Modeling pit lake water column stability using Ce-Qual-W2

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ABSTRACT: Field measurements of temperature, conductivity, and TDS in an acidic pit lake in southeast Tennessee show that the water column of the lake is currently density stratified. The relative depth of the pit is an intermediate value suggesting that while potentially stable, based on bathymetry alone, the pit's water column could mix. The potential for the pit's water column to turn over is a concern because mixing of the shallow low TDS water and the deep high TDS water could potentially degrade the water quality downstream. Water quality, temperature and bathymetric data were used with meteorological observations to develop a limnologic model of the pit using the Ce-Qual-W2 (v.3.0). A series of model simulations were designed to test the long-term stability of the pit's chemical stratification under changing temperatures, storm events, and water quality (TDS) conditions.

1 INTRODUCTION

An extensive field investigation occurred at a historic copper mine to characterize the physical and chemical characteristics of a 550 million gallon (2,082,000 m^3) stratified pit lake located in southeast Tennessee. The pit has a maximum depth of approximately 60 meters and a surface area of approximately 20 acres. A primary tributary enters at the north end of the pit and discharges from the south end of the pit. In cooperation with regulatory agencies, this stream was diverted into the pit as a sediment control measure. The boundary for this field study encompassed approximately 220 acres located near the bottom of the tributary's 1500-acre drainage basin.

Field studies conducted at the site between 1998 and 2002 suggest that the pit is chemically stratified and that the water column is resistant to large-scale mixing known as turnover. Specific conductivity results from depth profiles taken using a Hydrolab® multi-parameter probe demonstrated the presence of a deep high-conductivity water layer underlying a shallow lower conductivity layer (Fig. 1). A distinct chemocline observed at a depth of 7.5 to 8.5 meters separates the low TDS and high TDS layers.

The results from bi-monthly sampling events conducted from August 2001 through August 2002 yielded relatively constant temperature, pH, dissolved oxygen, Eh, total dissolved solids (TDS) and conductivity profiles below the top 8.5 meters of the pit. The water in the deep, high-conductivity layer known as the hypolimnion averaged 572 mg/L iron, 2966 mg/L sulfate, 14 ug/L copper and 37 mg/L manganese.

The shallow, low-conductivity water layer displayed more variability in temperature and other water quality parameters than the hypolimnion. This type of shallow lacustrine layer is termed a "mixed zone" because the water in this zone is affected by meteorological and seasonal fluctuations, changes in influent water quality and mechanical mixing from wind-driven and fluvial currents. The concentrations of total metals in the pit's mixed zone were generally lower than those in the deep water layer averaging 3 mg/L iron, 261 mg/L sulfate, 105 mg/L copper and 3 mg/L manganese. The water quality in the tributary both upstream and downstream of the pit was comparable to the water quality in the mixed zone of the pit lake.

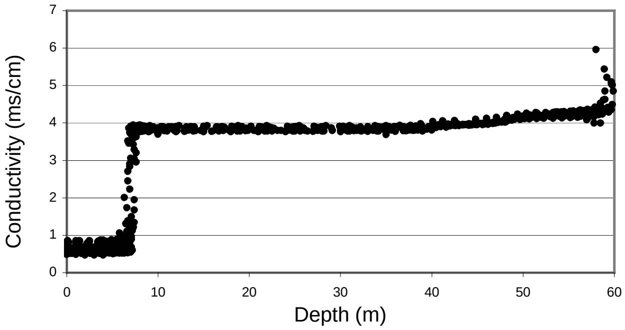


Figure 1. Pit conductivities (measured bi-monthly (8/01-8/02))

Both naturally occurring lakes and pit lakes generally fall into one of three stratification categories: well mixed lakes, seasonally mixed lakes, and lakes that do not mix (meromictic lakes) (Doyle & Runnells 1997, Wetzel 1983). While the pit lake appeared to display the chemical stratification of a meromictic lake throughout the 2001/2002 monitoring period, the pit's bathymetry suggests that the pit's water column could have the potential to turn over. Calculating the surface area to depth ratio known as the relative depth of water body can indicate the lake or pit's mixing status (Doyle & Runnells 1997, Anderson et al. 1985, Wetzel 1983). Lakes with a relative depth of greater than 20% generally do not mix. The classifications of lakes with lower relative depths vary and depend on other factors affecting the stability of a lake's water column such as density gradients, climatic conditions, and wind direction and intensity. While the pit lake is currently stratified, the pit's relative depth is 18.5%. Based on a bathymetry analysis alone, the pit's water column has the potential to circulate and turn over. The long-term stability of the stratification of the pit lake was further evaluated using a limnologic model.

Water quality, temperature and previously collected bathymetric data were used with meteorological data to develop a limnologic model of the pit lake using Ce-Qual-W2 version 3.0. Ce-Qual-W2 is a hydrodynamic model which provides a two dimensional representation of the mixing dynamics in reservoirs and lakes. Ce-Qual-W2 was originally developed by the Army Corps of Engineers, Waterways Experiments Station, Vicksburg, MS and is currently supported by Portland State University in conjunction with the Corps of Engineers.

To calibrate the model for the pit lake, simulated conditions predicted by Ce-Qual-W2 were compared to the temperature and TDS data collected on site between August 2001 and August 2002. Once the simulated conditions were in good agreement with the observed data, a series of model simulations tested the long-term stability of the pit's chemical stratification under changing water quality (TDS) conditions and during large (high wind) storm events. A discussion of the model's final calibration simulation for the pit lake is described followed by a discussion of a series of wind and water quality sensitivity simulations.

2 CALIBRATION

2.1 *Parameters and Initial Conditions*

The parameters, calculations, initial conditions and time-varying inputs used in the simulation that best predicted the observed temperature and TDS profiles for the pit are described below. The Ce-Qual-W2 model performed volume balance, energy balance, mass balance, wind, inflow, outflow, and heat exchange calculations. The pit lake simulations invoked the CeQual-W2 default equations and used values for variables recommend by the Ce-Qual-W2 User Guide for the evaporation model, transport solution and hydraulic coefficients. The water quality constituent calculations were implemented for TDS in all runs. Ice cover calculations were not used because the pit lake, located at temperate latitude and at an elevation of 442 meters, does not develop seasonal ice coverage. Output results included horizontal and vertical water velocity, TDS, temperature and density.

Ce-Qual-W2 calibration simulations lasted 1 year beginning September 2, 2001 and ending August 31, 2002 thereby including the fall and spring transitional seasons as well as the coldest months of the year when the pit is the most susceptible to turnover. The minimum timestep for the 12-month period was specified at 10 seconds and Ce-Qual-W2 averaged a timestep of 9 seconds over the duration of the simulations.

