PRELIMINARY ASSESSMENT OF A MONITORING AND MANAGEMENT MODEL FOR SULFIDIC MINE TAILINGS PONDS UNDER SHALLOW WATER COVERS

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ABSTRACT
Shallow water covers are one of the most effective and commonly used methods of managing sulphide-rich reactive mine tailings in temperate climates. However, wind-induced waves and currents during episodic storm events can raise concerns about deteriorating pond water quality that may compromise regulatory effluent discharge criteria. Wind-induced flow may erode and resuspend the tailings from the bed and transport and deposit in areas where the flow-induced bottom shear stress is smaller than the threshold shear stress for deposition. Knowledge of the distribution of expected TSS and metal and sulphate concentrations in the tailings pond during and after a storm event is therefore needed to facilitate planning of appropriate remedial measures. The present paper presents a conceptual description of such a monitoring and management model. The model was used to calculate episodic high TSS concentrations in the Heath Steele Lower Cell tailings area, near Miramichi, New Brunswick, Canada. The model results showed reasonable agreement with measured data. The results highlight the potential of the model as an effective post-flooding monitoring and management tool for mine tailings ponds.

RÉSUMÉ
Les couvertures aquatiques de faible profondeur sont une des méthodes les plus efficaces et couramment utilisées des résidus miniers réactifs sulphure-riches dans les climats tempérés. Cependant, les vagues et les courants induites par le vent pendant les événements d'orage épisodiques peuvent élever des inquiétudes concernant de la degradation de la qualité d'eau dans le parc à résidus de mine, qui peut compromettre les critères de décharge des effluents régulateurs. L'écoulement induite par le vent peut éroder et remettre en suspension les résidus miniers du fond et les transport et le dépôt dans les secteurs où la tension de cisailles de fond induite par l'écoulement est plus petite que les cisailles de seuil accentuent pour la déposition. La connaissance de la distribution prévue des solides qui sont en suspension et les concentrations des metaux et sulfate dans le parc à résidus pendant et après un événement d'orage est donc necessaire pour faciliter la planification de mesures réparatrices appropriées. Ce papier présente une description conceptuelle d'un tel modèle pour la surveillance et intervention. Le modèle a été utilisé pour calculer les hautes concentrations de TSS épisodiques dans le parc à résidus Lower Cell à la mine Heath Steele, près de Miramichi, Nouveau-Brunswick, Canada. Les résultats du modèle concordaient avec les données measurées. Les résultats soulignent le potentiel du modèle comme l'outil de survillance et intervention après l'innondation des residus miniers.

1. INTRODUCTION

Environmental management of reactive mine wastes represents a significant cost component of mining operation. The final closure plan of a mining operation must provide assurance of compliance of tailings management with regulatory environmental guidelines. In temperate climates, such as in Canada and Scandinavia, one of the most effective and commonly used methods of managing reactive mine tailings is to place them under an engineered shallow water cover. This is generally achieved by constructing tailings impoundment dams, placing the tailings in the impoundment and maintaining shallow cover water above. The water covers reduce sulphide oxidation, acid generation and subsequent mobilization of metals, which are detrimental to the environment (Pedersen et al. 1997; Yanful and Catalan 2002).

The depth of water cover implemented at various sties varies over a wide range (0.6–3.3 m at Cell 14, Quirke Mine, Elliot Lake, Ontario; 0.6–2.0 m at New Tailings Area, Falconbridge, Ontario; 0–2.0 m and 0.5–6.0 m at Heath Steele Upper and Lower Cells, New Brunswick, respectively; 0.6~5.0 m at Shebandawon Tailings Pond, Ontario; 1.0–5.0 m at Løkken Tailings Pond, Norway). However, at most sites, the water depth is close to or less than 1.0 m in most part of the pond. The effectiveness of water covers in reducing resuspension with such shallow water depths depends on several factors including tailings physico-chemical properties, topography and climate of the area, and tailings erosion behaviour. Of particular importance is the need to consider wind-induced waves and currents, and subsequent oxidation of the tailings.

Wind stress at the surface of the water cover generates waves, surface drift currents and associated pressure driven counter current flow (CCF) (Wu and Tsanis 1995). Analysis by Yang (2001) and Wu and Tsanis (1995) suggested that for fully developed low-aspect ratio CCF, the bottom shear stress is independent of the water depth. Bottom shear stress due to waves, on the other hand, increases significantly in areas where the water depth to wavelength ratio becomes smaller than 0.5.

When the combined bottom shear stress from the waves and currents exceeds the threshold shear stress for erosion at higher wind speeds, resuspension of the tailings starts to occur. During episodic storm events the high wind speed can substantially increase the total suspended solids (TSS) concentration in the pond. Once resuspended, the tailings can deposit only when the deposition flux due to gravity predominates over the turbulent buoyant flux. However, the flow circulation may transport the suspended tailings before allowing them to deposit in areas where the bottom shear stress is smaller than the threshold shear stress for deposition.

