Stratification controls of pit mine lakes

P.W. JEWELL

P.W. Jewell, member SME, is associate professor with the Department of Geology and Geophysics, University of Utah, Salt Lake City, UT. Paper number TP-07-042. Original manuscript submitted November 2007. Revised manuscript accepted for publication June 2008. Discussion of this peer-reviewed and approved paper is invited and must be submitted to SME Publications Dept. prior to May 31, 2009.

Introduction

Pit mine lakes result when openpit mining that extends below the natural water table ceases and the water table begins to rebound. A number of environmental concerns surround pit mine lakes, and perhaps the most important concern is the long-term chemical evolution of pit lake water (Miller et al., 1996; Davis and Eary, 1997; Eary, 1999; Lewis, 1999; Kempton et al., 2000). Water quality in pit mine lakes is a worldwide environmental concern. In the Great Basin of the western United States alone, dozens of openpit gold mines will undergo closure and form pit lakes during the first half of the 21st century (e.g., Shevenell et al., 1999).

The hydrology of a pit lake can be described within the context of a simple mass-balance model in which water enters by ground water or surface water inflow and leaves by ground water or evaporation (Fig. 1). Chemical constituents enter or leave the lake in the same manner with additional sources and sinks from dissolution and chemical weathering of minerals due to water-rock interactions in the pit lake walls; adsorption/desorption onto clays, metal oxides and organic matter; and the formation of solid phases that become sequestered in sediment at the pit lake bottom.

The ability to predict the redox state of pit waters is crucial to any prognostic model of lake water quality (e.g., Cursius et al., 2004; Martin and Pedersen, 2004). The behavior of many metals and colloidal iron is strongly redox dependent. For instance, most sulfide minerals are insoluble in low redox state waters (Stumm and Morgan, 1996), meaning that the dissolution of sulfides in these environments is minimal. On the other hand, colloidal iron strongly adsorbs Se, As and dissolved metals such as Cu^{2+}, Zn^{2+} and Cd^{2+} in oxygenated environments and will dissolve and release these elements in anoxic waters (e.g., Martin and Pedersen, 2002; 2004). Therefore, redox conditions in the water column play a critical role in determining which suite of trace metals may end up in solution when ground water interacts with ore-bearing rocks.

Abstract

Large-scale openpit mining often produces lakes with a significant environmental liability. Permanently stratified lakes are usually anoxic and, thus, can produce abnormally high concentrations of redox-sensitive metals and anions. The tendency of pit lakes to permanently stratify is favored by ground water inflow with moderately high total dissolved solids and high precipitation – evaporation + runoff (P – E + R) values. Simple dynamic models and climate data suggest that pit mine lakes in relatively wet, cool climates are more likely to permanently stratify than pit lakes in arid regions such as the Great Basin of the western United States that are characterized by negative P – E + R conditions and small surface runoff potential.

Surface waters of lakes tend to be oxygenated due to the exchange of gases with the atmosphere. In the deeper portion of lakes, oxygen is consumed by organic matter produced by photosynthesis at the surface or the oxidation of sulfide minerals at depth. The replenishment of oxygen to these deep waters is dependent on solar heat flux, which warms the upper water and tends to stratify the water column; vertical solute gradients, which also stratify the water; and wind shear stress, which tends to mix the water column. The redox state of the deep water of lakes is thus dependent on the two counteracting effects of density (due to differences in heat and mass distribution) and velocity shear.

Previous studies of stratification in natural and pit mine lakes have focused on simple lake depth/area ratios (e.g., Lyons et al., 1994; Doyle and Runnels, 1997) on the assumption that large area/depth ratios allow more wind mixing and, thus, are less prone to stratification and the development of anoxia. While this approach is a useful general measure of lake mixing and stratification, it does not allow specific physical controls of water stratification to be examined. In addition, the presence of high walls around pit mine lakes tends to shelter the lake surface from winds. With few exceptions (e.g., Hamblin et al., 1998; Stevens and Lawrence, 1998), this potentially important factor for inhibiting water column mixing has not been examined in detail.

