# A review of methods to calculate current and future evaporation rates from pit lakes with high concentrations of total dissolved solids

**J Lindauer**  *WSP USA Inc., United States of America*

**S Byers**  *WSP USA Inc., United States of America*

**G Lehn**  *WSP USA Inc., United States of America*

**E Evans**  *WSP USA Inc., United States of America*

**D Castendyk**  *WSP USA Inc., United States of America*

**B Moravec**  *BHP Legacy Assets, United States of America*

## Abstract

*For pit lakes in arid environments, lake evaporation and mechanical evaporation methods (e.g., misters) are sometimes used to manage water levels to avoid discharge to the receiving environment (e.g., aquifers). For terminal lakes, the steady-state water surface elevation remains below the regional water table. This creates a perpetual sink in the local water table such that the pit retains mine impacted water on site. One management strategy for flow-through lakes involves enhancing evaporation using misters to prevent the lake from reaching its steady state water level, thereby producing an artificial terminal pit lake. Evapo-concentration coupled with the deposition of mister-generated aerosols landing within the pit catchment can increase the concentration of total dissolved solids (TDS) in lake water over time. As TDS concentration increases, the activity of water decreases, reducing the vapor pressure and decreasing the evaporation rate. Consequently, the long-term management plan and water balance for artificial terminal lakes must account for TDS concentrations in future projections of evaporation rates.*

*This review evaluates methods to calculate current and future evaporation rates, including methods that consider the impact of TDS concentrations on the activity of water. First, we review methods used to estimate current evaporation rates, including: (1) pan evaporation, (2) water balance, (3) energy balance, (4) combination mass transfer and energy balance method (called 'combination method', e.g. Penman equation), (5) pan and combination method (called 'PenPan'), (6) water isotope mass balance, (7) temperature-only models [e.g. the Hargreaves and Samani (H-S) equation], and (8) eddy covariance measurements.*

*Next, using a modified Penman equation paired with an ocean water equation of state, we showed how increased TDS concentrations in a theoretical lake can reduce the activity of water and estimated evaporation rate. Results of this exercise showed that simulated evaporation was greatly impacted above TDS concentrations of 300,000 mg/L. For long term management plans and water balances that utilize predictions of future evaporation rates, it is preferred to use a method like the H-S equation since it requires only downscaled temperature from a climate projection, whereas the modified Penman requires wind speed, relative humidity and other meteorologic variables which are not typically generated by climate projections and have greater uncertainty. To show how a H-S equation can be modified to account for TDS concentrations, we used the modified Penman to establish the coefficients for TDS and site conditions to establish a modified H-S equation.*

*Key Words: Evaporation, Total Dissolved Solids, Modified Penman equation, Modified Hargreaves and Samani equation*

A review of methods to calculate current and future evaporation rates
from pit lakes with high concentrations of total dissolved solids

J Lindauer & S Byers & G Lehn & E Evans
& D Castendyk & B Moravec

# 1 Introduction

For pit lakes in arid environments, lake evaporation and mechanical evaporation methods (e.g., misters) are sometimes used to manage water levels and avoid flow conditions and/or lake water discharge to receiving environments (e.g., aquifers). Evaporation coupled with the deposition of mister-generated aerosols within the pit catchment can increase the concentration of total dissolved solids (TDS) in lake water over time. As TDS concentrations increase, the activity of water decreases, reducing the vapor pressure and the evaporation rate. Consequently, for long-term water balances and closure plans for pit lakes with high TDS concentrations, it is important to account for TDS concentration effects on evaporation rates.

Accurate evaporation rates are notably important for pit lakes that are actively managed using enhanced evaporation to prevent the surface water level from reaching steady state conditions. All pit lakes are initially terminal sinks, and many become flow-through systems after the lake surface rises above the surrounding water table. Enhanced evaporation is a useful short term management approach that can maintain artificial terminal conditions in pit lakes, but forecasts of long-term water management with this approach require an accurate prediction of future evaporation rates that accounts for TDS.

This review evaluates the strengths, assumptions, and limitations of methods to calculate current and future evaporation rates, including methods that consider meteorological conditions, heat storage, and the impact of TDS concentrations on the activity of water. First, we review methods used to estimate current evaporation rates, including: (1) pan evaporation, (2) water balance, (3) energy balance, (4) combination mass transfer and energy balance method (called 'combination method', e.g. Penman equation), (5) pan and combination method (called 'PenPan'), (6) water isotope mass balance, (7) temperature-only models [e.g. the Hargreaves and Samani (H-S) equation], and (8) eddy covariance measurements. Next, we applied a commonly used evaporation estimation method (i.e., Penman) with an ocean water equation of state to show how TDS concentrations lead to reductions in the evaporation rate, with more substantial reductions in the evaporation rate occurring beyond a TDS concentration of 150,000 mg/L. Finally, we provide an example of predicted future evaporation rates using a novel, temperature-dependent, modified Hargreaves and Samani (H-S) equation.

# 2 Methods for quantifying evaporation

Table 1 shows the list of methods for estimating evaporation rates reviewed here. The method types are grouped into two functional groups which we refer to as potential evaporation and actual evaporation methods. Method types in the potential evaporation group include potential evapotranspiration (PET), reference crop evapotranspiration (RET), free-water, and open water evaporation. The actual evaporation methods described here can be used to directly estimate evaporation from a specific water body. Each of these method types are used to represent different hydrologic concepts and are defined in the following paragraphs.

Potential evapotranspiration (PET) is:

> "the rate at which evapotranspiration would occur from a large area completely and uniformly covered with growing vegetation with access to an unlimited supply of soil water and without advection or heat-storage effect." Dingman (2015, p. 292)

Potential evapotranspiration (PET) methods are designed to be solely dependent on climatological and meteorological inputs and not influenced by surface or boundary conditions, thus, it can be considered a valuable tool for understanding the upper limit of total evaporation.

Reference crop evapotranspiration (RET) is water transpired from a crop of known height, surface resistance, and albedo, that is not short of water (Dingman 2015; McMahon et al. 2013) and can be used to estimate evaporation from a lake. RET methods are a modification of PET methods; however, they allow for greater consideration of surface conditions.

