PHYSICAL LIMNOLOGY OF THE EQUITY MINE PIT-LAKES

by

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ABSTRACT

Two adjacent pit-lakes – Waterline and Main Zone – are located at the Equity Silver Mine site near Houston, British Columbia, Canada. The upstream Waterline is the smaller of the two pit-lakes at 43 m deep and 460 m long, while the Main Zone Pit-lake is larger at 120 m deep and 710 m long. The Waterline Pit-lake drains into the Main Zone Pit-lake through the Waterline Outflow. Treated acid rock drainage (ARD) water and sludge are being discharged into the Main Zone. Water is also withdrawn from the Main Zone Pit-lake at a depth of 20 m and discharged to nearby creeks. A study of the physical limnology of the two pit-lakes was undertaken during 2001 and 2002 in conjunction with a study of their chemistry.

Marked differences between the two pit-lakes in terms of the intra-annual and inter-annual evolution were observed. The Waterline Pit-lake is meromictic, while overturn occurred at least once a year in the Main Zone Pit-lake during the observation period. Anoxia was observed in the Waterline Pit-lake below the epilimnion, likely the result of chemical oxygen demand and lack of oxygen replenishment. On the other hand, the Main Zone Pit-lake was always well oxygenated due to the circulation generated by overturn and the sludge discharge. Turbidity in the Waterline Pit-lake occurred mainly at the base of the epilimnion due to the formation of oxidation precipitates, whereas in the Main Zone Pit-lake, the treated ARD and sludge discharge generated turbid water near the bottom. Phytoplankton were absent in the Waterline Pit-lake, but near surface peaks in chlorophyll a (chl a) were observed in the Main Zone. Preliminary investigation indicates that upwelling was not likely in the Waterline Pit-lake, but possible in the Main Zone. Conductivity-temperature-depth (CTD) and thermistor data revealed possible groundwater intrusion into the Waterline Pit-lake and portrayed the impact of the accidental sludge discharge to the Waterline. Destratification in the Main Zone Pit-lake was observed in summer of both 2001 and 2002. It may have been due to wind-driven upwelling or alternatively due to sludge discharge. A more detailed heat and salt budget is needed to determine the exact cause(s) of destratification.

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ρ_a	density of air
ρ_{aft}	density of water after mixing
ρ_{bef}	density of water before mixing
ρ_u	density of the upper layer/surface water
λ_{m-1}	eigenvalue for the m-1th vertical internal seiching mode
ΔP	total change in potential energy
$\Delta Z_i = Z_i - Z_{i-1} = B_i$	thickness or bench height of the ith layer
A	area of the lake at depth z
A_{bi}	bottom area of the ith layer
A_{ti}	top area of the ith layer
B_i	thickness or bench height of the ith layer
C_D	drag coefficient of air/water
F	dimensionless number for the subsurface withdrawal
g	gravitational acceleration
g'_{tb}	reduced gravitational acceleration for the top and bottom layers
H	total depth of a water body
h	vertical distance between the halocline and inlet of the withdrawal pipe
h_b	thickness of the bottom layer
h_t	thickness of the top layer
k	equilibrium/gas exchange constant for oxygen
L	longitudinal length of a water body
m	the total number of layers of a stratified water body
Q_c	critical subsurface withdrawal rate
T_{m-1}	internal seiching period for the m-1th vertical mode
U_w	wind velocity
u_*	friction velocity
V_i	volume of the ith layer
V_{pit}	volume of the Main Zone pit below current water level of 1259.3m
V_{sludge}	volume of the sludge solid discharged into the Main Zone pit
$V_{wasterock}$	volume of the waste rock backfilled into the Main Zone pit
V_{water}	volume of water in the Main Zone pit
W	Wedderburn Number
Z_i	absolute altitude of the top of the ith layer
z	depth/distance below the water surfce
z_m	maximum depth of a water body

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1 INTRODUCTION

While mining of precious materials such as metals from the earth has enormous benefit to society, it also raises many environmental concerns. Open-pit mining often results in the formation of pit-lakes as groundwater and surface runoff accumulate in the pit after cessation of mining operations. Water either passively overflows into surrounding water bodies when the pit is full or is pumped out of the pit to keep the lake surface at a certain level. In either case, the quality of the out-going water discharged from a pit-lake is of primary importance to the preservation of the surrounding environment.

1.1 Background Information

The Equity Silver Mine site is located near Houston, British Columbia, Canada, 575 km north northwest of Vancouver (Figure 1.1). Two pit-lakes, the 'Main Zone' and the 'Waterline' were formed after the cessation of mining operations. The Main Zone Pit-lake is the receiving water body for the outflow from the Waterline Pit-lake, and also serves as the site for sub-aqueous disposal of treated acid rock drainage (ARD). Water is also withdrawn from the Main Zone Pit-lake and discharged into nearby natural streams.

Previous Studies on Pit-lakes- An abandoned open mine pit becomes a pit-lake when it fills with natural inflow of groundwater and precipitation. Deliberate flooding and artificial inflow of tailing pond water and/or treated acid rock drainage (ARD) can also occur. Brenda Mines Pit-lake in Kelowna, British Columbia, Canada, formed with a combination of natural inflow and discharge of tailing pond water into the pit (Stevens and Lawrence 1997). Island Copper Mine Pit-lake on the northern tip of Vancouver Island formed from deliberate flooding of the pit with seawater and capping it with fresh water (Wilton 1998; Fisher 2002). Sleeper Mine Pit-lake in the United States formed with artificial pumping of groundwater into the pit (Beale et. al 1998).

Pit-lakes have been an environmental concern in terms of water quality since they are often polluted with heavy metal from ARD discharge (Watkins 2000) and/or with high acidity

such as the Berkeley Pit-lake and the Liberty Pit-lake in the United States (Miller et al. 1996; Davis and Eary 1997). Water always drains naturally or is pumped from the pit-lake at, or close to, the surface to a nearby creek, lake or coastal ocean, therefore the suitability of a pit-lake for sub-aqueous disposal of hazardous materials depends on mechanisms controlling vertical transport of contaminants. Stevens and Lawrence (1997, 1998) characterized relationships between vertical transport and governing factors such as molecular and turbulent diffusion, density stratification, wind, and penetrative convection. The effect of surface flushing with fresh water to the vertical migration of contaminant was also investigated. Hamblin et. al (1999) investigated the potential of sub-aqueous disposed hazardous materials for migrating upward from bottom to surface, using the dynamic reservoir simulation model (DYRESM). Fisher and Lawrence (2000) evaluated the effectiveness of freshwater cap to retain the newly injected ARD in the Island Copper Mine Pit-lake for passive treatment. Fisher and Lawrence (2001) also discussed the role of double diffusion in causing vertical migration at an interface.

Site History and Characteristics- Equity Silver Mine was opened in 1980 by Placer Dome Inc. Ore mining was operated in four zones: Main Zone, Waterline Zone, Southern Tail Zone and North Zone (north of the Waterline Zone). Most of the ore present at the site was extracted in the Main Zone (29 million tons) and the Southern Tail Zone (7.2 million tons). The open pit mining in Main Zone commenced in 1983 and ceased at the end of 1991. Work on a smaller pit, the Waterline, located northeast of the Main Zone, began in 1988 and continued into early 1994. In the North Zone, the underground mining operation started in 1992 and finished in early 1994 (Saretzky 1998). A cavern in the North Zone, connected by an adit to the Waterline, collapsed soon after the cessation of mining operation in the North Zone.

Mining operation resulted in an open pit in the Southern Tail Zone, the Main Zone and the Waterline Zone (Figure 1.2 and 1-3), but only the Main Zone and the Waterline Zone became pit-lakes. The open pit in the Southern Tail Zone was completely backfilled with waste rock from the Main Zone and covered with soil in 1984. A small portion of the Main Zone pit was backfilled with waste rock of its own and the neighboring Waterline

Zone (Baase 1991). However, the rest of the Main Zone pit was allowed to fill with water from various sources such as groundwater, episodic overflow of the diversion of Berzelius Creek (Figure 1.3), treated water discharge, precipitation and localized drainage. In 1993, Placer Dome decided that it would be best to discharge the treated acid rock drainage (ARD) sludge into the Main Zone pit for long-term subaqeous storage and, on average, roughly 1% of Main Zone pit volume has been filled by the sludge discharge every year. Unlike the Main Zone pit, the Waterline pit has had no waste rock or sludge deposits.

Pits Description- When mining operation in the Main Zone was completed in 1991, the deepest depression of the open pit was at an elevation of 1090m (Baase 1991). Subsequently, the pit was partially backfilled with waste rock and deposited with the sludge solid resulting from the treatment of the acid rock drainage (ARD) collected at the site. Presently, the water elevation is at around 1260 m and the maximum water depth of the lake is approximately 120 m (Figure 1.4). This indicates that waste rock and ARD sludge has filled the bottom 50m of the pit. The Main Zone Pit-lake centerline, or thalweg, runs from north to south. The maximum depth along the length of the lake varies from 120m in the south to 90m in the north. At the current water level, the length and width of the pit-lake measures approximately 710 m N-S and 290 m E-W.

The Waterline Pit-lake is much smaller, narrower and shallower than the Main Zone. With a northeasterly trend, Waterline has a maximum depth of 43 m near its northern end. It measures 460 m long and averages 60 m in width at the current water surface level. At the southern end, water from the Waterline Pit-lake overflows into the Main Zone Pit-lake. If the water level were raised to 1265 m, the two pit-lakes would join and become a single water body. A now underwater adit at the northern end of the Waterline Pit-lake connects a collapsed cavern in the North Zone located north-northwest of the Waterline pit. The volume and character of water that may enter through this adit is unknown.

Diversion Channels- Diversion channels were constructed on the perimeter of the property to re-route streams and creeks to minimize the flow through the mine site. The Berzelius Diversion bypasses water around the east side of the Waterline pit and the tailing pond,

and joins Foxy Creek at the northeastern corner of the mine property. Water was re-routed around the east side of the Main Zone pit, draining north through the Bessemer Creek bypass into the Berzelius Diversion canal or south through the Bessemer diversion to join Bessemer Creek (Figure 1.3). In addition, water from Lu Lake overflowing into the Lu Creek Diversion canal flows around the west side of the tailing pond and diversion pond, and also joins with Foxy Creek at the northwestern corner of the mine site property.

Despite the diversion canals, additional inflow into the Waterline pit was generated by the substantial leakage from Berzelius Diversion at the northeast corner of the pit. The leakage was severe enough (roughly 1.3 Mm^3/yr) that Placer Dome began to replace part of the creek's bottom with a thick layer of low permeability compacted till in 2000 to mitigate this problem (Aziz 2001). Nevertheless, as of summer 2002, obvious streams of water running down the northern pit-wall of the Waterline indicate more corrective measures may be necessary in the future.

Ore Recovery- The mine is situated on top of an intermontane geological region, one of the four tectonic belts running from northwest to southeast on the west coast of Canada. The three major metal deposits being mined at the site were gold, silver and copper. In the early stage of mine operation, antimony and arsenic were leached from the concentrate and recovered as byproducts; however, due to metallurgical difficulties this process was discontinued. During the period of active mining from 1980 to 1994, approximately 34 million metric tones of rock were mined, of which 2.2 million kilograms of silver, 16 thousand kilograms of gold and 84 thousand kilograms of copper were extracted. Moreover, 84 million tons of waste rock was also generated in the process (Ministry of Energy and Mines, 2001).

Acid Rock Drainage- Acid rock drainage (ARD) was first noticed on the site in 1981. It is mainly generated from the oxidation of sulfides in waste rock as well as from fresh rock faces that are exposed to open air and are susceptible to weathering. The buffering capacity of the Waterline and Main Zone pit-lakes is adequate to neutralize the direct runoff of acidic water generated from the surrounding pit-walls. However, large amounts

of acid generating waste rock were dumped in various areas of the mine site (i.e. the Bessemer waste dump, the Southern Tail pit and a small portion of the Main Zone pit). The ARD collected from the Bessemer waste dump and the backfilled Southern Tail pit is treated and discharged into the Main Zone Pit-lake (see below).

Pit-lake Management- Flowing along a sludge discharge channel at the northern end of the Main Zone, the treated ARD water and sludge are discharged into the Main Zone Pit-lake above water surface. Then. As of 2002, the total volume of sludge solid discharged is on order of 1% of the total volume of the pit. An underground barrier was built between the Main Zone pit and the Bessemer waste dump, located immediately west of the Main Zone and containing acid-generating waste rock, to prevent groundwater from flowing into the waste dump and producing additional ARD (Wilbur 2000). The water level in the Main Zone pit has to be kept below 1265 m in order to ensure the workability of the groundwater divide. Therefore, a pipeline was constructed to a barge which pumps water from 20 m below the water surface on the west side of the Main Zone (Aziz 2002, 2003). The water withdrawn from the Main Zone Pit-lake is then discharged to either Buck Creek via Bessemer Creek southwest of the site or to the diversion pond, where the Main Zone water is mixed with the treated ARD water and discharged to either Buck Creek or Foxy Creek (Aziz 2000).

Weather Conditions- The Equity Silver Mine site sits about 1300 m above sea level and generally has a long winter and short summer. The lake surface of the Main Zone pit generally starts to freeze in early to mid November, whereas, the smaller Waterline Pit-lake starts to freeze about 4-5 weeks earlier. At the end of winter, the lake ice begins to thaw and disappears completely in early to mid-June.

The average monthly air temperature (1990-2000) at the Equity Silver Mine site is shown in Figure 1.5. The warmest months are July and August (~ 11 °C). Temperatures cool dramatically in the fall from September (~ 7 °C) to November (~ -5 °C). The mean air temperature normally stays below freezing from mid/late-October until mid-April and the coldest month is January (~-10 °C). When spring arrives in early May, the air warms up at fairly uniform rate until July.

Precipitation reaches both pit-lakes in the form of rain or snow, depending on the time of year. Figure 1.6 and Figure 1.7 show the average monthly amounts of rainfall and snowfall as well as the corresponding total water equivalent precipitation on the mine site over the period of 1999-2000. June tends to have the most rainfall and December tends to have the heaviest snowfall. There is no well-defined dry season for the mine site as there is a significant amount of precipitation in every month of the year; nevertheless, with the assumption that 10 parts of snow generally melts into one part of water (Cutnell and Johnson 1995), the period of late winter to early spring (February-April) is comparatively drier than the other seasons in terms of the actual amount of water equivalent precipitation.

Except for occasional calm periods, both my personal experiences and the anemometer readings of the Main Zone and Waterline pits indicate that gentle breeze always blows in the middle of both pit-lakes. The average wind at the Waterline is about 30% stronger (3 m/s) than that at the Main Zone (2 m/s) possibly due to the fact the wind coming from a rather open space gets stronger in a narrower space over the Waterline Pit-lake. The wind on the Main Zone Pit-lake occurred from all directions, although the southerly wind was dominant. On the Waterline Pit-lake, wind was blown predominantly along the thalweg and came from the south most of the time.

1.2 Research Study and Objectives

Funding was provided by the Natural Science and Engineering Research Council of Canada (NSERC), with matching funds from five mining companies and in-kind support from Placer Dome Equity and Lorax Environmental, the study was conducted cooperatively between the Oceanography group of the Department of Earth and Ocean Sciences at University of British Columbia (UBC) and the Environmental Fluid Mechanics (EFM) group of the Department of Civil Engineering at University of British Columbia (UBC).

The Equity Silver Mine Pit-lake project was initiated in June 2001 to study the mechanisms controlling the metal concentration in different parts of the water bodies as well as to determine the most suitable remediation strategy to remove the dissolved metal content in the lake water. The research project is divided into two main areas, geochemistry and physical limnology, the latter of which is the major focus of this thesis.

The objectives of this thesis are:

- to investigate the basic hydrology of the Waterline and Main Zone pit-lakes;
- to describe the evolution of the pit-lakes in terms of measured properties such as temperature, conductivity, oxygen content, chlorophyll and turbidity;
- to determine the cause(s) of differences in pit-lake behavior between the Waterline and Main Zone pit-lakes;
- to examine the impact of artifacts on the evolution of the pit-lakes such as the ARD discharges, subsurface withdrawal; and
- to examine the relationship between the lake properties and the meteorological condition at the pit-lakes.

1.3 Scope

The fieldwork program of this project commenced in June 2001 and ended in June 2003. However, only the data collected from June 2001 to October 2002 will be examined in this thesis.

This thesis is divided into six chapters. The investigation of the hydrological properties of the Waterline and Main Zone pit-lakes is the main focus of Chapter 2. Chapter 3 presents the methodology of data and sample collection and measurement planning in the field. The evolution of measured properties for the Waterline Pit-lake and the Main Zone Pit-lake is described in detail in Chapters 4 and 5, respectively, in which an attempt is also made to determine the physical processes leading to changes in lake properties during the observation period. Conclusions and recommendations are articulated in chapter six.

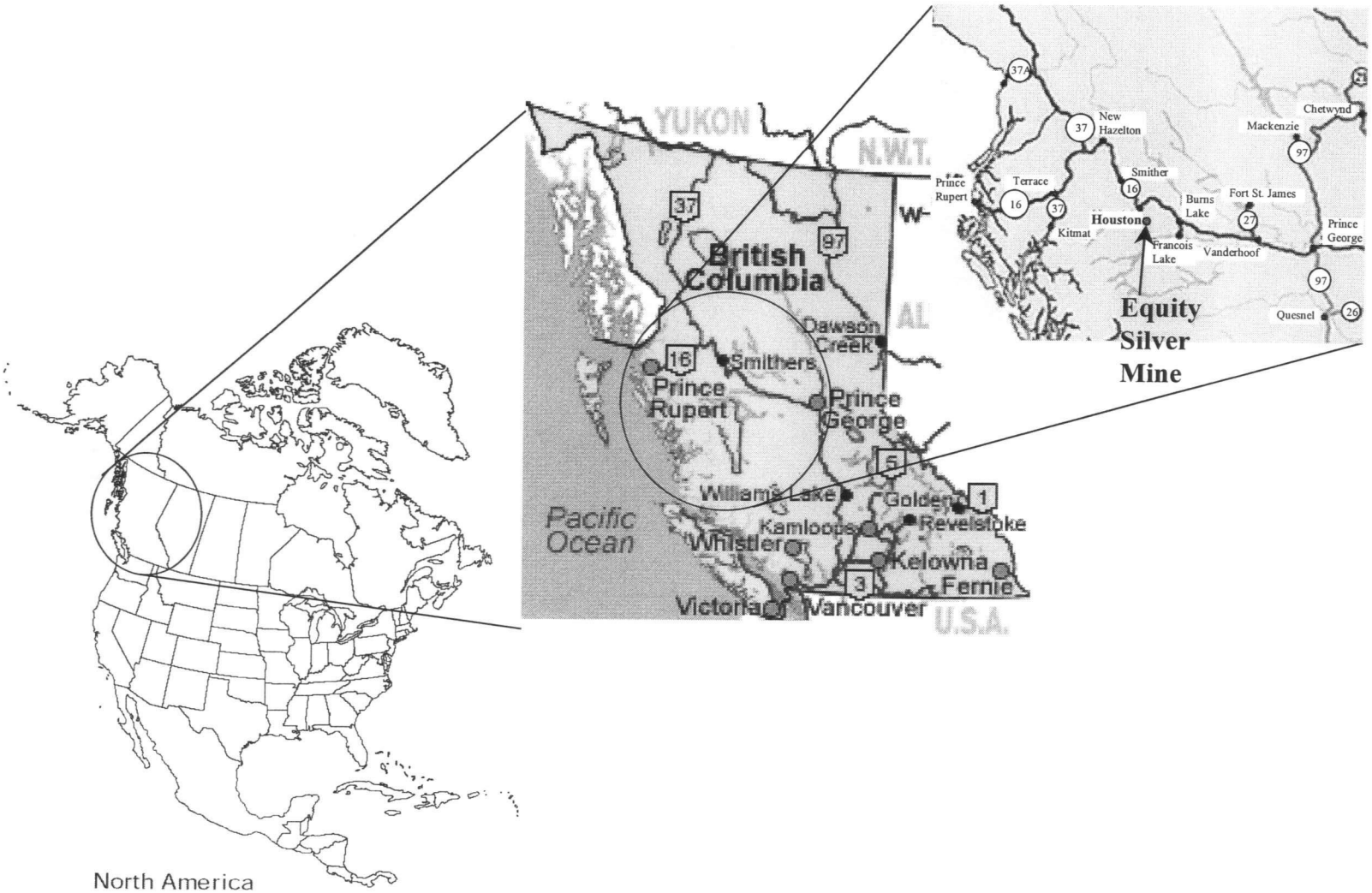


Figure 1.1 Location of the Equity Silver Mine

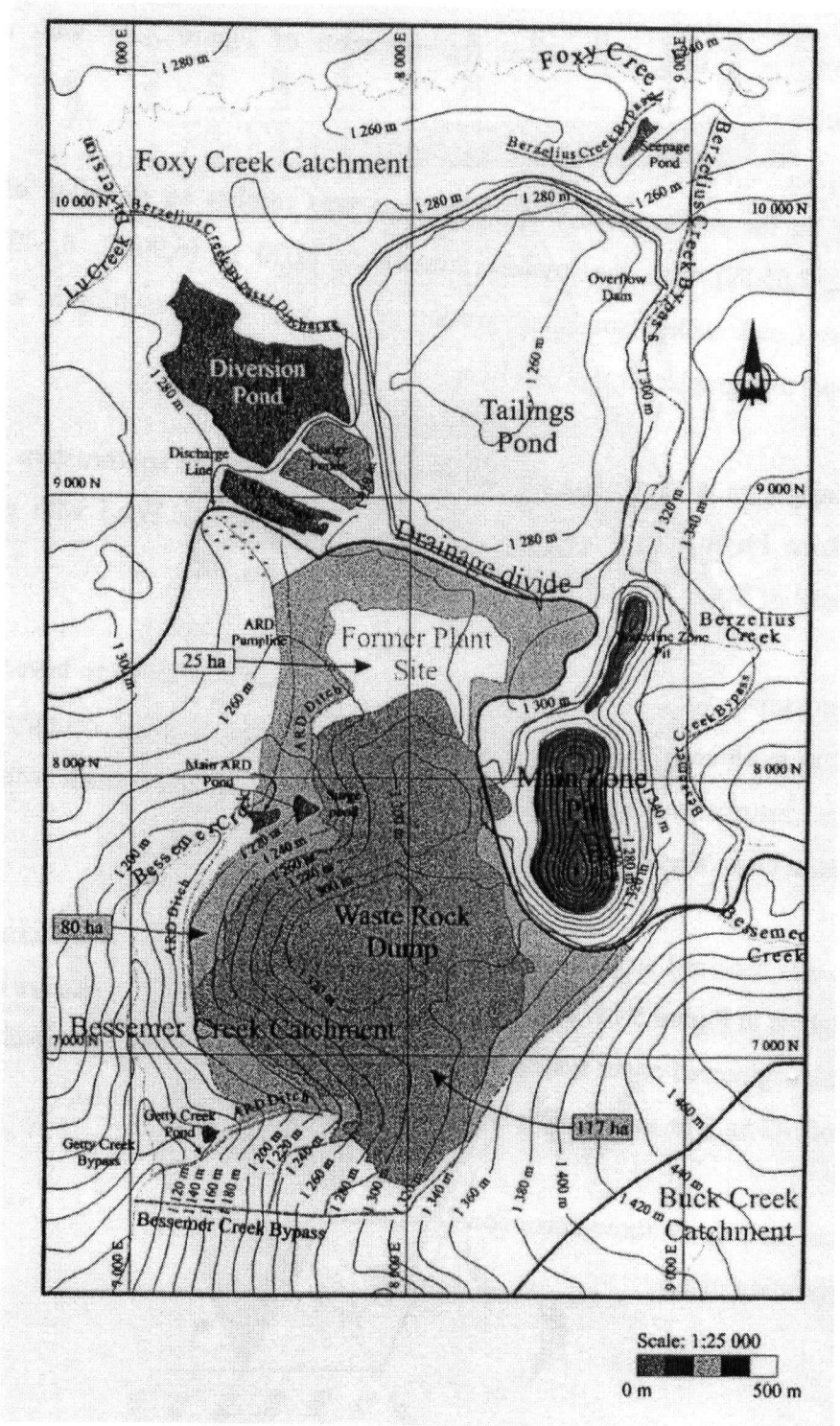


Figure1.2 Site plan of the Equity Silver Mine (adapted from Sarezky 1998)

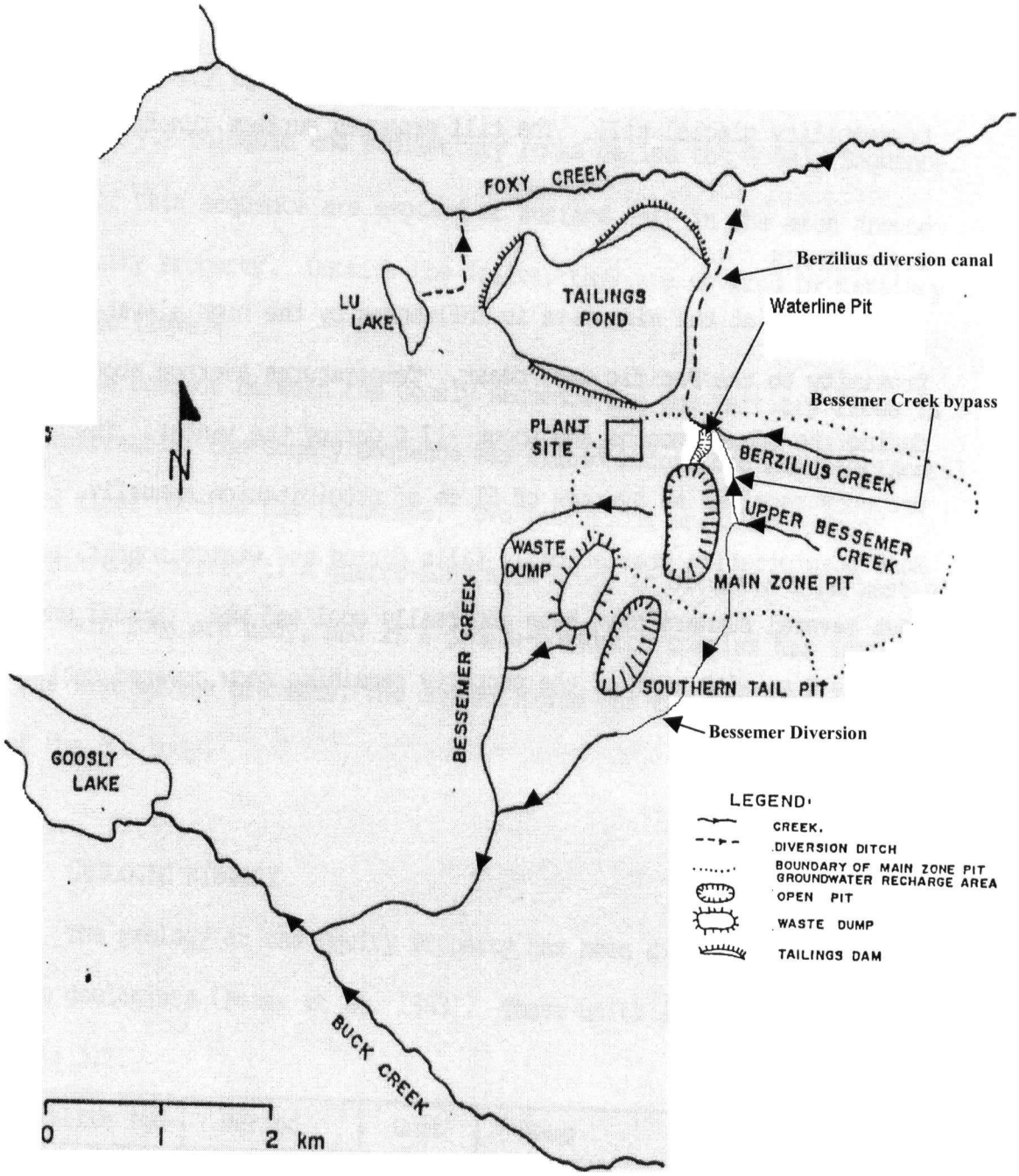


Figure 1.3 Creeks and diversion canals at the Equity Silver Mine (adapted from Sperling 1985)

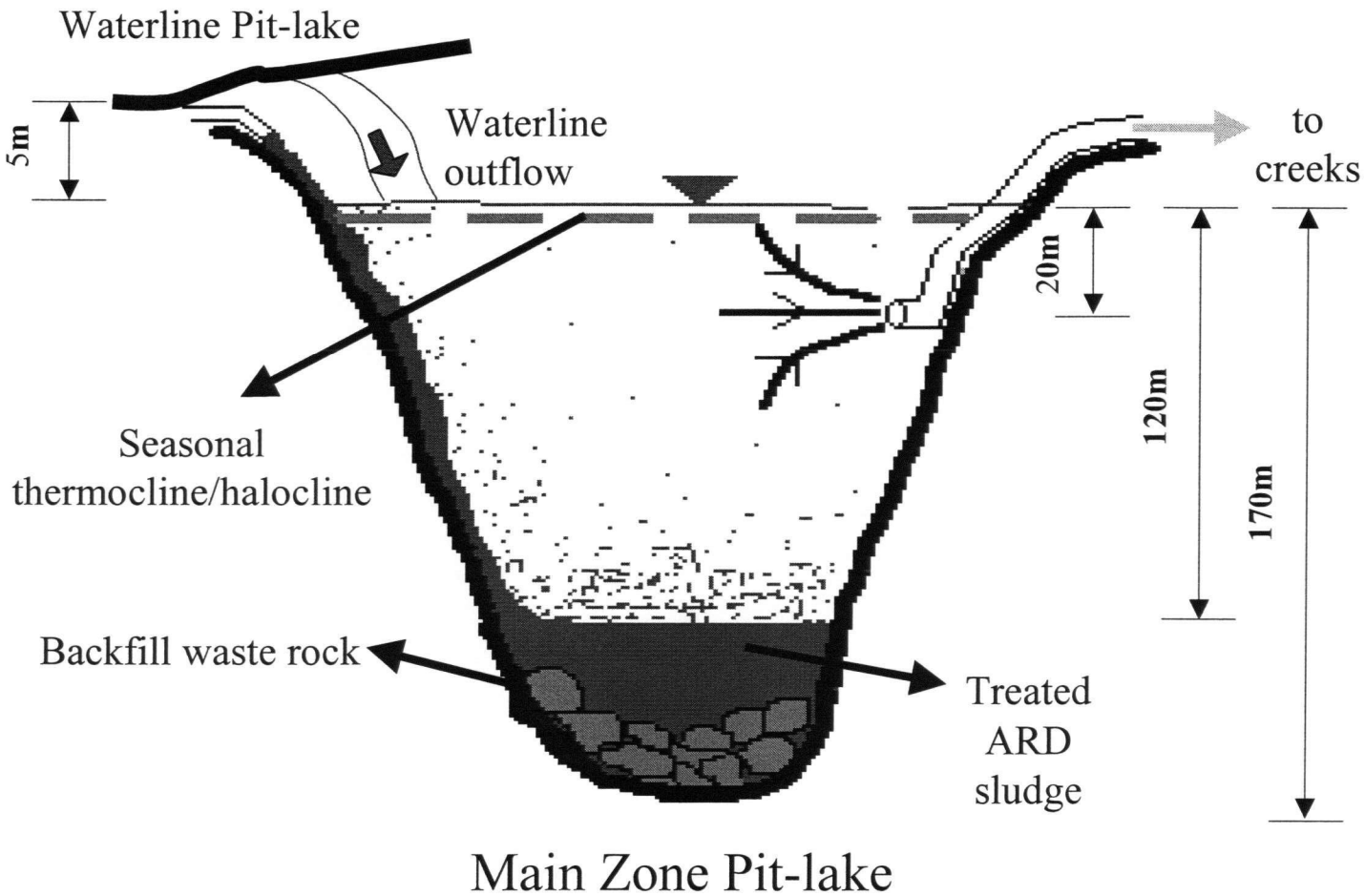


Figure 1.4 Schematic of the Main Zone Pit-lake cross section (not to scale)

