High Resolution Estimates of Tailings Facility Evaporation Using Landsat Data

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Abstract

A three-temperature (3T) energy balance model was developed to predict monthly distributed actual evaporation (AE) from a large TSF in Nevada, USA for the period of 1996 through 2015. The 3T energy balance model uses Landsat surface reflectance and temperature data to predict the AE as a relative fraction of local weather station estimated potential evaporation on 30 m centers (pixels). Additionally, Landsat reflectance data were used to develop a site specific algorithm to estimate the TSF footprint on six month time intervals. Estimated monthly AE ranged from over 150 mm/month during the summer months, to less than 20 mm/day during the winter months. Estimated TSF evaporation increased over time from an annual maximum of 60 l/s to greater than 350 l/s due to the increase in the evaporative surface of the TSF. Landsat based estimates of the TSF surface area were in agreement with storage curve tailings area estimates, and also provided a high resolution estimate of the tailings footprint over time.

Keywords: actual evaporation, Landsat, model, water balance

Introduction

Evaporation is often the largest unknown component of a tailings storage facility (TSF) water budget, which can result in significant errors about the rate and sources of tailings seepage and other losses. Potential evaporation (PE) can be estimated using weather station measurements; however, PE assumes a continuous water supply and cannot account for the variable nature of TSF operations. Actual evaporation (AE) rates depend on factors such as: climate; tailings moisture content, texture and water holding capacity; and solution salinity. Most TSFs have a large surface area which allows spatial and temporal estimates of AE using satellite data and an energy balance energy model. Specifically, biweekly Landsat datasets can be used to estimate AE from land surfaces with 30 × 30 m resolution. Satellite based energy balance models have been previously used to estimate evapotranspiration from irrigated agricultural and riparian habitat areas (i.e. METRIC and SEBAL, see Allen et al, 2011). However, these model applications are generally labor intensive and costly. Landsat data also can be used to determine the growth of the TSF over time.

A three-temperature (3T) energy balance model was developed to predict monthly AE from a large TSF in Nevada, USA for the period of 1996 (start of operations) through 2015. The site is located in a semi-arid climate with an average December temperature (coldest month) of -4 °C and an average July temperature (warmest month) of 20 °C. The tailings embankment is constructed using centerline raise methods with cyclone underflow sand deposition. Cyclone deposition typically occurs during the summer (May to September) with whole tailings deposition from the perimeter of the facility from October to April.

The 3T energy balance model predicts the AE as a relative fraction of nearby weather station estimated PE, using Landsat surface reflectance and temperature data on 30 m centers (pixels). The local weather station calculated PE is then used to predict the daily changes in AE at each pixel during the periods between each Landsat data event. Additionally, Landsat reflectance data were used to develop a site specific algorithm to estimate the TSF footprint every six months.

Methods

AE estimates were based on calculations using a 3T model based on the physics of the full energy balance (Qiu and Zhao, 2010) as determined from local weather and data from Landsat satellite imagery. A total of 157 images, evenly distributed over the period 1996-2015, were selected for processing and input into the 3T model. A summary of the methodology of the energy balance approach used is provided below.

At the TSF where tailings exist under dry and wet conditions, evaporation can be estimated by:

$$LE = R_n - G - H \tag{1}$$

where LE is the latent heat flux in watts per square meter (W/m^2), R_n is the net radiation (W/m^2), G is the soil heat flux (W/m^2), and H is the sensible heat flux (W/m^2).

The R_n at satellite overpass is the sum of the net short wave radiation (R_{ns}) and the net longwave radiation (R_{nl}).

$$R_n = R_{ns} + R_{nl} \tag{2}$$

$$R_{ns} = (1 - \alpha) R_s \tag{3}$$

where α is the albedo (unitless) that varies for most pixels from 0.18 to 0.30 and R_s is the incoming solar radiation (W/m^2). The net longwave radiation (R_{nl}) equals:

$$R_{nl} = R_{lin} - R_{lout} - (1 - e_o)\, R_{lout} \tag{4}$$

$$R_{lin} = e_a \sigma T_{swet}^4 = 0.85\,(-\ln \tau_{sw})^{0.09}\, \sigma\, T_{swet}^4 \tag{5}$$

$$R_{lout} = e_0 \sigma T_s^4 \tag{6}$$

where R_{lin} and R_{lout} are the incoming and outgoing longwave radiation, respectively (W/m^2), e_o is the broadband surface emissivity (unitless), e_a is the effective atmospheric emissivity (unitless), σ is the Stefan-Boltzmann constant (5.67 × 10^{-8} W/m^2/K^4), τ_{sw} is the broadband atmospheric transmissivity for short-wave radiation (unitless), T_s is the surface temperature in Kelvin (K) as calculated from the thermal band, T_{swet} is the surface temperature of the coldest non-ponded pixels. Qiu and Zhao (2010) assume an average value of $e_o = 0.925$ and use the simple function $e_a = 0.92 \times 10^{-5}\, T_a^2$ for the estimation of the emissivity values.

