Closure Water Balance Model to Support Closure Designs for a Mine in Laos

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Abstract

SRK Consulting (Australasia) Australia Pty Ltd (SRK) are currently assisting with the development of closure plans for portions of a mining Development Area located in Central Laos. To support closure planning, it is important to identify which pits and dumps represent significant contaminant sources, and to understand how effectively contaminant release can be mitigated as part of the closure design.

A catchment delineation process was undertaken in which flow paths and catchment areas were defined to reflect the Life of Mine (LOM) topography, landforms and features within individual precincts. A closure water balance model (CWBM) was constructed to allow assessment of impacts for closure options at the precinct, sub catchment and catchment scale.

Stochastic rainfall was developed based on the available climatic data for the years 1994 2015 and showed good correlation with long term averages. Runoff from natural (i.e. non mining) areas for the CWBM was developed using the Australian Water Balance Model (AWBM). Unique calculations of hydrologic fluxes were conducted within GoldSim for mine pits, backfilled pits, water management structures, waste rock landforms and non mining areas. Within the CWBM, flows from natural areas and precincts were aggregated at nominated water quality assessment points to provide flow estimates for water quality predictions.

In general, pit voids and water management structures follow a distinct seasonal pattern, with ephemeral outflows during the wet season, and no outflow during the dry season. The assessment predicts that this seasonal pattern will be maintained after closure, such that the pit voids and water management structures maintain perennial lakes through the dry season, and overflow during the wet season. In addition, most pit lakes will be gaining water bodies, i.e. receiving significantly more seepage from groundwater than they are losing to groundwater and will spill.

Keywords: Hydrology, Hydrogeology, water quality, water balance

Introduction

The subject mine (the site) is an open cut gold and copper mining operation located in Central Laos. Mining operations comprise several gold and copper open pit operations, with the gold operations currently in care and maintenance. Figure 1 shows the site layout comprising open pits, waste rock dumps, and water management structures.

For the purposes of closure planning, the operations have been separated into three distinct areas, based on geographical location and operational status. The current assessment primarily deals with the Western and Central Development Areas which comprise a series of open pits and waste rock dumps for both copper and gold operations, that fall primarily west of the main river that passes through the site. The other two areas comprise the tailing storage facilities (TSF) and a copper open pit operation that includes the process plant and other infrastructure.

The assessment formed part of a multi disciplinary approach to support development of overall closure designs (the overall approach is described in a companion paper, Chapman et al. 2018).

