Reclamation of a Pit Lake at a Coal Mine in the Pacific Northwest

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Abstract TransAlta Centralia Mining, LLC (TCM) developed reclamation plans for the Central Packwood Pit at its Centralia Mine in Washington that included a pit lake. Models of pit lake hydrology and water quality were developed to guide the reclamation plans and to support the probable hydrologic consequences assessment. The modeling relied on the extensive water quantity and quality data collected at the site. The model predictions were then coupled with relevant water quality and limnological information from near neutral pit lakes and natural lake analogues in order to assess the likely biochemical and limnological conditions for the lake.

Keywords pit lake, mine reclamation, probable hydrologic consequences

Introduction

TCM is currently conducting reclamation at the Centralia Mine located about 6 mi (9.7 km) northeast of the town of Centralia, Washington. Plans for reclamation of the Central Packwood Pit were revised after mining was discontinued following a slope failure in the pit footwall. The revised plans addressed reclamation of approximately 460 ha of disturbed land, including designs for a pit lake of approximately 87.7 ha, referred to as the Central Packwood Lake.

This paper describes the development of the water balance and water quality models that were used to support the design of the pit lake and for the probable hydrologic consequences assessment (PHC) of the reclamation plan. The PHC assessment included the expected range in lake filling times, the expected fluctuations in lake levels and lake outflows, the expected water quality in lake outflows, and the expected water quality and limnological conditions within the lake. The lake water balance and the mass balance water quality model were supported by considerable site data. Results from geochemical modeling and from natural lakes and pit lake analogues were also used in the assessment.

Climate data, including precipitation, evaporation, temperature and wind speed, have been collected at the Centralia Mine since 1981. The site has a predominately marine climate, characterized by mild temperatures. A dry season extends from late spring to midsummer, with precipitation frequently limited to a few light showers. Winter storms are common with strong winds and heavy precipitation during the months from October through March. These storms are frequent and may continue for several days. TCM has also obtained periodic measurements of groundwater elevations and water quality sampling from a network of monitoring wells and has conducted aquifer tests at these wells. Water quality samples have also been collected from surface runoff from active mine areas and reclaimed areas. These data have been used to develop the pit lake water balance and water quality predictive models. Furthermore, TCM has obtained water balance measurements at Pit 7, a flooded mine pit, and water quality samples at selected depths from partially flooded mine pits. These data have been used to assess the reliability of the predictive models and assessments.

Water Balance Modeling

The water balance model is fundamental to the design of the pit lake and for predicting solute loads to the lake. A pit lake daily water balance simulation model was constructed using the pit lake bathymetry, groundwater inflows (GWin) using simplified groundwater flow equations, and estimates of daily surface water inflows (SWin), direct precipitation on the surface of lake (P), the evaporation from the surface of the lake (E), and surface water outflows (SWout). The daily change in pit lake water volume ΔS was simulated using the general water balance equation:

$$\Delta S = P + SW_{in} + GW_{in} - E + - SW_{out}$$

P and E in the water balance are determined from the daily precipitation and evaporation records from the eleven year record and the lake surface area corresponding with the water elevation in the lake in the water balance simulation. The daily change in the pit lake water elevation in the water balance simulation is calculated from the daily change in water volume (ΔS) divided by the lake surface area at the simulated water elevation in the lake. The surface water outflow (SW_{out}) is the lake outflow calculated using the outlet rating curve and the water elevation in the lake. Models for simulating surface water inflows (SW_{in}) and groundwater inflows (GW_{in}) are required to complete the lake water balance simulation. The lake water balance analysis was simulated on a daily basis to provide information on the expected fluctuations in lake levels and lake outflows.

The groundwater inflow to the pit has been negligible during mining and pumping was required only for pit inflows from surface runoff during and immediately following precipitation events. The Dupuit-Forchheimer radial flow discharge formula (Bear 1979) was used to estimate groundwater inflow from the mine spoils along the east of the lake and from the undifferentiated bedrock and coals around the south and west sides of the lake. The one dimensional form of the steady-state analytical equation was used to estimate groundwater inflow from the alluvium and underlying bedrock on the north side of the lake. The hydrogeological characteristics and the boundary conditions for the analytical models were derived from site monitoring wells, well tests and site groundwater investigations provided in the mine permit application. The approach modeled groundwater inflow as a series of steady state solutions. The empirical data and modeling results indicate that the overall rate of groundwater flow toward the pit is quite low relative to inflows from precipitation and surface water due to the low permeability and steeply dipping geologic strata.

