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A SPATIAL FLUX BOUNDARY MODEL FOR TAILINGS DAMS

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ABSTRACT

Closure of mines and the associated rehabilitation is of utmost importance to the mining industry. Rehabilitation of tailings dams is one of the most challenging aspects, as not only does the potential for producing leachate pose a challenge to the rehabilitation designer, but also other aspects such as stability and settlement must be considered. The water balance of a tailings dam is unique in the sense that it usually hosts a pond that in turn causes a phreatic level in the dam. The position of the phreatic surface defines the saturated and unsaturated zones in the impoundment, which of course varies spatially and temporally. Predictive modelling for this hydrologic system becomes difficult, as numerical models capable of analysing the combined saturated/unsaturated zones are not adequately refined to accurately solve the flux boundary problem for infiltration at the surface of the tailings. This paper describes a conceptual approach that was developed to enable accurate modelling of the unsaturated zone in the tailings dam at Kidston Gold Mine, Queensland, Australia. The technique made it possible to accurately predict the spatial variation of infiltration to the tailings as a result of the presence of the phreatic table.

RÉSUMÉ

La réhabilitation associée à la fermeture de mines est d'extrême importance pour l'industrie minière. La réhabilitation des résidus de barrages représente un des plus grands défis puisque non seulement le potentiel de production de filtrat pose un défi au designer de réhabilitation mais aussi d'autres aspects tels que stabilité et établissement doivent être considérés. L'équilibre en eau des résidus d'un barrage est unique dans le sens qu'il nourrit habituellement un étang qui à son tour cause un niveau phréatique dans le barrage. La position de la surface phréatique définit les zones saturées et insaturées dans l'étang laquelle, bien sûr, varie spacialement et temporellement. Un modèle de prédiction pour ce système hydraulique devient difficile puisque les modèles numériques capable d'analyser les zones combinées saturées/insaturées ne sont pas raffinés adéquatement pour résoudre exactement le problème de frontières de flux pour l'infiltration à la surface des résidus. Cet article décrit une approche conceptuelle qui a été développée pour rendre possible un modèle précis de la zone insaturée dans les résidus du barrage de Kidston Gold Mine, Queensland, Australie. La technique a rendu possible la prédiction exacte de la variation spaciale de l'infiltration des résidus comme résultat de la présence de la nappe phréatique.

1. INTRODUCTION

Kidston Gold Mine is located 360 km south-west of Cairns in north Queensland, Australia. Mining operations commenced in 1984 and by December 1999, 3.2 million ounces of gold had been recovered from the Eldridge and Wises Hill Pits. Proven reserves will support a projected mine life until June 2001. The climate is tropical with a distinct dry and wet season (November to April) when 80% of the average 702 mm precipitation falls. Annual potential evaporation averages 1700 mm (Rykaart, 2001), resulting in a net negative water balance.

1.1 Kidston Tailing dam description

Tailings (68 Mt) was stored in an engineered tailing dam (310 ha) between 1984 through to October 1997. Prior to 1991 the deposition technique was long-beach deposition at the back end of the impoundment with decant towers along the upstream edge of the main embankment. In 1991 the strategy was changed to one of sub-aerial deposition around the periphery of the impoundment with the final decant tower located in the back south-east portion of the dam where it is buttressed into a local hill, Paddy's Knob (Figure 1) (Currey, 1998).

The 5.8 km long embankment wall, which encircles about 70% of the perimeter of the tailing dam, is constructed from waste rock, and was progressively raised in five lifts (3 downstream and 2 centreline). The embankment height varies between 32 m at its highest point at the northern end, to less than 1 m in the south.

Seepage from the embankment (due to the presence of chimney & blanket drains) is collected via 2-3 m deep interception trenches cut down through a decomposed granitic layer. Seepage from the base of the dam is limited by the impervious nature of the underlying Einasleigh Metamorphics. Tests confirmed an average base permeability of 9.6 x 10^{-9} m/s (Gutteridge, Haskins & Davey, 1984; Rykaart, 2001).