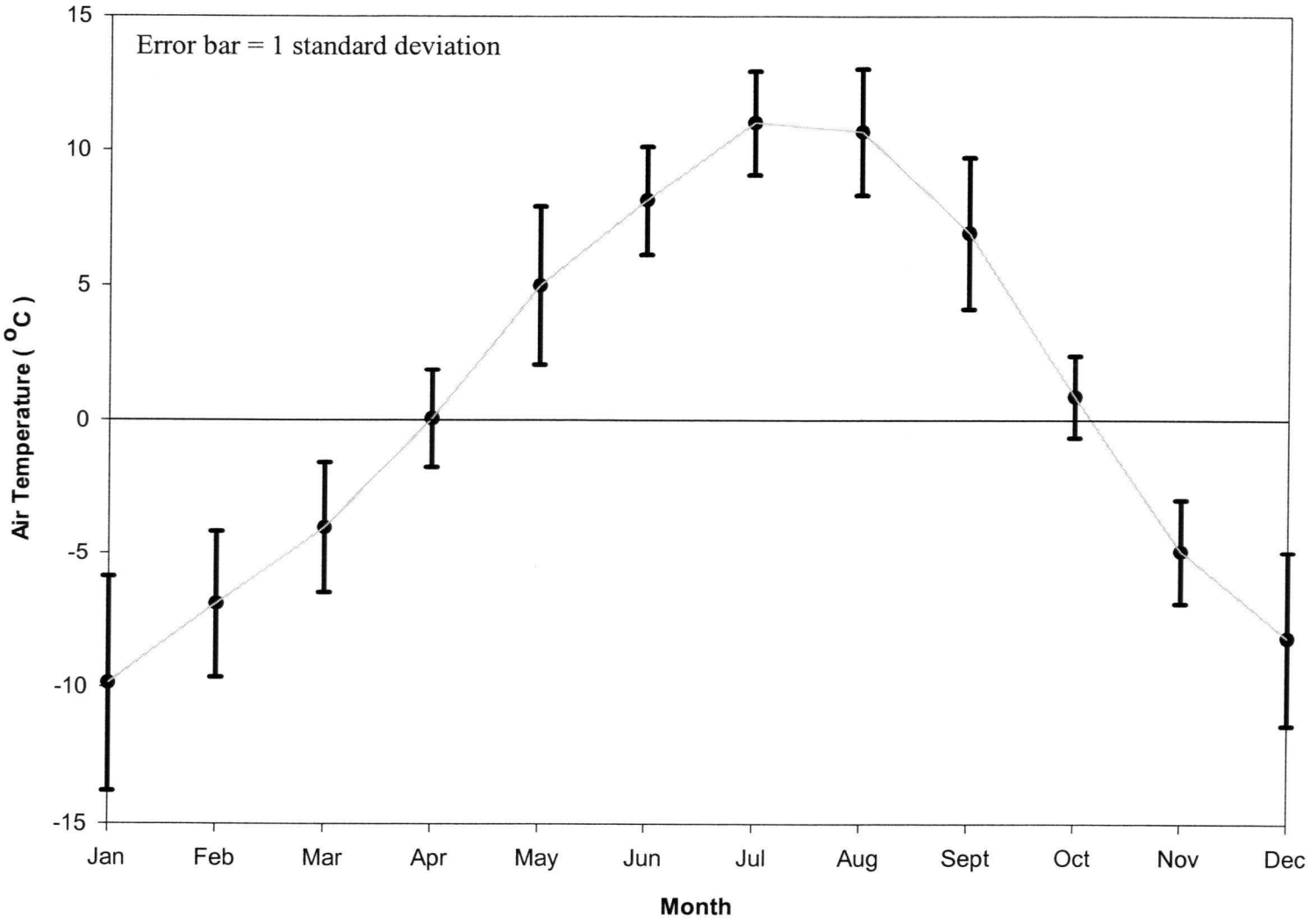


Figure 1.5 Average monthly temperature at the Equity Silver Mine during the period of 1990-2000 (based on Aziz 2001)

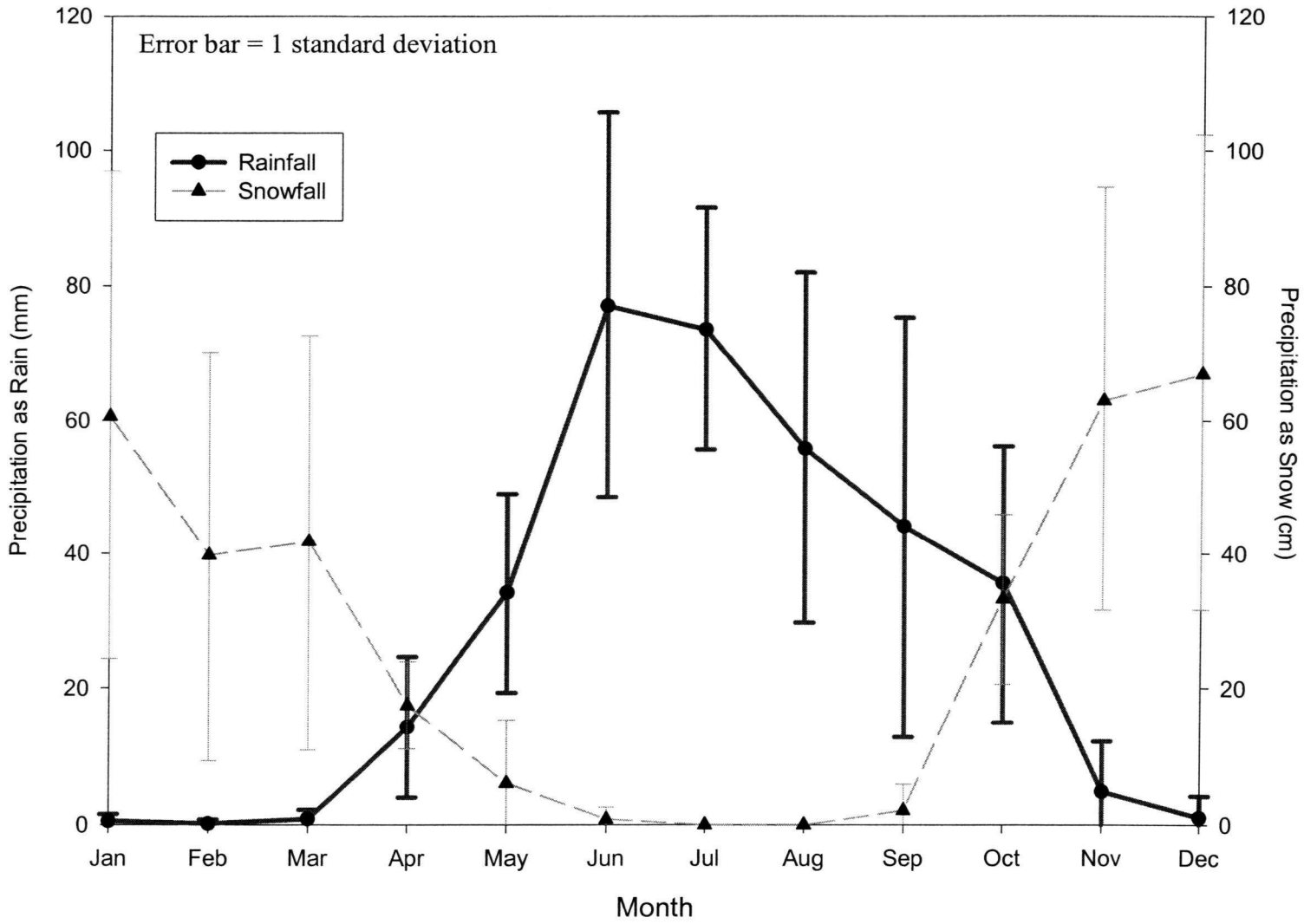


Figure 1.6 Average monthly precipitation at the Equity Silver Mine during the period of 1990-2000 (based on Aziz 2001)

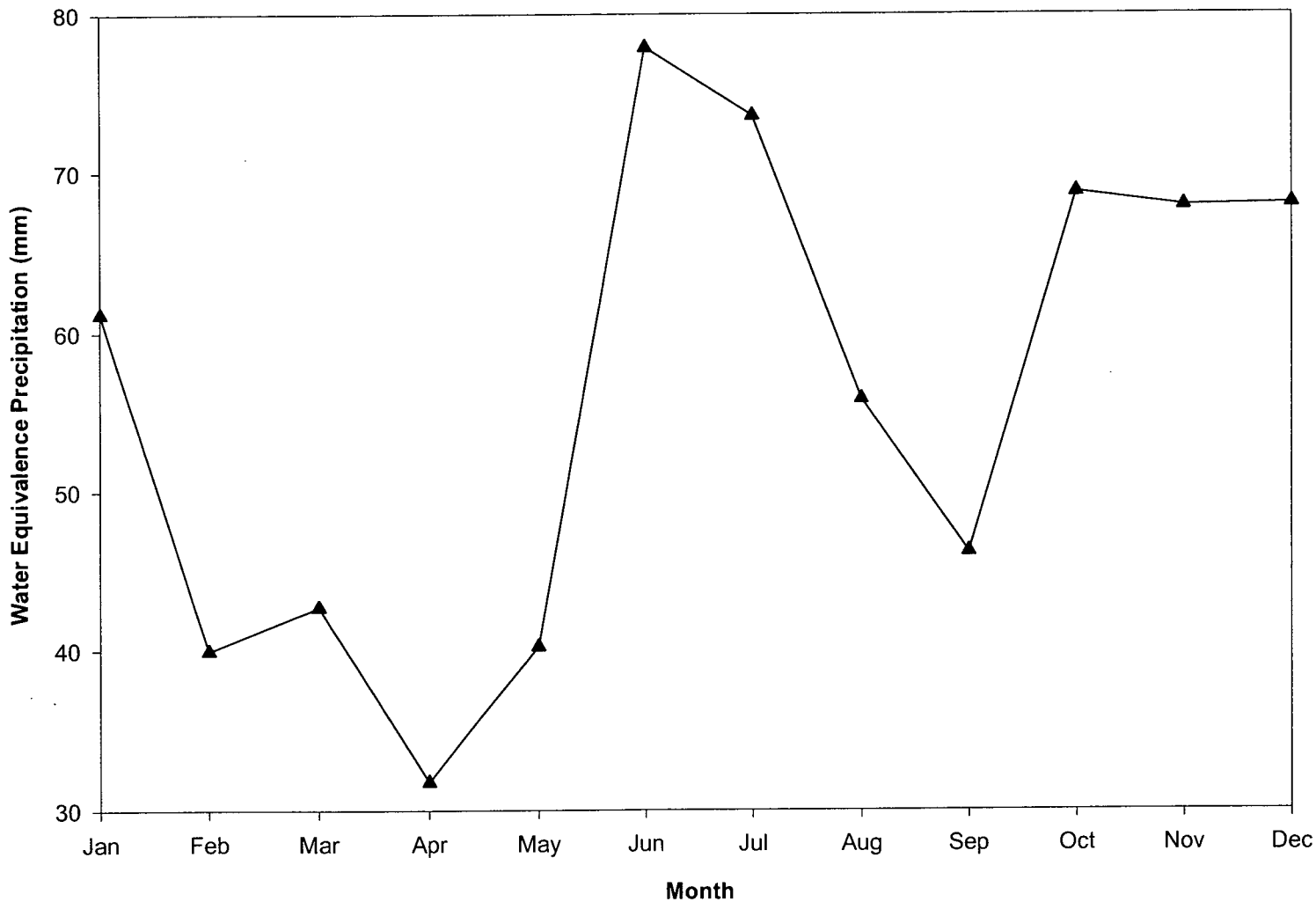


Figure 1.7 Average water equivalence precipitation (snowfall+rainfall) in the Equity Silver Mine (1990-2000)
Note that 10 parts of snow are assumed to be equivalent to 1 part of rain according to Cutnell and Johnson (1995)

2 PIT-LAKES HYDROLOGY

2.1 Physical Characteristics of The Waterline and Main Zone Pit-lakes

The Waterline and Main Zone pit-lakes are adjacent water bodies in the Equity Silver Mine site. The Waterline Pit-lake is shallower, narrower and smaller than the Main Zone Pit-lake. The physical characteristics of both pit-lakes are determined from a pit diagram (see Figure 1.3) and summarized in Table 2.1 as followed.

Table 2.1 Estimated physical characteristics of the Equity Mine pit-lakes

	Main Zone	**Waterline**
Maximum length	710 m	460 m
Maximum width	470 m	150 m
Mean width	290 m	57 m
Maximum depth	120 m	43 m
Mean depth	47 m	18.5 m
Current average water level	1260 m	1265 m
Lake surface area (at current water level)	20.5 ha	2.6 ha
Pit-lake volume (at current water level)	9.7 Mm^3	0.48 Mm^3

2.2 Hypsographic Characteristics

The pit area and maximum volume were determined from the contour map of Baase (1991). Since the wall of both the Waterline and Main Zone pits are benched (Figure 2.1), the volumes of the pit-lakes are calculated by sub-dividing into box-layers (9 for the Main Zone and 5 for the Waterline) such that they always lie between two consecutive benches. The volume of each box-layer, except for V_1, is determined by the following equation,

$$V_i = \left(\frac{A_{bi} + A_{ti}}{2} \right) B_i \qquad (2\text{-}1)$$

where V_i is the volume of ith box layer; A_{bi} and A_{ti} are the bottom and top area, respectively, for the ith layer and $B_i = Z_i - Z_{i-1} = Z_i$ is the bench height for the ith layer. The bottom area for every box includes the area of the bench, whereas the top area does

not. On the other hand, the box volume for V_1, bounded by the 1090 m, which is the pit bottom elevation, and 1125 m contour lines, is calculated with an assumption that the layer takes on the shape of a circular cone,

$$V_1 = \frac{A_{t1} B_1}{3} \tag{2-2}$$

The hypsographic curves for the Waterline and Main Zone pits are shown in Figure 2.2. By subtracting the volume of the backfilled waste rock and the previously deposited sludge (1993-2000), the pit-lake volume in 2000 can be calculated. However, when calculating the present volume of water in the pit, adjustments have to be made in order to take into account of the subsequent sludge discharges (2001-present) after the pit was filled to the current water level (see section 2.3).

The Main Zone pit volume can be confirmed by comparing to the total volume of water and solids added during the pit-filling stage from 1991 to 2000 when the water level reached 1259.3 m (Table 2.2). Added into the Main Zone pit were:

(i) *Backfilled waste rock*- Portion of the waste rock from the Waterline and Main Zone were backfilled into the Main Zone pit until 1991 (Baase 1991).

(ii) *Base volume*- The volume of water that was already present due to groundwater and precipitation runoff in the Main Zone pit was estimated before the pit-filling (Aziz 2000).

(iii) *Berzelius Diversion inflows*- Placer Dome strategically diverted water from the Berzelius Diversion canal to the Main Zone pit to speed up the filling process. However, during the 1999 freshet, an unknown amount of water overflowed into the Waterline pit, and drained into the Main Zone pit (Aziz 2000).

(iv) *Groundwater, runoff and precipitation*- Placer Dome estimated the combined volume of groundwater, runoff and precipitation inflow base on the water balance during the period of September 1999 and November 2000.

(v) *Treated water*- The ARD was collected and treated on the site. The resulting treated water was discharged into the Main Zone pit since 1997 (Aziz 2000).

(vi) *Sludge*- The sludge, which is the by-product of the ARD treatment, has been discharged into the Main Zone pit since 1993 (Aziz 2000).

Table 2.2 The breakdown of inflows to the Main Zone pit during the period of pit-filling (1991-2000)

	Mm^3
Back-filled waste rock *(Baase, 1991)*	1.48
Base volume of pit water before pit-filling at 1993 *(Aziz 2000)*	0.26
Inflows from Berzelius Diversion	>2.13
Groundwater + runoff + precipitation *(Aziz 2000,2001)*	5.62
Sludge discharge *(Aziz 2001)*	1.06
Treated water discharge *(Aziz 2001)*	0.92
Total volume of inflow for pit-filling	>11.5
Estimated total lake volume below 1259.3 m	12.2

As shown in the Table 2.2, the total volume of water and solid inflows into the Main Zone pit from 1993 to 2000 was at least 11.5 Mm^3. In 1999 and 2000, the volumes of inflow from the Berzelius Diversion were not known and were not accounted for when calculating the total inflow volume into the Main Zone pit (Appendix A). As a result, our estimate of the lake volume, which is about 12.2 million cubic meters, agree reasonably well with the total inflow volume during the pit-filling period.

2.3 Present Pit-lakes Volume

Before the retention time of a lake can be determined, the volume of water currently residing in a lake must be known. The management strategies for the Waterline and Main Zone pit-lakes are different. For example, Main Zone Pit-lake has been the repository for the treated ARD sludge as well as waste rock. On the other hand, Waterline Pit-lake does not have any artificial solid discharge or input. Therefore, an adjustment has to be made when calculating the volume of water in the pit-lake.

Waterline Pit-lake- The maximum water level is controlled by the Waterline Outflow located at the elevation 1265 m. The lake seems to always stay at the maximum level as water always overflows into the Main Zone pit during the ice-free period. With the assumption that the volume of natural sedimentation is negligible, the pit-lake water volume can be estimated directly from the hypsographic curve for the Waterline pit in Figure 2.2. The pit-lake volume is roughly 0.48 Mm^3.

Main Zone Pit-lake- The total volume of water in the Main Zone pit is not simply the same as the volume of the open pit before it was filled up with water to a certain level. Since a significant amount of space is taken by the waste rock that was dumped into the pit before it was flooded (Baase 1991), as well as the ARD sludge solid that has been discharged subsequently since the decommission of the Main Zone pit in 1993 (Aziz 2001: email communication), the total volume of the lake water in the pit has to be corrected accordingly.

The total volume of the waste rock ($V_{wasterock}$) deposited in the Main Zone pit is approximately 1.48 x M m^3 (Baase 1991). Meanwhile, sludge was discharged into the pit even after the pit-filling stage. An additional 0.12 Mm^3 of sludge was discharged (Aziz 2002: email communication), resulting in the total volume of 1.18 Mm^3 sludge accumulated (V_{sludge}) at the pit bottom by the end of year 2001. With our estimate of the pit volume for the Main Zone (V_{pit} =12.3 Mm^3), the volume of water in the pit lake can be determined using the equation 2-3:

$$V_{water} = V_{pit} - V_{sludge} - V_{wasterock} \qquad (2\text{-}3)$$

Natural sedimentation is assumed negligible and the total volume of water in the Main Zone Pit-lake is approximately 9.7 Mm^3.

2.4 Water Drainage

The Equity Mine pit-lake system consists of 4 hydrological units: Main Zone Pit-lake, Main Zone's 'upslope' watershed areas, the Waterline Pit-lake and the Waterline's 'upslope' watershed area (Figure 2.3). Emerson and Smith (1991) referred the area immediately to the east of the Main Zone pit and Waterline pit as 'upslope'. For the purpose of this thesis, the 'upslope' drainage areas associated with the Main Zone pit and Waterline pit are the area immediately east of the two mine pits and west of the Upper Bessemer Creek and Berzelius Creek Diversion. Note that for the purpose of studying the hydrological properties of the pit-lakes, the pit wall is incorporated with the pit-lake's hydrological unit because most precipitation that falls onto the pit wall becomes surface runoff and the time of travel to the lake is very short.

The Waterline Pit-lake is located immediately northeast of the Main Zone Pit-lake and its water surface elevation sits 5 m above that of the Main Zone Pit-lake at 1265 m. During the ice-free period, lake water from the Waterline Pit-lake spills over and flows into the Main Zone Pit-lake through the Waterline outflow and, hence, the Waterline pit and its drainage area are also part of the Main Zone's hydrological system. Also, the estimated leakage from Berzelius Creek to the Waterline Pit-lake of 1.3 Mm^3/yr (Aziz 2001) and discharge of treated ARD water to the Main Zone (see Appendix A) augment the overall volume of water inflow to the pit-lake system as illustrated in Figure 2.3.

For the purpose of calculating the volume of water input into the pit-lakes, several assumptions or adjustments were made in this thesis for simplification. Firstly, the yield of 14.0 $L/s/km^2$ (Aziz 2002, 2003) for water drainage stays constant throughout the entire watershed area of the Main Zone/Waterline hydrological system and the yield has already taken into account the water loss before reaching a water body from processes such as evapo-transpiration. Since the total area of the two pit-lakes is comparable to the total watershed area (pit-lake area to drainage area ratio = 1:0.88), a significant portion of water going to the pit-lakes is direct precipitation. In consequence, the on-land water loss should be relatively insignificant to the total amount of water reaching the pit-lakes. Secondly, by

balancing the outflow (withdrawal) minus the inflow (sludge and treated water) with the changes in pit-lake volume (due to corresponding changes in water elevation, Aziz (2000, 2001) suggested that the total amount of water inflow to the Main Zone Pit-lake through groundwater, precipitation and normal runoff were 3.3 Mm^3 from August 1997 to September 1999 and 9.4 Mm^3 from September 1999 to end of November 2000. Using that as a reference, along with the assumed value of yield for drainage, it is possible to back-calculate the annual groundwater flow to the Main Zone Pit-lake, which is 0.44 Mm^3/yr. However, this assumes the groundwater inflow into the Waterline Pit-lake to be zero. Thirdly, water loss to the atmosphere through evaporation at the lake surface is small. For example, with lake temperature of 10 °C, air temperature of 0 °C and wind speed of 3 m/s, the evaporative moisture flux, according to Fischer et al. (1979), at the water surface would be roughly 0.47 mm/day (equivalent to 35 m^3/day and 180 m^3/day in the Waterline Pit-lake and the Main Zone Pit-lake, respectively). Therefore, it can be ignored. Lastly, discharging tailing pond water into the Main Zone Pit-lake was not a usual practice at the Equity Silver Mine and was done only in the summer of 2002; as a result, inflow of tailing pond water was excluded when calculating the total water drainage into the Main Zone Pit-lake. The hydrological characteristics of both pit-lakes are summarized in Table 2.3 and Table 2.4, whereas detail breakdown of the watershed system, the corresponding drainage areas and calculation of retention time can be found in Appendix B.

Table 2.3 Hydrological characteristics of the Waterline and Main Zone pit-lakes

	Waterline	**Main Zone**
INFLOWS (Mm^3/yr):		
Direct precipitation	0.050	0.25
Direct drainage	0.059	1.5
Leakage from Berzelius Creek Diversion	1.3	0
Groundwater inflow	0	0.44
Total inflow	1.4	2.4
PIT-LAKE VOLUME (Mm^3):		
Total volume at current water level	0.48	9.6
MEAN RETENTION TIME (yr):		
Bulk retention time	0.34	4.0
Effective retention time (see section 2.5)	0.050-0.14	N/A

2.5 Retention Time

The bulk retention time is defined as the volume of the water body divided by the total inflow rate and gives a measure of how fast the water may get flushed out of the lake. However, due to the differences between the Waterline and Main Zone pit-lakes in terms of the stratification, inflow and catchment, retention times are adjusted below to give more meaningful retention times.

Waterline Pit-lake- As opposed to the bulk retention time applied in the Main Zone Pit-lake where overturn occurs at least once a year (see chapter 5), the bulk retention time for the Waterline Pit-lake might not be a representative parameter since the pit-lake seems to be permanently stratified. Therefore, a retention time effective for the surface mixed layer (epilimnion) would be preferable in this case and would be smaller than the bulk retention time.

The major water inflows into the Waterline Pit-lake are direct precipitation and runoff from the wall, including leakage of water from the Berzelius diversion canal above the Waterline pit, all of which are assumed to contribute to the epilimnion. The rate of water leakage was estimated to be about 1.3 Mm^3/yr (Aziz, 2001). The halocline depth during the sampling period (2001 Summer to October 2002) ranges from 2.9 m in June to 8.8 m in January, corresponding to the volume of 0.071 Mm^3 to 0.19 Mm^3 (Figure 4.1). As a result, the mean effective retention time of the epilimnion varies from about 0.6-1.7 months.

Main Zone Pit-lake- In the Main Zone Pit-lake, whole-lake mixing happens at least once a year due to the fall turn-over according to the data collected from June 2001 to August 2002 (see chapter 5). Bulk retention time is more appropriate in this case from the perspective of annual water and nutrient budget calculation. However, discharging treated ARD sludge into the pit-lake reduces the retention time in two ways: (1) by increasing the flow of water and (2) by gradually reducing the volume of the pit-lake as sludge solid fills the bottom.

The bulk retention time for the Main Zone Pit-lake is approximated to be 4.0 years. However, the Equity Silver Mine Ltd. started to fill the Main Zone pit with water in 1993 and took about 7.5 years (until November 2000) for the water level to reach the current average level (~1259.3m). The discrepancy between this and the estimated retention time is possibly due to the lack of inflow from the Waterline Pit-lake (Waterline pit had probably not yet been filled during the filling stage of the Main Zone pit; however, no record was found with regard to the filling stage of the Waterline pit).

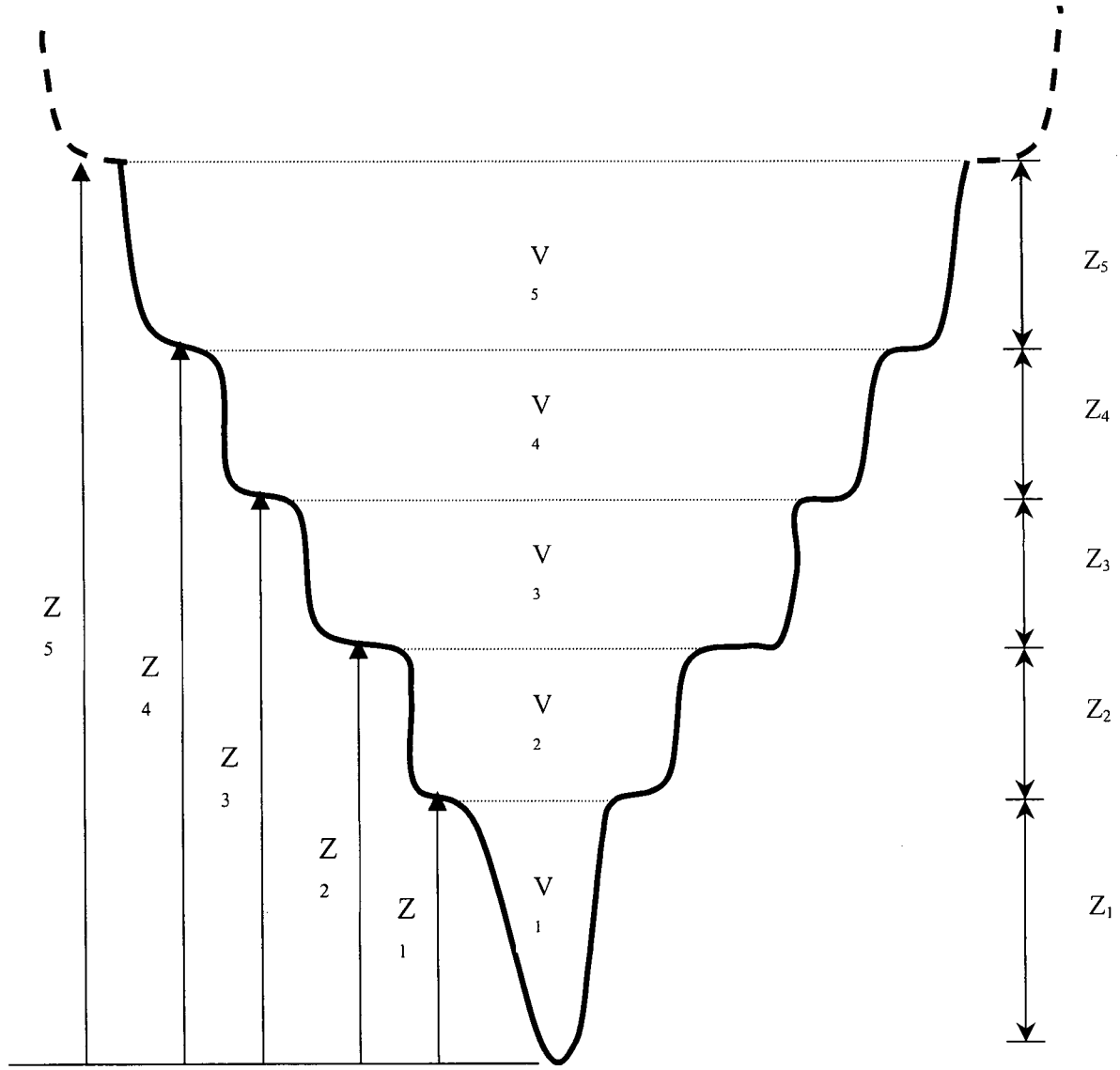
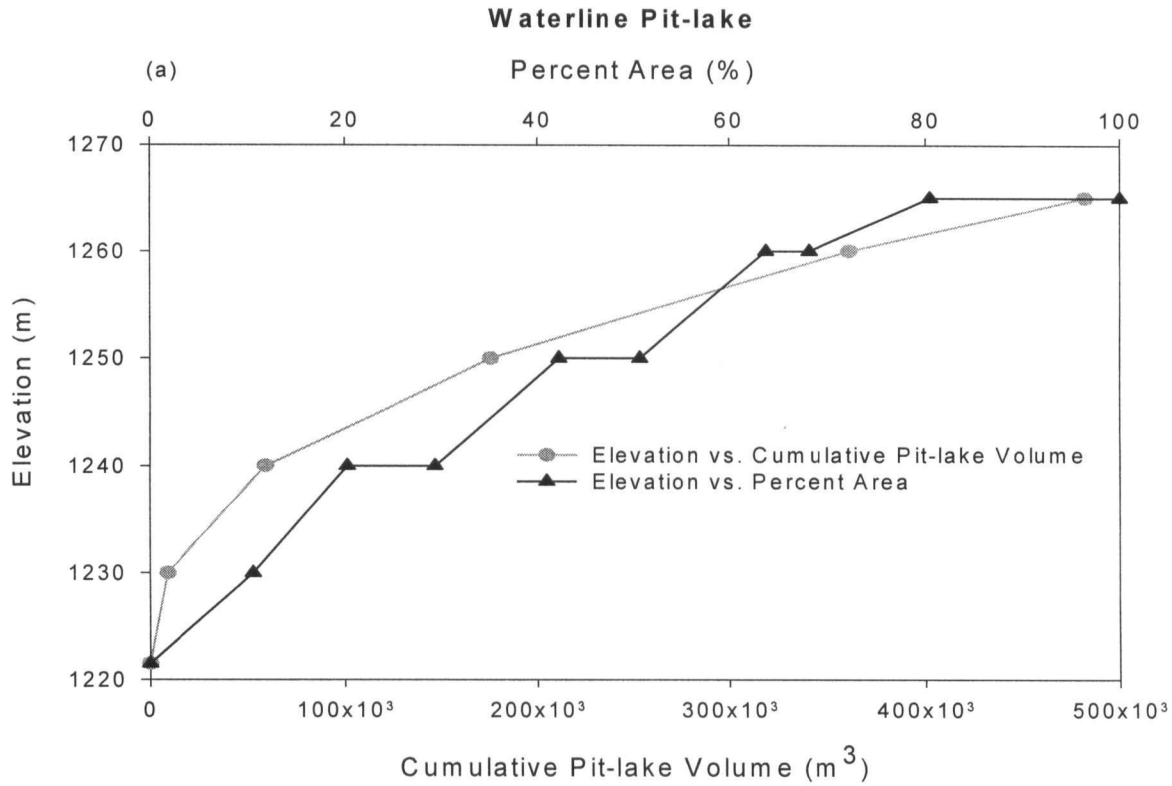


Figure 2.1 Schematic sketch for the Waterline and Main Zone pits cross section



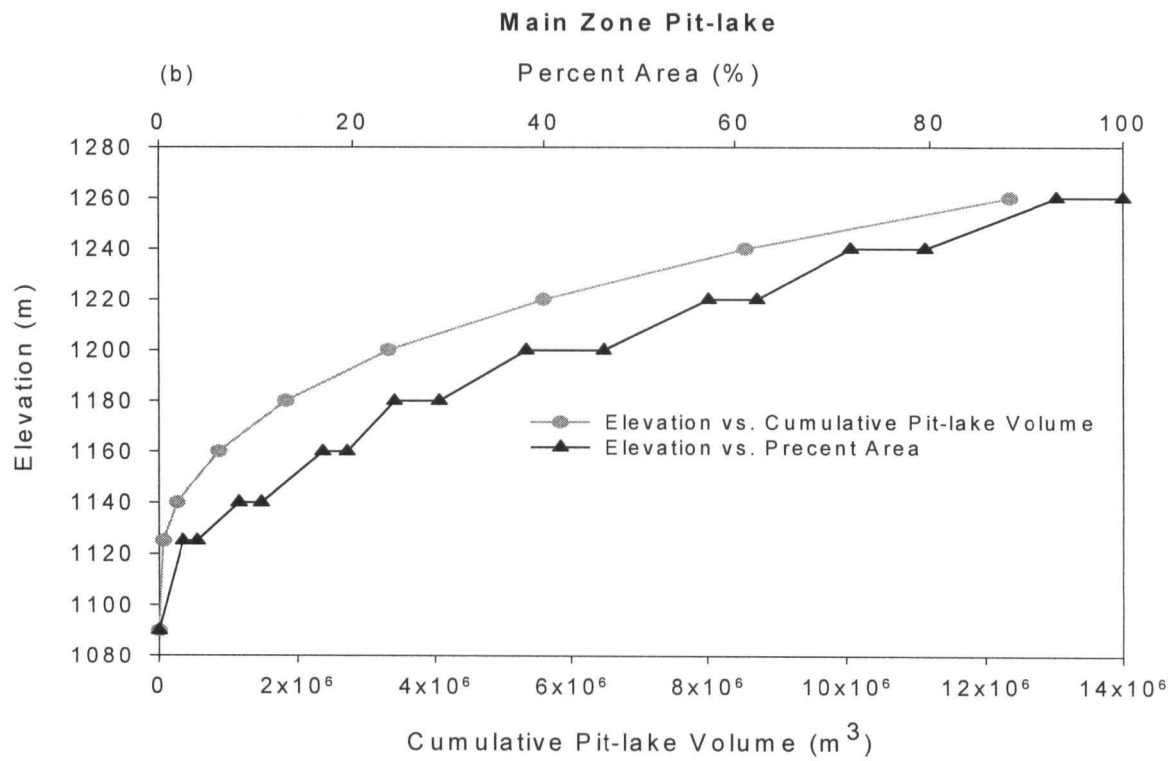


Figure 2.2 Cumulative volume and percent area curves for the (a) Waterline and (b) Main Zone pit-lakes

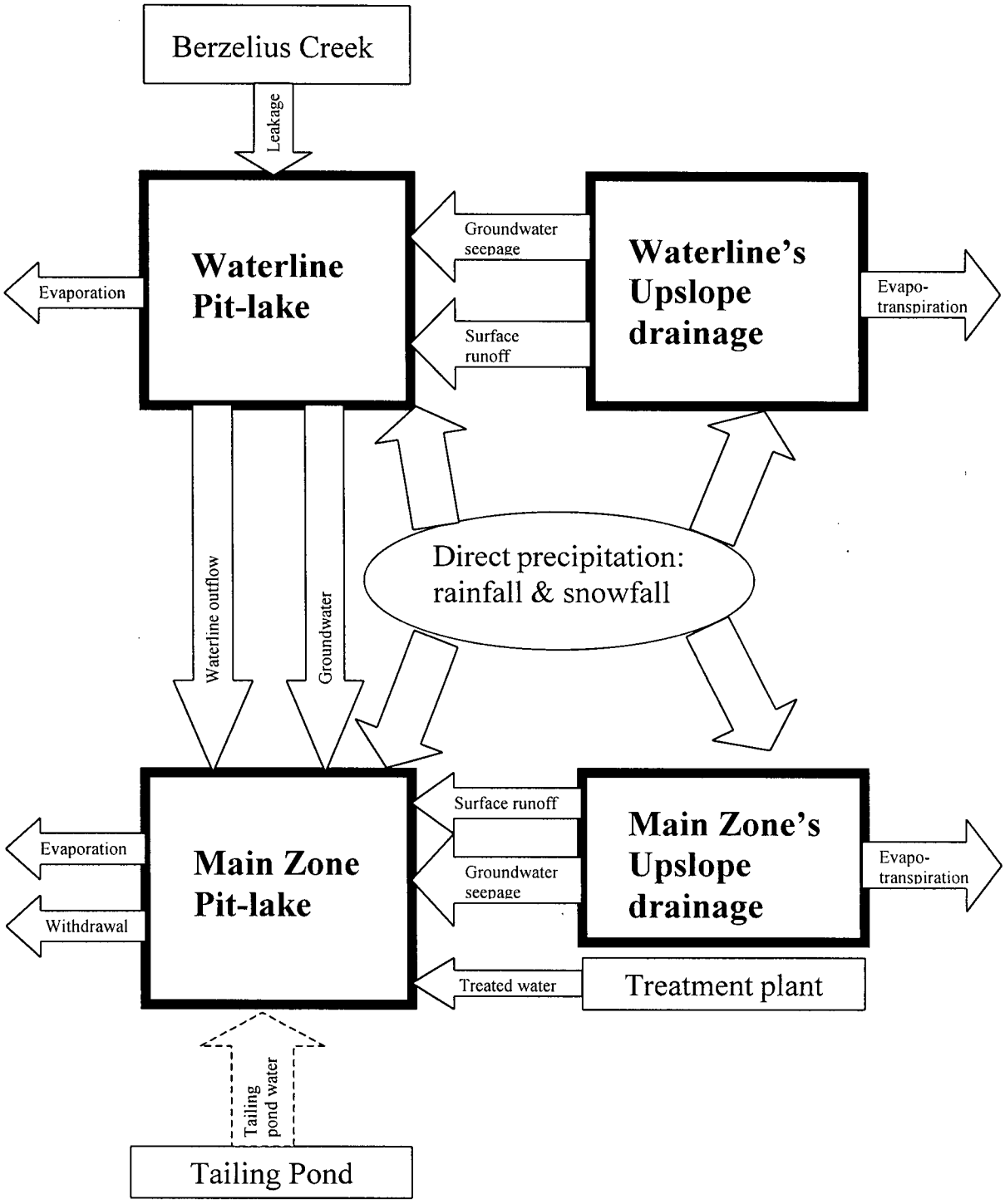


Figure 2.3 Flow chart of the water drainage for the Waterline and Main Zone pit-lakes. Note that the discharge of tailing pond water was not included into the hydrology study of the pit-lakes in this thesis.