Several rainfall-runoff models were evaluated in a water balance analysis of the flooded Pit 7 performed using records on daily rainfall and evaporation, pit pumping and periodic pit water level measurements. A seasonal curve number model using a curve number of 89 for the period from April 1 through October 31 and a curve number of 98 for the period from November 1 through March 31 was found to provide the best results for the Pit 7 water balance. These seasonal curve number estimates bracket the curve number estimate obtained from the empirical tables for bare soil at the site (Natural Resource Conservation Service 2004). These "calibrated" seasonal curve numbers were used to model the rainfall-runoff relationship during reclamation when the lake is filling.

The seasonal runoff curve numbers were adjusted to model the rainfall-runoff relationship for the lake water balance after final reclamation when the lake is full. The rainfall runoff response during the period from April 1 through October 31 is expected to decline considerably following reclamation because of the higher infiltration rates and higher evapotranspiration loss from the forest cover during this period. A seasonal curve number of 70 is specified in the Mine Permit Application for forest cover conditions at the site and was selected to represent the seasonal curve number for the low antecedent moisture conditions during the dry period from April 1 through Oct 31. A seasonal curve number of 96 was used to model the surface runoff and delayed interflow response to rainfall for the high antecedent moisture conditions during the wet period from November 1 through March 31. The reduction in the winter season curve number from 98 to 96 was selected based on the relatively low water loss during the winter by interception and evapotranspiration of the forest cover following reclamation.

While these seasonal curve number adjustments were initially based on professional judgment, the reliability of the estimates were evaluated by comparing the surface runoff volume estimated by applying the seasonal curve number model to a nearby 538 ha watershed with forest cover comparable to the reclamation cover planned for the Central Packwood Lake drainage. The surface runoff from this drainage was collected in a pond where it was pumped around mining operations. The pumped volume measured over a 19 month period was within 5 % of the net runoff volume estimated for this drainage using the seasonal curve number model and the daily precipitation and evaporation records.

Surface water runoff from the surrounding watershed provides about 65 % of the lake inflow when the lake is full. The remaining inflow is mostly from direct precipitation on the lake surface while groundwater inflows average only about 1.2 % of the total lake inflow. The simulation results show that the lake water elevations are below the outlet control elevation during the months of July through October, although the duration of the period of no outflow from the lake varies with the seasonal patterns of precipitation and evaporation. The annual lake outflows averaged 2.27 Mm^3 based on the 11-year simulation period. With a total lake capacity of 16.529 Mm^3, the mean residence time for water in the lake is estimated to be approximately 7.3 years.

Water Quality Modeling and Assessment

The evolution of water quality in the Central Packwood Lake will be controlled largely by the quality of water entering the lake during and after reclamation. Pit wall mineralogy is also cited as a control of pit lake water quality (Boehrer and Schultze 2006). However, the spoil material and the bulk of the overburden at the pit is not acid forming and the exposed coal seams and any acid forming overburden material will be covered with neutralizing spoil material. Thus, pit wall mineralogy is not expected to adversely impact lake water quality or pH levels.

The water balance modeling and representative concentrations for the various water sources were used to construct a mass balance model to simulate the evolution of water quality in the lake during lake filling and after reclamation. The water quality of the surface water draining the east spoil pile was used to represent the surface water quality entering the lake during reclamation operations. The water quality of surface water entering the lake following reclamation was based on the average concentrations in samples collected in runoff from reclaimed areas at the Centralia Mine. The median concentrations in samples from groundwater wells were used to represent the water quality in lake inflows from each of the groundwater sources around the lake.

The water quality modeling results for the lake during filling and after the lake is full are summarized in Table 1. These results show that sulphate and sodium are the dominant ions in lake water. The TDS and most of the major ions and trace constituents are predicted to decline over time due to the reductions in the concentrations in surface water inflows and the larger contribution of essentially pure water from precipitation when the lake is full. Nitrate concentrations are predicted to increase due to the site data indicating higher nitrate in surface water from areas following reclamation.

The pH of water entering the lake is projected to be near neutral based on samples of surface runoff from active mine areas and reclaimed areas. Although a mass balance of hydrogen ions could be used to model pH in the lake, pH was not modeled because it will be affected by biogeochemical processes within the

Constituent	Units	Lake Filling	Final
Total Alkalinity	mg/L ($CaCO_3$)	107	55
Calcium	mg/L	81.6	62.5
Chloride	mg/L	4.0	4.0
Iron	mg/L	1.378	0.380
Magnesium	mg/L	25.0	20.5
Manganese	mg/L	1.923	0.921
Nitrate/Nitrite	mg/L	0.195	0.423
Potassium	mg/L	4.9	3.2
Selenium	mg/L	0.0001	0.0004
Sodium	mg/L	197	75
Sulphate	mg/L	595	317
Total Dissolved Solids	mg/L	1033	579
Total Phosphorus	mg/L	0.713	0.175