After October 1997 tailings deposition was changed to thickened tailings deposited in the mined out Wises Hill Pit, and rehabilitation of the tailing dam started.

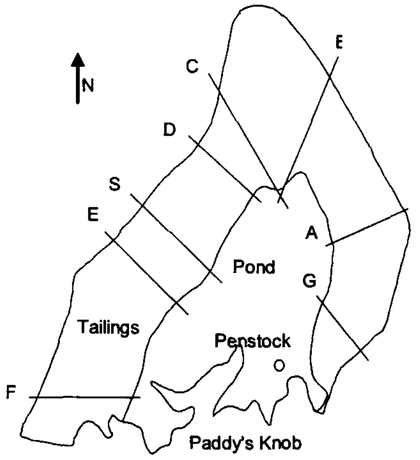

Figure 1. Simplified plan view of the Kidston tailing dam, showing the penstock location after 1991, and the piezometer section lines.

1.2 Kidston tailing dam rehabilitation philosophy

Kidston Gold Mine opted not to rehabilitate the tailing dam using the Australian Environment Protection Agency (EPA) best practice guidelines, which entails placing a soil cover to limit oxygen and water infiltration and act as a growth medium (EPA, 1995). The closure plan called for direct vegetation of the tailings surface with native grass and tree species. Although uncommon, this method of rehabilitation is often used in South Africa (Blight, 1989), and even recently in New Zealand (Mason *et al.*, 1995). The philosophy behind Kidston's rehabilitation approach is based on economical and technical grounds. Firstly, should the vegetation be found to establish on the tailings surface, it would render an imported soil growth medium redundant. Secondly, the increased evapotranspiration rates is expected to result in a lowering of the tailing dam phreatic level, and ultimately in a reduction in the seepage rate from the dam, thereby achieving compliance.

2. PROBLEM STATEMENT

Kidston Gold Mine need to prove that the closure alternative of direct vegetation to the tailings would not pose any environmental risk. To this effect Kidston initiated comprehensive research programs (Ritchie & Currey, 2000), of which the understanding of the unsaturated zone water balance of the tailing dam is but one component. The following section describes the principles, which led to the development of the conceptual model described in this paper.

2.1 The spatial infiltration hypothesis

A large saturated zone exists in the tailing dam due to the presence of the pool. The established phreatic line has a shape, which is governed by the tailings properties, and the exit location is determined by the presence of drains in the embankment walls. If one thus considers a typical cross-section at any location through the tailing dam (Figure 2) there would be a unsaturated zone of tailings which varies in thickness from the embankment end to the pool end.

The top tailing dam surface (beach profile) along this typical cross-section would be subject to all the usual water balance components of precipitation (P), evapotranspiration (ET), Infiltration (I), runoff (R), recharge (Re), and seepage (S). We would however expect that there would be a spatial variation in the magnitude of these components as we move between the embankment and the pool. The reason for this is the availability of moisture in the profile, which is governed by the presence of the phreatic level (Staley, 1957; Blight, 1997). Therefore, at a point close to the embankment we would expect evaporation to be a minimum, and as we move towards the pool the evaporation should increase until it reaches a maximum (potential evaporation) at the pool edge. Similarly we would expect infiltration to be a maximum close to the embankment, decreasing towards the pool. This is simplistically illustrated by the graph in Figure 2.

This paper illustrates an attempt to show what the spatial distribution of the surface fluxes are, thus paving the way for accurate unsaturated zone water balance modeling.

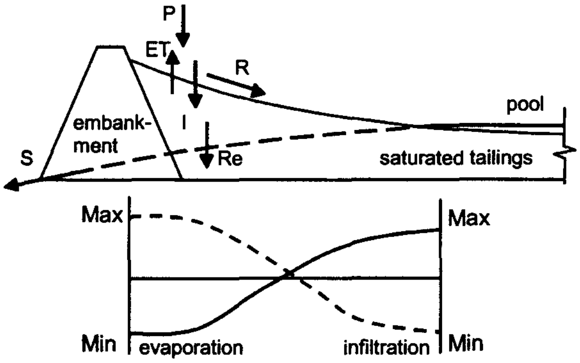

Figure 2. Spatial surface flux distribution through a typical tailing dam cross-section.