This paper develops a simple model that can be used by mining professionals and regulators to determine whether pit lakes will stratify or not. Summaries of existing pit mine lakes suggest that, while a small number of pit lakes are permanently stratified (e.g., Levy et al., 1997; Stevens and Lawrence, 1998; Gammons and Duaime, 2006), most undergo seasonal water turnover and thus tend to be oxygenated (Tables 1 and 2). Details of permanently stratified pit mine lakes are used to test the model against real data. A study by the author of a large, unstratified pit lake at Yerington, NV (Jewell, 1999) provides detailed measurements of wind and water data that are not available in most studies and thus aid in model development and validation.

Controls of lake stratification

Permanent stratification of a water body results when the density gradient is sufficiently high that the velocity shear does not break down the stratification. The balance between these two forces is best shown by the dimensionless gradient Richardson number

$$Ri = \frac{g\left(\frac{\partial \rho}{\partial z}\right)}{\rho_o\left(\frac{\partial V}{\partial z}\right)^2} \quad (1)$$

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where
g is the gravitational constant,
ρ is water density,
ρo is the density of water at 25°C,
V is horizontal velocity and
z is vertical distance.

Using the units of meters, kilograms and seconds, the water column has a stable vertical density profile and will remain stratified if $Ri > 0.25$ (Turner, 1973).

Variables in the gradient Richardson number, particularly the velocity profile, are difficult to measure on a routine basis. A more easily employed criterion is the Wedderburn number, which is obtained by multiplying Ri by the ratio of the thermocline depth (H) to the maximum length of the lake at the depth of the thermocline (L) and recasting the velocity gradient as the surface friction velocity (u*) (Imberger and Patterson, 1990) as follows

$$W = \frac{g' H^2}{u_*^2 L} \quad (2)$$

Reduced gravity is defined as

$$g' = \frac{g \Delta \rho}{\rho} \quad (3)$$

The friction velocity, u*, is defined as

$$u_*^2 = \left(\frac{\rho_a}{\rho_w}\right) C_D U_w^2 \quad (4)$$

where
ρa is air density,
ρw is water density,
Uw is wind speed and
Cd is a dimensionless drag coefficient.

Changes in the air/water density ratio ($\rho a/\rho w$) over a variety of temperatures are minor. For the purpose of this study, a ratio of 1.27 kg m^{-3}/1,000 kg m^{-3} = 0.00127 is assumed. The drag coefficient is a function of wind speed. C_D is larger for higher wind speeds due to the rougher water surface that enhances friction (e.g., Pond and Pickard, 1983). Because winds that cause mixing in lakes are relatively strong, a relatively high drag coefficient of 0.0018 is assumed.

In general, $W > 1$ indicates a lake that is permanently stratified (Imberger and Patterson, 1990). Substituting values for Eq. (3) into Eq. (4) yields

$$W = \frac{g' H^2}{\left(2.2 * 10^{-6}\right) U_W^2 L} \quad (5)$$

Evaluation of stability variables

It is now possible to use Eq. (5) to evaluate the potential for permanent stratification using published values of wind speed, lake size and density profiles. A further simplification is made by relating the thermocline thickness (H) to lake length (L).

Pit lake thermocline thickness. In all lakes, thermocline thickness is a function of wind strength and duration. The most comprehensively investigated relationship between these two variables (Hanna, 1990) is

$$\log(H) = 0.336 * \log(L) - 0.245 \quad (6)$$

This relationship has been evaluated with published data from permanently and seasonally stratified pit mine lakes (Fig. 2). Equation (6) tends to underpredict thermocline thickness, which is surprising given possible wind-sheltering effects of pit lake high walls. For this study, the slope of Eq. (6) is retained while changing the y-intercept to zero in order to achieve a best fit of pit lake data (Fig. 2).

Wind. Very strong surface winds create large surface currents and, therefore, tend to break down vertical density gradients (Eqs. (1) and (5)). Although long-term wind records are readily available for thousands of localities, relatively little understanding exists of how the wind regime of pit mine lakes is affected by high walls that surround the lake. Wind shear separation would be expected at the rim of the pit, resulting in significantly less wind strength at the lake surface. At the Brenda pit mine lake in British Columbia (Hamblin et al., 1999), meteorological instruments deployed adjacent to the pit lake and at

FIGURE 1

Generalized water balance of lakes: P = precipitation, E = evaporation, R = surface runoff, Gi = ground water in and Go = ground water out.