In order to accurately simulate conditions in the pit lake, a series of initial conditions and time varying inputs were specified to reflect field observations.

This pit lake is a simply shaped oblong water body approximately 550 by 145 meters. It has stepped walls and no significant branches. To simulate this bathymetry, the pit was divided into 9 longitudinal segments and 47 horizontal depth layers (Fig. 2). Shallowest layers were 0.5 meters thick. Layers in the observed thermocline/chemocline were 0.1 meters thick. Layers in the deep section of the pit were initially 5 meters thick but several 2.5-meter layers were created near the base of the pit for better geometrical resolution.

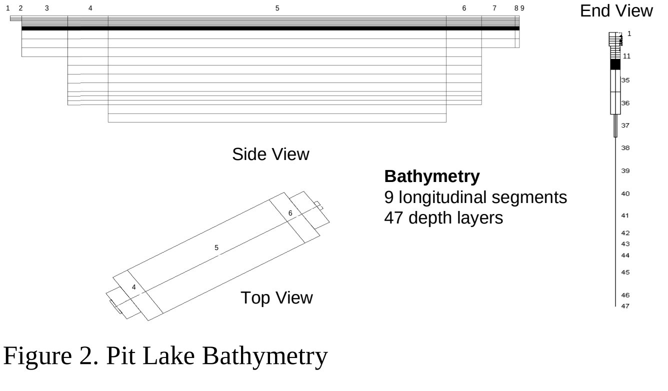


Figure 2. Pit Lake Bathymetry

The initial vertical temperature and TDS profiles for the water column were specified using data from field and laboratory measurements. Temperatures were measured using the Hydrolab® probe on 8/14/2001 and ranged from approximately 24°C near the surface to 11°C at depth (Fig. 3). TDS values were calculated by summing measured ion concentrations from discrete water samples taken between August 2001 and January 2002 (Fig. 4). An average TDS concentration was calculated for each depth interval. The resulting profile ranged from 333 mg/L TDS in the shallow waters to close to 5000 mg/L TDS at depth. An initial density profile is not specified in Ce-Qual-W2; the modeling routines calculate density using temperature and the concentration of TDS for freshwater simulations.

other Hydrolab® probe located at the upgradient weir gauge, which continuously monitored the water temperature of the tributary.

The concentration of TDS in the pit's influent was modeled both at 220 mg/L and 350 mg/L for two separate calibration simulations. A TDS concentration of 220 mg/L represents the average measured inflow concentration between August 2001 and July 2002.

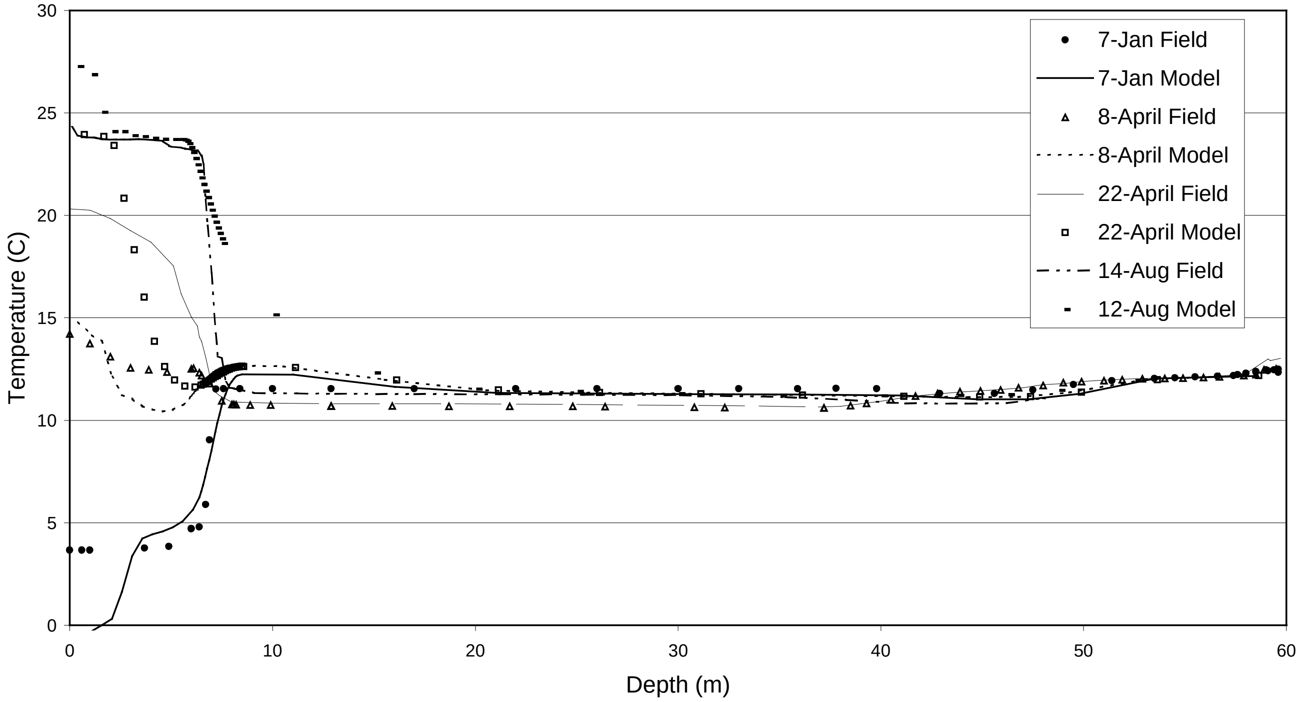


Figure 3. Measured and modeled temperature profiles

The pit lake was modeled with its primary tributary entering the pit at the northern edge and exiting at the southern edge. As part of this study, the tributary's flow was measured at 30-minute intervals at two weir gauges located immediately upstream and downstream of the pit lake. The averages of inflow and outflow measurements recorded in the first five observation-months (11/2001 to 3/2002) were 0.60 m^3/s (9,480 gpm) and 0.64 m^3/s (10,110 gpm) respectively. The model was run with the influent set at a steady 0.64 m^3/s. Sensitivity simulations were also conducted at higher and lower flow rates. For example, one run was conducted using the highest observed monthly outflow (0.96 m^3/s in May of 2002). Another used the lower 12-month average flows (0.54 m^3/s), and a third varied the flow using monthly averages. Resulting temperatures, densities and velocities were not sensitive to changes in the average inflow within this range.

Field observations and laboratory measurements from the pit's primary tributary were used to specify the water quality in the pit lake's influent. Detailed temperature measurements were available from an-

A slightly elevated concentration of 350 mg/L was used in a second calibration simulation, which better reproduced the average TDS concentrations observed in the pit's mixed layer.