3. SURFACE FLUX CALCULATION METHODOLOGY

Estimating tailing dam water balances has always been an important issue, be it for operational- or closure water management. Most of the saturated zone water balance components are relatively well understood and can be estimated or measured with relative ease and with a high degree of confidence. However, the same cannot be said for the surface flux components above the unsaturated zone. The measurement of these fluxes is difficult, expensive and time consuming, and as a result engineers look towards numerical modelling to provide the answers. Important advances have been made in this regard, with the development of software like SoilCover (SoilCover, 1997), HELP (Schroeder *et al.*, 1994), UNSAT-H (Fayer & Jones, 1990), SWACROP (Feddes *et al.*, 1984), HYDRUS (Simunek *et al.*, 1998), and SWIM (Ross, 1990), to name but the few most well known.

These models all attempt to calculate the surface flux components using a multitude of methods and assumptions. The most important single component is accurate calculation of evaporation, and the most accurate method to calculate this is using the Modified Penmann Formulation as proposed by Wilson *et al.* (1994). The only known model that currently uses the Modified Penmann Formulation is SoilCover, and that makes it the most appropriate tool to use.

Due to the detailed field data required for accurate use of a model like SoilCover, and the fact that it is only a 1-Dimensional (1-D) model, the surface flux is often oversimplified using coarse recharge numbers. It is common practice to solve these water balance problems using saturated/unsaturated groundwater modelling software like SEEP/W (GEO-SLOPE, 1991). These packages do not allow for the calculation of the surface fluxes, but require some form of recharge input. To obtain this recharge value the modeller will calibrate towards a known parameter, mostly being a phreatic level, and as such the most suitable recharge value might not represent the surface flux situation accurately.

The authors suggest that by using the proposed conceptual model to determine the spatial surface flux distribution, the tailing dam water balance can be accurately calculated based on actual calculated, not inferred infiltration rates. The spatial distribution surface flux functions calculated using the conceptual model can thus be used directly as a surface flux input in regional saturated/unsaturated groundwater modelling packages, effectively bridging the current gap between the two modelling systems.

4. CONCEPTUAL MODEL

Modelling the complete unsaturated profile of the tailing dam, using SoilCover, proved to be difficult due to the temporal, and more important, the great spatial variability of the phreatic level. To overcome this problem a conceptual model of the typical tailing dam cross-section was developed, which would act as the basis for all SoilCover modelling. The conceptual model defines the geometry (boundaries) of a typical tailing dam cross-section via a set of functions that describe the shape of the tailing dam beach profile and the phreatic line shape.

4.1 Beach shape function

The beach shape function was developed using the principles of particle segregation down a slope. Due to the hydraulic deposition of tailings, particle segregation takes place as the excess water flows to the pond. The coarsest particles settle out first, close to the embankment, whilst the finer slimes only settle in the pond base. Numerous researchers have studied this aspect, both in natural streams (Morris & Williams, 1999) and more specifically on tailing dam beaches (Blight, 1987).

The Kidston tailing dam surface was investigated and seven representative section lines was chosen and accurately surveyed (Figure 1). The slope of the beach profile proved to be on average 1%, and followed the classical exponential shape observed by Blight (1987) in his master profile studies. Figure 3 presents the measured beach slopes along the seven section lines together with the best-fit function to describe the beach shape. For comparison the measured profile of a gold tailing dam in South Africa as reported by Blight (1987) is included. The function, which follows the principles of the tailings master profile (Blight, 1987) is expressed as follows:

$$\frac{h}{y} = \left(1 - \frac{H}{X}\right)^{n} \qquad [1]$$

In equation [1], H (m) is the distance along the beach profile as measured from the embankment to the edge of the pool, and X is the maximum length of the beach profile (650 m for the typical tailing dam cross-section at Kidston). The height of the beach surface above the pool level at any point along the beach profile is given by h (m), and the maximum height of the beach surface above the pool level, which is at the embankment is given by y (3.4 m for the typical tailing dam cross-section at Kidston). The dimensionless shape constant, n = 1.85, and is based on the best fit with respect to the measured beach profiles.

