Numerical Simulation of Total Suspended Solid Concentration in Oil Sands Tailings Ponds

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Abstract The three-dimensional hydrodynamic and sediment transport model COSED-UF was used to help assess total suspended solid concentration in oil sands tailings ponds in support of planning level engineering design of a tailings pond. Before implementation, the applicability of the model was assessed using the published suspended solid concentration data for Syncrude's Mildred Lake Settling Basin. This assessment shows that the model results of the suspended solid concentrations were generally in good agreement with the published data. This paper describes the main methodology and results of the modeling study.

Keywords Oil sands, tailings pond, lutocline, resuspension, TSS, COSED-UF.

Introduction

Large tailing ponds have been constructed or are planned for oil sands mining projects near Fort McMurray, Alberta, Canada. The tailings ponds are used for managing the tailings from the bitumen extract process. Oil sands tailings typically contain a mixture of solvent, solids (clay, silt, and sand), water, residual bitumen, salts, metals, and organic compounds (Gosselin *et al.* 2010). The coarse solids in the tailings settle out quickly in the tailings ponds, leaving the fine solids (clay and silt) to form fluid fine tailings, which are stored and left to gradually settle. A layer of water known as a 'free water cap' is maintained in the tailings ponds to facilitate solid settling and to reduce resuspension of the fine solids due to wind-wave action. The water in the free water cap usually has a relatively low Total Suspended Solid (TSS) concentration and is recycled for use in the bitumen extraction process to reduce water withdrawal from the Athabasca River. The TSS concentration in the free water cap (Fig. 1) is of particular concern for the operation and management of the tailings ponds, because high TSS levels affect the recycle use of the tailings pond water and may reduce the efficiency and life-span of process cooling systems.

The TSS level in the tailings ponds is influenced by the processes of deposition, vertical mixing and resuspension of the fine solids, which tend to aggregate into large flocs in the tailings ponds due to cohesiveness. Typically, three distinct vertical layers (Lawrence *et al.* 1991, Ward *et al.* 1994) are developed in the tailings ponds. The development of this vertical distribution of the solids has been observed in the Syncrude's Mildred Lake Settling Basin (MLSB), as shown in Fig. 1. The upper layer, known as the mixed layer or the free water cap, has relatively low TSS concentrations, with uniform vertical distribution of concentration usually less than 0.1 % by weight. The intermediate layer or transition zone, known as the immature Thin Fine Tailings (TFT)or lutocline, contains neutrally buoyant fine particles and is characterized by sharp TSS concentration gradient (0.1 % to 15 % by weight within less than a meter)and water density gradients (Ward *et al.* 1994). The fine particles in the lutocline layer can be entrained into the free water cap under wind-driven current effects and wave actions. The lower layer, known as

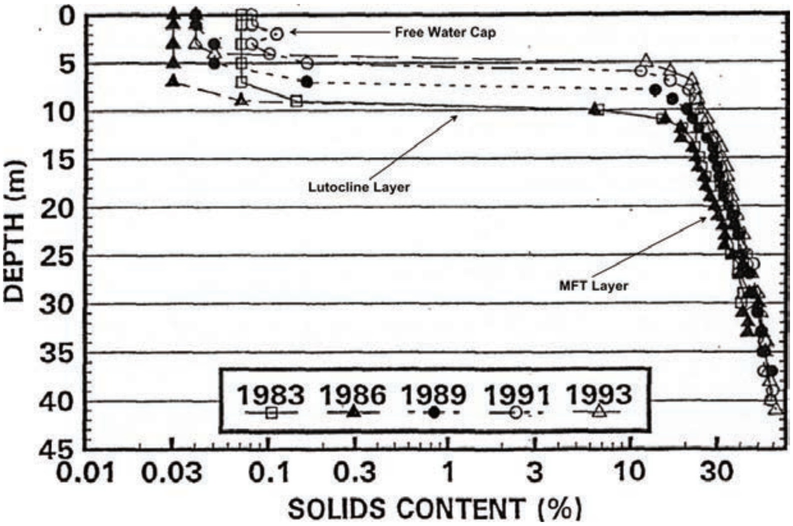

Fig. 1 *Measured solids concentration profiles in Mildred Lake settling basin (Ward et al. 1994).*

the dense layer or the Matured Fine Tailings (MFT), is characterized by high solids concentrations, 15 % to 60 % by weight. The solids in the MFT layer are usually stationary and are only subject to resuspension under extremely strong wind events and wave action.

