# Optimization of Settling Pond Effluent Quality[1]

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## ABSTRACT

Settling ponds are used extensively for the treatment of neutral and acidic mine drainage as they are a relatively adaptable and low cost solution. However, the efficiency of settling ponds for the removal of suspended solids and precipitated metals may be compromised if the pond is not properly designed. The significance of this work is that a comprehensive three-dimensional computational fluid dynamic (CFD) model has been developed as a tool to investigate the major processes influencing pond performance: pond hydraulics, particle settling, and sludge resuspension. Model output has been validated using data from the Tailings Management Area (TMA) at Xstrata Copper's Kidd Metallurgical Site (Metsite) in Timmins, Ontario, Canada. Differences between the model predictions and field measurements that correlate with the total suspended solids (TSS) concentration were found to be less than 5% at conditions of high pond inflow. This work has found that small particles present in the pond inflow exert a dominant influence on the effluent TSS concentration, and coagulant addition was shown to be an effective means of controlling the outlet TSS concentration. The model has also been successfully utilized to assess proposed changes to the pond configuration; for example, addition of baffles was demonstrated to increase short-circuiting and inhibit particle settling. In the future, the model is to be employed to define a TMA management strategy that minimizes environmental risk and operating costs.

Additional Key Words: Computational fluid dynamics, Metals removal, Suspended solids, Lime treatment, Dredging, Sludge resuspension, Hydraulic residence time, Coagulation

## INTRODUCTION

The mining industry must manage and treat tailings wastewater such that environmental discharges meet water quality regulations. The use of lime addition followed by large, shallow settling ponds is frequently applied for tailings wastewater treatment to limit particulate and metals emissions to the environment. However, lime treatment tends to form a dispersed sludge with finely sized particles (i.e. median particle size $d_{50}<10\mu m$), so solids removal requires long settling times. The sludge that is produced is of low density and is easily liable to be resuspended under critical flow conditions (Mian and Yanful, 2003). Therefore, optimization of pond design and treatment to control TSS

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carryover at levels having negligible impact on the downstream ecosystem and receiving waters is a common goal for many mining facilities.

The design and operation of settling ponds should consider multiple factors including: pond geometry (i.e. inlet/outlet configuration, water depth, and length/width ratio), properties of solid particles, flow rate, and environmental conditions such as wind, spring runoff, and ice cover (Marsalek et al., 2000; Adu-Wusu et al., 2001; Mian and Yanful, 2004). However, quantitative evaluation of the effects of these factors on settling pond performance through a numerical modeling approach is limited. Most of the reported studies pertain to lab-scale experimental investigations focused on obtaining empirical equations to predict solids settling and resuspension behavior in tailings ponds (Mohamed et al., 1996; Mian and Yanful, 2004). While these empirical methods can provide general predictions of pond performance, they are not able to integrate all the key factors in one model. More importantly, these empirical models ignore the complex three-dimensional hydrodynamic characteristics (e.g. short-circuiting and dead zones) that can significantly affect settling efficiency.

These shortcomings can be overcome by the use of computational fluid dynamic (CFD). CFD is the science of predicting fluid flow, mass transfer, chemical reactions and related phenomena by solving the mathematic equations governing these processes using numerical algorithms (Versteeg & Malalasekera 2002). CFD has come into use recently for evaluating municipal wastewater solids settling and river/reservoir hydrodynamics (Lakehal et.al., 1999; Kleine and Reddy, 2005). However, the application of CFD for the evaluation of full-scale mine tailings pond design and performance has not been reported.

The primary objective of this research was to develop a comprehensive CFD model to fully describe the tailings pond settling processes. A secondary objective was to validate the modeling approach and apply it to improve the hydraulics and settling performance of a settling pond at Xstrata Copper's Kidd Metsite, located at Timmins, Ontario, Canada.

## DESCRIPTION OF STUDY SITE

Kidd Metsite commenced operations in 1966 to process the copper and zinc ore from the nearby Kidd Mine. Operations consist of a concentrator, copper smelter and refinery, as well as zinc, indium, cadmium and sulphuric acid plants. In late 2004, nickel ore from the Montcalm Mine was introduced in a separate milling circuit in the Concentrator. The majority of waste products from metallurgical operations are discharged to the Tailings Management Area (TMA). The TMA covers about 1250 ha, with about 650 ha actively used for tailings disposal. Annual tailings quantities vary, with 2.78 million tonnes disposed in 2008. The tailings are centrally discharged as thickened slurry from spigot points at the apex of a gradually sloped, inverted cone. The spigot points are periodically alternated to evenly distribute the slurry over the cone surface and limit acid generation from the sulphidic waste rock.