The G (W/m^2) was estimated using an empirical equation for soils with no or little vegetation (leaf area index less than 0.5) (Allen et al., 2011).

$$G = R_n \times \left\{1.80\,\frac{T_s - 273.15}{R_n} + 0.084\right\} \tag{7}$$

where T_s is the surface temperature (K).
The H (W/m^2) was estimated from:

$$H = (R_{nd} - G_d)\,\frac{T_s - T_{swet}}{T_{sd} - T_{swet}} \tag{8}$$

where R_{nd} is the net radiation of a reference dry soil surface without evaporation (W/m^2), G_d is the soil heat flux in dry soil (W/m^2), T_{sd} is the temperature of a reference dry soil surface (K).

The instantaneous evaporation (E_{inst}) in millimeters per hour (mm/hr) at the time of the satellite overpass is calculated as:

$$E_{inst} = 3600\,\frac{LE}{L} \tag{9}$$

where 3600 is the time conversion from seconds to hours, and L is the latent heat of vaporization (at 20°C about 2.45×10^6 Joules per kilogram (J/kg)).

E_{inst} was extrapolated to daily evaporation values using the hourly standardized reference evapotranspiration for a short crop (ETo_{inst}) (ASCE-EWRI, 2005) to calculate the Reference ET Fraction (*EToF*), defined as:

$$EToF = \frac{E_{inst}}{ETo_{inst}} \tag{10}$$

EToF was then applied to the daily reference evapotranspiration (ETo_{daily}) to calculate daily evaporation (E_{daily}):

$$E_{daily} = EToF \times ETo_{daily} \tag{11}$$

where ETo_{daily} is the daily reference *ETo* in millimeters per day (mm/day).

ETo_{daily} and ETo_{inst} were calculated from a series of consistent hourly meteorological measurements of air temperature, air relative humidity, wind speed, and incoming solar radiation available from a nearby weather station. The weather station environment is similar to the TSF, located approximately 40 km southeast of the TSF and at a similar elevation.

The Landsat data processing using the 3T model produced 30 m by 30 m areal predictions of the actual monthly evaporation for the period from 1996-2015. The aerially distributed monthly evaporation rates were then summarized to yield monthly evaporation volumes from the TSF.

The boundary of the TSF between 1996 and 2015 was estimated on an approximate six month time interval using Landsat reflectance data and application of a site-specific processing algorithm. The boundary between the TSF embankment and impoundment area was based on the location of the cyclone header pipe visible in aerial photographs. Estimated TSF areas were validated against aerial photographs and area estimates from the TSF annual monitoring report.

Results

The estimated monthly average AE depths and rates from 1996 through 2015 are provided in Figure 1 and Figure 2, respectively. To delineate AE from the actively wetted embankment areas, predicted AE was separated into impoundment and embankment areas. Examples of the predicted growth of the TSF and the spatially distributed AE in the winter and summer of 2005 and 2015 are provided in Figure 3.

Mining operations were suspended between July 1999 and September 2004, resulting in decreased AE due to water no longer being directed onto the TSF surface as part of the tailings slurry (Figure 1 and 2). Tailings deposition resumed October 2004 with the restart of mining and estimated AE increased (Figure 1 and 2).

Estimated monthly impoundment AE rates were in excess of 150 mm/month during the summer months when solar energy and evaporative demand is at its peak, to less than 20 mm/month during the winter months when evaporative demand is at its minimum (Figure 1). Due to the increase in the evaporative surface of the TSF, estimated TSF impoundment AE volume rates increased over time from an annual maximum of 60 l/s in

