WATER BALANCE AND SEEPAGE ESTIMATES FOR THE SEWAGE LAGOON
AT MAYO, CENTRAL YUKON TERRITORY

By

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ABSTRACT

A water balance study was carried out during summer 2003 to determine the rate of seepage from the sewage lagoon at Mayo, central Yukon Territory. The lagoon is largely dry, with over 85 % of the total area covered by vegetation or bare soil. Measurements of precipitation, inflow, and pond water level, and estimates of evaporation were made to determine the rate of seepage from the lagoon. Precipitation was measured in a network of rain gauges, inflow at the Mayo lift station, and pond water level with staff gauges. Evaporation was estimated by a modified form of the Priestley-Taylor method, and from an evaporation pan placed in an infiltration pond. Daily estimates of seepage from two infiltration ponds at the lagoon were $29 \text{ mm day}^{-1} \pm 4 \text{ mm day}^{-1}$ and $22 \text{ mm day}^{-1} \pm 4 \text{ mm day}^{-1}$, which are consistent with the design infiltration rate of 20 mm day^{-1} . Input of wastewater to the lagoon is low in comparison to its storage capacity, and as a result the retention time at the lagoon is low. The water balance indicates a retention time of less than one month.

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NOMENCLATURE

<i>Symbol</i>		<i>Symbol</i>	
P	Precipitation	γ	Psychrometric constant
ΔS	Change in storage	e_{sa}	Saturation vapour pressure
E	Evaporation	L_v	Latent heat of vapourization
R	Seepage	α	Priestley-Taylor alpha
I	Inflow	Q	Discharge
MAAT	Mean annual air temperature	RT	Retention time
ET	Evapotranspiration	V	Volume
PE	Potential evaporation	e_a	Vapour pressure
Q^*	Net radiation	$K_{\downarrow}$	Solar radiation
Q_E	Latent heat flux	I_H	Heat index
Q_H	Sensible heat flux	T	Mean monthly temperature
Q_G	Ground heat flux	T_w	Water temperature
Q_w	Lake heat storage	T_a	Air temperature
RH	Relative humidity		
β	Bowen ratio		
S	Slope of the saturation vapour pressure-temperature curve		

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CHAPTER ONE

OVERVIEW AND OBJECTIVES

1.1 Introduction

The purpose of this thesis is to examine the water balance of the sewage lagoon at Mayo, central Yukon Territory. The lagoon was designed as an infiltration system, but despite a continuous inflow of wastewater it has remained relatively dry since its construction in 1992. Specifically, the research is designed to determine the rate of seepage from the lagoon.

The lagoon in Mayo was built to provide primary and secondary sewage treatment and to eliminate direct discharge of wastewater from Mayo to Stewart River. The previous sewer line was prone to plugging and the buildings along the connection were at risk of back ups and flooding during periods of intense rain, or, in the spring, due to the elevated groundwater table. Outside the Village limits, residents not connected to the sewer lines discharge wastewater to leaching pits or privies.

In June 1990, recommendations of a sewage treatment study which proposed the construction of a four celled sewage lagoon were adopted by the Village of Mayo (Geo-Engineering Ltd., 1990). Based on numerous criteria, some of which were cost, land availability, population, maintenance requirements, and water use, it was decided that sewage produced in Mayo would be treated using two 2-day anaerobic cells plus larger infiltration cells. The location chosen for the 16 hectare lagoon was west of the Village, north of the confluence of Mayo and Stewart rivers (Figure 1.1).

Figure 1.1. Aerial photograph of the Mayo area, YT. The force main (A) carries sewage to the lagoon (B). The infiltration cells of the lagoon are largely dry, with small ponds in the center of each cell. Stewart River is to the west and south of the lagoon and Mayo River is to the east. The airport subdivision (C) and some houses on Na Cho Nyak Dun land (D) do not have sewer connections to the lagoon. Parts of aerial photograph A28299-221 (National Air Photo Library, 1996).

Permafrost in the Mayo region is discontinuous but it was found in ten of the eleven boreholes drilled at the proposed lagoon during site investigations in March 1990 and January 1992. Soils at the lagoon consist of fine sands, silts and gravel underlain by alluvial, ice-poor soils that form part of the Mayo River delta. Ice-rich silts and clays were found at 4 m and > 7.5 m depth (EBA, 1992a). If frozen, these soils are well-suited to retain wastewater over the winter when treatment is minimal. However, these fine-grained, poorly drained soils are susceptible to thawing beneath a pond. This is common near Mayo where there are several thermokarst lakes (Burn and Smith, 1990). This makes construction in these soils difficult and their long-term stability questionable.

The lagoon is designed as an infiltration system. The infiltration cells have an effluent design storage of 365 days and possess a total usable volume of 260,000 m³. Currently, the wastewater from 200 households, approximately 450 residents, is discharged to the Mayo lagoon. About 30 to 40 households outside the Village limits in the airport subdivision and some of those on Na Cho Nyak Dun land still rely on septic systems. Waste from the septic system of one business is deposited by truck weekly into the lagoon. Inflow measured at the Village of Mayo lift station varies from a minimum of 350 m³ day⁻¹ in the summer up to 850 m³ day⁻¹ in the winter, when the water system runs continuously to prevent freezing. Two of the four cells at the lagoon contain a minimal amount of water and have never been full (Figure 1.1).

To determine why the sewage lagoon in Mayo is dry, a water balance study was carried out at the lagoon during summer 2003. The water balance:

$$P = \Delta S + E + R \quad [1.1]$$

was used to estimate the amount of seepage from the lagoon. Total input (P) at the lagoon is in the form of direct precipitation and wastewater inflow from the Village of Mayo lift station. These values were measured daily along with soil moisture and changes in pond water level (ΔS). Daily evaporation (E) was calculated for the ponds using a modified form of the Priestley-Taylor (1972) model. Runoff in terms of lateral flow of water is restricted at the lagoon by berms, so seepage (R) was considered to be the vertical flow of water and was estimated as the residual of the water balance equation. Estimates of seepage (mm day^{-1}) were determined for the lagoon from 15 July to 15 August. These estimates assisted determination of why the lagoon at Mayo contains minimal wastewater.

1.2 Research objectives

The research objectives were:

1. To determine the water balance of the lagoon.
2. To quantify the amount of seepage.
3. To determine the retention time of wastewater in the lagoon.

1.3 Thesis structure

This thesis is comprised of five chapters. The water balance of central Yukon Territory along with the design and hydrology of Mayo sewage lagoon is described in the next chapter. This is followed by a description of site conditions and field methods in Chapter Three. The results of the water balance, seepage estimates and residence time

calculations for the lagoon are discussed in Chapter Four. Finally, Chapter Five presents a summary, conclusions from the study and suggestions for future research.

CHAPTER TWO

WATER BALANCE OF CENTRAL YUKON

2.1 Introduction

This chapter presents a description of the water balance for central Yukon. It examines the influence of low air temperatures and permafrost on the hydrologic cycle. The literature concerning the water balance of arctic and sub-arctic regions is reviewed. A brief description of sewage lagoon design and operation is included, along with a detailed description of the Mayo sewage lagoon. The use of a water balance approach to model seepage from the lagoon in Mayo is discussed.

2.2 The water balance of central Yukon

Water balances model the hydrology of an area and are often used to determine the value of a residual component in the hydrologic cycle. Precipitation, evaporation, runoff and storage vary widely and can be affected by several factors including latitude, topography, drainage, soil type and vegetation. As a result, the hydrologic regime in northern latitudes can vary substantially from the regime in the South. Research on the water balance in the North indicates that the hydrologic cycle is altered from that in temperate regions by lower temperatures and frozen ground (Brook, 1983; Chacho and Bredthauer, 1983; Onesti and Walti, 1983; Roulet and Woo, 1986a; Ford and Bedford, 1987).

2.2.1 Low temperatures

Low temperatures prevail for most of the year across central Yukon with a freezing season from mid-October to late April. This reduces the annual amount of precipitation and evaporation as cold air can not hold as much moisture as warm air. For this reason, inland northern climates are characteristically quite dry.

2.2.2 Permafrost

Permafrost is ground that remains at or below 0 °C for two or more consecutive years (ACGR, 1988). The seasonally frozen and thawed layer above permafrost is known as the active layer. Permafrost is a thermal condition, and its thickness increases with latitude as a result of decreasing mean annual air temperatures (MAAT) (van Everdingen, 1987; French and Slaymaker, 1993). Its distribution varies from continuous in the far north to widespread discontinuous to sporadic in the southern Yukon (Figure 2.1). The southern limit of the continuous permafrost zone approximately coincides with the -6 to -8 °C MAAT isotherm, and the southern limit of the discontinuous permafrost zone coincides with the -1 °C MAAT isotherm (Brown, 1970). Central Yukon is in the extensive discontinuous permafrost zone where 50 to 90 % of the terrain is underlain by permafrost. The areas underlain by permafrost in Mayo include undisturbed sites such as damp lowland forests and peatlands, but permafrost is generally absent beneath cleared areas and water bodies, and in gravel substrates (Burn, 1991; Williams and Burn, 1996).

2.3 Precipitation

Precipitation decreases with temperature and with distance from the coast

Figure 2.1. Map of permafrost distribution in Yukon Territory, showing the location of Mayo (after Heginbottom *et al.*, 1995).

(Rouse, 1993). Total annual precipitation ranges from 300 to 600 mm over central Yukon (Figure 2.2) (Fisheries and Environment Canada, 1978). The variation in precipitation is due to the influence of Selwyn and St. Elias mountains. The rain shadow caused by St. Elias Mountains lowers precipitation over most of central Yukon, including the Mayo area. However, these values should be viewed with caution since precipitation for northern regions is limited by a small measurement network, lack of alpine stations, and gauge-catch deficiencies which lead to underestimates of precipitation, especially snowfall, by a considerable amount (Woo *et al.*, 1983).

Precipitation in central Yukon is dominated by rainfall, which at Mayo is highest in July. In the Low Subarctic, snow remains on the ground for up to seven months of the year (Church, 1974; Rouse, 1993). Snowmelt in spring and early summer results in a substantial release of several months' stored water.

2.4 Evaporation

Evaporation is the loss of water from a surface by conversion from liquid to vapour, and includes water lost to the atmosphere from lakes, rivers, ponds and bare soil. Transpiration is the loss of water from stomata of plants. These two processes are difficult to differentiate so evapotranspiration (ET) is often used to represent the combined loss of water by evaporation and transpiration. The terms evaporation and evapotranspiration will be used interchangeably to represent the loss of water from the ponds and unsaturated infiltration cells at the lagoon as both surfaces contained living vegetation. Potential evaporation (PE) is an estimate of evaporation under conditions unrestricted by moisture availability, such as over open water.

Figure 2.2. Mean monthly precipitation and temperature measured at Mayo Airport, 1971-2000 (Environment Canada, 2002).

For evaporation to occur, energy is required to convert liquid water to vapour and a vertical humidity gradient is needed to draw vapour away from the surface. The energy required for evaporation is available from net radiation (Q^*) at the surface which for a homogeneous terrestrial site is partitioned according to:

$$Q^* = Q_E + Q_H + Q_G \quad [2.1]$$

where Q_E is the latent heat or evaporative flux, Q_H is the sensible heat flux, and Q_G is the ground heat flux. Over water, the surface energy balance is represented as:

$$Q^* = Q_E + Q_H + Q_W \quad [2.2]$$

where Q_W is the flux of heat into water.

Total annual ET decreases from the equator toward the poles (Baumgartner and Reichel, 1975), but its relative magnitude within the water balance increases because rates of precipitation decline more rapidly than evaporation (Rouse, 1990). This applies, in the North, to the summer months when increased insolation and higher temperatures make ET losses similar to those in temperate regions (Rouse, 1990). The increased solar radiation ($K_{\downarrow}$) during the summer months increases Q^* , and, hence, the energy available for evaporation. Peaks in evaporation over land surfaces often occur in late June or early July when $K_{\downarrow}$ is at a maximum. As a result of Q_W , lake evaporation often reaches a maximum in July, but in shallow ponds which warm more rapidly, the peak can occur as early as June (Ferguson *et al.*, 1970).

Available data indicate that lake evaporation may account for over 50 % of total precipitation in a large portion of the permafrost region (Prowse, 1990). The annual ET/P

ratio for the Low Arctic is 0.5, and for the snow-free period only, the ratio increases to 1.0 (Rouse, 1984; Price and Woo, 1988). According to Marsh and Bigras (1988), evaporation from lakes in the Mackenzie Delta may be greater than summer precipitation, and, in some cases, annual precipitation over a 5-year study period. In September, evaporation begins to decline and is minimal during the winter months, but moisture loss to the atmosphere may still occur from ice and snow by sublimation (Ferguson *et al.*, 1970; Prowse, 1990).