Wastewater streams, including acid rock drainage from the tailings cone, process wastewater from the Metsite and runoff from rain and snowmelt events, collect in perimeter ditches to be conveyed to two storage ponds, Pond A and Pond C. Lime is added at the outlet of each pond for pH adjustment and metals precipitation. Ditch 10 is a separate, unattenuated contributor of process wastewater and runoff, merging with the main flow after the Pond A lime station. As shown in Figure 1, all lime treated wastewater flows into Pond D, where primary solids settling occurs. Water volumes stored in Ponds A and C are modulated to respond to precipitation and melt events and regulate the release of water to Pond D. Pond E, downstream of Pond D, is used for final polishing and residual solids removal. The Pond E discharge is adjusted to a pH below 9 by $CO_2$ injection before flowing into the Porcupine River.

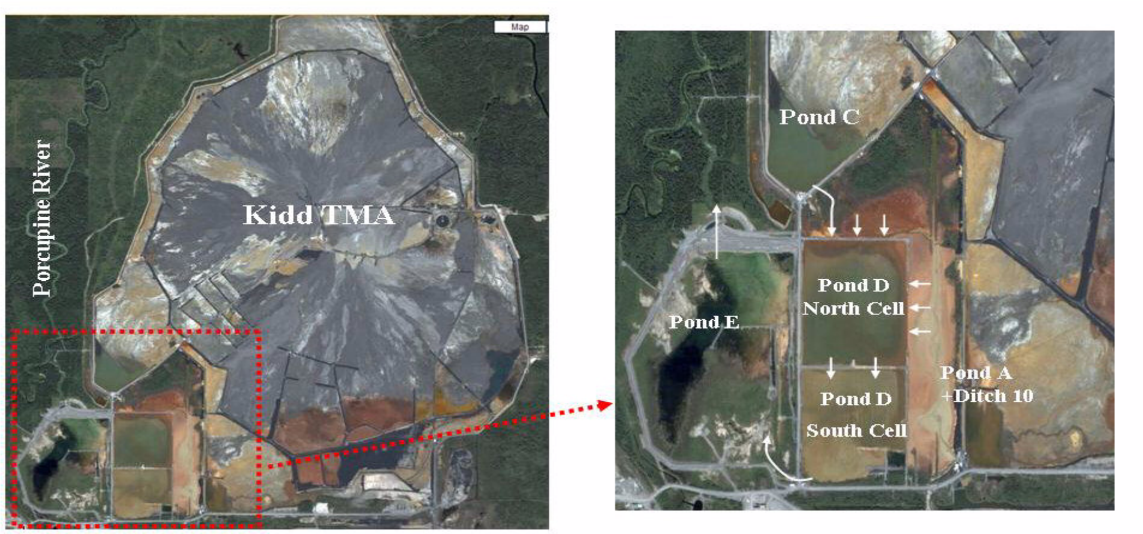


Figure 1: Kidd TMA general layout (left) and TMA pond system (right)

The main role of Pond D is to capture the suspended solids and precipitated metals present in the pond influent. As shown in Figure 1, Pond D is subdivided by the Split Dyke into North and South Cells. The dyke is partially submerged during peak flows. Ponds D measures roughly 500 m in width and 950 m in length.

Operational experience under adverse conditions has revealed higher than desired TSS concentrations at the outlet from Pond D. High solids carryover is most commonly associated with high flows or strong winds. Although the presence of Pond E assures that environmental objectives are satisfied, solids carryover from Pond D in excess of internal control targets is undesirable as this increases the Pond E dredging frequency, with consequent costs and difficulties. Therefore, there is a strong desire to understand the flow hydraulics and settling performance in Pond D and develop engineering solutions that ensure that Pond D performance goals are achieved for all conditions.

## NUMERICAL MODELING APPROACH

A comprehensive CFD model has been developed using the commercial CFD code Fluent 6.3. The code is based on the finite volume method (FVM) described by Versteeg & Malalasekera (2002). The CFD model incorporates multiple factors with bearing on the pond performance: flow hydrodynamics, solids settling rates and sludge resuspension.