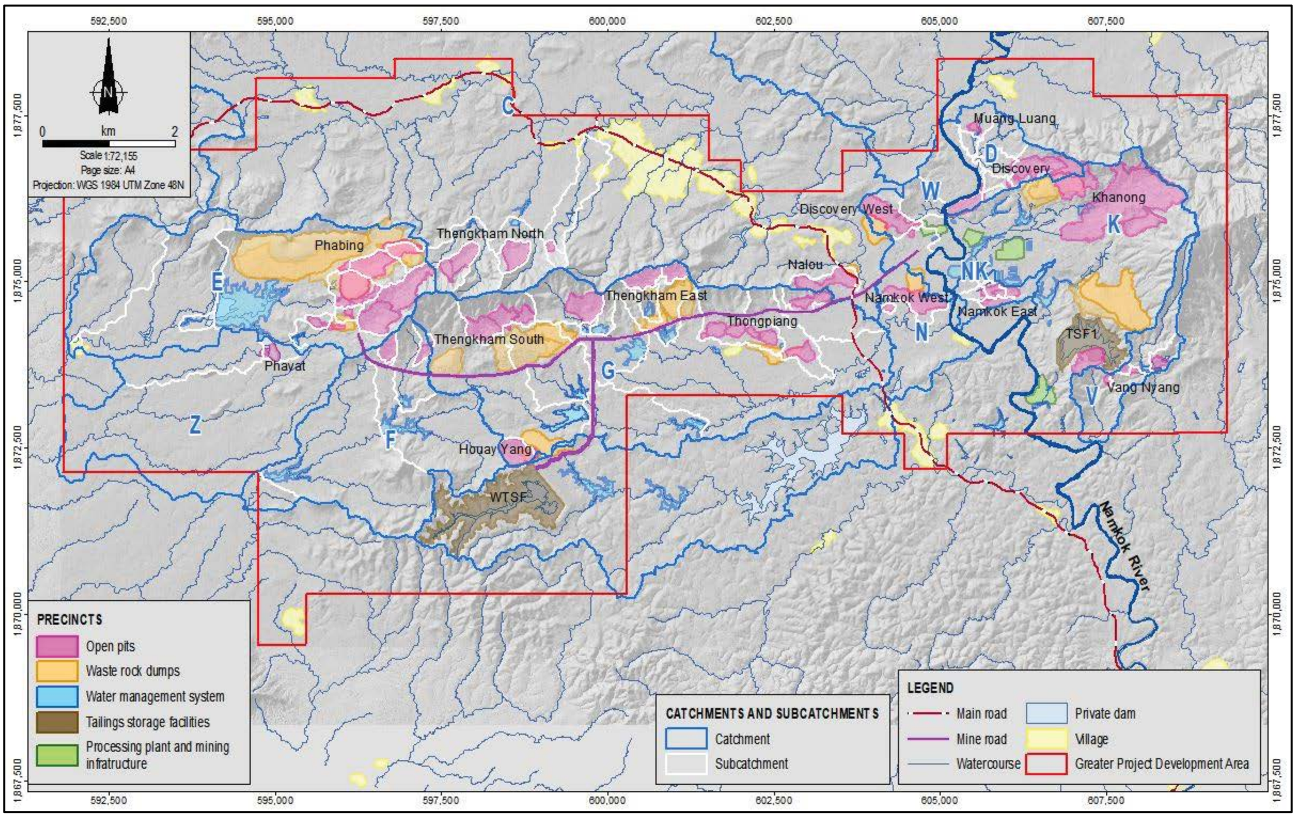


Figure 1: **Subject Mine site – general layout.**

Climate

The site is characterised by a tropical climate, with a distinct dry season (October to April) and wet season (May to September). Daily rainfall and evaporation data have been collected since 1994, and monthly average values are summarised in Figure 2.

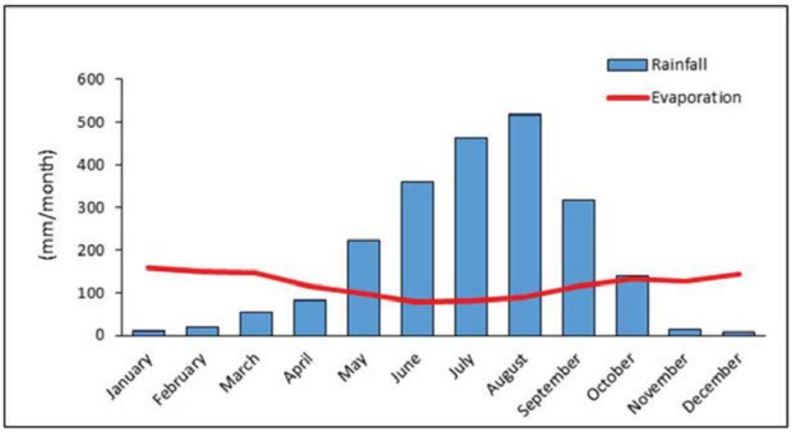


Figure 2: **Measured monthly rainfall and evaporation (1994 - 2015).**

The mean annual rainfall for the region is approximately 2,250 mm/year, of which up to 80% occurs in the wet season. Mean annual evaporation in the region is approximately 1,450 mm/year. The site has a net positive water balance (i.e. rainfall>evaporation), most evident during the wet season from May through September. During the dry season (November through April) the site has a net negative water balance.

Hydrology

The Project area drains into the Namkok and Xe Noy River systems. The site was additionally divided into smaller catchments (see Figure 1) of which C, D, G, N, NK, V, Wand Z discharge into the Namkok River, while catchments E, F and Z drain into the Xe Noy River towards the west. The catchments generally form headwater streams, i.e. first and second order streams before joining the Xe Noy and Namkok Rivers. Due to the distinct dry and wet seasons, significant seasonal fluctuations occur in streamflow. During the dry season headwater streams are considered ephemeral. Larger reaches of streams (i.e. the Namkok and Xe Noy rivers) receive significant baseflow during the dry season and are considered perennial.