A review of methods to calculate current and future evaporation rates
from pit lakes with high concentrations of total dissolved solids

J Lindauer & S Byers & G Lehn & E Evans
& D Castendyk & B Moravec

'Open water evaporation' refers to a group of methods developed to estimate evaporation from shallow surface-water bodies. Open water evaporation equations are commonly based on meteorological inputs and, similar to PET methods, do not consider advection or heat storage effects (Dingman 2015). However, these methods can be modified to consider advection and heat storage.

Free-water, or potential, evaporation ($E_0$) is: "the rate (flux) of evaporation that would occur from an extended open-water surface under current meteorologic conditions without heat-storage or water-advected-energy effects" (Dingman 2015, 258). Previous studies have shown that calculated potential evaporation ($E_0$) and potential or reference evapotranspiration ($ET_0$) from either well-watered short vegetation or a free-water surface give similar estimates of evaporation (Jansen et al. 1990). Additionally, free-water evaporation can be adjusted to estimate lake evaporation, which "is determined by adjusting free-water evaporation to account for the advection and heat-storage effects in a given water body" (Dingman 2015, p. 258). Methods for quantifying evaporation and their respective strengths, assumptions, and limitations are summarized in the following sections.

Lastly, actual evapotranspiration refers to the amount of water that evaporates and transpires.

**Table 1        Methods of estimating and calculating evaporation rates**

| Method Type | Method | Potential Evaporation | Actual Evaporation |
|---|---|---|---|
| Temperature Based | Hargreaves and Samani | × | − |
| Pan | Class-A Pan | × | − |
| | Floating Pan | × | − |
| Water Balance | Water Balance | − | × |
| Combination1 | Penman | × | − |
| | Penman-Monteith | × | − |
| Energy Balance | Priestley-Taylor | × | − |
| Pan/Combination1 | PenPan | × | − |
| Water Isotope Mass Balance | Water Isotope Mass Balance | − | × |
| Eddy Covariance | Eddy Covariance | − | × |

1-    Combination- Combination mass-transfer and energy-balance approach

## 2.1        Pan methods

### 2.1.1        Pan evaporation

Pan evaporation is a direct measurement approach to estimating evaporation. A pan is an open circular basin containing a known volume of water, and is often placed above the ground surface, or can be placed level with the ground surface or even on a floating platform level with the water surface. The water in the pan is allowed to interact with the atmosphere and associated boundary effects, allowing water to evaporate at a 'field' rate. After a known time, the change in volume can be calculated to quantify evaporation from the pan.

Pan evaporation approximates free-water evaporation, requiring no meteorological data inputs (Dingman 2015). This method is limited, particularly in the case of a Class-A pan, by the above-ground terrestrial siting, which allows solar radiation and ambient air to heat or cool the pan and, therefore, the water, altering thermodynamic conditions of evaporation. These pan conditions are likely not reflective of the actual heat storage in a lake. Additionally, pans do not account for inflows and outflows, which impact temperature conditions in a lake. Pans generally do not correctly represent the actual energy balance of a body of water,

A review of methods to calculate current and future evaporation rates
from pit lakes with high concentrations of total dissolved solids

J Lindauer & S Byers & G Lehn & E Evans
& D Castendyk & B Moravec

requiring a pan coefficient to adjust measured pan evaporation to actual evaporation. A pan coefficient is derived from the evaporation of a pan compared to other evaporation estimates. Coefficients can come from site data, regional averages, or other methods. Furthermore, in waters with high TDS concentrations, TDS loading in a pan will occur at a higher rate due to the larger storage mass of water in lake and because evaporation only effects a small portion of the total water balance of the lake. Consequently, as pan water evaporates, the relatively higher concentration of TDS may incorrectly simulate lake conditions, potentially underestimating evaporation due to the impact on decreased pan water activity.

### 2.1.2  *Floating pan evaporation*

A variation of a terrestrially sited pan is a floating pan. A pan can be placed in a floating platform to compensate for the deviations that occur due to differences between the surface water interface and terrestrial conditions, particularly heat storage. As such, water evaporation in a floating pan more closely simulates lake evaporation. McJannet et al. (2019) found success, however, with limitations, in using this method in a pit lake environment. When floating pan evaporation was modelled with meteorological data collected from a station sited on a pit rim, McJannet et al. (2019) determined that estimated evaporation at the rim did not correctly simulate actual evaporation due to differences between meteorological conditions at the pit rim and at the lake water surface. However, when corrections were applied to the meteorological data collected at the pit rim to represent conditions at the surface water interface, the modelled evaporation provided accurate results. Thus McJannet et al. (2019) concluded that defining wind conditions at the surface of a pit lake contributes to a more refined evaporation estimate relative to a remote evaporation station located outside or above the pit walls.

While the floating evaporation pan may provide good estimates of evaporation, floating pans often need to be custom built and include potential safety risks such as extended time on water in a pit lake for personnel, consequently it may not be practical for all sites.

## 2.2  Water balance

A water balance approach can be used to solve for actual evaporation from a lake when the inflows, outflows, and lake volume are well characterized and constrained. This approach is simple in theory and complex in practice for most reservoirs and natural lakes (Dingman 2015). As calculated by water balance, evaporation is a sum of the inflows minus the outflows. For best results, this demands that all channelized inflows to a given lake be continuously measured, a detailed hydrogeologic characterization of groundwater inflows and outflows to and from a lake, and a detailed bathymetric survey followed by construction of a hydrograph showing the relationship between water level and volumetric storage (i.e., stage-storage). Significant assumptions must also be made to estimate non-channelized runoff to the lake. The water balance approach can be applied to almost any system; however, it is best suited for well-characterized lakes.

