FACTORS AFFECTING FALL TURNOVER IN BRACKISH LAKES

by

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M.Sc., Iran University of Science and Technology 2009

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Applied Science

in

THE FACULTY OF GRADUATE AND POSTDOCTORAL STUDIES

(Civil Engineering)

The University of British Columbia (Vancouver)

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Abstract

This study investigates fall mixing in brackish lakes. Data from the Colomac Zone 2 Pit Lake is used to study the effects of salinity structure, and the ratio of runoff plus direct precipitation to evaporation (P^*/E), on fall turnover. Zone 2 Pit Lake is currently not subject to turnover, but the model CE-QUAL-W2 is used to investigate conditions under which it, or other similar lakes, might turnover in fall. Accordingly, a curve is generated which separates meromictic and holomictic states for different combinations of salinity stratification and P^*/E ratios given the bathymetry of Zone 2 Pit Lake, and the meteorological forcing it was subject to in 2010. It is shown that in brackish lakes, increases in the salinity of the surface layer due to evaporation can drive turnover.

Preface

I, Davood Hasanloo, was the main contributor with respect to research for the hydrodynamic modeling of Colomac Zone 2 Pit Lake, along with all other content of this thesis.

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Notation

α	water thermal expansion coefficient [K ⁻¹]					
θ	temperature (dew point or water surface) [°C]					
ρ	water density [kgm ⁻³]					
$ar{ ho}$	mean density [kgm ⁻³]					
$ ho_{air}$	air density [kgm ⁻³]					
$\rho(z)$	density at z [kgm ⁻³]					
$\rho(z)_{S=0}$	density for pure water [Kgm ⁻³]					
A(0)	surface area [m ²]					
A(z)	area of the pit at $z [m^2]$					
$b_1 = 8.221 \times 10^{-4}$	density constant [kgm ⁻³]					
$b_2 = -3.87 \times 10^{-6}$	density constant [kgm ⁻³ °C ⁻¹]					
$b_3 = 4.99 \times 10^{-8}$	density constant [kgm ⁻³ °C ⁻²]					
$C_D = 0.001$	wind drag coefficient [dimensionless]					
<i>c</i> _p	specific heat of water [J kg ⁻¹ K ⁻¹]					
ea	air vapor pressure [mm Hg]					
es	saturation vapor pressure at water surface [mm Hg]					
fs	salinity stratification factor [dimensionless]					
f(w)	wind function [Wm ⁻² mm Hg ⁻¹]					
8	acceleration of gravity [m ² s ⁻¹]					

h	total depth [m]					
h_{mix}	depth of surface layer [m]					
H _e	evaporative heat flux [Wm ⁻²]					
H _{net}	net heat flux at water surface [Wm ⁻²]					
J_b^0	surface buoyancy flux [Wkg ⁻¹]					
<i>k</i> = 0.41	von Karman constant [dimensionless]					
m _E	evaporation rate [kg m ⁻² s ⁻¹]					
P*/E	ratio of effective precipitation to evaporation [dimensionless]					
S	salinity [kgm ⁻³]					
St	total stability [Jm ⁻²]					
St _S	salinity stability [Jm ⁻²]					
St_T	temperature stability [Jm ⁻²]					
Т	water temperature [°C]					
\overline{T}	mean temperature [°C]					
T_{md}	temperature of maximum density [°C]					
V	total volume [m ³]					
W	wind speed [ms ⁻¹]					
<i>W</i> ₁₀	wind speed measured at 10 m [ms ⁻¹]					
Z	depth from the surface [m]					

Acknowledgements

This work was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC). The author would also like to thank Dr. Gregory A. Lawrence, Canada Research Chair in Environmental Fluid Mechanics and Dr. Roger Pieters, from UBC department of Earth and Ocean Sciences, for their helpful comments and support of the project.

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August 2014

Dedication

This thesis is dedicated to my parents and my beloved wife, for their endless love, support and encouragement.

Chapter 1

Introduction

Fresh water lakes in sufficiently cold climates are dimictic with turnover in both fall and spring, in contrast to saline lakes which are often meromictic (permanently stratified). In this study, we are interested in lakes of intermediate salinity, namely brackish lakes, where turnover may or may not occur depending on a variety of factors. Pieters and Lawrence (2009) showed that a fresh water cap from ice-melt can suppress spring turnover in a brackish lake (salinity, $S \sim 1$ kgm⁻³). Karakas et al. (2003) and Boehrer et al. (2003) studied the influence of introducing fresh river water in a series of brackish pit-lakes ($S \sim 2$ kgm⁻³). They showed that the variation of conductivity in the epilimnion agrees well with the estimates of the accumulated precipitation-evaporation balance within the surface layer. Bluteau (2006) studied the effect of salt exclusion in brackish water bodies ($1 \text{ kgm}^{-3} \le S \le 8 \text{ kgm}^{-3}$), and showed that flooding salt lakes ($S \sim 10 \text{ kgm}^{-3}$) with freshwater had a significant impact on the deep circulation. They concluded that the introduced fresh water could supress the deep circulation for several years and therefore shape the salinity profile and promote meromixis.