3 FIELD METHODOLOGY

A two-year field program was conducted from June 2001 to June 2003. The fieldwork consisted of pit-lake sampling and CTD surveys. During the first year, the major focus was the Main Zone Pit-lake. A thermistor chain was deployed in June 2001 and a meteorological station was set up in October 2001. Meanwhile, limited chemical sampling and CTD surveys were also done in the Waterline Pit-lake. After further funding for study in the Waterline Pit-lake was received, a meteorological station and thermistor chain were deployed in June 2002. In addition, during the summer of 2002, remediation experiments were conducted in mesocosms, or limnocorrals (Crusius et al. 2003, McNee et al. 2003). However, these limnocorral experiments, along with other geochemical sampling such as sediment traps, will not be described here.

There are two temporally different types of field measurements: discrete and continuous. Discrete surveys, such as conductivity-temperature-depth (CTD) casts, collection of water samples and lake ice and secchi depth, were made during the eleven sampling trips to the site over the two-year span from 2001 to 2003 (June, August and October in 2001; January, March, June, August and October in 2002; January, March and June in 2003). Continuous lake water temperature and meteorological measurements were collected by moored thermistor chains and meteorological stations deployed on the rafts to monitor the changes in pit-lake conditions and physical forcing during the periods between sampling trips. Figure 3.1 illustrates the location of the rafts and deployments of the moored equipments in both pit-lakes. Note that this thesis will describe data collected from June 2001 to October 2002.

3.1 Lake Surveying

3.1.1 Sampling and Measurement Location

While most of the lake surveys were done from the rafts at the location where the water depth was maximum (Figure 3.1), occasional measurements at different points of interest

(e.g. near the sludge discharge, Waterline Outflow and various points along the lake thalweg) were also carried out. However, before the rafts were established in the Waterline, all measurements were conducted from a boat.

Moreover, there are major tributary inflows in both pit-lakes such as the Berzelius leakage to the Waterline, the ARD discharge and Waterline Outflow to the Main Zone. As a result, sampling of water inflows to the pit-lakes was necessary since they could affect the water balance, heat balance, material budget of chemicals of interest and even the mixing mechanisms of the water bodies.

3.1.2 Physical Parameters

There is a range of physical parameters that need to be determined in order to have a better understanding of the physical mechanisms that control the water quality in the Waterline and Main Zone pit-lakes. Parameters that have been monitored include spatial and temporal distribution of specific conductivity, temperature, and oxygen content and external forcing such as wind speed and direction, air temperature and relative humidity, solar radiation, properties of the sludge discharge and Waterline Outflow, and hydrological properties of the pits.

Specific Conductance and Water Temperature- In-situ conductivity and temperature were measured using a SBE19 CTD profiler (Figure 3.2). Most of the CTD casts were done from the rafts in the Waterline and Main Zone with occasional measurements at various other locations. Table C.1 lists the time, location and operator(s) of all CTD casts that were done from June 2001 to October 2002.

Conductivity is a measure of the ability of a water parcel to conduct electricity. This depends directly on the concentration of charged atoms and molecules, namely ions, derived mostly from dissolved inorganic materials. However, temperature also affects conductivity strongly, necessitating the adjustment to a standard temperature. As a result,

all conductivity data recorded with the CTD were subsequently corrected to 25 °C (specific conductance) so that it reflects the relative ionic content of a water parcel. An equation for converting to conductivity at 25 oC has not been determined for the Equity pit-lake water. As a result, conductivity was corrected to 25 °C using an equation for potassium chloride. With the assumption that the ions present are conservative, the specific conductance serves as a tracer to identify water parcels with various origins and histories.

Discrete water samples were also collected in 500 ml Nalgene bottles for specific conductance determination using a Radiometer CDM210 conductivity meter and/or Guildline Portasal Salinometer, and density determination using an Anton Parr DMA 5000.

Specific conductance is an indirect measure of salinity and density. Salinity is a measure of the mass of dissolved salts (ionic constituents) in a given mass of solution. Salinity can be determined from specific conductance using an extension of practical salinity scale (PSS78) developed by Hill et. al (1986) and valid for 0-40 practical salinity units (PSU), assuming the dissolved ion content of pit-lake water is similar to that of seawater. Density of water can then be calculated using an equation of state specific for pit-lake.

Since an equation of state has yet to be determined for the Waterline and Main Zone pit-lakes, density estimates can be made with the equation of state for seawater 1980 (EOS80). However, EOS80 may not give accurate results since pit-lake water has different chemical composition from seawater, which contains major ions such as Ca^{2+}, Mg^{2+}, K^{+}, Na^{+}, Cl^{-}, CO_3^{-}, HCO_3^{-}, NO_3^{-} and SO_4^{-}. The equation of state developed by Chen and Millero (1986) gives better results, since it is valid for low salinity water (0-0.6 PSU). Although the salinity in the Waterline and Main Zone pit-lakes ranges from 0.5 to 1.4 PSU, the equation of state by Chen and Millero (1986) will be used in this thesis to calculate density difference between layers to determine the possibility of upwelling and to estimate seiching periods in the pit-lakes (Chapters 4 and 5).

Turbidity and Fluorescence- Turbidity of the water was measured by a transmissometer attached to the SBE19 CTD system (Figure 3.2). Since the transmissometer is only

sensitive to water with low turbidity, an optical backscatter sensor (OBS) was added to the CTD in June 2002 to measure high turbidity water, to observe the relative differences within the sludge plume (see Chapter 5) and to delineate the boundary of unconsolidated sludge at the bottom.

A fluorometer was also attached to the CTD system to measure fluorescence, an indicator for the presence of a certain pigment within plant cells, namely chlorophyll *a* (i.e. chl-*a*), and thus, an indicator for the presence of phytoplankton biomass. The units here are based on the response of the fluorometer to 0.5mg/L of coproporphyrin methyl ester being equivalent to 50 μg/L of chl-a. The fluorescence data has not been calibrated to actual chl-a samples collected. Like turbidity, chl-*a* is an imperfect scientific measure as chlorophyll concentration can vary with the composition of phytoplankton community and with chlorophyll degradation products (phaeophytins). Nevertheless, from fluorescence measurements we could infer the presence or absence of phytoplankton, and the time and depth of the algal blooms.

Oxygen Content- The depth at which water samples were collected for oxygen determination and the results are listed in Appendix C (Table C.2 and C.3). Water samples for oxygen content analysis and conductivity were collected (1) using a 5 L Niskin bottle, which was attached to a marked Kevlar line 1 m above the CTD, or (2) using a tygon tube and peristaltic pump in winter. Samples for oxygen determination were then carefully transferred to 250ml glass stopped bottles, and fixed immediately. All samples were kept in the dark until analyzed by the Winkler Titration Method (Culberson 1991). The conversion of titration volume to the amount of dissolved oxygen was done according to Dickson (1996).

Primary physical factors determine the saturated oxygen concentration level including water temperature, salinity, partial pressure of oxygen in the atmosphere and exchange processes with the atmosphere. Water temperature governs the solubility of oxygen in water with reduced solubility at higher temperature. Meanwhile, the effect on the saturation level from the partial pressure of oxygen in the atmosphere is directly

proportional to altitude. At high altitude, atmospheric pressure is lower and the partial pressure of oxygen, and the saturation level is lower relative to that at the sea level. In fact, the saturation level decreases by approximately 4% per 300 m or per 1000 ft (Horne and Goldman 1994). Meteorology also has an effect on the partial pressure and hence, affects the saturation level of oxygen as the atmospheric pressure at sea level does not stay constant due to continuous passing of weather systems. However, pressure fluctuations due to meteorological effects is relatively minor and is usually ignored. Salinity only minimally impacts the solubility of oxygen. The water in the Equity Mine pit-lakes is brackish, on the order of 1000 μS/cm or ~ 0.5 in practical salinity units (PSU). For a change of 1 PSU, the variation in oxygen solubility is about 0.6 % (UNESCO 1973). For this reason, the salinity effect on oxygen saturation is ignored.

Secchi Depth- Secchi depths were determined by slowly submerging a 30.5 cm brass disk with white face upwards. The disk was attached to a marked rope. The depth at which the disk disappeared on the way down and the depth at which the disk reappeared on the way up were recorded and averaged. Most measurements were facing the sun to avoid shadows and to minimize bias due to an inconsistent amount of sunlight reaching the disk.

Potential Density – Water samples throughout the depth of both pit-lakes were collected by using a Niskin bottle (Table C.4 and C.5), and stored in 500 ml Nalgene bottles and kept cool and in dark in order to minimize any subsequent biological and related chemical activities. Density of the water samples was determined at 20 °C and atmospheric pressure using an Anton Parr DMA 5000 Density Meter, while the temperature of the water samples at certain depths was referred from the CTD profile. Potential density of samples at discrete depths was then estimated based on the international equation of state for seawater, or EOS80 (Millero et al 1980).

3.1.3 Miscellaneous Sample Collections

Runoff Sampling- Occasional sampling of a small waterfall on the east side of the Main Zone pitwall, which was normally absent during dry periods, was done after rainstorms. Samples were also collected from various seeps on the southern end of the Main Zone pit and the water leakage from Berzelius Creek at the northern end of the Waterline pit.

Ice Sampling- During winter, ice forms on the surface of both pit-lakes. During freezing, most salt is excluded from the ice. Therefore, during spring, when the ice thaws, it forms a relatively fresh water layer floating on the lake surface, resulting in salinity stratification. However, the ice will not be totally salt-free as some amounts of salt are still trapped inside the ice when it freezes up in the winter. For this reason, the strength of the early spring stratification and the mixing depend mainly on how much salt was trapped and stayed within the ice. For these reasons, an ice sample was collected for chemical and conductivity analyses.

3.2 Continuous Pit-lakes Monitoring

Temperature loggers and meteorological stations were moored in the Main Zone and Waterline pit-lakes to measure continuous changes in the lake temperature and the weather conditions.

Main Zone Raft- In the Main Zone Pit-lake, a 15 ft by 16 ft raft was built in 2001 June and situated over the deepest spot (Figure 3.1). The raft is held in place with four anchoring ropes over the top of the pit-wall to minimize both translational and rotational movement of the raft. There are two sampling holes in the raft: one for the deployment of a thermistor chain and the other one for the collection of water samples and CTD castings.

Waterline Raft- In the Waterline Pit-lake, two rafts were deployed in June 2002: one near the southern end of the pit and the other over the deepest spot near the northern end (Figure

3.1). Similar to the Main Zone, each of the two rafts in the Waterline also has 4 anchoring ropes. There is one sampling hole on each of the Waterline rafts, mainly for collecting water samples and CTD castings. Both the meteorological station and the thermistor chain were deployed on the northern raft.

Thermistor loggers- There was a main thermistor chain, with temperature sensors attached at certain depths (Figure 3.3), extending from the water surface to the lake bottom, deployed in each of the Main Zone and the Waterline pit-lakes in June 2001 and 2002, respectively. A complimentary thermistor chain about 6m long was added in June 2002 to the Main Zone in order to increase the spatial resolution of the temperature measurement in the upper layer and across the thermocline. Also, temperature loggers were deployed individually at the major tributaries to the pit-lakes, which will be discussed later in this chapter.

The thermistor loggers used were TR-1000, TR-1000F, XL-200, WADAR, Stowaway, Stowaway Tidbit and LM. Tables in Appendix C give the sampling depth and sampling period for all the instruments providing continuous measurements. Note that the sampling period was different from instrument to instrument and from one deployment to another, depending on their memory size and the time length between sampling trips. For convenience, the sampling period was generally chosen to be an integral divisor of an hour. There were time periods when data was missing during servicing of loggers.

Meteorological Stations- There were two meteorological stations installed on the pit-lakes: one on the Main Zone raft and the other on the northern raft in the Waterline. They both carried an anemometer to measure the wind speed and direction, a pyranometer to measure the short wave solar radiation, and a relative humidity and air temperature sensor (Figure 3.3). The meteorological station was installed on the raft in the Main Zone Pit-lake in October 2001; whereas the Waterline meteorological station was not installed until July 2002, when the northern raft was deployed and held in place in the Waterline Pit-lake.

The sampling interval of these stations was 15 minutes. There were some periods when data is missing during servicing with the exception of the Waterline meteorological station, which is capable of being uploaded without interruption.

Rainfall and snowfall data was collected at an existing meteorological station close to the ARD treatment plant about 1.5 km northwest of the Main Zone meteorological station and 1 km west-northwest of the Waterline meteorological station.

Lake Bottom- A pressure sensor was placed in the summer of 2002 in the Main Zone Pit-lake to determine the water-level fluctuations. Coupled with rainfall and snowfall data as well as the water withdrawal records for the Main Zone Pit-lake, changes in the water elevation can be used to determine the water balance and to further confirm the hydrological characteristics of the pit-lakes determined in Chapter 2.

Sludge Discharge Channel- Since the sludge density and the resulting properties of the density current are temperature dependent, a temperature sensor was deployed in the sludge discharge outflow channel in October 2001 (Figure 3.4). For a similar reason, a temperature sensor was placed in the Waterline Pit-lake close to the outflow to the Main Zone; however, it did not occur until June 2002. Discrete water samples were also collected from the sludge discharge and the Waterline Outflow for conductivity, density and other chemical analyses.

Waterline Outflow- A pressure sensor used to measure the pit-lake surface elevation was deployed in June 2002 close to the Waterline Outflow. In September 2002, a temperature sensor was also deployed at the same location. The pressure sensor was later moved to a deeper water approximately 20 m away from the outflow in October before the winter season of 2002/2003.

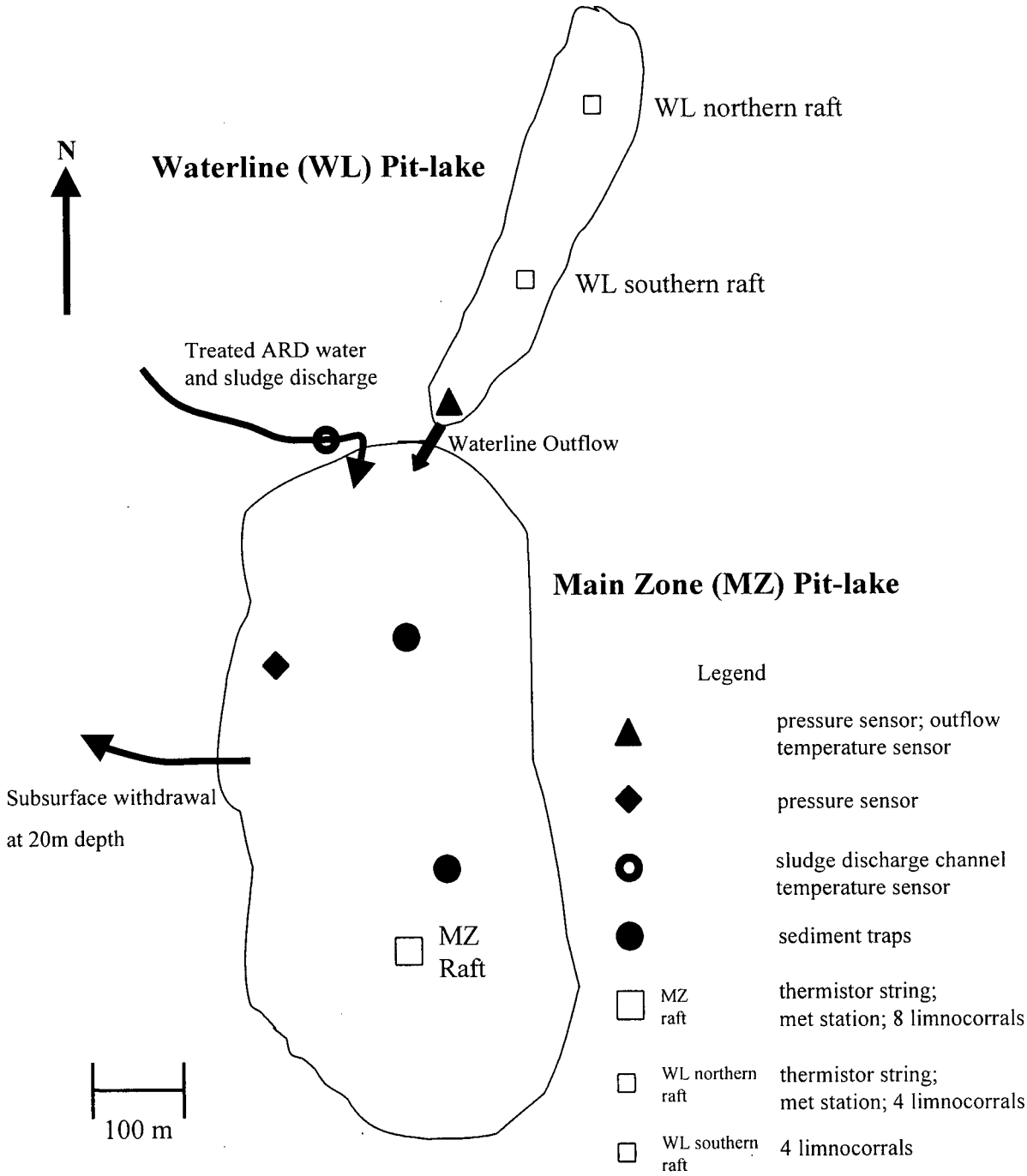


Figure 3.1 Location of the rafts and moored equipments in the Waterline and Main Zone pit-lakes

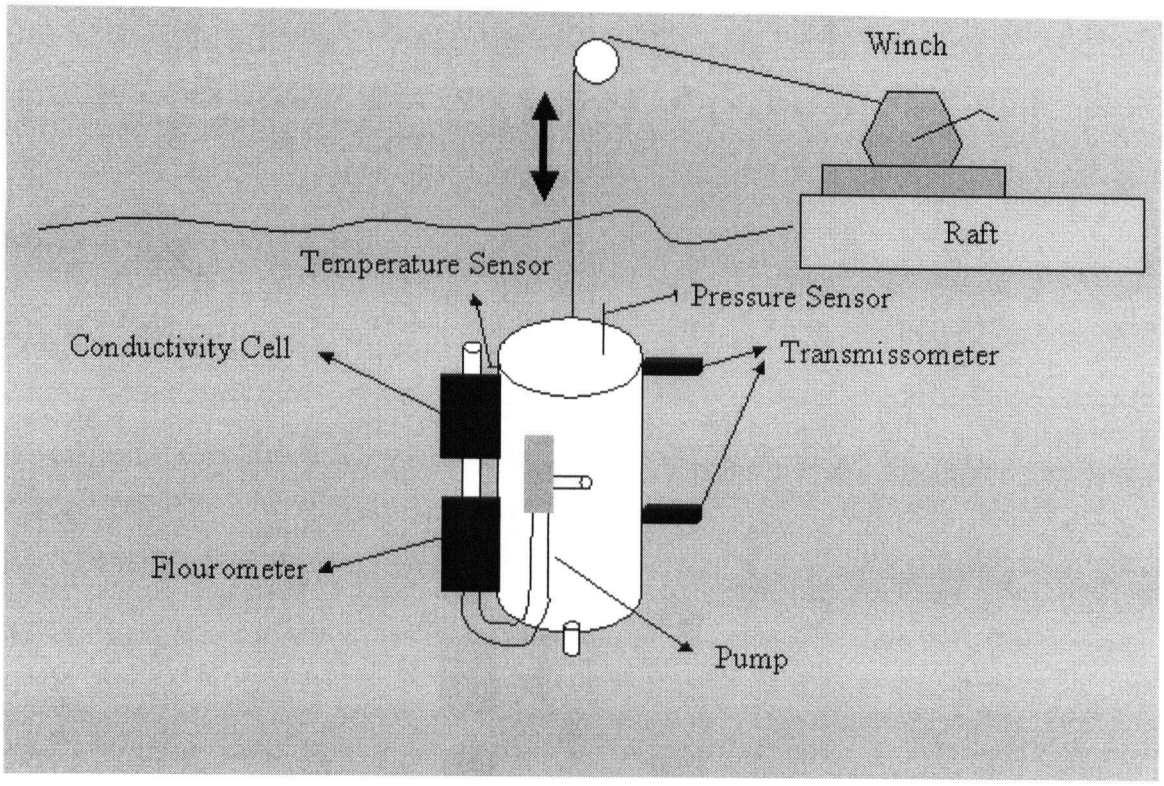


Figure 3.2 Set up of CTD casting and water sample collection on the raft

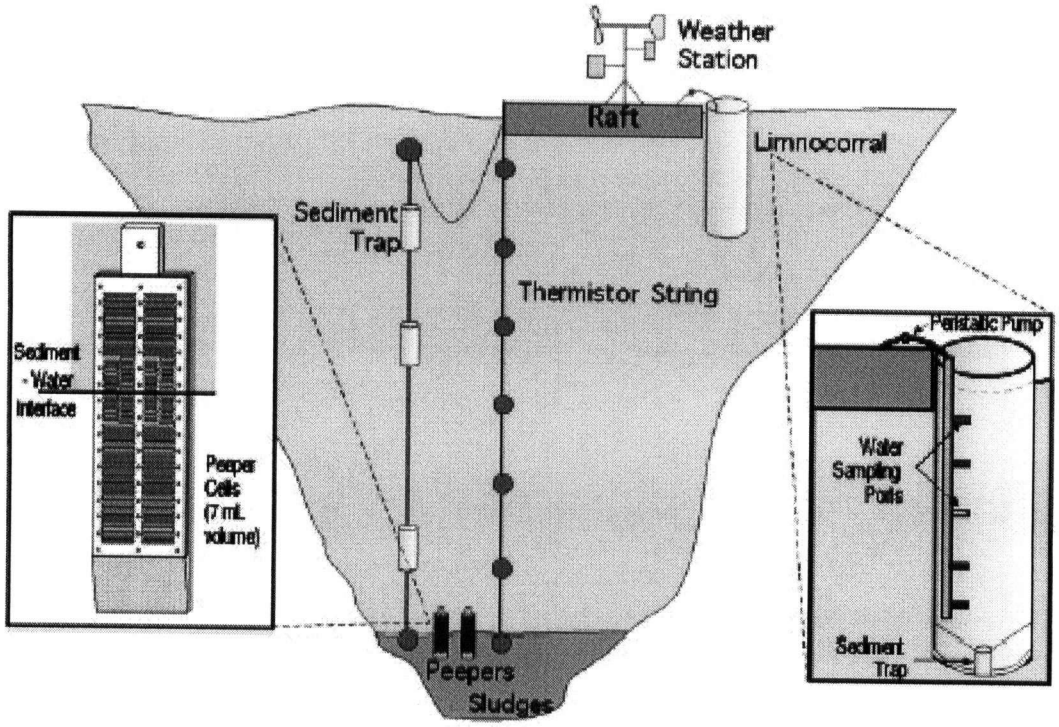


Figure 3-3 Schematic of the Main Zone Pit-lake field deployment of some measuring and sampling equipments attached from the raft (adapted from Crusius et al. 2003)

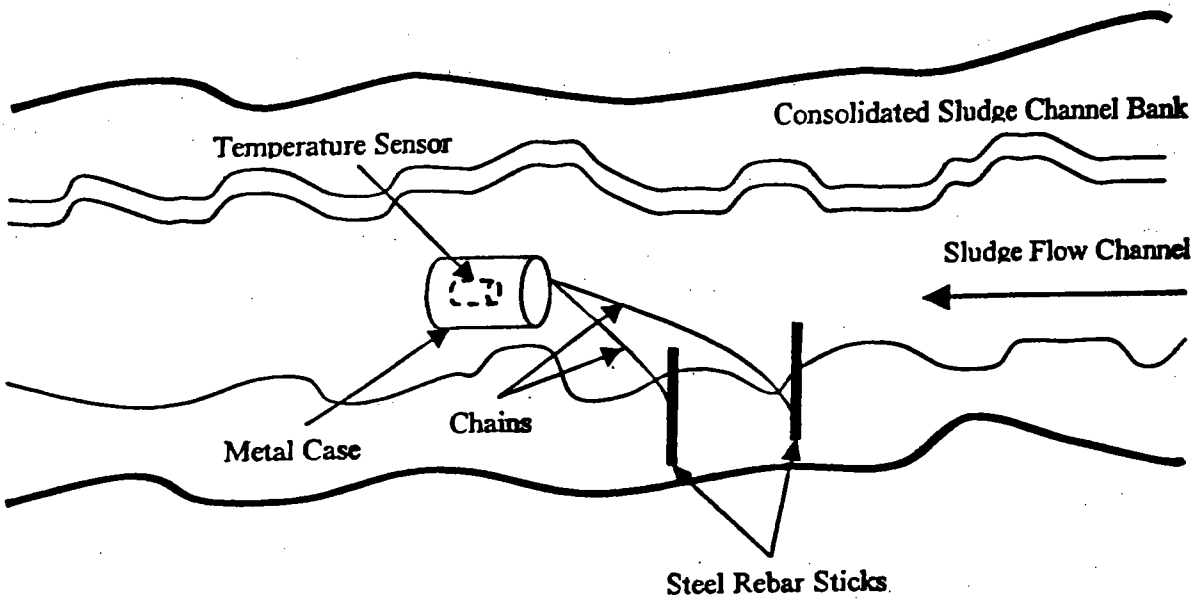


Figure 3.4 Schematic of field deployment of the temperature sensor in the treated ARD and sludge discharge channel

4 EVOLUTION OF THE WATERLINE PIT-LAKE

The meromictic Waterline Pit-lake is a part of the Main Zone hydrological system. While the main concern is water quality of the Main Zone Pit-lake, water quality in the Waterline Pit-lake cannot be ignored since it directly overflows into the Main Zone Pit-lake, and thus acts as a significant input of water and chemical content. As a result, the mixing status of the Waterline Pit-lake determines not only the surface water quality of the Waterline, but could also affect the water quality of the Main Zone Pit-lake. Temperature, specific conductance, dissolved oxygen, turbidity and chlorophyll will be used as indicators to estimate the physical response of the pit-lake to a variety of factors such as meteorology and ARD discharge. These indicators can also provide insight into other events potentially occurring in the pit-lake such as the water intrusion, upwelling, internal seiching and the persistent anoxia in the lower part of the pit-lake.

4.1 Chronology of Events

Aside from the hydrology of the Waterline Pit-lake (see Chapter 2), there are several important hydrological events to be noted:

- The Waterline Pit-lake has been serving as a repository for water inflows such as surface runoff and leakage from the nearby Berzelius Creek. However, such inflows stop when the water freezes in winter (November to April).

- There was no backfilled waste rock deposit in the Waterline Pit-lake.

- There were generally no discharges of treated ARD and sludge to the pit. However, on July 27/28, 2002 (day 573/574 where day 1 is January 1st, 2001 as used throughout), the treated ARD water and sludge originally to be discharged into the Main Zone Pit-lake, accidentally spilled over the bank of the ditch onto the access road north of the Main Zone pit and flowed into the southern part of the Waterline Pit-lake close to the

Waterline Outflow. However, after the spill, a muddy sludge deposit was found on the shallow lake bottom at the southern end of the pit-lake, and the colour of the surface water there changed from pale green to yellowish brown.

- The surface water leaves the pit-lake through the Waterline Outflow at the southern end of the water body during the ice-free period.

4.2 Temperature and Conductivity

The Waterline Pit-lake has a very interesting vertical stratification structure with four identifiable permanent layers (Figure 4.1). In this thesis, the epilimnion of the Waterline Pit-lake is defined as the top layer (layer 1) above the uppermost density jump. The hypolimnion, the water column below the epilimnion, is made up of three main layers (will be discussed in 4.2.2). Part of layer 2 gets mixed into the epilimnion (Layer 1) in fall; therefore the mixolimnion includes layer 1 and the upper part of layer 2. The bottom part of layer 2, layer 3 and layer 4 make up the monimolimnion, which is permanently stratified during the study period

4.2.1 Epilimnion

The epilimnion and the upper part of layer 2 (will be discussed in section 4.2.2) that gets entrained into the epilimnion form the mixolimnion (0-9 m).

In late June 2001, the relatively thin and fresh epilimnion was 4 m deep and had a conductivity of 1025 μS/cm, likely the result of ice melt and freshet in spring (Figure 4.2). Surface temperature was around 11 ^{o}C at the time.

In mid-August 2001, surface temperature warmed to 15 °C; and conductivity decreased lightly to 1000 μS/cm (Figure 4.2). No apparent deepening was observed for both the thermocline and halocline and they remained at 4 m.

Deepening and cooling were observed in the fall and by early October, the epilimnion extended to a depth of 7.5 m and cooled to 5 °C. Meanwhile, conductivity increased to 1150 μS/cm. The thermocline and halocline were not as sharp in the fall as in the summer; nonetheless, they occurred at the same depth.

After the early October sampling trip, the epilimnion deepened further and was observed to be at 9 m deep in late January 2002. The surface temperature was close to 0 °C. Consistent with the reverse thermal stratification in the epilimnion, water temperature increased with depth, reaching about 5 °C at the base of the epilimnion. At the same time, conductivity of the epilimnion increased slightly from 1150 μS/cm in October 2001 to 1210 μS/cm in January 2002. Both temperature and conductivity in the epilimnion were found to be similar in March 2002 as in January 2002.

To observe the evolution of the epilimnion in more detail, Figure 4.3 shows continuous temperature measurement in the Waterline Pit-lake from July to October 2002. Through summer, both air temperature (Figure 4.3a) and surface water temperature (Figure 4.3b) measurements show diurnal fluctuations (due to sunlight) and biweekly variations (passing of synoptic weather systems). In summer, for example, the surface water was warmed by as much as 5 °C in a day (e.g. day 597 as shown in Figures 4.3b).

In early July 2002, the epilimnion slowly warmed and reached roughly 16 °C on July 23rd (day 570). After that, the air temperature dropped by 10 °C over 6-7 days, and the epilimnion temperature also decreased to approximately 10 °C in early August. Similar to the increased air temperature in mid to late August, the epilimnion slowly warmed again to 12-13 °C. Temperatures started to cool in late August and early September, with the epilimnion around 8 °C in mid-September. The cooling trend continued through the fall with the epilimnion temperature lowered to 5-6 °C by early October.

