Surface Boundary Conditions for Finite Element Simulation of Platinum Tailings in a Semi-Arid Environment

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Abstract

The evaporation fluxes from a platinum tailings beach were measured before, during and after a period of slurry deposition. The time series measurements were made using a surface renewal system, set up above the tailings beach. Results of the measured evaporation were compared with atmospheric potential evaporation. The comparisons demonstrated that actual evaporation was lower than potential prior to deposition, equal to potential during, as well as following deposition, and finally lower than potential some days after cessation of deposition. These phenomena were assumed to result from the simultaneous evaporation drying and consolidation processes in the deposited layer, and implication for appropriate beach surface boundary conditions for finite element modelling of the tailings, were developed and tested. The final outcome will contribute to realistic simulation of the ingress and fate of slurry water and rain in tailings impoundments.

Keywords: Tailings water evaporation, infiltration, surface renewal, tailings water modelling

Introduction

In the semi-arid areas of southern Africa, Annual Potential Evapotranspiration (PET), the atmospheric demand for water uptake, can exceed annual rainfall by more than threefold. Nevertheless, the intensity and volumes of daily rainfall result in water ingress into platinum tailings porous media and result in periodic recharge to a phreatic surface. In this semi-arid environment, evaporation losses from bare surfaces are primarily dependent on the hydraulics of the porous medium, which controls the fluxes of water and vapour to the surface, rather than the atmospheric demand. However, the fate of deposited water and rainfall is difficult to assess, particularly at high rates of rise, due to the partition of fluxes, comprising surface runoff to the pool, infiltration during rain and slurry deposition, percolation from the deposited layer post deposition, entrainment of interstitial water and evaporation from wetted and drying surfaces. Practitioners have often resorted to empirical approaches to estimate evaporation losses and infiltration rates. This can result in significant error to the overall water budget, poor estimates of recharge to the phreatic surface and confounding conditions for water management.

In this paper, a series of simultaneous observations of atmospheric driving forces, material characteristics and water dynamics were conducted in situ. The observations included full meteorological monitoring and characterisation of the tailings hydraulic properties. In-situ observations included automatic recording lysimeters in the tailings beach to measure evaporation rates and tailings pore water sensors in selected profiles on the beach to measure infiltration and percolation flux states. Finally, a Surface Renewal station was erected on the tailings beach to observe actual evaporation fluxes prior to, during and post deposition. The Surface Renewal observations, presented in this paper, were compared with estimates of PET, using meteorological observations, and the possible mechanisms controlling the evaporation from the beach were deduced. The results are used to inform finite element modelling simulations of the saturated and unsaturated pore water processes.

Methodology

Evaporation from surfaces can be determined directly from the Latent Energy Flux (λE) above the surface. The Latent Energy Flux is one of the terms making up the total energy balance of evaporating water, given by:

$$Rn = G + H + \lambda E \quad (1)$$

where:
Rn = Nett Irradiance (Watts/m^2);
G = Soil Heat Flux (Watts/m^2) and
H = Sensible Heat Flux (Watts/m^2).

Equation 1 can be solved for the Latent Energy Flux as:

$$\lambda E = Rn - G - H \quad (2)$$

The evaporation rate, E, can be calculated from the Latent Energy Flux (λE), since the Specific Latent Heat of Vaporisation (λ) is known. The nett irradianc, Rn, can be measured with a Nett Radiance sensor and G can be measured using Soil Heat Flux Plates. This leaves the Sensible Heat Flux, H, which is measured using Surface Renewal (SR) principles (Mengistu and Savage, 2010; Savage, 2017; Hu *et al.*, 2019).

The SR method is based on the premise that a parcel of air connected to the surface (a in Figure 1), after it has been enriched or depleted (b in Figure 1), is renewed by an air parcel from above (g ang h in Figure 1). The SR technique for estimating Sensible Heat Flux from surfaces therefore involves high-frequency temperature measurements (10 Hz, in this case), using unshielded and naturally-ventilated fine wire thermocouples at a specific height above the surface, (Mengistu and Savage, 2010). The high-frequency temperature measurements are analysed to describe the temperature "ramping" (renewal) process (e-h in Figure 1). These functions are saved and solved for the amplitude "a" (see g in Figure 1) and period "τ" (see g in Figure 1). The Sensible Heat Flux is calculated as a function of a/τ.

