Preliminary Evaluation of the Physical Stability of the Faro, Grum and Vangorda Pit Lakes

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SCOPE OF WORK

This report attempts to assess the likelihood of meromixis in the Faro, Grum and Vangorda Pit-lakes. Lakes are generally density stratified due to vertical variations in temperature and the concentration of dissolved and suspended substances. This stratification can change with the seasons and from year to year. The first step in most limnological studies is to determine the regime of stratification of the lake(s) in question. The ratio of the surface area to the depth of most Pit-lakes is generally much higher than in natural lakes. Natural sources of mixing (typically wind and surface heating and cooling) are less likely to provide enough energy to destroy any density stratification that may occur. Therefore, Pit-lakes are often, but not always, *meromictic*, meaning they are permanently stratified.

A potential complication with the Faro, Grum and Vangorda Pit-lakes is the proposed routing of natural streams through them. These streams would be another potential source of mixing in the Pit-lakes, particularly if they enter the pits by cascading down steep pit walls. This study will estimate the magnitude of those factors enhancing the stability of the lake (e.g. the salinity of the water column; summertime heating; and the introduction of buoyant water at the surface by ice-melt, direct precipitation and runoff) and comparing them with those factors causing mixing (e.g. the energy of the streams, wind, and penetrative convection).

INTRODUCTION

Three pit-lakes are located in the Faro area lead-zinc deposits about 360 km north east of Whitehorse. The physical characteristics of these pits are summarized in Table 1. Data for the Equity Waterline pit lake located near Houston B.C. are also presented for comparison in Table 1. There is a significant amount of important data available for the Waterline pit lake which is not available for the Faro pit lakes. The area of the pits as a function of depth is shown in the Appendix.

Annual cycle

The annual cycle of the pit lakes can be broken into three periods: ice cover (November-May), warming (June-August) and cooling (September-October).

Table 1. Summary of available pit lake characteristics

PIT	FARO	GRUM	VANGORDA	WATERLINE
Ultimate water level (m ASL)	1158.2	1231	1122.5	1265
Depth (m)	182	90	96	40
Area (m2)*	5.96E+05	2.79E+05	1.23E+05	2.60E+04
Volume (m3)*	4.21E+07	9.31E+06	4.25E+06	4.80E+05
Annual Inflow (m)	9.9	1.3	63.7	
Precipitation (m)	0.4	0.3	0.4	
Evaporation (m)	0.5	0.4	0.5	
Surface outflow (m)	9.8	1.2	63.6	
Groundwater outflow (m)	0.0	0.0	0.0	
Retention time (yrs)	7.2	27.2	0.5	

* computed from area data discussed in Appendix

Temperature and conductivity (salinity) profiles for the Equity Waterline pit-lake during the warming and cooling periods are plotted in Figure 1. There is little change in either temperature or salinity below 9 m. Important changes above this level do occur though. The epilimnetic temperature increases and decreases as we would expect. Through the warming period the salinity can either increase due to fresh inflow or decrease with wind mixing. Between June 29th and August 17th the epilimnetic salinity decreases slightly (Figure 1b).

In the Waterline Pit-lake, the surface layer cools from 15 °C on August 17th to a uniform temperature of around 5 °C on October 3rd (Figure 1c). During the cooling period the epilimnetic salinity decreases as a result of penetrative convection and wind mixing. The salinity of the epilimnion increases from August to October as it has mixed down into deeper water (Figure 1d).

Water below about 4 °C is buoyant and reverse stratification occurs as the surface cools and ice forms. The ice cover may be limited to 0.5 m if snow insulates, otherwise ice could be up to 2 m thick. We will model lake behaviour over this range of ice thickness. Ice expels much, but not all, of the salt providing increased salinity contrast and increased lake stability when it melts.

Salinity stability

Mixing a stratified water body raises the center of mass of the water body and the work against gravity needed to lift the center of mass is the stability, given in J/m^2. Both warmer surface temperatures and lower salinities contribute to the buoyancy of the surface layer. To examine the possibility of meromixis we would like to remove the effect of temperature. To do this we define the salinity stability as the energy needed to mix the water body with a given salinity stratification while at a constant temperature.