Samad and Yanful (2003) have indicated that depending on the magnitude of design wind speed, pond geometry, critical bed shear stress for erosion and other tailings physical properties, the maximum water depth necessary to completely eliminate resuspension in a tailings pond may become as high as 5.0 m. This depth is about the same as the maximum depths observed at several sites in Canada. However, the distribution of water depth over the tailings pond and the wind speed and direction during storm events may still cause resuspension from shallower areas. At the Heath Steele Lower Cell, Peacey and Yanful (2003) observed that the TSS concentration occasionally exceeded the regulatory guideline for effluent discharge during periods of high wind speeds, although the maximum water depth in the pond was about 6.0 m.

Tailings resuspension may also increase tailings oxidation rate (Catalan and Yanful 2002) and may compromise the chemical quality of the cover water. The general implication of this phenomenon from a management perspective could be manifold. It requires an extensive climatic and environmental monitoring program in place, which may not even be adequate to identify the causes for deteriorating pond water quality. Also, appropriate infrastructure is necessary to provide adequate treatment facilities to maintain pond water quality at a desired level or to treat the effluent before discharge. The level of requirement is usually not known apriori.

During and at the end of a storm event the pond water quality, in terms of TSS and other metal and sulphate concentrations, is expected to attain its lowest levels. Knowledge of the distribution of these parameters in the pond therefore would enable operators and field monitoring staff to plan appropriate remedial measures. In the event of systematic occurrence of high TSS and other species concentrations, this knowledge would help in deciding the need for re-engineering works, such as dredging in shallow areas or selecting appropriate preventive measure against erosion. The present paper introduces a conceptual description of such a monitoring and management model. The model was used to calculate episodic high TSS concentration levels in the Heath Steele Lower Cell and gave results that showed reasonable agreement with measured data.

2. STUDY AREA DESCRIPTION

2.1 The Heath Steele Lower Cell

The Heath Steele Mine Lower Cell tailings area, used in this study to demonstrate the applicability of the modelling approach, is located 50 km northeast of Miramichi, New Brunswick, Canada. The mining operation in this lead-zinc mine began in 1937 and continued till 1999, when it was permanently shut down. From 1963 the mine tailings were deposited in a 190 ha new tailings area consists of the Upper and Lower Cells (Fig.1). The impoundments were flooded in 1966. The water depth in the Lower Cell varies between 0.5 m and 6.0 m and is less than 2.5 m in most places. Effluent from the Upper Cell enters the Lower Cell at the western end of the internal dam after being treated with thiosalts. The resulting treatment sludge is deposited in the shallow western part of the pond (Peacey and Yanful 2003). Further details of the study area can be found elsewhere, for example, Peacey and Yanful (2003) and Yanful and Catalan (2002).

The main reason for selecting the Heath Steele Lower Cell as the study site is that, over the years, a substantial database of pond performance has been developed. Although the database does not cover all the parameters required for the validation of the proposed model, it provides a reasonable set of information for an initial assessment of the model.

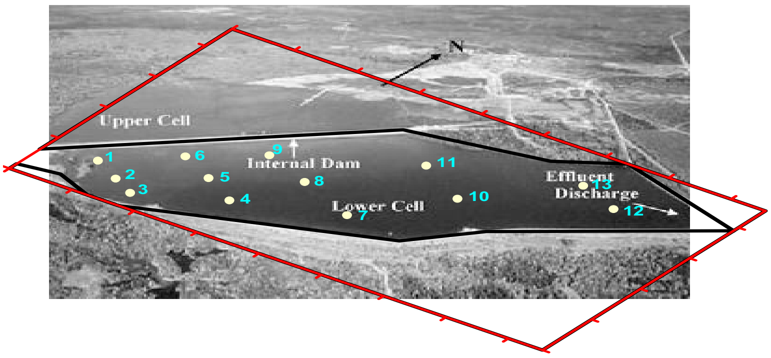

Figure 1: The study area and computational domain (photo after Peacey and Yanful 2003). Also shown are the locations where depth data are available.

2.2 Tailings Properties

Peacey and Yanful (2003) reported that for most part of the tailings pond where the water cover was less than 2.5 m deep, the tailings was overlain by finer compacted sludge. The bed tailings contained pyrite (~50%), chlorite (~20%), talc (~10%), muscovite (~10%) and quartz (~10%) as the main minerals. The sludge was formed through the addition of slaked lime and contained calcite (40-50%), gypsum (10-30%), muscovite (~20%) and quartz (~10%) as the main minerals.

The particle size distribution did not vary much between the bed tailings and the sludge; however, considerable difference in specific gravity of the two was observed. The median particle size (d_{50}) was ~ 0.011 mm.

3. RESUSPENSION AND OXIDATION PROCESSES

3.1 Wind-induced Waves and CCF

The flow field in the pond set in motion by persistent and strong winds causing tailings resuspension and subsequent increased oxidation. Two different aspects of fluid motion govern this flow field: a) surface waves, and b) surface drift and associated counter current flow (CCF) at the bottom.

Wave growth due to wind can be estimated using the methodology proposed in the Coastal Engineering Manual (CEM) of the US Army Corps of Engineers (CERC 2002). Samad and Yanful (2003) have shown that there is a reasonable agreement between predicted and field measured wave heights. Wave-induced bottom shear stress can be calculated applying linear wave theory and the quadratic friction law.