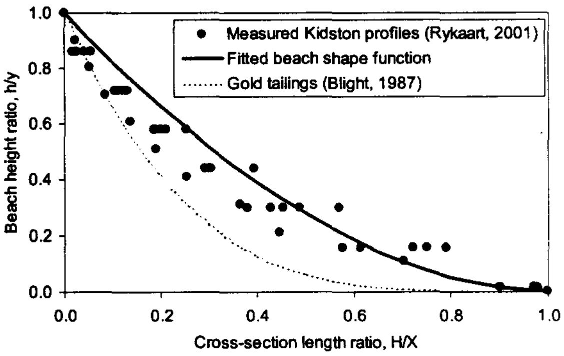

Figure 3. Fitted beach shape function for the beach profiles measured on the Kidston tailing dam.

4.2 Phreatic line shape function

Developing a function for the shape of the phreatic line was based primarily on observational methods. 42 Piezometers was installed along the seven representative section lines in the dam (Figure 1) and the database of measured levels (spanning from 1997 to 2001) from the

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installed piezometers was used to develop a calibrated function that supports the shape well. This function is presented by:

$$\frac{h}{y}=\left(1-\frac{H}{X}\right)^{-n} \qquad [2]$$

H and X are as defined for equation [1]. The depth of the phreatic level below the pool level at any point along the beach profile is given by h (m), and the maximum phreatic level depth below the pool level, which is at the embankment is given by y (10.0 m for the typical tailing dam cross-section at Kidston). The dimensionless shape constant, n = 4, is based on the best fit with respect to the measured piezometer levels. Figure 4 presents how the shape function fits measured piezometer data from the seven section lines.

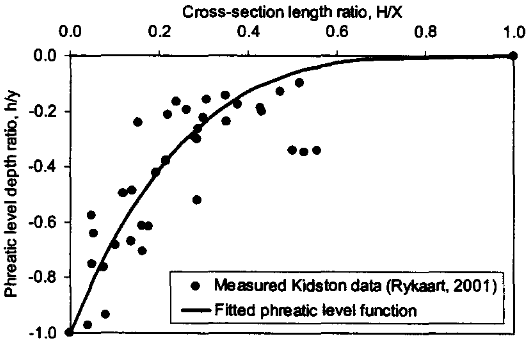

Figure 4. Fitted phreatic line shape function based on measured piezometer levels from the Kidston tailing dam.

4.3 Combined conceptual model

Combination of the beach shape and phreatic line shape functions makes it possible to know exactly what the depth to the phreatic level would be at any point along the typical tailing dam cross-section (Figure 5). For the typical Kidston tailing dam cross-section the maximum depth to phreatic level is 13.4 m.

5. MODELING METHODOLOGY

5.1 SoilCover Calibration

To conduct any modelling with a degree of certainty, model calibration is required. The SoilCover model for the results reported in this paper, was calibrated using the continuous data set of climatic, Bowen ratio, matric suction and phreatic level data measured at a single location on the tailing dam.

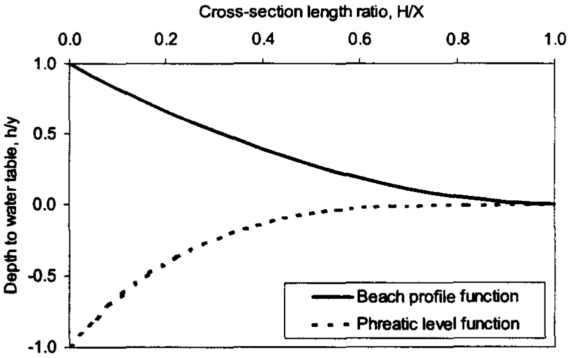

Figure 5. Combined beach- and phreatic line shape functions for the typical Kidston tailing dam cross-section.