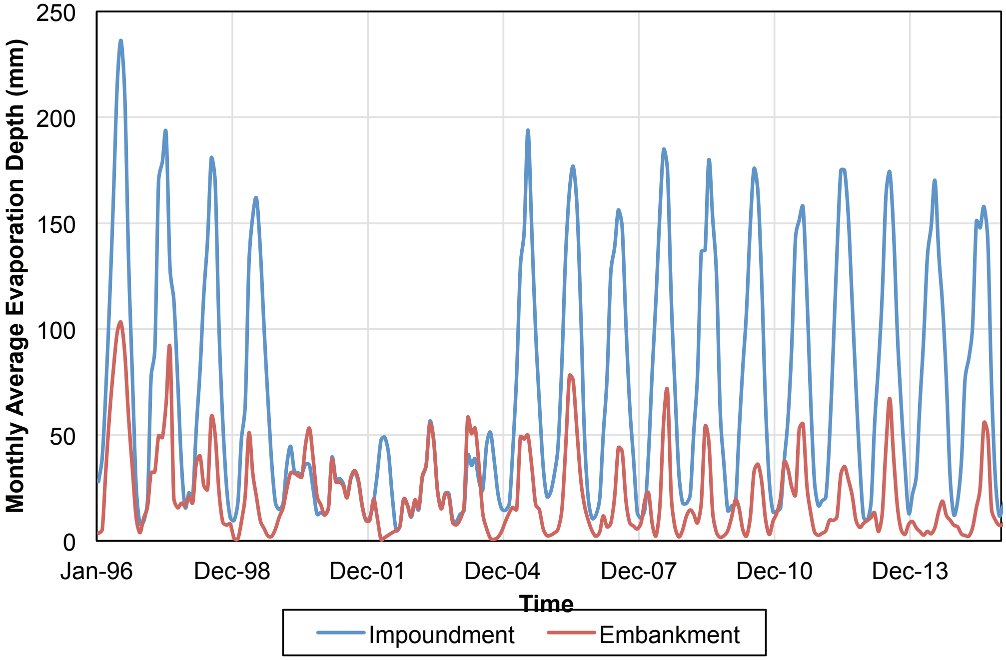


Figure 1 *Estimated monthly evaporation depth*

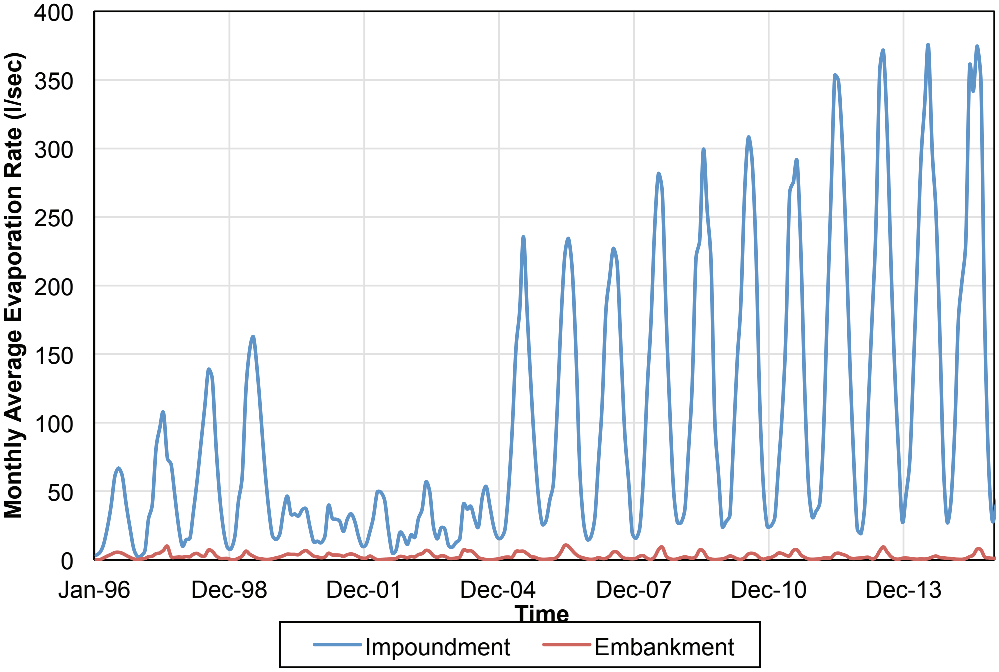


Figure 2 *Estimated monthly evaporation rate*

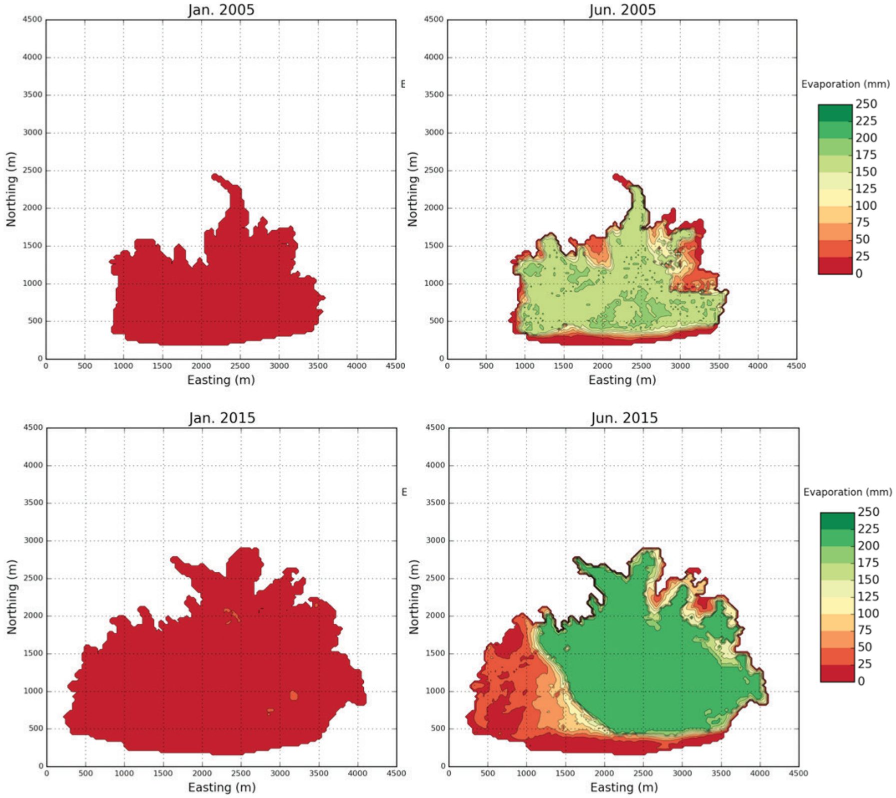
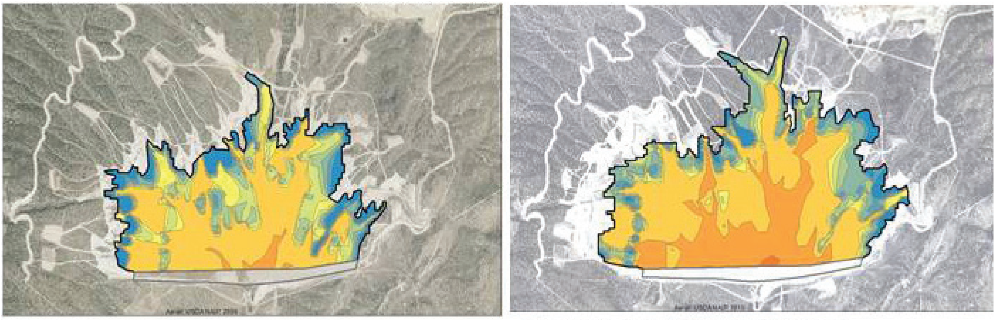


Figure 3 *Example distributed evaporation from the TSF*

1996 to 350 l/s or greater after 2012 (Figure 2, Figure 3).

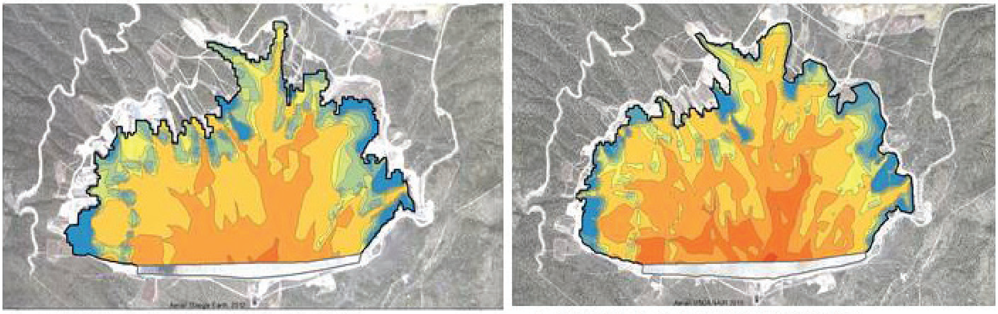
Greater AE depths were estimated for the impoundment than the embankment due to the higher moisture retaining characteristics of the finer grained impoundment tailings and presence of wet/ponded conditions in the decant pond area (Figure 1 through 3). Additionally, water was added to the embankment only during the summer cyclone period. The greater impoundment AE depth and surface area compared to the embankment resulted in considerably greater estimated AE rates from the impoundment (Figure 2).

