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The Development of Water Balance Models for Tailings Management

S. J. Watson
Golder Associates

Summary The management of water on a tailings storage facility (TSF) is an important aspect of the overall management of a TSF. A useful tool to assist with TSF water management is a water balance model that tracks water inflows and outflows, and the change in surface water storage on a TSF. This paper discusses the components of a TSF water balance model and the uses of such a model. A case study illustrating the development of a water balance model for the TSFs at Kalgoorlie Consolidated Gold Mines is then presented.

1. INTRODUCTION

In recent years the management of tailings storage facilities (TSFs) has received increasing attention from government regulators and operators within the mining industry. One important aspect of tailings management that relates to the safe operation and efficient management of a TSF is the control of water within the storage area.

Water management in a TSF largely involves controlling the size and position of the decant pond through careful management of slurry deposition and decant water return to the processing plant. External influences such as rainfall, evaporation and seepage complicate the overall management of water on a TSF.

A useful tool to assist with the water management in a TSF is a water balance model, which accounts for all of the water inflows and outflows, and the change in water storage within the TSF. TSF water balance models can be developed for individual paddocks within a TSF, for an entire TSF, or for a series of TSFs that are independent or interconnected.

Two types of TSF water balances can be developed to assist with water management. An overall water balance can be developed for a TSF by accounting for the change in surface water storage and interstitial void storage. This requires all of the internal and external water flows to be accounted for in the water balance model.

Alternatively, the model can be simplified to account for the change in surface water storage only. In this case some of the external flows, such as seepage from the facility, and the processes that cause a change in interstitial void storage can be neglected. This has the advantage of simplifying the model by reducing the number of parameters and processes that have to be included in the model. A disadvantage of this approach is that the overall water balance for the TSF facility can not be evaluated.

This paper focuses on this second approach for TSF water balance model development, although most of the information presented is also applicable to the first approach.

2. COMPONENTS OF A WATER BALANCE

2.1 General

A water balance is an account of all quantities of water added to, stored within, or removed from a system over a specified period of time, such as a day, week, or month. In general, a water balance for a TSF is dynamic, which means that the components of the water balance vary continuously with time.

The main components of a TSF surface water balance are classified as storages, inflows or outflows, and are presented in Table 1.

Table 1: Components of a TSF Surface Water Balance

POND INFLOWS	POND OUTFLOWS
Slurry Bleed Water	Seepage / Drainage
Seepage / Drainage Return	Return Water
Rainfall	Evaporation
Additional Pumped Water	Spillway Overflow
Consolidation Water	

The difference between the inflows and the outflows is the quantity of water that is added to (positive difference) or removed from (negative difference) water storage upon the TSF.