The density of water is a function of temperature, salinity and pressure. For depths less than about 150 m pressure is not important, and in fresh water lakes salinity is not important. Therefore, in fresh water lakes the stability, i.e. the work required to mix the entire water body to a uniform density, is dominated by temperature. As the surface of fresh water lakes cool in fall, their stability decreases, and fall turnover occurs when wind driven circulation is sufficient to overcome this stability. However, in brackish lakes, vertical gradients in salinity can increase the stability and resist turnover. The strength of the contribution of salinity gradients to stability is affected by ice-melt, precipitation, runoff and evaporation. Each of these factors can play a role in accelerating or preventing turnover.

The present study uses data from the Colomac Zone 2 Pit Lake ($S \sim 860 \times 10^{-3}$ kgm⁻³) to investigate the effects of two of the main factors affecting fall turnover in brackish lakes: the salinity difference between the top and the bottom of the lake, and the ratio of runoff plus direct precipitation to evaporation during fall. Even though Zone 2 Pit Lake is currently not subject to turnover, we use the model CE-QUAL-W2 to investigate conditions under which it, or other similar lakes, might turnover in fall.

This thesis is organised as follows:

• The location, geometry, climatic conditions, and field measurements of temperature and conductivity for Zone 2 Pit Lake in 2010 are described in Chapter 2.

- The model setup, calibration and verification as well as the procedure used to define different model scenarios are summarized in Chapter 3. The equations used to calculate the lake stability and important surface fluxes in Zone 2 Pit Lake are also included in this chapter.
- Comparisons between the modeled and observed temperature and salinity data are presented in Chapter 4. How the results from different model scenarios were used to create a curve relating the meromixis of Zone 2 Pit Lake to its evaporation, precipitation and initial salinity stratification is also explained in Chapter 4.
- In chapter 5, the importance of the main parameters affecting the turnover in Zone 2 Pit Lake is discussed through comparing surface fluxes of cooling, wind stirring and evaporation.

Chapter 2

Study Site

Zone 2 pit is located at the Colomac gold mine, 220 km north of Yellowknife, Northwest Territories, Canada (64° 24' N, 115° 5' W). The pit was created by excavation of the main ore deposit. At closure in 1997, the pit was allowed to fill with ground water and runoff inflow. In addition, excess water from Tailings Lake was pumped into the pit between 1998 and 2002, accounting for ~60% of the water in the pit lake.

The bathymetry of the resulting pit lake is shown in Fig. 1. The lake is 900 m long and 110 m deep with a volume of approximately 8.3 Mm³. The total catchment area is about 29 hectares with a surface water area of about 17 hectares. The mean monthly rainfall and run-off from historical data (1995-2003) are 172 mm and 110 mm, respectively (Schultz, 2004).

Since 2004, observations from a raft moored near the center of Zone 2 Pit have included weather data collected by a Campbell Scientific CR10X weather station, temperature data from a mooring, and profiles collected with a Seabird SBE19plus profiler (Pieters and Lawrence, 2011). To illustrate the stratification in 2010, the first available profile of temperature and conductivity from 9 August 2010 is shown in Fig. 2. The profile shows the lake was stratified in both temperature and salinity. The temperature shows a warm surface layer of about 5 m depth and reaching 19 °C at the surface (Fig. 2a). The salinity (Fig. 2b) shows four layers: (1) 0 - 5 m is the epimilimnion (surface layer) with salinity reduced to 730×10^{-3} kgm⁻³ due to snow melt, ice melt and freshet runoff; (2) 5 – 20 m is the hypolimnion (which is mixed in fall); (3) 20 – 70 m has slightly reduced salinity due to the influence of groundwater inflow and (4) below 70 m the deep water has the highest salinity. The first two layers comprise the mixoliminion (seasonally mixed); the bottom two layers comprise the monimolimnion (isolated deep water). The temperature and conductivity of this CTD cast will be used as the initial condition of the model.

The first panel of Fig. 3 shows the variation of lake water temperature at different depths from 9 August to 27 October 2010. The meteorological data from Zone 2 Pit Lake, including wind speed, air temperature, dew point, cloud cover and solar radiation in 2010 are plotted in Fig. 3 b-d. The lake is stratified in early August with a surface layer depth of about 5 m. As the air temperature and solar radiation decreased during the fall, the lake cooled and mixed down. Even though the lake temperature became almost homogenous on 17 October (day 290), the surface layer did not deepen to more than 15 m by that time. On 19 October (day 292), the surface water cooled further and reverse stratification occurred near the surface. This phenomenon continued until ice formed at the surface around 22 October 2010 (day 295).