TSF areas estimated from Landsat reflectance data were also used to predict the tailings depth distribution (Figure 4). In addition, the biweekly AE data allowed us to understand the progression of the tailing placement, such that tailing material estimates (i.e. underflow, overflow, mixed and slime tailings) could be made. These data were then used to develop a distributed seepage model based on tailing material properties and a predicted water balance using site specific data and the AE model. To validate the Landsat TSF area estimates, they were compared to mine annual report storage curve estimates and showed good agreement (Figure 5). The TSF had a rapid growth progression early-on during operations between 1996 and 1999 as the embankment grew and the basin was filled in with tailings.



June 2006, Aerial: USDA NAIP, 2006

July 2010, Aerial, USDA NAIP, 2010



June 2012, Aerial: Google Earth, 2012

July 2015, Aerial: USDA NAIP, 2015

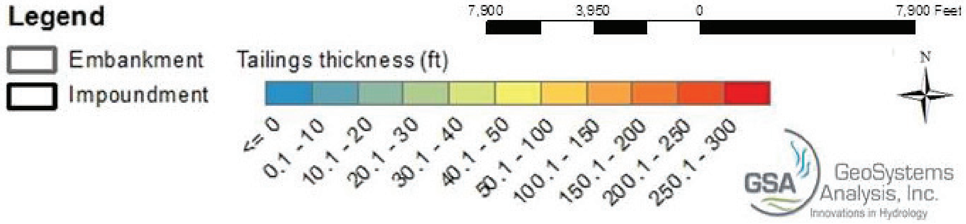


Figure 4 *Estimated Tailings Depth Distribution*

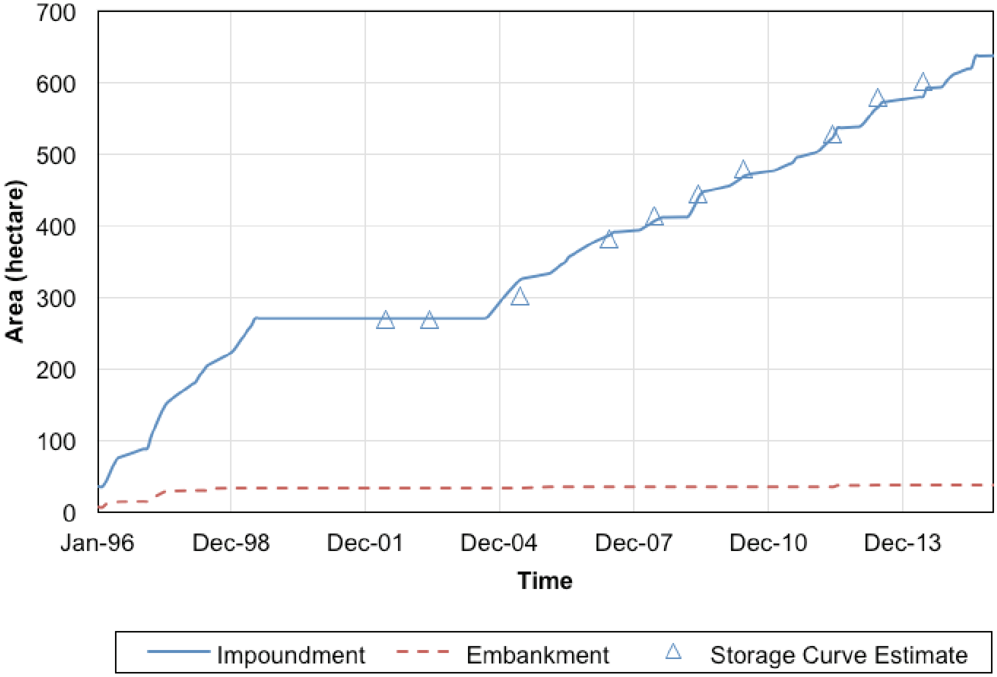


Figure 5 *Estimated TSF embankment and impoundment areas*

Conclusions

The 3T model provides a cost-effective and accurate method to calculate high resolution spatial and temporal estimates of TSF AE, and it also captures seasonal changes in AE and surface ponding. Estimated monthly AE ranged from over 150 mm/month during the summer months, to less than 20 mm/day during the winter months. Estimated TSF evaporation increased over time from an annual maximum of 60 l/s to greater than 350 l/s due to the increase in the evaporative surface of the TSF. Landsat based 3T model estimates of the TSF surface area were in good agreement with storage curve tailings area estimates, and also provided a high resolution estimate of the tailings footprint distribution over time. Additional benefits to the method include the ability to predict tailings depth and the progression of tailings placement over time which can then be used to prepare estimates of tailings material types and a distributed seepage model.

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