The data loggers were not fully operational for the entire monitoring period (1996-2001), and as a result three individual portions of uninterrupted data, which spans over a number of months were chosen to do the model calibration against.

Excellent data existed for the physical description of the model in terms of physical and hydraulic tailings properties, as well as tailings hydraulic conductivity. Good correlation's between modelled and measured tailings suctions were obtained, although only by spreading all rainfall events over a 24-hr period. Using actual measured rainfall intensities created significant instabilities in the modelling, and as a result was not used. The measured Bowen ratio data further supported the trends observed in the modelling.

The outcome of the calibration procedure was that SoilCover could be used with confidence to calculate the water balance in the upper unsaturated zone of the tailing dam (Rykaart, 2001).

5.2 Solving the conceptual model using SoilCover

In order to conduct SoilCover modelling on the typical tailings dam cross-section (650 m long) (Figure 5) a decision was made to divide the section into 13 zones (each 50 m wide). An individual SoilCover model would then be run for each zone, and by integrating the computed surface fluxes over the entire tailings cross-section a good estimate of the cumulative result would be obtained. This approach thus allows for a 2-Dimensional (2-D) solution using the 1-D SoilCover model.

5.3 Tailings properties used in SoilCover modelling

Extensive laboratory testing, including 66 grain size distribution- and 25 soil water characteristic curve tests was done on the tailings material. The tailings varies from well graded sands (SW) (Unified Soil Classification System, Holtz & Kovacs (1981)), with an average D_{50} of

0.26 mm, to fine sands (ML), and an average D_{50} of 0.03 mm (Rykaart, 2001).

The soil water characteristic curves indicated a saturated volumetric water content (θ) ranging between 34 and 56%, an Air-Entry Value (AEV) ranging between 1.1 and 12 kPa and a residual suction (ψ_r) ranging between 1.6 and 700 kPa (Rykaart, 2001). The data base of tested tailings properties was used to define three main tailings types for modelling purposes; coarse, intermediate and fine. Using a single averaged material type for the entire tailing dam cross-section would not be accurate as measured data had shown that the tailings becomes progressively finer as one moves away from the wall towards the beach (due to natural particle segregation). The choice of three material types was also based on work done by Kealy & Busch (1971), where they modelled seepage from mill-tailings, and found that three tailings types best describe the model.

The three soil water characteristic curves for these tailings types were respectively selected based on the 75, 50 and 25%-tile values of the θ, AEV and ψ_r measured values (Table 1). The steepness of the curves caused modelling instability and these curves had to be flattened in the high matric suction range. Figure 6 presents the soil water characteristic curve properties of the tailings as used in the SoilCover modelling.

TABLE 1: Soil water characteristic curve properties for the three chosen tailings types.

Tailings type	θ	AEV	ψ_r
Coarse	39%	2.5 kPa	9.0 kPa
Intermediate	42%	3.5 kPa	18.5 kPa
Fine	44%	6.0 kPa	100.0 kPa

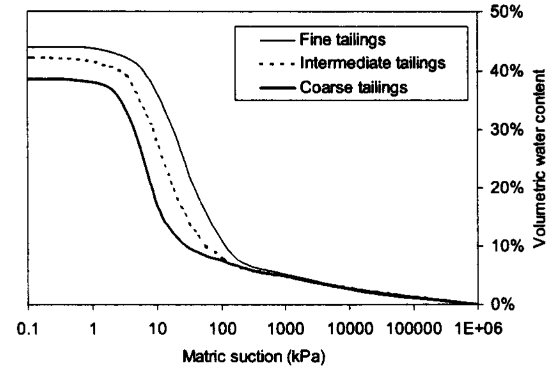

Figure 6. Soil water characteristic curves for the three selected tailings types used in the SoilCover modelling.

