Integrated Water Balance, Streamflow and Quality Model for Holistic Determination of Security of Water Supply and Ecological Flow Requirements at a West African Mineral Sands Mine

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Abstract

Management of water resources within the area of influence of mining is critical to ensure sufficient water at the correct quality for all stakeholders, including the mine itself and the associated ecological systems. To achieve this, a multi-disciplinary team of hydrologists, hydrogeologists, ecologists and engineers was assembled to determine the required ecological flows and water quality in the freshwater, wetland and estuarine systems surrounding the mine. An integrated GoldSim-based model was compiled to simulate streamflow and the mine water and salt balance, and utilised as the central tool to ensure that both the mining and environmental water objectives were met.

Keywords: Water balance, salt balance, streamflow model, water quality, ecological flow, ecological reserve, dam sizing, water security, mine water management

Introduction

Availability of the right volume of water, at the right quality, at the right time is essential for sustaining both aquatic and riparian ecosystems. The same can be said of mining operations. However, mining activities can negatively affect water resources by degrading land, altering watercourses, and exposing water to ore and tailings. Surface water in West Africa is an essential resource for both natural systems and local communities affected by mining. A comprehensive understanding of these competing needs was developed during the mine planning stage of Sierra Rutile Limited's (SRL) Sembehun project, with the aim to minimise environmental consequences and balance the mine's water requirements with those of the surrounding environment.

SRL intends to mine their Sembehun reserve, a mineral sands deposit, by open pit mining methods over a period of approximately 13 years (i.e. 2026 to 2039). Several watercourses flow through the mining area, transitioning from freshwater in the upper reaches to estuarine in the lower reaches and incorporating a complex combination of sensitive wetland, peat and mangrove habitats.

To ensure sufficient water supply for the mining operation, while ensuring the preservation of habitat and the associated aquatic fauna and flora, a multi-disciplinary team of specialists was assembled to work with the mine team, in a co-operative relationship, to achieve a mine design that would satisfy both mining and environmental objectives. A multi-disciplinary approach was adopted for the determination of the Ecological Flow (E-Flow) requirements of the surrounding watercourses, which consider both water quality and quantity requirements to preserve the surrounding habitat and associated aquatic fauna and flora. The process demonstrated the value of a detailed and integrated model (incorporating catchment runoff (streamflow), in-stream water quality, and the mine water and salt balance), when utilised as the key interfacing tool between mine planning and environmental teams. Such a model enables the assessment of mining scenarios and environmental mitigations, in an iterative manner, to mitigate the threat of mining-related environmental impacts in the form of, amongst others, reduction in catchment area (water quantity) and discharge of mine affected water (water quality).

Site Characterisation

Sembehun mine will occupy an area approximately 45 km2 in extent, shown on Fig. 1. Several watercourses drain through the proposed mining area, in a south-westerly direction. These watercourses are tributaries of the Bagru River, which drains into the Sherbro estuary. Tidal conditions dominate the Bagru River as it flows past the mining area and extend a substantial distance up the tributaries. Upstream of the tidal influence, freshwater conditions persist, where the in-stream water quality can be described as near pristine.

Rainfall, and the associated streamflow, in the Sembehun region is highly seasonal, with a Mean Annual Precipitation (MAP) of 2,811 mm. The high seasonality results in water security concerns for mining and industrial activities during the dry season (J&W 2024).

Several open pits are planned, where the ridges between the watercourses will be mined. Ore will be processed at a Wet Concentrator Plant (WCP). Pits will be backfilled with overburden material, as well as tailings material from the WCP for selected open pits, with in-pit Tailings Storage Facilities (TSFs), being established. In addition, an Initial TSF (ex-pit) will be required for the first three years of mining, until pit development is sufficient for in-pit tailings deposition.

Water required for minerals processing at the WCP will be sourced first from return water from the TSFs, with make-up water being sourced from an in-stream Process Water Dam (PWD), situated on the Solaieyea Creek. To minimise the influence of the PWD and water abstraction on the downstream aquatic environment, environmental releases from the PWD will be required.