The instrumentation established on the platinum tailings impoundment beach is illustrated in Figure 2.

The instrumentation was raised on stands to allow for the deposition of a tailings slurry layer (Figure 3). The observation period lasted for 68 days comprising 25 days prior to deposition, 16 days of deposition and 27 days post deposition. At the cessation of deposition, the tailings reached the lower of the two fine-wire temperature sensors (Figure 4), but consolidated some 0.3 m post deposition. During the data processing, allowance was made of the changing distance between the tailings surface and the fine-wire temperature sensors.

Results

The results of the actual evaporation derived from the Surface Renewal data are compared to the potential evaporation in the form of A-Pan estimates, made from applying the Penman-Monteith equation to the meteorological data observed during the test period (Figure 5).

The actual evaporation falls well below the potential at the start of the observation over dry tailings. Even after the slurry deposition

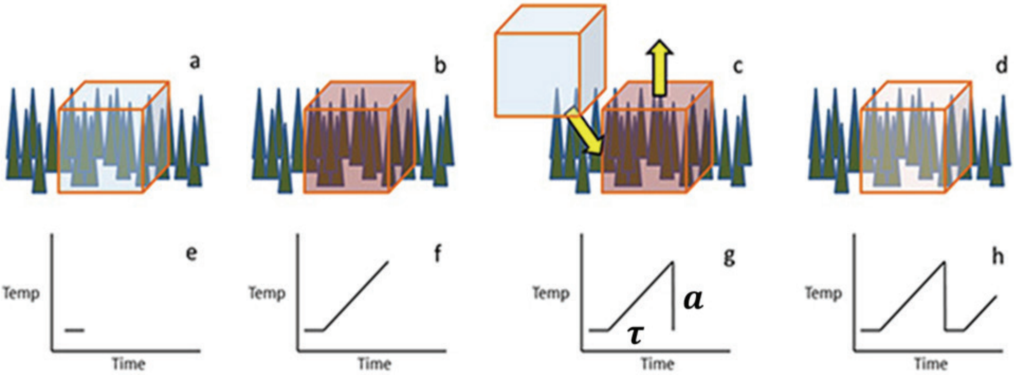

Figure 1 Illustration of the Surface Renewal process and temperature trace

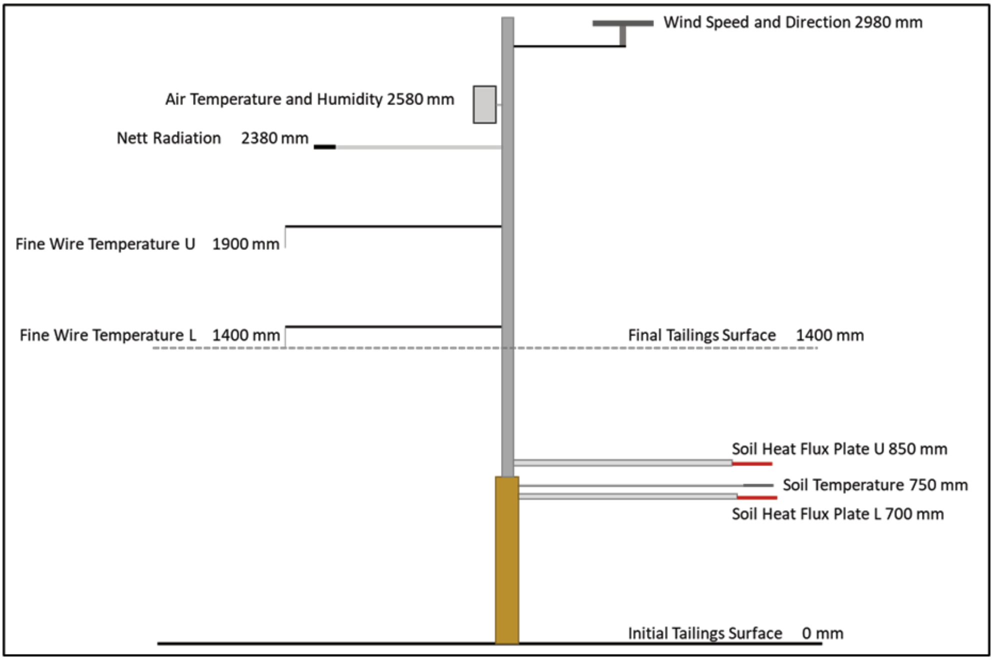

Figure 2** Instrumentation positions **for the Surface Renewal station

Figure 3** Surface Renewal **station at the start of the observations

Figure 4** Surface Renewal **station at cessation of deposition