2.5 Runoff

Runoff is the lateral flow of water over or beneath a surface. It may involve the overland flow of water from rainfall and snowmelt or movement of water in the active layer once thawing begins (van Everdingen, 1987). The highest runoff yields have been observed in basins underlain by permafrost. Carey and Woo's (1999) experiments in the subarctic compared hydrological characteristics on north and south-facing slopes in central Wolf Creek, southern Y.T. They found that the north-facing slope, underlain by permafrost, experienced increased runoff and limited infiltration. The south-facing slope, free of permafrost, yielded little runoff, since water was able to infiltrate into the soil.

Runoff estimates for central Yukon range from 200 to 500 mm per year (Fisheries and Environment Canada, 1978). For the Mayo River, long-term (1945-1951) runoff estimates for July and August are 38.4 mm and 24.8 mm, respectively (Environment Canada, 1992). Runoff estimates (1949-1979) for a larger drainage basin, the Stewart River near Mayo, are 71.5 mm and 46.5 mm for July and August, respectively (Environment Canada, 1992). Hydrograph peaks for both rivers occur in June (Figure

2.3). This is expected as snow melt in the North is responsible for the annual hydrographic peaks in spring and early summer.

2.6 Water storage

Water can be stored as snow, in soil, in surface depressions, in groundwater and in lakes, ponds and streams. Storage is therefore influenced by low temperatures and the presence of frozen ground. During the winter, recharge to surface waters, soil and groundwater is inhibited by available water, an ice cover over lakes and rivers and a frozen active layer. Ice cover on surface waters in the subarctic can be up to 1 m thick. The covered surface acts as a barrier, decreasing recharge to lakes and rivers (Prowse and Beltaos, 2002).

Groundwater recharge is restricted in the winter months since liquid water is unavailable. The majority of groundwater recharge therefore takes place when water stored as snow is released during spring melt and the water table rises adjacent to streams. Rainfall during the summer months also contributes to recharge in the discontinuous permafrost zone.

2.6.1 Surface water

Surface water, in the form of muskeg, lakes and ponds, is common in permafrost regions as a result of restrictions to infiltration. Thermokarst lakes are common in northern landscapes (Burn and Smith, 1990) and form where permafrost degradation in ice-rich ground causes a depression. Once settlement occurs, water that does not infiltrate begins to collect in the depression. Beneath these lakes, unfrozen zones called

Figure 2.3. Annual hydrograph for Mayo River (63°42'7" N, 135°51'43" W), 1945-1951 and Stewart River near Mayo (63°35'26" N, 135°53'48" W), 1949-1979 (Environment Canada, 1992).

“taliks” often form because the temperature of unfrozen water ($> 0^{\circ}\text{C}$) is higher than that of the surrounding permafrost. The water body serves as a source of heat to the surrounding ground. When the ground temperature beneath the water body rises above 0°C , permafrost begins to degrade.

2.7 Hydrology of northern sewage lagoons

2.7.1 Sewage lagoons

Sewage lagoons consist of a cell or cells that are connected in series or parallel. They can be natural features such as ponds, or artificial structures. Lagoons vary in terms of the number of cells, cell configuration, degree of treatment, type of cell, and retention time, which are all specific to the needs of the community and local environment. Regardless of design, the goal of wastewater treatment is to produce effluent that avoids risk to human health and has limited impact on receiving waters (Magditch, 1985; Townshend and Knoll, 1987).

Lagoons function by diverting raw wastewater into one end where it is treated to the primary level by allowing heavier solids to settle to the bottom (Magditch, 1985). In northern environments, these first cells are often oxygen deficient and are termed anaerobic or primary cells. To provide further treatment, these cells are often followed in series by one or more larger ponds, termed infiltration or secondary cells. These cells are usually facultative and make use of both aerobic and anaerobic conditions and a longer retention period to provide secondary treatment of sewage (Smith and Finch, 1983). Sufficient digestion of the effluent prior to discharge is often achieved with retention

times in excess of one year. Following retention, the treated wastewater is discharged to the local environment.

2.7.2 Mayo sewage lagoon design

The sewage lagoon in Mayo was designed for treated wastewater to be discharged through evaporation and infiltration rather than the conventional method of total retention and annual discharge. A combination of primary (short-term) and infiltration (long-term) retention ponds are used to treat the waste. An infiltration lagoon system was the chosen method of discharge due to the availability of land west of the Mayo River and the suitability of the soils in this area to provide further treatment of the effluent (EBA, 1992a). As reported by Middlebrooks *et al.* (1982), these types of systems are feasible in locations with low-cost land and high evaporation rates. They are less common in the North where total annual evaporation can be low. The presence of permafrost also makes this type of lagoon susceptible to long-term thawing beneath the ponds which may lead to structural instability and decreased retention times.

Year-round infiltration at the lagoon in Mayo is expected despite original design specifications that freezing of the cells during winter would diminish infiltration until spring (EBA, 1992a). Bathymetry of the infiltration cells at the lagoon during summer 2003 revealed depths of up to 2.9 m for pond 1 and over 1 m for pond 2. Ice thickness over water bodies in the Mayo area rarely exceeds 1 m (Burn, 2003). Freezing to > 1 m depth is therefore not expected in any of the cells at the lagoon. The presence of water in the cells year-round implies the ground beneath the ponds is unfrozen, although verification by drilling beneath the cells at the lagoon was not possible. Therefore,

seepage will occur year-round into ground beneath the unlined infiltration cells.

2.7.2.1 Primary treatment design

The Mayo sewage lagoon consists of four cells, and covers 13.5 ha including a 2.5 ha external buffer strip (Figure 2.4). Sewage enters the two primary cells of the lagoon via a 1200 m long force main (150 mm diameter) from the Village lift station (Figure 1.1). The force main passes under the Mayo River in order to reach the lagoon. The primary treatment system consists of two anaerobic cells which are each 40 m by 40 m, have a 4:1 internal slope and hold 2000 m³ of sewage. The maximum depth of the anaerobic cells is 3.8 m, with 0.3 m of sludge storage and a freeboard of 0.5 m (EBA, 1992a). The anaerobic cells have a proposed design detention time of 2 days (EBA, 1992a). They are lined with a 600 mm clay/silt liner placed at 100% Standard Proctor Density (SPD) and all berms were constructed using compacted silty sand with a permeability of $2.2 \times 10^{-8} \text{ cm s}^{-1}$ (EBA, 1992a). The liner and less pervious soils help to minimize seepage from the primary cells and the sides of the infiltration cells. An equalizer is located along the berm between the two primary cells to ensure similar liquid levels in these cells.

2.7.2.2 Secondary treatment design

Sewage from the anaerobic cells enters the infiltration cells by two 200 mm HDPE pipes buried 1.5 m beneath the floor of the infiltration cells (Figure 2.4). The pipes terminate at a lined discharge hopper located in the center of each infiltration cell. The discharge hoppers have a maximum depth of 3 m and a 4:1 slope. Wastewater that

Figure 2.4. Diagram of Mayo sewage lagoon (after EBA 1992a, Drawing Number SL-1)

enters the discharge hopper is diverted north and west where it begins to accumulate. Infiltration cell 1 has a usable volume of 120,000 m³, and infiltration cell 2 has a volume of 140,000 m³ (EBA, 1992a). The combined dimensions of the infiltration cells are 428 m by 281 m, and each cell has a liquid level of 2.5 m, a freeboard of 0.5 m and a berm height of 3.1 m (EBA, 1992a). The bottom of the infiltration cells were not compacted during construction. The sand at the base of the infiltration cells has a permeability of $2.2 \times 10^{-5} \text{ cm s}^{-1}$ (EBA, 1992a). The design seepage rate from these cells would therefore be approximately 20 mm day⁻¹. In the following text, any reference to the infiltration ponds refers only to the continuous wetted areas, whereas reference to the infiltration cells applies only to the unsaturated areas.

2.7.3 Water balance of Mayo sewage lagoon

The most striking feature of the sewage lagoon in Mayo is that it is mostly dry. Residents of Mayo state that the lagoon has remained this way since construction. Despite the substantial inflow, the majority of the surface area of the lagoon is covered with vegetation (Figure 2.5). To understand why the lagoon in Mayo is dry, a water balance was used to estimate the amount of seepage from the lagoon.

The water balance of a sewage lagoon is similar to that of a pond or small lake. Inputs in the form of inflow and precipitation are common to both systems. Evaporation and discharge are the outputs. Storage is in the form of changes in soil moisture and water level. Since the lateral flow of water is restricted at the Mayo lagoon, seepage (R) into the soil becomes the residual component of the water balance:

$$R = P + I - E - \Delta S \quad [2.3]$$

Figure 2.5. Photograph of Mayo sewage lagoon taken July 2003.

Since seepage was not directly measurable, it was determined as the residual in the equation using estimates of precipitation (P) and inflow (I), pond evaporation (E) and change in storage (ΔS). Lateral flow was not considered in the water balance because spring melt had ended prior to the beginning of the field season and more importantly, the high berms which surround the lagoon serve to restrict surface water flow. Measurements were made daily from 15 July to 15 August, 2003. The values were converted to depth (mm) and daily, weekly, and total estimates of seepage were obtained.

CHAPTER THREE

METHODOLOGY AND SITE CHARACTERISTICS

3.1 Introduction

This chapter presents a description of the study area and methodology. The physical characteristics of the site, particularly climate, permafrost conditions, soils, elevation, drainage and vegetation are discussed. A vegetation analysis and bathymetric survey completed in July 2003 are included in the description of current lagoon conditions.

3.2 Study site

3.2.1 Location and rationale

Mayo is situated at 63°36'N, 135°53'W in central Yukon Territory. The lagoon in Mayo is 1 km west of the Village, and approximately 200 m west of Mayo River (Figure 1.1). The confluence of Mayo and Stewart rivers is about 1000 m south of the lagoon. Mayo Airport, where solar radiation data and meteorological conditions were recorded, is 3 km north of the Village (Figure 1.1).

Mayo has been the site of several environmental research initiatives over the past 20 years. Much has been reported about the climate, vegetation, geomorphology and permafrost of the area (e.g., Burn, 1992; Williams and Burn, 1996; Bartleman *et al.*, 2001). In terms of site-specific literature, several engineering reports on the location and design of the Mayo sewage lagoon are available (Geo-Engineering Ltd., 1990; EBA, 1992a). Research equipment and accommodation are available in Mayo, which eased the

logistics of the project. The Village of Mayo expressed their support for the proposed research, and provided information on the lagoon prior to and throughout the field season.

3.2.2 Climate

The Mayo region has a sub-arctic continental climate, with low winter and high summer temperatures (Wahl *et al.*, 1987). The MAAT in Mayo is -3.1°C , and daily mean average temperatures range from -25.7°C in January to 16.0°C in July (Environment Canada, 2002). The prevailing winds recorded at Mayo Airport are south in winter and east in summer, at an average speed of 5.8 km hr^{-1} (Wahl *et al.*, 1987). Mean annual precipitation at Mayo is 313 mm, with a mean annual rainfall of 205 mm (Environment Canada, 2002). Rainfall is highest in July.

3.2.3 Permafrost

Permafrost in the Mayo area is relatively warm and thin (Burn, 1992), however there are some exceptions. Mean annual temperatures measured at the base of the active layer for seven sites in permafrost near Mayo ranged from -2.8°C to -0.2°C (Burn and Smith, 1988). The thickness of permafrost is variable throughout the region, but thicknesses of up to 40 m in valleys were reported by Burn (1991). Wernecke (1932) reported thicknesses of up to 135 m in the nearby mountains between 1350 m and 1980 m a.s.l.

The occurrence of permafrost is determined by the microclimate. Factors such as vegetation, shading, and soil type contribute to its thickness by influencing the mean

annual ground temperature. In the Mayo area, permafrost is generally absent beneath cleared areas such as fields, meadows and the airport, but present beneath the damp, lowland forests. Measurement of ground temperatures in a thaw slump near Mayo has demonstrated that removal of forest vegetation may raise the ground temperature by over 3 °C and lead to permafrost degradation (Burn, 2000). Removal of vegetation allows for increased receipt of solar radiation at ground level, and without vegetation to intercept falling snow, a deeper snow pack is able to develop and insulate the ground from colder air temperatures in winter. Re-growth of the vegetative cover may encourage permafrost to re-establish (Burn, 1991). Beneath the ground surface, high ice contents are found in fine-grained silts and clays due to their smaller pores and higher water content. Well-drained frozen sands and gravels tend to be ice-poor.