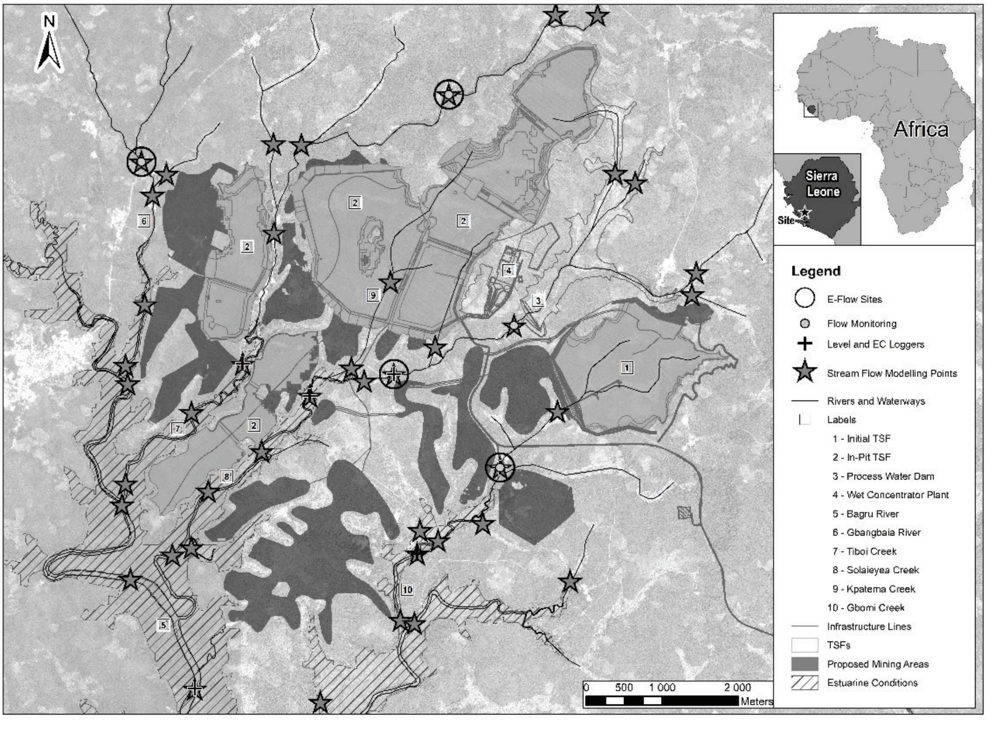

Figure 1 Map of mining area.

Groundwater and stormwater encountered within the open pits will be pumped into the adjacent watercourses, once suspended solids have been removed. Initial mine planning was that TSF return water and stormwater would be pumped to the PWD, for reuse in the WCP.

Potential threats due to mining were recognised by the mine planning team. These are expected to include direct loss of flow in the watercourses, due to abstraction of water for mining, loss of flow due to catchment reduction from the open pits and TSFs, change in baseflow to the watercourses due to the mine's interference with the groundwater regime, change in flow dynamics of the aquatic systems (for example seasonality and the freshwater-saltwater interface), deterioration in water quality and erosion as a result of mining, with consequent sediment deposition in watercourses and wetlands. These threats, in turn, can result in changes to the abundance and/or distribution of sensitive species, particularly in the dry season.

Overall Project Approach

With the key objective of supporting the mine design (in terms of availability of water and the associated required PWD capacity), while, at the same time, mitigating environmental impacts, a list of specialist studies required to determine the E-Flows requirements in the watercourses was compiled. Required studies comprised the following: hydrology, hydrogeology, geochemistry, wetlands, freshwater ecology and estuarine ecology. Several supporting studies were also required to provide data that would instill a greater degree of confidence in the outcomes of the studies and modelling. These studies included hydrological monitoring (rainfall, streamflow, water quality), estuary and river bathymetric survey, and sediment transport and geomorphology modelling. Mine design (i.e. Life of Mine (LoM) plan, stormwater planning, water management planning) was also required.

An integrated model was developed, incorporating catchment runoff and streamflow modelling for the mining area and the associated watercourses, as well as mine water and salt balance modelling. This model was used as the central interface between the mine design and the environmental studies determining the E-Flow requirements. It modelled the effects of the mining on the