Table 1 *Water Quality Modeling Results.*

lake and will vary with depth when the lake stratifies. The mass balance modeling approach treats all lake water quality parameters as conservative constituents. Concentrations of water quality constituents in the lake will deviate from the model predictions, depending upon the actual mass loading rates for various water sources and the influence of physical and biogeochemical processes within the lake. Iron and manganese can precipitate in the oxygenated waters of near neutral pit lakes and be removed by settling. Furthermore, a constructed wetland at the inlet to the lake is expected to result in reduced the iron and manganese loadings to the lake. Likewise, the chemical characteristics of the water entering the lake together with the climate of the site and the physical characteristics of the lake will influence biological processes, lake temperature, pH and chemical stratification. These processes will result in lake water chemistry that deviates to some degree from the mass balance modeling results. Nevertheless, the mass balance modeling results are still useful for geochemical modeling, for predicting trophic condition, and for assessment of likely biogeochemical processes within the lake and lake sediments.

The mass balance modeling indicates that total phosphorus loadings should stabilize at a level of approximately 0.0181 g/m^2 of lake surface per year. The phosphorus loading versus mean depth divided by residence time relationship in Vollenweider and Dillon (1974) indicates that lake will be oligotrophic. The trophic level and photosynthesis will have a significant influence on lake water quality. Calcium precipitation can be triggered by high pH levels corresponding with high rates of photosynthesis (Flite 2006). Biomass and calcium, iron, and manganese precipitates settle to the lake bottom along with the nutrients and the metals that adsorb to the settled organic and inorganic material. Likewise, sulphate reduction under anoxic conditions in deep water and lake sediment can remove sulfate. However, sulphate reduction is generally not significant under oligotrophic conditions, where the supply of organic matter limits the rate of sulphate reduction in the anoxic portions of lake sediments (Holmer and Storkholm 2001). These constituents may be sequestered in the lake sediments or some or all may be recycled depending upon geochemical conditions in the lake sediments. The fate of these constituents and the dissolved oxygen conditions will depend on the biological productivity of the lake and whether seasonal or sustained stratification develops within the lake.

Lake Stratification, Water Chemistry and Dissolved Oxygen

Most natural lakes in temperate zones exhibit thermal stratification during the summer but mix in the fall as the water near the surface cools and mixes with the deeper water in the lake. The lowland lakes in western Washington will mix throughout the winter and are referred to as monomictic (Bortleson *et al.* 1974). Many pit lakes and a few natural lakes do not mix throughout the water column but remain stratified over sustained periods and are referred to as meromictic (Boehrer and Schultze 2006). Dissolved solids become concentrated in the deep water in a meromictic pit lake resulting in a water density difference between the shallow and deep water that is sufficient to withstand the destabilizing forces of wind. Reduced metals, hydrogen sulfide, carbon dioxide and anoxic conditions are usually found within the deep water in a meromictic pit lake (Boehrer and Schultz 2006). While the density stratification in meromictic lakes isolates the metals and hydrogen sulfide in the deep water from mixing with the rest of the lake, there is a risk that an event such as a slope failure or extreme wind storm that could release metals, nutrients and hydrogen sulphide to the water in the upper portion of the lake. The Central Packwood Lake is not expected to become meromictic based on the physical characteristics of the lake, the expected chemical and biological conditions in the lake and a comparison with natural and pit lake analogues.

Meromictic lakes are usually deep compared to their surface area. This morphometric feature is quantified by Walker and Likens (1975) by the relative depth ratio (Zr) defined as the ratio of a lake's maximum depth to its mean diameter expressed as a percent. The relative depth ratio for the Central Packwood Lake is 3.4 %. This ratio is low compared to the pit lakes surveyed by Doyle and Runnells (1997), which typically have a Zr of 10 % or more.

Roesiger Lake (North Arm), an oligotrophic lake in western Washington, provides a good natural analogue for the Central Packwood Lake as the surface area, capacity, average depth, maximum depth and relative depth ratio are nearly the same. Based on this natural analogue, the Central Packwood Lake should be seasonally stratified and mix throughout the water column during the winter. However, the water in Roesiger Lake (North Arm) has very low concentrations of dissolved solids in comparison with the estimates for Central Packwood Lake. Thus, the comparison with this natural analogue is not alone sufficient to conclude that the lake will not become meromictic.

Inflow of iron rich or saline groundwater was the cause for meromixis in many pit lakes (Boehrer and Schultze 2006). In addition, calcite precipitation, iron cycle, and manganese cycle may add solute density to the lower water sufficient to establish meromixis (Boehrer and Schultze 2008). Analogues of near neutral pit lakes and geochemical modeling were used to assess whether meromictic conditions might develop in the Central Packwood Lake.