### Modeling of Pond Flow Hydrodynamics

The model solves the Reynolds averaged Navier–Stokes equations in three dimensions to compute the flow hydraulics. The standard k-ε turbulence model by Launder and Spalding (1974) is used for the characterization of turbulence.

### Modeling of Solids Settling

Suspended solids transport and settling is calculated by solving a convection–diffusion equation as follows:

$$\frac{\partial c}{\partial t}+(u\frac{\partial c}{\partial x}+v\frac{\partial c}{\partial y}+w\frac{\partial c}{\partial z})+v_s\frac{\partial c}{\partial z}=\frac{\partial}{\partial x_j}(\Gamma\frac{\partial c}{\partial x_j}) \qquad (1)$$

where c is the suspended solids concentration in water, u, v and w are water velocities in the x, y and z directions, respectively, $v_s$ is the particle settling velocity which is calculated through application of Stokes Law, and Γ is the diffusion coefficient due to turbulent mixing. In the present study, a constant Pond D feed TSS is assumed. Therefore, the first term in the above convection-diffusion equation can be ignored. The third term can be considered as an extra convection term in the vertical direction, which is caused by the fall velocity of solid particles.

### Modeling of Sludge Resuspension

Sludge resuspension involves complex physical processes. Zeigler and Lick (1986) and Partheniades (1986) performed experimental studies and suggested the following expression be used to predict the resuspension rate of cohesive materials, such as fine particles in settling ponds:

$$E=\begin{cases} M(\frac{\tau_0-\tau_c}{\tau_c})^n & if\, \tau_0 > \tau_c \\ 0 & if\, \tau_0 \leq \tau_c \end{cases} \qquad (2)$$

where E is the resuspension rate (kg/m$^2$ s), $_0$ is the total bed shear stress (N/m$^2$), $_c$ is the critical bed shear stress for resuspension (N/m$^2$), and M and n are experimentally determined coefficients.

The above equation indicates that sludge resuspension only occurs in high velocity areas where the bottom shear stress, $_0$, exceeds the critical shear stress, $_c$. Resuspension tests performed by Yanful and Catalan (2002) and Peacey and Yanful (2003) using particles from different tailings ponds with varying particle size distributions, showed that coefficients of M = 1/6, n = 4/3 and $_c$ = 0.058 N/m$^2$ are suitable for estimates of sludge resuspension in tailings ponds. These values are adopted in this study.

## BOUNDARY CONDITIONS

### Pond Inflow

Maximum flows to Pond D from Pond A, Pond C and Ditch 10 were calculated based on the 100-year storm event for Timmins using the GAWSER Hydrology Model[4]. A combined Pond D inflow of 620,000 m$^3$/d is anticipated for this circumstance. A reduced

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[4] The GAWSER model is a continuous event hydrological model developed for the Kidd Metsite TMA by Klohn-Crippen, Greenland and Golder, with adjustments made by Hatch in 2007.

flow of 270,000 $m^3$/d, representing the high flows normally encountered in operations during the spring freshet, was selected for model validation. The incoming water was distributed between culverts on the north dam and low points on the northern and eastern dams by solving hydraulic equations. This complex velocity distribution on the inlets was programmed into the CFD model using Fluent's User Defined Function (UDF) and applied as a model input at inlet boundaries.

A suspended solids concentration of 1,500 mg/L was used for the Pond D influent. This was determined based on historical monitoring data and a correlation developed from testing results in 2007. The value selected represents conservative, worst-case conditions. The particle size distribution (PSD) for incoming solids was based on Kidd Metsite TMA sludge data contained in a Canadian Mine Environment Neutral Drainage (MEND) report (1997). As shown in Figure 2, the sludge particles ranged in size from 0.5 to 25 μm. Five particle sizes (2μm, 4μm, 7μm, 10μm and 15μm) were selected for modeling. Each represents the midpoint of a 20% cross-section of the PSD.