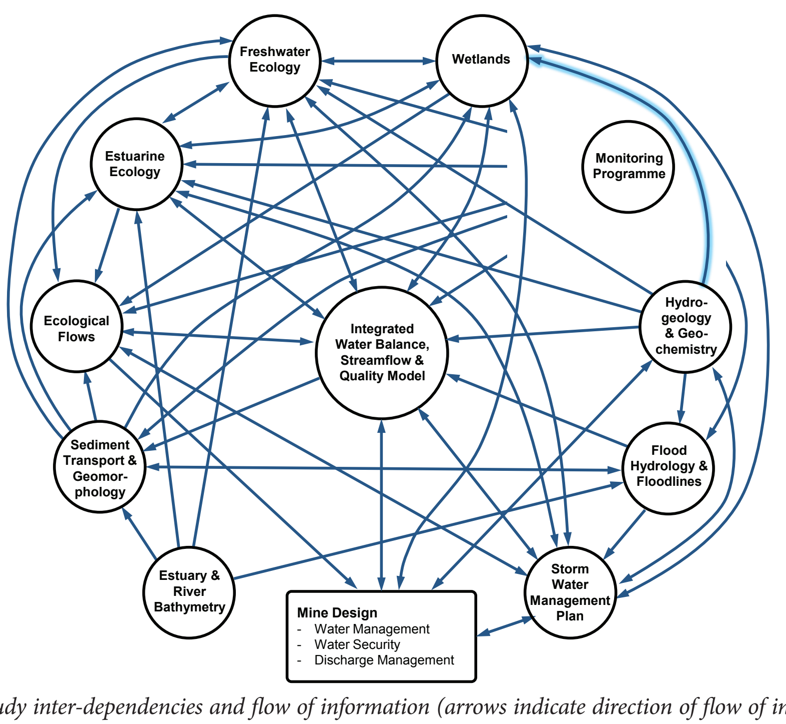

Figure 2 Study inter-dependencies and flow of information (arrows indicate direction of flow of information, with double-headed arrows indicating flow in both directions in an iterative manner).

water systems, providing this to the E-Flows team, and feeding the outcomes of the E-Flows assessments back to mine planning in an iterative process. Inter-dependencies and flow of information, including requirements for iteration between the various specialists, as well as the mine design team, were determined in an optimised, integrated approach. In this way the integrated model provided valuable input to the mine design team, in terms of the achievable assurance of supply and associated required capacity of the PWD, as well as input to the E-Flows team in terms of the baseline mining effects on streamflow and water quality. The E-flows teams provided feedback, in terms of acceptability of the anticipated changes in streamflow and water quality, with proposed mitigations. These were subsequently modelled in the integrated model. Associated influences on mining were then determined and fed back to the mining design team.

The specialist studies and flow of information are illustrated in Fig. 2. This complex network of information flows illustrates the inter-connectedness of the various studies and how the integrated model was a key input to the various studies and the mine design.

Integrated Model

GoldSim systems modelling software was used to develop a dynamic, daily time-step model for the mine and the associated catchments. The model comprised three main components, namely a catchment runoff and streamflow model, utilizing the Australian Water Balance Model (AWBM) (Boughton 2004) modelling algorithms, the mine water balance, and a water quality component modelling both the mine salt balance and the in-stream water quality. Utilizing the LoM plan, the effects of the mining activities on streamflow and water quality, over time, could be modelled.

Daily rainfall data, recorded at SRL's Area 1 operations, was available in a record spanning from 2000 to present. While this record was relatively short, spanning 23 years, it was determined by Golder (2018) and Jones & Wagener (2024) to be the most reliable rainfall record available in the region. A stochastic rainfall generator model, derived from Boughton (1999), was used in the model to generate statistically relevant synthetic rainfall data sets, which were used in Monte Carlo simulations to generate probabilistic water balance and streamflow output.

Inputs in the form of in-stream water quality monitoring data were obtained from the Environmental, Social and Health Impact Assessment (ESHIA) (Digby Wells 2023). This was used, along with typical mine water quality analysis results from Area 1, as input to the salt balance. In addition, mining inputs, such as, but not limited to, production, open pit, dam and TSF inputs, water management, demands and discharges, were obtained and incorporated in the modelling.

Output from the hydrogeology and geochemistry study were also utilised as inputs to the integrated model. These included anticipated groundwater ingress volumes and quality to the pits, streamflow losses due to mining and expected water quality in TSF return and seepage.