Where the transitions between these tailings types down the beach profile would be was not firm, but would be determined upon the outcome of the actual modelling. Kealy & Busch (1971) used a 6:6:1 ratio for their three tailings types, moving from the embankment towards the pool. For the typical Kidston tailing dam cross-section a final tailings zone ratio of 5:5:3 was adopted as a good transition for the tailings types. This means that for the first five of the 13, 50 m wide modelled zones, coarse tailings was used, the next five zones intermediate tailings, and the final three zones was modelled with fine tailings (250 m:250 m:150 m for this 650 m section).

To define the vertical saturated hydraulic conductivity on the tailings beach profile for each of the 13 zones, a theoretical function for saturated hydraulic conductivity was developed. This function was verified using measured field data (Figure 7). The data consists of 29 laboratory saturated permeability tests, 62 Guelph permeameter tests, 8 double-ring infiltrometer tests and 14 rainfall simulator tests (Rykaart, 2001). The resultant surface permeability function is described by the following expression:

$$k_S = 1.94\times10^{-5}\cdot e^{(-0.00977\cdot H)} \qquad [3]$$

Where k_s (m/s), is the vertical saturated hydraulic conductivity on the surface of the typical Kidston tailing dam cross-section at any given point along the beach profile, H (m) is the distance along the beach profile as measured from the embankment, and e is the base of the natural log.

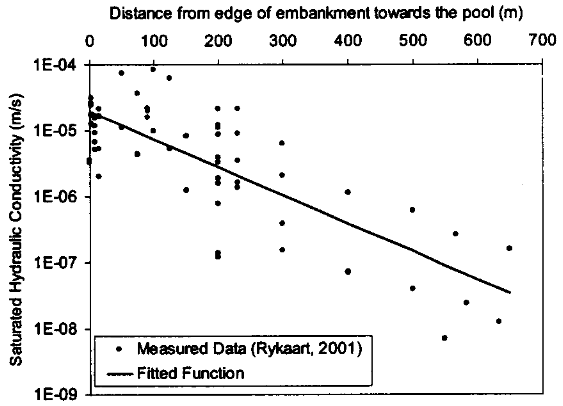

Figure 7. Vertical saturated hydraulic conductivity function for the beach profile of the typical Kidston tailing dam cross-section.

Any vertical tailings profile is not homogeneous, and the physical and hydraulic properties of each of the horizontal tailings layers can vary significantly. 27 Horizontal saturated conductivity, k_h, tests was performed on the Kidston tailings (Douglas Partners, 1997; Earthtech Consultants, 1999), with results varying over three orders of magnitude. This confirmed visual observation of thin slimes bands encased by otherwise coarse tailings. These slimes bands are never continuous, as the deltaic depositional method of the tailings prevents this.

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The average k_h/k_s ratio for the coarse tailings is 0.02, 0.03 for the intermediate tailings, and 0.06 for the fine tailings. In surface flux calculations, the surface properties have the greatest influence on the flow regime. This fact led to the decision that for the SoilCover modelling of the typical Kidston tailing dam cross-section, homogeneous vertical layers would be considered. Since the model calibration was done using a homogeneous profile with good effect, it is believed to be a reasonable assumption.

5.4 Overall tailing dam water balance

The use of the SoilCover model and procedure outlined above still presented a problem in the sense that there was no way to measure whether the integrated SoilCover answer was in fact correct. To overcome this problem a primary water balance of the entire tailing dam complex was done using available physical data. The water level in the pond was known since 1997, and this data together with survey data was used to calculate a stage curve for the tailing dam pond. Complete climatic data was available for the same period, which allowed for the determination of total rainfall as well as the calculation of potential evaporation from the pond and tailing dam. Data for seepage rates from collection drains around the tailing dam was used to calculate an overall seepage loss, and together an estimated runoff value into the pond was calculated as being in the order of 40%. This value was used as the guideline against which the SoilCover modelling had to be measured.