Water Balance Model Development

Approach

A Dynamic Systems Model (DSM) developed in GoldSim (version 11.1.5) has been used to simulate the flow of water for the various hydrologic components, including non mining areas, pits, waste rock dumps and sediment management ponds.

The objective of the model was to develop a post closure water balance for the site to evaluate the effects of closure options for mine infrastructure and larger catchments on water quality. The model included:

- Flow estimates for individual components, including runoff and recharge to the groundwater system.
- Flows from contributing natural areas.
- Combined flows from both natural areas and identified mine infrastructure at identified water quality
- monitoring or water quality evaluation points.

Stochastic Rainfall and Evaporation

Variation in rainfall is the primary source of uncertainty in the development of the closure water balance model (CWBM) for the Project Area. GoldSim allows the water balance to be simulated for many realizations incorporating stochastic rainfall data to develop probabilistic results. The stochastic rainfall generation module allows day to day rainfall patterns to vary, while maintaining consistent seasonal rainfall patterns. Evaporation was calculated based on monthly average site data for the period 1994 to 2015. A pan factor of 0.8 was adopted for natural water surfaces (pit lakes and sediment ponds).

Life of Mine Flow Logic Development

Prior to development of the CWBM, a catchment delineation process was undertaken to develop a flow logic tree for the final closure catchment configurations. For each catchment, the topography was updated to reflect the Life of Mine (LOM) landforms and features. This updated LOM topography was then analysed within a GIS environment to develop updated surface water sub catchments. Non mining impacted areas, were separated from mine impacted areas and infrastructure to allow the assessment of water quality impacts from mixing and/or diversion of natural runoff with mine impacted water. Surface areas for individual precincts and undisturbed areas in each catchment were calculated within the GIS environment and tabulated for use in the CWBM.

Within the CWBM, flows from natural areas and relevant precincts were aggregated at the nominated Assessment Points to provide flow estimates for water quality predictions used to assess the closure options for the site. Flows from individual precincts, as well as from Assessment Points, were utilised in the solute loading calculations provided in Linklater et al. (2018).

Runoff from Natural Areas

An Australian Water Balance Model (AWBM) module (Boughton, 2004) was developed within the GoldSim model to simulate runoff from non mining impacted areas. The AWBM is a commonly used catchment water balance model method which simulates storage within a catchment to simulate the variable nature of catchment morphologies. Overflow from the surface stores, when rainfall exceeds their capacities, is routed to a further two storages which allow generation of both baseflow and surface runoff components which feed stream flow. Values for surface storage capacities and factors for partitioning between surface flow and baseflow are ideally generated through calibration with gauging data from catchments within the study area.

Waste Rock Dump Runoff and Seepage

The battery limits for this study include 13 waste rock dump (WRD) landforms, not including backfilled pits. Runoff from the WRDs and seepage into the groundwater system were calculated for each landform within the CWBM using a waste rock dump module that was based on a curve number approach. Runoff is generated when daily rainfall exceeds initial abstraction (Ia) for the waste material. In order to account for the effect of consecutive rainfall days, initial abstraction was reduced by 90% if the rainfall on the preceding day exceeded 20 mm. The curve number adopted for backfill material was 60 and applied to all WRDs. All WRDs were initially assessed as uncovered and unvegetated landforms.

Seepage from WRDs was established at 15% of the annual rainfall. A portion of the seepage was assumed to daylight as toe seepage, and was directed into the surface water system, while the remainder was directed to the deeper groundwater system (referred to as basal seepage). For the initial iteration of the CWBM, toe seepage was assumed to occur at every WRD and was set to 30% of total seepage from the WRDs. Storage within the WRDs was not simulated in the CWBM. In some instances, percolation can be delayed by extended time periods, which would result in solute loads from the WRDs lagging behind peak runoff flows. The current approach may therefore not be conservative and calculated dilution ratios may be higher than would occur in reality.

Pit Water Balances

A total of 42 pits were included in the battery limits for this study. Two fundamental closure options have been identified for the pits: backfilling or flooding. Conceptually the groundwater level is expected to rebound to elevations similar to pre mining elevations for backfilled pits, with the backfill above the water table resembling WRDs (with similar options for closure, i.e. reshaping, covers, etc). Open pits are expected to form lakes due to the positive water balance and, as dynamic systems, required simulation of inflows, outflows, and changes in water storage over time.