A streamflow monitoring programme was designed and implemented. Monitoring locations were identified, distributed across the mining area, including both freshwater

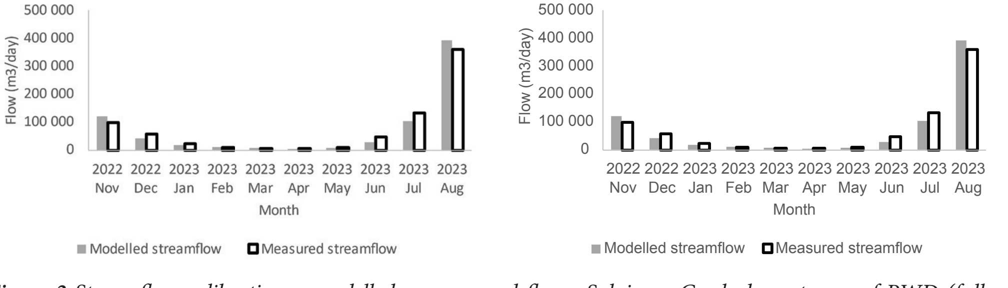

Figure 3 Streamflow calibration – modelled vs measured flows, Solaieyea Creek downstream of PWD (full period - left), (dry season – right).

and tidally influenced zones. A combination of continuous monitoring by means of water level loggers and EC probes, and weekly in-stream flow measurement using a hand-held velocity meter, was employed to monitor streamflow and EC for a period of 12 months (WCS 2023). This data was used to calibrate the streamflow model. It is acknowledged that one year is too short a period for calibration and validation of a streamflow model. However, the period was dictated by project time constraints.

The information was incorporated into the integrated model and the calibration achieved was considered reasonable, with the model considered suitable for predictive modelling. Fig. 3 illustrates the calibration achieved, by comparing the modelled versus measured streamflow, on a monthly basis, in the Solaieyea Creek, downstream of the proposed PWD.

Model Runs and Integration with Mine Planning and Specialist Teams

Baseline Model Outputs

Current status model runs were undertaken to develop reference (pre-mining) flows in the watercourses at each of the selected "Modelling Points" (MPs) (refer to Fig. 1). Monthly flows, expressed as various percentiles, based on the stochastic rainfall, were produced for each MP.

A preliminary storage-yield analysis was undertaken for the PWD, and it was determined that, at the initially planned PWD capacity of 2.9 Mm3, an assurance of supply of 93.5% would be achieved. To provide the desired assurance of supply of 95%, the PWD capacity would need to be 3.1 Mm^3.

Three water quality constituents were modelled, namely total dissolved solids (TDS), sulfate and aluminium (Al). It was determined by the hydrogeological and geochemical modelling that oxidation of sulfide in the ore and overburden material would result in mine water with low pH and elevated TDS, sulfate and metals (with Al used as a key indicator of metals toxicity to aquatic species, as directed by the freshwater ecologist (Tate 2024a)). Further, a lack of pH buffering capacity in the freshwater systems meant that should mine or tailings water be discharged directly into the freshwater reaches of the watercourses, without treatment, this would result in low pH and elevated TDS, sulfate and metals concentrations in the watercourses themselves.

Modelling results indicated TDS concentrations in the watercourses reaching up to 310 mg/L, from a pre-mining concentration of 50 mg/L and Al reaching up to 15 mg/L, from a pre-mining concentration of 0.03 mg/L. Similarly, the discharge of TSF return water into the PWD would result in TDS concentrations of up to 250 mg/L, with Al reaching 1.1 mg/L. These changes would be expected to have acute effects on the freshwater species, with an acute effect Al concentration being 0.1 mg/L (Tate 2024b). On the other hand, the discharge of mine water into the estuarine watercourse reaches was not considered by the estuarine ecology team to be problematic, given the high salinity and buffering capacity of sea water. The TDS concentration of the mine water was considered immaterial in relation to the TDS of sea water and Al (and other metals) would be expected to precipitate due to the high pH buffering capacity of the sea water (Clark 2024).

Iteration for Optimised Mine Design and E-Flows

Model results for each of the E-Flow sites were provided to, and utilised by, the E-Flows team. It was found that the freshwater system was most vulnerable to changes in streamflow, as well as quality, and the E-Flows assessment became driven by the freshwater system requirements.