The lagoon site was cleared of all vegetation during summer 1991, prior to geotechnical investigations in January 1992. The site was stripped of its active layer to begin thawing permafrost and ease construction. Half a meter of snow accumulated in the winter following clearing. Eleven boreholes were drilled around the proposed site of the lagoon during March 1990 and January 1992 (Figure 3.1), and permafrost conditions at the lagoon site were reported in the *Detailed Geotechnical Design* (EBA, 1992a). Drilling at the lagoon revealed the presence of permafrost in all boreholes except 10859-03. In 1992 this borehole was in a “swampy depression” and drilling was abandoned at 5 m. Water was found less than 0.5 m below the vegetative cover up to a depth of 1.5 m. The location of the depression during summer 2003 was approximately 30 m east of borehole 10859-03 (Figure 3.1). The depression may have receded over the 11 years from when the “swampy depression” was originally mapped. In the remaining 10

Figure 3.1. Diagram of approximate borehole locations drilled at the site of Mayo sewage lagoon in winter 1990 (10225) and winter 1992 (10859) (after EBA, 1992a). The location of the "swampy depression" and soil test pits are shown.

boreholes, ground ice below the proposed site varied from non-visible ice to visible excess ice (Table 3.1). The depth to the permafrost table during drilling in 1990 was between 0.6 and 2.0 m below the ground surface (Burn, 1991).

One of the criteria for site selection was soil that would permit infiltration and provide further treatment of lagoon effluent (Geo-Engineering Ltd., 1990). Near surface soils at the lagoon were variable and consisted of fine sands, silts and gravel (Figure 3.2) (EBA, 1992a). These were underlain by alluvial, ice-poor soils deposited by Mayo River. Below this were ice-rich silts and clays. The depth to ice-rich soil varied from 4 m beneath the base of the primary cells to > 7.5 m beneath the infiltration cells (EBA, 1992a).

A thermistor cable was installed in the northwest corner of the lagoon in January 1992, to monitor ground temperature conditions at the lagoon. Ground temperatures for 1993, 1994, 1995 and 1998 were available (Figure 3.3). Ground temperature fluctuations between 0 and 0.5 m depth occurred between 1993 and 1998, as expected given the seasonality in readings. Below 2 m depth, ground temperatures remained ≤ 0 °C from 1993 to 1995. In June 1998, ground temperatures below 2 m increased by at least 0.5 °C, raising the temperature to 0.8 °C between 3 and 4 m depth. There was no change below 5 m; temperatures remained around -0.5 °C.

Maintenance records available for the lagoon indicate several structural and functional problems as a result of permafrost degradation. In 1995, three years after construction, the primary cells had settled by 40 to 50 cm, and the infiltration cells had settled by up to 40 cm as a result of permafrost thaw (EBA, 1995a). Thawing of ice-rich ground beneath the route of the outflow pipe in infiltration cell 1 had also occurred,

Table 3.1. Ground ice conditions at the lagoon during geotechnical investigations in winter 1990 and 1992. Ground ice conditions at the lagoon are included in the *Detailed Geotechnical Design* (EBA, 1992a) and are defined by Linell and Kaplar (1966) as: Nbe (contains excess ice, microscopic), Nbn (without excess ice), Vc (visible ice, ice coatings on particles), Vs (visible ice, stratified or distinctly oriented ice formations), and Vr (visible ice, random or irregularly oriented ice formations).

Borehole Drill date	Completion Depth (m), elevation	Ground Ice Description	Depth (m)	Borehole Drill date	Completion Depth (m), elevation	Ground Ice Description	Depth (m)
10859-01 92/01/29	6.0 492.7	Nbe	0.1-1.5	10859-07 92/01/31	9.0 493.5	Seasonally frozen	0.5-2
		Nbe, Vr<5%	0.5-2			Unfrozen	2-4
		Nbe	2-3			Nbn, Vc <5%	4-5.5
		Nbe, Vc<5%	3-6			Nbe, Vc	5.5-7
						Vs 30%	7-9
10859-02 92/01/29	6.2 490.7	Seasonal frost	1-3	10859-08 92/01/31	10.5 489.2	Nbe	0.2-1.5
		Unfrozen	3-4.5			Nbe, Vc	1.5-4
		Vc <5%	4.5-6			Nbe, Vc, Vs 5-10%	4-6
		Vc <5%, Nbe	6-6.2			Vc, Vs 5-10%	6-8.5
						Vs 30%, Nbe	8.5-10
10859-03 92/01/30	5.0 489.0	Seasonally frozen	0-3	10225-03 90/03/02	7.5 493.0	Vs 20%, Nbe	10 ⁺
		Unfrozen	3-5			Seasonal frost	0-1
						Nbn	1-3
						Nbe	3-4
						Nbe, Vc trace	4-7.5

Table 3.1. Continued

Borehole Drill date	Completion Depth (m), elevation	Ground Ice Description	Depth (m)	Borehole Drill date	Completion Depth (m), elevation	Ground Ice Description	Depth (m)
10859-04 92/01/30	6.2 492.2	Seasonal frost Nbn, Vc trace	0.2-3 3-6.2	10225-04 90/03/02	3.2 494.5	Seasonal frost Nbn	0-2.5 2.5-3.2
10859-05 92/01/30	17.5 488.5	Seasonal frost Unfrozen Vr < 5% Unfrozen	0.2-1 1-16 16-17 17+	10225-05 90/03/02	4.5 494.0	Nbn Nbe	0-3 3-4.5
10859-06 92/01/30	14.0 491.6	Seasonal frost Nbe Unfrozen Vr-trace	0-0.5 0.5-1 1.2-8.5 8.5-14				

Figure 3.2. Cross-section of soil columns from boreholes 10859-07 and 10225-04 (after EBA, 1992a, Figure 1).

Figure 3.3. Ground temperature (°C) profile at Mayo sewage lagoon (after EBA, 1992a). Readings from a thermistor cable installed in the northwest corner of infiltration cell 2 on 31 January, 1992.

causing the pipe to sink (Figure 2.4) (EBA, 1995a). In October 1995, remediation was completed to return the lagoon to its original condition (EBA, 1995b).

In June 1998, a site inspection was completed to investigate the development of an open channel ("sinkhole") which had formed as a result of thawing of ice-rich ground in the southwest corner of primary cell 2. Several ice wedges were reported during construction of the berms in 1992, however no reported measures were taken to remove the ice wedges and replace them with impervious fill to prevent future thawing. At the time of the visit, the primary cells were reported to be full and discharging to the secondary cells which each contained a small pool of effluent surrounding the inlet hoppers (EBA, 1998). The soil liner in both primary cells was reported to be settling and causing tension cracks around the tops of the cells (EBA, 1998). Settlement of these cells was still evident during summer 2003 field investigations. The 1998 site visit reported the infiltration cells to be in good condition as a result of repair work completed in 1995. This was not the case in summer 2003. Signs of settlement and cracking in several areas along the floor of both infiltration cells were evident. A fox den in infiltration cell 2 had caused a 0.25 m² hole in the floor of the cell and extensive vegetation growth, including shrubs and immature trees, has created cracks beneath the floor of the cells.

Six soil pits were excavated to a maximum depth of 1.4 m on each side of the lagoon in August 2003 to investigate current permafrost conditions (Figure 3.1). Visible ice was encountered in only one pit, on the northeast side of the lagoon. Clay was the dominant soil type in this pit; the other pits contained mostly silt and sand. At 80 cm depth the clay was saturated and ice lenses were clearly visible. No visible ice or permafrost was encountered in the remaining 5 soil pits, including a second soil pit on the

northwest side of the lagoon excavated to 1 m depth. In summer 2003, permafrost was not found to be present within 1 m of the surface in the majority of test pits excavated around the cleared perimeter of the lagoon.

During field investigations around the proposed site of the lagoon in 1990, the depth to the permafrost table was < 2 m. Ground temperatures taken in June 1998 from the northwest corner of the lagoon indicated permafrost was degrading between 3 and 4 m depth. Thaw is expected beneath the ponds given the presence of water in them throughout the year. Melting permafrost has caused the lagoon to become structurally unstable, particularly around the primary and infiltration ponds as evident from settlement of the primary and infiltration cells, development of a “sinkhole”, and sinking of an outflow pipe.

3.2.4 Elevation and topography

Mayo is at an elevation of 495 m a.s.l. The lagoon was constructed on a flat to gently sloping area of land. North of the lagoon is a large outwash terrace with its surface at approximately 530 m a.s.l. Stewart River is south of the lagoon at an elevation of 480 m a.s.l. Flooding of the lagoon site during spring melt was of concern prior to site selection. The top of the berm at 493.9 m, is approximately 1.4 m above the 100-year flood level for Stewart River (EBA, 1992a).

3.2.5 Groundwater and drainage

Groundwater flows occur between topographically high recharge areas and lower discharge zones such as river valleys and other terrain depressions. Drainage at the

lagoon is towards Stewart and Mayo rivers.

3.2.5.1 Groundwater monitoring wells

Two monitoring wells were installed during construction of the sewage lagoon. Monitoring well 1 is located approximately 80 m south of primary cell 1 (Figure 2.4). The well was drilled to 8 m, and the approximate depth of the water table was 485 m a.s.l., 2.1 m below the ground surface, and approximately 6 m beneath the base of the infiltration cells (EBA, 1992b). This well usually remains frozen until early July (personal communication, J. M. Ewing, June 2003). Monitoring well 2 is located about 150 m south of the southwest corner of infiltration cell 2 in the surrounding spruce forest. The well was drilled to a depth of 10 m. No reports on the location of the water table could be found. This well apparently remains frozen year round.

3.2.6 Vegetation

The Mayo area lies in the northern boreal forest. Black and white spruce (*Picea mariana* and *P. glauca*), paper birch (*Betula papyrifera*), poplar (*Populus balsamifera*) and alder (*Alnus crispa*) are common in central Yukon (Burn, 1985).

The lagoon site was covered by spruce (*Picea sp.*), poplar (*Populus sp.*) and some willows (*Salix sp.*) prior to clearing. To facilitate construction in permafrost, the lagoon site was cleared of all surface vegetation prior to construction of the berms. All of the vegetation around the site was removed with the exception of the ground cover at the “swampy depression” in the southwest corner of the site (Figure 3.1) (EBA, 1992a). The outside of the berms were later re-vegetated with a combination of grass and wild

flowers. Horses graze along the exterior side slopes of the berms, keeping the grass trimmed and preventing other vegetation from emerging. Vegetation within the lagoon perimeter has been cleared on at least 5 occasions; the last clearing was during summer 2001.

In mid-July 2003, a vegetation survey of the lagoon was completed using a 2 m x 2 m grid. Twenty-two grid locations were sampled in the unsaturated infiltration cells and vegetation type and habitat were recorded using Johnson *et al.* (1995). Following grid sampling, the infiltration cells were inspected to identify any additional species not represented during grid sampling. Vegetation in and around the ponds was also recorded for the primary and infiltration cells. The survey revealed the majority of the lagoon was covered with vegetation characteristic of disturbed or waste ground (Table 3.2). This included flixweed (*Descurainia sophia*), fireweed (*Epilobium angustifolium*), common dandelion (*Taraxacum officinale*), lamb's quarters (*Chenopodium album*), strawberry blite (*Chenopodium capitatum*), and common plantain (*Plantago major*). Other vegetation found in the unsaturated portions of the infiltration cells such as wild strawberry (*Fragaria virginiana*) is common to dry ground and well-drained soil. Riparian vegetation surrounded the perimeter of the infiltration ponds and primary cells. Vegetation native to moist environments such as foxtail barley (*Hordeum jubatum*), willow (*Salix sp.*) and rough cinquefoil (*Potentilla norvegica*) was also found in the unsaturated areas of infiltration cell 1 and infiltration cell 2, away from the ponds. The "swampy depression" in infiltration cell 2 contained several types of vegetation unique to the lagoon including cotton-grass (*Eriophorum sp.*), currant (*Ribes sp.*) and several types of moss which were not identified but were restricted to this portion of the lagoon.

Table 3.2. Species representation at Mayo sewage lagoon during July 2003. Vegetation is represented as being characteristic of disturbed or cleared (C), dry (D), moist (M), marsh or pond (P) or waste ground (W).