Of particular interest is the salinity stratification at the end of the warming period (late August) defined as St*. It varies from year to year, but for Waterline it is approximately 200 J/m^2. We compare St* with the reduction in salinity stability during the cooling period ΔSt. During 2001, ΔSt for the Waterline Pit-lake was approximately 13 J/m^2. The meromictic ratio $M = St^*/\Delta St$ (15 for Waterline) is an indicator of the likelihood of meromixis. The higher M the more likely the lake is to be meromictic. We have insufficient data to calculate ΔSt for the three Faro area pit lakes, so we shall use the Waterline value as a point of comparison.

Streampower

If local streams are allowed to flow into the Pit-lakes they may have an important impact on lake stability. In particular, if a stream cascades down the pit wall into the lake, which is a possibility in Faro and Vangorda (J. Chapman, personal communication), it may plunge through the epilimnion and mix with hypolimnetic water before losing momentum.

The mixed water would eventually be flushed from the lake resulting in a decrease in the stability of the water column.

The power (flux of kinetic energy) of a stream is given by:

$$P = \frac{1}{2}\rho Q u^2 \tag{1}$$

where ρ is the density of water, Q is the volumetric flow rate, and u is the average velocity. Consider the stream draining the Vangorda catchment where $Q \approx 1\ m^3/s$ for the month of June. If the stream were a "typical" natural river, then $u \approx 0.5$ m/s. This is a conservative value, it is likely to be higher since the flow will be down a much higher slope than a "typical" natural stream (or even cascading). Substituting into (1) gives:

$$P = \frac{1}{2}(1000)(1)(0.5)^2 = 125 \text{ W} \tag{2}$$

The kinetic energy input per unit surface area for the month of June:

$$E_{JUNE} = \frac{PT}{A} = \frac{(125)(30)(24)(3600)}{123{,}000} = 2600 \text{ J/m}^2 \tag{3}$$

where T is the number of seconds in June and A is the surface area of the Vangorda pit. Following the same procedure for the Faro and Grum inflows (assuming u = 0.5 m/s and 0.3 m/s respectively) gives $E_{JUNE} = 400\ J/m^2$ and $12\ J/m^2$ respectively.

Not all of this energy is available for mixing, as much of it will be dissipated as the stream passes through the epilimnion. On the other hand, the estimate of P is probably low for three reasons: the average velocity is probably underestimated; the appropriate velocity to use is the RMS velocity, which will be larger than the average; and stream inflows for the whole year should be considered. A more accurate estimate of E is beyond the scope of the present study, but the values given above are accurate enough to call into question the appropriateness of diverting the streams through the pit-lakes. For the present study we will just consider the scenario where the streams are diverted.

Conceptual model

To investigate the possibility of meromixis in the Faro area pits we wish to estimate the salinity stability at the time of maximum heat content, St*, and compare this to the change in salinity stability observed in the Waterline Pit-lake, ΔSt_{WL}.

Model of warming period

A box model of the surface layer was run for the warming period. The salinity of the surface layer at the end of the warming period was used to compute the salinity stratification, St*.

Following Gorham and Boyce (1989) we calculate the likely surface layer depth at the time of maximum heat content in late August. The surface layer depths in the absence of significant river flow-through were estimated to be 3.1 m for Grum, 3.8 m for Faro and 2.5 m for Vangorda using a surface temperature of 15 C and a mean wind speed for late summer storms of 5 m/s.

Two scenarios were run to bound the evolution of the surface layer through the warming period. The first assumed that the surface layer deepens to the maximum depth right after ice melt. The second assumed that the surface layer depth increases linearly from the depth at ice-off to the depth at maximum heat content. The differences between the model predictions for each scenario are negligible.

Important to the stability is the thickness of the initial layer of fresher water on the surface of the pit at the start of the warming period. This fresher layer is formed from a combination of spring freshet runoff and ice melt during the complex sequence of events that occurs during ice-off. We parameterize this process by considering an effective ice-thickness and the model is run over varying values of this thickness.