Interaction of pit lakes with groundwater is also expected post closure. Water quality within pit lakes and overflow data is discussed as part of the geochemical assessment (Linklater et al. 2018).

The water balance for pit lakes was as follows:

Δwater volume = Pprecip + Qinflow + Rwall runoff + RNatural runoff + GWseepage - Epit – Qoutflow

(where Δ is a change in volume, P is precipitation, R = runoff, GW is groundwater, E is evaporation and Q is volume in consistent units). Pit wall runoff was calculated using a pit runoff factor. Runoff was assumed to occur only once rainfall exceeds 5 mm. For rainfall less than 40 mm, the runoff coefficient was set at 20% of daily rainfall, unless there was more than 5 mm of rainfall the preceding day, in which case the runoff factor was increased to 65% of daily rainfall. For daily rainfall above 40 mm, the runoff factor was set at 65%.

Outflow to groundwater from the pit lake, or inflow from groundwater, is proportional to the difference in head between the pit lake elevation and the surrounding groundwater table.

To facilitate development of an analytical solution to estimate flows both into, and out of, the pit lakes, flows were calculated within the CWBM by adding the results of a derivation of the McWhorter and Sunada (1977) equation for flow into a cylinder and out of a cylinder.

Sediment Management Pond Water Balances

Included in the battery limits for this study are twenty (20) sediment management ponds. The sediment ponds were assumed to be perched, and seepage was calculated as the footprint surface area (m^2) × hydraulic conductivity (m.s 1). Hydraulic conductivity was assumed to be 1.0 x 10 7 m.s 1.

Groundwater Recharge and Discharge

Groundwater recharge, including recharge from natural areas and seepage from all precincts, was aggregated for each catchment, or sub catchment, as applicable. A primary assumption was that, under steady state conditions, all recharge within a catchment will be returned to the surface water system at the discharge location of the given catchment (i.e. assuming no inter catchment groundwater flow). To account for potential additional losses, inter basinal flow, changes in aquifer storage and the potential for redirection of groundwater via karst features, a groundwater discharge factor was incorporated into the model (set at 0.5 in the CWBM).

Groundwater discharge was separate from the baseflow estimated as part of the AWBM runoff calculation. The AWBM baseflow represents transient storage within shallow soils, subsoils or alluvial materials associated with streams, whereas groundwater discharge represents outflow from catchment scale aquifer systems.

Modelling Scenarios

Two scenarios were developed as follows: a) base case scenario whereby WRDs and above grade backfilled pits remain uncovered; and b) mitigated case whereby WRDs and above grade backfilled pits are covered. In order to simulate flows for the mitigated case, adjustments to the WRD basal seepage, toe seepage and curve numbers were incorporated into the model, as outlined in Table 1.

Table 1: Runoff factor adjustments for waste rock dumps for base case and covered scenarios.

Scenario	Seepage factor (percentage daily rainfall)	Toe seepage (percentage daily rainfall)	Curve Number
Base case (uncovered)	10%	5%	60
Mitigated case (Covered)	5%	1.75%	75

Results

The model was used to simulate flows on daily time steps for an initial period of 10 years. A total of 100 realizations using stochastic rainfall data were run to develop a probabilistic assessment of flows within the model. Pits with lakes and water management structures were assumed at full capacity on commencement of the simulation period. The results of the simulation are compared with the mean monthly rainfall data for 1994 to 2015 in Figure 2 and suggest a reasonable correlation with observed data. The probabilistic rainfall as presented in Figure 3 shows that the highly seasonal precipitation patterns persist.

Probabilistic monthly storage volumes (in m^3) and outflow rates (m^3/month) for a typical pit lake are provided in Figure 8 for closure. In general, pit lakes follow a distinct seasonal pattern, with ephemeral outflows during the wet seasons, and no outflow during the dry season.