Relative to the Main Zone Pit-lake (see next chapter), conductivity of the surface water in the Waterline Pit-lake varied by a smaller amount over the course of the observation period. The epilimnion conductivity decreased from 1030 μS/cm to 1000 μS/cm from July to August 2001, likely the result of fresh water inflow (Figure 4.4). In the fall of 2001, conductivity started to rise, reaching 1160 μS/cm in October and 1210 μS/cm in both January and March 2002. In June 2002, the epilimnion began again as a thin fresh layer with conductivity back down to 1020 μS/cm. However, unlike in the summer of 2001, conductivity increased slightly through the summer of 2002 and reached 1150 μS/cm in late August. The formation and evolution of the epilimnion will be further discussed in section 4.6.1.

Note that the residence time of the Waterline Pit-lake's epilimnion is short in the summer (~50 days) (Chapter 2) and as a result, a significant fraction of the epilimnion would have been replaced by the inflow between consecutive conductivity measurements during the ice-free period. Besides mixing with the more saline water below the pycnocline, the conductivity of inflow into the Waterline also plays a role in determining the conductivity of the epilimnion.

4.2.2 Hypolimnion

In general, there were gradients in temperature and conductivity with depth present within each of the monimolimnion layers. The water temperature and conductivity in the monimolimnion change slightly with time.

Layer 2- In layer 2, the temperature *increased* from 4.2 °C at the top to 5 °C at the bottom of the layer (17 m). At the same time, the conductivity increased from 1400 μS/cm at the top 1500 μS/cm at 17 m, maintaining stability.

While the effect of meteorological forcing was evident close to the lake surface, the water column in layer 2 exhibited relatively stable temperatures all year long compared to that in the epilimnion. For example, in the summer of 2002 (June-August), the water column between 5 m to 6 m exhibited relatively stable temperature, ranging from 4.8 to 5.0 °C, and the temperature at 8 m was also relatively stable at 4.4 °C, neither showing diurnal and biweekly temperature changes throughout the summer. The water temperature at 6 m and 8 m slowly increased in late summer and early fall of 2002 (Figure 4.3). The magnitude and frequency of temperature fluctuations increased when the halocline deepened to the instrument depth. As the halocline deepened further, the instrument recorded temperatures in the epilimnion.

The water temperature from 10 m to 15 m (the lower half of layer 2) also shows a general warming trend during July 2002, but the temperature at 15 m started to cool in late September (Figure 4.3). A temperature jump at depths of 10 to 15 m was observed between day 570 and day 580 (Figure 4.3c). This was resulted from the accidental sludge discharge in July 2002 as will be discussed in section 4.2.2a. By early October 2002, temperatures for these depths (10 m, 12.5 m and 15 m) remained different from those in the epilimnion.

The conductivity for the lower part of layer 2 was relatively constant. However, changes in temperature and conductivity were observed at the base of layer 2 at a depth of 18 -19 m, likely the result of intrusions as will be discussed in section 4.2.2b.

Layer 3- At any given time, layer 3 is stratified with a gradient in temperature and conductivity. Water temperature increased from 5.2 °C at 20 m to 5.5 °C at 30 m. Conductivity also increased from 1500 μS/cm at 20 m to 1900 μS/cm at 30 m and maintained stability.

Water temperature and conductivity were relatively stable compared to the rest of the water column throughout the sampling period. The differences between the highest and the lowest temperature recorded for all depths were less than 0.1 °C from early July to

early October. Nevertheless, all depths showed a slight cooling trend at the rate of 0.01-0.02 °C/month in July and August 2002 (day 550-620) (Figure 4.3d). The cooling trend tapered off at the end of August.

Exception from stable temperature and conductivity was found at the interface between layer 3 and layer 4 (~30 m), where conductivity decreased by roughly 80 μS/cm from June 2001 to March 2002, and it increased by 190 μS/cm from March to June 2002 (Figure 4.4). This suggests possible subsurface inflow of relatively saline water between March and June (see section 4.2.2b).

Layer 4- Similar to layer 3, both water temperature and conductivity increased with depth, but at a lower rate than that in layer 3. Water temperature increased from 5.5 °C at 30 m to 5.6 °C near the bottom of the pit-lake, whereas conductivity increased from 1900 μS/cm at 30 m to 2100 μS/cm near the bottom.

Layer 4 also exhibited a similar cooling trend (0.01-0.02 °C/month) to layer 3 from day in July and August 2002 (day 550-620) (Figure 4.3e). Conductivity was stable with time. A slight increase in conductivity was observed in 2002 between March and June (Figure 4.4).

4.2.2a Effect of The Accidental Treated ARD and Sludge Discharge

The accidental discharge of treated ARD on July 27/28 (day 573-574) into the Waterline Pit-lake is the likely candidate as cause of the temperature jump observed in layer 2 (10 m, 12.5 m and 15 m). As shown in Figure 4.3, the temperature increase at 12.5 m was 0.3 °C and was the largest measured during this period compared to 10 m (0.15 °C) and 15 m (0.1 °C).

The discharge of treated ARD and sludge also altered the stratification structure in layer 2. Before the discharge, temperature increased with depth from 10 m to 15 m. After the discharge, the temperature at 12.5 m became warmer than that at 10 m and 15 m. This

indicates that the variation in temperature was neither the effect of seiching nor halocline deepening. External heat energy might have been brought in through the formation of an intrusion layer of warmer water, possibly close to the depth of 12.5 m, as the density current of treated ARD water became neutrally buoyant. This intrusion is confirmed by CTD data collected before and after the event (see section 4.4 for discussion of turbidity).

4.2.2b Potential Subsurface Intrusion

Evidence from temperature and conductivity measurements suggests that there are potential subsurface intrusions in the Waterline Pit-lake at the base of layer 2 (15-20 m) and at the base of layer 3 (30 m).

As shown in Figure 4.4, conductivity at 18 m decreased about 80 μS/cm from June 2001 to March 2002, and it increased by 130 μS/cm from March to June 2002. After that conductivity gradually decreased throughout the summer. Furthermore, conductivity appears to be uniform with depth from 15-20 m during the summer and winter seasons, signifying an active intrusion. However, it varies linearly in late spring, signifying a diffusion process and an absence of intrusion. On the other hand, conductivity at 30 m is uniform during winter season only (Figure 4.2b).

Figure 4.3f shows a 15-minute average temperature measurement at the depth of 15 m. It appears that during the period of day 550-560, temperature fluctuated with relatively high amplitude; however, the fluctuation tapered off gradually. Also, note that the trough of the fluctuation was lower than the average temperature immediately after (i.e. day 560-575). This suggests two possibilities: (1) The interface of a cooler water mass slowing moving away from 15 m, or (2) the presence of a cooler intrusion layer.

Figure 4.5 shows an enlarged version of the temperature fluctuation at 15 m depth in the Waterline Pit-lake. Temperature variations due to internal seiching usually have a somewhat constant frequency or period (time taken for one cycle to occur), and the

difference between peaks and troughs is usually steady. However, the temperature fluctuated in an irregular fashion at 15 m from day 552 - 553. The time scale for a cycle ranged from 10 minutes to roughly 60 minutes, and the size of the fluctuation varied considerably, ranging from 0.005 °C to 0.05 °C (resolution of the temperature logger is 0.005 °C), from cycle to cycle. Moreover, the water temperature varied in a chaotic manner during the period. Therefore, the temperature fluctuation was not mainly due to the internal seiching. Again, the potential presence of the intrusion layer could cause the inhomogeneity of the water mass at that particular depth due to the incomplete mixing with the host water.

4.2.3 Evolution of Stratification

General Behaviour- The Waterline Pit-lake has been meromictic since observation started in June 2001; namely it has stable stratification all year long and does not overturn in either fall or spring (Figure 4.4). CTD casts and temperature measurements show that only the top 9 m of the lake are susceptible to mixing due to convective cooling, wind stresses, seiching and surface waves (Figure 4.2). During summer (2001 and 2002) the halocline immediately below the epilimnion was approximately 3 - 3.5 m. However, the halocline was at the maximum depth of 9 m in late January 2002, indicating halocline deepening in the fall.

Nonetheless, the lake did not entirely overturn as the temperature and conductivity profiles below 9 m were retained. The temperature increased slightly with depth, but the conductivity also increased with depth, indicating the stability was primarily maintained by salinity gradient (salinity of the pit-water has yet to be determined).

Lake Stability- Since temperature stays relatively uniform with depth below epilimnion, salt content is the major factor controlling stability of the Waterline Pit-lake below the halocline. The temperature varies by only ~1 °C from the depth closest to the epilimnion (~4.5 °C) to the bottom (~5.5 °C). This temperature difference corresponds to about 0.056

σ_t assuming that the density-salinity-temperature relations behave as seawater. Over the same section of the water column, the difference in specific conductance was 700 μS/cm, which corresponds to about 0.49 σ_t (Millero et al. 1980, Fofonoff 1985). Although the seawater assumption is not ideal, as the water in the pit-lake has a different composition of dissolved ions, the above estimates provide a good indication of the dominance of salinity over temperature on density variation.

4.3 Dissolved Oxygen

Oxygen was measured in the Waterline Pit-lake on the water samples collected at discrete depths. The epilimnion was well oxygenated. Below this anoxia persisted year-round (Figure 4.6). The oxygen concentration stayed relatively constant throughout the epilimnion and the oxycline depth coincided with the position uppermost halocline (Figure 4.2).

4.3.1 Surface Oxic Layer

As shown in Figure 4.6, the oxygen content for the epilimnion ranged approximately from 9.1 mg/L to 10.3 mg/L in summer (June, August and October) and from 10.4 mg/L to 11.0 mg/L in winter (January and March). In summer, the percent oxygen saturation in the epilimnion always stayed above 90% and was slightly supersaturated in August 2002. In winter, the percent saturation dropped to around 85-90% even though the absolute oxygen content increased.

Three main processes govern oxygen content fluctuations in the epilimnion of the Waterline Pit-lake: the physical process of atmospheric gas-exchange and solubility, the biological process of phytoplankton growth, and the chemical process of oxidation reaction. In addition, density stratification plays a role in determining the vertical extent of the oxygenated surface layer.

Gas Exchange and Water Temperature- The warmer the water temperature, the less oxygen water parcel can hold. The second factor is oxygen exchange with the atmosphere, which can be a slow process. The primary factor is the effect of water temperature on the solubility of oxygen (Henry's Law). For example, excluding the other processes, if the epilimnion warms rapidly over a few days without staying in equilibrium with the atmosphere, the percent saturation would increase and the epilimnion could even become supersaturated as warm water holds less oxygen than cooler water. This effect was observed during the summer of 2002. Oxygen content decreased as water warmed from 9 ^{o}C in June to 13 ^{o}C in August, but the percent saturation in August is higher than June (Figure 4.6). Moreover, from October 2001 to January 2002, the oxygen content increased by roughly 10%, but the percent saturation stayed at the approximately the same level.

Surface turbulence generated by breaking waves may also introduce additional oxygen into surface water. However, no gas exchange occurs during winter when the lake is covered with ice.

Phytoplankton- The Waterline Pit-lake had no detectable phytoplankton biomass in the epilimnion and, thus, no dissolved oxygen was produced from photosynthesis during the daytime. This is contrary to the case in the Main Zone Pit-lake where the phytoplankton thrived. Therefore, oxygen level in the epilimnion was controlled by physical and chemical processes (see below).

Oxidation Reaction- Of all dissolved metal ions present in the Waterline Pit-lake, iron and manganese are the two major species with which dissolved oxygen in the water reacted or was consumed. The dissolved metal ions from below the epilimnion were entrained and mixed into the epilimnion due to convective and wind-induced shear mixing, reacting with the dissolved oxygen available in the epilimnion and forming precipitates.

In the Waterline Pit-lake, while little oxygen was utilized by the phytoplankton for respiration in winter, chemical reaction of oxygen with the dissolved iron and manganese ions caused the primary loss of dissolved oxygen in the epilimnion during the frozen

period. The oxygen decline close to the oxycline was about 1 mg/L from January 25 (day 390) to March 21 (day 445), 2002. During that same time, oxygen decline near the surface was 0.3-0.5 mg/L (Figure 4.6).

Effect of Density Stratification- From March to June 2002, the depth of the epilimnion reduced from 9 m to 3 m. As a result, the section of water column between 3 m and 9 m was cut off from oxygen replenishment from the atmosphere due to the strong density gradient at the halocline at 3 m. Consequently, the available, leftover dissolved oxygen within that layer was consumed from oxidation reaction.

Going into the fall of 2002, the epilimnion water was cooled to about 5 ^{o}C, and deepening of the halocline permitted oxygen replenishment to deeper depth. The oxygen content between 3 m to 9 m increased and became well oxygenated at approximately 10 mg/L (Figure 4.6).

4.3.2 Anoxic Layer

Below the uppermost halocline, the oxygen content decreased dramatically with depth. The oxygen concentration dropped by about 9.5 mg/L in about 2 m. Below 10 m, the water stayed almost completely anoxic all the time. As mentioned before, the coincidence of the oxycline and the upper halocline in the Waterline Pit-lake indicated that the mixing of oxygen to the lower part of the water column was inhibited by the density barrier. The anoxia is not likely to disappears in the near future as the stable stratification prevents any whole-lake overturn. This might have important implications for the treatment of pit-lake water as sulphur-reducing bacteria, which thrive in an oxygen-free environment, can potentially promote metal removal from the water body. The anoxia in deep water also kept certain metals such as iron and arsenic in the dissolved phase (Crusius et al 2003).

4.4 Turbidity

The turbidity of the epilimnion in the Waterline Pit-lake appeared to correlate with the position of the permanent halocline (i.e the interface below the epilimnion) as shown in Figure 4.7. The local peak of the turbid (or low transmissivity) water was always situated at the same depth as the conductivity jump during the period from June 2001 to August 2002. Secondary peaks also appeared at depth of 16.5 m and 19 m in March 2002 as well as at the depth of 12.5-13 m in July 2002. Moreover, on August 1, 2002 (day 578), there were three obvious turbid layers present in the pit-lake at the depths of 4.5 m, 12m and 17 m, likely caused by the accidental discharge of treated ARD and sludge into the pit on July 27/28 (day 573-574). The water at these depths cleared up considerably six days later on August 7 (day 584) though elevated deep water turbidity persisted. By August 27 (day 604), the turbid layers disappeared except for the one located at the halocline.

Before the accidental discharge of treated ARD and sludge to the Waterline on July 27/28, 2002 (day 573/574), turbidity in the Waterline Pit-lake was not likely caused by the suspended sludge particles, since there had been no sludge discharge into the pit-lake. The turbid layer at the halocline was likely caused by the oxidation reaction between the dissolved oxygen in the epilimnion and dissolved metal ions (iron and manganese) from below the halocline (see section 4.3). However, the relatively turbid water was observed at the halocline instead of throughout the entire epilimnion. It is probably because the precipitates, formed from oxidation of dissolved iron and manganese, grow in size and become heavier as more precipitate is formed on the particle surface. They sink when the buoyancy is outbalanced by the weight; however, the sinking may slow down or stops completely at a halocline when the particles experience a stronger buoyancy force at the halocline below which the ambient water is denser. As a consequence, the particles accumulate at the level where density jumps (at the haloclines below the epilimnion, at 17 m and at 20 m) occur. Even though mixing induced by wind shear could stir up the particulates especially in the epilimnion, their tendency to become heavier and, subsequently, sink would return most particles to the halocline level (Figure 4.7).

4.5 Chlorophyll

Phytoplankton did not appear to be present at detectable levels in the Waterline Pit-lake in 2001 and 2002, even though an algal bloom occurred during the summer season in the adjacent Main Zone Pit-lake (section 5.6). The fluorescence measured was not zero for the entire water column, but the fluorescence reading was very low and uniform over the entire water column, suggesting that few phytoplankton were present in the pit-lake.

4.6 Discussion

4.6.1 Formation and Evolution of Epilimnion

The conductivity of the epilimnion in the Waterline Pit-lake is potentially governed by several factors discussed below: (1) runoff and ice-melt, (2) wind mixing, and (3) penetrative convection.

(i) *Runoff and Ice-melt-* The combined effect of ice-melt as well as spring freshet appear to cause the low epilimnetic conductivity observed in spring. The epilimnion was 8.3 m thick and 1200 μS/cm in March 2002. In mid-June, the epilimnion was thinner (~2.9 m thick) and fresher at 1020 μS/cm. The ice likely played a major role in forming a fresher layer on the surface during icemelt in spring. Ice thickness was estimated to be about 0.9 m in March. Based on the ice measurement in March and the Waterline pit's hypsographic curve, the volume of ice present in the pit-lake was about 21,700 m^3 or 19,900 m^3 of water, assuming the density of ice to be 917 kg/m^3 (Cutnell 1995). Salt is expelled as the ice forms, therefore, as the ice melts on the lake surface a relatively fresh layer of water forms on top, lowering the conductivity of the surface water, and thus strengthening spring stratification. Estimates indicate the volume of water with zero conductivity needed to achieve the conductivity decrease in the epilimnion after the melting of ice was only 10,500 m^3, accounting for only 53% of the total freshwater from the ice-melt. The possible reasons for this

include the assumption of no salt included in the ice (an ice sample has yet to be analysed), the overestimation of the total ice volume, input of salt from the Berzelius Creek leakage (conductivity is not yet known), and the partial loss of surface freshwater to the Waterline Outflow.

As runoff from snowmelt and rainfall gradually decreases in summer (Figure 1.8), the leakage of the presumably low-conductivity water going into the pit-lake would also decrease. At the same time, the climate becomes drier as the season progresses, meaning less precipitation and less freshwater input to the pit-lake. Turbulent mixing of high conductivity water from the lower part of the pit-lake with the epilimnion may have caused the epilimnetic conductivity to increase during summer.

(ii) *Wind-* Water circulation within the mixed layer would be triggered during wind events, resulting in shear stress along the halocline, and thus mixing the lower layer water with the epilimnion water. Strong and persistent wind could also cause the density interface to tilt to an extent that a significant amount of the hypolimnetic water is brought up to the surface (i.e. upwelling). Two dimensionless numbers have been developed to evaluate the potential of upwelling: the Wedderburn Number, W (Spigel and Imberger 1980) and the Lake number, L_N (Imberger and Patterson 1989). Both dimensionless numbers are the ratio of the restoring force of the tilted stratification to the wind shear stress at the lake surface. The Wedderburn Number was developed for a two-layer stratified water body, while the Lake Number is more suitable for continuous or multi-layered stratification as in the case of the Waterline Pit-lake (Stevens and Imberger 1996). However, Stevens and Imberger (1996) used both numbers in continuously stratified water bodies and categorized the seiching and upwelling responses into four different regimes based on a combination of the W and L_N values.

The dimensionless Wedderburn number (W) is given by:

$$W = \frac{g' h_{iu}^{2}}{L u_{*}^{2}} \qquad (4\text{-}1)$$

where g' is the reduced gravitational acceleration (m/s^2); h_{iu} is the initial thickness of the epilimnion before tilting of the interface (m); L is the length of the water body (m); and u_* (friction velocity in an unit of m/s) = $(C_D \rho_A U_W^2 / \rho_u)^{0.5}$. Here, C_D is the drag coefficient, ranging from 0.001 to 0.0015 depending on the wind speed (Hicks 1972); ρ_A is the density of air (1.225 kg/m^3); U_W is the wind speed at 10 m above the water surface (m/s); and ρ_u is the density of the epilimnion water (kg/m^3).

Based on CTD measurement, the epilimnion was 5 m deep and the reduced gravity (g') was 0.0052 m/s^2 in June 2002. With a lake length (L) of roughly 460 m and an assumed hourly wind speed (U_W) of 3 m/s on the pit-lake, W and L_N were 17 and 0.2, respectively. Hence, W>>1 and L<1, indicating little mixing at the uppermost halocline and deep water seiching without upwelling (Stevens and Imberger 1986).

(iii) *Penetrative Convection-* In the fall, the combined heat loss due to long wave radiation (especially when the sky is clear), evaporation and conduction of heat to the atmosphere cools down the surface water and increases its density. As a result, sinking plumes of colder and denser water are generated, thereby establishing convective circulation in the epilimnion, impinging and eroding the halocline by entraining water from the lower layer. Consequently, the conductivity of the epilimnion increases and the stability of stratification decreases because of the reduced density difference between the upper and lower layer (Figures 4.2 and 4.4). For example, on a clear, cool night (~ 0 °C on day 613, see Figure 4.3) with mild wind (3 m/s) when the surface water temperature is relatively warm (~ 10 °C on day 613, see Figure 4.3), long wave radiation from the lake surface causes significant heat loss (~350 W/m^2, see TVA 1972 for the heat loss calculation). The latent heat loss due to evaporation accounts for 15 –100 W/m^2 (for relative humidity (RH = 0-99%); whereas the sensible heat loss is responsible for 52 W/m^2 (see Fischer et al. 1979 for the heat loss calculation).

In summary, while the fresher inflow from the Berzelius Creek leakage would tend to lower the conductivity, the combined effects of the wind and the heat loss would result in

the elevated level of specific conductance as well as the deepening of the halocline in the Waterline pit, especially in the fall.

4.6.2 Internal Seiche

The period selected for spectral analysis was July 14-24, 2002 (day 560-570). The temperature and power spectrum of the temperature record at 5 m depth is shown in Figure 4.8. Internal seiche and temperature oscillation in multiple internal wave modes were observed. The power spectrum shows that, in July 2002, the predominant fluctuation periods were 1.6 hours, 5.5 hours, 7.5 hours and 14.5 hours.

There are several interesting aspects that can be drawn from the above observation:

- The large density change between the epilimnion and hypolimnion allows the Waterline Pit-lake to be considered as a two-layer water body. For a two-layer system, the fundamental seiching period (T_1) can be calculated:

$$T_1 = 2L\sqrt{\frac{H}{g'_{tb} h_t h_b}} \tag{4-2}$$

where L is the length of the Waterline Pit-lake (460m); H is the mean depth (18.5 m); g'_{tb} is the reduced gravity for the top and bottom layers, and h_t and h_b are the respective thickness of the top and bottom layers. The density was determined using PSS78 extended to low salinity (Hill et. al 1986) and the equation of state developed by Chen and Millero (1986). Based on the data from a CTD cast in June 2002, g'_{tb} is equal to 0.0052 m/s^2. By assuming the epilimnion as the top layer and the entire water column below as the bottom layer, h_t = 5 m and h_b = 13.5 m, and the fundamental seiching mode was calculated to be 1.8 hours.

- The Waterline Pit-lake is, however, stratified into multiple layers. Therefore, seiching periods other than the fundamental mode should also occur. Lighthill (1969) suggested that a m-layered water body normally possess (m-1) (vertical) baroclinic modes having different periods and vertical structure. For a multi-layer system, the period for $(m-1)^{th}$ vertical uni-modal seiching modes is given by:

$$T_{m-1} = \frac{2L}{\sqrt{g\lambda_{m-1}}}, \qquad \text{m-1} = 1,2,3\ldots\ldots \tag{4-3}$$

where λ_{m-1} is the eigenvalue for calculating the seiching period according to Munnich (1992). Assuming the pit-lake is a three-layer system (0-4 m; 4-19 m and 19-43 m) and based on CTD measurement in June 2002, the first (T_1) and second (T_2) vertical seiching modes should be 1.7 and 2.7 hours. The period of the first vertical mode (T_1) calculated from Equation 4-2 is similar to the period of fundamental seiching mode obtained from the two-layer approximation by Equation 4-1. It also closely agrees with the observation (Figure 4.8).

There are several sources of error causing deviation of the predicted values from the observed values: (1) invalid assumption of a three-layer system and (2) topography of the Waterline Pit-lake. Firstly, the Waterline Pit-lake was not stratified into distinct layers, especially near the bottom where the stratification was somewhat continuous. Secondly, Equation 4-2 is derived from multi-layered stratification in a rectangular water body with flat bottom. Wiegand and Chamberlain (1987) and Munnich et al. (1992) respectively investigated the seiche in a multi-layered water body at Wood Lake in western Canada and Alpnacher See in Switzerland. The first and second seiching modes were observed in both cases, and Equation 4-2 accurately matched the calculated values with the observed values. However, both water bodies have relatively wide and flat bottoms. At the depth about two-third way down from the water surface to the bottom, the longitudinal span is about 75-80% of that at the water surface for both Wood Lake and Alpnacher See. However, the length of the Waterline

Pit-lake decreases dramatically with depth. At 30 m (two-third of the maximum depth of 45 m), the longitudinal span is only 30% of that at the water surface.

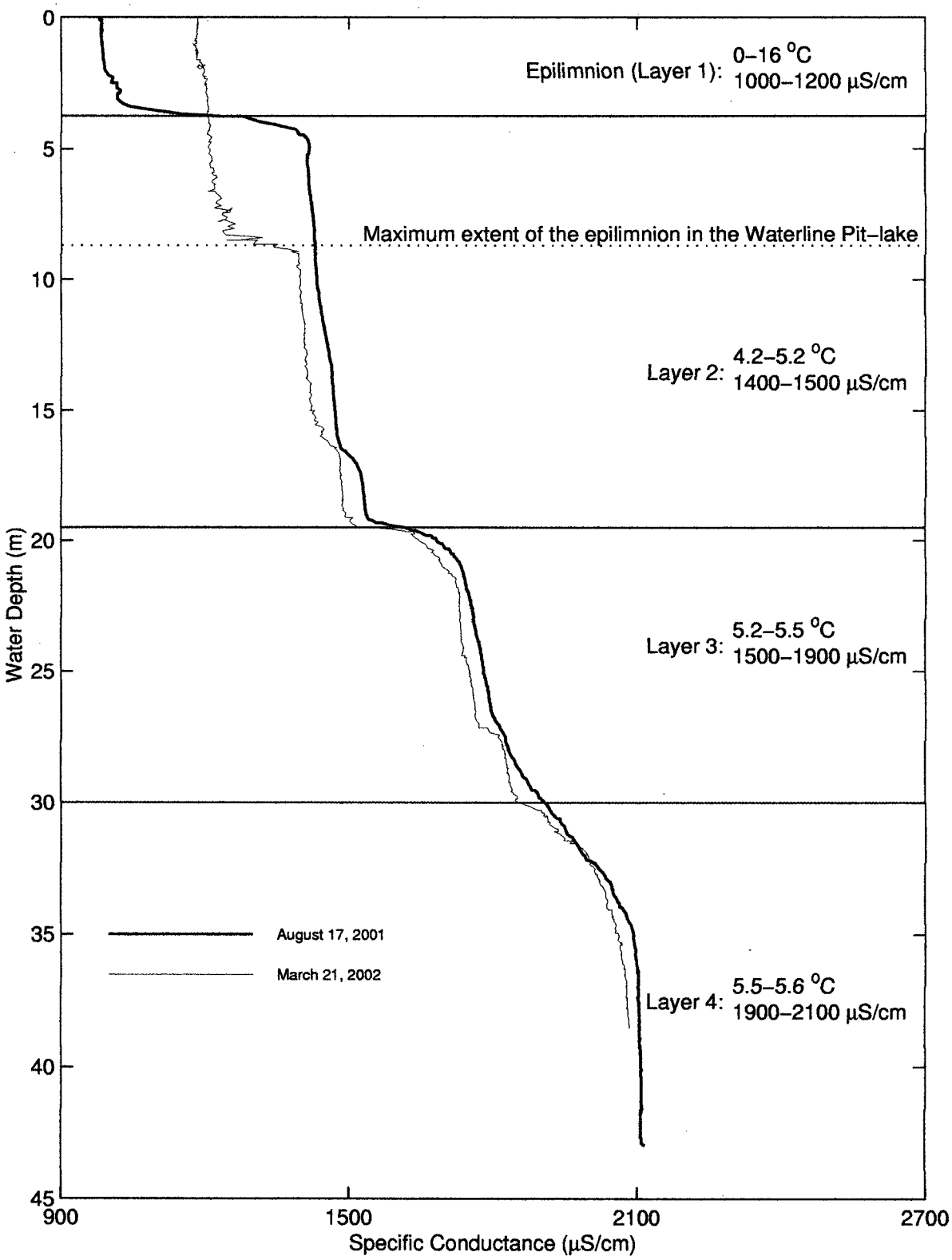


Figure 4.1 Schematic diagram of the Waterline Pit-lake conductivity stratification

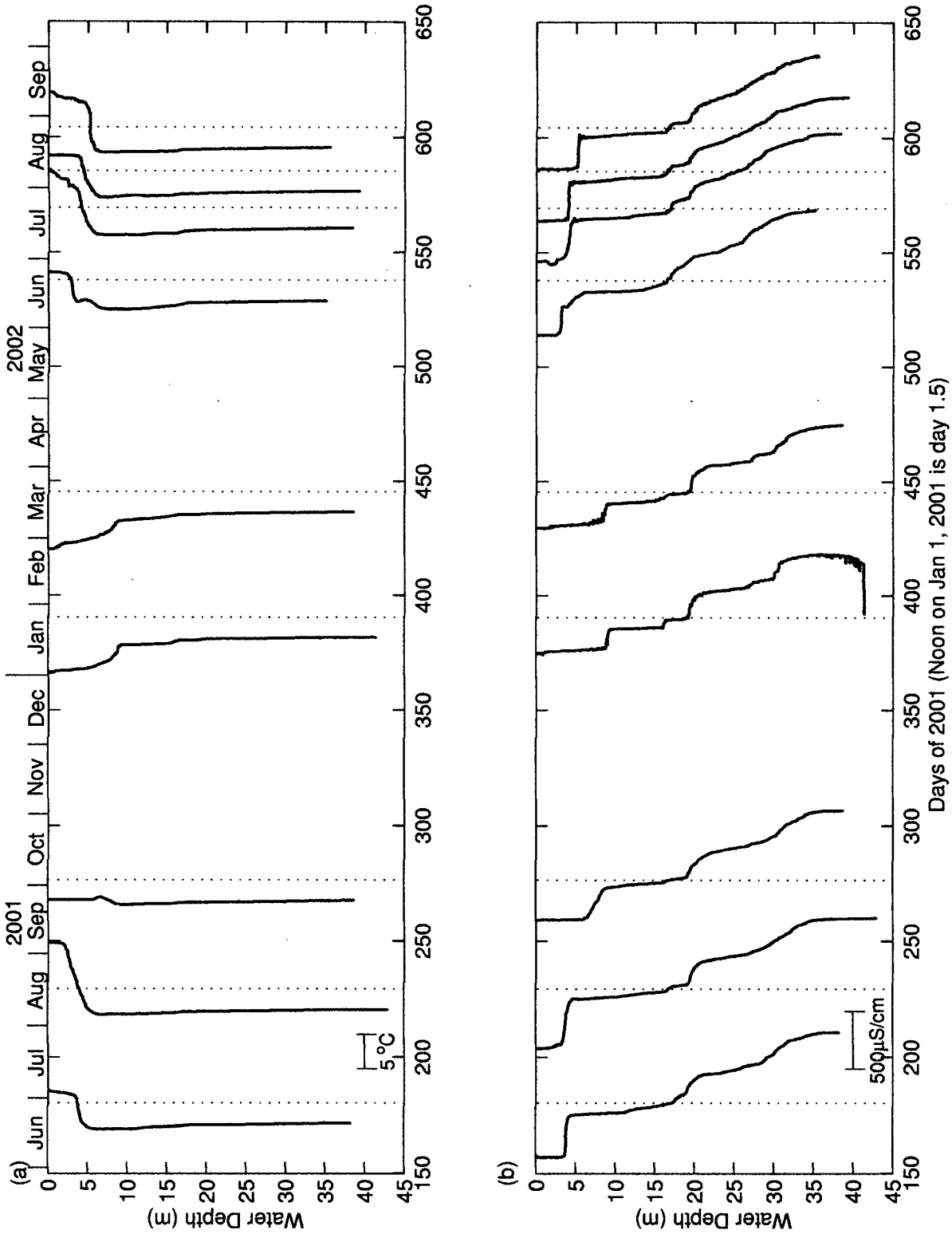


Figure 4.2 The evolution of (a) temperature and (b) conductivity stratification in the Waterline Pit-lake from June 2001 to August 2002. Note that the dotted lines (...) represent the date of the casts as well as the reference temperature of 8.5 °C and specific conductance of 1490 µS/cm.