has reached the Surface Renewal station, the actual evaporation continues to lie below the potential. This is most likely due to the albedo of the slurry limiting evaporation at potential rates. As the tailings particles settle, the water phase at the surface evaporates at the potential rate and continues to do so, even after cessation of deposition. This is assumed to occur due to the consolidating tailings resulting in a diminishing pore space, and thus continuing to provide free water (fully saturated water) to evaporate at the potential rate. As the drying and draining processes progress, however, evaporation becomes lower that potential, as the hydraulic properties of the tailings result in increasing pore water tension. Where the atmospheric demand drops significantly, though, the actual evaporation matches the potential, even though unsaturated conditions prevail.

The assumed progress of the actual/potential evaporation ratio is illustrated in Figure 6. The observed evaporation ratio is shown in blue line with red markers. The

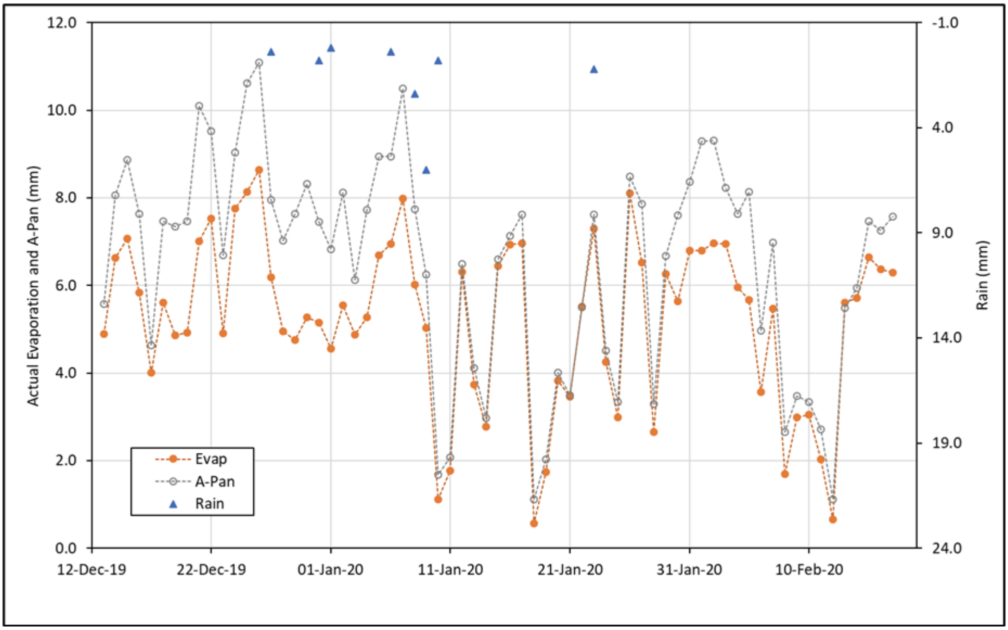

Figure 5 *Results of the actual evaporation, (Evap) and potential evaporation (A-Pan).*

actual evaporation is shown the continue at the potential rate after cessation of deposition and over the initial consolidation and drying phase. In a rigid soil or porous media, the evaporation rate would start diminishing as soon as water application or rain ceases, as illustrated by the orange line in Figure 6.