Chapter 3

Methods

Fall mixing in Zone 2 Pit Lake was simulated using the CE-QUAL-W2 model, a 2D hydrodynamic and water quality model, version 3.71 (Cole and Wells, 2011). The bathymetry of Zone 2 Pit was divided into two segments along its length and into 172 layers in depth with a thickness of 0.2 m (from 0 - 5 m from the surface), 0.5 m (from 5 to 20 m) and 1 m (below 20 m).

The model was calibrated to temperature and salinity data from 2005 and was validated using data from 2008 through 2010. In 2006 and 2007, the lake underwent aeration (Pieters et al. 2014), and data from those years were not used in the process of model verification. Data from 2010 was selected for the investigation of fall mixing, because in 2010 the water surface elevation was almost constant (less than 0.2 m change over the open water season). The model was started on 9 August 2010 at noon (day 221.5) at the time of first observed profile of the open water season, shown in Fig. 2, and ended on 15 November 2010 by which time ice formation had begun. The model average time-step was about 300 s, and results were output and plotted hourly.

Model parameters were set as follows:

- The height of the wind speed measurements was set to 2 m.
- The wind sheltering coefficient (WSC) was chosen to be 0.7, because of the partial sheltering of wind from the Zone 2 Pit side walls.
- Sediment temperature was set to 3°C to approximately match the deep water temperature (Pieters and Lawrence, 2011). Deep temperatures are < 4 °C because of the presence of permafrost.
- The extinction coefficient was set as a time varying input calculated from the field measurements of penetrating light using a transmissometer (WETLabs C-Star at 650 nm with 25 cm path length attached to the SeaBird SBE19plus profiler). The attenuation length for 2010 varied between 0.2 m at the start of the model run on 9 August 2010 to 2 m at the end of the model run on 15 November 2010, indicating that lake was becoming clearer.

To study how the salinity structure of a brackish lake may affect meromixis, scenarios with different initial salinity profiles were investigated. Examples of these profiles are shown in the second panel of Fig. 2. Each profile is generated by dividing the surface salinity deficit from the observed salinity profile by the initial salinity stratification factor (f_s). The profiles have identical bottom salinity, but different surface salinities, and thereby changing the salinity stratification. A salinity profile generated using $f_s = 16$ is, for example, less stratified than a profile with $f_s = 8$. These scenarios represent hypothetical variations in the amount of fresh water

at the surface, which depends on the meteorological conditions at the pit lake, and on the year-toyear variation in freshet runoff, ice-melt, rain and evaporation. To study the effect of meteorological conditions on mixing and the potential for meromixis, the ratio of the effective precipitation (sum of precipitation and runoff) to the evaporation (P*/E) was also varied in different model runs.

3.1. Calculation of lake stability and important surface fluxes

The concepts of lake stability, along with the evaporative, wind and buoyancy fluxes were used in this study to quantify the factors affecting fall mixing in Zone 2 Pit Lake, and are summarized in the following.

3.1.1. Lake stability

Lake stability was used to quantify the ability of the water body to resist turnover (Schmidt 1928; Idso 1973). The total stability (St_{TOT}) is,

$$St_{TOT} = \frac{g}{A_0} \int_0^h (\rho(z) - \bar{\rho}) z A(z) \, dz \quad [\text{Jm}^{-2}]$$
(1)

where $g \,[\text{m}^2\text{s}^{-1}]$ is the acceleration of gravity, $A(z) \,[\text{m}^2]$ is the area of the pit at depth z from the surface, $A_0 = A(0)$ is the surface area, $h \,[\text{m}]$ is the total depth, $\rho(z) \,[\text{kgm}^{-3}]$ is the density, $\bar{\rho} = \frac{1}{V} \int_0^h \rho(z) A(z) \, dz$ is the mean density, and $V \,[\text{m}^3]$ is the total volume. The total stability can be divided into salinity and temperature components as follows. As seen in Eq. 1, the total stability is calculated based on the total density, $\rho(z)$,

$$\rho(z) = \rho(z)_{S=0} + b(T(z))S(z) \quad [\text{Kgm}^{-3}]$$
⁽²⁾

where $\rho(z)_{S=0}$ [Kgm⁻³] is the density for pure water (UNESCO 1981; Gill 1982); b(T(z))= $b_1 + b_2 T(z) + b_3 T(z)^2$ [Kgm⁻³] is the coefficient of haline contraction, with $b_1 = 8.221 \times 10^{-4}$ [Kgm⁻³], $b_2 = -3.87 \times 10^{-6}$ [Kgm⁻³ °C⁻¹], and $b_3 = 4.99 \times 10^{-8}$ [Kgm⁻³ °C⁻²]; T [°C] is temperature and S [kgm⁻³] is salinity (Ford and Johnson 1983). The total density can be separated into salinity and temperature components as follows,