The model computes daily salinity for the warming period by conserving volume and salt and accounting for input of stream runoff and direct precipitation, outflow, evaporation and changes in surface layer depth. The runoff, precipitation and evaporation data are given in the Appendix. The salinity at the end of the model run is then used to compute the salinity stability as described earlier.

The following assumptions were made,

- The start of the warming period at ice-off is taken as June 1st and the end of the warming period at maximum heat content is taken as August 31st.
- The hypolimnion of each pit has a salinity of 600 mg/L. Of interest is the water density. Salinity, TDS or specific conductance is used to infer the density. Here salinity S [mg/L] is assumed to be 0.5*C25 [mS/cm] and density is computed from salinity using Chen and Milero (1996).
- Local streams are diverted around the pit lakes.
- Direct precipitation has a salinity of 10 mg/L.
- Brine pockets form in the ice and the mean salinity of the ice melt is assumed to be 25% of the salinity of the surface waters, based on measurements from the Equity pit-lakes.

RESULTS AND CONCLUSIONS

The results of the model for the three Pit-lakes, assuming the local streams are diverted, are plotted in Figure 2. The value of St* increases as ice thickness increases. Typical ice thicknesses observed in the Faro area pits is approximately 3.5 to 4.0 feet (John Chapman, personal communication), comparable to that observed in the Equity Waterline Pit-lake. The meromictic ratio for 1 m of ice thickness is 11, 6 and 5 for Faro, Grum and Vangorda, respectively. Thus, if streams are diverted meromixis seems likely for all the pits, and in each case the likelihood increases with increasing ice thickness. Significant inaccuracies in the estimates remain and this should not be taken to indicate a guarantee of meromixis.

Meromixis can be enhanced by significant salt input such as the dissolution of salts from waste rock and pit walls. It can also occur where evaporation is the major outlet of water from a lake, resulting in concentration of salts. On the other hand flow of relatively fresh water from, for example the local catchment, can export salt and reduce the salinity contrast in the long term.

If the local streams are allowed to flow through the pit lakes they would have a major impact on the physical limnology of the Vangorda and Faro Pit-lakes, and a lesser impact on the Grum Pit-lake. For example, the stream flow into Vangorda would result in a bulk retention time of only 6 months and the surface layer would have a retention time of less than a week. In addition, the stream power would be much greater than the salinity stability of the pit lake. The model would have to be refined to include the effects of streamflow induced mixing. There is certainly the possibility that the flushing of mixed fluid from the lake would lower the salinity stability and reduce the likelihood of sustained meromixis.

REFERENCES

Chen, C. A. and Millero, F. J., 1986. Precise thermodynamic properties for natural waters covering only the limnological range. Limnology and Oceanography, 31(3), 657-662.

Gorham, E. and F. M. Boyce, 1989. Influence of lake surface area and depth upon thermal stratification and the deth of the summer thermocline. Journal of Great Lakes Research, 15(2), 233-245.