Species	Infiltration Cell		Swamp	Infiltration Pond		Primary Cell	
	1	2		1	2	1	2
Brassicaceae (Mustard)							
<i>Barbarea orthoceras</i> American winter cress	M		M				
<i>Descurainia sophia</i> Flixweed	W	W			W		
<i>Rorippa islandica</i> Marsh yellow cress	M						
<i>Capsella bursa-pastoris</i> Sheppard's-purse		W					
<i>Thlaspi arvense</i> Stinkweed		W					
Rosaceae (Rose)							
<i>Fragaria virginiana</i> Smooth wild strawberry	D	D					
<i>Potentilla norvegica</i> Rough cinquefoil	M	M	M			M	M
Fabaceae (Pea)							
<i>Epilobium angustifolium</i> Fireweed	W	W				W	W
<i>Epilobium ciliatum</i> Northern willowherb				M			
Asteraceae (Aster)							
<i>Taraxacum officinale</i> Common dandelion	W	W					W
<i>Hieracium umbellatum</i> Narrow-leaved hawkweed	C	C			C		
<i>Matricaria matricarioides</i> Pineappleweed	C	C		C		C	
<i>Achillea millefolium</i> Common yarrow		C					
<i>Erigeron acris</i> Northern daisy fleabane	M						M
<i>Erigeron glabellus</i> Smooth fleabane	M						
<i>Bidens cernua</i> Nodding beggarticks				P			
<i>Chenopodium album</i> Lamb's-quarters	W	W			W		
<i>Chenopodium capitatum</i> Stawberry Blite	W						
Poaceae (Grass)							
<i>Poa sp.</i> Bluegrass	M	M	M				

Table 3.1. continued

Species	Infiltration Cell		Swamp	Infiltration Pond		Primary Cell	
	1	2		1	2	1	2
<i>Hordeum jubatum</i> Foxtail barley	W/M	W/M			W/M	W/M	W/M
<i>Beckmannia syzigachne</i> Slough grass	M	M					
<i>Elymus innovatus</i> Hairy wild rye	C	C					
Equisetum							
<i>Equisetum</i> sp. Horsetail	M	M				M	
Shrubs							
<i>Rosa acicularis</i> Prickly rose		C					
<i>Rubus idaeus</i> Wild red raspberry	C	C					
<i>Salix</i> sp. Willow	M	M	M	M	M	M	M
<i>Betula pumila</i> var. <i>glandulifera</i> Dwarf birch	M	M					
<i>Ribes</i> sp. Current			M				
<i>Betula occidentalis</i> Water birch					M		
Trees							
<i>Populus</i> sp. Poplar	M	M		M			
<i>Picea</i> sp. Spruce	M	M					M
Polygonaceae (Buckwheat)							
<i>Rumex</i> sp. Dock	M						
<i>Polygonum lapathifolium</i> Dockleaf smartweed	M						
<i>Solidago simplex</i> Rand's goldenrod				M	M		
Caryophyllaceae (Pink)							
<i>Stellaria longipes</i> Long-stalked chickweed	M	M				M	
Aquatics							
<i>Polgonum amphibium</i> Water smartweed				P			
<i>Lemna minor</i> Common duckweed				P	P		
<i>Hippuris vulgaris</i> Common mare's-tail						P	P

Table 3.1. continued

Species	Infiltration Cell		Swamp	Infiltration Pond		Primary Cell	
	1	2		1	2	1	2
Cyperaceae (Sedge)							
<i>Eriophorum</i> sp. Cotton-grass			D				
<i>Carex utriculata</i> Beaked sedge.				P			
<i>Carex media</i> Norway sedge	W						
Bryophytes (Moss)			D/M				
<i>Trifolium hybridum</i> Asike clover	W	W					
Other							
<i>Plantago major</i> Common plantain	W	W					

3.2.7 Pond configuration

Knowledge of the volume and surface area of each pond was needed to calculate the water balance of the lagoon. Changes to the primary cells have occurred since construction and include slumping around the perimeter and settling of the cells (Section 3.2.3). Slumping around the primary ponds has caused the surface area of primary cell 1 and primary cell 2 to decrease to 1330 m² and 1260 m², respectively. A design volume of 2000 m³ was used for these cells because the maximum depth for each primary cell during sampling in 2003 was greater than original design specifications (Section 2.7.2.1). The maximum depths measured in primary cell 1 and primary cell 2 were 4.6 m and 4.0 m, respectively.

The lagoon was surveyed by theodolite and GPS in July 2003 to determine the surface area of the infiltration ponds. Infiltration pond 1 was elongated in the north-south direction and had a surface area of 6912 m² (Figure 3.4). The bathymetry of the ponds was also determined to obtain their maximum depth and volume. Rope marked every 5 m was run in an east-west direction across each pond. At each point, the depth was measured using a staff gauge and the location was recorded by GPS for future mapping in Surfer 7.0 and ArcView 3.2. In total, seven transects were repeated in the east-west direction for infiltration cell 1 and four transects in the east-west direction for infiltration cell 2. The same procedure was repeated in the north-south direction, giving a total of eleven transects for infiltration cell 1 and seven transects for infiltration cell 2.

The calculated volume of infiltration pond 1 was 2013 m³. The maximum depth was 2.9 m and its approximate location was in the center of the discharge hopper. This depth measurement was close to the maximum original design depth of 3.0 m for this

Figure 3.4. Bathymetry of infiltration pond 1 showing depth contours of 20 cm. The location of the vegetation buffer around the pond is shown along with the approximate location of the discharge hopper.

location. The remaining parts of the pond to the north and west were shallower. The rest of the pond was < 1.0 m with much of the pond near the perimeter less than 20 cm deep.

Infiltration pond 2 was roughly circular in shape and had a surface area of 7777 m^2 and a volume of 2902 m^3 (Figure 3.5). The discharge hopper for this pond was not at the point of maximum depth (1.1 m). The maximum depth in this pond should have coincided with the center of the discharge hopper, but the maximum depth may have been missed during sampling, given depths were taken every 5 m and the area of the center of the discharge hopper in the infiltration cells is approximately 6 m^2 . This may have a minor impact on the calculated volume of the pond. The volume of the ponds measured during July 2003 are vastly different from the original design specifications for infiltration cells 1 and 2 presented in Section 2.7.2.2, respectively $120\,000 \text{ m}^3$ and $140\,000 \text{ m}^3$.

3.3 Methodology

Daily measurements of rainfall, evaporation, soil moisture, change in pond water level and inflow were made from June to mid-August 2003 (Figure 3.6). However, instrument failure and other problems allowed the water balance for the lagoon to be calculated only for the continuous period, 15 July to 15 August.

3.3.1 Inflow

Wastewater inflow is measured daily at the Village of Mayo lift station ($\text{m}^3 \text{ day}^{-1}$). To determine the amount of inflow in mm day^{-1} , the measured values were divided by the surface area of the primary cells and infiltration ponds since inflow is

Figure 3.5. Bathymetry of infiltration pond 2 showing depth contours of 10 cm. The location of the vegetation buffer around the pond, which included the “swampy depression”, is shown along with the approximate location of the discharge hopper.

Figure 3.6. Location of instruments used to determine the water balance of Mayo sewage lagoon. Measurements of precipitation, evaporation from lysimeters and soil moisture were taken along the four transects. The location of the weather station tower, staff gauges and evaporation pan equipment are shown.

confined to these areas. The two primary cells were treated as a single cell because an equalizer between the cells maintains a similar water level in both cells. Inflow as measured at the lift station was used to represent daily inflow (m^3) to these cells. The calculated discharge from the primary cells represented the inflow component in the water balance for each of the infiltration ponds. The total discharge (m^3) from the primary cells was divided by the wetted surface area (m^2) of each infiltration pond to determine the inflow (mm).

3.3.1.1 Blockage experiment

A blockage experiment on the primary cells at the lagoon was performed on 13 August to determine the extent of wastewater lost between the lift station and the lagoon. Inflow to primary cell 1 was blocked by an inflatable plug placed in the force main and all inflow was diverted to primary cell 2. The outflow pipe for primary cell 2 was blocked so the only wastewater discharge was from primary cell 1. To eliminate movement of wastewater between the two cells the equalizer manhole was also blocked. A staff gauge in each primary cell was read every 3 minutes to ± 1 mm to determine the change in water level over a 73 minute period. Inflow ($\text{m}^3 \text{s}^{-1}$), measured electronically at the Village of Mayo lift station, was also recorded every 3 minutes. Over the 73 minute period, ΔS for primary cell 2 was 18 mm, and inflow was 20 m^3 . An inflow of 20 m^3 as measured at the lift station would have caused an increase in pond water level for primary cell 2 (surface area = 1260 m^2) of 16 mm, which is 2 mm lower than the value of ΔS measured for primary cell 2. This indicated that there were no losses in transmission along the force main, but there were errors involved in the experiment that arose from

either error in measurement, which at maximum was 6 %, slippage of the staff gauge and/or the periodic shut down of the pumps at the lift station. The staff gauges were firmly secured in the gravel perimeter of the primary cells, but may have shifted. During the experiment the pumps at the lift station were shut off every 6 minutes to prevent high water levels from sounding the alarm. This may have caused a delay in the timing of wastewater leaving the lift station.

3.3.2 Precipitation

The location of the rain gauges and lysimeters are shown in Figure 3.6. Four transects were set-up in an east-west direction across the infiltration cells. Precipitation was measured at every other station and evaporation was measured at every station along each transect (Figure 3.7).

Rainfall was collected in rain gauges and measured daily using a 50 ml graduated cylinder. For rainfall events of only a few millimeters, a 10 ml graduated cylinder was used. In total there were ten rain gauges, five in each infiltration cell. Each rain gauge was kept upright and stable by recessing it 10 cm below ground level. The gauges were 20 cm in height and had a diameter of 10.6 cm. The collecting surface was downward sloping and narrowed to a diameter of 3 cm. This helped to minimize evaporation. The cross-sectional area of each gauge was 91.6 cm^2 . Rainfall measured at the lagoon was compared to data obtained at Mayo Airport.

3.3.3 Groundwater level

A water level sensor was lowered down monitoring well 1 to determine the

Figure 3.7. Photograph of a rain gauge (a) and lysimeter (b) along a transect.

depth to the groundwater table. This was performed daily and depth to the water table (cm) was obtained.

3.3.4 Evaporation

Evaporation estimates incorporated into the water balance for the lagoon were made using a modified form of the Priestley-Taylor (1972) model. This method was used to represent evaporation from the primary cells and infiltration ponds. Estimates obtained using this method were compared to data from an evaporation pan, which measured evaporation directly on days when no precipitation was recorded. To obtain an estimate of evaporation from the unsaturated areas of the lagoon, the energy balance approach was used and values were compared to estimates obtained using lysimeters. Generalized estimates of potential evaporation were obtained using Thornthwaite's (1948) method.

3.3.4.1 Thornthwaite's equation

Potential evaporation (PE) (mm month^{-1}) estimates were calculated using (Thornthwaite, 1948):

$$PE = 16 \left(\frac{10T}{I_H} \right)^a \quad [3.1]$$

where,
$$a = (0.675I_H^3 - 77.1I_H^2 + 17,920I_H + 492,390) \times 10^{-6} \quad [3.2]$$

and,
$$I = \sum (T \div 5)^{1.514} \quad [3.3]$$

I_H is the heat index and T is mean monthly temperature above 0 °C. For months with mean temperatures below 0 °C, PE is considered zero (Sellers, 1965). Estimates of evaporation were made using 2003 temperature data from Mayo Airport to determine annual evaporation.

3.3.4.2 Lysimeters

Lysimeters were also used to estimate evaporation. Estimates were obtained by measuring the change in weight of a known volume of soil on a daily basis. Soil cores were taken along each transect and placed in aluminum cans, with some damage to the vegetative cover. The cans were filled with soil and placed such that the top of the can was level with the surrounding ground. A total of 22 lysimeters were placed around the lagoon, 11 in each infiltration cell. The lysimeters were weighed to ± 1 g at approximately the same time each day. The change in weight from the previous day, divided by the surface area of the lysimeter (86.5 cm²), less the previous day's precipitation, provided an estimate of ET (mm day⁻¹).