CCF induced bottom shear stress was calculated from the gradient of vertical velocity profile near the bed. The velocity profile proposed by Yang (2001) was used taking a description of eddy viscosity proposed by Wu and Tsanis (1975).

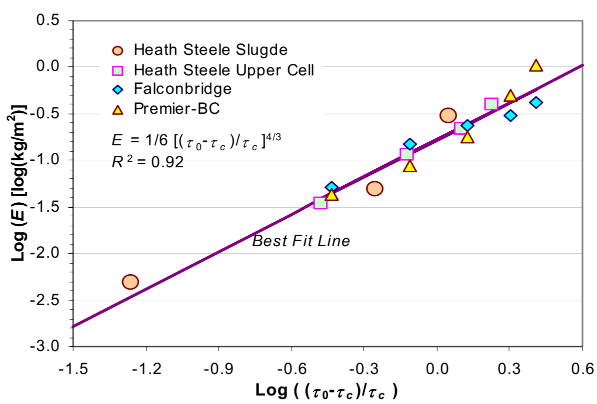

Figure 2. Estimation of coefficient and exponent in the erosion equation from circular flume data (after Samad and Yanful, 2003).

The total bed shear stress from the waves and CCF was obtained by linear summation of their contributions. Details of the mathematical formulations can be found in Samad and Yanful (2003).

3.2 Tailings Erosion and Deposition Rates

Yanful and co-workers (Samad and Yanful 2003; Peacey and Yanful 2003; Yanful and Catalan 2002, etc.) have shown that mine tailings predominantly display cohesive behaviour. Although the erosion of cohesive bed is primarily guided by bed shear, it also depends on many factors including tailings physico-chemical properties, mineralogy, and microbial processes. The flux of eroded mass can be estimated using the general form of the classical Partheniades (1965) equation. The algorithm assumes that erosion occurs when the combined bed shear stress from waves and CCF exceeds the critical bed shear stress for erosion, so that:

$$\varepsilon = M(\tau_0/\tau_c - 1)^n \quad \text{for} \quad \tau_0 > \tau_c \qquad [1a]$$

$$\varepsilon = 0 \quad \text{for} \quad \tau_0 = \tau_c \qquad [1b]$$

where ε = erosion rate (kg/m^2), M and n = coefficient in appropriate dimension and exponent, respectively, τ_0 = combined bed shear stress (N/m^2), and τ_c = critical bed shear stress for erosion (N/m^2). The coefficient and exponent for the Heath Steele Lower Cell sludge were obtained from erosion test data presented by Peacey and Yanful (2003). The relationship is also shown in Fig.2 along with erosion test results from other mine sites in Canada. The critical shear stress obtained was 0.055 N/m^2, about one-half of the value obtained for other tailings (Samad and Yanful 2003).

It is argued that for cohesive sediments, erosion and deposition never occur simultaneously (Krishnappan and Marsalek 2002). Deposition occurs when the bed shear stress is smaller than the critical shear stress for deposition (τ_D). The deposition flux can be calculated using an approach similar to that proposed by Krone (1962) and Odd and Owen (1972):

$$\delta = C_B W_s (1 - \tau_0/\tau_D) \quad \text{for} \quad \tau_0 < \tau_D \qquad [2a]$$

$$\delta = 0 \quad \text{for} \quad \tau_0 = \tau_D \qquad [2b]$$

where δ = deposition rate (kg/m^2/s), C_B = near-bed tailings concentration (kg/m^3), W_s = tailings fall velocity (m/s). Unlike Eq.1, Eq.2 is dimensionally homogeneous. For C_B, a triangular concentration profile was assumed.

The critical bed shear stress for deposition, like that for erosion, needs to be obtained through laboratory experiments. However, the authors are not aware of any such experiments for mine tailings. Krishnappan and Marsalek (2002) have reported the ratio τ_c/τ_D = 2.5 for fine sediments from a storm water management pond. The same magnitude of the ratio was used in this study.

The fall velocity, W_s (m/s), can be calculated using Stokes' law. For spheres of diameter smaller than 0.063 mm, this is given by:

$$W_s = \frac{1}{18\nu}\frac{\rho_s - \rho}{\rho} gD^2 \qquad [3]$$

where ν = kinematic viscosity of water (m^2/s), ρ_s and ρ = specific densities of tailings (2.95 for the Heath Steele sludge) and water, respectively, g = acceleration of gravity (m/s^2), and D = Stokes' particle diameter (~ d_{50}).