## 2.3  Combination

### 2.3.1  *Penman*

The Penman equation combines energy balance and mass transfer approaches to calculate evaporation from commonly collected climatological and meteorological variables, including solar radiation, air temperature, wind speed, and relative humidity. An advantage of the Penman equation is that it does not require surface water temperature and can be used with daily and monthly timestep datasets. The Penman equation is preferred for lakes less than 2m deep (McMahon et al. 2013). Considerable research has supported the use of the Penman equation, and without the need for surface water temperature, it is suitable for modelling and predictive applications (Dingman, 2015).

A review of methods to calculate current and future evaporation rates
from pit lakes with high concentrations of total dissolved solids

J Lindauer & S Byers & G Lehn & E Evans
& D Castendyk & B Moravec

### 2.3.2 *Penman-Monteith*

Like the Penman equation, the Penman-Monteith equation combines energy balance with mass transfer methods, allowing estimation of evaporation from commonly collected data like solar radiation, temperature, humidity, and wind (Allen et al. 1998). The Penman-Monteith equation differs from the Penman equation through accounting for evapotranspiration from "a vegetated surface by incorporating canopy conductance" (Dingman 2015, p. 282). This variation is referred to as the FAO-56 Penman-Monteith method (FAO-56). While the Penman-Monteith equation is a RET method, it can be used in open water environments by applying published coefficients (Allen et al. 1998) or may be an accurate method to model lake evaporation, as shown by McJannet et al. (2008). McMahon et al. (2013) note that the FAO-56 reference crop variation of the Penman-Monteith equation is best suited for use with monthly timestep data and when applied to humid environments. Furthermore, McMahon et al. (2013) note that the FAO-56 equation may not be well suited for windy and semi-arid conditions.

## 2.4 PenPan model

The PenPan model combines the Penman equation and pan evaporation, often Class-A pans, and is used to model evaporation from a pan using local meteorological data. The PenPan model differs from the Penman equation in the accounting of solar radiation, albedo, a wind function, and a constant that accounts for the additional energy inputs to the surface of a pan (Johnson & Sharma 2010). Additional modifications can be applied to account for guards (like a bird guard) over the surface of a pan that can alter the evaporation rates as compared to an unguarded pan. The PenPan model is a technique shown to accurately estimate evaporation from a pan (Roderick et al. 2007). Overall, the PenPan model offers the affordability (when the necessary climate data is available) of a pan while increasing confidence in evaporation estimates with the added benefit of modelling via the Penman equation.

Additionally, both Johnson and Sharma (2010) and Roderick et al. (2007) demonstrated the use of the PenPan model in a forensic capacity to identify variables leading to inconsistencies in pan evaporation rates. In the case of Roderick et al. (2007), changes to pan evaporation rates in Australia were attributed mainly to changes in wind over time, with minor contributions to the reduction of evaporation attributed to vapor pressure and air temperature.

## 2.5 Priestley-Taylor

A common PET method is the Priestley-Taylor equation. Priestley-Taylor is an energy flux-based approach that does not account for wind (McMahon et al. 2013). Included in the Priestley-Taylor equation is what is known as the 'Priestley-Taylor constant', which is used to account for the difference between actual evaporation and the calculated evaporation rate. Although it is called a 'constant', it is not in fact constant and is subject to spatiotemporal variability by surface type, time range, and season. Consequently, the constant used by Priestley and Taylor of 1.26 for "advection free saturated surfaces" may not correctly simulate site conditions (McMahon et al. 2013, p. 1336). By accounting for the vapor pressure deficit and available energy, the Priestley-Taylor coefficient can be adjusted to closely represent to site conditions (McMahon et al. 2013).

## 2.6 Water isotope mass balance

Determination of evaporation losses from lakes, particularly in dynamic systems and arid environments, can be challenging due to uncertainty in water budgets, flow monitoring, and water body volumes. Isotope models based on the Craig-Gordon model (C-G model) for evaporation are an inexpensive and simple method to estimate evaporative losses by using stable hydrogen ($\delta^2$H= [($^2$H/$^1$H)$_{sample}$/($^2$H/$^1$H)$_{SMOW}$–1] *1000; SMOW: Standard Mean Ocean Water) and oxygen ($\delta^{18}$O= [($^{18}$O/$^{16}$O)$_{sample}$/($^{18}$O/$^{16}$O)$_{SMOW}$–1] *1000; SMOW: Standard Mean Ocean Water) isotope composition of the water body and inflowing water (Craig & Gordon 1965). Evaporation preferentially removes the lighter isotopes ($^1$H and $^{16}$O) from a water body, leaving the remaining water enriched in the heavier isotopes ($^2$H and $^{18}$O). The steady-state isotopic composition of the water body

A review of methods to calculate current and future evaporation rates
from pit lakes with high concentrations of total dissolved solids

J Lindauer & S Byers & G Lehn & E Evans
& D Castendyk & B Moravec

represents a balance between the evaporative loss of the lighter isotopes to the atmosphere and the replenishment of unaltered water from inflowing water sources. The C-G model predicts the amount of evaporation within a water body based on fluxes and isotopic compositions on these competing processes. C-G evaporation models have been applied in a variety of hydrologic regimes, including mine pit lakes (Skrzypek et al. 2015, Gammons et al. 2006, Mayr et al. 2007).

Water isotope mass balance models may involve the following assumptions:

- Depending on data availability, the assumption may need to be made that steady-state conditions involve water level and isotopic composition remaining generally stable as evaporative losses are replenished by inflows.
- The isotopic composition of atmospheric water vapor is needed in the models. In the absence of direct measurements, the isotopic composition can be estimated using the isotopic composition of local precipitation, which requires the assumption that ambient water vapor over a lake has a signature that is not impacted by microclimates.

Additionally, water isotope models may include the following limitations:

- Independent errors can be introduced to the evaporation rate calculation from various data sources. G-C models require inputs from metrological measurements, published datasets, and site-specific measurements. Each dataset introduces uncertainty into final calculations.
- Depending on data availability, inflow values may need to be estimated from multiple isotope measurements and be weighted. Although large swings in inflow isotopic composition may not be expected, year-to-year inflow variability adds uncertainty to predictions.
- Evaporation is estimated as a ratio of evaporation to inflow (E/I) rather than a direct evaporation rate. Calculations of an evaporation rate require estimates of, or data for, annual inflows into a lake.
- A C-G evaporation model cannot distinguish between natural and enhanced evaporation processes. Therefore, the isotopic fractionation mechanism for enhanced evaporation may need to be assumed to be similar to the mechanism of natural evaporation.