3.3.4.3 Energy balance approach

A weather station was erected in infiltration cell 1, approximately 40 m east of the pond in the cell (Figure 3.6). The station consisted of a 3-m high steel tripod placed on a wood platform approximately 30 cm off the ground (Figure 3.8). A Campbell Scientific CR10x data logger was used to record incoming solar radiation, net radiation, and the ground heat flux. Solar radiation (Wm⁻²) was recorded using a silicon pyranometer (model SP Lite, Campbell Scientific, Edmonton, Alberta). The pyranometer

Figure 3.8. Photograph of the weather station tower.

was secured to a metal platform, 1 m above the ground surface. There was no shade in the lagoon. A net radiometer (model NR Lite, Campbell Scientific, Edmonton, Alberta) was used to record net radiation (Wm^{-2}). The radiometer was secured on a metal pole 1 m above the ground surface and was positioned south of the other apparatus to minimize the effects of shading from the weather tower. Ground heat flux (Wm^{-2}) measurements were made using CSD Middleton CN3 Heat Flux Plates buried 5 cm and 10 cm beneath the ground surface. The logger was secured to the platform and stored in a tightly closed plastic box. A 12 V battery supplied power to the logger. Measurements were taken every 30 s and written to the logger as 30 minute averages. Data were downloaded every few days. Temperature and humidity gradients were established by measuring air temperature (T_a) and relative humidity (RH) at two defined heights. HOBO RH/Temp data loggers (model H08-003-02, Onset Computer Corporation, Bourne, Ma.) were placed in Net Radiation Shields secured to the weather station tower 1.25 m and 0.25 m above the ground surface. T_a ($^{\circ}\text{C}$) and RH (%) were recorded by the loggers every 30 s. These data loggers do not process measurements, so Microsoft Excel was used to determine averages for each 30 minute interval. Due to the frequency of the measurements, data were downloaded daily.

3.3.4.3.1 Energy balance calculations

The Bowen ratio energy balance method requires determination of Q^* at a site and allocation of this energy to each of the various components in the energy balance equation [equation 2.1]. In this study, the weather station was placed over unsaturated ground and measurements of net radiation, rate of heat flow through the soil, and vertical

temperature and vapour pressure profiles were made from 15 July to 15 August. These estimates were not incorporated into the water balance but were used to gain an understanding of the amount of evaporation from the unsaturated infiltration cells and to determine why these cells are largely dry.

The Bowen ratio (β) is the ratio of sensible to latent heat flux and is calculated using differences in temperature (ΔT) and vapour pressure (Δe) at two heights (Bowen, 1926):

$$\beta = \frac{Q_H}{Q_E} = \gamma \frac{\Delta T}{\Delta e} = \gamma \left(\frac{T_2 - T_1}{e_2 - e_1} \right) \quad [3.4]$$

where γ is the psychrometric constant ($0.066 \text{ kP}^\circ\text{C}^{-1}$). If $\beta > 1$, then the sensible heat flux exceeds the latent heat flux. In general, wet surfaces have a lower β than dry surfaces. The vapour pressure gradient may be calculated from measurements of temperature. The saturation vapour pressure is calculated using (Burman and Pochop, 1994):

$$e_{sa} = 0.611 \times \exp \left(\frac{17.27T_a}{T_a + 237.3} \right) \quad [3.5]$$

Saturation vapour pressure values (e_{sa}) may also be obtained from Table 94 of the Smithsonian Meteorological Tables (Smithsonian Institute, 1971). Actual vapour pressure (e_a) may then be calculated using the relative humidity (RH):

$$e_a = RH \times e_{sa} \quad [3.6]$$

By substituting equation [3.4] into equation [2.1], Q_E is determined using:

$$Q_E = \frac{Q^* - Q_G}{\beta + 1} \quad [3.7]$$

Q_H is therefore solved as the residual of the energy balance equation [2.1] or by:

$$Q_H = \beta \times Q_E \quad [3.8]$$

Once the values of Q_H and Q_E have been calculated, the energy balance may be portioned into the ratios Q_E/Q^* , Q_H/Q^* and Q_G/Q^* . Evaporation (E) may be estimated using Q_E and the latent heat of vapourization (L_v) ($2.45 \times 10^6 \text{ Jkg}^{-1}$ at 20°C):

$$E = \frac{Q_E}{L_v} \quad [3.9]$$

Evaporation was calculated for each 30 minute interval and these values were summed each day to give an estimate in mm day^{-1} .

3.3.4.3.2 Priestley-Taylor α

Estimates of evaporation were made using the Priestley-Taylor (1972) model. To estimate Q_E , the model requires measurements of mean T_a to determine S , the slope of the saturation vapour pressure curve, and measurements of Q^* and Q_G (Louie, 1979). An evaporability parameter, α , is included in the calculation of Q_E (Priestley and Taylor, 1972):

$$Q_E = \alpha \left(\frac{S}{S + \gamma} \right) (Q^* - Q_G) \quad [3.10]$$

where,

$$\alpha = \left(\frac{S + \gamma}{S(1 + \beta)} \right) \quad [3.11]$$

and S ($\text{kPa}^\circ\text{C}^{-1}$) is calculated using (Burman and Pochop, 1994):

$$S = \left(\frac{409.8 \times e_{sa}}{T_a + 237.3} \right) \quad [3.12]$$

Equation [3.5] is used to calculate e_{sa} . Rouse and Stewart (1972) found that S may also be approximated from the relationship:

$$\frac{S}{S + \gamma} = 0.434 + 0.012T_a \quad [3.13]$$

for a temperature range of 6.6 to 27.7 °C. Similarly to β , α depends on microclimatic conditions and has been shown to vary widely (Eaton, 1999). Typically, wet surfaces have a higher α than dry surfaces. Dry lichen heath surfaces in the high arctic have been found to have an average α of 0.95 (Rouse and Stewart, 1972), whereas α of 1.26 was found for a variety of saturated surfaces (Priestley and Taylor, 1972).

3.3.4.4 Pond evaporation

The surface energy balance over saturated areas at the lagoon was determined using equation [2.2]. The heat storage component (Q_w) was not incorporated into the equation as the ponds at the lagoon were relatively shallow which greatly reduced overall heat storage (Ferguson *et al.*, 1970). Q_w has also been found to be relatively small compared to Q^* (Woo, 1976) and despite daily fluctuations, Q_w tends to zero over a number of days (Louie, 1979). No water temperatures (T_w) were measured in the ponds

close to the surface, but a HOBO data logger in a sealed watertight case was placed at the bottom of primary cell 1 where T_w was measured every 4 hours. Between 15 July and 27 July, T_w remained constant at 8.6 °C. On 28 July, the average daily T_w increased to 9.3 °C. The minimal change in T_w over the 13 day period indicated that heat storage increase at the bottom of the pond was not great. Although water near to the surface would have been influenced by changes in solar radiation, over the period of study, large changes in T_w for the ponds were not expected. Temperature measurements for a small thermokarst lake near Mayo showed that T_w at 1.5 m and 2.5 m depth remained close to 20 °C between late-June and early-August (Burn, 2003). Omission of Q_w therefore caused equation [3.10] to become:

$$Q_E \approx \alpha \left(\frac{S}{S + \gamma} \right) Q^* \quad [3.14]$$

T_a and K_d are relatively constant within a radius of a few kilometers (Stewart and Rouse 1976) so measurements made over the unsaturated ground of infiltration cell 1 were used in equation [3.14]. An α of 1.26 was considered representative of evaporation from the ponds at the lagoon.

A RH/Temp Hobo data logger in a Stevenson screen was used to record T_a every hour over infiltration pond 2. These measurements were not used in equation [3.14] as the frequency of measurements was much less than measurements of Q^* and RH made every 30 s. Instead, T_a measured over the unsaturated ground of infiltration cell 1 was used in equation [3.14]. A comparison of daily average T_a over the two surfaces revealed a maximum daily difference of 3 °C, with an overall mean difference of 1 °C. The

measured 1 °C increase in temperature over the pond is not expected and may be partly due to differences in sensor housing since the data loggers were stored in different types of shields. Restrictions to ventilation and differential heating of the shields may have altered the measurements. Negligible changes to Q_E as a result of temperature differences are expected, as a change in temperature of 1 °C alters the ratio $S \div (S + \gamma)$ by only 0.012 (Stewart and Rouse, 1976).

Stewart and Rouse (1976) and Louie (1979) used the same T_a and $K_{\downarrow}$ for different terrain types over a limited distance, however, Q^* measurements were corrected to represent differences in surface terrain. Q^* in this study was measured over the unsaturated ground of infiltration cell 1 and was also used to represent Q^* from the ponds since direct measurements were not taken. Differences in Q^* amongst surface terrain largely depend on albedo. Surfaces with a low albedo absorb well, and this increases Q^* (Oke, 1987). Over water the reflectance ranges from 0.03 to 0.1 (small zenith angle), whereas over light, dry soil, the albedo is closer to 0.4 (Oke, 1987). The value of Q^* over the ponds was not corrected and therefore may have lead to an underestimation of evaporation from the ponds.

3.3.4.5 Evaporation pan

Evaporation pans are used to simulate evaporative losses from ponds or small lakes and are a common means of obtaining evaporation estimates (Ferguson *et al.*, 1970). A class “A” evaporation pan was placed in the pond of the west infiltration cell to measure water loss under saturated conditions (Figure 3.9). Evaporation was measured daily by changes in water level observed using a fixed point gauge centered in the pan.

Figure 3.9. Evaporation pan equipment in infiltration pond 2 showing the location of the evaporation pan (a), staff gauge (b), anemometer (c) and Stevenson screen (d), where T_a and RH were recorded. Photograph was taken in mid-July, 2003.

Water was added or removed from the pan using a calibrated cylinder with millimeter gradations. Evaporation (E) from the pan (mm day^{-1}) was obtained from:

$$E = \Delta S - P \quad [3.15]$$

A correction factor of 0.7 for heat transfer through the sides and bottom of the pan was applied to the measurements of evaporation made using the pan (Ferguson *et al.*, 1970; Louie, 1979).

3.3.5 Soil moisture

A *ThetaProbe* soil moisture sensor was used during June and early July to gain an estimate of the moisture content of the soil at the lagoon. Daily readings were taken along the transects (Figure 3.6). The probe began to malfunction in July but previous readings were erroneous on several days so all values were omitted from analysis. Weekly soil samples were also taken along the transects to determine the moisture content of the soil. The top few centimeters of soil were removed using soil tins of a known volume. Due to the stony nature of the soil in some areas around the lagoon, the volume of these samples could not be preserved, thus the samples were analyzed on a gravimetric basis only. In August, the frequency of the measurements was increased and samples were collected every few days. Soil moisture data were not incorporated into the ΔS component of the water balance equation and were used only to demonstrate dry conditions at the lagoon.

3.3.6 Pond water level

Loss of water from the infiltration ponds and primary cells was measured using

staff gauges (Figure 3.6). The water level (mm) was read at approximately the same time each day to ± 1 mm. The change in water level for each staff gauge was used to obtain a daily average change in water level for each pond. Four staff gauges were placed in each infiltration pond. A staff gauge was also placed in each primary cell.

3.3.7 Summary

Daily measurements of inflow, precipitation, soil moisture, change in storage and estimates of evaporation were made over a 32-day study period to determine the water balance of Mayo sewage lagoon. A vegetation and bathymetric survey of the lagoon was completed to demonstrate current lagoon conditions. A blockage experiment of the primary cells showed that all inflow measured at the Village of Mayo lift station reaches the lagoon and there are no losses in transmission along the force main.

CHAPTER FOUR

WATER BALANCE AND SEEPAGE ESTIMATES

4.1 Introduction

This chapter presents the water balance of the Mayo sewage lagoon specifically for 15 July to 15 August, 2003. References to the months of July or August refer only to the periods 15-31 July and 1-15 August. The water balance was assessed to determine the rate of seepage from the sewage lagoon during this period. The values obtained from measurements of inflow, precipitation and change in pond water level are discussed, and estimates of evaporation made using the modified Priestley-Taylor (1972) model, energy balance approach, lysimeters and an evaporation pan are included. Weekly seepage estimates for the infiltration ponds are presented. Error estimates for the various components of the water balance are included along with a comparison of measured solar and net radiation, precipitation and temperature data at Mayo Airport and the lagoon. The water balance of the lagoon is extended to an annual period using inflow and precipitation measurements and estimates of potential evaporation.

4.2 Inflow

Wastewater inflow to the lagoon decreased over the summer, from a high in early-June to a low in mid-August. During the study period, inflow averaged $418 \text{ m}^3 \text{ day}^{-1}$, ranging from $340 \text{ m}^3 \text{ day}^{-1}$ to $510 \text{ m}^3 \text{ day}^{-1}$ (Figure 4.1). Average daily inflow and standard deviation for July and August was $424 \text{ m}^3 \pm 29 \text{ m}^3$ and $412 \text{ m}^3 \pm 41 \text{ m}^3$, respectively. Total inflow was 7210 m^3 for July and 6180 m^3 for August.

Figure 4.1. Total daily inflow of wastewater to the lagoon measured at the Village of Mayo lift station.