$$\rho(z)_T = \rho(z)_{S=0} + [b(T(z)) - b(\bar{T})]S(z) \quad [Kgm^{-3}],$$
(3)

and

$$\rho(z)_S = b(\bar{T})S(z) \quad [\text{Kgm}^{-3}] \tag{4}$$

where $\overline{T} = \frac{1}{v} \int_0^h T(z) A(z) dz$ is the mean temperature. The second term of Eq. 3 adjusts the density, $\rho(z)$, such that the temperature of maximum density (T_{md}) shifts from 3.984°C, to the appropriate value for the given salinity; this adjustment is largest near T_{md} , the region of interest here.

Substituting Eq. 3 and Eq. 4 into Eq. 1 gives:

$$St_{TOT} = St_T + St_S$$
,

where

$$St_{T} = \frac{g}{A_{0}} \int_{0}^{h} (\rho(z)_{T} - \bar{\rho}_{T}) z A(z) dz \quad [Jm^{-2}],$$
(5)

is the stability due to temperature, and

$$St_{S} = \frac{g}{A_{0}} \int_{0}^{h} (\rho(z)_{S} - \bar{\rho}_{S}) z A(z) dz \quad [\text{Jm}^{-2}]$$
(6)

is the stability due to salinity.

3.1.2. Evaporative flux

The evaporative flux (E) in the CE-QUAL-W2 model is estimated by:

$$H_e = f(w)(e_s - e_a) \quad [Wm^{-2}]$$
⁽⁷⁾

where $f(w) = 9.2 + 0.46W^2$ [Wm⁻²mm Hg⁻¹] is the evaporative wind speed function, e_s [mm Hg] is the saturation vapor pressure at the water surface, e_a [mm Hg] is the atmospheric vapor pressure and W [ms⁻¹] is the wind speed at 2 m. To calculate the saturation vapor pressure, e_s , CE-QUAL-W2 uses:

$$e = \exp\left[2.3026(\frac{m\theta}{\theta+n} + 0.6609)\right] \quad [mm Hg]$$
 (8)

where θ is temperature [°C]; m = 7.5 and n = 237.3 [°C] if $\theta > 0$; and m = 9.5 and n = 265.5 [°C] if $\theta < 0$. If the water surface temperature is used for θ , Eq. 8 gives e_s , and if the dew point is used, then the equation gives e_a (TVA 1972).

3.1.2. Wind shear and buoyancy fluxes

Wind stirring, cooling and the evaporation-precipitation balance were the main processes which their effect on the fall mixing in Zone 2 Pit Lake was explored. The following equations are used to quantify the fluxes due to these processes. Following Imboden and Wuest (1995), the shear flux due to the wind is given by:

$$J_R = \left(\frac{\rho_{air}c_D}{\rho}\right)^{3/2} \frac{W_{10}^3}{kh_{mix}} \quad [Wkg^{-1}]$$
(9)

where ρ_{air} [kgm⁻³] is air density, $C_D = 0.001$ is the wind drag coefficient, ρ [kgm⁻³] is water density, h_{mix} is surface layer depth, k = 0.41 is the von Karman constant and W_{10} [ms⁻¹] is wind speed measured at 10m.

Another source of mixing is the surface buoyancy flux, J_b^0 [Wkg⁻¹]. It can result from cooling or an increase in salinity due to evaporation, or from a combination of both processes. The surface buoyancy flux is given by:

$$J_b^0 = -\frac{\alpha g}{\rho c_p} H_{net} + \frac{gbS}{\rho} m_E \quad [Wkg^{-1}]$$
(10)

where α [K⁻¹] is the thermal expansion coefficient of water, c_p [J Kg⁻¹ K⁻¹] is the specific heat of water, g [ms⁻²] is the acceleration of gravity, H_{net} [Wm⁻²] is the net heat flux at water surface, S [kgm⁻³] is salinity, b [Kgm⁻³] is the coefficient of haline contraction, and m_E [kg m⁻² s⁻¹] is the evaporation minus effective precipitation rate ($E - P^*$). The first term on the right hand side of Eq. 10 is the buoyancy flux due to cooling, and the second term is the flux due to the evaporation minus effective precipitation.

Chapter 4

Results

A comparison between the 2010 field and modeled temperature contours is shown in Fig. 4. Note that the shallowest temperature in the field data is 1 m while the model data extend to the surface. Overall, there is reasonable agreement between the observed and modeled temperature. The pit lake is strongly stratified in early August with a surface layer of about 5 m and surface temperatures over 19°C. Through the fall, solar radiation and air temperature gradually decreased (Fig. 3) and as a result, the surface layer cooled and deepened. Wind stirring also contributed to surface mixing, and the deepening was accelerated during wind storms (e.g. day 287).