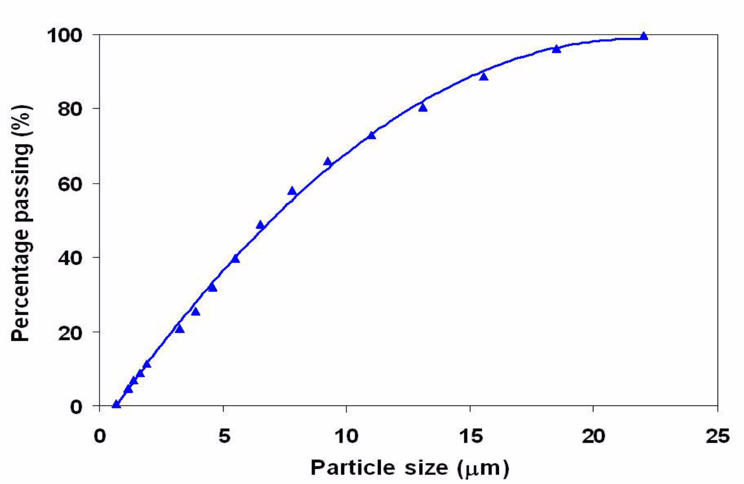


Figure 2: Particle size distribution of Kidd TMA sludge (MEND, 1997)

**Water Surface**

The pond water surface was modeled as a rigid surface with zero shear and zero diffusive flux of TSS. The South Cell water elevation was fixed at 283.70 m for all modeling cases in this study to maintain sufficient freeboard below the spillway invert. Water elevation in the North Cell was estimated using an Excel spreadsheet to solve basic hydraulic equations accounting for inputs such as South Cell water elevation, total flow, and Split Dyke/culvert elevation profiles.

**Pond Bottom**

The pond bottom was defined numerically as a boundary wall. The sludge resuspension rate was as described by Equation 2 with resuspended particles adding to the solids concentration at the specific pond location and behaving according to Equation 1. The wind induced sludge resuspension has not been incorporated in this study. The sludge PSD was adjusted as a function of travel distance from the north dam on the assumption that larger, faster settling particles will be disproportionately represented closer to the inlet. Pond bathymetry for the CFD model was based on surveys performed prior to dredging campaigns, representing the case with minimum pond residence time. For this work, the North Cell uses the 2007 spring pre-dredge bathymetric data and the 2006 fall survey information is used for the South Cell. The average water depths above the settled sludge layer in the North Cell and South Cell are 0.2 m and 0.5 m, respectively.

## RESULTS AND DISCUSSION

### Model Validation

Model validation was performed for a combined Pond D inlet flow of 270,000 $m^3$/d. The distribution of flows entering Pond D via the north dam culverts and overtopping on the north and east dams is 2.14 $m^3$/s, 0.97 $m^3$/s and 0.02 $m^3$/s, respectively.

Figure 3 presents the comparison between CFD model predictions and actual measurements for TSS at the Split Dyke location and at the outlet of Pond D. Good agreement was observed between the predicted and actual results. The percentage error between the model and actual data at the Split Dyke and outlet locations is less than 5%.

Figure 3 also provides an explanation for the seemingly illogical increase in TSS at the pond outlet relative to the intermediate Split Dyke location. The TSS concentration contours show western sections of the Split Dyke where flow overtopping occurs, resulting in a more direct route between the pond inlet and outlet than that which passes through the gap in the Split Dyke. The outcome is a shorter residence time for flow entering Pond D from the western edge of the north dam and, as consequence, higher TSS at the Pond D outletthan  at the Split Dyke.

The results also suggest that the two smallest particle size fractions (2 μm and 4 μm) account for 98.7% of the TSS present at the pond outlet. Particles of greater than 7 microns are effectively deposited in the pond as intended.

### Effects of Coagulation Treatment on Pond Settling Efficiency

The modeling results indicate that small particles (i.e. particle size < 4 μm) in the pond inflow have a dominant influence on the effluent TSS concentration. For better solid/liquid separation, coagulant chemicals can be added to increase particle sizes and thereby improve settling performance.

The effect of coagulant addition on Pond D performance was evaluated for the same flow conditions as imposed in the validation case. The PSD of a coagulated sludge from a similar facility employing lime treatment was used for CFD modeling (MEND, 1997). Table 1 compares the properties of Kidd TMA sludge with the coagulated sludge.