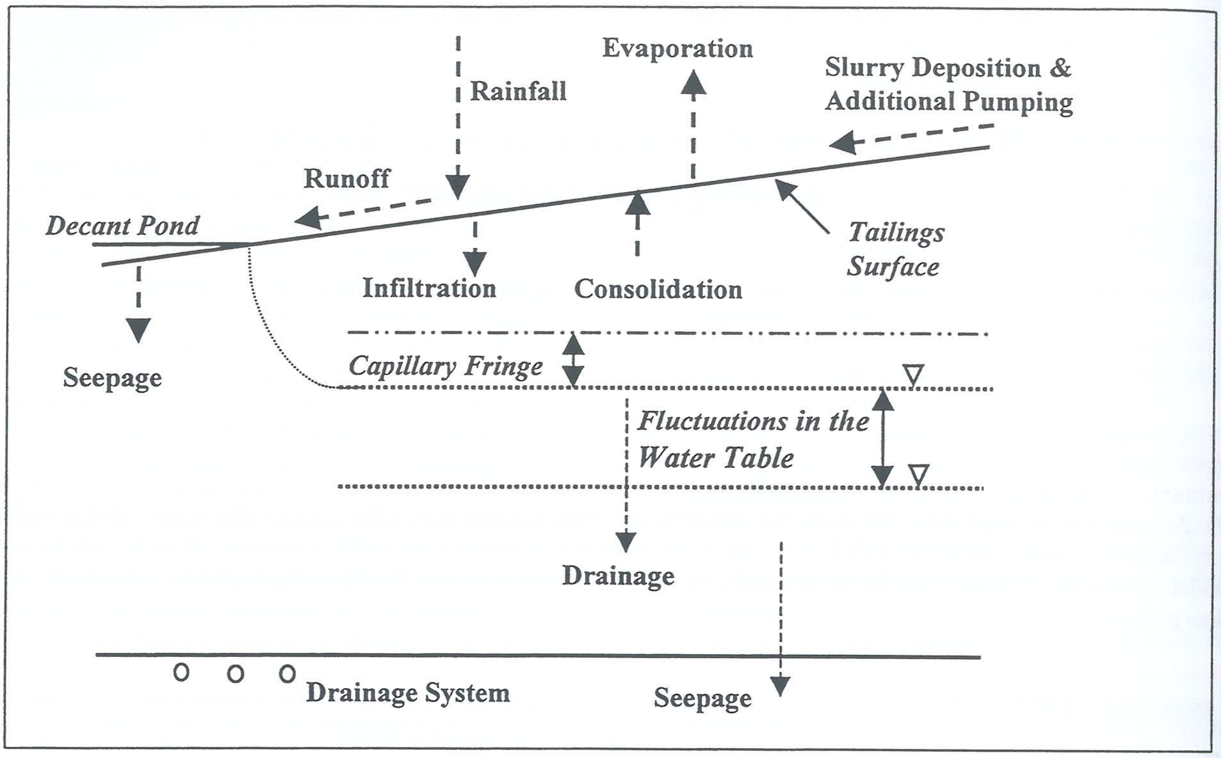

Figure 1: Schematic representation of the water inflows into a TSF and outflows from a TSF.

A schematic representation of the internal and external water flows is given in Figure 1, and a description of the inflows and outflows is given below.

2.2 Slurry Deposition

Mine tailings are generally deposited in TSFs as a slurry from single or multiple discharge points. Slurry deposition is therefore an external inflow of water into the facility.

In TSFs under active deposition, the rate at which slurry water is discharged into the facility is generally the largest of the water inflows into the facility. Slurry water deposition is also the water inflow that is most easily managed by the operators of a TSF.

Using the simplified (surface water) approach for TSF water balance model development, the volume of slurry water that reaches the surface water pond (decant pond) has to be evaluated. The volume of slurry water being deposited into the facility can be readily calculated from the tonnage being deposited, the slurry solid content, the specific gravity of the tailings solids and the density of the slurry water. However the volume of water discharged into the facility is greater than the volume of water that reaches the decant pond because some of the slurry water is held in interstitial voids, some infiltrates into the underlying tailings, and some is lost to evaporation.

A rough estimate of the volume of slurry water that inflows into the decant pond can be obtained by assuming that a fixed percentage of the slurry water reaches the pond. A more accurate approach is to account for the processes that have a *significant* effect on the volume of water that reaches the decant pond. These processes include sedimentation of the tailings with release of slurry water (termed bleed water), followed by loss of the bleed water to evaporation and infiltration, as a function of the area under active deposition.

2.3 Tailings Consolidation

Water that is released to the tailings surface during consolidation of the tailings is an inflow of water into the decant pond. The volume of water released by consolidation depends on:

- the mineralisation, physical and chemical properties of the tailings
- the depositional history of the tailings, particularly the rate of tailings deposition
- the thickness of tailings
- the permeability of the TSF foundations.

Generally, in a facility that has a small decant pond, the majority of water that is released to the surface during consolidation of the tailings evaporates. However, if the tailings has been deposited with a rapid rate of rise, or the majority of the tailings surface is covered by the decant pond, then a larger proportion of consolidation water is likely to inflow into the decant pond.

An estimate of the volume of water released into the decant pond by consolidation of the tailings is best obtained from a consolidation model of the facility.

It should be noted that if an overall water balance is being developed for a TSF, water release due to consolidation not only results in an inflow into the decant pond, but also reduces the volume of water stored in interstitial voids.

2.4 Return Water

Most TSFs are constructed with a decant facility to remove surface water off the TSF. The majority of operations return water to the processing plant, whereas some allow for evaporation or disposal of the water. Returning process water to the plant reduces overall raw water and reagent consumption, thereby reducing costs. It has the added advantage of minimising the volume of contaminated slurry water that requires treatment or storage.

At any point in time, the volume of water returned to the process plant from a TSF depends on a number of factors including:

- the volume of decant water available on the TSF
- the pumping capacity of the water return system
- the maximum volume of process water able to be used by the processing plant.

Plant return water is generally the outflow from a TSF that is most readily controlled by the TSF operator.

2.5 Seepage and Drainage

Seepage and drainage from a TSF is an external outflow from the facility into either an underdrainage collection system, if such a system has been installed, or into the surrounding environment.

It is important to minimise seepage from a TSF for both environmental and economic reasons, to minimise adverse environmental impacts, such as groundwater contamination and salinisation of the root zone, and to minimise the loss of process water and chemicals.