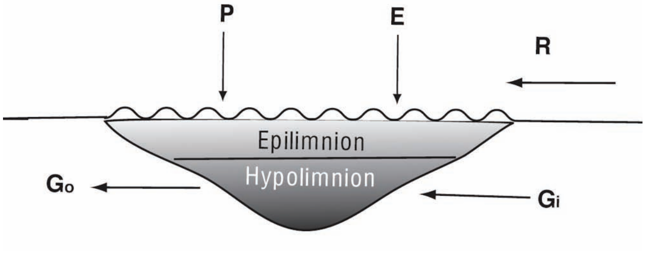


FIGURE 2

Predicted vs. measured thermocline depths of pit mine lakes for data shown in Tables 1 and 2.

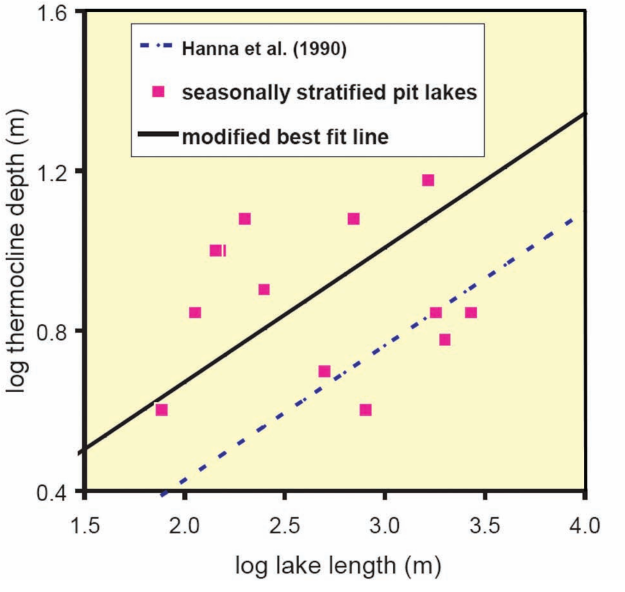


Table 1

Summary of permanently stratified pit mine lakes.

Pit Lake	Location	Effective length, m	Thermocline depth, m	Density anomaly (Δρ/ρ)
Brenda[1]	British Columbia	700	12	0.036
Spenceville[2]	California	77	4	0.0045
Gunnar[3]	Saskatchewan	250	8	0.0009
Berkeley[4]	Montana	1,800	7	0.0006
Lake 1a[5]	Germany	2,700	7	0.018
Lake 1b[5]	Germany	2,000	6	0.077

[1]Stevens and Lawrence (1998)
[2]Levy et al. (1995)
[3]Tones (1982)
[4]Doyle and Runnels (1997)
[5]Boehmer et al. (1998, 2000)

the pit rim showed significant (up to 50%) reduction in the wind speed. Vertical and horizontal distances between the two stations were 50 and 500 m (164 and 1,640 ft), respectively. At the Yerington pit lake in Nevada, a meteorological station deployed at the southwestern edge of the lake over a one-year period (May 1998 through May 1999) (Jewell, 1999) allowed comparison with synoptic wind records at the Reno airport, approximately 70 km (43 miles) away. Vertical distance between the rim of the pit and surface of the water was approximately 25 m (80 ft). In spite of the obvious differences between the two lakes (Tables 1 and 2), results at Yerington were similar to those reported by Hamblin et al. (1999), with wind speed magnitude at the pit lake being approximately 50% of the values reported during periods of high wind speed at the airport (Fig. 3). Maximum wind speeds over this one-year period were approximately 10 m/s (22 mph) at the Reno airport and considerably lower at the Yerington pit lake (Fig. 4).

Pit lake length. The maximum length of a pit lake is relatively easy to document (Table 1). Because the walls of pit lakes are relatively steep, the maximum length of the lake thermocline is approximated as 90% of the maximum length of the lake.

Wedderburn number calculations. Substituting Eq. (6) into Eq. (5) for given wind velocities yields an expression for the Wedderburn number in terms of pit lake length and vertical density anomaly (Δρ/ρ). For the six permanently stratified lakes (Table 1) wind velocities of 5 and 7.5 m/s (11 and 17 mph) (Fig. 5 (a) and (b), respectively, were assumed. Calculated Wedderburn numbers >1 are seen in all six stratified lakes for both wind speeds (Table 1, Fig. 5). Based on this limited data set, Fig. 5 demonstrates that vertical density gradients > 0.0005 yield a Wedderburn number >1. This density anomaly will form the basis for understanding the water balance necessary to maintain these gradients and thus permanent stratification in pit mine lakes.