A weather station associated with this study collected detailed meteorological observations including air temperature, dew point, wind speed and wind direction at 30-minute intervals. These observations were used directly in the model to simulate meteorological conditions at the site. Values between 0.7 and 0.9 are commonly used for the Ce-Qual-W2 wind-sheltering coefficient (WSC) when lakes are located in mountainous terrain (Ce-Qual-W2 v3.0, User Manual). The model results for the pit lake calibration runs were insensitive to variations in the WSC in this range.

2.2 *Calibration Results*

Ce-Qual-W2 predicted temperatures for the pit lake that were in close agreement with the temperatures measured in the field. Ce-Qual-W2 temperatures from the central and deepest segment of the pit are shown in Figure 3 with measurements from the central and deepest sampling station of the pit. The largest variation between modeled and measured values occurred in the spring (March through May). Measured temperatures for these months are homogenous through the pit's surface layer. Ce-Qual-W2 temperature profiles show the formation of a secondary thermocline at 3 meters depth during the spring. Secondary thermoclines are typically observed in natural lakes during the spring and summer as seasonal temperatures warm. Such discontinuity layers typically form from periods of minimal mixing due to calm, hot weather and last for only a few days or weeks until stronger mixing resumes (Wetzel, 1983). The presence of these predicted discontinuity layers in the model results suggests that the Ce-Qual-W2 model of the pit is underestimating the extent of vertical mixing over relatively small time scales in the top 5 meters of the pit. The underestimation may result in part from the use of 30-minute wind speeds that average and thereby minimize gusting. Since average values were used for inflow and outflow, mixing from increased inflow due to rain events was largely underestimated as well. For example, the average measured inflow for March, April and May of 2002 was 0.69 m^3/s (~11,000 gpm), 0.65 m^3/s (~10,400 gpm), and 0.95 m^3/s (~15,000 gpm). The corresponding daily flow records show five peak flows from storm events where flow was greater than 1.26 m^3/s (20,000 gpm) for a total of 12 days and greater than 1.89 m^3/s (30,000 gpm) for a total of 6 days. These higher flow values would cause more mechanical mixing in the shallow portions of the pit lake than those predicted by the model using average flows.

The Ce-Qual-W2 calibration runs predicted concentrations of TDS in agreement with field observations from August 2001 through July 2002. Initially, the concentration of TDS in the main inflow was 220 mg/L. The resulting TDS concentrations in the pit's shallow depths were slightly lower when compared to the average measured value (Fig. 4). Therefore, as previously discussed, the model was run with a slightly elevated influent concentration of 350 mg/L. The new results better reproduced field observations for the entire depth of the pit. Over the course of all of the one-year calibration simulations, the Ce-Qual-W2 TDS values showed progressively weaker gradients between 7 and 11 meters. However, throughout the monitoring period, the measured TDS and conductivity profiles of the pit maintained sharp gradients between 6.5 and 7.5 meters depth (Figs 1, 4).

The Ce-Qual-W2 calibration density profiles are displayed in Figure 5. For comparison, several density measurements were taken onsite with hydrometers in late September. Water density at the pit's surface was measured 0.999 g/ml at 18°C. The density of deep-water samples was 1.0035 g/ml at 11°C. These measurements compare well to Ce-Qual-W2 profiles from early October (17°C surface waters). The simulated surface densities were 0.999 g/ml at 17°C and 1.0032 g/ml at depth (11°C).

As vertical density gradients increase in the water column, increased energy is required to break gradients down and mix the water column (Wetzel 1983). The large chemically induced density gradient at 7 to 8 meters depth in this pit lake persists throughout the yearlong model simulation. This suggests that