## 2.7      Hargreaves and Samani

The H-S equation is a temperature dependent approach to calculating evaporation, using mean, maximum, and minimum temperature along with solar radiation to derive an evaporation rate. The advantage of a temperature-based method for calculating evaporation is that evaporation can still be calculated in systems where only temperature data is available. Since radiation data may not be collected at a site, this approach offers flexibility since solar radiation can be calculated based on the latitude of a site and day of the year. Additionally, since the H-S only requires temperature data, a method like the H-S equation can be used to assess potential impacts in future evaporation rates due to climate change, as downscaled climate projections provide future temperatures which can be applied to predict future evaporation. Limitations of this method include that it assumes that there are no impacts from the heat storage of a lake and that a water body will respond immediately to changes in air temperature.

Evaporation rates as calculated using the H-S equation need to be adjusted to fit site conditions. Coefficients can be pulled from literature, empirically derived, or calculated to match evaporation rates calculated by other approaches, like the Penman equation. If possible, the H-S equation should be calibrated to the most representative evaporation data available. The H-S equation's simplicity makes it ideal for use in operational water balance models.

## 2.8      Eddy covariance

Eddy covariance is a state-of-the-art evaporation measurement method that measures boundary layer conditions above the water surface. The advantage of eddy covariance is that it allows for direct measurement of the vertical flux of moisture and wind as evaporation occurs. Eddy covariance systems have been successfully sited adjacent to a lake as well as on a buoy during studies of evaporation (Jansen et al.

A review of methods to calculate current and future evaporation rates
from pit lakes with high concentrations of total dissolved solids

J Lindauer & S Byers & G Lehn & E Evans
& D Castendyk & B Moravec

2022, Lensky et al. 2017, Metzger et al. 2018, Mor et al. 2018). Since eddy covariance is considered the most direct method available to estimate evaporation, it can be used as a baseline for assessing other methods of estimating evaporation, such as those previously discussed in this paper. Two difficulties with eddy covariance are that it can be cost-prohibitive and has rigorous siting requirements, such as a sufficient surface area for setting up the tower and must be located with sufficient fetch across the study area.

# 3      Accounting for TDS in evaporation

As an example of how the previously discussed methods can be applied to a lake with high TDS, a modified Penman method, described by Akridge (2008) was paired with an ocean water equation of state described by Siadatmousavi and Seyedalipour (2019) and the UNESCO Equation of State described by Chapman (2006) to calculate theoretical evaporation rates under various TDS concentrations. Next, the results of the modified Penman calculations were used to establish coefficients that account for the impact of TDS concentrations that could be applied to a modified H-S equation for prediction of future evaporation rates. The unmodified H-S equation was described by Snyder and Eching (2002).

To understand the application of the modified Penman and modified H-S equations to the conditions at a lake with high TDS, theoretical meteorological and water chemistry data were used to calculate potential evaporation rates. The modified Penman equation was chosen to evaluate a method best applied to past or present evaporation rates while the H-S equation was selected to evaluate a method that can be applied to predictions of future evaporation rates.

## 3.1      Approach

### 3.1.1      Modified Penman method

Calculation of evaporation rates using unmodified and modified Penman equations were used to assess the effect of TDS concentrations on evaporation rates. The unmodified Penman equation calculations did not account for the reduced activity of water and served as a baseline for determining the impact of TDS concentrations. The modified Penman equation calculations used the activity of water as calculated from an ocean water equation of state described in Siadatmousavi and Seyedalipour (2019). While there are many ways to measure and calculate the activity of water, the ocean water equation of state was used for this exercise because it derives the activity of water from TDS, which is suitable for this high-level assessment.

The Penman equation, as previously discussed, requires multiple variables important to evaporation, such as latent heat of vaporization, the saturation vapor pressure, the psychometric constant, wind, solar radiation, and other variables (Akridge, 2008). The modified version of the Penman equation used here accounts for the impact of the activity of water on vapor pressure and is summarized as follows:

- Latent heat of evaporation ($\lambda$) is the heat required to convert a liquid to vapor while maintaining a constant temperature.

- The saturation vapor pressure ($e_s$) reflects the pressure that water vapor and water are in equilibrium, above which water will precipitate and below which water will evaporate. Importantly, saturation vapor pressure is modified to account for the lower activity of water ($a_w$) due to high TDS concentrations. The activity of water was calculated using the ocean water equation of state.

- The psychrometric constant (P) is a ratio of the specific heat to the latent heat of vaporization of water and can be calculated from atmospheric pressure (AMS 2012).

- Wind function [f(u)] represents the atmospheric resistance that occurs as water vapor is moved through the water-surface interface and is calculated from wind speed.

- Net radiation ($R_n$) is "the difference between incoming effective solar radiation and outgoing long-wave radiation" (Akridge 2008, p. 1456). This can either be directly measured or calculated based on the latitude of the site and the time of year.

A review of methods to calculate current and future evaporation rates
from pit lakes with high concentrations of total dissolved solids

J Lindauer & S Byers & G Lehn & E Evans
& D Castendyk & B Moravec

Table 2 shows the measurement terms, the input terms, and the modified Penman equation.