Density gradients and water balances

The density of water is a function of both temperature and dissolved constituents. Here, the role of temperature, a factor affecting lake density in seasonally stratified temperate latitude lakes, is examined, and the amount of dissolved solutes necessary to produce permanent stratification is calculated.

Seasonal variation of heat flux results in temperature gradient between the epilimnion and the hypolimion. Hypolimnion water temperatures tend to mirror the mean annual temperature of a given area because the largest influx of water to the lower portion of the lake is from ground water (e.g., Jewell, 1999). Surface temperatures are a complex function of net solar radiation and air temperature, pressure and relative humidity. In most mid-latitude lakes, the temperature contrast between the hypolimnion and epilimnion varies from 5° to 20°C (9° to 36°F), resulting in a maximum density contrast of 0.004 to 0.005 g/cm^3 (Fig. 6), sufficient to yield a Wedderburn number >1 on a seasonal basis (Fig. 5).

For a lake to become permanently stratified, the density contrast from solutes must be sufficiently large that stratification is maintained following late season thermal homogenization of the water column (Fig. 7). There are two necessary conditions: the total dissolved solids of the lake must be sufficiently great that when freshwater runoff enters the lake, the vertical density gradient is high enough to maintain stratification and a sufficiently large amount of freshwater enters the epilimnion that a stable, permanent density gradient can be established. The former condition is satisfied if the lake hypolimnion

Table 2

Summary of seasonally stratified pit mine lakes.

Pit lake	Location	Effective length, m	Thermocline depth, m
Yerington[1]	Nevada	1,650	15
Main Zone[2]	British Columbia	800	4
Waterline[2]	British Columbia	500	5
Blowout[3]	Utah	200	12
Blackhawk[3]	Utah	150	10
Aurora[4]	Nevada	110	2.5
D lake[5]	Saskatchewan	140	7
B-zone[5]	Saskatchewan	600	10

[1]Jewell (1999)
[2]Crusins (2003)
[3]Castendyk (1999)
[4]Kempton (1996); length calculated from area and assuming circular shape
[5]Tones (1982); length calculated from area and assuming circular shape

has total dissolved solids (TDS) of ~800 ppm (Fig. 6). In other words, if zero TDS water were to enter a lake with 800 ppm TDS water, a density gradient > 0.0005 and Wedderburn number >> 1 would result, and the lake would most likely become permanently stratified.

The latter condition is a function of the general water balance and climatology of the area surrounding the lake. For instance, the amount of fresh water added to a lake epilimnion to maintain a density contrast of >0.0005 depends on the thickness of the epilimnion during thermal stratification. Adding 5 mm (0.20-in.) of freshwater (zero TDS) to a 10-m- (33-ft-) thick epilimnion would produce the required 0.0005 density difference. However, the 5 mm (0.20 in.) of freshwater would have to be added to the epilimnion during the period of thermal stratification (generally from late spring through the fall), which in most cases would also be the period of maximum evaporation. A prerequisite for permanent stratification is thus that precipitation + runoff be greater than evaporation during the summer months.

Mean precipitation and evaporation data were assembled for the area adjacent to two permanently stratified pit lakes (Spenceville, CA, and Butte, MT) and adjacent to a seasonally stratified lake in the Great Basin of the U.S. (Yerington, NV). For these three lakes, the degree of stratification imitates the seasonal water balance (Fig. 8). The Sierra Nevada Mountains are characterized by a strong positive water balance during the winter months (snowpack), while western Nevada's water balance is negative year-round. The very strong stratification at the Spencville lake is enhanced by surface runoff that is approximately the same magnitude as direct precipitation (Levy et al., 1997). Butte, MT, represents an intermediate case in which the water balance is evaporative but there is a sufficiently high-density gradient that the lake maintains stratification. This could be due to the relatively high pit lake walls, >300 m (>984 ft) when the mine began to initially fill, that inhibit wind shear stress (Figs. 3 and 4) as well as surface runoff from the surrounding drainage.