3.3 Oxidation and Sulphate Production

Oxidation and the subsequent sulphate production in tailings ponds occur as dissolved oxygen present in the water comes into contact with mine tailings. While resuspended tailings oxidize due to freely available oxygen in water (Hustwit et al. 1992), oxidation of the tailings at the bottom of the pond requires oxygen to diffuse through the overlying water (Morin 1993; Lapakko 1994). Oxygen consumption for oxidation of the tailings at the bed can be determined using the diffusion law. The steady state solution for oxygen flux at the bottom for unoxidized tailings is given as (Gautam and Yanful 2001):

$$O_2 \text{ flux} = \frac{\partial m}{\partial t} = C_0\sqrt{D^* K^*} \qquad [4]$$

where ($\partial m/\partial t$) = oxygen mass flux into the water (kg/m^2/s), C_0 = oxygen concentration at the air-water interface (kg/m^3), D^* = effective diffusion coefficient of oxygen in tailings (m^2/s), and K^* = oxidation reaction rate (/s). The oxygen flux can then be converted to the rate of sulphate production using the rate law and reaction rate constant

Gautam and Yanful (2001) obtained the rate of sulphate production for resuspended tailings from shake flask experiments. They proposed that:

$$SO_4^{-2} \text{ flux} = \frac{\partial m_s}{\partial t} = sE \qquad [5]$$

where ($\partial m_s/\partial t$) = sulphate mass flux (kg/m^2/s), s = sulphate production from shake flask ($kg_{[SO_4^{-2}]}/kg_{[tailings]}$/s) and ε = tailings erosion rate (kg/m^2). Gautam and Yanful (2001) obtained a value of s as 1.88 $mg/L_{[SO_4^{-2}]}$/day per $g/L_{[tailings]}$ for the Heath Steele mill tailings, which contained about 60% pyrite, 25% quartz and 8% kaolinite as the main mineral constituents.

3.4 Water Balance and Pond Water Level

The difference in the net inflow to and outflow from the pond would influence the water depth in the pond. In case of excess water it would build-up the water level, while a net loss would reduce the pond level. In either case the TSS and sulphate concentrations would be affected. The modified concentrations were modelled adopting the water balance approach. Although the model was not applied in the present set of computations, as the required climatic data were not available, the basic concepts are presented here for ready reference.

The fundamental water balance relation used is as follows:

$$\Delta S = I - O \qquad [6]$$

where ΔS = change in storage (m^3), I = net inflow volume (m^3) and O = net outflow volume (m^3).

The net inflow volume may include the contributions from precipitation (rain- and snowfall), catchment runoff, pit runoff, mill discharge, overburden pump-back or any other contribution. The outflow includes all the losses from the pond, such as evaporation, seepage, discharge to water treatment plants, and reclaimed water.

The change in storage volume is converted to the gain (or loss) in pond water level using the volume-elevation relationship of the pond. The volume-elevation relationship can be constructed once the bathymetry of the pond is known.

The change in concentration in the pond can be then calculated from the change in storage data. For the change in concentration distribution, modified water depths could be used.

3.5 Modelling Approach

The approach for modelling the physical processes is aimed at obtaining the distribution of TSS and sulphate concentrations over the pond. The distributions are obtained by dividing the pond into a number of grid cells with suitable square grid spacing and then computing the parameters at each grid cells.

The input parameters required in the model are the observed or forecasted wind speed and direction, pond geometry, bathymetry, critical shear stresses for erosion and deposition, oxidation rate constants for bed and resuspended tailings, and meteorological data. At each grid cells fetch length corresponding to the specified wind direction is computed.

Based on the wind speed, fetch and the water depth, wave- and CCF- induced bottom shear stresses are calculated to obtain the total bed shear stress. The erosion algorithm then computes the flux and eroded mass and subsequently the TSS concentration. The sulphate concentrations from bed and resuspended tailings are computed at this stage. The deposition algorithm is used along with the depth-weighted average TSS concentration to provide the reference concentration near the bed. Finally the water balance in the pond is calculated using appropriate weather data and the modified concentrations are determined.

At every step of the computation, possible alternative options and controlling sequences are included to provide wider applicability of the scenarios that may arise in practical situations. For example, different methods of wind-wave computation formulations, options for atmospheric stability effects on wave growth, and selection of appropriate friction factor description, are included in the computational procedure. A conceptual description of the computation procedure is presented in Fig.3.

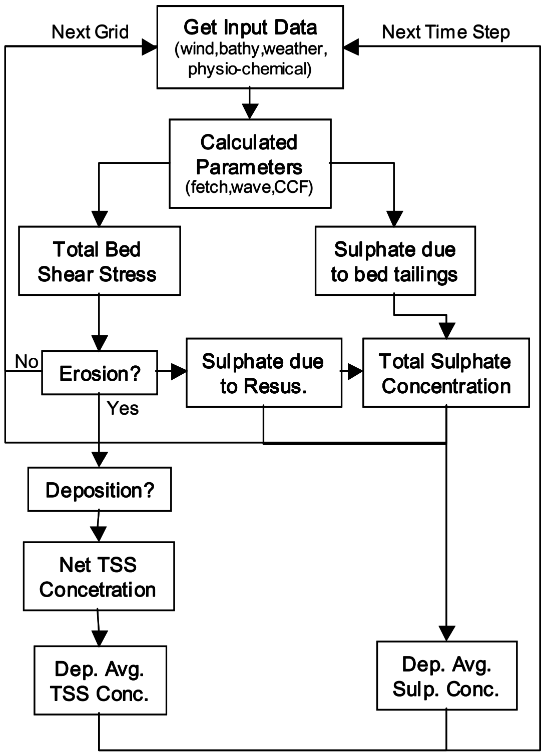

Figure 3. Conceptual flow chart of computational sequence.