Table 1: Comparison of the properties of Kidd TMA sludge and coagulated sludge

| Sludge Type | Color | Percentage solid (wt %) | Median particle size, $d_{50}$, (μm) | Bulk density ($g/cm^3$) | Dry sludge density($g/cm^3$) | pH |
|---|---|---|---|---|---|---|
| Kidd TMA Sludge | Grey-brown | 3.4 | 6.67 | 1.08 | 3.24 | 10.85 |
| Coagulated Sludge | Grey-brown | 3.9 | 16.11 | 1.06 | 3.04 | 10.54 |

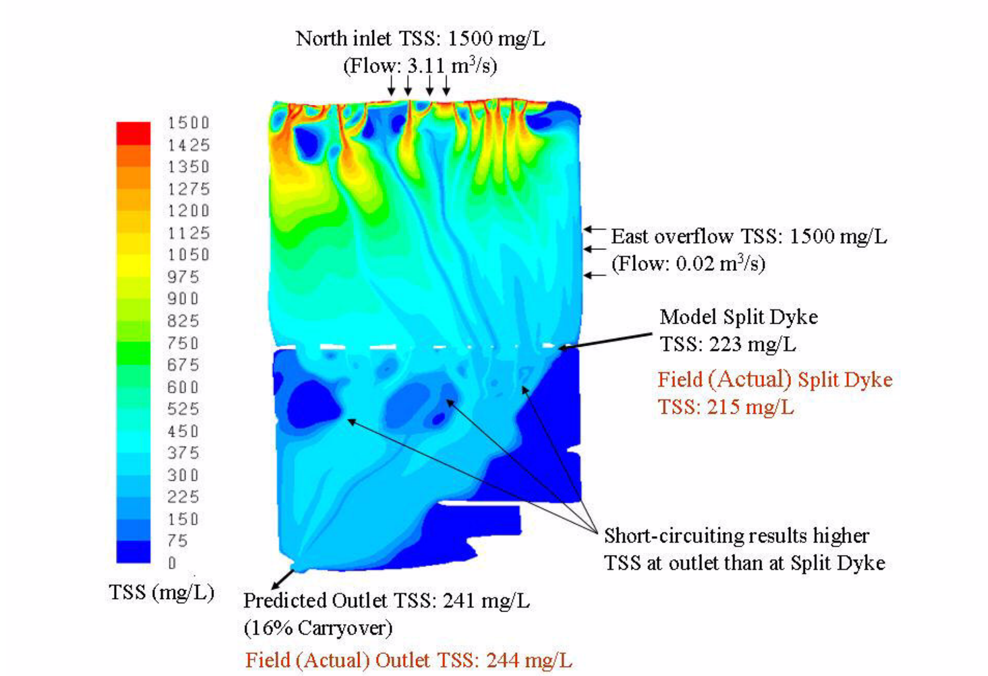


Figure 3: Suspended solids profiles in Pond D at a flow of 270,000 $m^3$/d

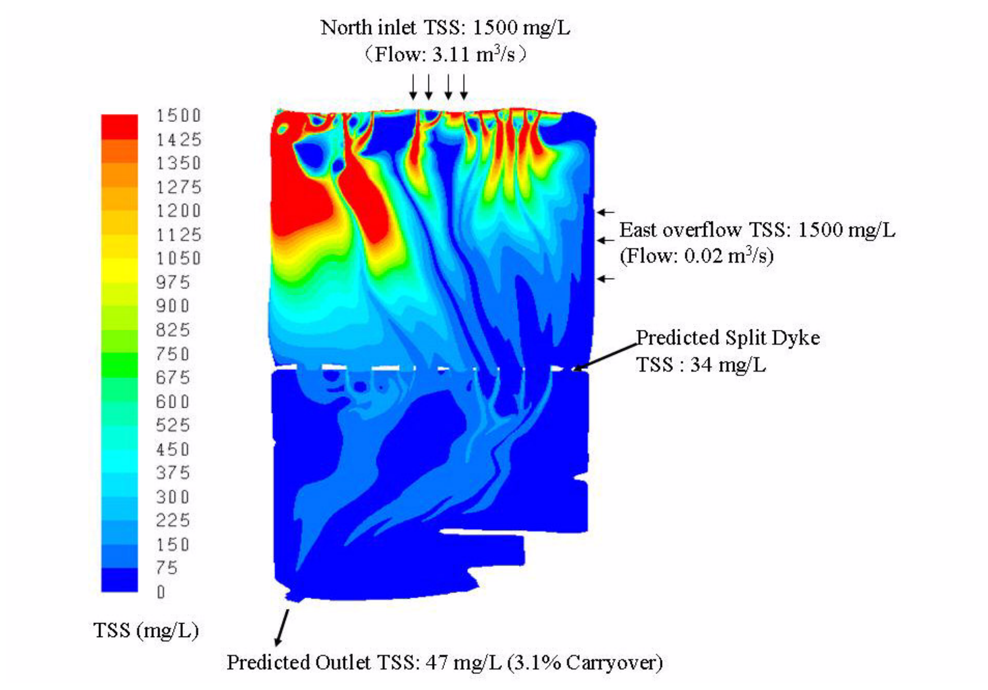


Figure 4: Suspended solids profile after coagulant addition

Figure 4 shows that the TSS concentration in the effluent is lowered to 47 mg/L following application of coagulant chemicals, a reduction of 81% compared to the non-coagulated condition as shown in Figure 3. This indicates that coagulation treatment should be considered as an option for high Pond D flow conditions. The CFD model may be used with PSD information from bench-scale coagulation trials to define the optimal flow value at which to initiate coagulant use and appropriate coagulant dosage in order to minimize costs for chemicals and Pond E dredging.