Ward *et al.* (1994) described an energy balance approach for simulating wind driven resuspension in the tailings ponds by assuming that wind energy and TSS potential energy are in an equilibrium state. The simulation model by Ward *et al.* (1994) was developed specifically based on the data for the Syncrude's MLSB. This approach does not account for processes such as wind-driven current effects and wave action on vertical mixing and bottom sediment resuspension, lutocline development, density gradient effects resulting from thermocline and lutocline, flocculation settling, and TSS spatial variation. Moreover, the energy balance relationship involves a single calibration parameter, which is highly dependent on tailings material properties and tailings pond geometry. Therefore, the calibrated model for the MLSB cannot be easily transferred to the other tailings ponds.

Currently, some oil sands mining projects are using a number of measures to reduce the TSS level in the tailings ponds, such as injecting CO_2 to increase settling velocity, increasing the free water cap depth to minimize wave effect on resuspension, and reducing pond size to minimize fetch and wave height. In tailings pond design, engineers need input information such as the relationship between TSS (levels and exceedance probabilities) and pond geometry (free water cap depth and pond size). To date, there has been no published study on modeling the effects of the free water cap depth and pond size on TSS levels. Lawrence *et al.* (1991) derived a relationship between minimum pond depth and fetch based on maximum near-bottom orbital wave velocity and critical velocity for bottom sediment resuspension. This simple approach did not directly or explicitly account for the effects and processes mentioned above, in particular the wind-driven current and lutocline entrainment. As a result, this relationship can only be used as a conceptual and qualitative tool for tailings pond engineering planning and design.

This paper presents the application of the integrated, three-dimensional (3D) hydrodynamic and sediment transport mode lCOSED-UF. The COSED-UF model is capable of simulating the effects of tailings pond size and depth on TSS levels and providing information for tailings pond planning, design, and operation. The application involved substantial efforts to adapt and evaluate the 3D model using the published TSS and water temperature data from the MLSB. This paper describes the methodology and results of the modeling study.

Approach

The COSED-UF model used in this study is a highly integrated, fully 3Dhydrodynamic, multiple size class cohesive and non-cohesive sediment transport, morphodynamic, wind wave, particle tracking and water quality model. The model, originally developed at the University of Florida, is a public domain program and has been applied in Environmental Impact Assessments (EIA) and in support of engineering design for a large number of coastal, river, lake, and mine resource development projects over the past decade. It was accepted as a reliable EIA tool by Canadian government agencies, first nation groups, and Environment Canada. To validate it as a reliable tool for simulating tailings pond solid resuspension and TSS concentrations under wind-driven current effects and wave action, the model was evaluated using the published TSS and temperature data from the Syncrude's MLSB, which layout plan is shown in Fig. 2.

The Syncrude's MLSB was built in late 1970's. It has a size of approximately 6 × 3 km, a surface area of more than 12 km^2, and a free water cap of 5 m during the period when the published TSS measurements were obtained. The TSS concentrations and water temperatures were measured at 1 m depth and 700 m offshore from the pond's SW corner during an open water season from September 4 to November 7, 1991 (Ward *et al.* 1994).

The COSED-UF model was set up for the MLSB with a rectilinear grid (horizontal resolution of 500 m by 500 m and a vertical resolution of 0.25 m). The model simplified the MLSB geometry as a rectangular domain with a constant water cap depth of 5 m, and the inflow and outflow were not accounted for in the study. The following physical processes were simulated in the model: air-water momentum and heat exchanges, wind-driven current, wind-generated wave, water density gradient effects due to thermocline and lutocline, flocculation settling, lutocline development, vertical mixing and bottom sediment resuspension under current, and wave effects. The model inputs include hourly wind speed and direction, air temperature, dewpoint temperature, and cloud cover data from the Fort McMurray Airport climate station. A lutocline