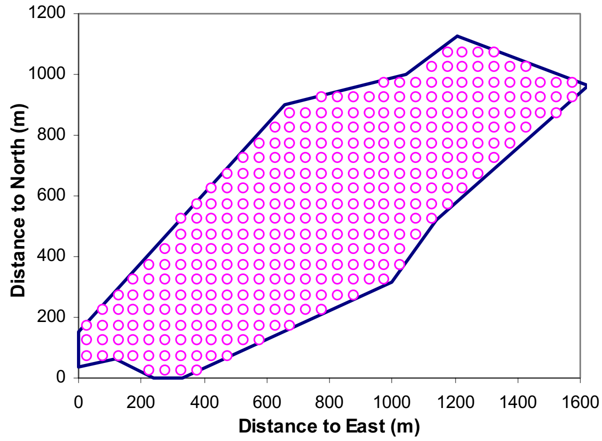

Figure 4. Pond boundary and computational grids.

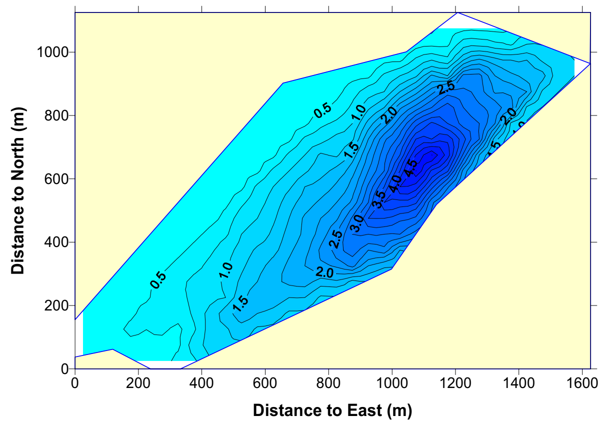

Figure 5. Contours (in m) of reconstructed bathymetry.

4. MODEL APPLICATION

4.1 Pond Boundary and Computational Grids

The pond boundary of the Heath Steele Lower Cell was digitised and used in the model to generate computational grids with 50-m square spacing. Generated grids and the pond boundary are shown in Fig.4.

4.2 Reconstructed Bathymetry

Peacey and Yanful (2003) reported depth measurement at 13 locations in the pond as shown in Fig.1. It was also reported that the water depth along the internal dam remained very shallow. Based on this information a bathymetric map was developed for application in the model. As shown in Fig.5, the bathymetric distribution was kept the same at the known locations in the pond.

4.3 Simulation Period

In the Heath Steele Lower Cell, occasional high concentration of TSS was observed. The highest TSS concentration of 157.2 mg/L was recorded on May 11, 1999 as shown in Fig.6. On May 12, 1999 the concentration was reduced, but still remained high at 64.4 mg/L. Other periods of high TSS concentration include May 13, 1996 (93.2 mg/L) and May 14, 1997 (63.3 mg/L). Because of this very high concentration of TSS, the days of May 11, 1999 and May 13, 1996 were selected as the simulation period. The time step selected was one hour and a quasi-steady behaviour of the parameters was assumed within the time steps.

4.4 Wind Data and Fetch Lengths

Although Peacey and Yanful (2003) reported average hourly measured wind speed at the pond site for May 11, 1999, they did not report the wind direction. Wind speed and direction data were collected from the Environment Canada station at Bathurst (Meteorological Service of Canada Climate ID # 8100503) located north of the study area. The data represent two minutes average wind speed recorded on the hour, and the hourly average wind direction. The wind speed recorded at Bathurst station corresponds very well with the data presented by Peacey and Yanful (2003) for May 11, 1999 and is shown in Fig.7. However, the wind direction data could not be used with the same level of confidence.

The area topography has a large influence on the wind direction, which affects the effective fetch length and subsequently the magnitude of wind-induced waves. Wind direction at Bathurst remained nearly unchanged over the day with an average wind direction of 297.2^{o} from the north (Fig.7). The distribution of effective fetch lengths in the pond for this direction is shown in Fig.8. It shows that although the longest axis of the pond has a length of about 1600 m, the maximum fetch obtained was only about 650 m. Furthermore, the region with maximum fetch lengths appeared to coincide with the region with deeper water cover, where least influence of waves on resuspension is expected. Preliminary calculations also show that this wind direction would not produce the TSS concentration as high as 157.2 mg/L. As a result the authors felt it more justified reorienting the wind direction at the site following the longest axis of the pond, which is about 225^{o} from the north. The corresponding fetch length distribution is shown in Fig.9.

The final wind data selected for May 11, 1999 include wind speed of Peacey and Yanful (2003) and a direction of 225^{o} from the north. For May 13, 1996 data from the Bathurst station were used with the same wind direction.