Conversely, Yerington's water balance is strongly evaporative with limited surface runoff, and the lake will most likely never permanently stratify. This case is probably typical for the Great Basin as whole, where evaporation exceeds precipitation for all but the very highest elevations.

Discussion

This simple model of pit lake stratification controls is intended to point the way toward a relatively quick method for environmental professionals and regulators to predict whether a pit mine lake will become permanently stratified and thus develop anoxic waters. While more sophisticated numerical models will no doubt be required to gain detailed understanding of the physical limnology of pit mine lakes, the procedure outlined here represents a potentially cost effective alternative. More rigorous testing of this method will require additional data from other permanently stratified pit lakes.

The key to application of this method is calculation of the modified Wedderburn number, as outlined above.

FIGURE 3

Examples of wind speeds recorded in 1998 at the surface of the Yerington, NV, pit mine lake and the Reno, NV, airport.

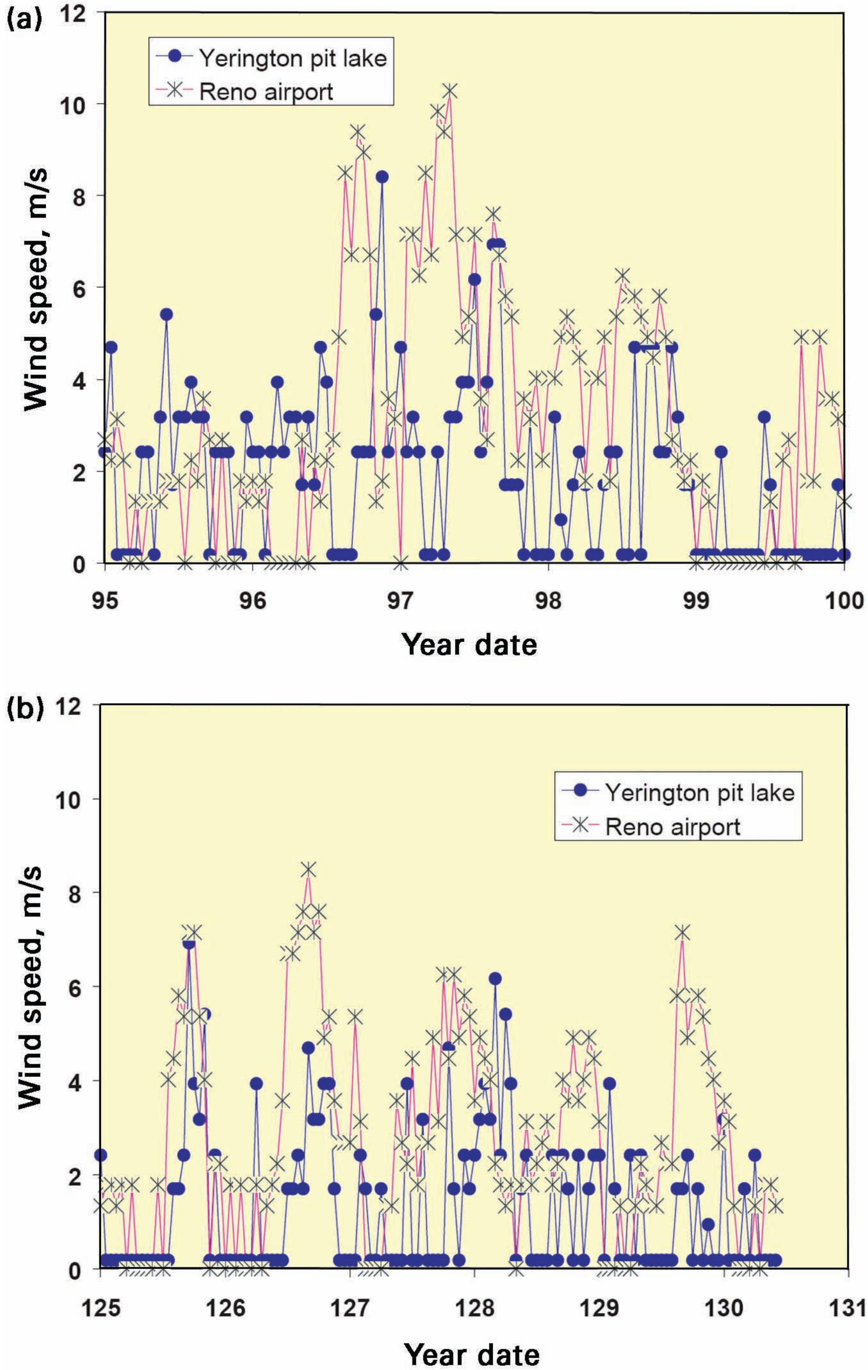


FIGURE 4

Histograms of hourly wind records at the Yerington pit lake and Reno airport from May 1998 to May 1999 (Jewell, 1999).

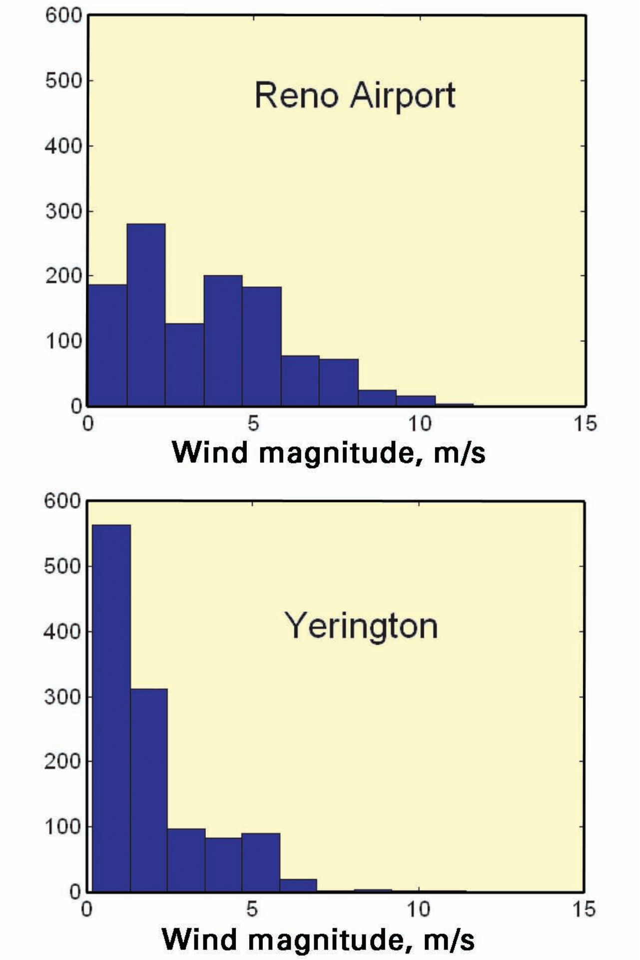
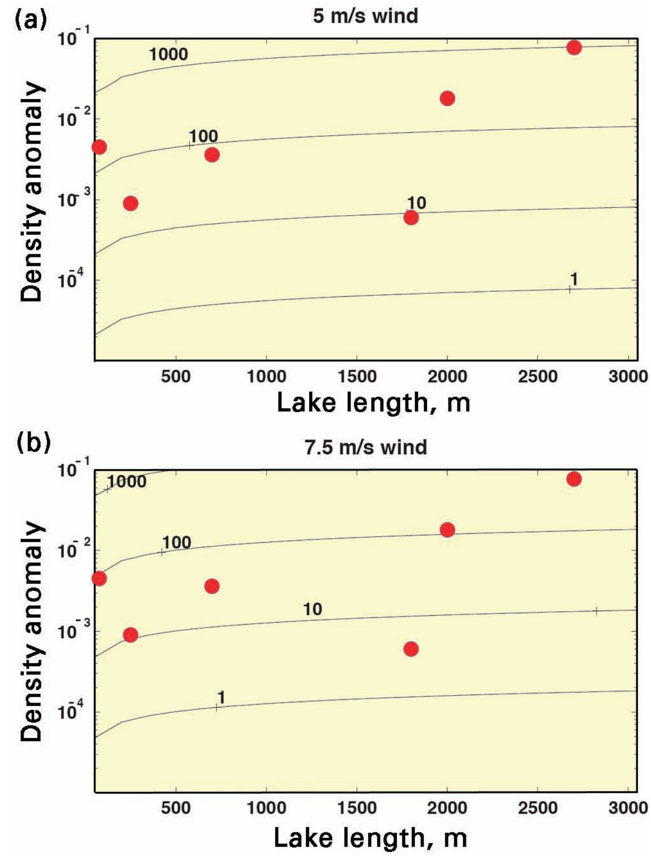