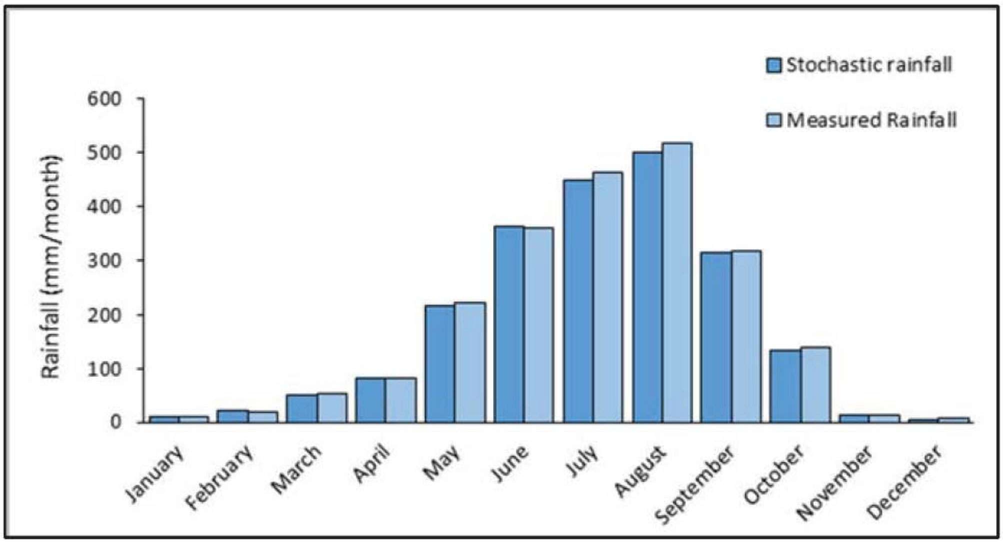


Figure 3: **Comparison of measured (1994-2005) and (2015–2025) stochastic rainfall from the CWBM.**