4.5 Time variation of TSS concentration

The variation of depth-weighted average TSS concentration with time is shown in Fig.10 along with corresponding wind speed data. The figure shows that with the increase in wind speed, the average TSS concentration in the pond starts to increase. At the beginning, with a wind speed of 5.6 m/s, the average TSS concentration was just above the initial concentration, which was assumed to be zero for this computation. The concentration increased rapidly with the persistent, strong winds and started to drop when wind speed decreased and reached a value close to 3.0 m/s, allowing deposition to predominate. At every time step the average concentration from the previous time step was assumed as the initial value. The figure also shows the measured TSS concentration of the day (May 11, 1999), however, the precise time of sampling was not known. When the time was assumed as 12:00 noon, as shown in the figure, measured and computed concentrations show excellent agreement. The maximum concentration over the storm period was much higher than the observed, ~ 325 mg/L.

The computed results for May 13, 1996 are shown in Fig.11. The wind speed data for this date was taken from the Bathurst station. Here, also, the comparison with measured data was dependent on the selection of the time of sampling. When it was assumed as 14:00 hrs, the comparison was excellent.

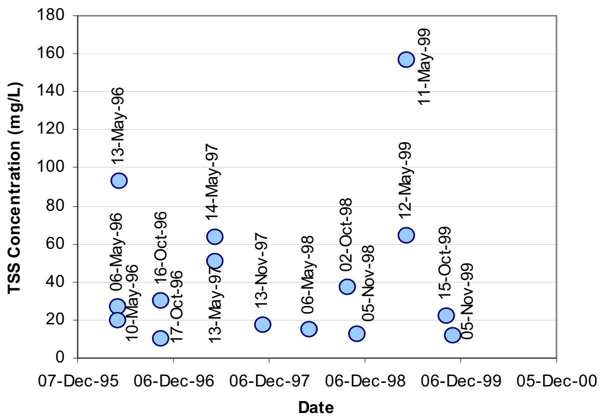

Figure 6. Observed TSS concentration data at Heath Steele Lower Cell (after Peacey and Yanful 2003).

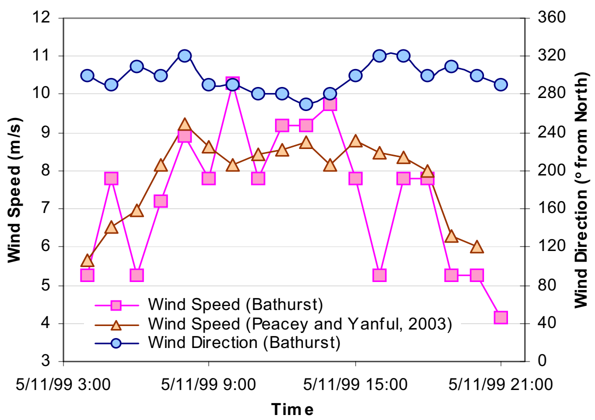

Figure 7. Recorded hourly wind speed and direction.

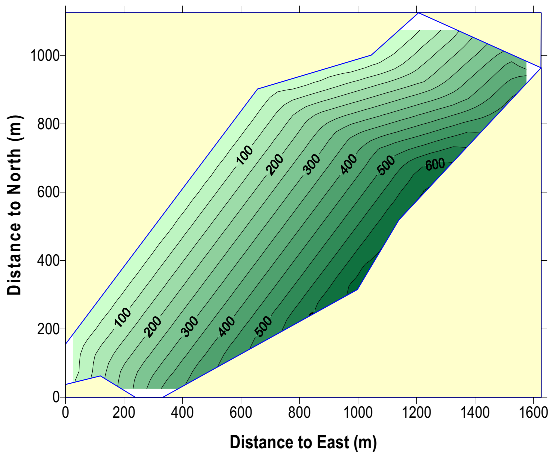

Figure 8. Fetch length distribution for the wind direction from Bathurst (298^{o} from north) wind direction.

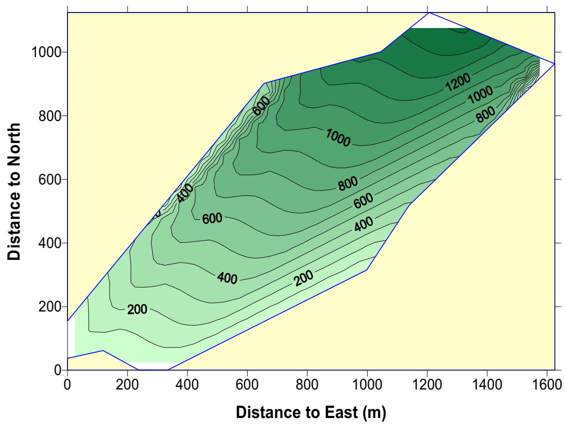

Figure 9. Fetch length distribution corresponding to the northwesterly (225^{o} from north) wind direction.

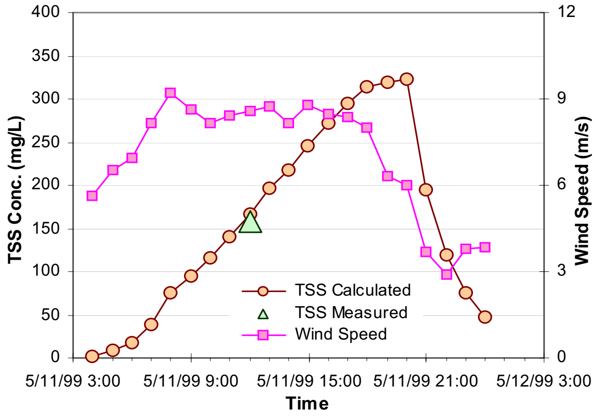

Figure 10. Variation of calculated average and measured TSS concentration with time for May 11, 1999.