FIGURE 5

Wedderburn number calculations (Eqs. 5 and 6) for (a) wind strength of 5 m/s (11 mph) and (b) wind strength of 7.5 m/s (17 mph). Wedderburn numbers greater than 1 indicate stable stratification of the water column. Crosses represent the six permanently stratified pit lakes of Table 1.



This, in turn, requires determination of a number of variables including morphometry of the lake, generalized wind records of the area (often available today as Internet data bases) and the precipitation-evaporation-runoff regime of the area. The latter is undoubtedly the most difficult variable to determine since detailed water balance studies, particularly of the key variable of surface water inflow into the lake, are not straightforward measurements. ■

Acknowledgments

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FIGURE 6

Water density anomaly (density = 1 g/cm³) as a function of temperature and total dissolved solids (TDS) (McCutcheon et al., 1993). Arrow represents observed seasonal temperature variation at the Yerington pit lake (Jewell, 1999).

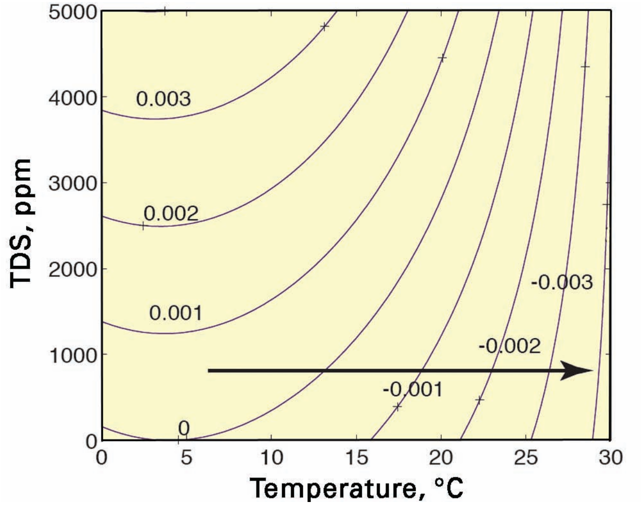

FIGURE 7

Idealized diagram of density profiles of seasonal and permanent stratification. $\Delta\rho_T$ represents the density anomaly due to temperature, and $\Delta\rho_S$ is the density anomaly due to solute concentration. The figure demonstrates how seasonal density anomalies due to solute gradient ($\Delta\rho_S$) must be sufficiently great to maintain stratification following surface thermal cooling in order for a lake to become permanently stratified.

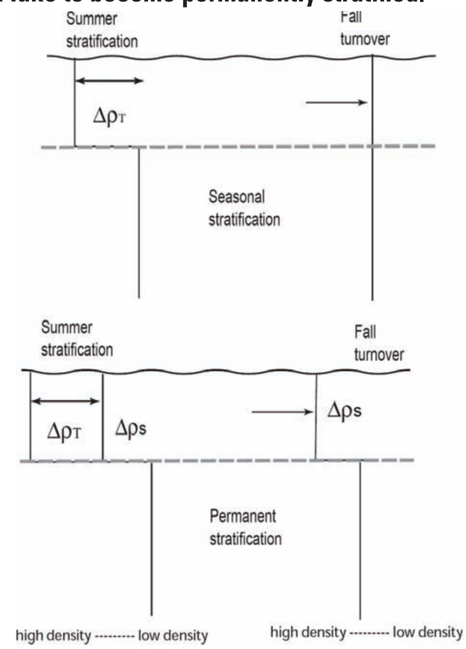

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FIGURE 8

Summary of precipitation-evaporation data for southwestern Montana (Butte pit mine lake), western Nevada (Yerington pit mine lake) and northern Sierra Nevada (Spenceville pit mine lake). Data from Desert Research Institute's Western Regional Climate Center (http://www.wrcc.dri.edu). The positive water balance of the permanently stratified Spenceville lake contrasts with the strong negative water balance of the Yerington mine.)