**Table 2      Modified Penman equation inputs and calculations**

| Symbol | Description | Source, Equation, or Comments |
|---|---|---|
| **Measurements** | | |
| T | Temperature | Theoretical meteorological data |
| RH | Relative humidity | Theoretical meteorological data |
| $U_2$ | Wind speed | Theoretical meteorological data |
| $R_n$ | Radiation | Calculated based on theoretical latitude and time of year |
| $\rho_w$ | Water density | Calculated based on theoretical TDS concentrations[1] |
| **Input Terms** | | |
| λ | Latent heat of evaporation | $\lambda = 2.501 - 0.002361T$ |
| $e_s$ | The saturation vapor pressure | $e_s = 0.6108 a_w exp \dfrac{17.27T}{237.3 + T}$ |
| $a_w$ | Activity of water[2] | $a_w = -30.285 + 77.650\left(\dfrac{\rho_w}{1,000}\right) - 62.712\left(\dfrac{\rho_w}{1,000}\right)^2 + 16.3\left(\dfrac{\rho_w}{1,000}\right)^3$ |
| Δ | Saturation vapor pressure gradient | $\Delta = \dfrac{4098 e_s}{(237.3 + T)^2}$ |
| **γ** | Psychrometric constant | $\gamma = 0.001013 \times P \div (0.622 \times \lambda)$ |
| P | Average atmospheric pressure | $P = 101.3 * \left(\dfrac{293 - 0.0065 \times MET\ Elevation\ (m)}{293}\right)^{5.26}$ |
| e | Daily mean vapor pressure | $e = \dfrac{e_{max} - e_{min}}{2}$ |
| $e_{max/min}$ | Vapor pressure | $e_{max/min} = \dfrac{RH e_s}{100}$ |
| f(u) | Wind function | $f(u) = 6.43(1 + 0.536 U_2)$ |
| **Results** | | |
| λE | Evaporation | $\lambda E = \dfrac{\Delta}{\Delta + \gamma} R_n + \dfrac{\gamma}{\Delta + \gamma} f(u)(e_s - e)$ |

1-    Chapman (2006)

2-    Siadatmousavi & Seyedalipour (2019)

### 3.1.2    Modified H-S method

Next, modifications were applied to the H-S equation using TDS coefficients derived from the results of the modified Penman equation calculations. The measurement inputs, input terms, and the H-S equation are shown in Table 3. TDS coefficients were calculated based on the percent difference between the Penman equation baseline evaporation rates and modified Penman equation TDS-corrected evaporation rates. As previously mentioned, coefficients can be derived using a number of methods, including published data, empirically, or by matching with other evaporation calculation approaches.

Final modified H-S evaporation was calculated by applying a Site coefficient. Unlike the TDS coefficients, which change depending on the TDS concentration, the Site coefficient is a static value. For this theoretical lake, a Site coefficient was calculated by taking the percent difference between evaporation as calculated using the modified Penman and evaporation as calculated using the H-S equation with the TDS coefficient applied. This novel approach results in evaporation estimates that are responsive to changes in air

A review of methods to calculate current and future evaporation rates
from pit lakes with high concentrations of total dissolved solids

J Lindauer & S Byers & G Lehn & E Evans
& D Castendyk & B Moravec

temperature and TDS concentration. This modified H-S method can be implemented in mine water balance models to support long-term water management decision making.

Table 3     Modified Hargreaves and Samani inputs and calculations

| Symbol | Description | Source, Equation, or Comments |
|---|---|---|
| Measurements | | |
| $T_m$ | Mean Temperature | Theoretical meteorological data |
| $T_x$ | Maximum Temperature | Theoretical meteorological data |
| $T_n$ | Minimum Temperature | Theoretical meteorological data |
| Input Terms | | |
| 0.408 | Radiation conversion factor | MJ m$^{-2}$ to mm |
| 0.0023 | Empirical Coefficient | — |
| $R_a$ | Extraterrestrial Radiation | Calculated based on theoretical latitude and time of year |
| $C_{TDS}$ | TDS Coefficient | Calculated from the percent difference between the baseline and TDS corrected evaporation rates as calculated using the modified Penman equation |
| $C_{Site}$ | Site Coefficient | Calculated from the percent difference between evaporation calculated using the modified Penman and the H-S equation with $C_{TDS}$ applied |
| Results | | |
| $ET_h$ | H-S (Snyder & Eching 2002) | $ET_h = 0.408\big(0.0023R_a[T_m + 17.8]\sqrt{T_x - T_n}\big)$ |
| $ET_h$ | Modified H-S | $ET_h = 0.408\big(0.0023R_a[T_m + 17.8]\sqrt{T_x - T_n}\big) \times C_{TDS} \times C_{Site}$ |

## 3.2     Assumptions and limitations

As these are theoretical calculations of evaporation, the primary limitation is how the water activity was calculated, specifically the use of the ocean water equation of state and the UNESCO Equation of State. Siadatmousavi and Seyedalipour (2019) describe the equation for the activity of water as highly unique to site-specific conditions, requiring unique equations of state. In the case of Siadatmousavi and Seyedalipour 's research at Lake Urmia, Iran, an equation of state developed for the Dead Sea was applied. Because this is a calculation for a theoretical lake, the standard ocean water equation of state paired with the UNESCO Equation of State is considered suitable. Furthermore, to calculate the activity of water using the ocean water equation of state and the UNESCO Equation of State assumes that the equations will correctly represent the activity of water at TDS concentrations above those observed in the ocean. The composition of the water will have impacts on the activity of water as well. By using these particular equations to relate TDS to the activity of water, variation is introduced by not accounting for the unique ionic strengths of dissolved solids or the major ions found in a pit lake (i.e., Na-SO$_4$) vs sea water (Na-Cl). Thus, as stated by Siadatmousavi and Seyedalipour, it is important that a site-specific equation of state is used for real world applications.

Also, a maximum TDS concentration of 500,000 mg/L was used as an upper limit since it is higher than concentrations observed in high TDS water bodies on Earth (Don Juan Pond in Antarctica has a TDS of ~440,000 mg/L and is the saltiest water body on Earth). The maximum TDS achievable in a body of water will depend on water body conditions and elemental composition of the water.

Additionally, the H-S equation as applied in this example relied on the results of the modified Penman equation to derive coefficients that allow the H-S equation to represent site conditions. In real world applications, more steps can be taken to derive coefficients that utilize multiple sources of historical data and empirical observations.