In some cases the seepage that is collected in seepage collection dams or from recovery bores is returned to the plant. In others, the seepage water is returned back into the TSF from which it has emanated. In the latter case, the seepage water that is recovered becomes a surface inflow into the facility.

If the water balance is being developed to account for changes in surface water storage only, the seepage from the decant pond into the underlying tailings is more important than seepage from the base of the TSF. The rate of seepage from a decant pond is a function of the tailings depth, tailings permeability, pond size and to some extent the facility size. The rate of seepage from a decant pond can either be estimated using Darcy's law, or can be evaluated using 2-dimensional sectional seepage models.

2.6 Rainfall and Evaporation

Rainfall is an external water inflow and evaporation is an external water outflow from a TSF, but unlike slurry deposition and water return, these water flows are largely unable to be controlled by the operators of the TSF.

The volume of rainfall that reaches the decant pond of a TSF depends on the amount of runoff and evaporation that occurs from various regions of the decant pond catchment.

A decant pond catchment can generally be divided into five main regions, discussed below:

- Wet Beach - is the area of tailings beach under active deposition. In this area the tailings are already saturated so 100% of the rainfall is likely to become runoff.
- Drying Beach - is the area of tailings beach that has recently undergone deposition, but is no longer an active beach. The tailings in a drying beach are also close to saturation, so 100% of the rainfall can be assumed to runoff. There will be some evaporative losses from the runoff.
- Dry Beach - is the area of tailings beach that has dried to the point that the voids are no longer fully saturated. In this case some (or all) of the rainfall is lost to infiltration and evaporation, depending on the intensity and duration of the rainfall event. There may also be significant cracking of the tailings surface in a dry beach area, which can affect the volume of water lost to infiltration and evaporation. The remaining volume of rainfall can be assumed to report to the decant pond.
- Decant Pond - rainfall falling directly on the decant pond is a direct inflow into the pond. Water loss from the decant pond due to evaporation also needs to be included in the water balance.
- Surrounding Catchment – Some TSFs located within valleys may receive runoff from the surrounding catchment during a rainfall event if drainage channels or bunds are not constructed to divert the catchment runoff.

If a TSF water balance model is being developed to account for changes in surface water storage, then only the volume of rainfall and runoff reaching the decant pond, and the volume of evaporative loss from the pond need to be accounted for in the model.

Alternatively, if an overall water balance model is being developed to account for changes in surface and interstitial storage, then the volume of rainfall infiltrating into the residue and the volume of water lost to evaporation in the various regions of the TSF must be included in the model.

2.7 Climatic Data

One aspect of TSF water balances that requires special consideration is the climate data to be used in the simulation.

It is not possible to predict future rainfall and evaporation rates, so various techniques are used to obtain climate data for the simulations.

One approach is to use measured historical daily rainfall and evaporation data for the area. A long period of historical record is preferential because it allows a number of simulations to be run, starting at different times in the historical records. This allows a range of climatic conditions to be applied to the simulated deposition strategy. The simulation results can then be interpreted to give probabilistic results, such as daily water return volumes and decant pond elevations. An advantage of this approach is that it can be used to examine the effect of climatic extremes by simulating a series of wet or dry years.

A less accurate approach is to use average monthly rainfall and evaporation rates. The main disadvantage of this technique is that the averaging procedure smooths out the rainfall, moderating the effects of irregular rainfall events.

2.8 Spillway Overflow

Some TSFs are designed with spillways to remove excess water from the decant pond when the elevation of the water surface in the decant pond exceeds the elevation at the base of the spillway. Typically spillways are used to transfer excess water into other TSFs (or other water storage facilities) to maintain sufficient freeboard within an interdependent system of TSFs.

2.9 TSF Geometry

To account for the changing geometry as slurry is deposited into a TSF, a water balance model must incorporate the following:

- The depth of the decant pond as a function of pond volume
- The surface area of the decant pond as a function of the pond volume (or depth)
- An approximate rate of rise of the tailings during the period that tailings is being deposited.

These geometrical relationships are extremely important as they affect many of the water balance components, including evaporation and seepage from the decant pond, rainfall runoff from most of the beach areas, rainfall recharge of the decant pond, and consolidation water flow into the decant pond.