The lagoon covers 135,000 m² with the infiltration cells occupying almost 90 % of this area. A survey of the infiltration ponds by theodolite and GPS revealed that less than 15 % of the lagoon is covered by wastewater. The wastewater is confined to the two anaerobic cells and two small ponds in the larger infiltration cells. Based on the 2003 survey, the total surface area of the four ponds is 17,279 m². An estimated 4900 m² of freely evaporating vegetation surrounds the infiltration ponds. Since wastewater is confined to these wetted areas, daily inflow, as measured at the lift station, was divided by the surface area of the primary cells to determine the water balance for these cells, which were treated as a single unit (Section 3.3.1). The discharge (m³) from the primary cells, calculated by water balance, was used to represent the inflow component of the water balance for the infiltration ponds.

Wastewater inflow is recorded by a digital meter at the Village of Mayo lift station. A blockage experiment at the lagoon showed no loss in transmission of wastewater along the force main (Section 3.3.1.1). Sources of error for the inflow estimates are minimal and include the addition of wastewater by truck delivery from one local business and residential septic tanks. Deposits are made weekly and consist mostly of grey-water. Waste collected from septic tanks along the Dempster Highway is also discharged once a year into the Mayo sewage lagoon. Over the study period, wastewater from trucked sources accounted for an additional 65.5 m³, or less than 1 % of inflow. This resulted in an adjustment of total inflow to 13,456 m³.

4.3 Precipitation

Precipitation was measured at the lagoon using 11 rain gauges and was reported

over a 24 hour period (10 am to 10 am). Precipitation at the lagoon during July and August was $17.4 \text{ mm} \pm 1.6 \text{ mm}$ and $10.7 \text{ mm} \pm 2.6 \text{ mm}$, respectively (Figure 4.2). Thirty percent of the total precipitation for July fell on 15 July, with four smaller rainfall events of $< 3.5 \text{ mm}$ on 26 July and 29-31 July accounting for the remaining 65 %. Ninety-three percent of the total precipitation during August fell on 12 August. From 1-11 August, only 0.7 mm of rainfall were recorded at the lagoon. All other rainfall events after 12 August were $< 1 \text{ mm}$. This resulted in a lowering of the groundwater table in August. A comparison of rainfall totals for 15-31 July and 1-15 August revealed that rainfall recorded at the lagoon underestimated rainfall measured at Mayo Airport by 18 %. Precipitation measured at the airport was 21.2 mm and 13.0 mm for 15-31 July and 1-15 August, respectively. Values measured at the airport were 2.6 mm lower than the 30-year average for 1-31 July and 1 mm higher for 1-31 August.

Daily differences in precipitation measurements at the lagoon and airport were expected due to differences in measurement periods. Precipitation at the airport is measured hourly over a 24 hour period (12 am to 12 pm). The lagoon is approximately 1 km southwest of the airport so localized precipitation events are possible and help to explain why precipitation was recorded at the lagoon and not the airport on several days. However, these rainfall events were $\leq 0.2 \text{ mm}$ and cannot account for the large variation between the two sites. An under-catch by the rain gauges at the lagoon likely accounted for the majority of water loss. Evaporation from the rain gauges at the lagoon may also have contributed to differences between the sites.

Figure 4.2. Daily precipitation measured at the lagoon. Data are the mean of eleven measurements taken from transects along the infiltration cells.

4.3.1 Groundwater

Groundwater depth was measured at monitoring well 1 during summer 2003 (Figure 4.3). During installation of the well in November 1992, the approximate location of the groundwater table was reported to be 2.1 m below the ground surface. In summer 2003, the well remained frozen until 7 July and the groundwater table was highest in early July following thawing. Throughout the summer the groundwater level declined, with the exception of six days in early August, in response to rainfall in late July (Figure 4.2). There were no obvious increases in groundwater level following 9.9 mm of rainfall on 12 August. This was due to the lag time between rainfall events and increases in groundwater level. Groundwater levels were not monitored after 15 August, when a rise in groundwater level would have been likely. The groundwater depth decreased a total of 40 cm over the summer and was lowest at the end of the study period.

4.4 Storage

Changes in water storage at the lagoon are the result of variations in soil moisture and pond water level. During the study period, gravimetric analysis of soil samples revealed the average percent moisture content of samples taken along the transects was < 15 % (Table 4.1). Maximum percent moisture contents for infiltration cell 1 were highest during June, which may have been the result of available water following spring melt. However, these results should be viewed with caution as large fluctuations in moisture content were found between samples due to variability of soils at the lagoon. Soil samples collected from infiltration cell 1 and infiltration cell 2 during

Figure 4.3. Location of the groundwater table below the surface at monitoring well 1 during summer 2003.

Table 4.1. Gravimetric soil moisture content of samples taken along the four transects at the lagoon from infiltration cell 1 and infiltration cell 2. Weekly average, minimum and maximum percent gravimetric soil moisture values are presented.

Week	Infiltration cell	No. of samples	Average gravimetric soil moisture (%)	Minimum gravimetric soil moisture (%)	Maximum gravimetric soil moisture (%)
10-17 June	1	15	13.6 ± 7	2.9	25.5
	2	15	5.1 ± 2.9	0.8	11.0
17-23 June	1	10	14.1 ± 6.3	3.3	23.8
	2	10	4.7 ± 2.9	2.0	9.1
24-30 June	1	5	10.6 ± 7.7	0.7	20.6
	2	5	1.8 ± 1.3	0.7	3.3
1-7 July	1	11	6.9 ± 8.5	1.1	31.9
	2	11	2.2 ± 1.8	0.6	6.8
15-20 July	1	5	8.0 ± 5.6	2.8	17.6
	2	5	4.2 ± 1.8	1.8	6.0
21-27 July	1	6	4.8 ± 4.7	0	13.1
	2	6	2.0 ± 1.7	0.7	4.5
28 July-3 August	1	5	8.3 ± 3.6	5.8	14.6
	2	5	4.2 ± 1.7	2.3	6.4
4-10 August	1	24	5.1 ± 4.8	0	18.1
	2	22	2.3 ± 1.2	0.2	4.5
11-15 August	1	18	6.8 ± 5.1	0	16.5
	2	18	4.5 ± 3.3	0	12.7

15 July to 15 August had average moisture contents of $6.1 \% \pm 4.9 \%$ and $3.3 \% \pm 2.4 \%$, respectively. The soil at the lagoon responded to changes in precipitation during the study period with small increases in percent moisture content following rainfall. However, the water balance was only calculated for the continuously wetted areas at the lagoon so these values were not incorporated into measurement of ΔS for the water balance.

4.4.1 Pond water level

The water level in the primary cells and infiltration ponds was monitored over the summer. The primary cells were treated as a single unit, because over the study period the difference in storage was only a few millimeters. Daily fluctuations in ΔS for primary cells 1 and 2 indicate the equalizer may not have been performing precisely as per design, the staff gauges were sinking or there were errors in measurements of ΔS . It was assumed that inflow to primary cells 1 and 2 from the force main was equal over the study period. Over 32 days, the water level increased by 5 mm in primary cell 1 and decreased by 3 mm in primary cell 2, a difference of only 8 mm, but ΔS fluctuated daily between each cell (Figure 4.4). The limited change in storage over the study period indicated most of the wastewater entering the primary cells left by discharge or evaporation at approximately the same rate. Given the presence of a clay liner, the discharge was assumed for the purposes of this study to be to the infiltration cells only. However information contained in maintenance records (Section 3.2.3) indicated that seepage from the primary cells has occurred in the past.

During June, ΔS for infiltration pond 1 and infiltration pond 2 were similar, but

Figure 4.4. Cumulative daily change in water level for primary cell 1 (●) and primary cell 2 (○). Only values of ΔS from 15 July to 15 August were incorporated into the water balance.

the two ponds began to respond differently in early July (Figure 4.5). Between 15 July and 15 August, the water level in infiltration pond 1 dropped $75 \text{ mm} \pm 1 \text{ mm}$. Between 9-11 August, staff gauge I1B in infiltration pond 1 (Figure 3.6) went dry but readings were resumed following a major rainstorm event on 12 August. The largest single rise in water level in infiltration pond 1 occurred the same day, averaging 16.0 mm . For infiltration pond 2, the average increase in water level over the study period was $43 \text{ mm} \pm 1 \text{ mm}$.

The difference in ΔS for the two infiltration ponds is too high to attribute to measurement error alone. The difference in ΔS between the ponds over the study period was 118 mm . Water levels in the ponds were highest in late May and early June (Figure 4.5). The water level in both infiltration ponds began to decline around 8 June. By mid-June all excess surface water had infiltrated and/or evaporated. Around the end of June, the ponds began to exhibit differences in water level. The water level in infiltration pond 1 decreased from 15 July to 15 August. However, the water level in infiltration pond 2 increased. The staff gauges were secured to metal poles inserted into the bottom of the ponds. Readings between the five staff gauges in infiltration pond 1 and four staff gauges in infiltration pond 2 were similar in magnitude and direction. In order to read the gauges from the edge of the ponds, staff gauges were inserted around the perimeter of the ponds in $< 40 \text{ cm}$ of water. Due to the "bowl-like" configuration of pond 2, it is possible that the perimeter of this pond settled as a unit over the summer to cause the measured increase in water level. Seasonal ground ice around the shallow perimeter of the pond, formed during the winter months, may have thawed during the summer, causing the pond to settle around the perimeter. The staff gauges were not leveled at the beginning of the

Figure 4.5. Cumulative daily change in water level for infiltration pond 1 and infiltration pond 2. Only values of ΔS from 15 July to 15 August were incorporated into the water balance.

summer so it is difficult to state with certainty whether settlement had occurred. Heaving of the staff gauges in infiltration pond 1 was not likely, therefore, the average error in measurement of ΔS for infiltration pond 1 over the study period was ± 1 mm.

4.5 Evaporation

4.5.1 Introduction

Evaporation was estimated from the dry areas of the lagoon using lysimeters and the energy balance approach. The estimates by lysimeter were not as reliable, due to flooding, on days when precipitation exceeded evaporation. Solar radiation, net radiation and temperature measurements made over unsaturated ground were used to estimate evaporation from the saturated areas of the lagoon using an α of 1.26. Estimates of evaporation from the wetted surface were compared with estimates obtained from an evaporation pan.

4.5.2 Energy balance over the dry surface

Solar radiation and net radiation were measured over dry ground in infiltration cell 1 (Section 3.3.4.3). From 15 July to 15 August, daily mean incoming solar radiation ($K\downarrow$) (Figure 4.6) and net radiation (Q^*) (Figure 4.7) at the Mayo sewage lagoon were 196 Wm^{-2} and 80 Wm^{-2} , respectively. These corroborate well with measurements taken at Mayo Airport where moisture conditions were similar but the vegetative ground cover differed. Incoming solar radiation at the lagoon during July averaged 203 Wm^{-2} while Q^* averaged 87 Wm^{-2} . The decreasing number of daylight hours reduced $K\downarrow$ and Q^* in August to 189 Wm^{-2} and 72 Wm^{-2} , respectively. A similar trend was seen in $K\downarrow$ and Q^*

Figure 4.6. Average daily $K_{\downarrow}$ measured at the lagoon ($\circ$) and Mayo Airport ($\bullet$).

Figure 4.7. Average daily Q^* measured at the lagoon ($\circ$) and Mayo Airport ($\bullet$).

measurements at the airport, which were less than at the lagoon in July by 7 and 6 %, respectively and in August by 9 and 7 %, respectively. This appears to be a systematic error and is likely due to differences in receipt of diffuse radiation, because solar radiation and net radiation fluctuated together. The proximal location of trees to the south of the radiation equipment at the airport may have resulted in some scatter of $K_{\downarrow}$. Calibration errors for the instruments may have also contributed to lower $K_{\downarrow}$ and Q^* measurements at the airport. The factory calibrations were used to convert instrument voltage to measured radiation.

During July, latent, sensible and ground heat accounted for 57 %, 40 % and 4 % of net radiation, respectively (Table 4.2). Evaporation decreased to 42 % of Q^* in August, while 55 % was used to heat the air and 4 % to warm the soil. For July and August, β was 0.7 and 1.31, respectively. The mean value of β over the study period was 0.92. β was lowest during the wettest periods when Q_E/Q^* was highest due to the availability of surface moisture (Table 4.3). Changes in air temperature at the lagoon coincided with changes in solar radiation, Q_E/Q^* and β . At the lagoon, average T_a for July and August decreased from 16.6 °C to 13.8 °C, respectively (Figure 4.8). Average monthly (15-31 July and 1-15 August) T_a values at Mayo Airport were consistent with values measured at the lagoon. Monthly (1-31 July and 1-31 August) T_a comparisons between airport data (2003) and the long-term average (1971-2000) also showed close agreement. T_a at Mayo Airport in July 2003 was 0.7 °C higher than the 30-year average and in August it was 0.2 °C lower. The cooler temperatures during August were accompanied by an increase in relative humidity, causing ET to decline and Q_E/Q^* to become small.