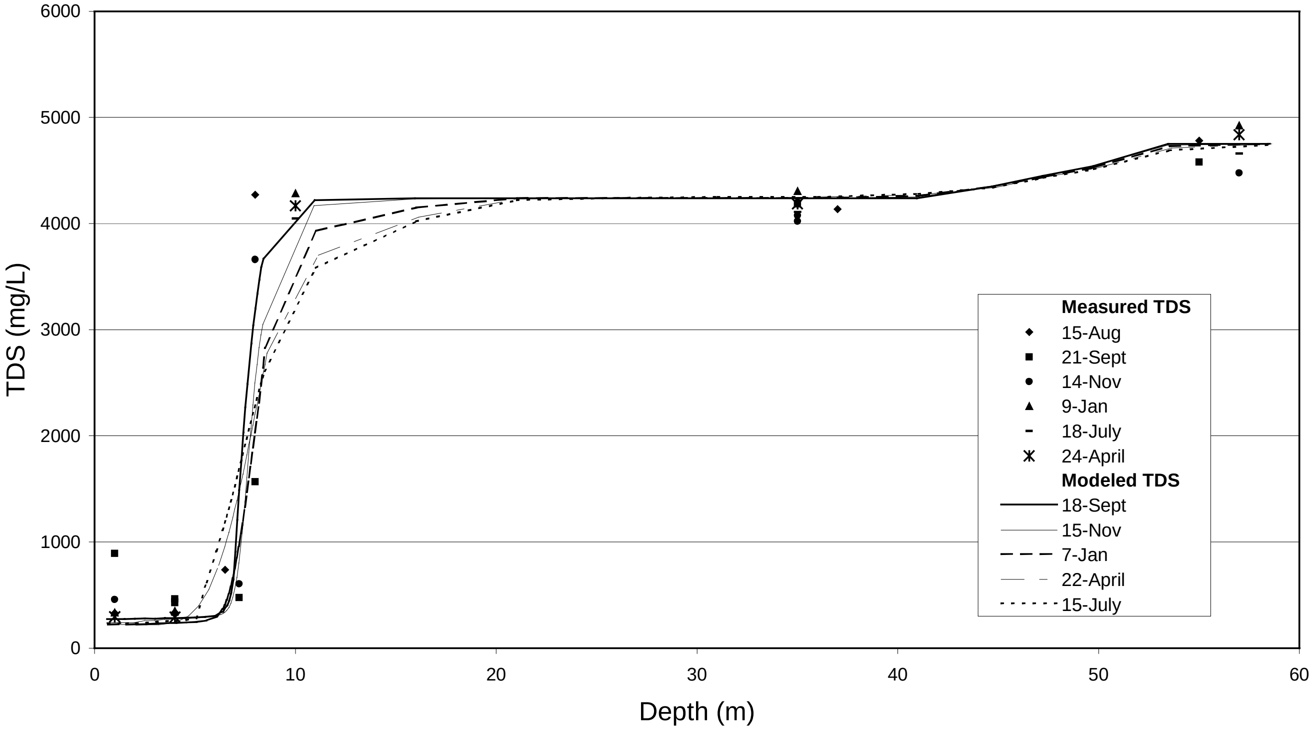


Figure 4. Measured & Modeled TDS profiles

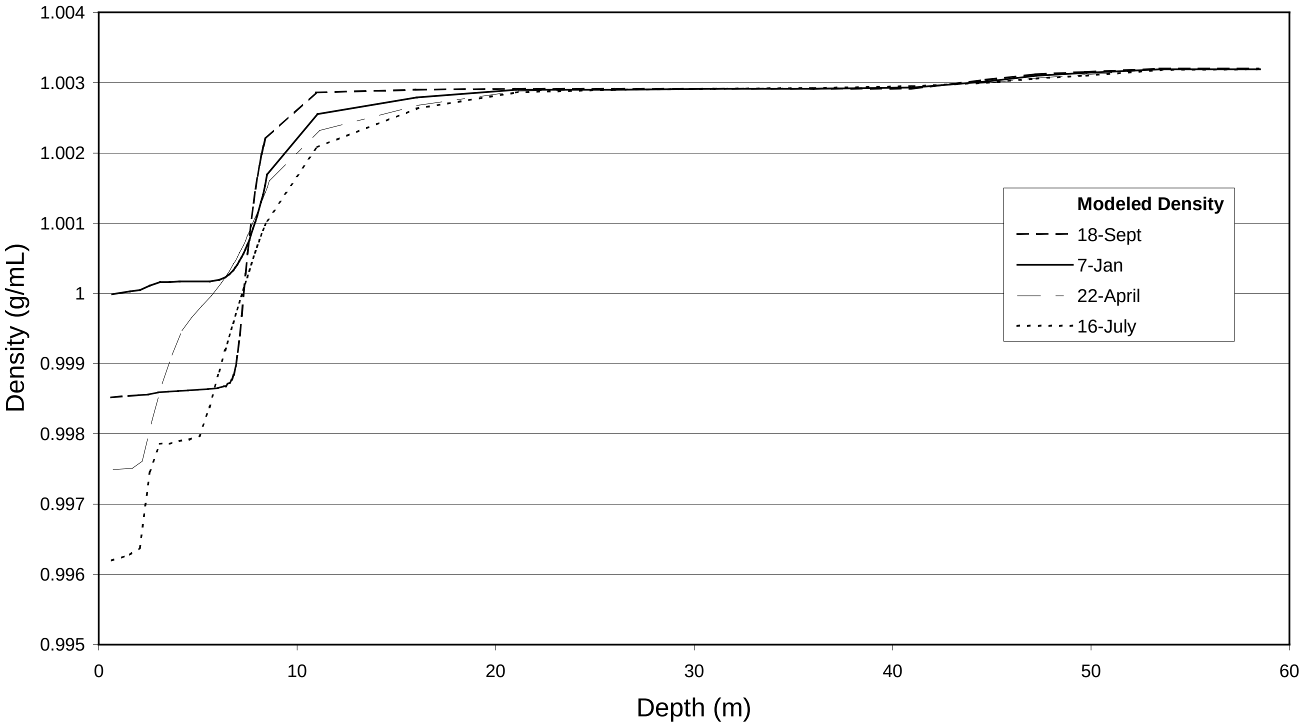


Figure 5. Modeled water density profiles

the pit's shallow water mass and the deep water mass are resistant to mixing and that the chemocline is very stable. The Brunt-Väisälä Frequency (N) or buoyancy frequency is calculated from water density using Equation 1 below and represents the resistance of the water column to vertical mixing and hence provides an indicator of the stability of stratification in the pit lake (Goldman & Horn 1983):

$$N^2\ (s^{-2}) = -\ (g / \rho_o) * (d\rho / dz) \qquad (1)$$

Where ρ_o = the average water density for the depth interval, z = depth (m), g = acceleration of gravity (9.8 m/s^2), and ($d\rho/dz$) = density difference (kg/m^3) over depth z (m) where z is defined as positive downward. Large buoyancy frequencies indicate the depths with the highest stability in a lake's water column that are the most resistant to vertical mixing. Wind (or other forces) must have sufficient energy to overcome the density gradients in these areas and destabilize the water column. When this occurs water from above the gradients will mix with water from below the gradients.

The buoyancy frequency was calculated for the pit lake between adjacent model layers using Ce-Qual-W2 density output. As shown in Figure 6, the water column has a prominent peak in the buoyancy frequency at approximately 7 meters depth coincident with the chemocline. This peak is visible throughout the year including the coldest months when the pit has a small or inverted temperature gradient and is most susceptible to vertical mixing. The magnitude of this peak relative to lesser peaks in the profile suggests that considerable energy would be required to mix waters above and below the chemocline.

Since water density is primarily controlled by temperature and TDS in terrestrial water bodies, the discrepancy between modeled TDS and measured TDS gradients from 7 to 10 meters (Figs 1, 4) suggests that this Ce-Qual-W2 calibration model is underestimating the density gradient between the shallow and deep water-masses in the pit lake. Since the magnitude of the buoyancy frequency peaks and the stability of stratification increase with sharper density gradients, Ce-Qual-W2 is likely underestimating the density gradients and hence the stability of the pit's stratification.

A secondary peak located in the mixed layer appears in the buoyancy frequency curves during the spring and summer. The presence of shallow secondary peaks above the primary chemocline indicates discontinuity layers forming with shallow secondary thermoclines that were previously discussed. Below 7 meters, the buoyancy frequency in the pit decreases and remains low without sharp fluctuations indicating that density contrasts are not sufficient to prevent mixing below the chemocline within the deep water mass. Vertical and horizontal velocity patterns indicate the major flow patterns in a water body. In a temperate zone, a simplified stratified lake typically has two major flow cells. Wind drives currents in the upper cell (surface layer or mixed layer) with the surface flow aligned with the wind and a return flow occurring at the bottom of the upper cell. The flow at the bottom of the upper cell then drives circulation in the opposite direction in the lower cell (the hypolimnion).