**Effects of Baffles on Pond Hydraulics and Settling Efficiency**

Adding baffles to Pond D was considered as an option to achieve performance improvements. The baffle concept was intended to reduce flow short-circuiting and increase the pond residence time. Installation of two baffles was proposed in each cell, with the baffles dividing each cell into thirds in the north-south direction and the length of each baffle being equal to half of cell width. The baffles were assumed to be perfect barriers with no potential for overtopping.

In this study, the CFD model was used to predict pond hydraulics and settling efficiency with and without the baffles. Simulations were performed at the maximum design flow of 620,000 $m^3$/d. Figure 5 shows the velocity fields for both cases. The results indicate that, contrary to the intent of reducing short-circuiting in the pond, the addition of baffles in the proposed configuration actually compounds the short-circuiting issue. Bigger dead zones are also produced in the pond, particularly on the downstream edges of the baffles, resulting is less effective utilization of the pond volume.

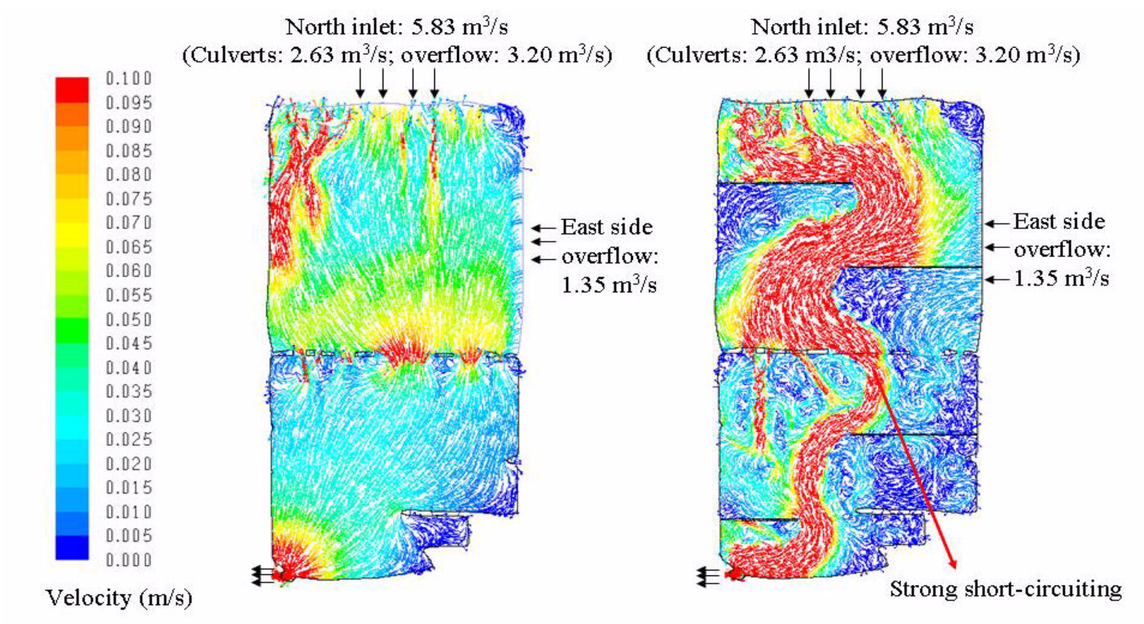


Figure 5: Velocity field comparison for cases without (left) and with baffles (right).