Table 4.2. Daily mean estimates of the energy balance and related variables from unsaturated ground of infiltration cell 1. Q^* , Q_E , Q_H and Q_G were measured in Wm^{-2} and T_a was measured in $^{\circ}C$. The ratios, β and α are dimensionless.

	15-20 July	21-27 July	28 July- 3 August	4-10 August	11-15 August
T_a	18.2	17.2	12.7	12.9	16.2
Q^*	109.8	85.0	70.8	80.4	48.9
Q_E	58.6	49.9	26.9	33.7	32.3
Q_H	46.7	31.8	42.4	44.3	13.5
Q_G	4.5	3.3	2.5	2.4	3.1
Q_E/Q^*	0.53	0.59	0.38	0.42	0.66
Q_H/Q^*	0.43	0.37	0.60	0.55	0.28
Q_G/Q^*	0.04	0.04	0.04	0.03	0.06
β	0.80	0.64	1.58	1.31	0.42
α	0.85	0.95	0.66	0.73	1.12

Table 4.3. Daily mean of the energy balance and related variables for the dry and wet periods at the lagoon measured over unsaturated ground of infiltration cell 1. Q^* , Q_E , Q_H and Q_G were measured in Wm^{-2} . T_a was measured in $^{\circ}C$ and P was measured in mm and represented the total precipitation for each period. The ratios, β and α are dimensionless.

	16-25 July	26-31 July	1-11 August	12-15 August
No. of days	10	6	11	4
P	0.23	12.0	0.70	10.0
T_a	18.3	13.7	13.1	16.0
Q^*	110.8	46.0	83.4	41.5
Q_E	60.6	34.7	29.6	31.2
Q_H	45.3	11.2	50.9	8.1
Q_G	4.9	1.18	2.9	2.3
Q_E/Q^*	0.55	0.75	0.35	0.75
Q_H/Q^*	0.41	0.24	0.61	0.20
Q_G/Q^*	0.04	0.03	0.03	0.06
β	0.75	0.33	1.72	0.26
α	0.88	1.26	0.62	1.27

Figure 4.8. Average daily air temperature measured over infiltration cell 1.

The term α signifies a surface's resistance to evaporation (Rouse *et al.*, 1977). High α values are associated with a high Q_E/Q^* and are often characteristic of a freely evaporating surface. In most instances, $0 < \alpha < 1.26$, with $\alpha = 1$ representing the lower limit of PE, and $\alpha = 1.26$ indicating evaporation from a completely saturated surface (Stewart and Rouse, 1976; Rouse, 1990). Surface wetness and the ability of vegetation to transpire are the main controls on evaporation (Rouse *et al.*, 1977). In this study, Q_E/Q^* and α were highest in July. For July, August and the study period, α values were 0.93, 0.72 and 0.85, respectively.

Evaporation estimates for July and August using the energy balance approach were $30 \text{ mm} \pm 1.1 \text{ mm}$ and $16 \text{ mm} \pm 0.76 \text{ mm}$, respectively. Daily evaporation from the dry areas of the infiltration cells was 1.7 mm in July and 1.1 mm in August.

4.5.3 Lysimeters

Weighing lysimeters were used to gain an estimate of evaporation from the infiltration cells. However, lysimeters can be problematic as they are prone to flooding during large rainfall events and can alternatively dry out over time, increasing their resistance to evaporation. Gravimetric analysis of soil moisture on samples removed from the lysimeters on 18 August revealed an average moisture content of $8.1 \% \pm 2.5 \%$. The longest continuous decline in evaporation occurred during 4-7 August, when minimal rainfall was recorded at the lagoon. Evaporation estimates made during July and August were $15.4 \text{ mm} \pm 0.69 \text{ mm}$ and $13.4 \text{ mm} \pm 0.89 \text{ mm}$, respectively. Data were missing for 17-18 July and were approximated from measurements taken on 16 July and 19 July. Daily evaporation during July and August was 0.9 mm. Daily evaporation

estimated by lysimeters did not produce the same trend or magnitude as evaporation estimated using the energy balance approach and underestimated evaporation by 46 % for July and 20 % for August (Figure 4.9).

4.5.4 Evaporation from the ponds

4.5.4.1 Priestley-Taylor (1972) model

Estimates of evaporation from the wetted areas of the lagoon were made using a modified form of the Priestley-Taylor (1972) model. For July and August, evaporation estimates for the ponds were $65 \text{ mm} \pm 1.8 \text{ mm}$ and $48 \text{ mm} \pm 1.2 \text{ mm}$, respectively. These values were more than double evaporation estimated using the energy balance approach over the dry ground of infiltration cell 1. Average daily evaporation from the ponds during July and August was 3.8 mm and 3.2 mm, respectively. The change in evaporation from July to August over the ponds was similar to the decline in evaporation over land. Since there were no moisture restrictions over the ponds, the decline in evaporation was likely the result of decreased solar radiation in August and a reduction in air temperature and an increase in relative humidity.

Evaporation estimates from the ponds coincide with other estimates of evaporation from saturated surfaces in the North (Table 4.4). Daily evaporation values are variable and may be the result of differences in Q^* for the various study locations, weather variations, methods used to estimate evaporation and/or measurement errors. For this study, potential errors in evaporation estimates made using the modified Priestley-Taylor (1972) model arose largely as the result of not having measured Q^* directly over the ponds. Assuming a maximum underestimation of evaporation by 25 %,

Figure 4.9. Evaporation estimates over the unsaturated ground using the energy balance (●) approach and lysimeters (○).

Table 4.4. Evaporation rates for saturated terrain types presented as comparison to evaporation rates from the ponds in this study.

Study Period	Terrain Type	Location	Daily Evaporation (mm)	Reference
6-20 July	Small tundra pond	Ellesmere Island, N.W.T. (78°03'N, 82°12'W)	0.97	Marsh and Woo (1977)
1 July-late August	Lake	Resolute Bay, N.W.T. (74°69'N, 94°9'W)	1.0	Woo <i>et al.</i> (1981)
Mid May-early August	Wetland	Baker Lake, N.W.T. (64°27'N, 97°47'W)	2.9 (1982) 3.7 (1983)	Roulet and Woo (1986a)
22 June-1 August	Lake	Baker Lake, N.W.T. (64°27'N, 97°47'W)	4.4	Roulet and Woo (1986b)
Open water period, 126 d	Lakes	Mackenzie Delta, N.W.T.	1.3-2.5	Marsh and Bigras (1988)
4 May-22 August	Marsh	James Bay, Ontario. (51°10'N, 79°47'W)	2.8	Price and Woo (1988)
16 June-16 August	Lake	Churchill, Manitoba (58°44'N, 93°49'W)	4.9	Bello and Smith (1990)
21 June-18 August	Tundra lakes	Northern Manitoba (58°45'N, 93°57'W)	4.8	Boudreau (1993)
15 July-15 August	Wastewater ponds	Mayo, YT (63°36'N, 135°53'W)	3.5	This study

this would cause Q_E to increase by a similar amount. If all other components of the water balance remained unchanged, this would cause a daily reduction in seepage from the infiltration ponds.

4.5.4.2 Pan evaporation

To investigate the accuracy of evaporation estimates from the ponds, daily evaporation was measured using an evaporation pan placed in infiltration pond 2. The change in water level in the pan was a direct measure of E-P, as these were the only contributions to ΔS . On days without precipitation, the decline in water level was due solely to evaporation. A rain gauge was placed close to the pan to measure rainfall. Evaporation estimates from the pan for July and August were $60 \text{ mm} \pm 2.1 \text{ mm}$ and $45 \text{ mm} \pm 1.1 \text{ mm}$, respectively (data were missing on 16 July and 15 August and had to be averaged using measurements taken the previous days). Daily evaporation estimated using the evaporation pan followed a similar trend to daily estimates made using the modified Priestley-Taylor (1972) model and were underestimated by only 8 % for July and 7 % for August (Figure 4.10).

4.6 Seepage

Several assumptions had to be made in order to calculate seepage from the infiltration ponds: 1) seepage from the primary cells was negligible due to the presence of a clay liner, 2) evaporation rates from the primary cells and infiltration ponds were equal, 3) inflows to the infiltration ponds from the primary cells were equal and were calculated using the water balance for the primary cells, and 4) there was no contribution to the

Figure 4.10. Evaporation estimates from the infiltration ponds and primary cells using the modified Priestley-Taylor (1972) model (●) and evaporation pan (○).

infiltration ponds from melting ground ice. The first assumption is knowingly false over the long term as maintenance records report that development of a sinkhole in the southwest corner of primary cell 2 and settlement of the clay liner resulted in seepage from these cells. Seepage was not detected from the primary cells in 2003, but settlement of these cells was evident which may have led to cracks in the liner. The assumption that seepage from the primary cells is negligible was required in order to calculate seepage from the infiltration ponds using equation [2.3].

4.6.1 Weekly seepage estimates

A weekly water balance was calculated for the primary cells (Table 4.5) and infiltration ponds (Table 4.6a and 4.6b) over the study period. Seepage from both infiltration ponds was estimated due to the differences in ΔS between the ponds (Section 4.4.1). The primary cells were treated as a single unit due to the minimal difference in ΔS over the study period.

Average daily inflow to the primary cells over the study period was $162 \text{ mm day}^{-1} \pm 13.5 \text{ mm day}^{-1}$, while discharge from these cells was $159 \text{ mm day}^{-1} \pm 13.8 \text{ mm day}^{-1}$. Average daily rates of seepage from infiltration cell 1 and infiltration cell 2 were $29.2 \text{ mm day}^{-1} \pm 4.3 \text{ mm day}^{-1}$ and $22.0 \text{ mm day}^{-1} \pm 4.4 \text{ mm day}^{-1}$, respectively (Figure 4.11). Total water losses from infiltration pond 1 and infiltration pond 2 over the 32-day study period were 935 mm and 702 mm, respectively. The average daily seepage estimate from the infiltration ponds was consistent with the design seepage rate of 20 mm day^{-1} (Section 2.7.2.2).

Errors in seepage estimates are dependent on the errors associated with the

Table 4.5. Weekly water balance components including discharge (Q) estimates (mm and m^3) for the primary cells at the lagoon. Weekly values of I, P, E and ΔS are included and all values are in mm. The values of ΔS are averaged from the weekly values of ΔS for primary cell 1 and primary cell 2. The combined surface area of the primary cells is 2590 m^2 .

	15-20 July	21-27 July	28 July-3 August	4-10 August	11-15 August
I (m^3)	2650	2920	2860	2960	2000
I (mm)	1023.2	1127.4	1104.2	1142.9	772.2
P	5.2	3.7	8.6	0.7	10.0
E	28.3	26.1	21.5	24.8	10.7
ΔS	-1.0	0	-1	-4.0	-2.0
Q (mm)	1001.1	1105.0	1092.3	1122.8	773.5
Q (m^3)	2593	2862	2829	2908	2003
Q/I	0.98	0.98	0.99	0.98	1.0

Table 4.6a. Weekly seepage estimates (mm and m³) for infiltration pond 1 at the lagoon. Weekly values of I, P, E and ΔS are included and all values are in mm. The pond surface area is 6912 m² and the surface area of the vegetation buffer is 1652 m².

	15-20 July	21-27 July	28 July- 3 August	4-10 August	11-15 August
I (m ³)	1297	1431	1415	1454	1002
I (mm)	187.6	207.0	204.7	210.4	145.0
P	6.4	4.3	9.9	0.87	12.4
E	35.1	26.8	21.0	26.9	13.3
ΔS	-44	-12	-3	-7	-3
R (mm)	202.9	196.5	196.6	191.4	147.1
R (m ³)	1402	1358	1359	1323	1017
R/I	1.1	0.95	0.96	0.91	1.0

Table 4.6b. Weekly seepage estimates (mm and m³) for infiltration pond 2 at the lagoon. Weekly values of I, P, E and ΔS are included and all values are in mm. The pond surface area is 7777 m² and the surface area of the vegetation buffer is 3248 m².