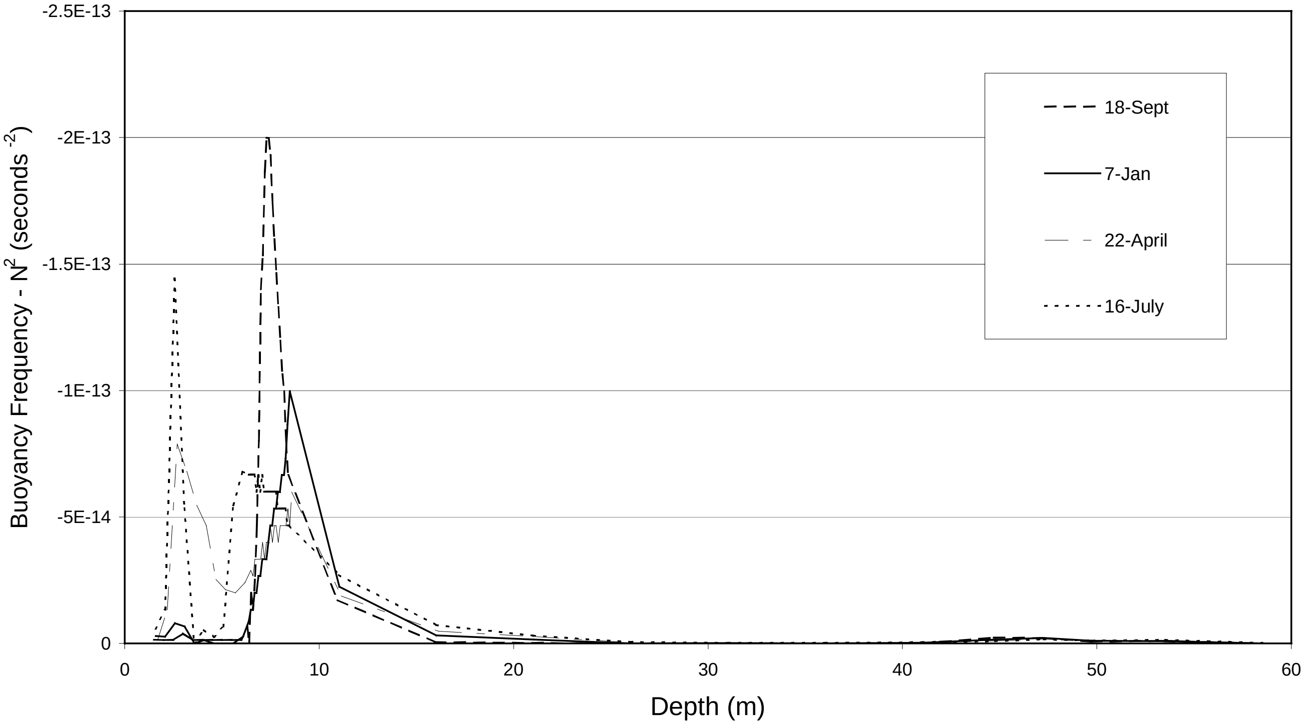


Figure 6. Buoyancy Frequencies from modeled densities

The velocity data for the pit are typical for a highly stratified system where the water below the chemocline does not mix with the surface layer and kinetic energy in the surface water is not transmitted to the deeper waters. Horizontal velocities (along the lake centerline) in the mixed layer of the pit are several orders of magnitude higher than vertical velocities ranging from 2.5×10^{-3} to 5.5×10^{-3} m/s; vertical velocity values range from -7.5×10^{-5} to 1.5×10^{-5} m/s (positive vertical velocities represent downward moving water) (Figs 7-8). Velocity values in these ranges suggest that the horizontal velocities in the mixed layer are driven by wind stress and river advection. The lower vertical velocities are the result of eddy diffusion of momentum or slow convective stirring. The velocities below the chemocline of the pit are much lower than those in the mixed zone indicating that little kinetic energy is transferred below

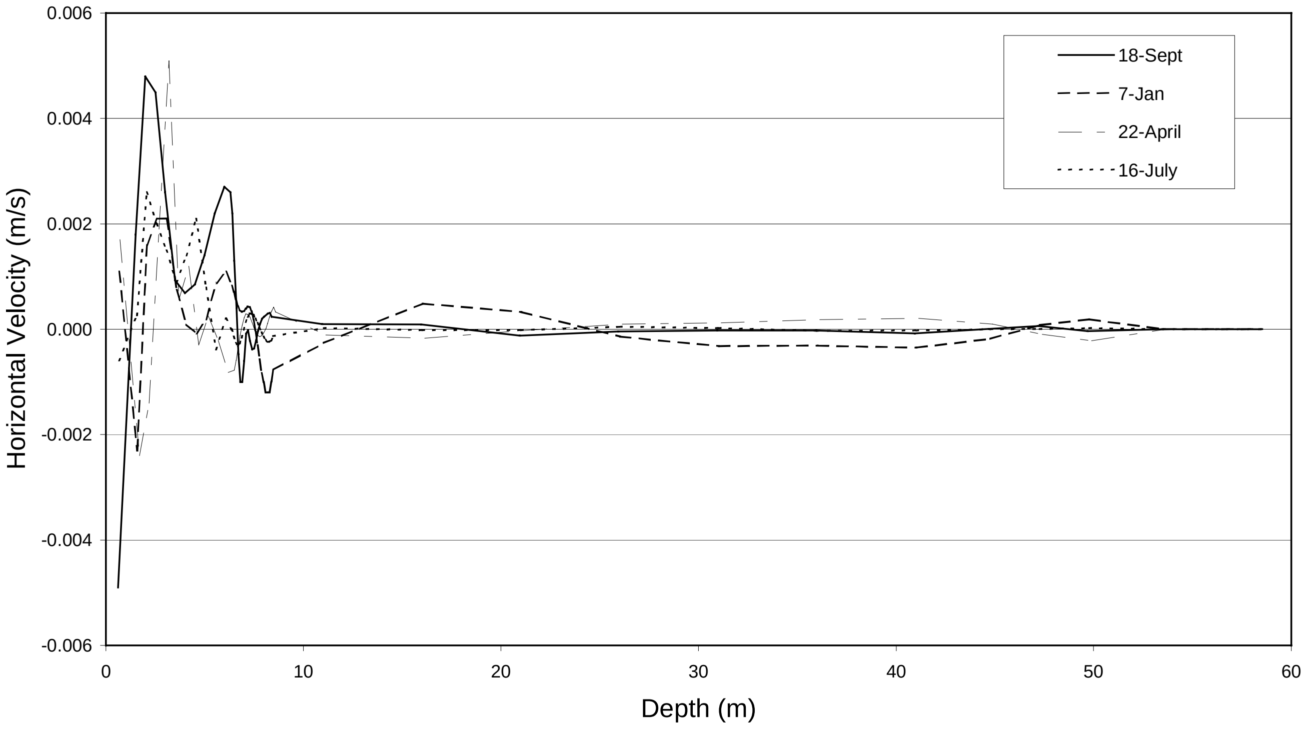


Figure 7. Modeled horizontal water velocities

the chemocline. In the deep-water mass, horizontal and vertical velocities are on the scale of ±10^{-5} m/s and ±10^{-6} m/s respectively (Figs 7-8).