Flite (2006) studied the South Pit Lake, a near neutral meromictic pit lake in South Carolina with a relative depth ratio of 9.18 %. A phytoplankton bloom resulting from high phosphorus loads increased pH levels, which led to calcite precipitation. Calcite dissolved in the lower portions of the lake water column when it encountered water with higher CO_2 and lower pH. This cycling of calcium along with intrusion of iron rich groundwater induced a strong enough density difference for the lake to become meromictic. Analysis of the predicted Central Packwood Lake water chemistry using PHREEQC (Parkhurst and Appelo 1999) shows the water to be undersaturated with respect to calcite at near neutral pH. Calcite saturated occurs when pH increases above 8. However, calcite precipitation in surface water and lakes requires high levels of supersaturation for nucleation to take place (Suarez 1983, Kosamu and Obst 2009). Given the expected lake water chemistry from mass balance simulations, the level of supersaturation required for calcite precipitation is unlikely to occur in the oligotrophic Central Packwood Lake.

Hatfield Consultants (2011) studied nine near neutral coal mine pit lakes in western Alberta. These pit lakes may be better analogues as all are classified as oligotrophic. The relative depth ratio appears to have some influence on meromixis in these pit lakes. The lakes that fully mixed during the spring and fall featured relative depth ratios ranging from 2.4 % to 5.4 % while the lakes with relative depth ratios ranging from 4.7 % to 9.4 % were meromictic. However, Hatfield Consultants (2011) identified the inflow of higher salinity groundwater as the most significant factor contributing to meromixis. They also found that the anoxic water in five of the six meromictic lakes was confined to the very deep portion of the lake well and had little impact on the relative amount of suitable habitat for aquatic life. Groundwater inflows are only 1.2 % of the total Central Packwood Lake inflow, which is unlikely to cause meromixis.

Finally, two flooded mine pits at the Centralia Mine are useful analogues for the Central Packwood Lake. Results of monitoring performed at various depths within the flooded pits are summarized in Table 2. These results indicate that the water in the flooded pits does not change much with depth and the entire water column remains oxygenated during sampling in the fall and winter. From these pit analogues we can expect that the Central Packwood Lake will mix throughout the water column during the fall and winter and that entire water column should remain oxygenated.

Conclusions

Based on the physical characteristics of the Central Packwood Lake, the modeling results and the comparison with natural and pit lake analogues, the Central Packwood Lake is expected to stratify during the summer but mix throughout the water column during the fall and winter similar to natural lakes in western Washington. Phosphorus loading results indicate that the Central Packwood Lake will be oligotrophic. The concentrations of major ions in the lake are expected to be similar to the concentrations in Table 1 as predicted by mass balance modeling. Calcium precipitation is not expected to have a significant influence on calcium concentrations within the lake water column. Iron and manganese and other metals are expected to be at lower concentrations than predicted by the modeling results in Table 1 due to the removal by a constructed wetland at the inlet to the lake and by settling of organic and inorganic sediments within the lake.

Pit	Date	Depth (m)	Temp (°C)	Specific Conductance (mS/cm)	pH	DO (mg/L)	note
3E	11-Nov-10	1.5	11.4	1800	6.87	na	
3E	11-Nov-10	3	11.4	1800	6.91	na	
3E	11-Nov-10	27.5	11.3	1800	7.35	na	
3E	11-Nov-10	32	11.3	1900	7.3	na	
3E	11-Nov-10	41	11.3	1900	7.53	na	bottom +1.5m
Pit 7	30-Nov-07	1.5	8	2000	7.5	13.8	
Pit 7	30-Nov-07	3	7.9	2000	7.59	13.8	
Pit 7	30-Nov-07	12.2	7.9	2000	7.75	12.8	
Pit 7	30-Nov-07	15.25	8.3	2000	7.76	13.0	bottom +1.5m
Pit 7	30-Nov-07	16.75	8	2000	6.76	0.7	at bottom
Pit 7	7-Feb-08	1.5	3.6	1800	7.89	12.9	
Pit 7	7-Feb-08	19.5	3.6	1900	7.96	12.1	bottom +1.5m
Pit 7	11-Mar-09	1.5	5.6	2000	8.32	14.4	
Pit 7	11-Mar-09	18.7	5.6	2100	7.75	7	bottom +1.5m

Table 2 *–Flooded Pit Water Sampling Results, Centralia Mine.*

The results of the study demonstrate the importance of collecting adequate site data to support the development of predictive models and to evaluate the reliability of the predictions. Predictive models alone cannot account for all of the geochemical and limnological processes that are important considerations for end pit lake design. Therefore, the model predictions should be coupled with relevant water quality and limnological information from pit lakes and natural lake analogues in order to assess the likely physical, chemical and limnological conditions for the pit lake.

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