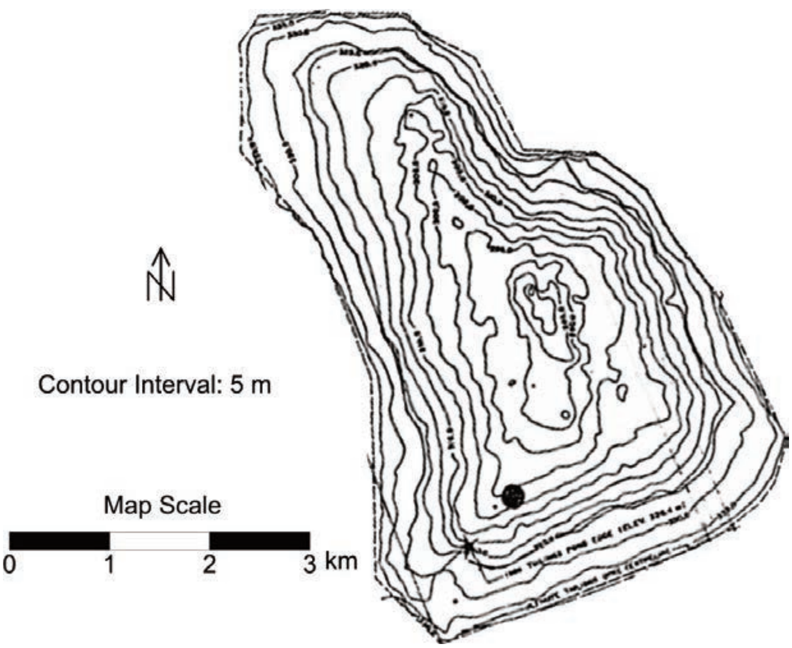

Fig. 2 *A map showing MLSB geometry and survey site (dot; Ward et al. 1994).*

layer was initialized using the measured MLSB solids content profiles (Fig. 1) with a thickness of 1 m and maximum TSS concentration of 25,000 mg/L. The initial TSS concentration in the free water cap was set equal to 600 mg/L. The flocculation settling velocity was calculated as a function of TSS concentration (Jiang and Mehta 2000).

Applicability Evaluation

In testing the model application, a number of model parameters were adjusted to achieve the best agreement with the published data, mainly flocculation settling velocity, critical velocity for solid resuspension, Secchi depth (a measure of water clarity), light extinction coefficient for water, and bottom sediment temperature. In the thermal simulation, the typical parameters found in northern lakes for the Secchi depth (1.0 m), light extinction coefficient (0.45 m^{-1}) and bottom sediment temperature (4 °C) were found to be applicable for the MLSB, and the modeled time series of the near-surface water temperatures are in very good agreement (Fig. 3) with the observations. Measurements of the MLSB temperature after October 29, 1991 were taken under ice-cover conditions which were not modeled by COSED-UF. Therefore, the simulation results should not be compared to the observations during this period.

Most of the model testing efforts involved adjusting the flocculation settling velocity and critical velocity for solid resuspension (Jiang *et al.* 2013). The flocculation settling velocity introduced in Jiang and Fissel (2012) was used in the model, and appropriate parameters included in the settling velocity formula were chosen such that the suspended fine solids settled at a speed consistent with the observed TSS data from the MLSB. The critical velocity for solid resuspension was set equal to 0.05 m/s, which was reported in Lawrence *et al.* (1991) and based on laboratory flume experiments. The modeled time series of the near-surface TSS concentrations at the survey site are generally in very good agreement with the observations (Fig. 4), and the modeled TSS time series patterns are consistent with the wind events (not shown). The modeled TSS profiles (Fig. 5) exhibit very uniform TSS concentrations in the free water cap and very sharp TSS gradient in the near-bottom lutocline layer, which are consistent with the observations (Fig. 1).

Noteworthy discrepancies are observed in mid-September and late October (Fig. 4),

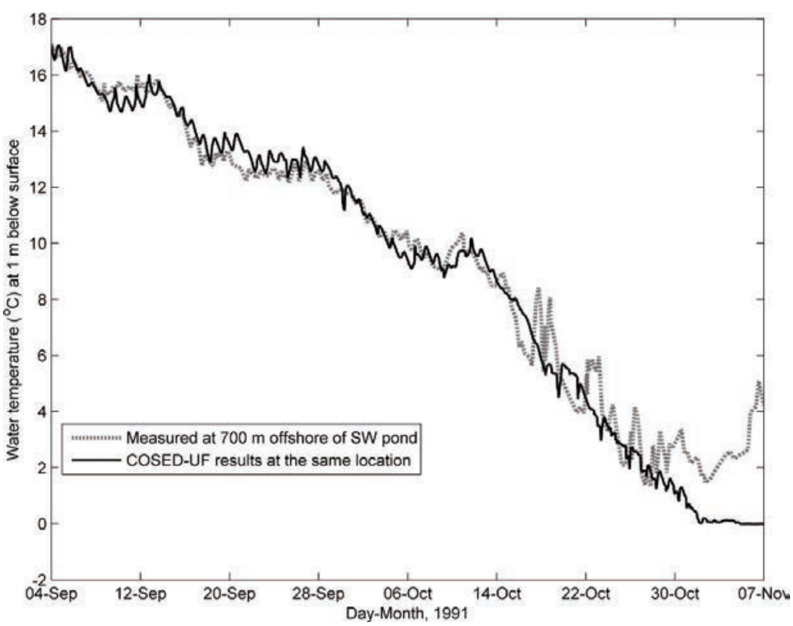

Fig. 3 *Time series of the modeled water temperatures at the survey site, with comparison to the observations.*