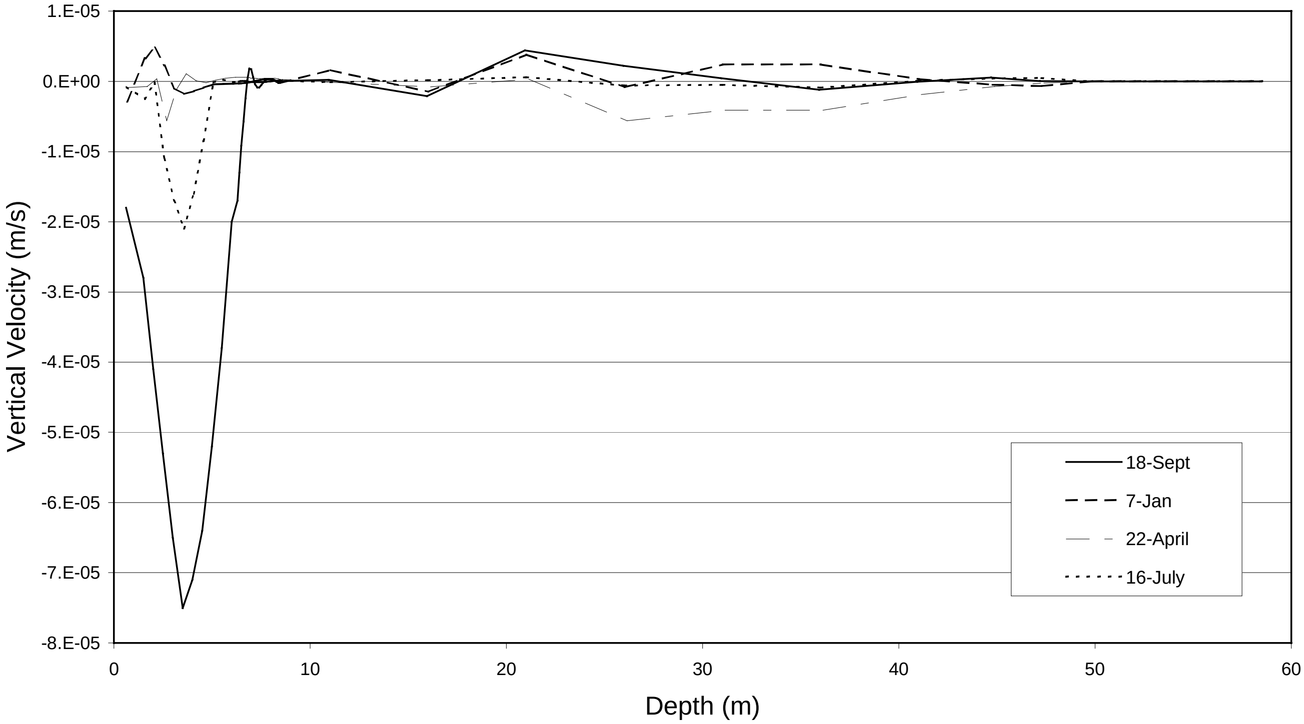


Figure 8. Modeled vertical water velocities.

These low velocities indicate that mixing of constituents below the thermocline/chemocline is on the scale of molecular diffusion (10^{-5} cm^2/s).

The buoyancy frequencies, densities and velocities from the Ce-Qual-W2 calibration models of the pit suggest that the currently observed stratification is very stable under present conditions. While many factors affect stability of a water body, the pronounced, chemically induced density gradient between the shallow and deep water-masses from 6.5 and 8.5 meters depth is the controlling factor for this pit lake.

3 SENSITIVITY SIMULATIONS

Once the calibration of the Ce-Qual-W2 model of the pit lake was completed, a series of sensitivity simulations were designed to evaluate the stability of the pit with changes in water quality of the inflow and high wind.

3.1 *High TDS in influent*

The buoyancy frequencies, densities and velocities from the Ce-Qual-W2 models of the pit suggest that the pit's stratification is very stable under present conditions. While many factors affect the stability of a water body, as discussed above, the pronounced chemical gradient between the shallow and deep waters appears to be the controlling factor for this pit lake. Both temperature and water quality (TDS) affect the density of the pit water. Inverted density gradients are observed in many natural lakes when air and surface water temperatures are coolest. The shallow dense waters begin to sink and convectively mix with deeper water. With sufficient wind energy, mixing can increase in scale to the complete circulation of the water column (turn over) (Wetzel 1983). However, in this pit lake, the concentration of TDS in the deep water mass is elevated such that the density gradient of the water column does not invert with the temperature gradient. Inverse temperature gradients occur in the winter months in both measured and predicted temperature profiles at the depth of the primary chemocline (~7 m) where cooler water resides over warmer water (Fig 3). Since the pit does not turnover in the winter months, the chemical gradients must maintain the density gradient and prohibit complete mixing of the water column.

To further characterize the stability of the pit lake's stratification, the pit was simulated with varying concentrations of TDS in the influent/shallow layer to determine how large a density gradient is needed to keep the pit stratified given its bathymetry, average flows and meteorology.

The TDS in the pit's inflow was increased in a series of sensitivity tests to the intermediate concentrations of 1000 mg/L and 2000 mg/L respectively. Other parameters and inputs into these simulations were identical to those in the calibration simulation discussed earlier (in this section). Increasing the TDS in the pit lake's inflow reduced the density gradient of the primary chemocline. When the concentration of TDS in the inflow increases, the model results show that the TDS of the pit's surface layer quickly increases and then stabilizes (and presumably reaches a steady-state condition) near the inflow concentration.

The pit lake remained stratified throughout these intermediate TDS simulations. For example when the incoming TDS concentrations are elevated to levels of 2000 mg/L, the TDS in the surface layer increases rapidly and then stabilizes near 2000 mg/L by the second simulation month. The TDS in the deep layer does not change over time and continues to match field observations. As expected, the resulting density gradient between shallow and deep water is less pronounced than in previous simulations, however, temperature and TDS profiles remain stratified throughout the simulation. A peak in the buoyancy frequency at the depth of the thermocline/chemocline indicates that the pit remains stably stratified, even in the coldest months. The magnitude of the peak increases in the winter but remains as high as 1.8 $x10^{-7}$ s^{-2} indicating that density gradients in the pit are still large enough to prevent mixing between the shallow and deep water-masses. With 2000 mg/L TDS in the inflow, the vertical velocities in the pit's mixed layer are higher over the first 2 simulation months than those predicted by the calibration run. However, the velocities still form the pattern expected for a stratified system. The contrast between horizontal and vertical velocities also is large; horizontal velocity values peak at ±8 $x10^{-3}$m/s and vertical values at -1.1 $x10^{-4}$ m/s. Similarly, the difference between shallow and deep vertical velocities is large. Vertical velocities in the deep water-mass peak at 1.6 $x10^{-5}$ m/s.