Also marked in Fig. 4 is the depth of the surface layer, as given by the maximum gradient in density, from CTD profiles (Fig. 4a) and from model data (Fig. 4b). The depth of the surface layer in the model is in reasonable agreement with the four observations. Looking at the model results, there was a major deepening of the density interface between days 283 and 287, when a large wind storm event and a significant reduction in the air temperature occurred. On 19 October (day 292), the surface temperature dropped below that of the deep water and reverse temperature stratification occurred. As shown in Fig. 3, prior to the reverse stratification, all the temperature lines did not overlay, indicating that turnover did not happen. From day 292, as the surface continued to cool, the reverse stratification strengthened and deepened. From 20 to 23 October (day 293 to 296), the wind was calm and the air temperature was about -10°C (Figure 3b,c), suitable conditions for ice to appear on the surface. From the field observations, ice-on occurred on 22 October (day 295), and in the model, ice-on occurred a day later.

Modeled and observed temperature, salinity and density profiles are compared in Fig. 5. The largest difference between the modeled and measured data was seen in the surface layer. The error in the profiles was always less than 1°C for temperature and 10×10^{-3} kgm⁻³ for salinity. Fig. 5 also shows the deepening of surface layer through the fall. The depth of the surface layer, determined from the maximum gradient in the density profiles varied from 5 m on 9 August 2010 (day 221) to almost 10 m on 7 October 2010 (day 280) (Fig. 5c).

As mentioned earlier, the amount of fresh water at the surface of the lake is a key parameter which affects the salinity stability and controls meromixis. Ice melt, precipitation, runoff and evaporation are all parameters which affect the surface fresh water in Zone 2 Pit Lake. To explore the effect of these on lake stability and fall mixing, a series of about 300 different model scenarios were run with different combinations of f_s (initial salinity stratification factor) and P*/E, the results of which are summarized in Fig. 6. Of those 300 simulations we will

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focus on 8 scenarios, cases A through H, the characteristics of which are given in Table 1. For low f_s and high P*/E the model runs were meromictic (open squares), and for high f_s and low P*/E the model runs were holimictic (solid squares). The values of f_s for the boundary line marking the transition between meromictic and holomictic were calculated by averaging the f_s values of the points closest to the boundary. For example, a scenario with $f_s = 8$ and P*/E = 0 did not turnover, but it did turn over with $f_s = 8.125$ and P*/E = 0; the boundary was then estimated as the average of these two values. The criteria used was that the f_s of the two points should be very close to each other (less than 0.5 difference in value), and for the scenario that turned over, the duration of turnover must also be very short (a few hours). This suggests that even a small change in f_s can be very important when the lake is relatively close to turnover.

The base case, which represents observed conditions in Zone 2 Pit, is an example of a meromictic scenario. The base case had $P^*/E > 1$ and was far from being holomictic. Even in the absence of precipitation ($P^*/E = 0$), the initial salinity stratification would have had to be reduced by a factor of $f_s \approx 8$ for Zone 2 Pit to turnover, showing that the base case salinity stratification had more than enough stability to avoid turnover.

Chapter 5

Discussion

To investigate the effects of varying P*/E and f_s , two sequences of simulations are presented. In the first sequence, P*/E = 0.75 and f_s varies from 15.75 (case A) to 64 (case D). In the second sequence, $f_s = 15.75$ and P*/E varies from 0.75 (case A) to 0 (case G), see Fig. 6. These cases will now be examined in greater detail.

Plots of both salinity and stability for the first sequence (cases A to D) are shown in Fig. 7. Each of these cases has the same ratio $P^*/E = 0.75$, and since $P^*/E < 1$, the evaporation is greater than precipitation, fresh water is removed from the surface over the course of simulation, and salinity increases in the surface layer. Consider first case A. The total stability is always positive (Fig. 7e), which indicates that it does not turnover, even when the lake becomes isothermal at day 293. The time series of salinity at each of the layer depths is shown in Fig. 7a. The salinity of the surface layer is initially just below 852×10^{-3} kgm⁻³, it rose to 858×10^{-3} kgm⁻³ at the time the lake was isothermal, and while it was only slightly less than the salinity of the deep water (~ 860×10^{-3} kgm⁻³), the remaining salinity stratification was sufficient to prevent turnover (Fig. 7a). In case B (Fig. 7f), the initial salinity stratification is reduced compared to

case A (Fig. 7e), and while the salinity stability declines through the summer, it remained positive until close to the time that the lake became isothermal (Fig. 7f). In case B, turnover does occur briefly, however the details are difficult to see from Figures 7b and 7f and this case will be examined more closely below. In case C, the salinity of the surface layer rises above the salinity of the deep water on 02 Sep 2010 (day 245) more than a month before turnover (Fig 7c); at about the same time (05 Sep 2010), the salinity stability goes negative (Fig. 7g). In this case, the salinity of the surface layer is initially closer to the salinity concentration of the deep water (larger f_s), and evaporation increases the surface salinity above that of the bottom layers (shown in Fig. 7c beginning at day 245). In case D, with the largest f_s , the surface salinity rises above that of the bottom layer even earlier (day 237), the salinity stability goes negative sooner (Fig. 7h), and the period of turnover was longer (Table 1).