5.5 SoilCover climate data

The daily climatic data required for the SoilCover modelling presented in this paper consisted of a year of typical average data for the Kidston site. This data includes minimum and maximum air temperature, minimum and maximum relative humidity, net radiation, windspeed, and rainfall. The typical data set was made up using continuous on-site weather station data from 1996, historic daily data from 1983, as well as regional records dating back 50 years (Rykaart, 2001). The total annual precipitation used was 702 mm.

6. SPATIAL INFILTRATION

Solving of the 13 individual SoilCover runs, using each of the chosen tailing types, as well as the final optimal combined solution, each presents different spatial distribution functions for the surface flux components. Figure 8 presents the distribution of the actual evaporation/potential evaporation ratio (AE/PE). It is evident that the AE/PE ratio is the least close to the embankment and gradually increases to a value of 1, near the edge of the pool. This is consistent with the proposed hypothesis in Figure 2.

The overall AE/PE ratio for the fine tailings exceeds that of the coarse tailings, and that can be explained by the increased capacity of the fine tailings to retain moisture, as well as the increased capillary suction.

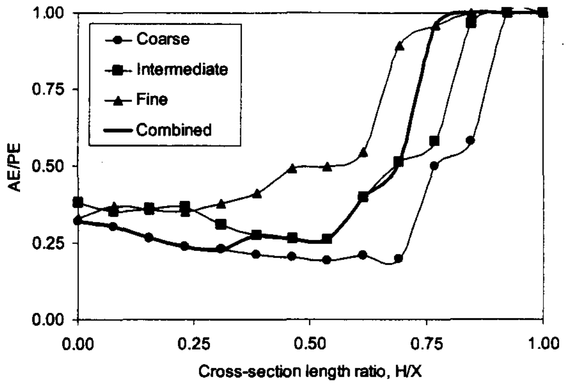

Figure 8. Spatial AE/PE distribution along the typical Kidston tailing dam cross-section.

It is interesting to note that the spatial AE/PE distribution is not linear, but remain almost constant in each case before rapidly increasing from a H/X ratio of ≈0.6 (325 m) for the fine tailings, to ≈0.72 (468 m) for the coarse tailings. The reason for this is the rapidly decreasing depth to the phreatic level as a result of the two exponential shape functions (Figure 5). The coarse tailings AE/PE ratio remain constant for longer due to the inability to replenish water from the water table, due to the lower AEV.

The net infiltration ratio (NIR) is used to present the net infiltration (NI) data on the same basis as the AE/PE ratio. The NIR presented in Figure 9 is defined as:

$$NIR = 1 - \frac{NI_z}{NI_t} \qquad [4]$$

In equation [4], NI_z is the zonal net infiltration for each of the 13 modelled zones, and NI_t, is the total net infiltration integrated over the entire typical tailing dam cross-section. The NI is defined as:

$$NI = P - R - ET \qquad [5]$$

The trends in Figure 9 again follow the spatial infiltration hypothesis, with the maximum net infiltration occurring at the embankment end, and the least happening at the pool end of the tailing dam. There is little difference between the coarse and intermediate tailings curves, both showing a steep drop in infiltration from a H/X ratio of ≈0.75 (488 m). The fine tailings show an overall lower NIR, and drops steeply from a H/X ratio of ≈0.6 (390 m).

Combination of the AE/PE function, and the net infiltration function as presented in Figure 10, shows how these two spatial flux distribution functions compliment each other, and allow for a direct comparison with the hypothetical graph depicted in Figure 2.

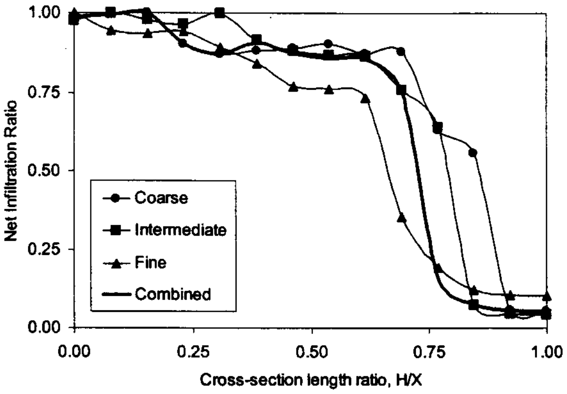

Figure 9. Spatial net infiltration distribution along the typical Kidston tailing dam section.