3. USES OF A WATER BALANCE MODEL

A TSF water balance model, which accounts for the storages, inflows and outflows discussed in Section 2, can be used to:

- Improve deposition strategies in the short or long term to maximise water recovery or maximise water evaporation, depending on the water return requirements
- Estimate the likelihood of exceeding the maximum operational water elevation for a range of climatic conditions
- Estimate the freeboard necessary to contain extreme rainfall events, such as a 1:1000 year storm event
- Estimate the likelihood and extent of a return water shortfall under average or extreme climatic conditions
- Manage the water in TSFs containing acid generating tailings that may require a permanent water cover
- Provide inputs for a qualitative and quantitative risk assessment of a TSF.

4. DEVELOPMENT OF A TSF WATER BALANCE MODEL FOR KCGM

4.1 Background

KCGM is Australia's largest gold producer from one operation, with annual gold production in excess of 23 tonnes. Approximately 13.7 million tonnes of ore are processed annually to produce the gold, which results in approximately 13.7 million tonnes of waste tailings being generated annually.

The waste product is a sandy (fine-grained) silt tailings which is discharged as a slurry into the KCGM TSFs. In excess of 23,000 kL of slurry water are discharged daily into the TSFs. A proportion of this slurry water reports to the decant ponds and is available for return to the processing facilities.

KCGM spends several million dollars a year on process water for the plant. It was therefore considered desirable to develop a water balance model for the KCGM TSFs to enable reasonably accurate prediction of return water from the TSFs. Another purpose of the model was to enable comparison of differing tailings management strategies and/or TSF construction options to maximise water recovery.

4.2 KCGM Tailings Storage Facilities

KCGM has three active TSFs called Fimiston I, Fimiston II and Gidji. Tailings from the Fimiston processing plant is predominantly discharged into Fimiston II, with excess tailings directed to Fimiston I. A much smaller volume of tailings is discharged into the Gidji TSF from the Gidji roaster.

Fimiston II is the largest TSF covering approximately 3.6 km^2. Tailings discharge is cycled between three paddocks, with each paddock receiving approximately 2 months of deposition, followed by 2 months of drying and 2 months of wall raising.

Fimiston I and Gidji are also divided into paddocks so that tailings deposition can be cycled between paddocks to allow for drying of the tailings. This allows for upstream raising of the perimeter walls with tailings borrowed from the adjacent beach.

An important consideration in the development of the water balance model was the incorporation of a flexible deposition strategy to enable the cycling between facilities to be modelled, and also to enable different deposition strategies to be evaluated.

4.3 Model Framework

The model was developed in Microsoft Excel as it was desirable to have a model that could be readily adapted in the future, and which allowed for the incorporation of add-in programs, such as @RISK, at a later date.

The model structure incorporates a graphical menu to direct the user to various sheets in the model and a control menu to enter simulation parameters and run the water balance simulations. There are a number of data entry sheets setup in the model, including an operational data sheet which allowed for the entry of different deposition strategies. A climatic data sheet has also been included in the model, containing 25 years of historical rainfall and evaporation data to be used for the model simulations. The model also contains a master calculation sheet for the water balance calculations and various report sheets to view the simulation results.

The model was developed to track water flow into and through each TSF paddock on a daily basis and daily return water availability.

The model was also developed to track three water quality parameters, namely pH, magnesium ion concentration and the concentrations of total dissolved salts (TDS). This functionality was included so that the model could simulate the quality of the water returned to the processing facilities.

The chemical species of interest (hydrogen ions, magnesium ions and other salts) were assumed to be conservative solutes. This allowed the chemical concentrations to be tracked using a mass balance approach.

4.4 Water Balance Components

The following components were incorporated into the KCGM TSF water balance model:

- slurry deposition
- rainfall and evaporation
- water return to the plant
- seepage losses.

Consolidation water release to the decant pond was not included in the water balance model, as this inflow was considered negligible given the overall water flow volumes for the KCGM TSFs.

Some other important processes that were incorporated into the model equations include:

- the loss of slurry (and therefore slurry water) to borrow pits around the perimeter of the tailings surface following upstream raising of the perimeter embankment
- loss of rainfall to cracks
- effect of salinity on evaporation
- runoff factors for each month for a range of rainfall events
- varying rates of seepage from each decant pond as a function of the pond size, residue depth and paddock area.

4.5 Model Simulations

The model has been developed so that different water balance simulations can be run once all of the operational and tailings data has been entered into the model. Water balance simulations can be run for a specified period of deposition using either wet, dry or randomly selected sets of daily historical rainfall and evaporation data. If the climate sets are set to be randomly selected, up to 25 different climate scenarios can be run against the specified depositional strategy.