The pit lake's water column was also modeled with unrealistically high TDS concentrations in the mixed layer. One model ran the pit lake simulation with sustained, high TDS in the inflow. In this case, TDS was elevated to the average value for the deep pit (4325 mg/L). Results suggest that the pit's shallow and deep water-masses would potentially mix to at least 55 meters. In this simulation, the surface waters of the pit are approximately the same temperatures as the deep waters by the end of October. In mid-December, the temperature profile of the pit is isothermal and half a degree cooler. The pit's temperature remains constant with depth but continues to cool until January to low near 6°C. By mid-February the pit begins to thermally stratify and a new thermocline develops by the end of the run in April at approximately 7 meters depth. The concentration of TDS in the pit's shallow waters is equal to that in the deep pit by the end of the first simulation day. Due to the temperature gradient observed until the end of October, the density of the pit varies with depth until mid-November. Ce-Qual-W2 velocity profiles provide evidence of circulation to at least 55 meters in December and January. Relative vertical velocities through the pit increase by mid-December and reach a maximum of 7.5 $x10^{-4}$ m/s between 10 and 20 meters depth in early January. Horizontal velocities peak deep in the pit at 3.1 $x10^{-2}$ m/s suggesting the circulation of surface waters to depths. At this time, the calculated buoyancy frequencies are at or near zero over the depth of the pit. The pit seems relatively stable under current meteorological conditions at extreme concentration of 3000 mg/L TDS in the inflow, however, a slight increase to 3500 mg/L causes a simulated winter turnover event.

3.2 *High Wind Simulations*

In many seasonally mixed lakes, the wind provides sufficient energy to overcome density gradients and cause large-scale mixing. While it does not appear that normal winds in this basin are sufficient to cause the pit lake to turn over, a series of simulations were designed to test the stability of pit's stratification under storm conditions.

Nation Climatic Data Center (NCDC) records indicate that thunderstorms are a common occurrence in southern Appalachian Mountains. Between 1950 and 2002, fifty-four "damaging" storms were reported in this area of eastern Tennessee. In a year-long monitoring effort, the University of Tennessee (UT) Civil Engineering Department recorded forty-four-mph maximum wind gusts in this drainage basin, but these high wind speeds were not sustained (University of Tennessee 2000). Since neither historical wind speed measurements nor the wind speeds associated with the reported storms were available for the basin from NCDC, storms were simulated as worst-case scenarios that exceeded the winds measured in the UT study.

Storms were simulated during the winter when the density gradient in the pit was at its minimum. The pit's surface waters cool with lowering air and inflow temperatures, and therefore reach maximum density between December and April (assuming stable concentrations of TDS). Pits and lakes are most susceptible to turnover when vertical density gradients are smallest because less energy (from wind) is required to circulate the water column.

A 5-year simulation was conducted for the pit with a 24-hour 45-mph sustained windstorm in the final January of the simulation. The "storm day" was the very cold day in January when the pit lake's water column had turned over in the highest TDS sensitivity simulation. The flow of the tributary was simultaneously increased reach to storm water levels during the storm. The pit lake did not circulate in the 5-year simulation under constant 45-mph winds.

Less realistic 24-hour high-wind simulations were also conducted on one-year simulations in order to define the upper limit of the pit's resistance to mechanical mixing. Results from more extreme simulations are discussed below.