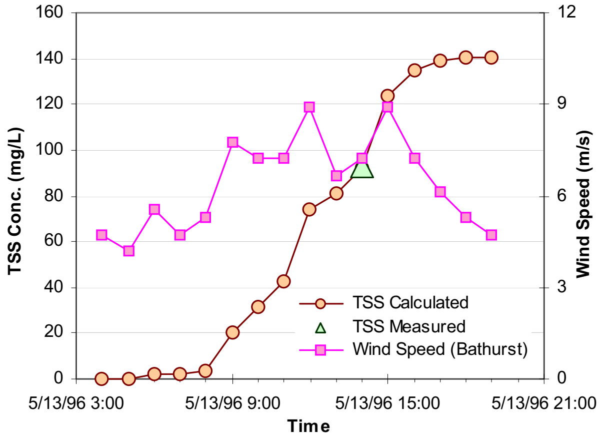

Figure 11. Variation of calculated average and measured TSS concentration with time for May 13, 1996.

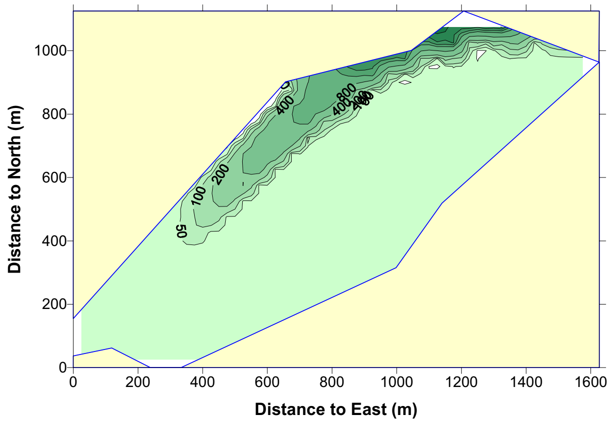

Figure 12. Map of instantaneous TSS concentration (mg/L) at 08:00 hrs on May 11, 1999.

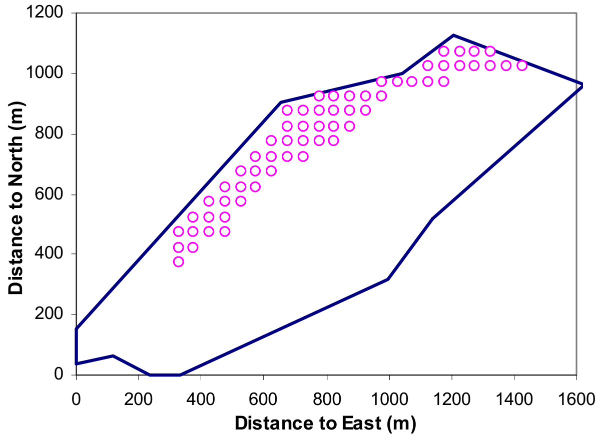

Figure 13. Grid locations where erosion was predicted at 08:00 hrs on May 11, 1999.

Because the wind direction was assumed the same on the two dates, the change in TSS concentration shows similar behaviour at the same wind speeds.

Although several major assumptions are made with respect to the input data in the model application, the results are, however, encouraging having shown good agreement with available field data. The results also suggest that the quasi-steady approach adopted in developing the model was reasonable.

4.6 Instantaneous distribution of concentrations

TSS Concentration

Instantaneous TSS concentration would be the highest at places where the highest erosion occurred. The concentration corresponding to the strongest wind speed (9.23 m/s) at 08:00 hrs on May 11, 1999 is shown in Fig.12. It shows that erosion would occur in the northeast along the internal dam where the water depths were small (bathymetry is shown in Fig.5). The grid points where erosion occurred are presented in Fig.13.

Sulphate Concentration

The distribution of total sulphate production rate in the pond at 08:00 hrs on May 11, 1999 is shown in Fig.14. It shows the combined contributions from the oxidation of bed and resuspended tailings assuming that tailings were initially unoxidized. Areas with higher water depths show small sulphate concentrations. In shallower areas oxidation of bed tailings increases due to the faster oxygen ingress to the bottom. As a result elevated sulphate release can be observed in areas where no resuspension was expected. Higher resuspension contributes to higher sulphate production as also can be observed in the figure.