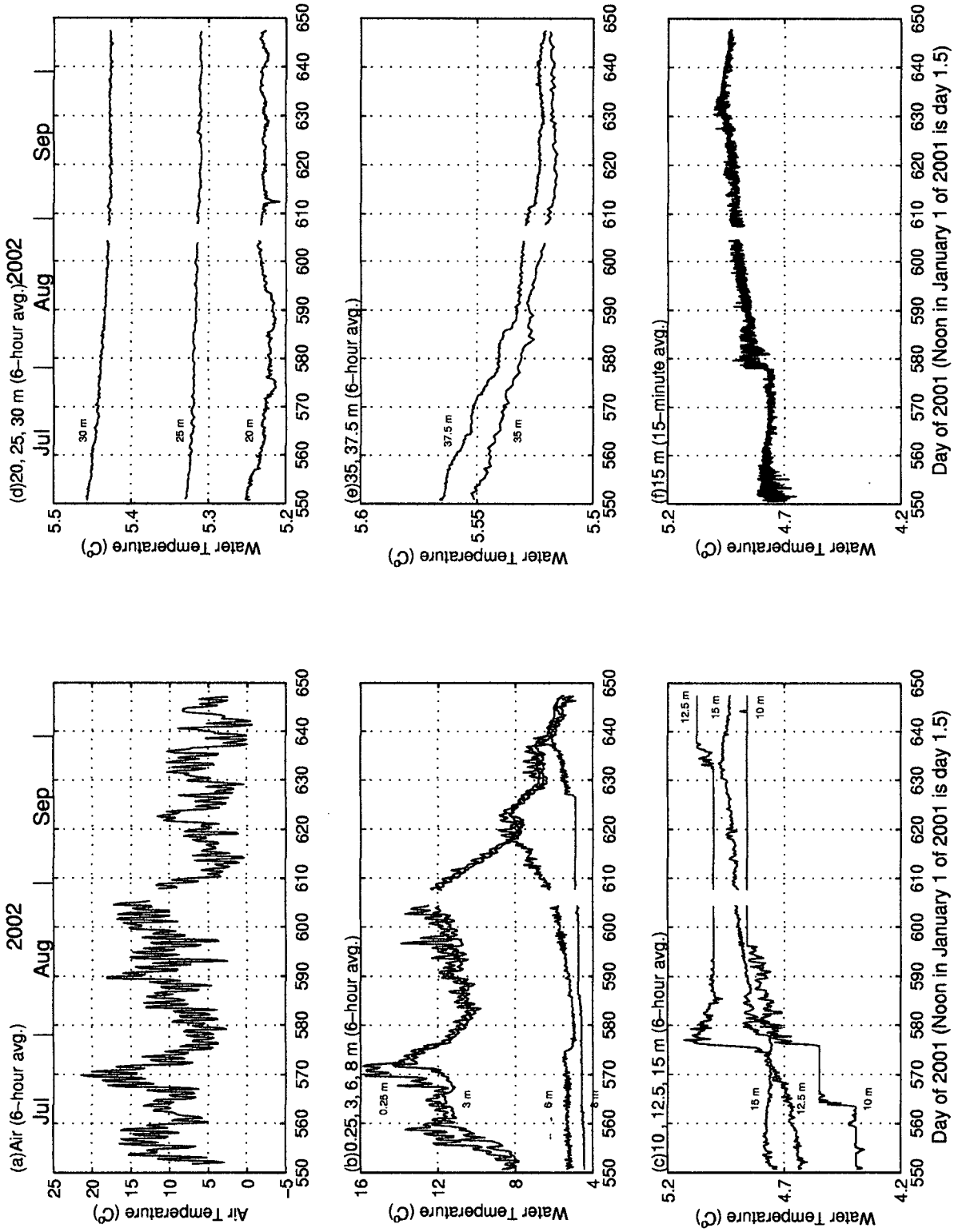


Figure 4.3 The (a) air and (b)-(f) water temperature in the Waterline Pit-lake. Note that (a)-(e) is 6-hour average, whereas (f) is 15-minute average

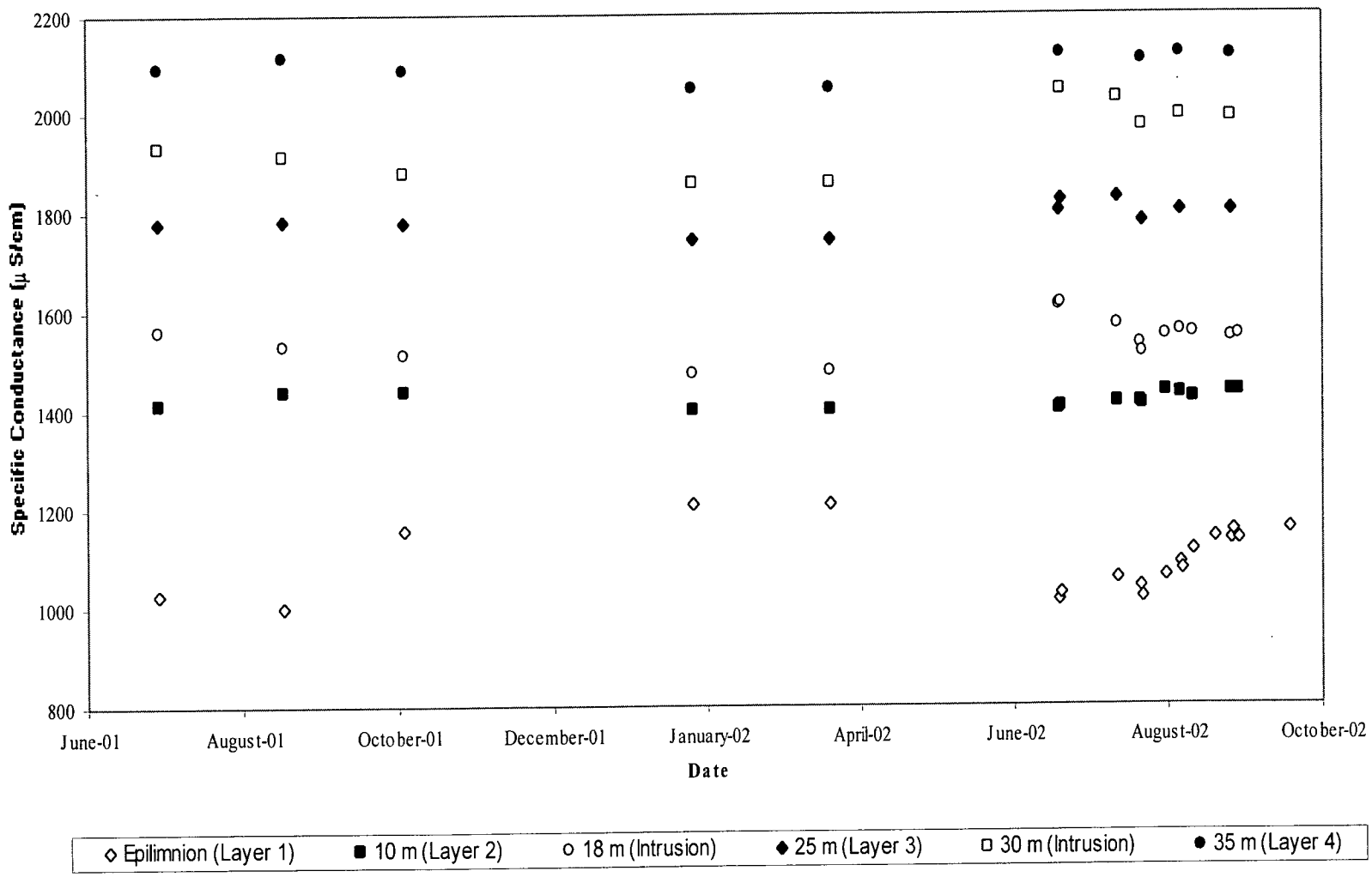


Figure 4.4 Evolution of the specific conductance at various depths of the Waterline Pit-lake from June 2001 to August 2002

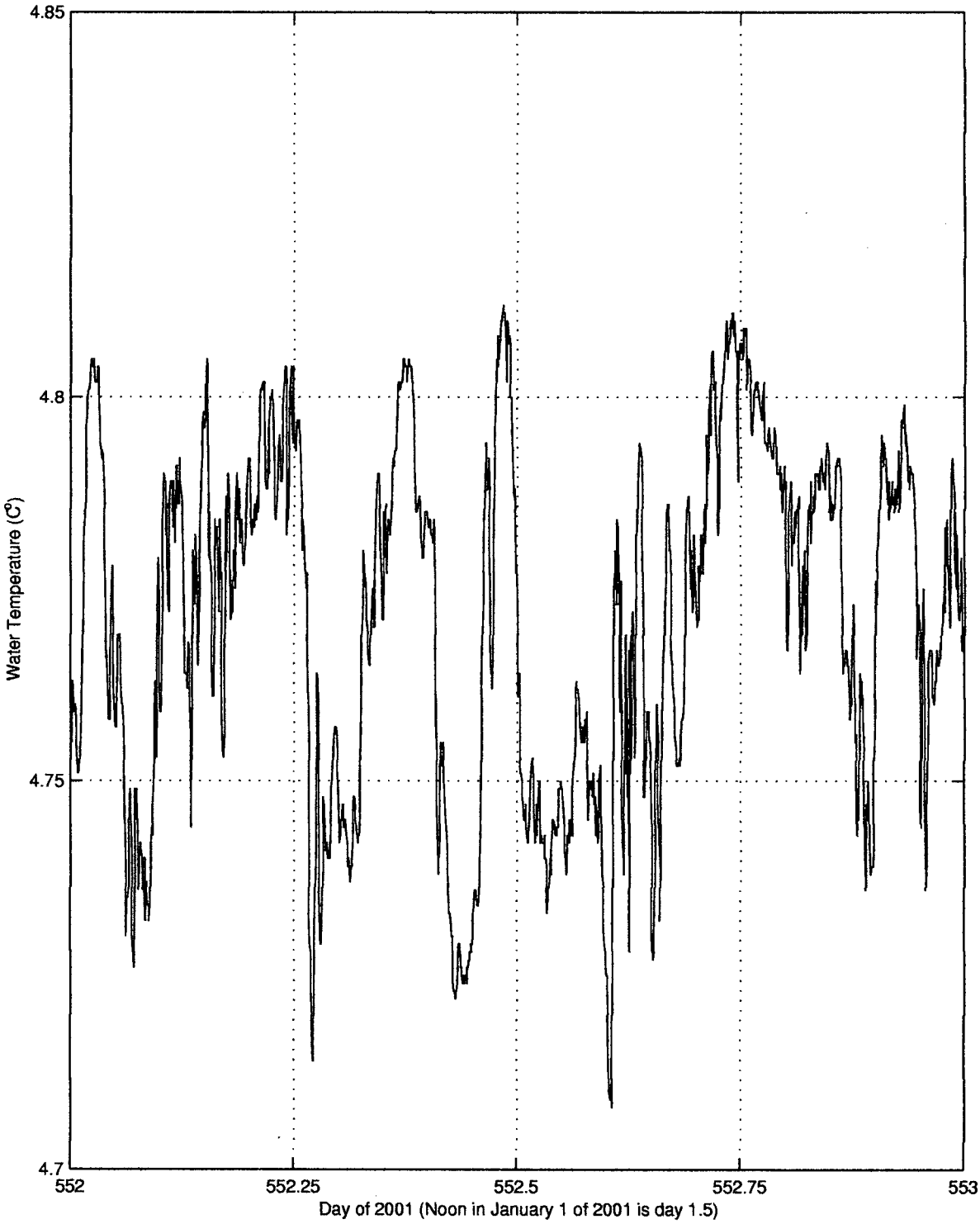


Figure 4.5 The Waterline Pit-lake temperature (15-minute average) for the depth of 15 m during the period of July 7-8 (day 552-553)

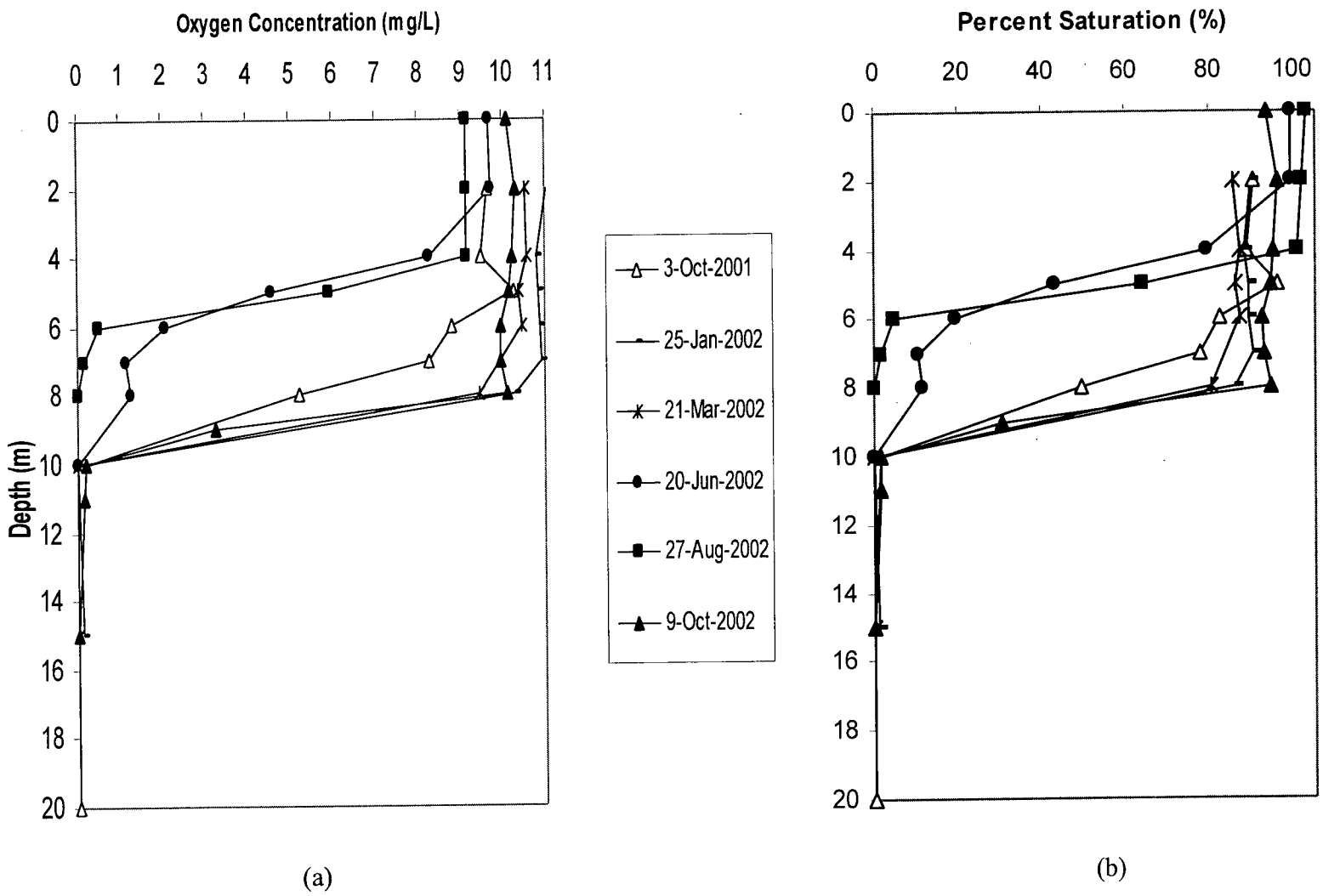


Figure 4.6 The Waterline Pit-lake (a) oxygen concentration and (b) percent saturation from October 2001 to October 2002

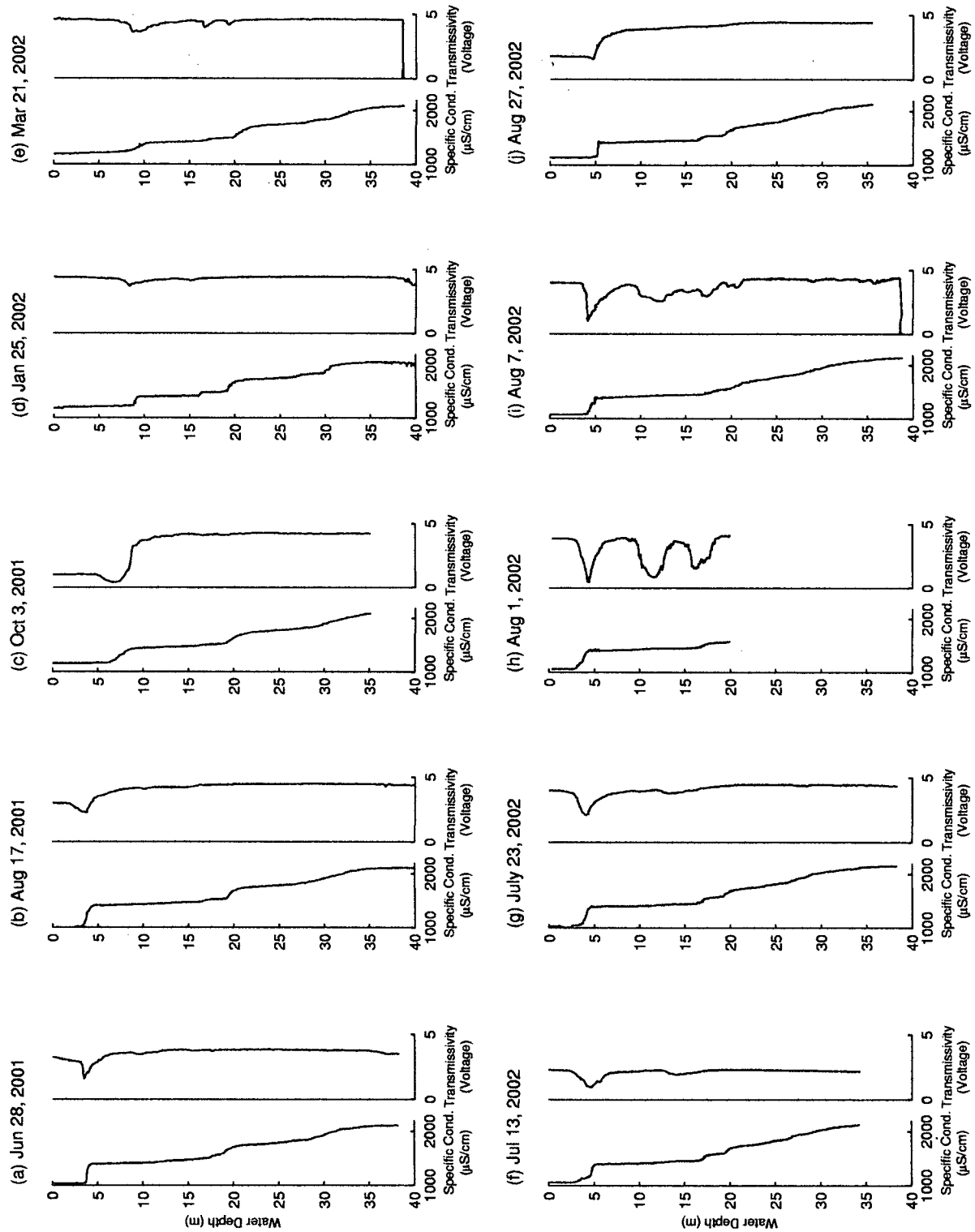


Figure 4.7 The specific conductance and transmissivity for the Waterline Pit-lake from June 2001 to August 2002

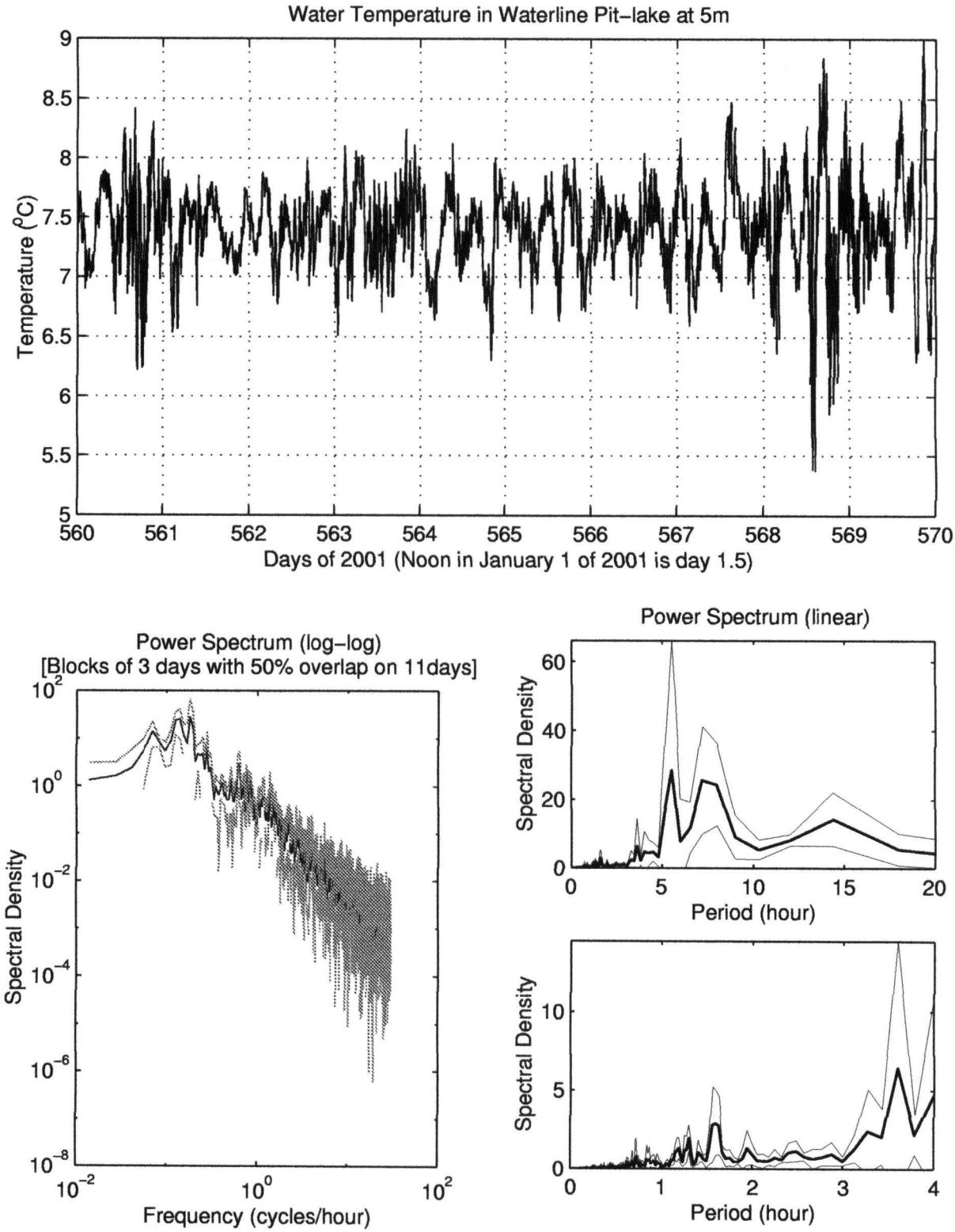


Figure 4.8 The Waterline Pit-lake temperature (15-minute average) and its power spectrum for the depth of 5 m during the period of July 14-24, 2002 (day 560-570). Note that the light line (—) represents the 95% confident interval

5 EVOLUTION OF THE MAIN ZONE PIT-LAKE

The Main Zone Pit-lake is the bigger of the two pit-lakes at the Equity Mine site. It is the receiving water body of the outflow from the Waterline Pit-lake and from the treated ARD sludge discharge. In order to avoid additional groundwater flow through the waste dump to the west of the Main Zone, the water level of the Main Zone Pit-lake is generally kept below 1265 m. To do this, water is withdrawn from the Main Zone Pit-lake at a depth of 20 m below the surface from a barge located just off the east shore. This water is either discharged directly to Buck Creek via Bessemer Creek, or to the diversion pond where it is mixed with treated ARD and subsequently discharged to either Buck Creek or Foxy Creek (Aziz 2000). To meet water quality standards, a set of dilution ratios was developed for the discharge volume based on the flow rate of the receiving creeks. Pit-lake water is discharged throughout most of the non-frozen period, but a relatively large amount is discharged in late spring and early summer when creek flows are maximal. However, the dilution requirements were established without a detailed knowledge of the mechanisms controlling metal concentrations in the pit-lake, and the discharge strategy is modified based on continuous monitoring of pit-lake water quality.

5.1 Chronology of Events

In addition to the hydrology described in Chapter 2, the following events should be noted:

- The surface water of the Waterline Pit-lake flows into the Main Zone Pit-lake during the non-frozen period (May to October).

- Typically, treated ARD and sludge are discharged into the Main Zone Pit-lake in summer; however, in the winter of 2002, treated ARD and sludge were discharged into the pit-lake from February 21 (day 417) to March 15 (day 439). The discharge rate was estimated to be 800 US gallons per minute (USG/M) or 0.05 m^3/s (Aziz 2003, email communication).

- In July 2002, an adjustment was made to the treatment of the ARD, resulting in a sludge with a higher settling rate.

- Pit-lake water is withdrawn from 20 m depth to keep the lake level below 1265 m.

- Water from the tailing pond was discharged into the Main Zone Pit-lake in October 2002; however, the impact of the discharge to the Main Zone is beyond the scope of the thesis..

5.2 Temperature and Conductivity

Figures 5.1 and 5.2 illustrate the evolution of temperature and conductivity stratification in the Main Zone Pit-lake from June 2001 to August 2002. There were two main layers present in the pit-lake: epilimnion and hypolimnion. The epilimnion is the water column above the density step and the hypolimnion is the water column below.

5.2.1 Epilimnion

At the beginning of the study period in late June 2001, a thin (~2.5 m) but well-defined epilimnion was observed with stratification supported both by higher temperature and lower conductivity than the underlying hypolimnion (Figure 5.1). Surface water was 9-10 ^{o}C and had a specific conductivity of roughly 2000 μS/cm, overlying the hypolimnion at 5 ^{o}C and 2540 μS/cm. The melting of lake ice and runoff from snowmelt is likely responsible for the formation of a fresh epilimnion in spring. In June 2001, the thermocline and halocline were located at the same depth.

Through the summer of 2001, surface temperature warmed and by August 13 2001 (day 225), the epilimnion was 14 ^{o}C. At this time the thermocline had deepened to 4.2 m while

the halocline remained around 2.5 m. The heating of water below the halocline was consistent with the photic zone depths of 10 m in August 2001 (section 5.5). Note that the conductivity of the epilimnion has increased markedly from mid-June (2000 μS/cm) to August (2400 μS/cm). This occurred in spite of precipitation, fresh local runoff and fresher inflow (~1000 μS/cm) from the Waterline. A similar pattern is also noted in 2002 (below) and the causes of this will be discussed in section 5.7.1.

Going into the fall, the epilimnion was observed to be 8 m deep in October 2001, with a temperature of 7 °C. However, conductivity had increased to roughly 2500 μS/cm (Figure 5.1). Not all of the conductivity increase can be accounted for by mixing with the deeper water as will be discussed in section 5.7.1.

The temperature evolution of the epilimnion through fall 2001 was recorded by thermistor data given in Figure 5.3. The progressive cooling of the surface resulted in temperatures becoming the same at all depths in October 2001. After that, the epilimnion, as well as the hypolimnion, cooled to 4 °C. This suggests turnover in the pit-lake occurred in early October 2001 (~day 280). Subsequently, the entire water column cooled until reverse stratification was established near the end of November 2001 (~day 330).

The water close to the surface continued to cool below the temperature of maximum density (~4 °C). In January 2002, the top 20 m was reverse stratified. The surface temperature was at the freezing point and increased with depth at rate of about 0.38 °C/m until 1.5 m and decrease to a rate of 0.15 °C/m until 20 m.

In March 2002, the reverse stratification was limited to the top 2.5 m at a rate of only 1.3 °C/m. The winter discharge of the treated ARD and sludge in February is probably the reason why the reverse thermal stratification was largely eroded. On the other hand, conductivity was essentially uniform over the entire water column and unchanged from January to March.

In mid June 2002, the epilimnion became warmer and fresher again at 11-12 °C and 1380 μS/cm. The ice had melted completely by early June 2002 (Aziz 2002, personal communication) and ice melt, in addition to spring runoff, again likely formed the fresher epilimnion. However, the conductivity of the epilimnion increased considerably to about 2100 μS/cm by the end of June.

While the average surface temperature in July 2002 remained at 11-12 °C, conductivity continued to increase steadily throughout the summer at a rate faster in 2002 than in 2001 and the conductivity contrast between the epilimnion and hypolimnion was eliminated by early August 2002. Subsequently, the conductivity remained relatively uniform over the entire water column and increased to 2650 μS/cm by the end of August, while thermal stratification persisted to the end of August.

Variation of meteorological conditions also leads to considerable fluctuation in the temperature of the epilimnion on both daily and multi-day time scales (Figures 5.3 and 5.4). For instance, the daily maximum surface temperature dropped by 3 °C in one day from August 15 to 16, 2002 (day 592-593). Fluctuation over longer time scales is also evident when the water temperature dropped by about 6 °C in 10 days from July 24 to August 2, 2002 (day 570-579). Also, as found in the air temperature record, there were two apparent sub-seasonal warming and cooling cycles in the summer of 2002 that coincide with the warming and cooling of the epilimnion (Figures 5.3 and 5.4). The water temperature decreased from 12 °C in mid-June to 9 °C in early July, increased to almost 15 °C in roughly 2-3 weeks in end of July, dropped back to 7.5 °C in early August and warmed up again to 10.5 °C in late August.

5.2.2 Hypolimnion

Unlike the epilimnion, the hypolimnion is not as sensitive to the short-term weather fluctuations partly because it is not in direct contact with the atmosphere and partly because the volume of hypolimnion is about 10 times larger.

In June 2001, the temperature in the hypolimnion was about 5.3 °C (Figure 5.2), slowly increasing to 6 °C in August 2001 and reaching 6.5 °C by October 2001 when the temperature of the hypolimnion became the same as that of the epilimnion. At the same time, conductivity increased slightly from 2540-2560 μS/cm from June to October 2001.

In the fall of 2001, the combination of surface cooling and fall overturn lowered the temperature of the hypolimnion to 3.5 °C in late November 2001. According to Chen and Millero (1986), the temperature of maximum density, corrected for salinity and atmospheric pressure, is roughly 3.6 °C, though the salinity in the Main Zone Pit-lake (S=1-2 ppt) is just above the valid range for their equation (for S=0-0.6 ppt). This is significantly lower than temperature of maximum density of 4 °C for pure water and is consistent with the minimum hypolimnetic temperature recorded at the beginning of the 2001/2002 winter season.

After the onset of ice cover in late November, the hypolimnetic temperature was constant until late in February 2002 when a sudden drop of water temperature occurred and the hypolimnion cooled to 3.2 °C, caused by the winter discharge of treated ARD and sludge (Figure 5.5). In contrast, the change in conductivity was relative small during the sludge discharge, with only a slightly increase from 2535 μS/cm in January 2002 to 2550 μS/cm in March 2002 (Figure 5.6).

The hypolimnetic temperature in mid June of 2002 was lower than the temperature at the corresponding time in 2001 because the hypolimnion was cooled below the temperature of maximum density by the winter injection of cold sludge and treated water. After the melting of ice in June 2002, the hypolimnion started to warm steadily and at a faster rate than that in 2001. The hypolimnion temperature in 2002 reached the maximum value of 2001 of 6.5 °C around the same time in late August, and it continued to rise, reaching 7 °C in early September. Throughout the summer of 2002, conductivity increased very slowly but steadily. By late July 2002, conductivity contrast between the hypolimnion and epilimnion disappeared. Conductivity in the hypolimnion continued to rise and reached to 2635 μS/cm by the end of August 2002.

5.2.3 Evolution of Stratification

Summer and Fall- In the Main Zone Pit-lake, both temperature and salinity stratification are present during the summer season. As shown in Figures 5.1 and 5.2, the pit-lake was stratified into two layers in both the summers of 2001 and 2002, with fresher and warmer water in the upper 1-4 m of the lake during summer. Both temperature and salinity contributed to stability. In late July 2002, the salinity stratification in the pit-lake has almost completely disappeared. The stability for the top 3 m of the pit-lake during this period appeared to be maintained by temperature only.

Complete destratification and overturn happened in both fall of 2001 and 2002 as indicated by the uniform specific conductance throughout the entire water column in winter; however, this happened much earlier in 2002 (late July) than in 2001 (October). Moreover, as shown in Figure 5.3, the temperature of the pit-lake also became uniform before the winter in both 2001 and 2002. The uniformity was first achieved well above the temperature of maximum density (6.6 °C in early October 2001 (day 280) and 7.1 °C in early September 2002 (day 615)), and may be the result of additional energy input from the treated ARD water and sludge discharge (Section 5.7.1).

Winter- In the winter of 2001/2002, temperature did not stay uniform as a reverse thermal stratification developed in the pit-lake (Figures 5.1 and 5.5). As the conductivity/salinity stayed relatively uniform throughout the entire water body in winter, temperature became the only factor maintaining the stability of the epilimnion. Erosion of the winter thermal stratification was evident with the increase of temperature at the base of the epilimnion in February following the input of treated ARD and sludge.

Spring- Heading into June 2002, the epilimnion had a much lower conductivity (~1370 μS/cm) than during winter after fall overturn, whereas the lower layer remained relatively unchanged from the winter value (~2560 μS/cm). Consequently, spring overturn did not appear to happen since a thin fresh layer of water was formed from a combination of melted ice and fresh water input from freshet, establishing early spring stratification. Even though the epilimnion reached its maximum water density when it was warmed to about 4

°C, salinity stratification was likely strong enough to prevent overturn from happening. Evidence of that is found in the difference in specific conductance between the epilimnion and the lower layer in early spring (Figure 5.6). Note that if spring overturn had occurred, the conductance would have been relatively uniform over the entire water column after the time of turnover.

It is also possible that fresh water from ice-melt was mixed down during spring overturn and then a cap of fresh water from spring runoff formed immediately after. However, temperature record in Figure 5.3 indicates a period of no uniform temperature in spring, suggesting that spring overturn did not occur in 2002.

5.3 Dissolved Oxygen

Unlike the Waterline Pit-lake, the Main Zone Pit-lake was relatively well oxygenated all year round throughout the entire water body (> 8.5 mg/L). The discharge of ARD and the absence of substantial biological and chemical oxygen demand in the water column and sediments likely contributed to the uniform and elevated oxygen level in the lower part of the water body. The sludge discharge was in contact with the atmosphere as it ran into the pit-lake, and additional oxygen is likely supplied from the entrainment of oxygenated surface water by the sinking sludge.