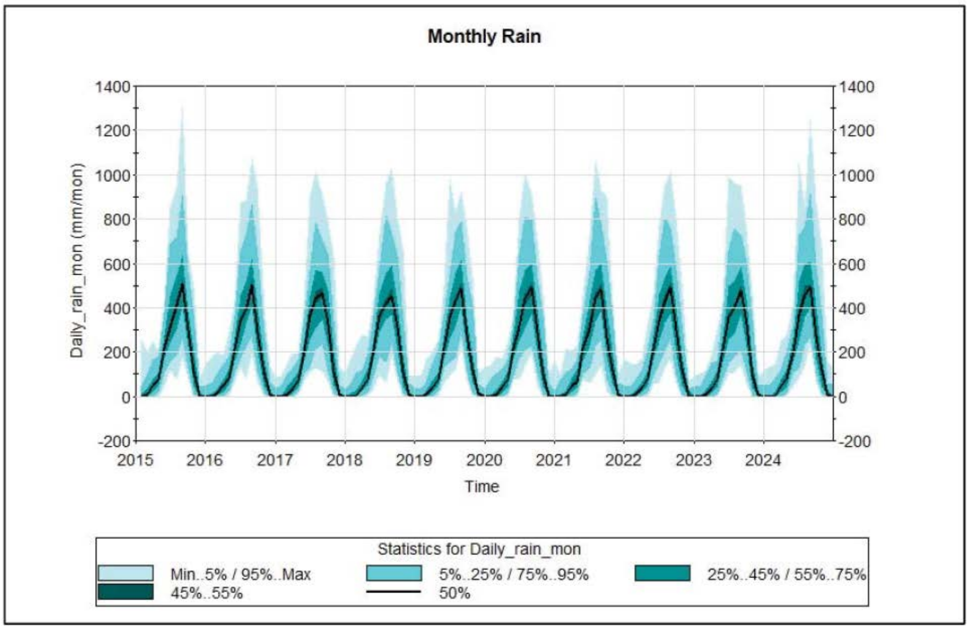
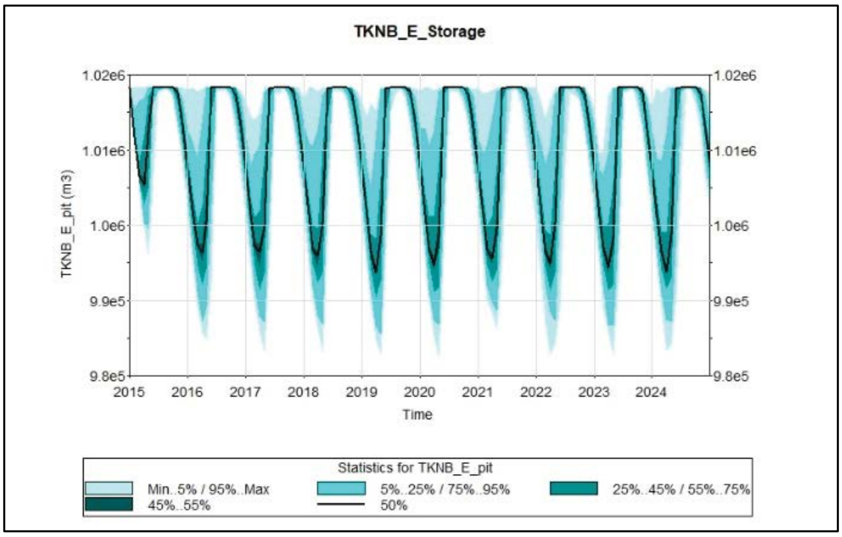
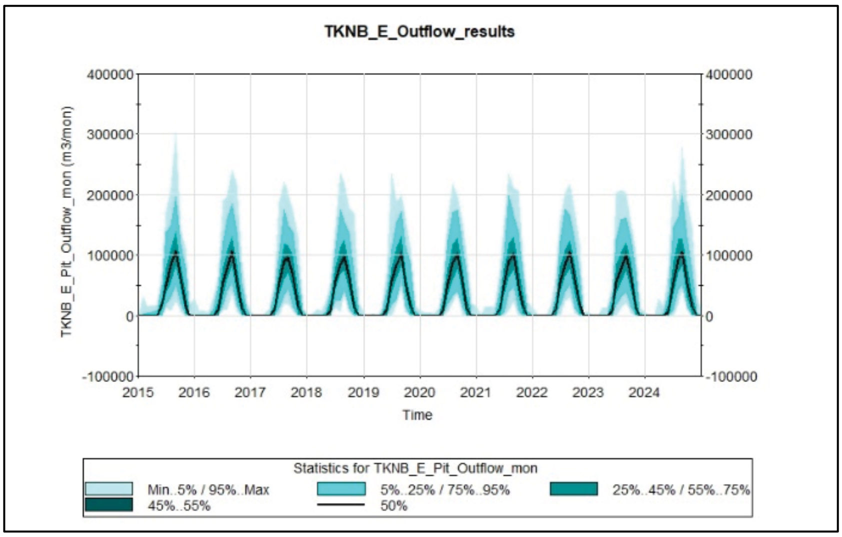


Figure 4: **Probabilistic rainfall results from the CWBM.**

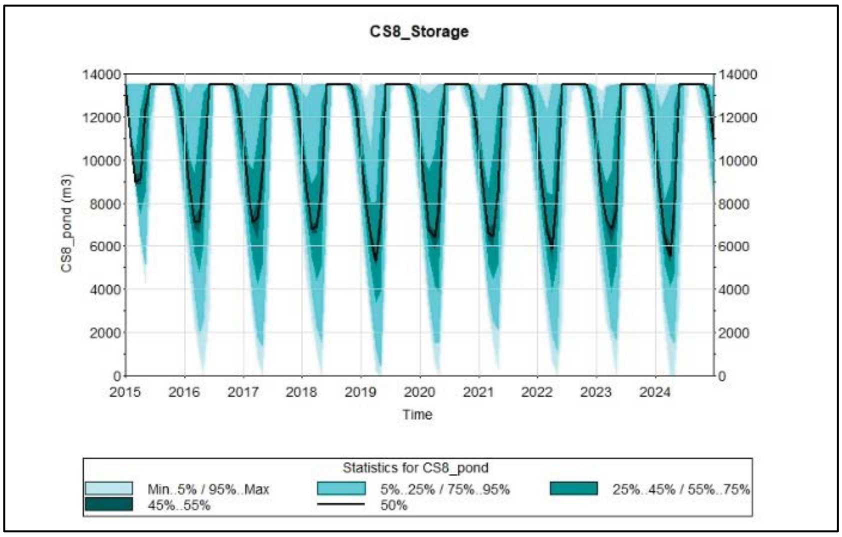
Based on the probabilistic results developed from the CWBM, even during the driest years, pit lakes will persist and will spill during the wet season. Similarly, during the wettest years, the water levels in the pits are reduced during the dry season with no outflow during the dry season. The sediment ponds are shown to follow a similar pattern (see Figure 5). Runoff from waste rock landforms also match seasonal rainfall patterns as shown in Figure 6, with flows expected during the wet season, and very low to no flows anticipated during the dry season. The probabilistic assessment for a representative WRD does not show any deviation for the typical seasonal runoff patterns for either the base case (uncovered) or the mitigated (covered) case. Runoff at Assessment Points (and from natural areas) also follows seasonal patterns, as demonstrated by the flow patterns predicted for Assessment Point CMN1 (Figure 6).