A review of methods to calculate current and future evaporation rates
from pit lakes with high concentrations of total dissolved solids

J Lindauer & S Byers & G Lehn & E Evans
& D Castendyk & B Moravec

## 3.3    Inputs and calculations

The calculation inputs for a theoretical site are presented in Table 4. The conditions for this calculation were meant to simulate conditions that might occur during summer or peak evaporation for a lake in an arid environment. An albedo value of 0.8 was used based on Akridge (2008).

**Table 4    Calculation inputs for the modified Penman equation**

| Parameter | Unit | Value |
|---|---|---|
| Water Temperature | °C | 21 |
| Air Temperature | °C | Min- 25, Avg- 30, Max- 35 |
| Relative Humidity | % | 35 |
| Wind Speed | km/h | 3 |
| Solar Radiation | W/m$^2$ | 290 |
| Albedo | – | 0.8 |
| Site Altitude | ft | 4,000 |
| Site Latitude | °N | 35 |

## 3.4    Results

Table 5 presents results of the modified Penman equation calculations, including the activities of water, densities of water, corrected evaporation rates as a function of TDS, percent reduction in evaporation rates compared to baseline, and TDS coefficients for application with the modified H-S equation.

The baseline activity of water was 1, which is the activity of fresh water. The calculated activities of water accounting for elevated TDS concentrations ranged from 0.98 to 0.14. The baseline evaporation rate was 24.1 centimetres per month (cm/mon). Evaporation rates for the TDS corrected calculations ranged from 23.9 to 9.3 cm/mon. Between a TDS concentration of 50,000 to 150,000 mg/L, the evaporation rate ranged between 23.9 and 23.4 cm/mon and the percent change in the estimated evaporation rate ranged from 0.6 to 2.6%. Around a TDS concentration of 200,000 mg/L the evaporation rate decreased to 22.8 cm/mon, a reduction in 5.1% from the baseline. Above 250,000 mg/L, the evaporation rate decreased by ever greater amounts. At a TDS of 300,00 mg/L the evaporation rate was 20.5 cm/mon, a reduction of 15%. The greatest decline in evaporation occurred up to a TDS concentration of 500,000 mg/L, where the evaporation rate was only 9.3 cm/month, a decrease in the estimated evaporation of 61%.

TDS coefficients ranged from 1 (0% reduction in evaporation due to TDS) at a TDS of 0 mg/L, to 0.39 (61% reduction in evaporation) at a TDS concentration of 500,000 mg/L.

**Table 5**   Activity of water and modified Penman evaporation rate calculation results at a water temperature of 21°C and an air temperature of 30 °C

| Total Dissolved Solids (mg/L) | Density of Water (kg/m³)[1] | Activity of Water[2] | Modified Penman Evaporation Rate (cm/mon) | Percent Reduction Compared to Baseline | TDS Coefficient |
|---|---|---|---|---|---|
| Baseline (0 mg/L) | 998 | 1 | 24.1 | 0 | 1.00 |
| 50,000 | 1036 | 0.98 | 23.9 | 0.6% | 0.99 |
| 100,000 | 1075 | 0.97 | 23.8 | 1.0% | 0.99 |
| 150,000 | 1116 | 0.92 | 23.4 | 2.6% | 0.97 |
| 200,000 | 1158 | 0.85 | 22.8 | 5.1% | 0.95 |
| 250,000 | 1203 | 0.75 | 21.9 | 9.1% | 0.91 |
| 300,000 | 1249 | 0.63 | 20.5 | 15% | 0.85 |
| 350,000 | 1297 | 0.5 | 18.7 | 22% | 0.78 |
| 400,000 | 1347 | 0.36 | 16.2 | 33% | 0.67 |
| 450,000 | 1399 | 0.24 | 13.1 | 46% | 0.54 |
| 500,000 | 1453 | 0.14 | 9.3 | 61% | 0.39 |

1- Chapman (2006)

2- Siadatmousavi & Seyedalipour (2019).

For the modified H-S equation, Table 6 presents the calculated evaporation rates using only the TDS coefficient, the evaporation rate using the TDS coefficient and Site coefficient, and for reference, the modified Penman evaporation rate from Table 5.

Evaporation rates calculated using the H-S equation with just the TDS coefficient produced evaporation rates between 17.9 cm/mon and 6.9 cm/mon. Evaporation rates calculated using both the TDS coefficient and the Site coefficient matched the rate predicted using the modified Penman equation. As shown in Figure 1, and indicated by the Site coefficient greater than 1, the H-S equation with only the TDS coefficients underestimated evaporation compared to the modified Penman equation. As expected, with the Site coefficient established, the evaporation rate as calculated using the modified H-S equation (with both the TDS and Site coefficient) matched the modified Penman evaporation rates.

A review of methods to calculate current and future evaporation rates
from pit lakes with high concentrations of total dissolved solids