For the second sequence (cases A, E, F and G), f_s was held constant at 15.75 (the initial salinity at surface was about 852×10^{-3} kgm⁻³), but P*/E varied from 0.75 to 0 (Fig. 8). As P*/E is reduced, more fresh water is removed from the surface, which increases the mean salinity of the lake (black dashed lines). For case A, the mean salinity was about 858.6×10^{-3} kgm⁻³ at the time the lake became isothermal, and that of the case G was about 860×10^{-3} kgm⁻³, indicating that more fresh water is lost from the surface of G by that time. The higher salinity concentration of the surface layer in case G, due to the absence of precipitation, resulted in the most unstable salinity structure, leading to an earlier and longer turnover of the water body (Table 1).

For cases B and E, which were close to the boundary line separating holomictic from meromictic condition, the salinity stability was positive until turnover. In the remaining cases that turned over, salinity stability was negative for an extended period before turnover (38, 49, 26 and 35 days before turnover in cases C, D, F and G, respectively). For both case B and E, not only does the salinity stability become negative close to the time that the pit lake becomes isothermal, but the duration of turnover was shorter compared to the other holomictic cases (Table 1).

To better understand the behaviour of cases B and E, their salinity and salinity stability were plotted in Fig. 9 on an expanded scale focusing on the time of turnover. The variation of salinity at different depths is shown in Fig. 9a and 9c. Due to the larger P*/E ratio and less fresh water loss from the surface in case B, the mean salinity was less than that of case E. As shown before, the stabilities of cases B and E were similar (Fig. 9b and Fig. 9d). Both the temperature and salinity stability of B and E were positive prior to turnover and declined toward zero close to the time of turnover. However, as shown in Fig. 9b and 9d, the total stability did become negative a few hours before it reached zero at turnover (Table 1). This suggests that there was a lag between the time of negative total stability and the time of homogeneity, when all the salinity lines are overlaid and the total stability is zero. The lag time is the time that a water body with total negative stability needs to mix all layers and reach a state of homogeneity; in these cases the lag time was about 3.5 hours for case B (Fig. 9b) and 2 hours for case E (Fig. 9d).

To understand the cause of negative total stability, consider the evolution of both the salinity and temperature stability in Fig. 9b and 9d. In B and E, both salinity and temperature stability became negative shortly prior to the turnover (3.5 and 2 hours respectively), and then both became zero at turnover. In case E, the temperature stability became negative just before the salinity stability (Fig. 9d). This indicates that the buoyancy fluxes due to the cooling process, which caused the negative temperature stability, first forced the total stability to become negative. However, in case B, it was the salinity stability that first became negative and gave rise to the negative total stability.

In order to characterize the factors driving homogeneity and turnover, the surface fluxes due to wind stirring, cooling and evaporation are compared for case E around the time of turnover, from 7 to 17 October 2010 (Fig. 10). During this time there were periods of both low wind, and winds of just over 6 m/s; the square of the wind speed is shown in Fig. 10a. The air vapor pressure in this period, increased from about 4 mm Hg on day 280 to 6.5 mm Hg on day 284, when the dew point was maximum (Fig. 3c), and then decreased to 2 mm Hg on day 290 (Fig 10b). The saturation vapor pressure at the water surface, on the other hand, was nearly constant at about 6 mm Hg.

For the majority of the times within this period, the evaporation rate, as shown in Fig. 10c, was larger than the precipitation rate, except for a period between day 283 and 284. It should be noted that evaporation itself is a function wind speed, but the relationship is weak at the low wind speeds observed in Zone 2 Pit. As in Eq. 7, evaporation is proportional to f(w) =

9.2 + 0.42 W^2 , where W is wind speed. For wind speeds increasing from 0 to 6 m/s, f(w) increases from 9.2 to 26, a factor of only 2.8. The other factor affecting evaporation is the difference between the saturated vapor pressure at the water surface and the atmospheric vapor pressure, ($e_s - e_a$), which is shown in Fig. 10b. Even though the wind speed plays a role, it is primarily the difference $e_s - e_a$ that defines the shape of the evaporation curve in Fig. 10c. Thus wind speed was not the dominant parameter affecting evaporation on Zone 2 Pit.