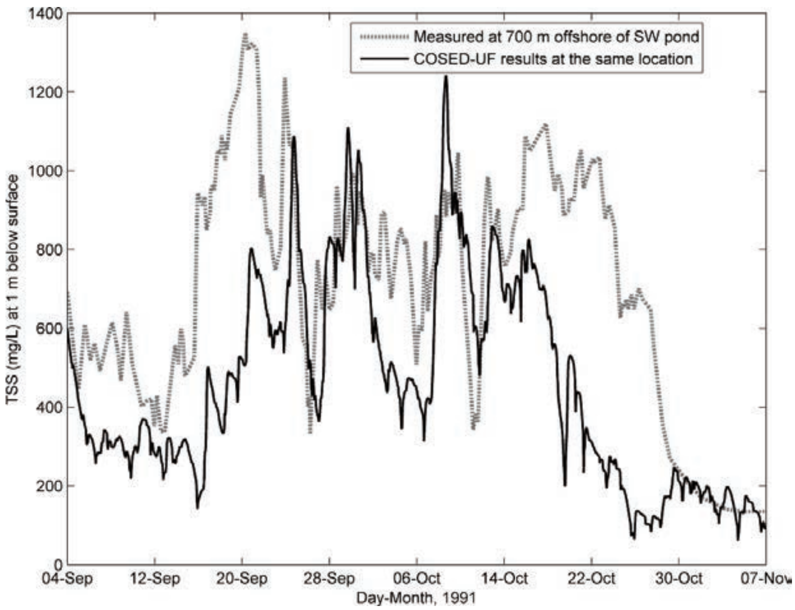

Fig. 4 *Time series of the modeled TSS concentrations at the survey site, with comparison to the observations.*

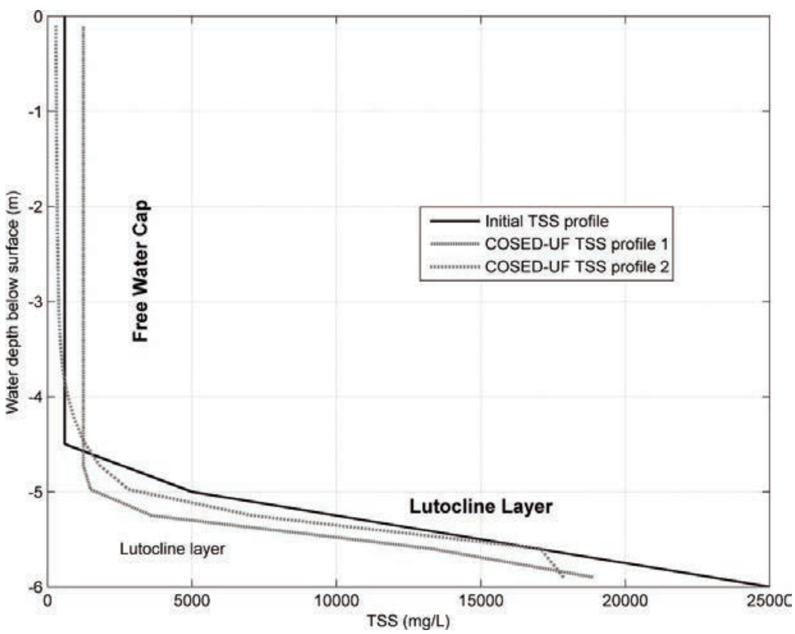

Fig. 5 *Initial and modeled TSS profiles.*

and might be caused by either inflow effects, which were not considered in this study, or onsite wind event effects. The wind data recorded at the Fort McMurray Airport climate station, about 50 km south of the MLSB, were used in the model because the wind data collected by Ward *et al.* (1991) at MLSB were not available in a digital format for use in this study. A visual comparison shows that on average, the wind speeds recorded at MLSB are higher than those at Fort McMurray by about 20 – 50 %. A factor of 1.1 was thus applied to the Fort McMurray wind data so that the peak wind speeds during the modeling period were comparable to those recorded at MLSB. The inflow conditions, such as discharge and TSS concentration, are believed to play important part for the TSS levels in the pond (Ward *et al.* 1991). However, the inflow effects were not considered in this modeling study because of unavailable inflow information.

Conclusions

Modeling TSS concentrations in oil sands tailings ponds is a very challenging task because of the unique processes characterized by the flocculation settling, development of the thin lutocline layer with sharp TSS gradient, vertical mixing across the lutocline and resuspension of the bottom sediment in the MFT layer under wind-driven current effects and wave action. The applicability assessment of the fully 3D, integrated circulation-wave-sediment-geomorphology numerical model, COSED-UF, for simulating the TSS concentrations in oil sands tailings ponds was conducted based on the published TSS data for the MLSB. The modeling results show that the model is a robust and reliable tool in simulating TSS concentrations in the tailings pond, and providing valuable information for supporting the engineering planning, design, and operation of the tailings ponds. The application and development of this model are ongoing. Future applications may include simulation of TSS concentrations in oil sands mine pit lakes that contain fine tailings. Future development of the model may include inclusion of an ice module, a MFT layer consolidating module, and an MFT layer thermal processes module.

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