J Lindauer & S Byers & G Lehn & E Evans
& D Castendyk & B Moravec

**Table 6        Hargreaves and Samani coefficient sand evaporation rate calculation results**

| Total Dissolved Solids (mg/L) | H-S Equation with Salinity Coefficients | | H-S Equation with Salinity and Site Coefficients | | Modified Penman (Table 5) |
|---|---|---|---|---|---|
| | TDS Coefficient | Evaporation Rate (cm/mon) | Site Coefficient | Evaporation Rate (cm/mon) | Evaporation Rate (cm/mon) |
| Baseline (0 mg/L) | 1.00 | 17.9 | 1.35 | 24.1 | 24.1 |
| 50,000 | 0.99 | 17.8 | 1.35 | 23.9 | 23.9 |
| 100,000 | 0.99 | 17.7 | 1.35 | 23.8 | 23.8 |
| 150,000 | 0.97 | 17.4 | 1.35 | 23.4 | 23.4 |
| 200,000 | 0.95 | 17.0 | 1.35 | 22.8 | 22.8 |
| 250,000 | 0.91 | 16.3 | 1.35 | 21.9 | 21.9 |
| 300,000 | 0.85 | 15.3 | 1.35 | 20.5 | 20.5 |
| 350,000 | 0.78 | 13.9 | 1.35 | 18.7 | 18.7 |
| 400,000 | 0.67 | 12.0 | 1.35 | 16.2 | 16.2 |
| 450,000 | 0.54 | 9.7 | 1.35 | 13.1 | 13.1 |
| 500,000 | 0.39 | 6.9 | 1.35 | 9.3 | 9.3 |
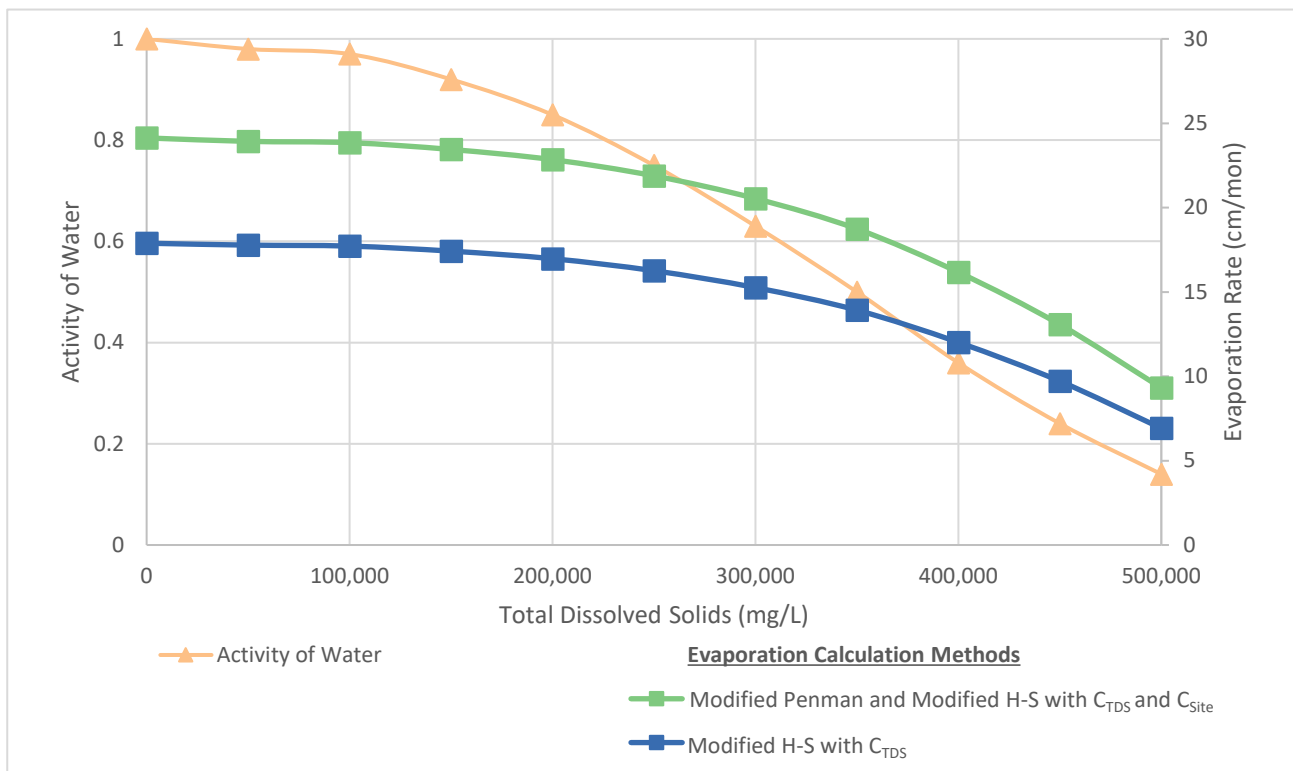


**Figure 1        Change in the activity of water and evaporation rates as a product of total dissolved solids**

A review of methods to calculate current and future evaporation rates
from pit lakes with high concentrations of total dissolved solids

J Lindauer & S Byers & G Lehn & E Evans
& D Castendyk & B Moravec

# 4        Discussion

Under the conditions of this theoretical scenario, there are two thresholds that can be observed. The first threshold is when TDS concentrations begin to have larger impacts on the activity of water (around 150,000 mg/L), and the second where increased TDS concentrations resulted in evaporation rate reductions of greater than 10% (around 300,000 mg/L). Increased TDS concentrations reduced the activity of water prior to reductions in evaporation rates. Note, this calculation was only completed for one month and assumed constant conditions.

The modified H-S calculations presented here can help mine operators estimate when and why water management strategies may need to change as TDS concentrations in water increase. For predictions of future evaporation rates, temperature-based methods, like the modified H-S equation are the preferred tool since they require only downscaled temperature from a climate projection, whereas an equation like the modified Penman requires wind speed, relative humidity and other meteorologic variables which are not typically generated by climate projections and have greater uncertainty. A temperature-based approach can be especially valuable when it is adjusted to account for the impact of TDS concentrations, as was done in this paper using the modified Penman. Accurate predictions of future evaporation rates are essential to meet water management objectives, such as avoiding discharge to downgradient aquifers. Furthermore, under climate change, shifts in local meteorology, particularly an increase in temperature, are expected and can be integrated into future water balances using the modified H-S method.

While an equation like the modified H-S equation has practical uses, there remain scenarios when an equation like the modified Penman is better suited. As previously mentioned, for past and present evaporation rates, the modified Penman equation is the preferred method since it accounts for more climatological and meteorological variables, like solar radiation, air temperature, wind speed, and relative humidity.

# 5        Conclusion

Water management plans for terminal and artificially terminal pit lakes involve minimizing the likelihood that water will discharge from the pit lake to downgradient aquifers. In arid climates, predictive water balances used to forecast lake water levels must account for TDS-corrected evaporation rates. This study reviewed common methods used to calculate current evaporation rates, and presented a novel, temperature-based approach to calculate future evaporation rates from TDS concentrations and temperature, called the modified Hargreaves and Samani equation (modified H-S). To apply the modified H-S method, one needs (1) future temperatures predicted from a climate model; (2) the activity of water predicted from past and future TDS concentrations; and (3) TDS and Site coefficients calculated from historic site meteorological data using the modified Penman equation. A hypothetical scenario for a pit lake located in an arid climate showed that evaporation rates begin to more greatly decrease around TDS concentrations of 300,000 mg/L. By integrating the modified H-S equation into a pit lake water balance, pit lake managers can anticipate the point in time when current water management strategies (e.g., demisters) will no longer be sufficient to contain water on site and can plan for new management strategies.