The three surface fluxes that drive turnover are compared in Figure 10d. Whenever the surface temperature declined below the temperature of maximum density ($T \approx 3.795^{\circ}$ C for $S = 860 \times 10^{-3} \text{ kgm}^{-3}$), the cooling flux became negative. The change in the cooling flux (Eq.10) is determined by the thermal expansivity (α) which is positive for $T > T_{md}$ and negative for $T < T_{md}$ (Eq. 10).

In order to calculate the salinity flux due to evaporation, the rate of fresh water added to the surface due to precipitation and runoff were subtracted from the evaporation rate. During the period close to turnover, the salinity flux due to evaporation was larger than the fluxes due to surface wind stirring and cooling. Even though there was a relatively large storm close to the time of turnover, the surface mixing due to the wind stirring was not the largest flux. Therefore, the evaporation in case E was dominant in bringing the lake from the state of negative stability into homogeneity. As shown in Eq. 10, the magnitude of the evaporation flux is proportional to the surface salinity of the lake. Close to day 288, the flux of evaporation is about 10 times the flux due to wind stirring (Fig. 10a). Therefore, in order for the wind stirring flux to be the turnover dominant flux, the surface salinity would have to be reduced to less than 1/10 of its current condition.

Fig. 11 is shown to illustrate how these surface fluxes affected the salinity, temperature and density of the lake in case E close to the time of turnover. This figure shows the evolution of salinity, temperature and density profiles every 10 minutes for a period between day 287.5 and 287.9 (12:00 PM and 9:36 PM, 14 October 2010). The salinity density (Eq. 4), temperature density (Eq. 3) and total density (Eq. 2) are also shown in the right panels from top to bottom, respectively.

First, the variation of the concentration in the salinity profiles is evaluated to see how well the model is behaving within this very fine resolution. Fig. 11a shows that as water evaporated from the surface, the surface salinity increased. For example, it takes about 2 hours for the first salinity profile, $S_1(z)$, with the surface salinity of 859.14659 × 10⁻³ kgm⁻³ to turn into the 13th profile, $S_{13}(z)$, with the surface salinity of 859.14887 × 10⁻³ kgm⁻³. Conservation of salt gives $\int_0^{110} S_1(z)A(z)dz = \int_d^{110} S_{13}(z)A(z)dz$, where *d* is the depth of evaporation. Solving gives d = 0.112 mm. The depth of evaporated water can also be estimated using d = $\int_{287.5^{10}}^{287.583} [I_e(t) - I_p(t)]dt$, where I_e is the evaporation intensity and I_p is the precipitation and runoff intensity shown in Fig. 10c. The evaporation depth calculated from this method is 0.114 mm, which is almost the same as *d* calculated from the conservation of salt method.

Because the surface layer salinity is increasing due to evaporation (Fig. 11a), the surface salinity density also increases (Fig. 11c). During this time the temperature is decreasing (Fig. 11b) and the corresponding temperature density of the surface layer first increases, as the temperature cools to $T_{md} = 3.795$ °C, and then decreases again as the temperature cools below T_{md} (Fig. 11d). For the profiles at the beginning of this period there is also a maximum in the temperature density at a depth of about 75 m (Fig. 11d), which is the result of surface layer water at a temperature above T_{md} overlying deep water with temperature below T_{md} (Fig. 11b).

As the evaporation and cooling act on the water surface, they created instability which affects both the salinity and temperature profiles. The instabilities mixed down to the bottom of the surface layer ($D \approx 70$ m) until the total density, at the surface became larger than that at the bottom (red arrow, Fig 11e), and the entire density profile became unstable. At this time (day 287.7), the total stability became negative for the first time (Fig. 9d), and this profile, which is unstable in both salinity and temperature started mixing down to the bottom of the lake ($D \approx 110$ m). Within the unstable period, i.e. from the time that the entire profile of total density first became unstable (4:50 PM, 14 October 2010, red arrow) until the water column is entirely mixed (6:50 PM, 14 October 2010, black arrow), the surface density instabilities were increasing at a rate higher than the rate of mixing. This is why, within the unstable period, the total density at

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the surface is larger than that at the bottom. This is due to the evaporation and cooling fluxes, close to day 288 (Fig. 10d), which affected the salinity and temperature densities, respectively.