	15-20 July	21-27 July	28 July- 3 August	4-10 August	11-15 August
I (m ³)	1297	1431	1415	1454	1002
I (mm)	166.7	184.0	181.9	187.0	128.8
P	7.3	5.2	12.2	1.0	14.2
E	40.1	37.0	30.5	35.2	15.2
ΔS	-3	19	9	-4	7
R (mm)	136.9	133.2	154.6	156.8	120.8
R (m ³)	1065	1036	1202	1219	939
R/I	0.82	0.73	0.85	0.84	0.94

Figure 4.11. Daily seepage from infiltration pond 1 (●) and infiltration pond 2 (○).

various water balance parameters. Table 4.7 presents adjustments to I, P, E, ΔS and R as a result of errors in measurement over the study period.

4.6.2 Annual seepage estimates

An annual water balance was devised for the lagoon for 1 September, 2002 to 31 August, 2003 using inflow recorded at the Village of Mayo lift station, precipitation recorded at Mayo Airport, and potential evaporation estimated using Thornthwaite (1948) (equation 3.1) (Table 4.8). Changes in storage were assumed to be negligible over the year. The annual water balance for the lagoon in Mayo was calculated using equation [2.3] and the following assumptions: 1) $\Delta S = 0$, 2) half of the precipitation that fell during the winter months (October to March) entered the ponds of the lagoon during spring melt, 3) $PE = 0$ for all months in which $MAAT < 0^\circ\text{C}$, 4) seepage from the primary cells was negligible and all inflow to the primary cells was discharged.

Total inflow over the year was $220,230 \text{ m}^3 \pm 4092 \text{ m}^3$, and total precipitation recorded at Mayo Airport was 270.4 mm. Due to the presence of an ice cover over the ponds for up to 7 months, only half of the snowfall was assumed to enter the ponds during snowmelt, lowering total precipitation to 216.2 mm. The remaining half of the water released from melting snow and ice was assumed to contribute to recharge of soil moisture, and later evaporated during the summer months. Potential evaporation estimated for the year was 269.7 mm. Total precipitation (m^3) and potential evaporation (m^3) were calculated using the total surface area (m^2) of the four ponds at the lagoon estimated during summer 2003. Using equation [2.3], total seepage over the year was estimated to be $219,306 \text{ m}^3 \pm 4301 \text{ m}^3$, giving a daily average seepage rate of 35 mm

Table 4.7. Absolute and percent error estimates for I, P, E, ΔS and R for the lagoon from 15 July to 15 August, 2003.

Variable	Pond 1 Original values	Pond 2 Original values	Absolute and/or percent error	Pond 1 Adjusted values	Pond 2 Adjusted values †
Total I (m ³)	6599	6599	65.5 m ³ (1%)	6632	6632
I (mm)	954.7	848		959	853
P (mm)	33.9	39.9	18%	39.9	47.1
E (mm)	123.1	158.0	25%	153.9	197.5
ΔS (mm)	-75	43	1 mm (pond 1) 118 mm (pond 2)	-74	-74
R (mm)	941	687	4 % (pond 1) 12 % (pond 2)	919	777
R (m³)	6501	5342		6352	6040

† assumes pond settlement and an adjusted value of ΔS equal to pond 1.

Table 4.8. Annual water balance and average daily seepage rates for Mayo sewage lagoon. The surface area of the four ponds at the lagoon used in the calculation of seepage was 17,279 m².

Month	I (m ³)	I (mm)	P (mm)	P (m ³)	PE (mm)	PE (m ³)	R (m ³)	R (mm)	R (mm day ⁻¹)
Sept	16020	927	21.2	366.3	28.9	499.9	15887	919	28.2
Oct	14220	823	0	0	0	0	14220	823	27
Nov	14510	840	0	0	0	0	14510	840	28
Dec	17970	1040	0	0	0	0	17970	1040	34
Jan	21240	1229	0	0	0	0	21240	1229	40
Feb	21370	1237	0	0	0	0	21370	1237	44
Mar	24990	1446	0	0	0	0	24990	1446	47
April	23900	1383	55.2	953.8	0	0	24854	1438	48
May	20610	1193	16.4	283.4	33.8	584.0	20309	1175	38
June	18600	1076	28.8	497.6	64.4	1112.8	17985	1041	35
July	13760	796	51.8	895.1	81.3	1404.8	13250	767	25
Aug	13040	755	42.8	739.5	61.3	1059.2	12720	736	24
Annual total	220230	12746	216.2	3735.7	269.7	4660.2	219306	12692	35

$\text{day}^{-1} \pm 8.5 \text{ mm day}^{-1}$.

Mayo has a combined sewer system, so monthly inflow over the year was found to be highest in March and April when runoff from melting snow and ice in town was registered at the lift station. Inflow was also high in January and February when the system was 'bled' to prevent freezing, and lowest in July and August. Estimated daily seepage was highest between January and May, and peaked in April (48 mm day^{-1}) when it was assumed that half of the precipitation that fell during the winter entered the lagoon. The annual average daily seepage rate was higher than the design seepage rate of 20 mm day^{-1} . In order to calculate an annual water balance, a wetted surface area of $17,279 \text{ m}^2$ was assumed constant over the year. However, the surface area of the infiltration ponds changes over the year in response to increased inflow, the presence of an ice cover, and melting ice and snow. From around November to May the infiltration ponds expand horizontally (personal communication, J. M. Ewing, 28 April 2004) due to an ice cover and increased inflow. Adjustments to the wetted perimeter of the infiltration ponds to reflect increased surface area over the winter would decrease the rate of seepage. Therefore, an underestimate of the surface area of the infiltration ponds overestimated the daily rate of seepage using the annual water balance approach by up to 40 %. However, during July and August seepage calculated using the annual water balance (Table 4.8) was consistent with estimates obtained for infiltration cell 1 and 2 from 15 July to 15 August, 2003.

4.7 Lagoon residence times

The residence time (RT) for a sewage lagoon refers to the length of time

wastewater is held within the cell. Knowledge of the RT of sewage lagoons is important because it has implications for the quality of treatment. The colder and more severe the climate, the longer the RT should be (Smith *et al.*, 1986). Twelve-months of retention is often long enough to ensure that wastewater has been sufficiently treated and that BOD₅ and fecal coliform levels comply with national standards. In high-latitude locations such as Mayo, the degree of treatment is greatly reduced during the winter months due to colder temperatures and reduced solar radiation. For continuous retention/discharge systems, which are common in the North, it is recommended that discharge occur in the summer or fall following enhanced biological activity during the summer months (Grainge and Shaw, 1971). A similar RT and reasoning should apply to infiltration lagoons.

Residence times are calculated using the volume (V) (m³) and rate of discharge (Q) (m³ time⁻¹) and may be reported in days, months or years:

$$RT = \frac{V}{Q} \quad [4.1]$$

For the primary cells, the average RT of the wastewater is 10 days $\pm$ 1 day (Table 4.9). This value is higher than the proposed detention time of 2 days (EBA, 1992a). This means that wastewater remains in the primary cells longer than anticipated. For infiltration pond 1, the RT of the wastewater was calculated to be 10 days $\pm$ 1.5 days, and for infiltration pond 2 the retention time was 17 days $\pm$ 4.2 days. If the values of ΔS for infiltration pond 2 in July and August were in error due to settling (Section 4.4.1), RT for this pond would decrease because the volume of the pond would have been overestimated. Retention times for the infiltration ponds are much lower than design

Table 4.9. Retention time of wastewater in the primary cells and infiltration ponds. The design RT and actual RT are presented.

Pond	Volume (m ³)	Total discharge over 32 days (m ³)	Design RT (days)	Actual RT (days)
Primary cells	4000	13195	2	10
Infiltration pond 1	2013	6459	>200	10
Infiltration pond 2	2902	5461	>200	17

which predicted wastewater would be retained over the winter.

4.8 Summary

Seepage estimates for infiltration cell 1 and infiltration cell 2 were consistent with the design seepage rate of 20 mm day⁻¹. Despite original design specifications that freezing of the infiltration cells during the winter would diminish infiltration until spring, seepage is occurring from these cells over the entire year. The minimal volume of wastewater at the lagoon and continuous seepage over the year has resulted in a total retention time of less than 1 month for wastewater in the lagoon.

CHAPTER FIVE

SUMMARY AND CONCLUSIONS

5.1 Summary

The main objective of this thesis was to determine the water balance of the Mayo sewage lagoon in order to determine the amount of seepage from the lagoon. The sewage lagoon in Mayo, Y.T. is largely dry, with < 15 % of the total lagoon area saturated. The high Bowen ratio (β) and large summer vapour deficit (P-E) are consequences of the dry infiltration cells. Evaporation from the ponds at the lagoon exceeded precipitation and was more than double ET over the unsaturated ground. Total ET over the dry ground also exceed precipitation for the period of study. Total precipitation at the lagoon was 28.1 mm and evaporation from the ponds was 112 mm.

During the study period, infiltration pond 1 lost $75 \text{ mm} \pm 1 \text{ mm}$ of wastewater while infiltration pond 2 gained $43 \text{ mm} \pm 1 \text{ mm}$. Changes in pond water level for infiltration pond 2 may, however, be in error. Overall, seepage accounted for the largest loss in the water balance. The projected seepage rate of 20 mm day^{-1} was consistent with values estimated using the summer 2003 water balance and annual water balance. Daily rates of seepage from infiltration cells 1 and 2 were $29.2 \text{ mm day}^{-1} \pm 4.3 \text{ mm day}^{-1}$ and $22.0 \text{ mm day}^{-1} \pm 4.4 \text{ mm day}^{-1}$, respectively. Total water loss from infiltration pond 1 and infiltration pond 2 was 935 mm and 702 mm, respectively. These values were consistent with the seepage estimate of 25 mm day^{-1} during July and August for the annual water balance.

Permafrost is thawing around the lagoon due to the initial disturbance to the active layer, annual clearing of vegetation and the presence of water year round at the lagoon. Thermistor readings taken from the northwest corner of the lagoon in 1998 showed that ground temperatures have risen above 0 °C between 3 and 4 m depth. Thawing permafrost has caused several structural failures since construction, most of which are related to subsidence and are the result of ice-rich soil thawing beneath the primary cells and infiltration ponds. Seepage is occurring year round from the infiltration ponds, greatly reducing the retention time of wastewater in the lagoon. Residence times calculated during summer 2003 were low. During the study period, RT for infiltration ponds 1 and 2 were 10 days and 17 days, respectively. Low residence times are discouraged in the design of northern sewage lagoons due to limited treatment of wastewater during the winter months.

5.2 Conclusions

The main conclusions that can be drawn from this study include:

- 1) A water balance can be successfully used to model seepage.
- 2) During summer 2003, evaporation at the lagoon exceeded precipitation, even for the unsaturated areas of the infiltration cells.
- 3) Seepage is the major loss of water from the lagoon and accounts for the greatest fraction of inflow.
- 4) Inputs to the lagoon are approximately equal to outputs and the infiltration ponds, at their current size, are, therefore, in equilibrium.
- 5) The retention time of wastewater at the lagoon is low due to the high infiltration

rate.

5.3 Future research

A weekly rate of seepage from the infiltration ponds at the Mayo sewage lagoon has been estimated in this study, showing that seepage accounts for the majority of wastewater losses at the lagoon. Now that seepage at the lagoon has been quantified and the various components of the water balance determined, investigations into the effects seepage may have on the operation and treatment of the lagoon are needed. Future research at the Mayo sewage lagoon should include investigations into long-term thaw and its implications for design and operation. A monitoring program to evaluate permafrost degradation at the lagoon was established with the installation of a thermistor cable in the northwest corner of the lagoon. Regular monitoring of ground temperatures is needed to determine any trends in warming so that predictions concerning the long-term stability of the lagoon and preparations for future maintenance can be made. Investigations into the impact that permafrost degradation may have on the hydraulic conductivity and retention time of sewage in the lagoon are also needed.

The assumption that seepage from the primary cells is negligible due to the presence of a clay liner is knowingly false since maintenance records of the lagoon report the collapse of the dyke on the west corner of primary cell 2 due to thaw of an ice wedge. Several observations on the settlement of the clay liners have also been made. To calculate seepage from the infiltration ponds this assumption had to be made, despite knowledge that seepage has occurred in the past. Future studies on seepage from the primary cells are needed as wastewater treatment in these cells is minimal. The length of

time for the blockage experiment (Section 3.3.1.1) should be increased due to the lag between the time wastewater leaves the lift station and when it reaches the primary cells. This would serve to confirm no losses in transmission along the force main. The low residence time of wastewater in the lagoon is of concern given several studies that support the need for increased retention time and summer/fall discharge of wastewater in the North. A monitoring program to determine the effects that seepage may be having on local groundwater and soil quality is recommended in the near future.

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