4.6 Model Calibration

Although historical and operational data has been used during the development of the model, many of the lookup tables upon which the model relies have been estimated from experience, or using surface or groundwater models with little hard data available for their calibrations.

The model is now in a stage of calibration to real data to refine various parameters, such as runoff coefficients for the various beach areas, seepage rates from the decant pond, beach drying times and dry beach crack volumes.

4.7 Model Output

The results from a water balance simulation are presented in tabular and graphical form in the KCGM TSF model. Results are generated for each TSF paddock and for user specified paddock combinations to obtain total processing facility results.

The output results generated for each paddock include:

- the volume of water returned to the process plant
- the percentage of total slurry water that is returned to the plant
- the TDS and magnesium ion concentration of the return water
- the pH of the return water.

The output results generated for each paddock are tabulated and produced graphically against the simulation time. An example of a paddock graph showing the volume of water available for return to the processing plant from a paddock in the Fimiston II TSF is given in Figure 2. This example has been generated from a simulation using 5 different climate sets (CS1 to CS5). As the model has not yet been calibrated, the volumes presented in Figure 2 are not an actual indication of water return volumes for the single paddock.

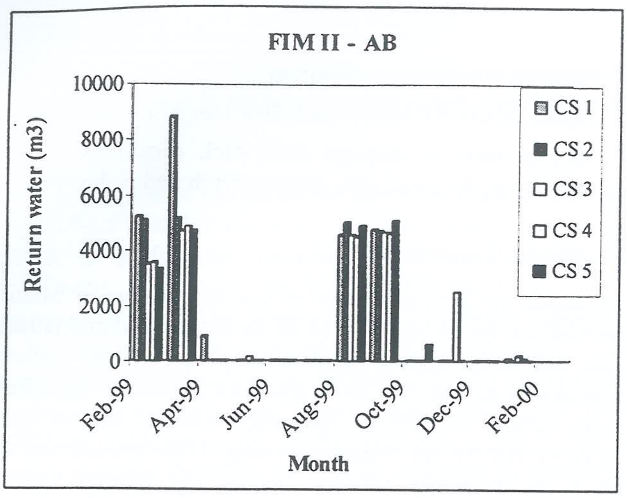

Figure 2: Example graph for a TSF paddock

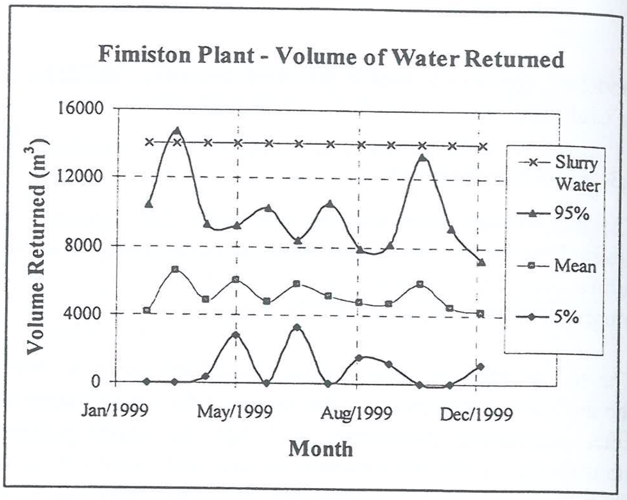

Figure 3: Example of a facility graph

The output results generated for each paddock for each climate set are combined to generate processing facility results. The paddock results are evaluated statistically to give the mean and 90% confidence interval (90% CI) values for the parameters listed above (for the paddock results).

The statistical results for the processing facilities are tabulated and produced graphically against the simulation time. An example of a facility graph showing the mean and 90% confidence interval limits for the volume of water returned to the Fimiston processing facility is presented in Figure 3. The 90% CI curves give the upper and lower limits within which there is a 90% confidence that the predicted values will fall. As for Figure 2, the volumes presented in Figure 3 are not an actual indication of water return volumes to the KCGM Fimiston processing plant because the model has not been calibrated to site data.

5. CONCLUSIONS

A water balance model is a useful tool to assist in water management in and around a TSF, and to indicate how much water is likely to be available for return to the processing plant. A water balance model can also be used to assist in the development of deposition strategies that are appropriate to the water return requirements of the mining operation.

It is generally not necessary to do an overall water balance for a TSF, as a surface water balance model provides reasonable estimates of surface water storage volumes, and the volume of water available for return to the plant.

The reliability of a water balance model is controlled by the accuracy of the input data. Some of the input data can be measured, but some data has to be estimated. In general, it is possible to make reasonable estimates of the input and output flows resulting in reliable output results from the water balance simulations.

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