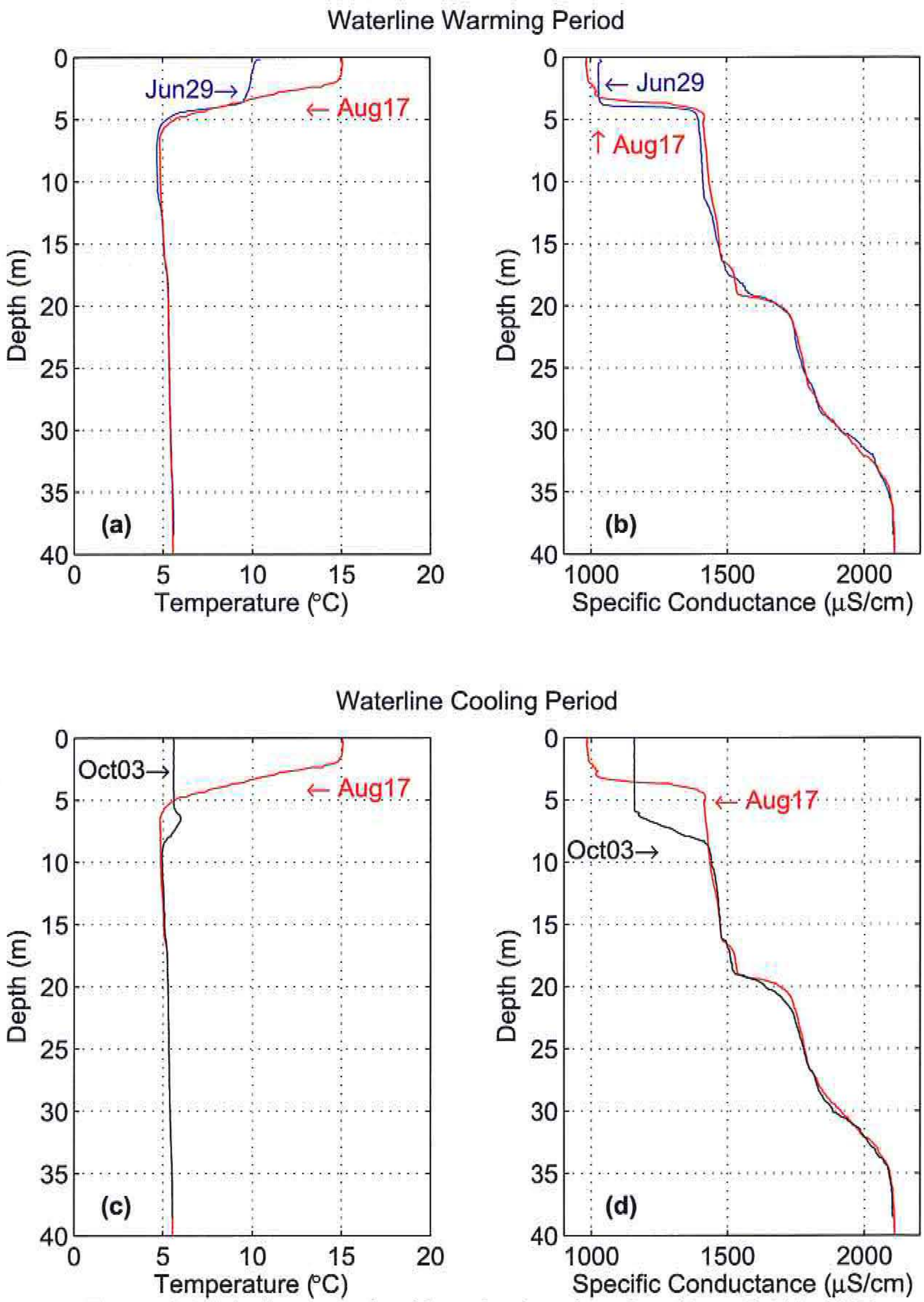


Figure 1. Waterline warming (Jun–Aug) and cooling (Aug–Oct) in 2001. The salinity stability was 194, 200 and 187 J/m^2 on Jun 29, Aug 17, and Oct 3, respectively.