Governed by different physical and biological mechanisms at different times of the year, the dissolved oxygen content varied as follows.

Surface water- In summer, the upper 7-8 m of the water column was well oxygenated (10.5-14.5 mg/L, Figure 5.7a) and was near saturation and at times saturated or supersaturated (Figure 5.7b). In August of both 2001 and 2002, the peak oxygen level was found to be about 2 m below the surface, well above the maximum level of phytoplankton at 5-10 m (Figure 5.12). This suggests that the August supersaturation is due to the physical process of surface warming rather than due to biological activity such as

photosynthesis. During the winter of 2002, oxygen content near the surface remained high.

Deep water- From 10m to 120m below the lake surface, the oxygen level was generally uniform with depth (Figure 5.8). Note that from June to October 2001, the oxygen content varied from 8 mg/L to 8.5 mg/L, while from January 2002 onward it remained at about 10 mg/L.

5.4 Turbidity

Surface Water- Transmissivity measurements from CTD casts indicate that surface water was always relatively turbid compared to water just below the epilimnion. In general, turbidity in the epilimnion increased through the summer. There are two possible causes for increased turbidity near the surface: biological activity and turbidity from sludge discharge. The presence of the phytoplankton and the suspended sludge particles decrease the depth of light penetration. The phytoplankton population remained relatively uniform over the entire lake surface. In contrast, the turbidity a very short distance from the sludge discharge point was low, suggesting little impact of the sludge on the surface water (Figure 5.9), even though the sludge was discharged above water surface.

Other inputs of suspended solid and particles, possibly from the Waterline Outflow as well as the runoff from the pitwall, could also play a role in causing turbidity close to the surface. An occasional secondary turbidity high was found in the summer season at the depth of the halocline. Some of the settling particles in the epilimnion above the halocline might have become neutrally buoyant and stopped sinking when experiencing a density jump and accumulated at the halocline.

Deep water- In the deeper part of the pit-lake where there were neither phytoplankton nor chlorophyll, the turbidity fluctuation in the water was largely due to sludge particles from the ARD discharge. A layer of turbid water with variable thickness was also found only

when the treated ARD sludge was being discharged (Figure 5.10). The top of the turbidity layer reached as high as 60m above the lake bottom. During the time when the sludge discharge ceased, the bottom turbid layer disappeared and that part of the water cleared up.

5.5 Photic Zone

The photic zone is defined as the region from the surface to a depth in which the light intensity is at least 1% of the insolation at the lake surface. In most lakes, the photic zone can be estimated as three times the Secchi depth (Horne and Goldman 1994). Using this approximation and Secchi depths for the Main Zone Pit-lake (Figure 5.11), the bottom of the photic zone varied from a maximum of 9-13 m in June to a minimum of 6 m in October in both 2001 and 2002. For the month of August, there was some difference in the photic zone between 2001 and 2002. The photic zone in August 2002 (~5.1 m) was 50% of that in August 2001 (~10.2 m). However, in both summers, the photic zone penetrated the entire epilimnion and into the upper part of the hypolimnion.

5.6 Chlorophyll

Fluorescence data suggests that chlorophyll was present in the Main Zone Pit-lake throughout the year even during the winter season under the ice layer (Figure 5.12). Nonetheless, the phytoplankton population and the optimum depth for growth varied seasonally. Recall that the plots in Figure 5.12 have not been calibrated to the discrete chl-a measurements, but they show the relative abundance of chlorophyll in the water column.

In June 2001 (i.e. May/June), the amount of phytoplankton was low with a peak at a depth of about 8 m, well below the halocline depth of 2 m (Figure 5.12). As summer progressed, the amount of phytoplankton increased and the peak became shallower, centered about 5 m in August and October 2001. While light inhibition of photosynthesis has been well

documented (Goldman et al. 1963, Pechlaner et al. 1972), the depth at which algae thrive could become shallower depending on the attenuation rate of the sunlight penetrating into the water and the availability of nutrients. Increased turbidity in the summer, possibly due to the presence of suspended particles derived from sludge discharge, as well as increasing phytoplankton population, reduced the maximum depth which sunlight could reach. Throughout the summer of 2001, the phytoplankton population rose, became shallower and spread over to a larger extent in the water column (vertical extent of 5 m in June to about 10 m in October).

During the winter season of 2001/2002 when the lake was frozen, most of the phytoplankton were found at the bottom of the ice layer at 1-2 m where the algae could carry out photosynthesis in the low sunlight level directly under the ice (Pechlaner et al. 1972). While the depth of the phytoplankton peak stayed at the same level for most of the winter, a significant amount of the algae disappeared by March 2002 likely as a result of mixing due to sludge inflow in February 2002. In June 2002, the population was smaller than that at the same time in 2001. Nonetheless, as the summer progressed, the phytoplankton population grew and the peak moved to shallower water again (Figure 5.12).

5.7 Discussion

5.7.1 Summer Destratification

Established after melting of the lake ice, the initial difference in conductivity between the epilimnion and the hypolimnion diminished throughout the summer. However, the reduction rate of this conductivity difference was much faster in the summer of 2002 (Figure 5.6).

The conductivity became almost uniform for the entire water column in late July 2002 (~2560 μS/cm), whereas, in 2001, the uniformity was not achieved until late October 2001 (~2550 μS/cm). The temperature of the entire pit-lake water column became uniform about 30 calendar days earlier than in 2001 (roughly October 4 for 2001 and September 3 for 2002). This could suggest that additional energy sources or factors (e.g. the sludge input, subsurface withdrawal, etc.) might be largely responsible for the early lake overturn in 2002.

Several factors are considered as follow:

(i) *Subsurface Withdrawal-* The pit-lake water was withdrawn at the depth of 20 m in the Main Zone Pit-lake in 2002 (Aziz 2003). If the withdrawal rate were large enough, the interface between the epilimnion and the hypolimnion could be drawn down to the depth of the withdrawal pipe and could remove the water from upper layer completely.

For a point source withdrawal with two-layer stratification, the critical withdrawal rate (Q_c) below which the halocline is relatively unaffected is given by:

$$Q_c = F\left(g' h^5\right)^{0.5} \tag{5-1}$$

where F is a dimensionless parameter set equal to 2.5 as suggested by Craya (1949); h is the distance between the bottom of the epilimnion and the withdrawal depth (m); and $g' = g(\Delta\rho/\rho)$ is a reduced gravitational acceleration (m/s^2), where g is the gravitational acceleration (9.8 m/s^2); $\Delta\rho$ is the density difference between the epilimnion and the hypolimnion and ρ is the reference density usually taken as that of the hypolimnion. For the density difference and epilimnion depth for June 2002 (g'=0.014 m/s^2, h = 1.5-2.5 m), the critical flow rate ranges from 380 m^3/s to 440 m^3/s. Based on data for other dates, the critical flow rate never fell below 50 m^3/s in both summer of 2001 and 2002. The relatively large distance between the halocline

and the pipe inlet results in a large critical rate. The maximum withdrawal rate during 2002 summer was about 2000 USG/M (0.13 m^3/s) (Aziz, email communication), even though the maximum pumping capacity was about 3000 USG/M (0.19 m^3/s) (Aziz 2001). Therefore, the withdrawal rate for the pit-lake is not likely to draw down the halocline, and thus, not likely to be the cause of the destratification observed during both summers.

(ii) *Convective cooling*- When the air is persistently cooler than the lake, a tremendous amount of heat is lost from the surface water to the atmosphere. In the condition when the water is warmer than the temperature of maximum density (~ 4 ^{o}C), convective circulation within the epilimnion is generated as the cooler surface water sinks to the bottom of the epilimnion, entraining fluid from the lower layer across the density interface. As a result, temperature and conductivity in epilimnion would be uniform. However, thermal and conductivity stratifications remained in the epilimnion (Figure 5.2), suggesting convective cooling is not likely the cause of the early destratification.

(iii) *Wind and Seiching*- Constant and strong wind could initiate water circulation in the epilimnion as follows: the surface water is pushed from the upwind to the downwind end of the lake and water accumulates at the downwind end; however, in order to maintain hydrostatic balance, the density interface in a two-layer stratified water body tilts in the opposite direction and slopes upward at the upwind end. When the wind stops, the tilted interface moves back and forth (i.e. seiching) until all the energy is dissipated through friction and viscosity.

There are four possible mechanisms that determine the extent of mixing during the process: (1) entrainment of the lower layer water at the interface due to shear mixing caused by the water circulation alone; (2) upwelling, when the tilted interface reaches the lake surface a significant amount of lower layer water would be brought up and mixed with the surface water; (3) downward migration of turbulent kinetic energy from water surface due to wind stress and surface waves, and (4) processes such as

shoaling of internal waves and benthic boundary layer turbulence near the interface may cause additional mixing. Mixing close to the benthic boundary layer (4) is not significant in this case because the pitwall is steep and most of the energy carried by an incoming wave would be conserved and retained in a reflecting wave. While the process to approximate the shear and turbulent mixing (1 and 3) at the interface is complex, the estimation of the possibility for upwelling (2) is comparatively simple and is discussed below.

For a two-layer stratified water body such as the Main Zone Pit-lake in summer, the Wedderburn number provides an indication of the likelihood for the upwelling. The dimensionless Wedderburn number is calculated according to Equation 4-1. In June 2002, water density for the epilimnion and hypolimnion was 1002.4 kg/m^3 and 1003.8 kg/m^3 (see Appendix D). With a lake length of roughly 790 m (see Chapter 2) and an assumption that the hourly average wind speed is 3 m/s, the Wedderburn Number for the Main Zone Pit-lake in June 2002 was 4.9.

For a box shaped, two-layer stratified water body with no interfacial mixing, the critical Wedderburn number is roughly 1 below which upwelling occurs. However, experiments conducted by Keulegan and Brame (1960) showed upwelling or partial upwelling for values of W in the range of 0.35 to 10 (as stratification is generally somewhat continuous rather than perfectly two layered). Therefore, there is some possibility for upwelling to occur in the Main Zone Pit-lake in the summer of 2002.

(iv) *Entrainment of epilimnion water-* A mixture of treated ARD water and sludge is discharged into the Main Zone Pit-lake. Because of its density is greater than the lake water, the mixture forms a sinking density current upon entering the water body. The density current entrains and drags the surrounding water along. In this case, water from the epilimnion would be brought down to the hypolimnion. Although the Waterline Outflow replenishes relatively fresh water to the epilimnion of the pit-lake, the epilimnion would still gradually disappear if the entrainment rate overwhelmed the replenishment rate of fresher water from the outflow. In other words, the balance

between the entrainment rate of the epilimnion and the replenishment of fresher water from the Waterline Outflow likely determines the conductivity, and depth of the epilimnion.

5.7.2 2001/2002 Winter Temperature Evolution

Change in Water Temperature Under Ice Before Sludge Input- Figure 5.5 shows that the temperature at 20 m gradually increased from 3.2 °C in December to 3.5 °C in January (almost as warm as the hypolimnion at 3.6 °C). The physical stirring of the hypolimnion due to sinking sludge would not be the cause since, unlike later on in February, there was no known discharge of treated ARD and sludge into the pit-lake during this period (also see below). Possible cause(s) of the phenomenon includes intrusion of groundwater, and the heat released from the underlying sludge, causing convective flow.

Response to Winter ARD and Sludge Discharge- The unprecedented winter discharge of the treated ARD sludge into the Main Zone Pit-lake in from February to March in 2002 (day 417-439) played a major role in changing (1) stratification structure of the pit-lake and (2) water temperature in the hypolimnion (Figure 5.5):

(1) Impact to the winter stratification: The sinking sludge discharge brought kinetic energy into the Main Zone Pit-lake, initiating and sustaining circulation in the water body, and eroding the reverse thermal stratification. Comparison between the input of kinetic energy (KE_{sludge}) from the sludge discharge and the change in potential energy (ΔPE) of the reverse stratification is made as follows. The change in potential energy of stratification, ΔPE, is given by:

$$\Delta PE = \int_0^{z_m} (\rho_{bef} - \rho_{aft}) zgAdz \qquad (5\text{-}2)$$

where z is depth (m); g is the gravitational acceleration (m/s^2); A is the area of the lake at depth z (m^2); ρ_{bef} is the potential density of water before change (kg/m^3); and ρ_{aft} is the potential density of water after (kg/m^3). The stratification is divided into layers so that the upper and lower boundaries of each layer coincide with the depths at which density measurements were made. Density measurements for the top 20 m obtained before (January 2002) and after (March 2002) the winter sludge discharge are used (Table D.2) and the density within a layer is linearly interpolated. Consequently, equation 5-1 is modified so that the total change in potential energy of the stratification is the sum of the changes in potential energy of all layers. The decrease in potential energy of the stratification was calculated to be approximately 10 MJ.

The total input of kinetic energy from the winter sludge discharge (KE_{sludge}) is assumed to be equal to the change in potential energy from sinking sludge solid (ΔPE_{sludge}) and is given by:

$$KE_{sludge} = \Delta PE_{sludge} = \rho_{sludge} Q \eta g h \tag{5-3}$$

where ρ_{sludge} is the sludge density (~1002 kg/m^3); Q is the total volume of sludge/treated water discharged (96,000 m^3); η is the percent sludge weight (3-5%); g is the gravitation acceleration; and h is the depth of the pit-lake(120 m). The calculated input of kinetic energy was of the order of 4 GJ, suggesting the mixing efficiency is very low since only a small portion of the kinetic energy brought by the sinking sludge converted into potential energy of the pit-lake stratification.

(2) Impact on the hypolimnion: The temperature of the hypolimnion decreased by 0.25 °C over the 22 days (Figure 5.5) of sludge discharge. Assuming the sludge was at the freezing point when entering the pit-lake, the water temperature of the hypolimnion would decrease by only 0.04 °C, suggesting the winter sludge discharge accounted only for a small portion (~15 %) of the total heat loss of the hypolimnion. While the sludge itself did not cause significant cooling, a rough heat budget within the pit indicates that the sludge acted to mix

a large amount of colder epilimnetic water with the hypolimnion, resulting in the substantial cooling observed.

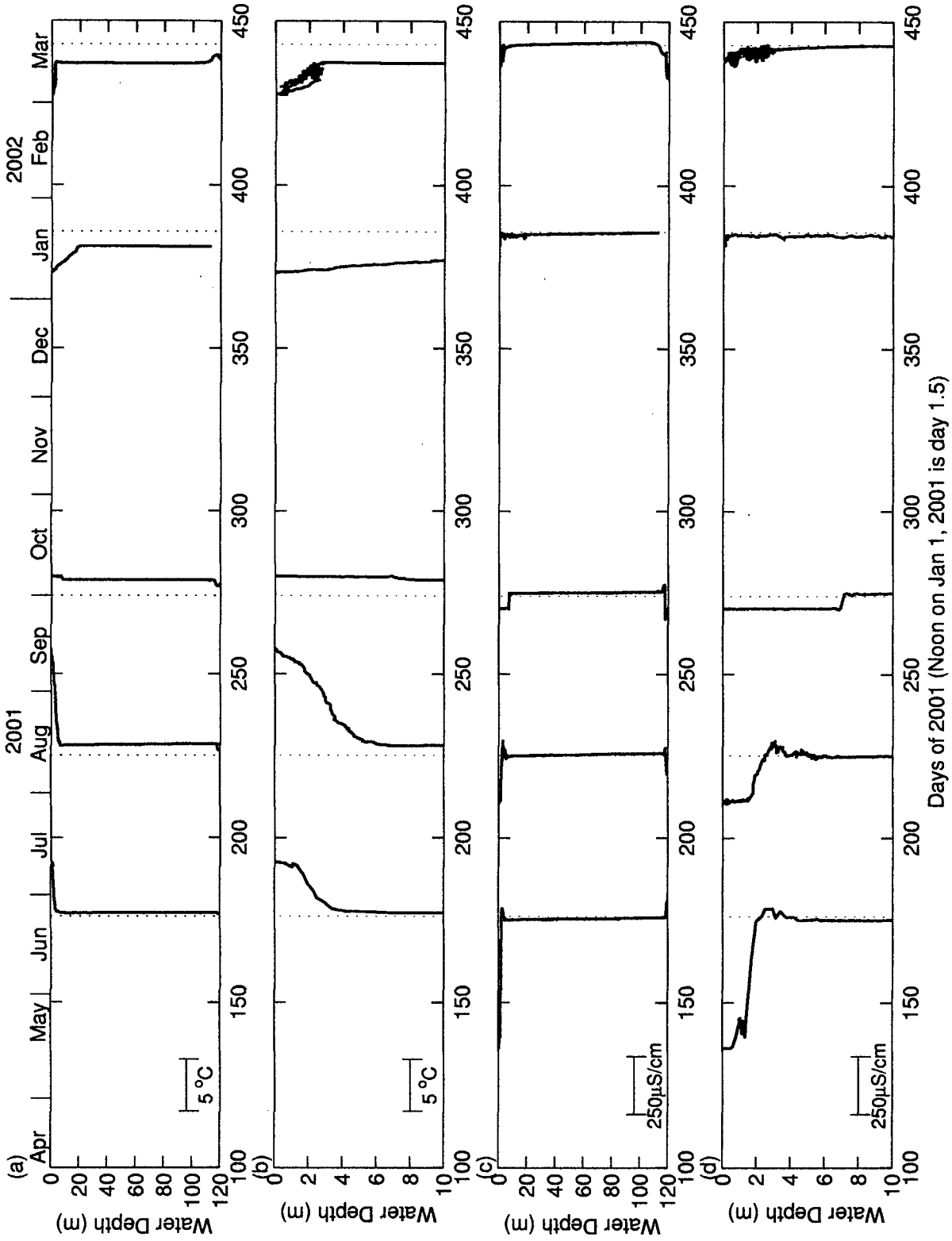


Figure 5.1 The evolution of (a-b) temperature and (c-d) conductivity stratification in the Main Zone Pit-lake from June 2001 to March 2002 for 0-120 m and 0-10 m. Note that the dotted lines (...) represent the date of the casts as well as the reference temnperature of 5 °C and specific conductance of 2550 µS/cm

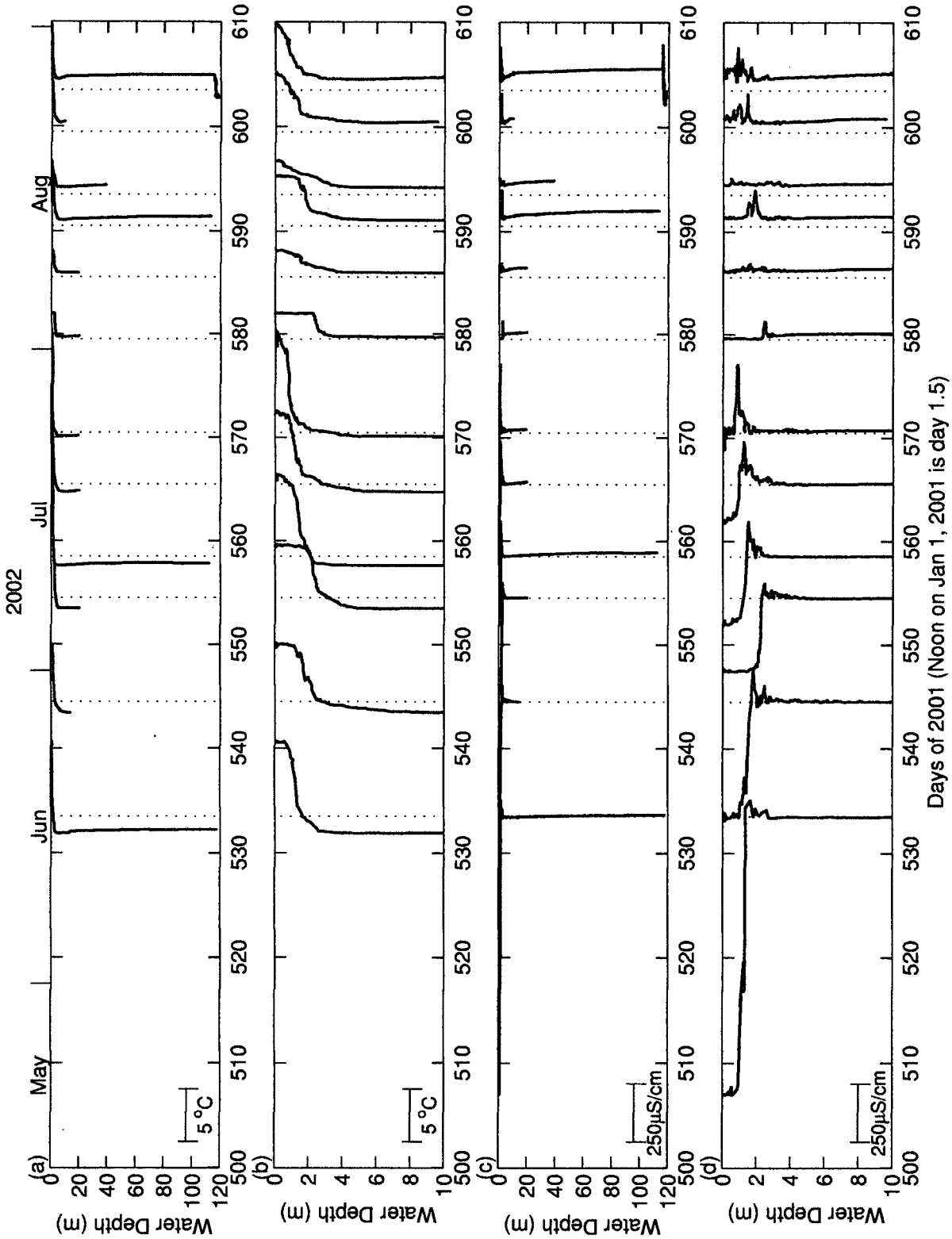


Figure 5.2 The evolution of (a-b) temperature and (c-d) conductivity stratification in the Main Zone Pit-lake from June to August 2002 for 0-120 m and 0-5 m. Note that the dotted lines (...) represent the date of the casts as well as the reference temperature of 5 °C and specific conductance of 2550 µS/cm

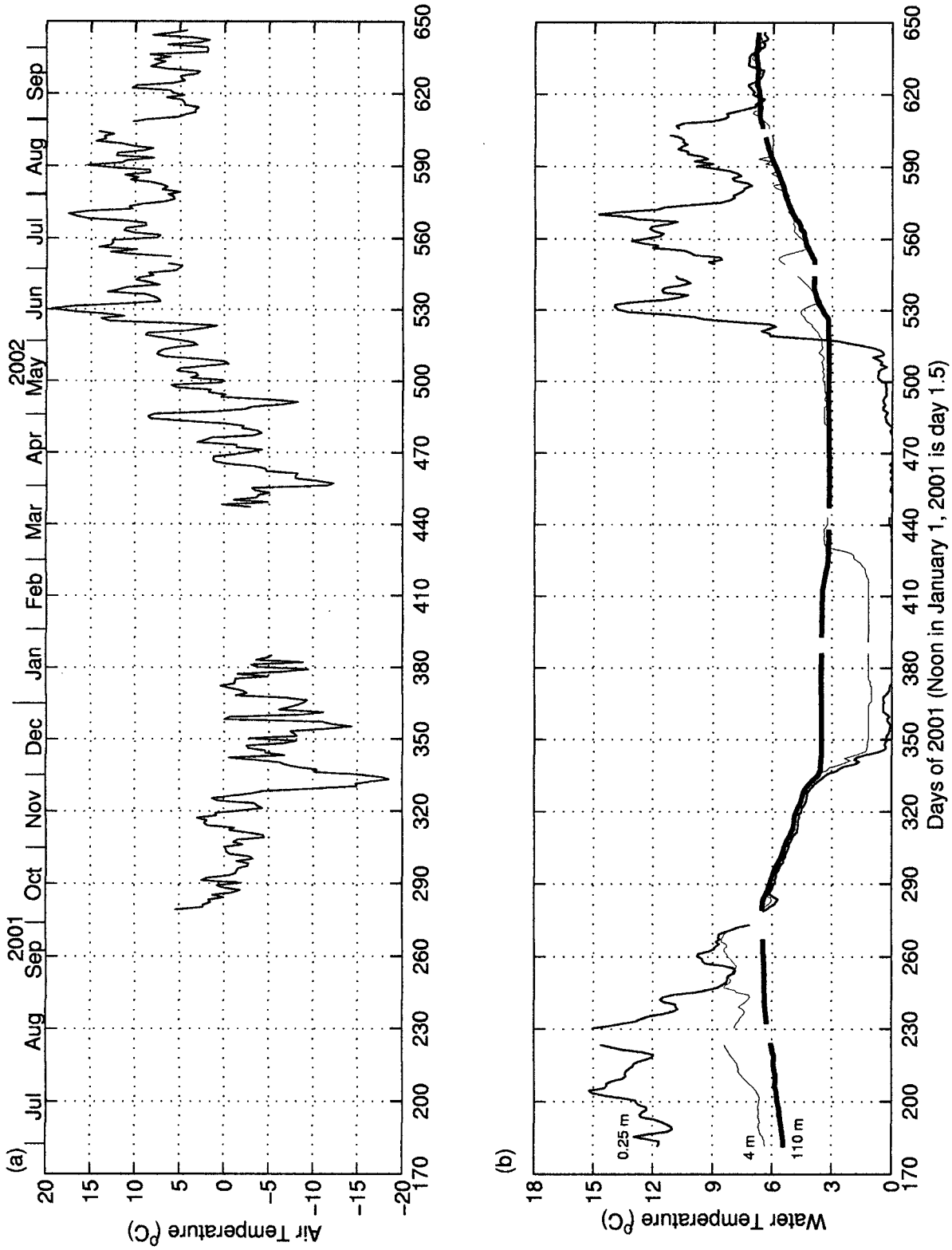


Figure 5.3 Daily average (a) air temperature and (b) water temperature at 0.25 m, 4 m and 110 m in the Main Zone Pit-lake

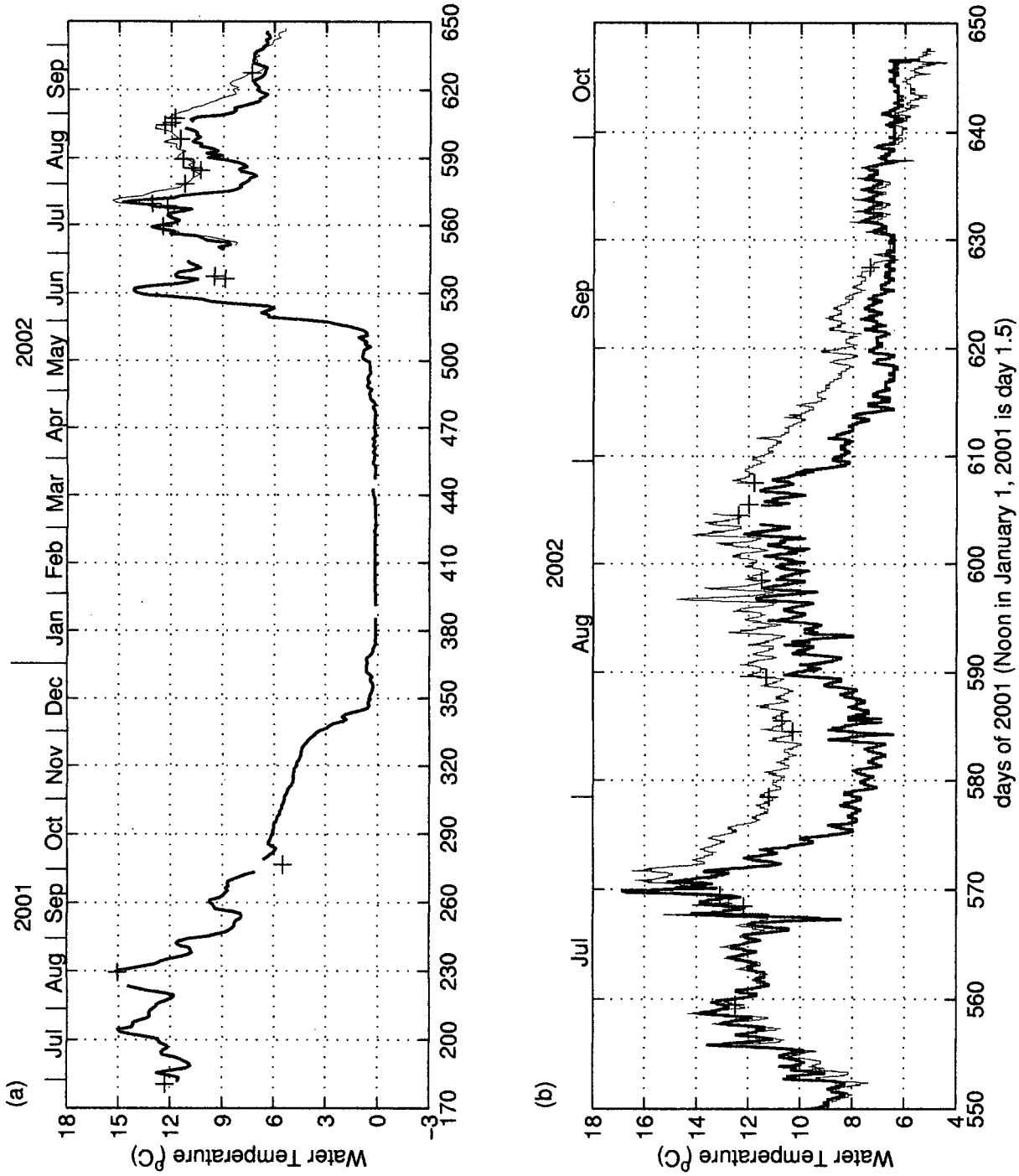


Figure 5.4 Surface water temperature (0.25 m) for (a) the period of study (July 2001-October 2002) with daily average, and (b) the expanded section (July 2002-October 2002) with 15-minute average of the Main Zone (▬) and Waterline (—) pit-lakes. Note that the (+) markers represent the isolated temperature measurements by the CTD in the Waterline Pit-lake

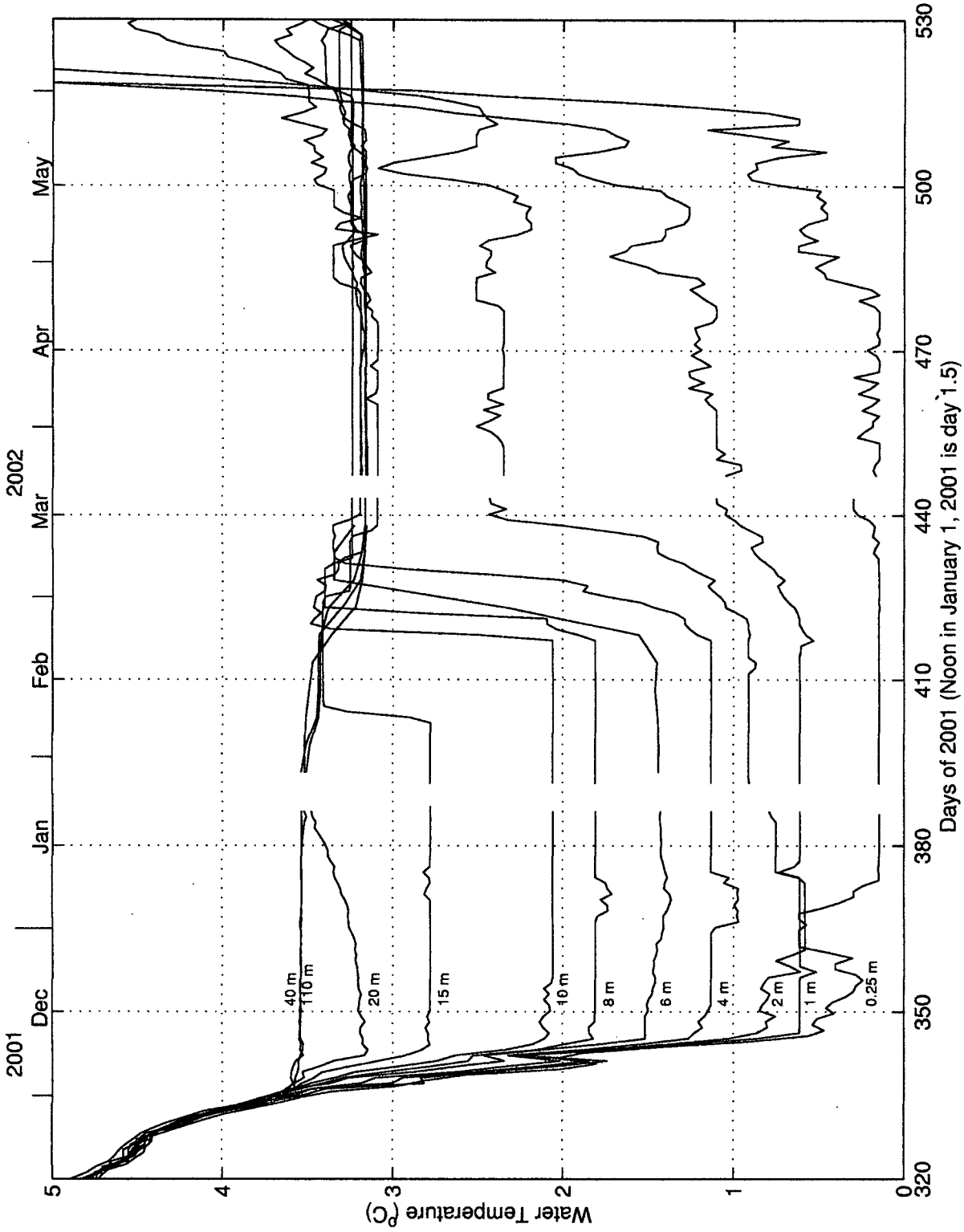


Figure 5.5 Daily water temperature of the Main Zone Pit-lake from November 2001 to June 2002