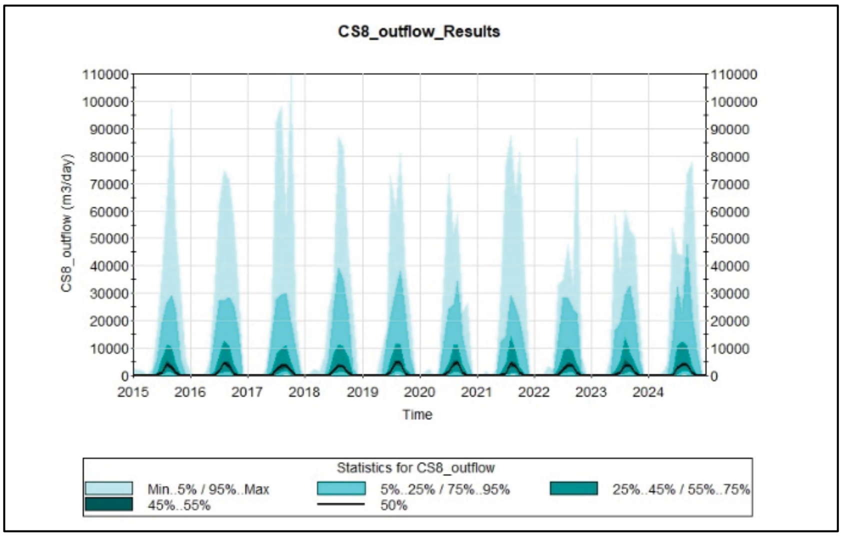
Pit Lake Storage Volume



Pit Outflow

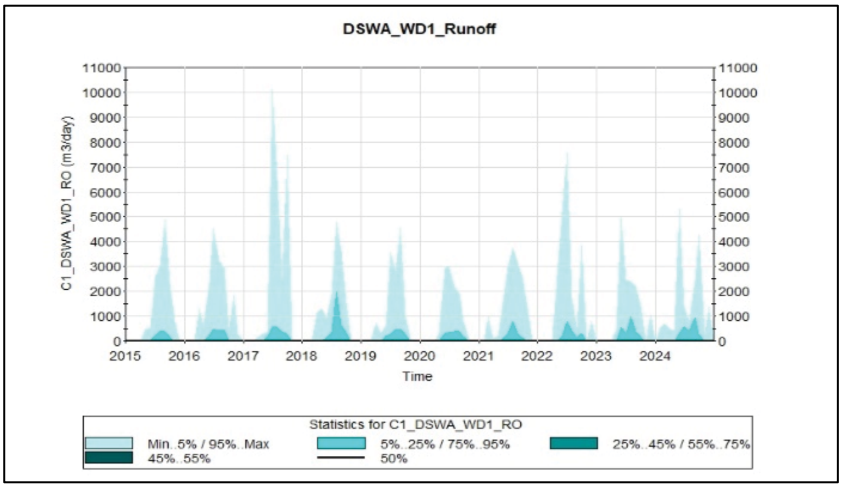


Sediment Management Structure Storage

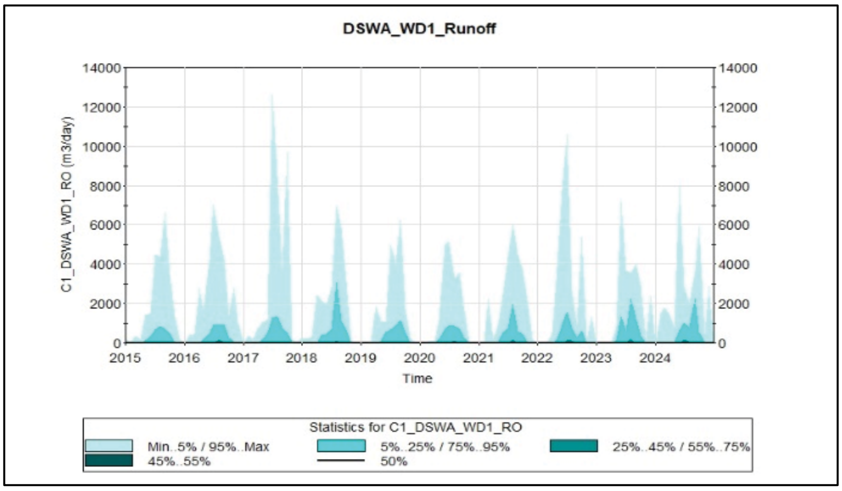


Sediment Management Structure Outflow

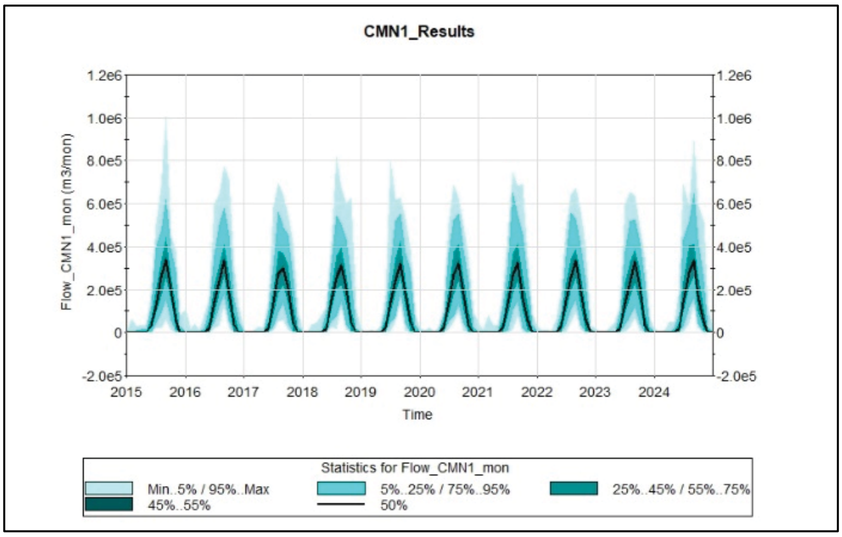
Figure 5: Representative probabilistic CWBM results for Pits and Sediment Management Structures.



WRD Runoff – Uncovered case



WRD Runoff –Covered case



Assessment Point CMN1 Runoff

Figure 6: Representative probabilistic CWBM results for Waste Rock Dumps and Assessment Points

Conclusions

Results of the water balance modelling indicated the following:

- The influence of the extreme seasonality of rainfall patterns is noted in all aspects of the model. Runoff from mine infrastructure and natural areas is unevenly distributed throughout the year, with very high flows in the wet season, and little to no flow during the dry season. Water volumes in storages, including pit lakes and sediment dams, vary significantly between wet and dry seasons.
- All pits form perennial lakes which overflow during the wet season.
- A majority of pits represent gaining water bodies, i.e. receiving more seepage from groundwater than they are losing. Groundwater mounding, which would be expected in an area with a positive water balance, is limited since in most cases spill points for pits are at or below the near-field water table elevations.
- Due to the scale of the assessment a large proportion of flows is derived from natural areas. This is primarily a function of the dispersed and small scale nature of mining at the site. This may have limitations on the suitability of the water balance results when considering precinct-scale closure options for future iterations of the closure plan.

The model is necessarily limited to use as a tool for evaluating closure options. The lack of available flow data for calibration of the model does add uncertainty to the results of the runoff and values; however, the predominant driver of runoff is the seasonal rainfall patterns, and uncertainties in runoff estimates are within the range of probabilistic results from the CWBM.

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