Desired E-flows were determined by the freshwater specialists, accounting for seasonality, baseflow, freshets and floods, and confirmed in terms of available habitat (Tate 2024a). These were fed back into the integrated model and the required environmental releases, from the PWD, to achieve these flows, were determined. Mine assurance of supply was then re-assessed on this basis. It was found that the desired E-Flows resulted in an assurance of supply of only 85%, based on a PWD capacity of 2.9 Mm^3 – substantially lower than the mine's desired 95%. Through iteration in the integrated model, it was found that by reducing the E-Flows requirement by 10% during the dry season (November to May) an assurance of supply of 93.5% could be achieved – similar to the baseline assessment, though lower than desired. To achieve 95%, a PWD capacity of 3.1 Mm^3 would be required, at substantial additional cost.

A further workshop was held with the E-Flows team to assess the consequence of reducing the E-Flows requirement. These reduced E-flows were re-assessed by the freshwater specialists and the results indicated that this reduction could be tolerated by the system. This compromise was therefore presented to the mine design team, i.e. a reduction in assurance of supply, as well as environmental releases, without the need to increase the storage capacity of the PWD.

E-Flows could not be met in the Gbomi Creek, downstream of the Initial TSF, primarily due to the reduction in catchment due to the TSF. It was concluded that the only viable mitigation would be to reduce the duration of the flow reduction as much as possible by rehabilitating the facility as soon as possible, to return the surface runoff to the watercourse. This could reduce the impact by approximately four years (assuming a one-year rehab. period) (i.e. from eight to four years).

The above process addressed the water quantity aspects. Water quality in the watercourses was found to be affected primarily due to the intent to discharge pit water directly into the closest watercourse, as well as due to the mixing of TSF return water and freshwater in the PWD. It was recommended that pit water should not be discharged into the freshwater reaches, but rather conveyed by pipe to the tidal, estuarine zone and discharged at riverbed level to ensure that it makes contact with saline water, which lies below the freshwater due to its higher density. To address the water quality issues in the PWD it was recommended that a separate facility be provided at the WCP, to receive TSF return water and ROM stockpile runoff and feed it directly to the WCP, with only makeup water being drawn from the PWD.

The above mitigations were assessed in the integrated model and found to substantially improve the water quality predictions, achieving concentrations below the Al acute effect limit of 0.1 mg/L in all watercourses. This is shown in Fig. 4 for the MP located downstream of the PWD (LTC5) on the Solaieyea Creek. The exception to this is at the end of LoM, as mining ramps down, TSF returns will need to be managed to avoid water quality deterioration.

Conclusions

The integrated model was utilized as the pivotal tool for quantifying the effects of the mine and its planned water management practices on the flow and water quality regimes in the watercourses flowing through the mining area. Water management alternatives and mitigations were tested, allowing for rational decision-making on the part of the mine design team.

By adopting key mitigations, including balancing assurance of supply against cost and required E-Flows, adopting an accelerated TSF rehabilitation strategy, separating TSF return water and ROM stockpile runoff from the PWD by providing a separate facility for these, and only discharging pit water into the tidal reaches of the watercourses, at river bed level, it was shown that the mine's influence

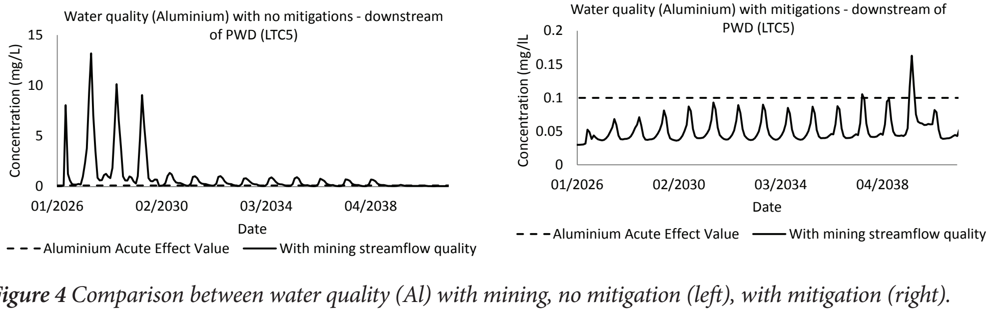

***Figure 4** Comparison between water quality (Al) with mining, no mitigation (left), with mitigation (right).*

on stream flow and water quality could be maintained at an acceptable level.

This study underscores the value of an integrated model as an essential tool to support mine planning and the management of the impacts on water resources. With a multi-disciplinary approach and a co-operative relationship between the mining and environmental teams, it is possible to achieve outcomes that satisfy both mining and environmental objectives.

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