## Acknowledgement

A review of methods to calculate current and future evaporation rates
from pit lakes with high concentrations of total dissolved solids

J Lindauer & S Byers & G Lehn & E Evans
& D Castendyk & B Moravec

# References

Akridge, G. D. 2008, 'Methods for calculating brine evaporation rates during salt production', *Journal of Archaeological Science*, Volume 35, Issue 6, 2008, Pages 1453-1462

Allen, R., Pereirea, L., Raes, D., Smith, M. 1998, 'Crop evaporation – Guidelines for computing crop water requirements – FAO Irrigation and drainage paper 56', *Food and Agriculture Organization of the United Nations*.

American Meteorological Society (AMS), 2012, 'Glossary of Meteorology'. *AMS*; [updated April 25, 2012; accessed May 15, 2023] https://glossary.ametsoc.org/wiki/Psychrometric_constant#:~:text=The%20ratio%20of%20specific%20heat,constant%2C% 20yields%20a%20moisture%20flux.

Chapman, R., 2006, The John Hopkins University of Applied Physics Laboratory, Laurel, viewed July 2023, https://science.widener.edu/~svanbram/seawater.html

Craig, H. and Gordon, LI. 1965, 'Deuterium and oxygen 18 variations in the ocean and the marine atmosphere. Stable Isotopes in Oceanographic Studies and Paleotemperatures', *Laboratorio di Geologia Nucleate*.

Dingman, L. S. 2015. 'Physical Hydrology (Third Edition)'. *Waveland Press, Inc.*

Jansen, F. A., Uijlenhoet, R., Jacobs, C. M. J., and Teuling, A. J. 2022, 'Evaporation from a large lowland reservoir – observed dynamics and drivers during a warm summer', *Hydrol. Earth Syst. Sci.*, vol. 26, pp. 2875–2898

Gammons, C.H., Poulson, S.R., Pellicori, D.A., Reed, P.J., Roesler, A.J. and Petrescu, E.M., 2006, 'The hydrogen and oxygen isotopic composition of precipitation evaporated mine water, and river water in Montana, USA', *Journal of Hydrology*, vol. 328, issue 1-2, pp.319-330.

Lensky, N. G., Lensky, I. M., Peretz, A., Gertman, I., Tanny, J., & Assouline, S, 2017, 'Diurnal Course of evaporation from the dead sea in summer': A distinct double peak induced by solar radiation and night sea breeze'. *Water Resources Research*, vol. 54, 150–160.

Mayr, C., Lücke, A., Stichler, W., Trimborn, P., Ercolano, B., Oliva, G., Ohlendorf, C., Soto, J., Fey, M., Haberzettl, T., Janssen, S., Schäbitz, F., Schleser, G.H., Wille, M., Zolitschka, B., 2007, 'Precipitation origin and evaporation of lakes in semi-arid Patagonia (Argentina) inferred from stable isotopes (δ18O, δ2H)', *Journal of Hydrology*, vol. 334, Issues 1–2, Pages 53-63

Metzger, J., Nied, M., Corsmeier, U., Kleffmann, J., and Kottmeier, C., 2018, 'Dead Sea evaporation by eddy covariance measurements vs. aerodynamic, energy budget, Priestley–Taylor, and Penman estimates', *Hydrol. Earth Syst. Sci.*, 22, 1135–1155.

McJannet, D, Webster I, Stenson, M, Sherman, B 2008, 'Estimating open water evaporation for the Murray-Darling Basin: a report to the Australian Government from the CSIRO Murray-Darling Basin Sustainable Yields Project', *CSIRO*

McJannet, D, Hawdon, A, Baker, B, Ahwang, K, Gallant, J, Henderson, S & Hocking, A 2019, 'Evaporation from coal mine pit lakes: measurements and modelling', in AB Fourie & M Tibbett (eds), Mine Closure 2019: Proceedings of the 13th International Conference on Mine Closure, Australian Centre for Geomechanics, Perth, pp. 1391-1404.

McMahon, T.A., Peel, M.C., Lowe, L., Srikanthan, R., McVicar, T.R. 2013, 'Estimating actual, potential, reference crop and pan evaporation using standard meteorological data: a pragmatic synthesis', *Hydrol. Earth Syst. Sci*, vol. 17, pp. 1331-1363.

Mor, z, Assouline, S, Tanny, J, Lensky, I.M., Lensky, N.G. 2018, 'Effect of Water Surface Salinity on Evaporation: The Case of a Diluted Byuoyant Plume Over the Dead Sea', *Water Resources Research,* vol. 54, 1460–1475.

Johnson, F, Sharma, A 2010, 'A Comparison of Australian Open Water Body Evaporation Trends for Current and Future Climates Estimated from Class A Evaporation Pans and General Circulation Models', *Journal of Hydrometeorology*, vol. 11, issue 1.

Roderick, M, Rotstayn, L, Farquhar, G, Hobbins, M 2007, 'On the attribution of changing pan evaporation', *Geophysical Research Letters*, vol. 34, L17403.

Siadatmousavi, S.M. and Seyedalipour, S.A. 2019, 'Seasonal Variation of Evaporation from Hypersaline Basin of Lake Urmia', *The Handbook of Environmental Chemistry*, pp. 1-17

Skrzypek, G., Mydłowski, A., Dogramaci, S., Hedley, P., Gibson, J.J. and Grierson, P.F., 2015, 'Estimation of evaporative loss based on the stable isotope composition of water using Hydrocalculator', *Journal of Hydrology*, vol. 523, pp.781-789

Snyder, R. and Eching S., 2002, 'Penman-Monteith daily (24-hour) and Hargreaves-Samani Equations for Estimating Reference Evapotranspiration from Monthly Data', *Regents of the University of California*