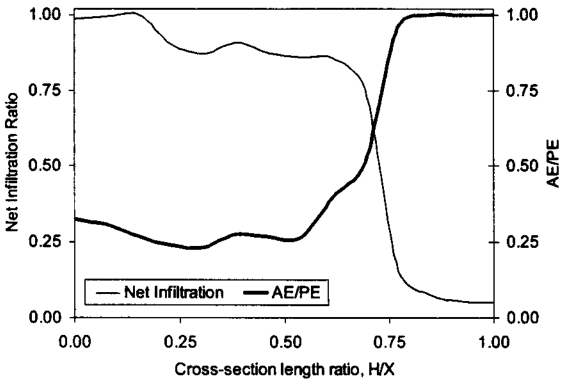

Figure 10. Combined spatial AE/PE and net infiltration distribution along the typical Kidston tailing dam section.

The unsaturated zone water balance results for all the modelled cases are summarised in Table 2. All the data has been expressed as percentage of the total precipitation. The negative NI indicates a net negative water balance from the system, which in this case would imply the lowering of the phreatic level. It is important to note that although the term ET is used, the modelled cross-section reported on here does not contain any vegetation, and as a result the ET refers to only evaporation.

Table 2: Overall surface flux water balance based on the typical Kidston tailing dam cross-section.

Tailings type	R	ET	NI
Coarse	51%	86%	-37%
Intermediate	32%	114%	-45%
Fine	20%	142%	-62%
Combined	40%	114%	-55%

The spatial net infiltration function for the typical Kidston tailing dam cross-section presented here, can be used as the input recharge value in other saturated/unsaturated groundwater modelling software like SEEP/W. Figure 11 present a step function showing how the monthly breakdown of the net infiltration data shown here can be used as input to other modelling packages. The idea is that such a function would be produced for each of the 13 zones, and these fluxes would be the top boundary condition in 2-D and 3-D predictive modelling. The tailing dam surface can thus be divided into 13 iso-zones (zones of equal net infiltration).

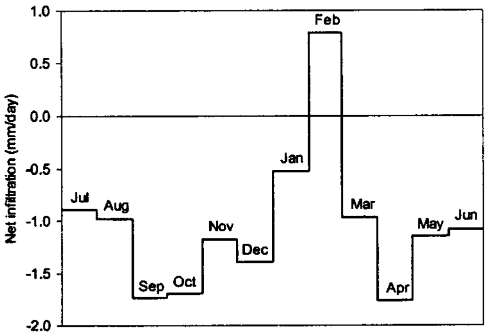

Figure 11. Monthly distribution of net infiltration aggregated over the entire typical Kidston tailing dam cross-section.

7. CONCLUSION

The authors presented a conceptual model to allow the calculation of accurate unsaturated zone surface fluxes along a 2-D tailing dam section, using the most accurate 1-D numerical model, SoilCover. The conceptual model is based fully on physical characterisation of the problem at hand, and can be applied and modified for any tailing dam.

The real benefit of this work is in bridging the gap between calculating true surface fluxes, for use in regional groundwater modelling. The spatial surface flux distribution functions can directly be used as input in 2-D and 3-D saturated/unsaturated flow models, and eliminates the need for recharge guesswork and estimations.

The calculated spatial surface flux distribution functions confirm the spatial infiltration hypothesis presented in this paper. By calculating a calibrated spatial infiltration function for a tailing dam, predictive modelling can be done, by merely manipulating the function according to the changed climatic conditions, without having to rerun the SoilCover model.

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8. ACKNOWLEDGEMENT

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