Figure 6 presents the comparison of bottom shear stress for the two cases. It can be observed that the strong short-circuiting in the baffled case significantly increases the local bottom shear stresses, especially at the tips of the baffles where the critical shear stress of 0.058 N/$m^2$ is generally exceeded. Thus, sludge resuspension becomes a significant factor contributing to pond TSS carryover. The predicted outlet TSS concentration for the baffled case is 624 mg/L (or 41.6% carryover), compared with 450 mg/L (or 30.0% carryover) without additional baffles.

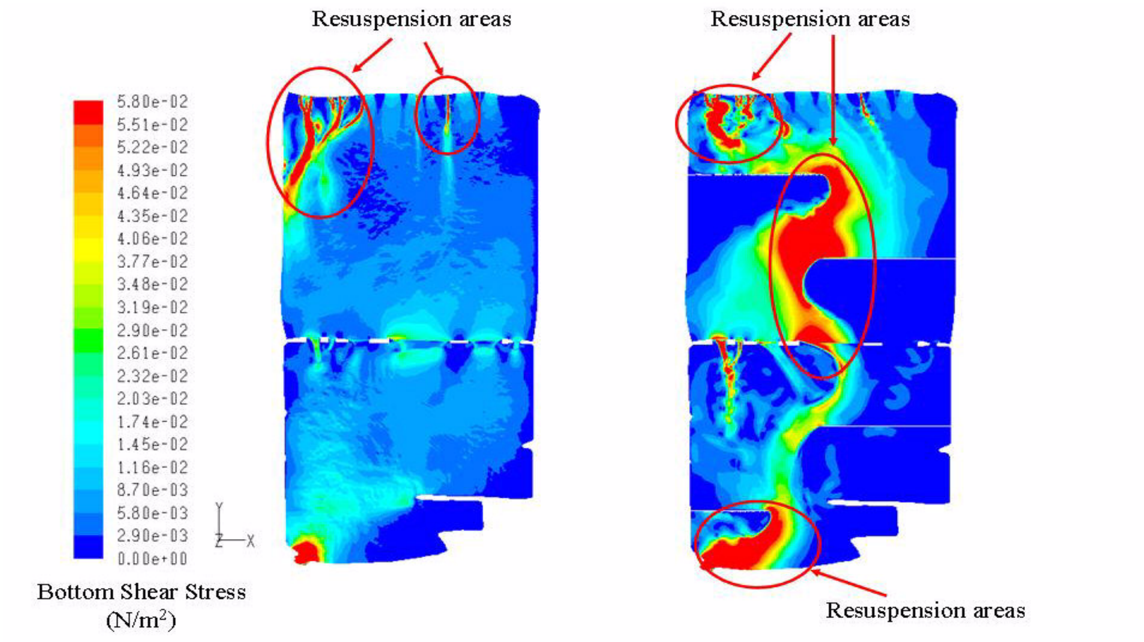


Figure 6: Comparison of bottom shear stress for the unbaffled and baffled cases

**CONCLUSIONS**

A comprehensive three dimensional CFD model was developed for predicting settling pond performance for the treatment of acid rock drainage. Pond hydraulics, solids settling and solids resuspension are incorporated in the model to generate integrated predictions of performance. The modeling results agree well with actual data from Xstrata Copper's Kidd Metsite. The simulation results indicated that adding coagulants can significantly lower the TSS concentration at the pond outlet. CFD output can be used with results from coagulant trials to define a pond management strategy to limit operating costs for chemicals and dredging while minimizing environmental risk. Application of the CFD model to evaluate engineering modifications to the pond has also been demonstrated. This study showed that inappropriate design and placement of baffles has the potential to compound flow short circuiting issues, resulting in poorer settling performance.

In summary, the developed model has been demonstrated to be a powerful and flexible tool for predicting Kidd Pond D settling performance. The model is effective for assisting with settling pond operation, developing operating strategy for adverse conditions, and evaluating pond improvement options.

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