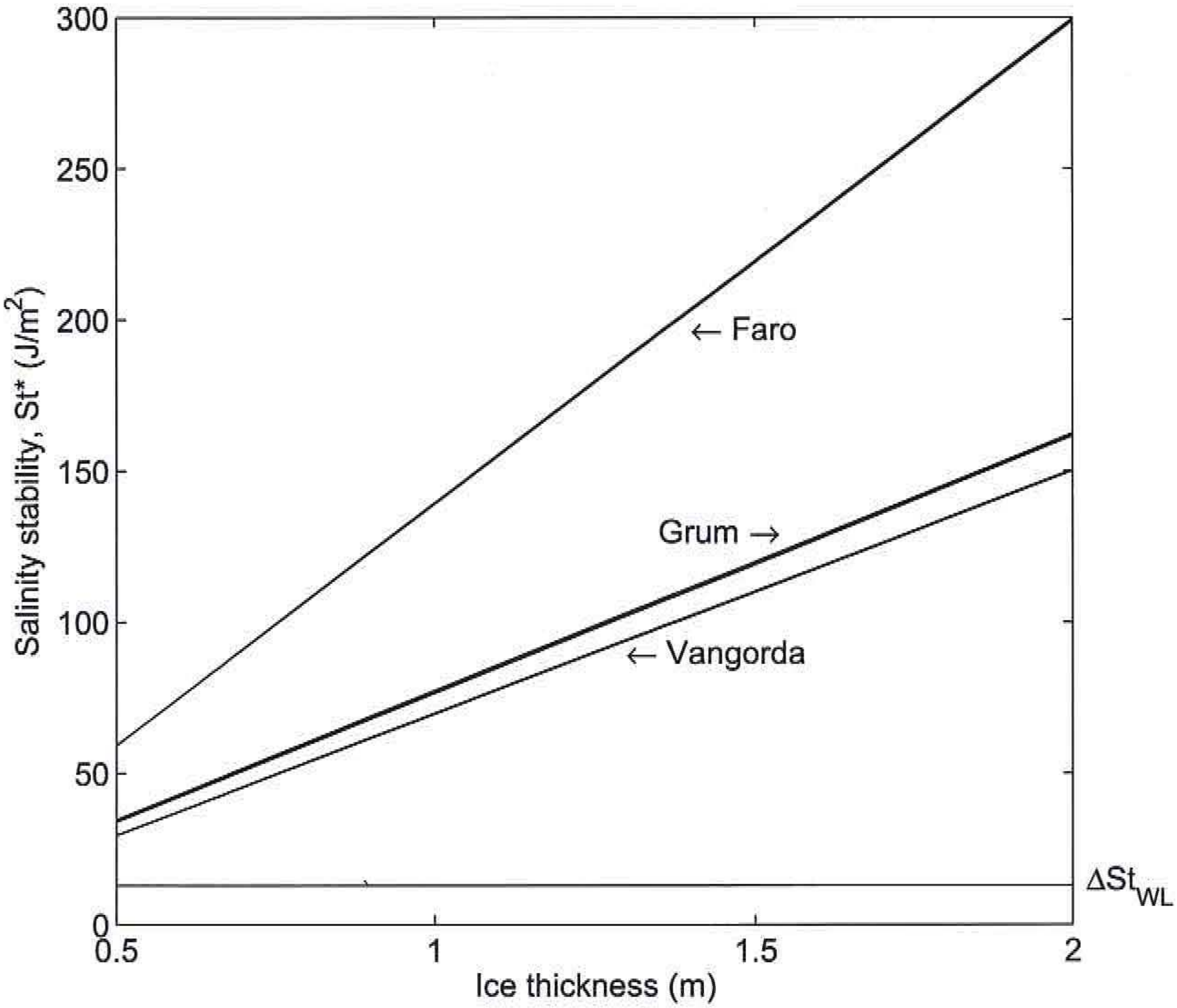


Figure 2. Predicted salinity stability at time of maximum heat content, St^*, for Grum, Faro and Vangorda pits with stream water diverted.

Appendix
Information provided

The ultimate water level for each pit is given in Table 1. Two sets of area data were given for each pit:

1. DepthCapacityCurves.xls

    Grum – Area and elevations very different than the new data. Not used.

    Faro –The area is about 10% lower than the area from the surface region given in the new data set. This data was used, as it was a complete set.

    Vangorda –The area in this data set is about 10% lower than the areas from the surface region given in the new data set. This data was used, as it was a complete set.

2. Pit Lake Volume Capacity Curves.xls, marked "New Data from Topographic Calc."

    Grum – Elevation matches ultimate water level. Data used.

    Faro – partial data going only 30 m below ultimate water level. Not used.

    Vangorda – partial data going only 30 m below ultimate water level. Not used.