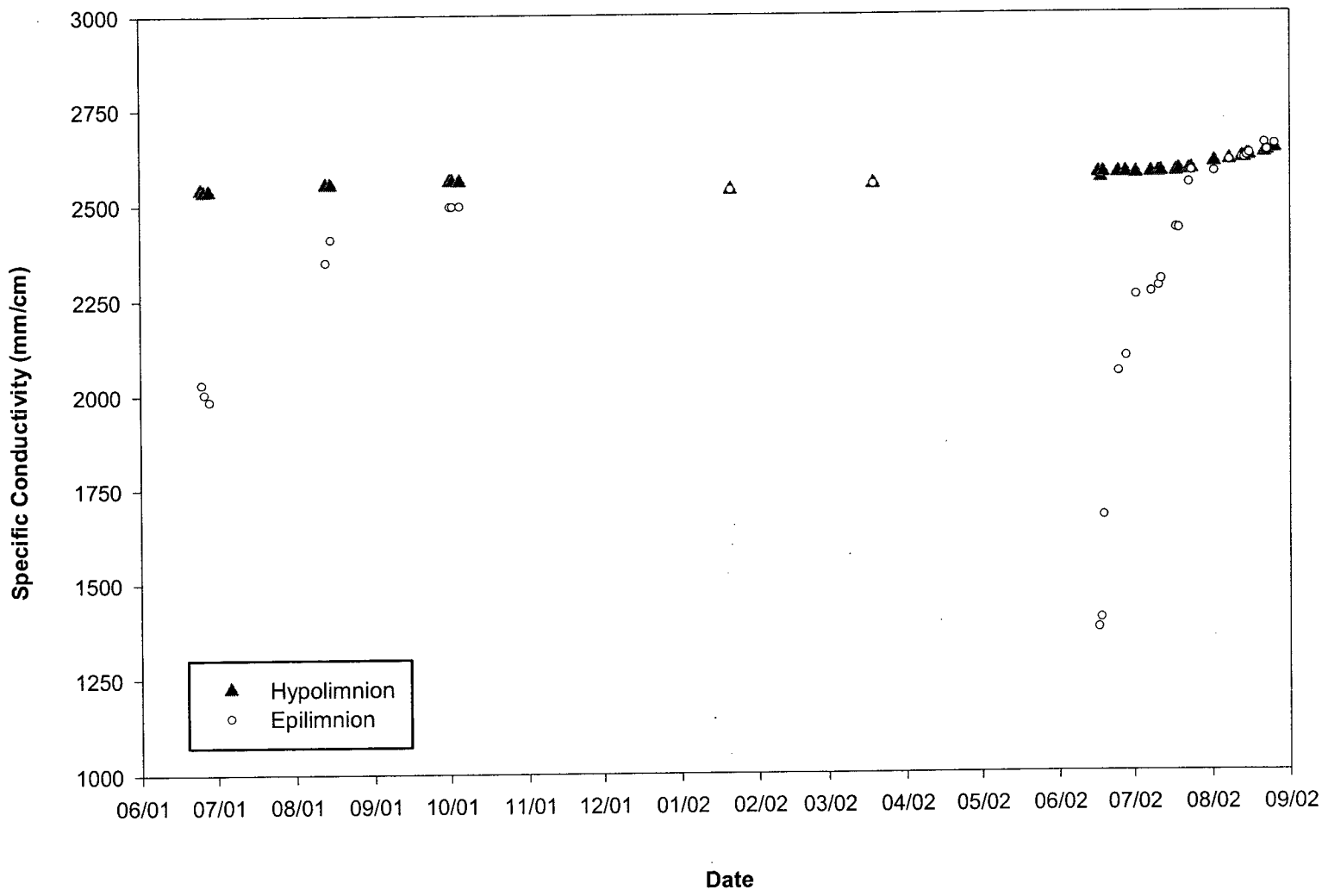


Figure 5.6 Evolution of specific conductance in the Main Zone Pit-lake from June 2001 to August 2002

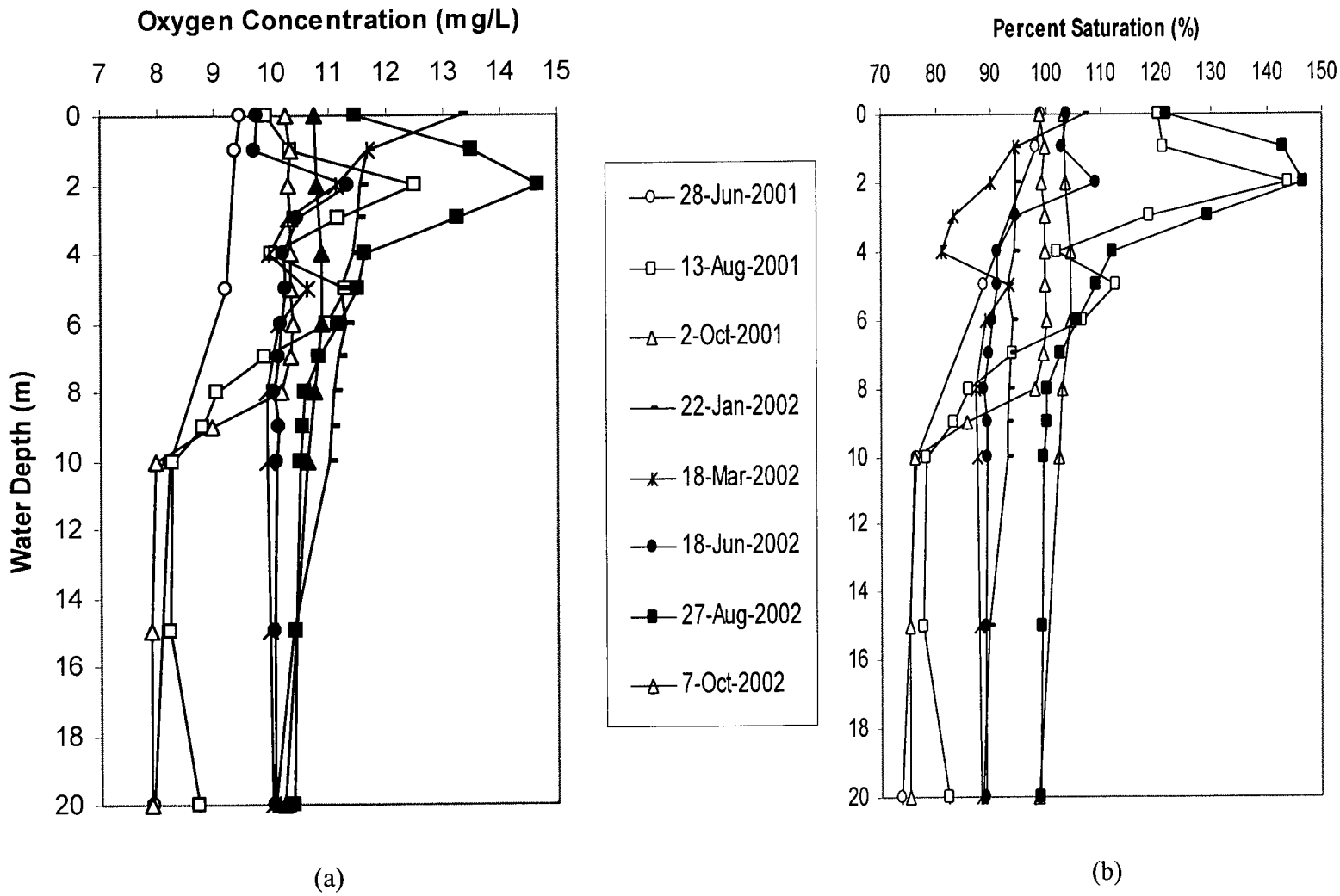


Figure 5.7 The Main Zone Pit-lake (a) oxygen concentration and (b) percent saturation for 0-20m from June 2001 to October 2002

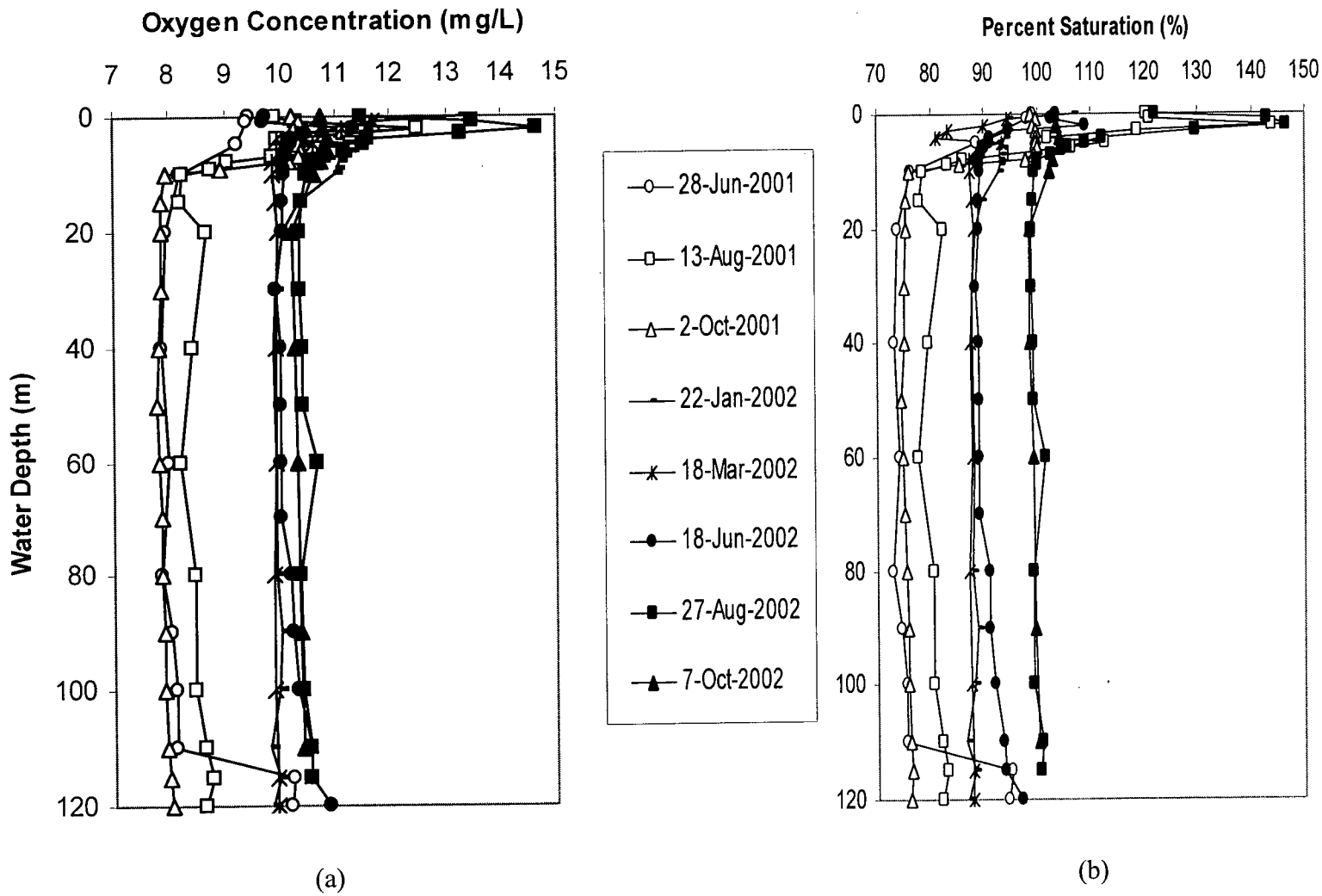


Figure 5.8 The Main Zone Pit-lake (a) oxygen concentration and (b) percent saturation for 0-120m from June 2001 to October 2002

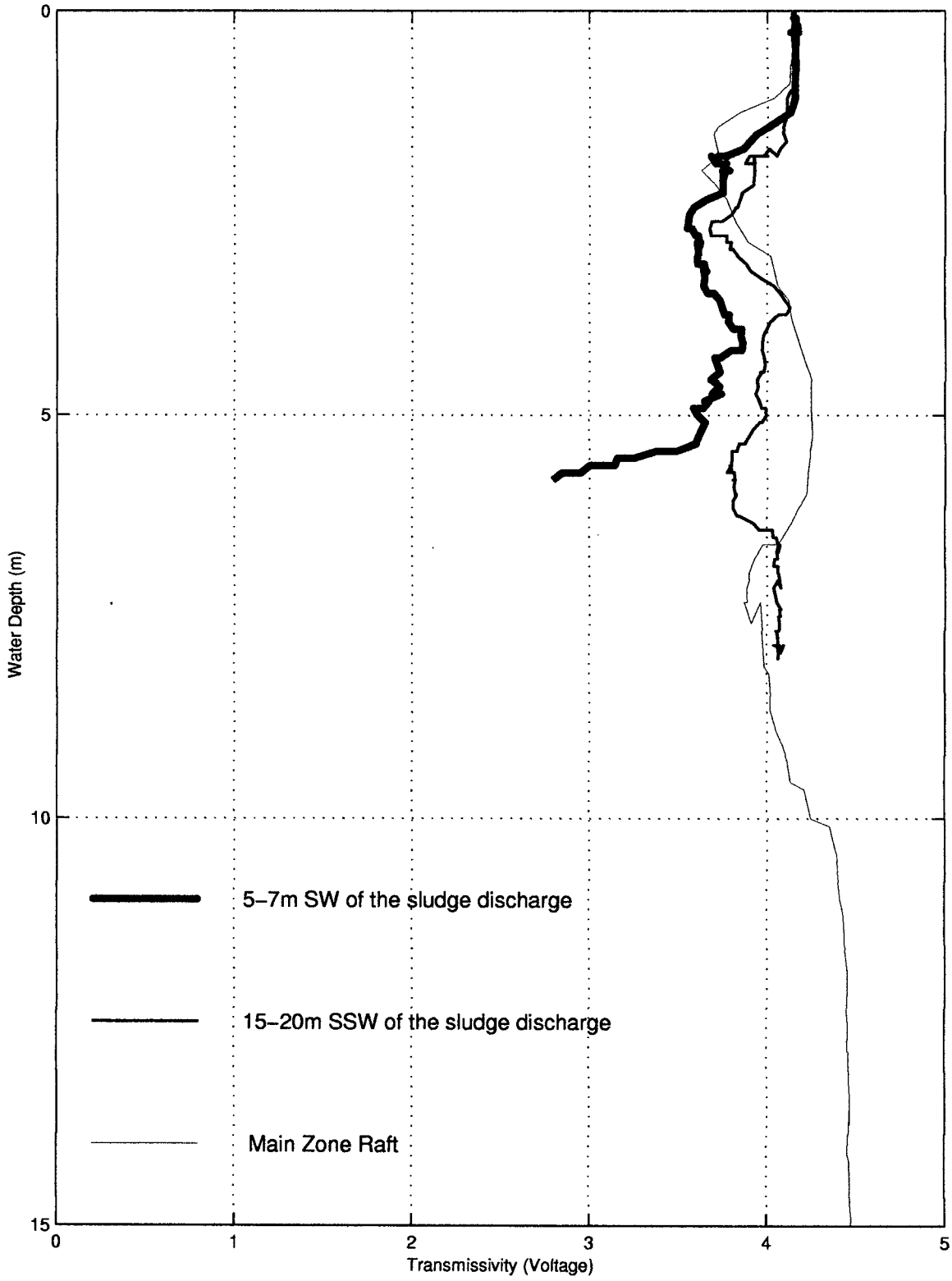


Figure 5.9 High transmissivity, indicating low turbidity, very close to the sludge discharge point

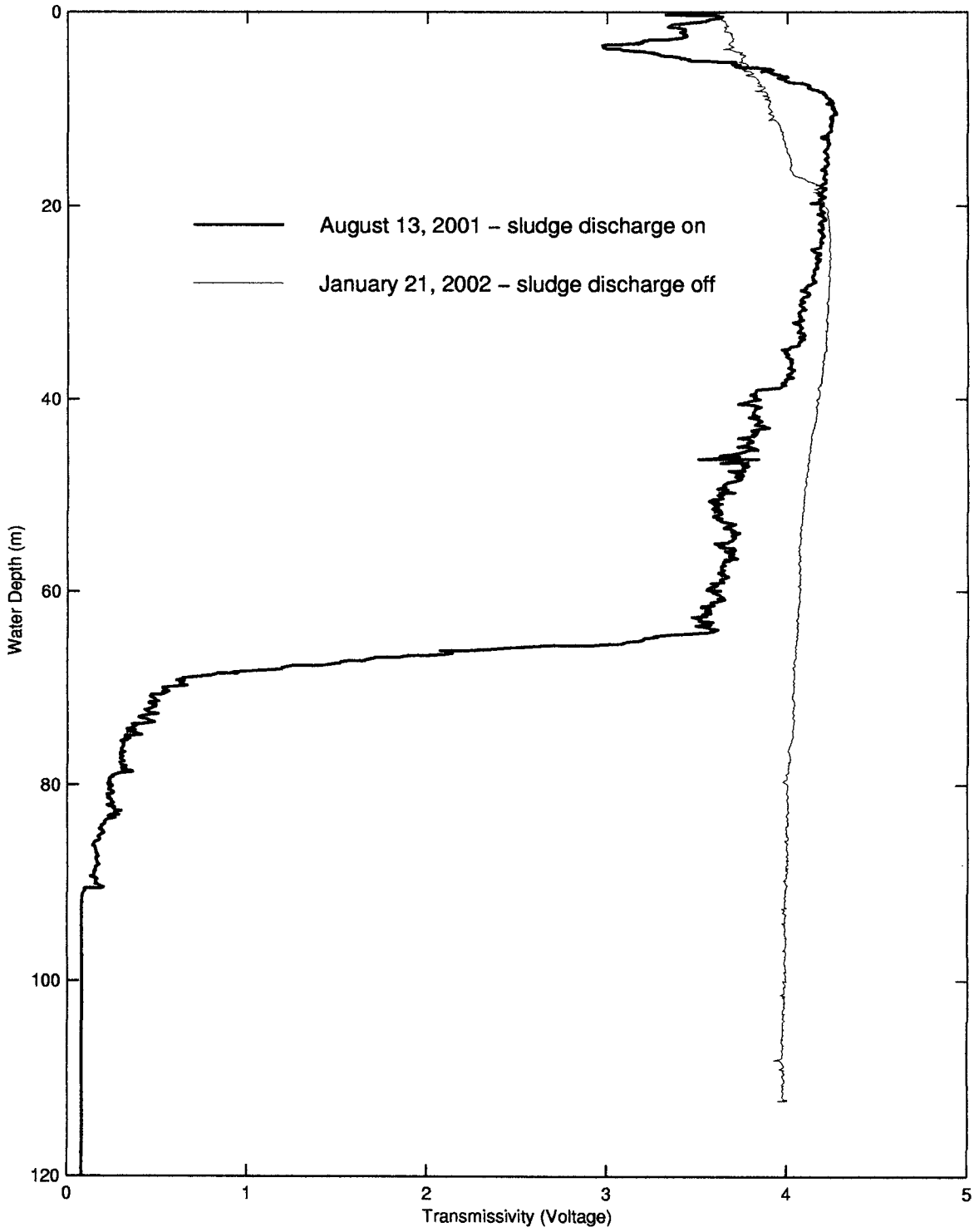


Figure 5.10 A bottom turbid layer generated by sludge discharge into the Main Zone Pit-lake

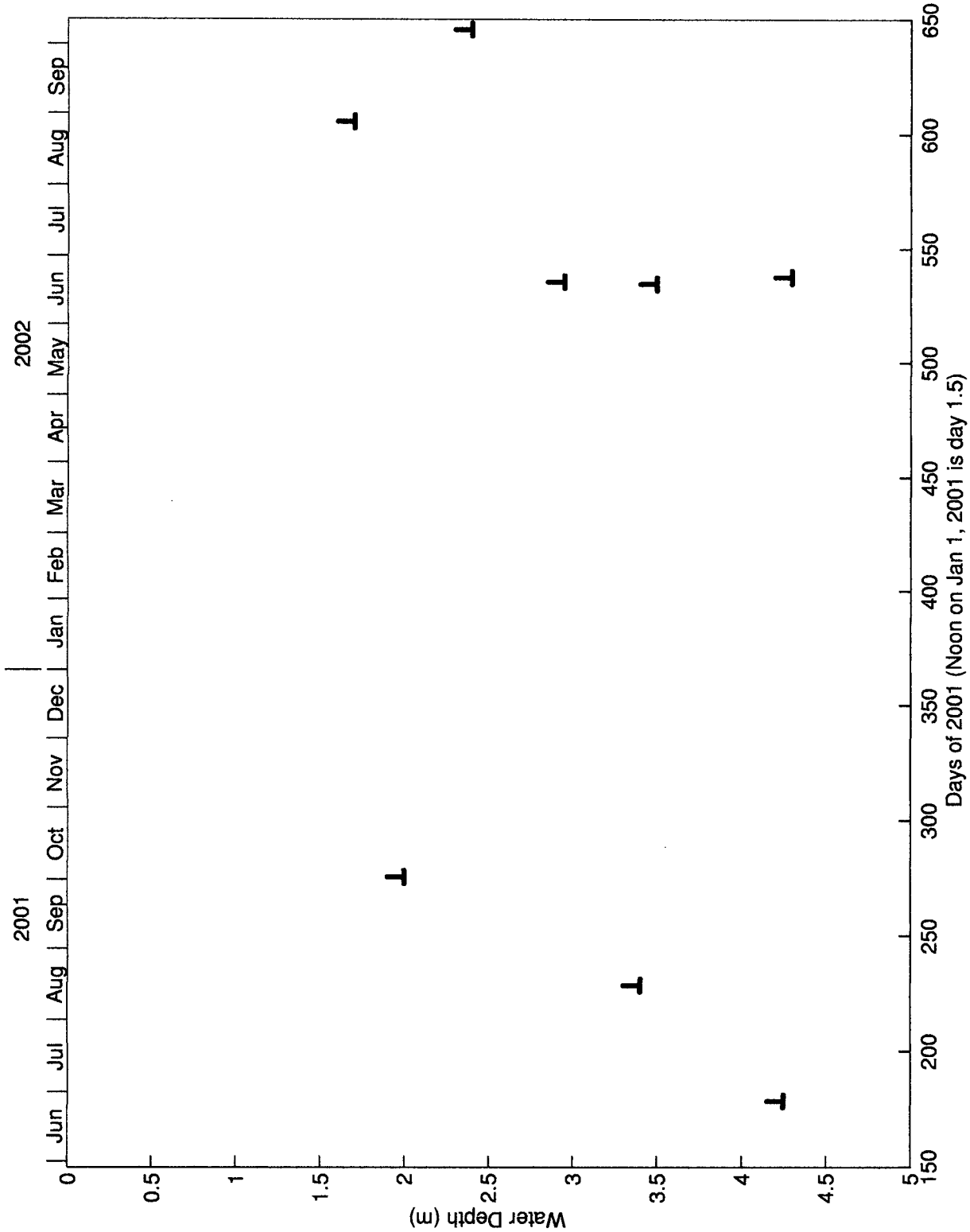


Figure 5.11 Secchi depth of the Main Zone Pit-lake

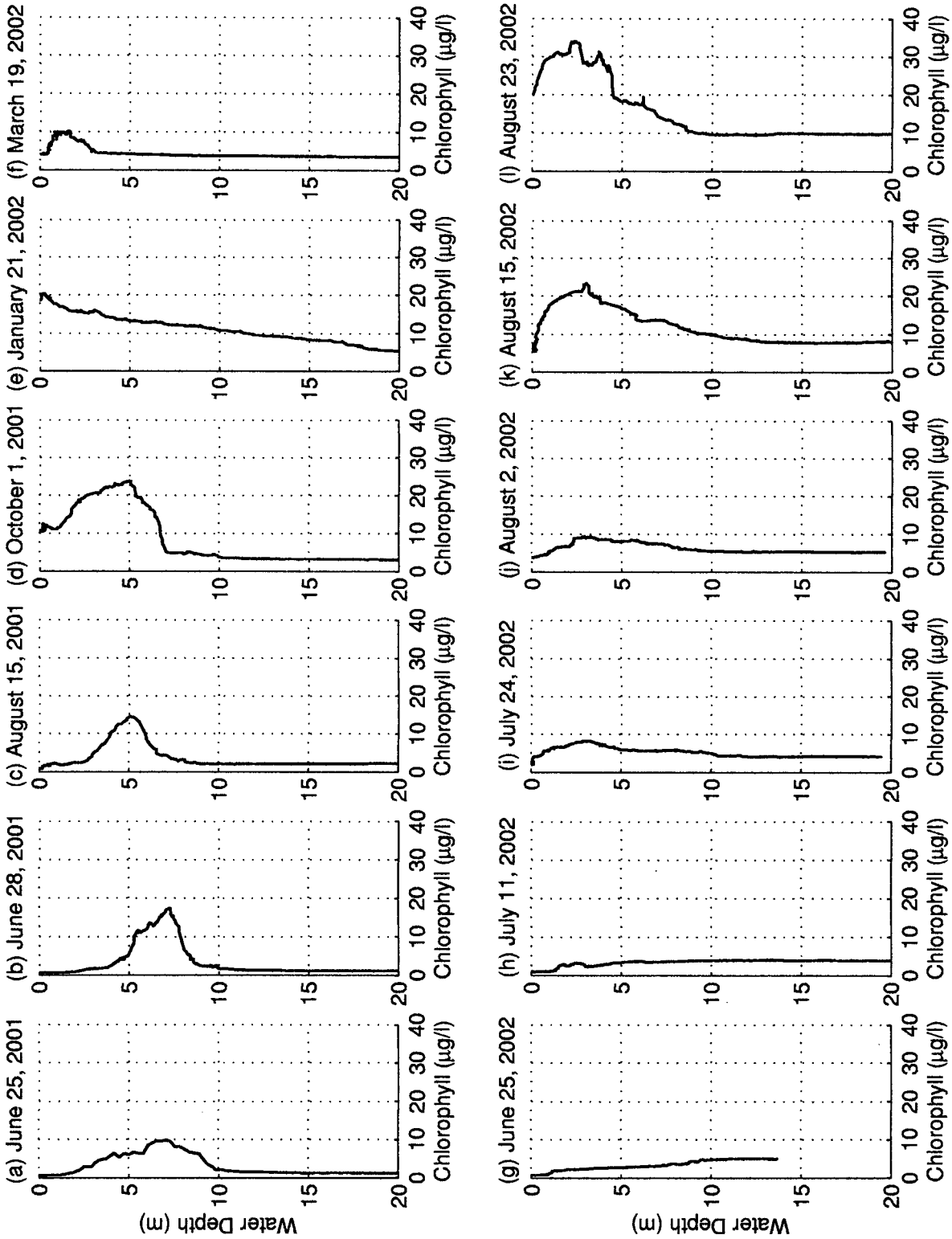


Figure 5.12 Chlorophyll evolution in the Main Zone Pit-lake from June 2001 to August 2002

6 CONCLUSIONS AND RECOMMENDATIONS

6.1. Summary and Conclusions

The two-year field observation and sampling program at the Equity Silver Mine pit-lakes – Waterline and Main Zone – commenced in June 2001, with a focus on the Main Zone Pit-lake during the first year and on both Main Zone and Waterline during the second year. Evolution of the physical limnology in the pit-lakes was investigated.

Both pit-lakes have been serving as repositories for groundwater and surface water inflow. However, only the Main Zone Pit-lake is the receiving water body for the discharge of treated acid rock drainage (ARD) for sub-aqueous disposal. Water in the Waterline Pit-lake drains into the Main Zone Pit-lake through the Waterline Outflow. Water is withdrawn from the Main Zone Pit-lake from 20 m below water surface.

The Main Zone Pit-lake is about 3 times deeper (120 m vs. 43 m) and 20 times larger (9.7 Mm^3 vs. 0.48 Mm^3) than the Waterline Pit-lake. Even though the total inflow to the Main Zone is about twice that to Waterline, the bulk residence time in Main Zone is longer (4 yrs vs. 0.3yrs).

The two water bodies are located immediately next to each other, but they behave in many different ways physically: overturning was observed in Main Zone, but permanent stratification occurred in the Waterline; anoxia was observed below the epilimnion in the Waterline, but well oxygenated conditions were encountered throughout Main Zone; a turbidity layer was present at the halocline in Waterline, but not in Main Zone; the Waterline Pit-lake was consistently fresher than the Main Zone Pit-lake; phytoplankton were presence in Main Zone but were absent in Waterline; a subsurface intrusion of the treated water and a possible groundwater intrusion in Waterline. The ARD discharge seems to be the leading candidate responsible for some of the physical mechanisms that have major implications for the pit-lake evolution: generation of turbid water near the

bottom; lake-wide circulation in the hypolimnion; entrainment of the epilimnion water into the hypolimnion; entrainment of atmospheric oxygen into the Main Zone pit-lake, and provision of nutrients.

The wind on Waterline is stronger (~30%) than that on Main Zone. Nevertheless, it is evident that major upwelling is unlikely in the Waterline Pit-lake, while the Main Zone Pit-lake is more susceptible to upwelling, which may explain the destratification of the Main Zone Pit-lake in the summer of both 2001 and 2002.

6.2. Suggestions for Further Research

Future research should focus on:

- determining the equation of state for both the Waterline and Main Zone pit-lakes;
- determining the cause(s) of the initial stability and the formation of the multi-layered stratification in the Waterline Pit-lake;
- confirming the groundwater intrusion in the Waterline Pit-lake through collecting water samples for chemical analysis and installing temperature sensors at, and close to, the depth of the suspected intrusion layer;
- investigating the cause(s) of the temperature increase at 20 m in the Main Zone Pit-lake in the winter of 2001/2002 (day 350-380) by performing heat budget calculation (total heat input from summer sludge discharge, total heat gain/loss to the atmosphere and change in the pit-lake's heat content);
- determining the entrainment properties of both the old (discharged before June 2002) and new (discharged from June 2002 onward) ARD sludge;
- performing a detailed heat and salt budget (input from the Waterline and ARD discharge) to ascertain the cause(s) of the early de-stratification of the Main Zone Pit-lake in summers of 2001 and 2002;
- determining the limnological effects of discharging tailing pond water into the Main Zone Pit-lake, and

- modelling the water quality at the intake of the withdrawal pipe (20 m) in the Main Zone Pit-lake.