Figure 10. Vertical velocities; 60-mph winds on January 5

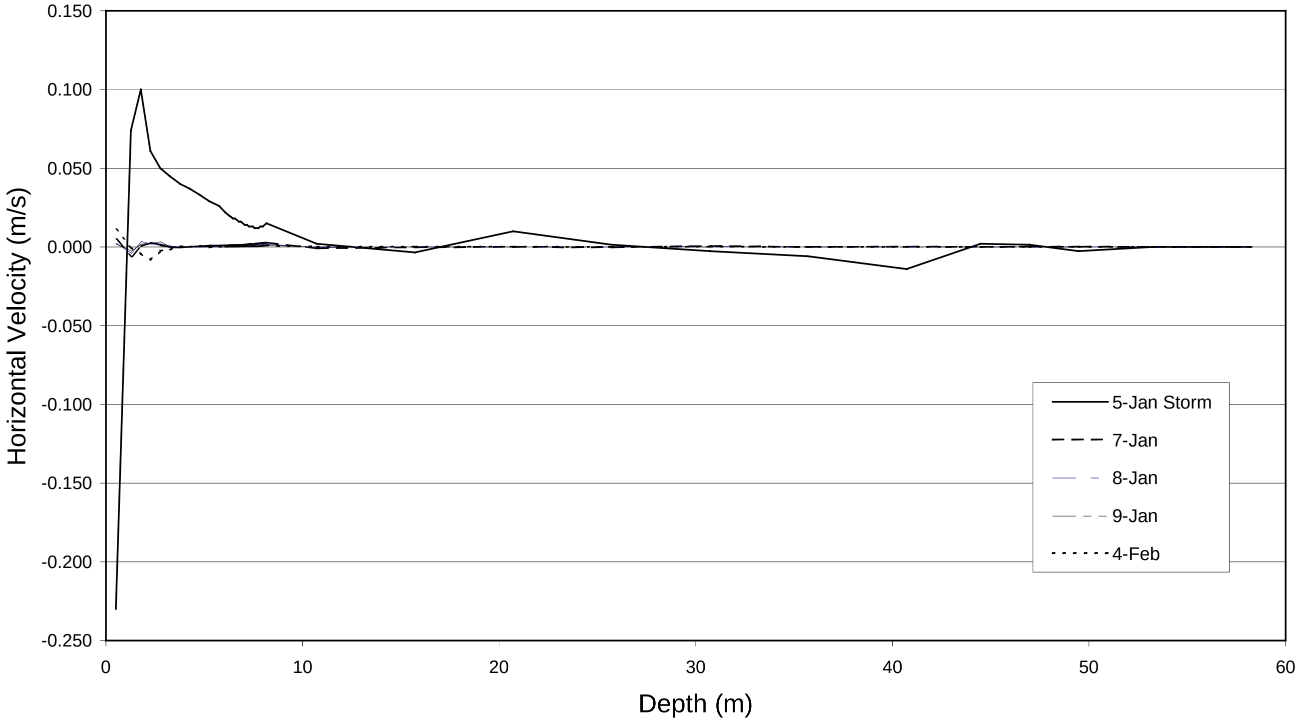
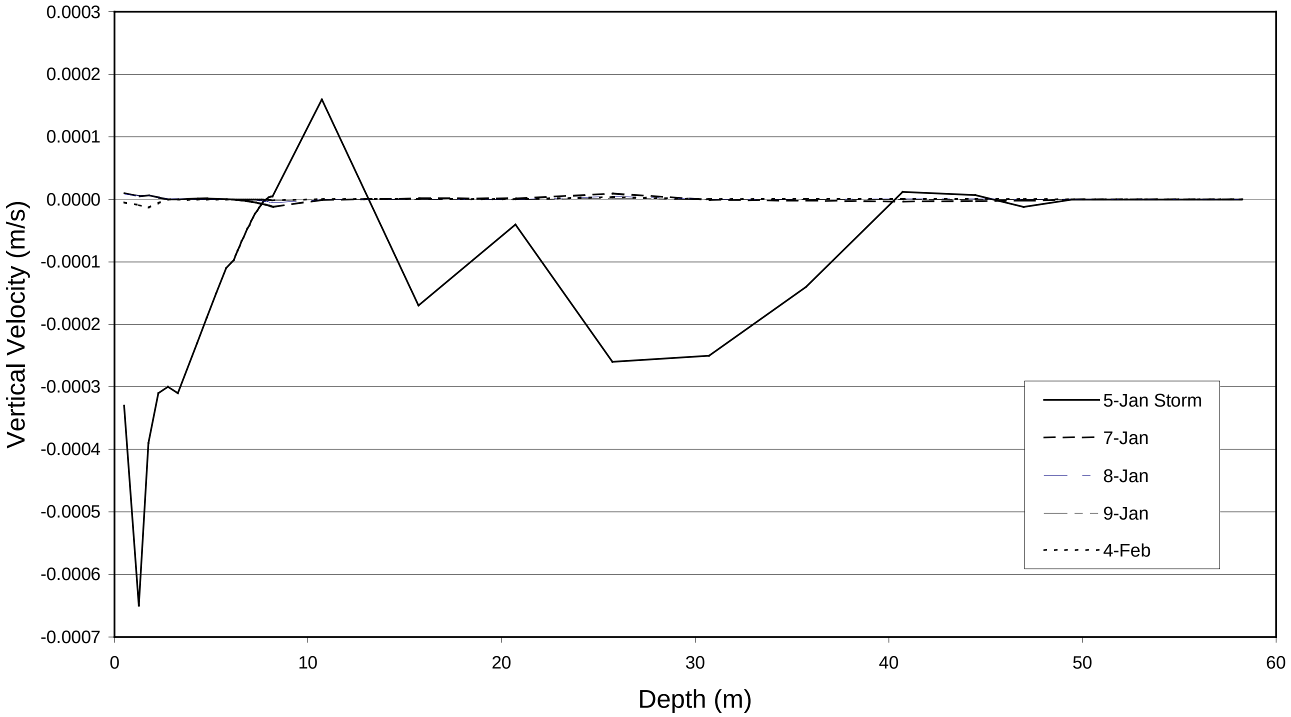


Figure 9. Horizontal Velocities; 60-mph winds on January 5

The worst-case storm scenario from this suite of sensitivity tests was a one-year simulation with 60-mph winds. As expected, the surface layer velocities in the pit lake increase on the day of the storm with the intense winds and heightened flows. The faster velocities suggest that mixing in the pit intensifies with the heightened wind, however, the velocity patterns suggest that the pit still has two major stratified flow cells with a smaller degree of mixing below the thermocline/chemocline (Figs 9-10).

Horizontal water velocities in the surface layer reach 1x10^{-1} m/s near the surface of the pit. The velocities decrease with depth in the first 7 meters and generally remain below 1.5x10^{-3} m/s (Maximum = 1x10^{-2} m/s) below the thermocline. Vertical velocities suggest that the shallow layer of the pit mixes vertically to about 8 meters. Vertical water velocities peak at 6.5x10^{-4} m/s near the surface of the pit lake and decrease with depth to 5x10^{-5} m/s at approximately 8 meters depth. Below the chemocline,



predicted vertical velocities increase to a maximum of 2.6×10^{-4} at 25 meters depth indicating transfer of momentum through the 8 meter deep chemocline. This velocity pattern between 9 and 20 meters implies that movement of surface water caused by the simulated storm event entrained water from the chemically stratified layer to a depth of about 20 meters. After the winds subside, the velocity profiles show this circulation pattern decrease in magnitude and within a few days, the velocity profiles are similar to those in the calibration simulation.

During the 60-mph windstorm and throughout the simulation, the pit's water column remained density-stratified. Large-scale circulation (e.g. destabilization and/or turnover) between the shallow and deep water-masses would have resulted in a constant density profile during or immediately following the storm.

Final sensitivity simulations were conducted with both high winds and high TDS in the pit's inflow. For example, if the pit is simulated with 2000 mg/L TDS in the inflow and shallow water, the pit did not turn over despite a 24-hour windstorm. These storm simulations with sustained high-winds at lessened density gradients suggest that pit lake's stratification is very stable under current conditions.

4 SUMMARY AND CONCLUSIONS

The Ce-Qual-W2 calibration model of this pit lake predicts temperatures, TDS and densities in good agreement with field observations. Results from Ce-Qual-W2 simulations suggest that the pronounced vertical density gradient between the pit's shallow and deep water-masses is the most important factor maintaining the stability of the pit lake's stratification. Over time, Ce-Qual-W2 is underestimating the sharp contrast of the TDS gradient and presumably the density gradient at 6.5 and 8.5 meters depth compared to that measured in the field. Since the stability of stratification increases with sharper density gradients, Ce-Qual-W2 is likely underestimating the density gradients and hence the stability of the pit lake's stratification.

When modeled with sustained high-winds, the pit lake remains stratified. The currently observed density gradient is sufficient to prevent large-scale water column circulation with a modeled increase in mechanical mixing of the surface layer. TDS sensitivity simulations suggest that the pit's stratification would remain stable at least up to a five-fold increase in TDS (2000 mg/L). The system also remains stratified under the extreme conditions of a decrease in density gradient between the shallow and deep layer as well as during very high winds during simulated storms. The bathymetry, in concert with the present day chemical stratification, effectively stabilizes the system against destabilizing winds and inflows.

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