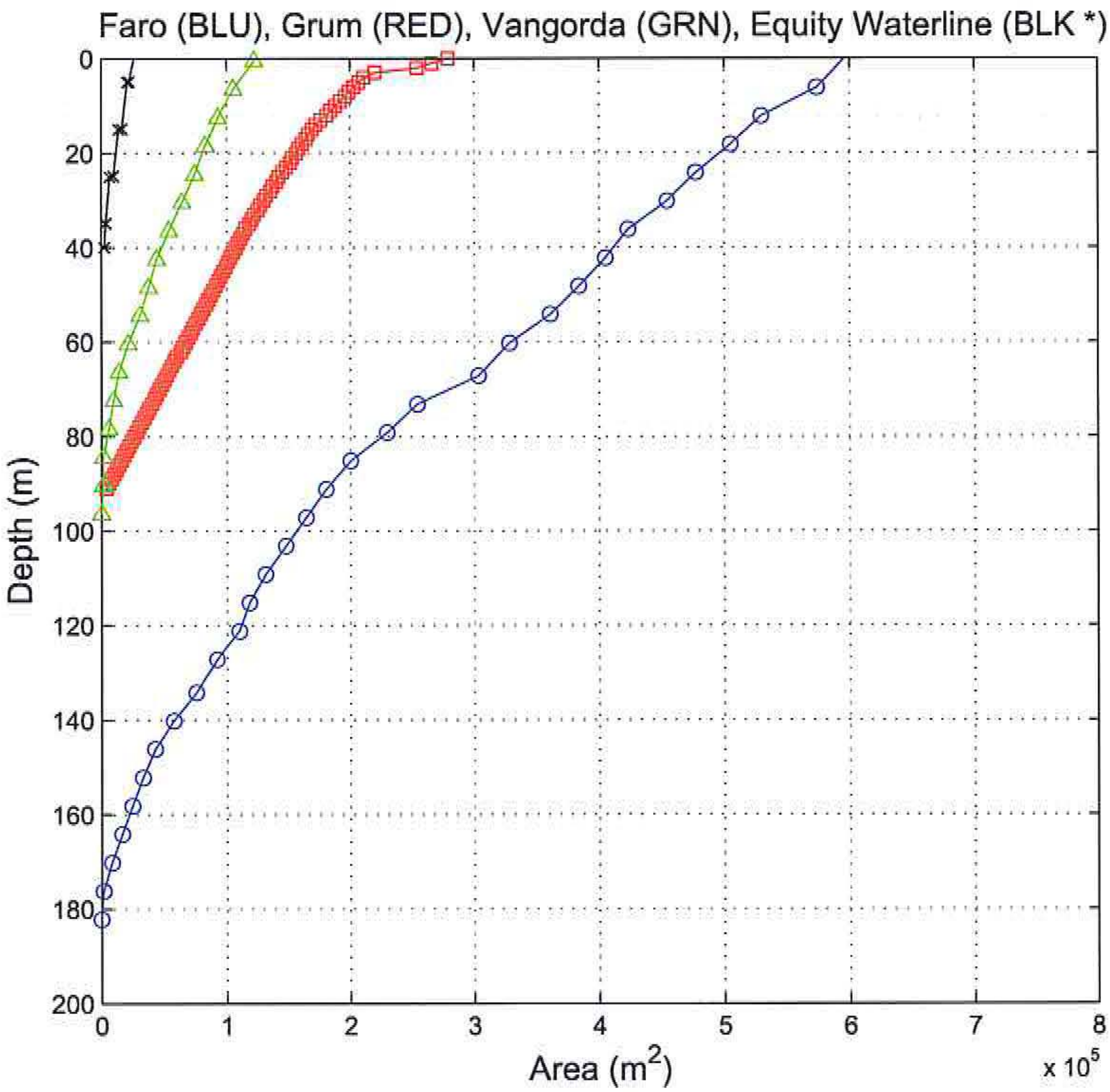
Attached are the following:

Figure showing area as a function of depth used for the pits

Grum: water balance

Faro: water balance

Vangorda: water balance



Area as a function of depth from ultimate water level for Faro area pits

Grum Pit Average Water Balance

Assumptions:
1) Grum Interceptor Ditch breached
2) Groundwater seepage from filled pit assumed negligible

Total catchment of Grum Pit (excl. pit lake surface) =	1.3 km^2
Surface area of pit lake =	0.2 km^2 (guesstimate - to be checked)
Mean annual runoff of Grum Pit catchment =	270 mm
Mean annual precipitation at pit lake =	450 mm
Groundwater loss rate from open pit =	0 m^3/s (assumed negligible)