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APPENDIX A

SLUDGE AND TREATED WATER DISPOSAL TO THE MAIN ZONE PIT-LAKE

Table A.1 Disposal of sludge and treated water into the Main Zone Pit-lake (adapted from Aziz 2001)

Year	Sludge Volume Pumped (m^3)		Treated Water (m^3)	Diversion to (m^3)	Reason/Comment
	Tailings Pond	Main Zone Pit	to Main Zone	Main Zone	
1985					
1986	72,948				
1987	174,437				
1988	69,000				
1989	101,000				
1990	245,000				
1991	197,000		127,000		
1992	115,000		135,245		
1993		131,676		750,000	from Berzelius to allow diversion ditch repair
1994		138,970		1,000,000	from Berzelius to allow sinkhole repair and borrow pit access
1995		151,000		250,000	from Berzelius
1996		151,620			
1997		265,000	635,635	130,000	from Berzelius (3 days @0.5 m3/sec)
1998		57,400	82,166		
1999		86,400	107,035	??	Overflow from Berzelius Diversion - unknown volume
2000		80,558	99,900	??	Seepage reduced through repairs to diversion
Total	974,385	1,062,624	1,186,981	2,130,000	

Note:

- Sludge typically 3-5% solids by weight
- No sludge pumped prior to 1986

APPENDIX B

RETENTION TIME OF THE WATERLINE AND MAIN ZONE PIT-LAKES

Table B.1 The Waterline Pit-lake hydrology

1. Determine the Waterline pit volume (V_{pit})

			References/Comment:
The average Waterline water surface elevation in 2001 =	1265	m	*Waterline Outflow elevation*
The estimated volume of the Waterline pit below the water surface elevation=	481945	m^3	*Chapter 2*

2. Determine the volume of sludge solid that went in to the Waterline pit (V_{sludge})

The assumed Waterline discharge of sludge in 2001 =	0	m^3
The total volume of Waterline sludge discharge (up to Dec 2000) =	0	m^3
The estimated total volume of sludge solid in the pit (as of 2001) =	0	m^3

3. Determine the volume of backfilled waste rock in Waterline pit ($V_{wasterock}$)

The approximated volume of backfilled waste rock in the Waterline pit =	0	m^3

4. Determine the volume of water of the Waterline Pit-lake (V_{volume})

The volume of water in the Waterline pit in 2001=	481945	m^3	*Determined by Equation 2-3*

5. Determine the annual runoff for the Waterline Pit-lake

5.1 Determine the annual drainage volume:

The assumed surface runoff yield =	14	L/s/km^2	*Aziz 2001*
The estimated total Waterline Pit drainage area =	0.133	km^2	
The annual drainage into the Waterline pit =	58720	m^3/yr	

5.2 Determine the annual direct precipitation:

The annual direct precipitation =	673.954	mm/yr	*Figure 1.8*
The pit area (water surface + pitwalls) =	0.0739	km^2	
The annual volume of direct precipitation =	49805	m^3/yr	

5.3 Determine the annual leakage volume from Bezelius Creek:

Estimated annual leakage from Bezelius Creek =	1300000	m^3/yr	*Aziz 2001*

Therefore the total amount of annual inflow = direct drainage+direct precipitation+leakage

The total amount of annual inflow =	1408525	m^3/yr

6. Determine the bulk retention time of the Waterline Pit-lake in 2001

The estimated bulk retention time of the Waterline Pit-lake =	0.34	yr

7. Determine the minimum effective (epilimnion) retention time of the Waterline Pit-lake in 2001

The minimum depth of the epilmnion =	2.87	m	*Fig.4.2*
The corresponding volume of water below the epilimnion =	410916	m^3	*Fig.2.2*
The volume of water in the epilimnion =	71029	m^3	
The estimated minimum retention time of the Waterline Pit-lake =	0.050	yr	

8. Determine the maximum effective (epilimnion) retention time of the Waterline Pit-lake in 2001

The maximum depth of the epilimnion =	8.79	m	*Fig.4.2*
The corresponding volume of water below the epilimnion =	289586	m^3	*Fig.2.2*
The volume of water in the epilimnion =	192359	m^3	
The estimated minimum retention time of the Waterline Pit-lake =	0.137	yr	

Table B.2 The Main Zone Pit-lake hydrology

1. Determine the Main Zone pit volume

References/Comments:

The average Main Zone Pit-lake water surface elevation in 2001 = 1259.3 m — *Aziz (2002)*

The estimated volume of the Main Zone pit below the water surface elevation = 12216214 m^3

2. Determine the volume of sludge solid that went in to the Main Zone pit

The sludge solid volume to total discharge volume ratio = 0.446 — *Aziz (2000, 2001)*

The assumed volume of sludge discharge into the Main Zone pit in 2001 = 122265 m^3 — *Aziz's email (May 6)*

The total volume of sludge discharge into the Main Zone pit (up to Dec 2000) = 1062624 m^3

The estimated total volume of sludge solid in the Main Zone pit (as of 2001) = 1184889 m^3

3. Determine the volume of backfilled waste rock in Main Zone pit

The approximated volume of the backfilled waste rock in the Main Zone pit = 1480000 m^3 — *Bosse (1991)*

4. Determine the volume of the Main Zone Pit-lake

The volume of water of the Main Zone Pit-lake in 2001 = 9551325 m^3 — ***Determined by Equation 2-3***

5, Determine the annual runoff for the Main Zone Pit

5.1 Determine the annual drainage volume from the Waterline Pit-lake:

The total amount of annual drainage from the Waterline Pit-lake = 1408525 m^3/yr — *Table B-1*

5.2 Determine the annual surface drainage volume (other than the input from the Waterline Pit-lake):

the assumed surface runoff yield = 14 L/s/km^2 — *Aziz 2000*

The estimated total Main Zone pit drainage area = 0.26 km^2 — *Estimated by Albert Leung of UBC*

ıe annual surface drainage (excl. input f/o the Waterline) into the Main Zone Pit-lake = 114791 m^3/yr — *Excluded inout from the Waterline*

5.3 Determine the annual volume of direct precipitation (snowfall +rainfall):

The annual direct precipitation = 673.954 mm/yr

The pit area (water surface + pit-walls) = 0.37 km^2

The annual volume of direct precipitation = 249363 m^3/yr

5.4 Determine the annual volume of groundwater inflow:

Estimated groundwater flow = 436000 m^3/yr — *Aziz (2001)*

Therefore the total annual inflow into the Main Zone Pit-lake = drainage from the Waterline+Main Zone direct drainage+direct precipitation+groundwater

The total amount of annual inflow = 2208679 m^3/yr

Now, a constraint can be put to the rentention time by selecting the lowest and highest sludge and treated water discharge into the Main Zone Pit-lake

6, Determine the maximum retention time for the Main Zone Pit-lake in 2001

The lowest treated water discharge rate in record (i.e. 1998) = 82166 m^3

The estimated maximum retention time for the Main Zone Pit-lake = 4.17 yr

7, Determine the miximum retention time for the Main Zone Pit-lake in 2001

The highest treated water discharge rate in record (i.e. 1997) = 635635 m^3

The estimated minimum retention time for the Main Zone Pit-lake = 3.36 yr

8, Determine the average retention time for the Main Zone Pit-lake in 2001

The average treated water discharge rate in record = 197830 m^3

The estimated minimum retention time for the Main Zone Pit-lake = 3.97 yr

APPENDIX C

FIELD DATA AND SAMPLE COLELCTION PLAN

Table C.1 Summary of CTD casts from June 2001 to October 2002

Date	Time	Cast Name	Location	Operator	SBE max. depth (m)	Comment
23-Jun-01	11:50am	eqa23u01	10-15m SW of the sludge discharge	AL/JC	2	sludge on
23-Jun-01	12:18am	eqb23u01	5-7m SW of the sludge discharge	AL/JC	6	sludge on
23-Jun-01	12:49am	eqd23u01	15m S of the sludge discharge	AL/JC	6	sludge on
23-Jun-01	1:22pm	eqe23u01	15-20m SSE of the sludge discharge	AL/JC	8	sludge on
23-Jun-01	1:58pm	eqf23u01	10-12m SW of the WL outflow	AL/JC	8	
23-Jun-01	2:17pm	eqg23u01	5-7m S of the WL outflow	AL/JC	16	
25-Jun-01	2:00pm	eqa25u01	MZ raft	AL/JC	120	
25-Jun-01	2:25pm	eqc25u01	MZ raft	AL/JC	120	hit unknown obj. at 40m
25-Jun-01	3:21pm	eqe25u01	30-35m N of raft	AL/JC	118	
26-Jun-01	12:31pm	eqa26u01	MZ transect (MZT): 75m S of raft	AL/JC	106	sludge at bottom
26-Jun-01	1:02pm	eqc26u01	MZT: 7-8m S of raft	AL/JC	118	
26-Jun-01	1:31pm	eqd26u01	MZT: E of barge; 100m N of raft	AL/JC	77	sludge at bottom
26-Jun-01	1:57pm	eqf26u01	MZT: 80m N of raft	AL/JC	90	no sludge bottom
26-Jun-01	2:18pm	eqg26u01	MZT: 80m from north pit-wall	AL/JC	90	sludge at bottom
27-Jun-01	4:25pm	eqa27u01	MZ raft	AL/JC	10	w/ Niskin bottle
27-Jun-01	4:57pm	eqc27u01	MZ raft	AL/JC	9	w/ Niskin bottle
27-Jun-01	5:25pm	eqd27u01	MZ raft	AL/JC	9	w/ Niskin bottle
27-Jun-01	5:53pm	eqe27u01	MZ raft	AL/JC	9	w/ Niskin bottle
28-Jun-01	11:42am	eqa28u01	MZ raft	AL/JC	60	w/ Niskin bottle
28-Jun-01	1:01pm	eqb28u01	MZ raft	AL/JC	88	w/ Niskin bottle
28-Jun-01	3:08pm	eqc28u01	MZ raft	AL/JC	118	w/ Niskin bottle
29-Jun-01	11:55am	eqa29u01	WL pit-lake	KM/JC	39	
13-Aug-01	11:37am	eqa13g01	MZT: 120-125m S of raft	PW/JC	63	
13-Aug-01	12:00pm	eqb13g01	MZT: raft	PW/JC	120	Sludge on
13-Aug-01	12:43pm	eqc13g01	MZT: 100-105m N of raft	PW/JC	120	
13-Aug-01	1:45pm	eqd13g01	MZT: 205-210m N of raft	PW/JC	118	
13-Aug-01	2:20pm	eqe13g01	MZT: 315-320m N of raft	PW/JC	90	sludge off
13-Aug-01	2:45pm	eqf13g01	MZT: 430-435m N of raft	PW/JC	92	sludge off
13-Aug-01	3:15pm	eqg13g01	MZT: 540-545m N of raft	PW/JC	65	sludge off
13-Aug-01	3:30pm	eqh13g01	MZT: < 50m to north pit-wall	PW/JC	23	sludge off
14-Aug-01	12:30pm	eqa14g01	MZ raft	PW/JC	20	
14-Aug-01	3:40pm	eqb14g01	MZ raft	PW/JC	10	w/ Niskin bottle
15-Aug-01	7:25am	eqa15g01	MZ raft	AL/JC	22	w/ Niskin bottle
15-Aug-01	8:40am	eqb15g01	MZ raft	AL/JC	52	w/ Niskin bottle
15-Aug-01	11:31am	eqc15g01	MZ raft	PW/JC	12	w/ Niskin bottle
15-Aug-01	12:23pm	eqd15g01	MZ raft	AL/PW	82	w/ Niskin bottle
15-Aug-01	2:18pm	eqe15g01	MZ raft	AL/PW	122	w/ Niskin bottle
16-Aug-01	10:22am	eqa16g01	MZ raft	AL/KM	30	stepped cast
17-Aug-01	10:48am	eqa17g01	WL pit-lake	PW/KM	43	
17-Aug-01	3:10am	eqb17g01	MZ raft	AL/JC/PW	15	inside limnocorral
01-Oct-01	10:12am	eqa01o01	MZ raft	AL/JC	120	Sludge off
01-Oct-01	3:08pm	eqb01o01	MZ raft	AL/JC/PW	11	Sludge on
02-Oct-01	1:39pm	eqa02o01	MZ raft	AL/PW	115	Sludge on
03-Oct-01	10:10am	eqa03o01	Waterline pit-lake	PW/JC	39	pit-wall shadow
03-Oct-01	10:35am	eqb03o01	Waterline pit-lake	PW/JC	39	pit-wall shadow; hit unknown obj. @ 20m
04-Oct-01	2:36pm	eqa04o01	MZ raft	AL/K	29	stepped cast
05-Oct-01	3:49pm	eqa05o01	MZT: 120-125m S of raft	PW/JC	79	touch bottom
05-Oct-01	4:04pm	eqb05o01	MZT: raft	PW/JC	117	sludge off
05-Oct-01	4:36pm	eqc05o01	MZT: 430-435m N of raft	PW/JC	92	sludge on
05-Oct-01	4:52pm	eqd05o01	MZT: <50m to north pit-wall	PW/JC	24	sludge off
21-Jan-02	3:26pm	eqa21j02	MZ raft	AL/JC/PW	112	~0.3m ice
22-Jan-02	10:45am	eqa22j02	MZ raft	AL/JC/PW	38	~0.3m ice
25-Jan-02	11:08am	eqa25j02	Waterline pit-lake	AL/JC	42	~0.5m ice
19-Mar-02	10:11am	eqa19m02	MZ raft	AL/JC	118	stepped cast; ~0.6m ice; sludge off
19-Mar-02	4:12pm	eqb19m02	MZ raft	AL/JC	120	sludge off; 0.6m ice
21-Mar-02	10:18am	eqa21m02	Waterline pit-lake	AL/JC	38	~0.9m ice
17-Jun-02	4:24pm	eqa17u02	MZ raft	AL/PW	117	
17-Jun-02	4:42pm	eqb17u02	MZ raft	AL/PW	117	
18-Jun-2	10:45am	eqa18u02	MZ raft	AL/PW	118	
19-Jun-02	9:40am	eqa19u02	MZ raft	AL/PW	118	
19-Jun-02	3:50pm	eqb19u02	MZ raft	AL/PW	118	

Table C.1 Summary of CTD casts from June 2001 to October 2002 (cont.)

Date	Time	Cast Name	Location	Operator	SBE max. depth (m)	Comment
20-Jun-02	11:23am	eqa20u02	Waterline pit-lake	AL/PW	26	
21-Jun-02	10:02am	eqa21u02	Waterline pit-lake	AL/PW	35	
25-Jun-02	9:57am	eqb25u02	MZ raft (outside limnocorral)	AL/DK	14	
25-Jun-02	11:09am	eqk25u02	MZ raft (outside limnocorral)	AL/DK	14	
28-Jun-02	9:25am	eqa28u02	MZ raft (outside limnocorral)	AL/DK	14	
28-Jun-02	10:10am	eqc28u02	MZ raft (outside limnocorral)	AL/DK	14	
28-Jun-02	11:52am	eqm28u02	MZ raft (outside limnocorral)	AL/DK	14	
02-Jul-02	10:03am	eqa02l02	MZ raft (outside limnocorral)	AL/PW	20	
02-Jul-02	1:13pm	eqk02l02	MZ raft (outside limnocorral)	AL/PW	20	
08-Jul-02	10:30am	eqa08l02	MZ raft (outside limnocorral)	PW/DK	20	
08-Jul-02	12:24pm	eqj08l02	MZ raft (outside limnocorral)	PW/DK	20	
11-Jul-02	9:32am	eqa11l02	MZ raft (outside limnocorral)	PW/DK	20	
11-Jul-02	10:47am	eqf11l02	MZ raft (outside limnocorral)	PW/DK	20	
11-Jul-02	11:13am	eqg11l02	MZ raft (outside limnocorral)	PW/DK	117	
12-Jul-02	9:33am	eqa12l02	MZ raft (outside limnocorral)	PW/DK	20	
12-Jul-02	11:03am	eqf12l02	MZ raft (outside limnocorral)	PW/DK	20	
12-Jul-02	11:29am	eqg12l02	MZ raft (outside limnocorral)	PW/DK	112	
13-Jul-02	1:28pm	eqa13l02	WL north raft (outside limnocorral)	PW/DK	35	
13-Jul-02	3:39pm	eqf13l02	WL south raft (outside limnocorral)	PW/DK	9	
18-Jul-02	1:18pm	eqa18l02	MZ raft (outside limnocorral)	PW/DK	20	
18-Jul-02	2:49pm	eqf18l02	MZ raft (outside limnocorral)	PW/DK	20	
19-Jul-02	12:00pm	eqa19l02	MZ raft (outside limnocorral)	PW/DK	20	
19-Jul-02	1:38pm	eqf19l02	MZ raft (outside limnocorral)	PW/DK	20	
22-Jul-02	1:40pm	eqa22l02	WL south raft (outside limnocorral)	PW/DK	9	
22-Jul-02	4:26pm	eqi22l02	WL north raft (outside limnocorral)	PW/DK	20	
23-Jul-02	11:13am	eqc23l02	WL north raft (outside limnocorral)	PW/DK	39	
23-Jul-02	3:05pm	eqd23l02	MZ raft (outside limnocorral)	PW/DK	117	stepped cast w/ 20xOBS
23-Jul-02	3:43pm	eqe23l02	MZ raft (outside limnocorral)	PW/DK	117	stepped cast w/ 5xOBS
24-Jul-02	2:46pm	eqf24l02	MZ raft (outside limnocorral)	PW/DK	20	
01-Aug-02	2:40pm	eqa01g02	WL south raft (outside limnocorral)	PW/DK	9	
01-Aug-02	12:20pm	eqf01g02	WL south raft (outside limnocorral)	PW/DK	9	
01-Aug-02	2:23pm	eqg01g02	WL north raft (outside limnocorral)	PW/DK	20	
02-Aug-02	2:35pm	eqa02g02	MZ raft (outside limnocorral)	PW/DK	20	
03-Aug-02	10:16am	eqa03g02	MZ raft (outside limnocorral)	PW/DK	20	pause every 5m dn/up
03-Aug-02	12:12pm	eqe03g02	MZ raft (outside limnocorral)	PW/DK	112	
06-Aug-02	2:21pm	eqa06g02	WL south raft (outside limnocorral)	PW/DK	9	
07-Aug-02	10:09am	eqa07g02	WL north raft (outside limnocorral)	PW/DK	39	
07-Aug-02	3:29pm	eqf07g02	WL north raft (outside limnocorral)	PW/DK	20	
08-Aug-02	9:10am	eqa08g02	WL north raft (outside limnocorral)	PW/DK	40	
08-Aug-02	2:21pm	eqd08g02	MZ raft (outside limnocorral)	PW/DK	20	pause every 5m dn/up
12-Aug-02	10:02am	eqa12g02	WL south raft (outside limnocorral)	PW/DK	9	
12-Aug-02	2:26pm	eqg12g02	WL south raft (outside limnocorral)	PW/DK	9	
12-Aug-02	3:03pm	eqh12g02	WL north raft (outside limnocorral)	PW/DK	20	
13-Aug-02	10:30am	eqd13g02	WL north raft (outside limnocorral)	PW/DK	39	
13-Aug-02	1:34pm	eqe13g02	MZ raft (outside limnocorral)	PW/DK	113	
14-Aug-02	9:30am	eqb14g02	MZ raft (outside limnocorral)	PW/DK	20	
14-Aug-02	2:11pm	eqe14g02	MZ raft (outside limnocorral)	PW/DK	20	
15-Aug-02	9:52am	eqb15g02	MZ raft (outside limnocorral)	PW/DK	20	
15-Aug-02	1:34pm	eqf15g02	MZ raft (outside limnocorral)	PW/DK	20	
16-Aug-02	8:49am	eqa16g02	MZ raft (outside limnocorral)	PW/DK	39	w/ ext. pressure sensor
20-Aug-02	1:36pm	eqa20g02	WL south raft (outside limnocorral)	PW/DK	9	
21-Aug-02	1:13pm	eqe21g02	WL north raft (outside limnocorral)	PW/DK	10	
22-Aug-02	3:00pm	eqg22g02	MZ raft (outside limnocorral)	PW/DK	10	
23-Aug-02	9:58am	eqc23g02	MZ raft (outside limnocorral)	PW/DK	117	
26-Aug-02	4:10pm	eqb26g02	MZ raft (outside limnocorral)	AL/DK	119	hit bottom
27-Aug-02	9:59am	eqa27g02	WL north raft (outside limnocorral)	AL/TT	16	
27-Aug-02	2:30pm	eqb27g02	WL north raft (outside limnocorral)	AL/TT	36	
28-Aug-02	2:21pm	eqa28g02	WL south raft (outside limnocorral)	DK/JC	14	
28-Aug-02	4:35pm	eqj28g02	WL north raft (outside limnocorral)	DK/JC	8	
30-Aug-02	10:31am	eqa30g02	WL north raft (outside limnocorral)	AL/TT	20	stepped cast (dn/up twice)
17-Sep-02	9:37am	eqa17s02	WL south raft (outside limnocorral)	PW/JC	8	
19-Sep-02	1:05pm	eqb19s02	WL north raft (outside limnocorral)	PW/JC	10	

Table C.1 Summary of CTD casts from June 2001 to October 2002 (cont.)

Date	Time	Cast Name	Location	Operator	SBE max. depth (m)	Comment
7-Oct-02	11:04am	eqa07o02	MZ raft (outside limnocorral)	AL/PW	118	
7-Oct-02	3:33pm	eqb07o02	MZ raft (outside limnocorral)	AL/PW	11	
8-Oct-02	9:32am	eqa08o02	MZ raft (outside limnocorral)	AL/PW	81	
8-Oct-02	11:31am	eqb08o02	MZ raft (outside limnocorral)	AL/PW	116	
9-Oct-02	11:00am	eqa09o02	WL north raft (outside limnocorral)	PW/JC	30	
9-Oct-02	3:18pm	eqb09o02	WL north raft (outside limnocorral)	PW/JC	36	
10-Oct-02	9:21am	eqa10o02	WL???	PW/JC	15	
10-Oct-02	9:41am	eqb10o02	WL???	PW/JC	15	
11-Oct-02	3:01pm	eqa11o02	WL???	PW/JC	9	
11-Oct-02	3:11pm	eqb11o02	WL???	PW/JC	8	

AL - Albert Leung; PW - Philip Whittle; JC - John Crusius; DK - Dennis Kramer; TT – Ted Tedford; KM – Kylie Moisey; K - Kyle; MZ - Main Zone; MZT - Main Zone transect; WL - Waterline; SBE19 - Sea Bird Electronic Inc. SBE19 (conductivity, temperature, pressure, fluorescence, transmissivity); OBS – Optical back scatter sensor.

Table C.2 Data of dissolved oxygen content and percent saturation in the Main Zone Pit-lake

	Oxygen Concentration (mg/L) / Percent Saturation (%)							
	2001			*2002*				
Depth (m)	Jun 27	Aug 14	Oct 1-2	Jan 22-23	Mar 18-19	Jun 17-18	Aug 26	Oct 7-8
0	9.46 / 99.11	9.93 / 120.37	10.24 / 98.81	13.30 / 106.96		9.74 / 103.74	11.48 / 122.00	10.75 / 103.34
1	6.39 / 98.66	10.32 / 121.26	10.34 / 99.78	11.65 / 94.63	11.67 / 94.40	9.69 / 102.79	13.48 / 142.90	
2		12.49 / 143.85	10.28 / 99.22	11.56 / 94.51	11.14 / 90.05	11.35 / 109.18	14.66 / 146.64	10.79 / 103.63
3		11.17 / 118.88	10.34 / 99.73	11.52 / 94.77	10.30 / 83.36	10.46 / 94.73	13.26 / 129.53	
4		9.99 / 102.08	10.34 / 99.71	11.40 / 94.22	9.96 / 81.20	10.23 / 91.35	11.61 / 112.10	10.89 / 104.41
5	9.23 / 88.78	11.30 / 112.82	10.35 / 99.82	11.23 / 92.95	10.62 / 93.49	10.24 / 91.31	11.61 / 109.15	
6		10.96 / 106.54	10.38 / 100.10	11.30 / 93.93	10.13 / 89.15	10.15 / 105.72	11.16 / 105.72	10.89 / 104.35
7		9.87 / 94.12	10.34 / 99.67	11.18 / 93.54		10.12 / 89.61	10.84 / 102.67	
8		9.05 / 86.04	10.17 / 97.96	11.10 / 93.26	9.90 / 87.34	10.05 / 88.79	10.58 / 100.25	10.73 / 103.02
9		8.77 / 83.26	8.95 / 85.71	11.04 / 93.19		10.11 / 89.31	10.55 / 100.03	
10	8.21 / 76.44	8.27 / 78.45	7.95 / 76.05	10.95 / 92.93	9.90 / 87.41	10.09 / 89.28	10.49 / 99.61	10.61 / 102.27
15		8.21 / 77.78	7.88 / 75.35	10.36 / 89.55	9.94 / 87.72	10.03 / 89.05	10.49 / 99.12	
20	7.93 / 73.69	8.69 / 82.35	7.88 / 75.35	10.04 / 88.39	9.99 / 88.08	10.03 / 89.12	10.37 / 98.79	10.22 / 98.46
30			7.87 / 75.21	9.92 / 87.88		9.93 / 88.35	10.37 / 98.84	
40	7.88 / 73.16	8.41 / 79.66	7.84 / 74.94	9.89 / 87.64	9.93 / 87.57	9.99 / 88.92	10.40 / 99.07	10.25 / 98.67
50			7.79 / 74.52			9.99 / 89.04	10.40 / 99.20	
60	7.98 / 74.09	8.19 / 77.63	7.81 / 74.66	9.93 / 88.02	9.94 / 87.87	9.99 / 89.10	10.64 / 101.53	10.30 / 99.06
70								
80	7.85 / 72.91	8.46 / 80.35	7.88 / 75.24	9.90 / 87.70	9.8 / 87.14	10.18 / 90.82	10.37 / 99.09	
90	8.03 / 74.57		7.91 / 75.62	10.02 / 88.75		10.21 / 91.02		10.34 / 99.49
100	8.10 / 75.24	8.47 / 80.36	7.91 / 75.62	9.96 / 88.24	9.90 / 87.41	10.33 / 92.05	10.39 / 99.23	
110	8.11 / 75.35	8.64 / 81.99	7.95 / 76.02	9.79 / 86.67		10.51 / 92.05	10.53 / 100.64	10.40 / 100.06
115	10.23 / 95.06	8.76 / 83.06	7.98 / 76.30	9.96 / 88.23	9.94 / 87.78	10.51 / 93.65	10.52 / 100.52	
120	10.17 / 94.35	8.64 / 81.97	8.05 / 76.16	9.82 / 86.94	9.93 / 87.69	10.88 / 97.00		

Table C.3 Data of dissolved oxygen content and percent saturation in the Waterline Pit-lake

Depth (m)	Oxygen Concentration (mg/L) / Percent Saturation (%)					
	2001	*2002*				
	Oct 3	Jan24	March 21	June 20	August 27	Oct 9
0				9.69 / 99.08	9.14 / 103.07	10.10 / 93.70
2	9.64 / 90.37	11.02 / 89.82	10.53 / 85.79	9.73 / 99.35	9.15 / 101.67	10.31 / 95.83
4	9.48 / 88.82	10.81 / 88.36	10.56 / 86.94	8.26 / 79.52	9.17 / 100.79	10.22 / 95.05
5	10.26 / 95.98	10.85 / 89.07	10.40 / 85.90	4.58 / 42.86	5.92 / 64.11	10.16 / 94.51
6	8.80 / 82.41	10.88 / 89.48	10.46 / 86.90	2.06 / 19.28	0.49 / 4.94	9.94 / 92.57
7	8.27 / 77.66	10.92 / 90.15		1.16 / 10.70	0.15 / 1.38	9.98 / 92.84
8	5.22 / 49.10	10.31 / 85.85	9.46 / 80.22	1.29 / 11.76	0.00 / 0.00	10.13 / 94.35
9						3.28 / 30.56
10	0.19 / 1.80	0.02 / 0.00	0.00 / 0.00	0.00 / 0.00		0.19 / 1.77
11						0.14 / 1.35
15	0.00 / 0.00	0.11 / 0.87	0.00 / 0.00			0.00 / 0.00
20	0.00 / 0.00					

Table C.4 Water samples ID and collection plan for the Main Zone Pit-lake

Depth (m)	Date of Samples Collection							
	2001			*2002*				
	Jun 27	Aug 14	Oct 1-2	Jan 22-23	Mar 18-19	Jun 17-18	Aug 26	Oct 7-8
0	EQ101	EQ201	EQ301	EQ401	EQ501	EQ601	EQ701	EQ801
1	EQ102	EQ202	EQ302	EQ402	EQ502	EQ602	EQ702	EQ802
2	EQ103	EQ203	EQ303	EQ403	EQ503	EQ603	EQ703	EQ803
3	EQ104	EQ204	EQ304	EQ404	EQ504	EQ604	EQ704	EQ804
4	EQ105	EQ205	EQ305	EQ405	EQ505	EQ605	EQ705	EQ805
5	EQ106	EQ206	EQ306	EQ406	EQ506	EQ606	EQ706	EQ808
6	EQ107	EQ207	EQ307	EQ407	EQ507	EQ607	EQ707	EQ807
7	EQ108	EQ208	EQ308	EQ408	EQ508	EQ608	EQ708	EQ808
8	EQ109	EQ209	EQ309	EQ409	EQ509	EQ609	EQ709	EQ809
9		EQ210	EQ310	EQ410	EQ510	EQ610	EQ710	EQ810
10	EQ110	EQ211	EQ311	EQ411	EQ511	EQ611	EQ711	EQ811
15		EQ212	EQ312	EQ412	EQ512	EQ612	EQ712	EQ812
20	EQ111	EQ213	EQ313		EQ513	EQ613	EQ713	EQ813
30				EQ413		EQ614	EQ714	EQ814
40	EQ112	EQ214	EQ314		EQ514	EQ615	EQ715	EQ815
50						EQ616	EQ716	EQ818
60	EQ113	EQ215	EQ315	EQ414		EQ617	EQ717	EQ817
70						EQ618		EQ818
80	EQ114	EQ216	EQ316	EQ415	EQ515	EQ619	EQ718	EQ819
90						EQ620		EQ820
100	EQ115	EQ217	EQ317	EQ416	EQ516	EQ621	EQ719	EQ821
110	EQ116	EQ218	EQ318			EQ622	EQ720	EQ822
115	EQ117	EQ219		EQ417	EQ517	EQ623	EQ721	EQ823
120	EQ118	EQ220	EQ319		EQ518	EQ624		EQ824

Table C.5 Water samples ID and collection plan for the Waterline Pit-lake

Depth (m)	**Date of samples collection**			
	2002			
	March 21	June 20	August 27	October 9
0		WL601	EQ722	WL801
2		WL602	EQ723	WL802
4		WL603	EQ724	WL803
5	WL501	WL604	EQ725	WL804
6		WL605	EQ726	WL805
7		WL606	EQ727	WL806
8		WL607	EQ728	WL807
9			EQ729	WL808
10		WL608	EQ730	WL809
11				WL810
15	WL502	WL609	EQ731	WL811
20		WL610	EQ732	
25		WL611	EQ733	WL812
30		WL612	EQ734	
35	WL503	WL613	EQ735	
40		WL614		

Table C.6 Main Zone Pit-lake thermistor sampling plan

Depth (m)	Instrument Type (Serial #)	Sampling Period (min)							
		2001			*2002*				
		Jun 29 - Aug 13	Aug 17- Oct 1	Oct 5 - Jan 22	Jan 25- Mar 20	Mar 22 - Jun 29	Jul 2- Aug 26	Aug 28- Oct 8	Oct 10 – Feb 21 *(2003)*
0.25	Stowaway (1281)	15	15	24	15	30	30	10	30
1	Stowaway (73154)	5	5	5	5	5	5	5	10
1.5	LM35**	N/A	N/A	N/A	N/A	N/A	15	15	15
2	Stowaway (73155)	5	5	5	5	5	5	5	10
2.5	LM35**	N/A	N/A	N/A	N/A	N/A	15	15	15
3.0	LM35**	N/A	N/A	N/A	N/A	N/A	15	15	15
3.5	LM34**	N/A	N/A	N/A	N/A	N/A	15	15	Not Deployed*
4	Stowaway (73156)	5	5	5	5	5	5	5	10
4.5	Stowaway*** (4880)	N/A	N/A	N/A	N/A	N/A	5	5	10
5	LM34**	N/A	N/A	N/A	N/A	N/A	15	15	15
6	TR-1000 (6776)	5	5	5	5	5	5	1	1
8	Stowaway (3610)	15	15	24	15	30	30	10	30
10	Stowaway (73097)	5	5	5	5	5	5	5	10
15	Stowaway (1284)	15	15	24	15	30	30	10	30
20	TR-1000 (6777)	5	5	5	5	5	5	1	1
30	TR-1000 (6778)	5	5	5	5	5	5	1	1
40	TR-1000 (6779)	5	5	5	5	5	5	1	1
50	TR-1000 (6780)	5	5	5	5	5	5	1	1
75	TR-1000 (6783)	5	5	5	5	5	5	1	1
110	TR-1000 (6850)	5	5	5	5	5	5	1	1
115	TR-1000 (6782)	5	5	5	5	5	5	1	1
119	Stowaway*** (4880)	5	5	5	5	5	N/A	N/A	N/A

* The sensor was turned off to save memory space for the Terra logging unit
** LM34 and LM35 are strapped to a separate chain attached to the Terra logging unit
*** The stowaway sensor at 119m moved to 4.5m from June 2002 onward

Table C.7 Waterline Pit-lake thermistor sampling plan

Depth (m)	Instrument Type	Sampling Period (min)		
		2002		
		Jun 15 – Aug 29	Aug 30 –Oct 10	Oct 11- Feb 22 *(2003)*
0.25	Stowaway (0076)	5	5	10
1	Stowaway (1282)	15	10	30
2	Wadar (182)	2.5	2.5	4
3	TR-1000 (6781)	1	1	1
4	Stowaway (73151)	5	5	10
5	TR-1000F (8837)	1	1	1
6	TR-1000F (8834)	1	1	1
8	Stowaway (73153)	5	5	10
10	Stowaway (73159)	5	5	10
12.5	XL-200 (7056)	15	15	15
15	TR-1000F (8838)	1	1	1
17.5	Wadar (181)	2.5*	Not Deployed**	Not Deployed**
20	TR-1000F (8839)	1	1	1
25	Wadar (183)	2.5	2.5	4
30	TR-1000F (8840)	1	1	1
35	Wadar (184)	2.5	2.5	4
37.5	TR-1000 (6775)	1	1	1

*No data was recorded during the period

**Due to the inability to communicate with computer.

Table C.8 Sampling Plan for meteorological station in the Main Zone and Waterline Pit-lakes

Metrological Data	Logger Type	Location	Sampling Period (min)							
			2001			*2002*				
			Jun - Aug	Aug - Oct	Oct 5- Jan 25	Jan 25- Mar 20	Mar 20- Jul 4	Jul 4- Aug 28	Aug 28- Oct 10	Oct 10- Feb 18 *(2003)*
Wind speed Wind direction Solar radiation	Terra	Main Zone raft*	N/A	N/A	15	15	15	15	15	15
Air temperature Relative humidity	Terra	Main Zone raft*	N/A	N/A	15	15**	15	15	15	15
Wind speed Wind direction Solar radiation Air temperature Relative humidity	Handar	Waterline northern raft	N/A	N/A	N/A	N/A	N/A	5	5	5

*The Main Zone and the Waterline meteorological stations were installed in October 2001 and June 2002, respectively

**Sensor failed to record data

Table C.9 Miscellaneous data collection and sampling plan

Data Type	Instrument Type (Serial#)	Sampling Period (min)							
		2001			*2002*				
		Jun - Aug	Aug - Oct	Oct - Jan	Jan - Mar	Mar - Jun	Jun -Aug	Aug -Oct	Oct – Feb *(2003)*
MZ water level	XL-200 (5424)	N/A	N/A	N/A	N/A	N/A	15	15	N/A
Sludge discharge temperature	Stowaway (73157)	N/A	N/A	15	15	15	15	15	10
WL water level	WL pressure sensor	N/A	N/A	N/A	N/A	N/A	5	5	5
WL outflow temperature	Stowaway tidbit (298666)	N/A	N/A	N/A	N/A	N/A	15	15	12

MZ - Main Zone; WL – Waterline