In many instances of estimating evaporation losses from a tailings surface, during water balance calculations, a general rule-of-thumb is used, in which a ratio of 0.8 is assumed for a wetting beach and 0,2 for a drying beach, as illustrated by the grey dashed line in Figure 6. It is clear that this could lead to erroneous estimations. Moreover, the parameterisation of numerical models in 2- and 3-Dimensions, to evaluate the ingress and seepage of rain and slurry water into variably saturated tailings porous media, could be significantly improved through taking into account the imbibition and evaporation fluxes derived in this study.

Indeed, recently, with the backing of the rigorous field experience described in this study, and a robust conceptual model, we have successfully implemented multiple transient iterations within multiple HYDRUS-1D models, that:

- Simulate the deposition of tailings over time, with alteration in column height, and importing of heads, saturation and mass water balance (including runoff to the pond) from previous iterations;
- Multiple model designs to represent various key locations within the tailings, depending on paddocks, under-drainage, and including beach and pond variations. Each of these can later be
- numerically upscaled to the full areal coverage for calculation of total flux and input to other models; and
- Sensitivity testing of model results using different conditions regarding climatic inputs, depositional time-series and material properties.

This multifaceted HYDRUS-1D implementation was undertaken using the PHydrus Python package (Collenteur *et al.*, 2019). An advantage of using PHydrus includes the ability to run HYDRUS-1D without interacting with the user interface manually, thus it enabled us to customise various algorithms to modify the model setup, run simulations and extract results. These algorithms additionally utilise other Python

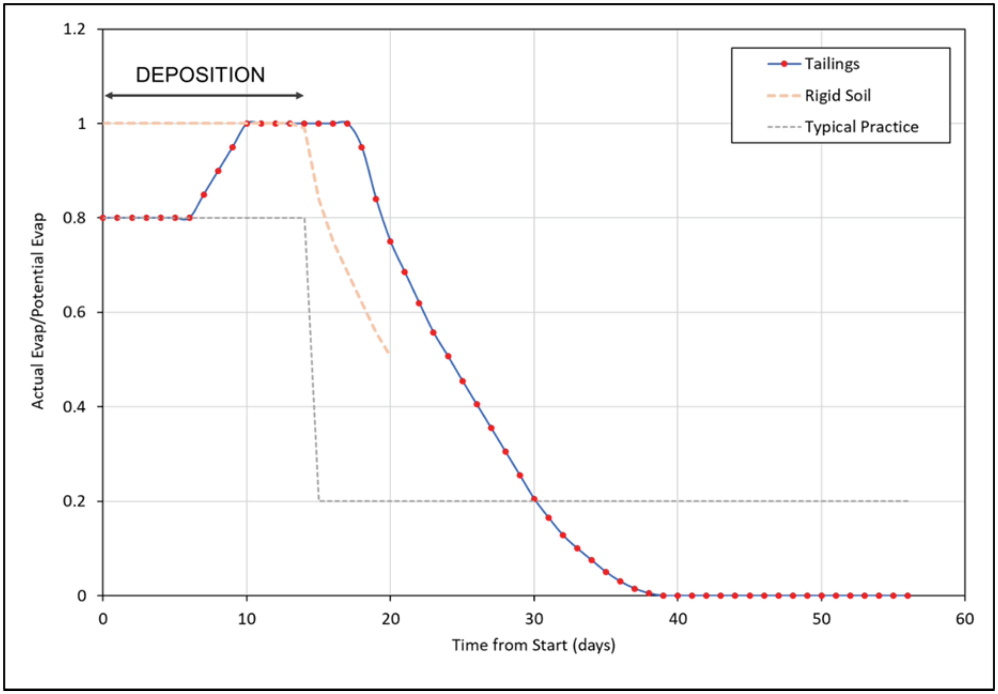

Figure 6 *Evaluation of the Actual/Potential Evaporation ratio*

libraries for data visualisation (including Plotly: Inc, 2015) to present model outputs.

Conclusions

The actual evaporation has been measured over a 60-day period pre-, during and post-deposition of platinum tailings on the impoundment beach. Guidelines have been developed to be used in water balance calculations and in detailed numerical modelling.

These techniques and findings can be applied to:

- tailings water management,
- prediction of phreatic surfaces for stability analyses and
- estimation of solute migration through and out of tailings impoundments.

Thus satisfying many of the requirements of the Global Industry Standard on Tailings Management (GISTM).

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