Month	No. of days in month	INFLOWS		OUTFLOWS			
		Runoff (1000 m^3)	Direct Precipitation on Lake Surface (1000 m^3)	Groundwater Recharge (1000 m^3)	Lake Evaporation (1000 m^3)	Discharge at Pit Outlet (1000 m^3)	Discharge at Pit Outlet (m^3/s)
Jan	31	6	1	0	0	7	0.003
Feb	28.25	4	1	0	0	5	0.002
Mar	31	4	1	0	2	4	0.001
Apr	30	9	2	0	11	0	0.000
May	31	72	18	0	18	73	0.027
Jun	30	74	19	0	22	71	0.027
Jul	31	52	13	0	22	43	0.016
Aug	31	36	9	0	16	29	0.011
Sep	30	49	12	0	6	55	0.021
Oct	31	25	7	0	2	30	0.011
Nov	30	11	3	0	0	14	0.006
Dec	31	8	2	0	0	11	0.004
Annual	365.25	351	90	0	99	342	0.011

Faro Pit Average Water Balance

Assumptions:
1) Faro Creek routed through Faro Pit
2) No dam constructed in SE access ramp, so pit fills to 1158.2 m (NAD 27) level and spills to buried Zone II Pit, which in turn spills to North Fork of Rose Creek.
The alternative is to constuct the dam and force the spill to occur at the SW ramp.

Total catchment of Faro Pit (excl. pit lake surface) =	17.3 km^2
Surface area of pit lake =	0.6 km^2
Mean annual runoff of Faro Pit catchment =	341 mm
Mean annual precipitation at pit lake =	400 mm
Groundwater loss rate from open pit =	0.0005 m^3/s (roughly based on calcs done by RGC)

Month	No. of days in month	INFLOWS		OUTFLOWS			
		Runoff (1000 m^3)	Direct Precipitation on Lake Surface (1000 m^3)	Groundwater Recharge (1000 m^3)	Lake Evaporation (1000 m^3)	Discharge at Pit Outlet (1000 m^3)	Discharge at Pit Outlet (m^3/s)
Jan	31	124	5	1	0	127	0.05
Feb	28.25	92	4	1	0	95	0.04
Mar	31	89	4	1	5	87	0.03
Apr	30	118	5	1	32	89	0.03
May	31	1097	45	1	54	1086	0.41
Jun	30	1892	77	1	67	1901	0.73
Jul	31	867	35	1	65	836	0.31
Aug	31	432	18	1	49	399	0.15
Sep	30	419	17	1	19	416	0.16
Oct	31	396	16	1	6	404	0.15
Nov	30	209	9	1	0	217	0.08
Dec	31	165	7	1	0	171	0.06
Annual	365.25	5899	240	16	296	5828	0.18

Vangorda Pit Average Water Balance

Assumptions:
1) Vangorda Creek routed through Vangorda Pit and NE Interceptor Ditch breached
2) The spill point for the pit is at 1122.5 m (estimated point where old Vangorda Ck channel intercepts southern pit wall.

Total catchment of Vangorda Pit (excl. pit lake surface) = 21.66 km^2
Surface area of pit lake = 0.12 km^2 (to be checked)
Mean annual runoff of Vangorda Pit catchment = 362 mm
Mean annual precipitation at pit lake = 380 mm
Groundwater loss rate from open pit = 0 m^3/s (assumed negligible)

Month	No. of days in month	INFLOWS		OUTFLOWS			
		Runoff (1000 m^3)	Direct Precipitation on Lake Surface (1000 m^3)	Groundwater Recharge (1000 m^3)	Lake Evaporation (1000 m^3)	Discharge at Pit Outlet (1000 m^3)	Discharge at Pit Outlet (m^3/s)
Jan	31	165	1	0	0	165	0.06
Feb	28.25	123	1	0	0	123	0.05
Mar	31	119	1	0	1	118	0.04
Apr	30	156	1	0	6	151	0.06
May	31	1458	8	0	11	1455	0.54
Jun	30	2515	15	0	13	2516	0.97
Jul	31	1152	7	0	13	1146	0.43
Aug	31	574	3	0	10	567	0.21
Sep	30	557	3	0	4	556	0.21
Oct	31	526	3	0	1	528	0.20
Nov	30	278	2	0	0	280	0.11
Dec	31	220	1	0	0	221	0.08
Annual	365.25	7841	46	0	59	7827	0.25