5. CONCLUSIONS AND RECOMMENDATIONS

The paper presents preliminary results of a monitoring and management model for mine tailings pond. The model considers wind-induced waves and counter-current-flows to obtain the total shear stress at the bottom, which was then used to calculate the mass of tailings resuspension

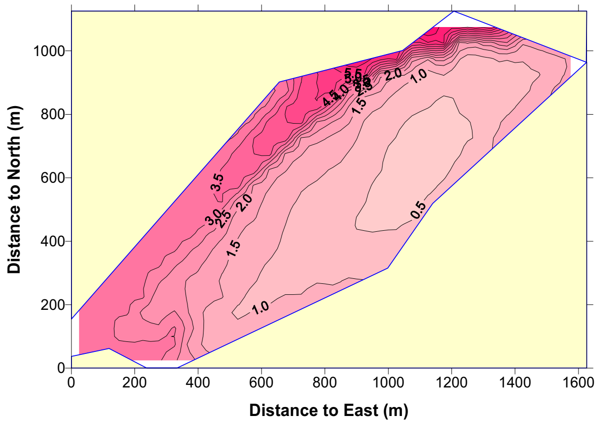

Figure 13. Map of instantaneous sulphate production rate (mg/L/day) at 08:00 hrs on May 11, 1999.

and deposition. Sulphate production from bed and resuspended tailings were also included. The model performs the computations at square grid cells within the pond boundary using the measured wind speed, direction, pond boundary, bathymetry, critical shear stresses for erosion and deposition, and tailings physical properties as input parameters. Although not included in the test model application presented in this paper, the model also includes a water balance component capable of providing the change in TSS and sulphate concentrations due to a change in storage volume of the pond.

The model was applied to the Heath Steele Lower Cell tailings pond located in New Brunswick, Canada. Computed results of TSS concentrations show good agreement with measured data for two different periods of high concentrations, and could explain the reasons behind such high values. The model also provided the effects of resuspension on sulphate production rates in the pond.

The model can be an effective tool in the monitoring and management of a tailings pond especially during and in the aftermath of a storm event when the TSS concentrations in the pond would be the highest. The use of the model for forecasting and prediction may help operators and field managers decide on appropriate measures in such events. Also in case of systematic, high releases of TSS, permanent remedial measures could be planned with the aid of the model.

6. ACKNOWLEDGEMENT

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7. REFERENCES

Catalan, L.J.J., and Yanful, K.E. 2002. Sediment-trap measurements of suspended mine tailings in a shallow water cover. Journal of Environmental Engineering, Vol. 128, No. 1, pp. 19-30.

Coastal Engineering Research Center. 2002. “Coastal Engineering Manual”. U.S. Army Crops of Engineer, U.S. Government Printing Office, Washington, DC.

Gautam, R. and Yanful, E.K. (2001). “Resuspension and consequent oxidation of mine tailings under shallow water cover”. GEOT-9-01, ISSN 0847-0262, University of Western Ontario, Canada. 32 p.

Hsutwit, N., Ackman T.E., and Erickson, P.E. 1992. The role of oxygen transfer in acid mine drainage (AMD) treatment. Water Environment Research, Vol. 64, pp. 817-823.

Krisnappan, B.G., and Marsalek, J. 2002. Transport characteristics of fine sediments from an on-stream stormwater management pond. Urban Water, Vol. 4, pp. 3-11.

Krone, R.B. 1962. “Flume studies of the transport in estuarine shoaling processes”. Hydraulic Engineering Laboratory and Sanitary Engineering Laboratory, University of California, Berkeley.

Lapakko, K.A. 1994. “Subaqueous disposal of mine waste: a laboratory investigation”. Proc. of the 3rd International Conference on Abatement of Acidic Drainage, Pittsburgh, USA. Vol. **I**, pp. 270.

Morin, K. 1993. “Rate of sulfhide oxidation in submerged environments: implications for subaqueous disposal”. Proc. of the 17th Annual BC Mine Reclamation Symposium, Canada. pp. 235-247.

Odd, N.V.M, and Owen, M.W. 1972. “A two-layer model of mud transport in the Tames estuary”. Proc. of Institute of Civil Engineers, London, UK, pp. 195-202.

Partheniades, E. 1965. Erosion and deposition of cohesive soils. Journal of Hydraulic Engineering Division, ASCE, Vol. 91, pp. 105-139.

Peacey, V. and Yanful, E.K. 2003. Metal mine tailings and sludge co-deposition in a tailings pond. Water, Air, and Soil Pollution, Vol. 145, pp. 307-339.

Pederson, T.F., McNee, J.J., Flather, D., Sahami, A., Mueller, B., and Pelletier, C.A. 1997. “Geochemistry of submerged tailings in Buttle Lake and the Equity Silver tailings pond, British Columbia, and Anderson Lake, Manitoba: What have we learned?”. Proc. of the 4th International Conference on Acid Rock Drainage, Vancouver, Canada. Vol. III, pp. 991-1005.

Samad, M.A., and Yanful, E.K. 2003. A design approach for selecting the optimum water cover depth for subaqueous disposal of sulfide mine tailings. Provisionally accepted for Canadian Geotechnical Journal.

Wu, J., and Tsanis, I.K. 1995. Numerical study of wind-induced water currents. Journal of Hydraulic Engineering, Vol. 121, No. 5, pp. 388-395.

Yanful, E.K., and Catalan, L.J.J. 2002. Predicted and field-measured resuspension of flooded mine tailings. Journal of Environmental Engineering, Vol. 128, No. 4, pp. 341-251.

Yang, Y. 2001. Wind induced countercurrent flow in shallow water. Ph.D. Dissertation, University of Western Ontario, London, ON, Canada. 223 p.