.4	05/2000	06	0-20	0.04	
10/99		50-60	1.86	14.6	05/2000		100-110	0.05	
10/99		80-90	5.68	13.8	05/2000		180-190	0.04	
10/99		100-110	0	21.8	05/2000	06-07	80-90	0.05	
10/99		120-130	10.3	9.36	05/2000		130-140	0.04	

Table D1 Continued

Date	Location	Depth Interval (cm)	Br	Cl
05/2000	07-03	40-50	0.05	
05/2000		80-90	0.06	
05/2000	08-01	20-30	31.4	
05/2000	11-04	0-20	59.0	
05/2000	12	0-20	0.05	
05/2000		50-60	0.05	
05/2000	C	20-30	13.5	
05/2000	W7-06	40-50	0.04	
07/2000	06-07	20-30	<0.01	
07/2000		50-60	<0.03	
07/2000		80-90	<0.01	
07/2000		110-120	<0.01	
07/2000		140-150	<0.01	
07/2000		160-170	0.02	
07/2000		180-190	0.02	
07/2000		210-220	0.02	
07/2000	07-03	0-20	<0.01	
07/2000		70-80	<0.01	
07/2000		100-110	<0.01	
07/2000		120-130	<0.01	
07/2000		130-140	<0.01	
07/2000		140-150	<0.01	
07/2000	03-08	0-20	1.08	
07/2000		40-50	2.35	
07/2000		70-80	1.40	
07/2000		100-110	0.62	
07/2000		130-140	0.52	
07/2000		140-150	0.42	
07/2000	04-12	20-30	0.02	
07/2000		50-60	0.03	
07/2000		80-90	0.15	
07/2000		110-120	0.09	
07/2000		140-150	0.07	
07/2000		180-190	0.08	
07/2000	02-11	0-20	13.6	
07/2000		40-50	3.91	
07/2000		70-80	2.83	
07/2000		100-110	1.86	
07/2000	02	0-20	0.34	
07/2000		90-100	2.63	
07/2000	W7-06	10-20	<0.01	
07/2000		50-60	<0.01	
07/2000		80-90	<0.01	
07/2000		110-120	<0.01	
07/2000		140-150	<0.01	
07/2000		170-180	<0.02	
07/2000		200-210	<0.02	
07/2000	08-01	0-20	0.48	
07/2000		40-50	5.47	
07/2000		70-80	2.98	
07/2000		100-110	1.97	
07/2000		130-140	1.55	
07/2000	12	0-20	<0.01	
07/2000	12	30-40	<0.03	
07/2000		70-80	0.02	
07/2000		130-140	0.01	
07/2000		160-170	0.02	
07/2000		190-200	0.05	
07/2000		220-230	0.05	
07/2000		250-260	0.04	
07/2000		280-290	0.04	
07/2000		290-300	0.04	
07/2000	10	70-80	0.20	
07/2000		100-110	0.05	
07/2000	11-04	0-20	3.53	
07/2000		40-50	1.59	
07/2000		70-80	1.54	
07/2000		100-110	0.38	
07/2000		130-140	1.43	
07/2000	01-10	20-30	0.09	
07/2000		50-60	0.61	
07/2000		80-90	0.10	
07/2000		110-120	0.04	
07/2000	C	0-20	0.16	
07/2000		40-50	0.02	
07/2000		70-80	0.01	
07/2000		100-110	0.01	