Chapter 6

Conclusions

The likelihood that a brackish pit lake undergoes fall turnover was examined. Pit lakes that are subject to ice cover and fresh water inflow can accumulate a fresh water cap. As a result, in summer, such a pit lake is stratified in both salinity and temperature. However, before ice formation the temperature of the lake cools close to the temperature of maximum density, and temperature will no longer contribute significantly to the total stability. It is therefore, the salinity stratification which prevents the lake from turning over. The hydrodynamic model CE-QUAL-W2 and extensive data set from the Colomac Zone 2 Pit were used to investigate the conditions under which brackish lakes are likely to become meromictic and the mechanisms by which turnover can occur. The following was observed:

1. A fresh water cap resulting from ice-melt and runoff resulted in meromixis.

2. Decreasing the strength of the fresh water cap decreases the likelihood of meromixis.

3. When cumulative evaporation is higher than the cumulative precipitation and runoff through the open water season (P*/E small), evaporation can increase the salinity of the surface layer and

even drive turnover. The perspective on turnover is different from that which has been gained from fresh water lakes. In brackish lakes, under certain circumstances, evaporation can drive turnover rather than wind stirring and temperature inversions.

This study also showed that there is a period of negative stability prior to homogeneity. It was shown that for scenarios with a stronger initial salinity stratification and a larger ratio of effective precipitation to evaporation, the time at which initial instability is observed increases, and both the duration of unstable period and the duration of turnover decrease.

Case	Stability factor (f _s)	P*/E	Time of initial instability (day)	Duration of instability (hr)	Duration of turnover (day)
H (BaseCase)	1	1.12	-	-	-
Α	15.75	0.75	-	-	-
В	31	0.75	287.7	3.5	0.2
С	48	0.75	286.1	15.5	1.7
D	64	0.75	285.7	17.0	2.3
E *	15.75	0.50	287.7	2.0	0.1
F	15.75	0.25	284.6	4.5	3.5
G	15.75	0.00	281.3	15.5	7.0

Table 1. Summary of simulations A to H

* Unlike other cases, the turnover was driven by both temperature and salinity instability.



Fig. 1. Zone 2 Pit Lake (a) bathymetry and (b) cross section showing the location of the sampling station (raft) with meterological station and mooring.



Fig. 2. The observed (a) temperature, (b) salinity and (c) density of Z2P on 9 August 2010. These data were used as the initial condition for the base case model. The color lines in (b) illustrate the different initial salinity stratifications corresponding to different values of the salinity stratification factor, f_s , used in the hypothetical model scenarios.



Fig. 3. Observed (a) hourly water temperature, (b) hourly wind speed, (c) daily mean air temperature and dew point, and (d) hourly solar radiation and daily cloud cover for day 221 to 300, 9 August to 27 October 2010.



Fig. 4. Contour plot of water temperature for (a) observed and (b) modeled data, day 221 to 295, 9 August to 22 October, 2010. The surface layer depth as determined from the maximum gradient in density is shown as (a) purple dots (from observed temperature and conductivity profiles) and (b) purple line (from model data).



Fig. 5. Comparison between observed (red) and modeled (black) (a) temperature, (b) salinity and (c) density for 9 August 2010 (day 221), 8 September 2010 (day 251), 17 September 2010 (day 260) and 7 October 2010 (day 280). The surface layer is cooler and deeper with each successive profile. As the first CTD profile of 9 August 2010 is the initial condition for the model temperature, salinity and density, the observed and model profiles are the same.



Fig. 6. Dependence of meromixis in Zone 2 Pit Lake on salinity stratification factor, f_s , and the ratio of effective precipitation to evaporation, P*/E. The red line marks the boundary between meromictic and holomictic regimes. The solid squares mark holomictic cases and open squares show meromictic cases. The base case represents observed condition in Zone 2 Pit during 2010.



Fig. 7. (a-d) Salinity and (e-h) salinity, temperature and total stability for cases A, B, C and D. In (a-d), the surface salinity, bottom salinity and mean salinity of the lake are shown by red, dark blue and black dashed line, respectively.



Fig. 8. (a-d) Salinity and (e-h) salinity, temperature and total stability for cases A, E, F and G. In (a-d), the surface salinity, bottom salinity and mean salinity of the lake are shown by red, dark blue and black dashed line, respectively.



Fig. 9. (a and c) Expanded salinity line plots and (b and d) expanded salinity, temperature and total stability for cases B and E respectively.



Fig. 10. (a) Wind speed squared, (b) saturated vapor pressure at water surface, e_s , atmospheric vapor pressure, e_a , difference between e_s and e_a , (c) evaporation and precipitation rate and (d) cooling, wind stirring and evaporation fluxes for case E.



Fig. 11. Profiles of (a) salinity, (b) temperature, (c) salinity density, (d) temperature density and (e) total density between day 287.5 and 287.9 (12:00 PM and 9:36 PM, 14 October 2010). The profiles are plotted at 10 minutes intervals. The first profile is shown in red and the last one in dark blue. In (e), the red arrow marks the first profile of total density to become unstable (4:50 PM, 14 October 2010), and the black arrow marks the first profile of total density to become homogenous (6:50 PM, 14 October 2010).

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