Numerical model development for sustainable management of mine water in a semi-arid environment

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Abstract

Bisha Mine is located in an arid to semi-arid area of Western Eritrea. The site lies within the Mogoraib River Basin, an ephemeral tributary of the Gash-Barka, one of Eritrea's five major river systems. Water for the mine site is principally derived from a wellfield aligned along the Mogoraib River, with the boreholes drawing water from both the alluvial gravels and the underlying fractured bedrock. This aquifer system also provides water for the local Bisha community as well as baseflow to the regionally important Barka River located 12km downstream of the site.

Sustainable water management is key to both continued operation of the site and for other groundwater dependent users/systems in the area. Water levels show both seasonal trends related to surface water flow during the wet season (July – September) superimposed on longer term trends related to groundwater abstraction.

In order to determine how to best sustainably manage water at the site, both during operations and in closure, a linked regional groundwater/site water balance model was developed using the MODFLOW/MT3D/GOLDSIM codes. Quantifying recharge in this climatic environment presented one of the most significant technical challenges for the study in terms of both baseline data collection and analysis of environmental data.

Groundwater modelling was used to optimise wellfield design and operation in order to minimise groundwater level drawdown. It was recommended that future boreholes should be drilled deeper to focus abstraction on the underlying fractured bedrock, and that abstraction rates should ideally be reduced and distributed across the wellfield to improve the sustainability of the operation.

Keywords: Semi arid environment, groundwater recharge, groundwater flow modelling

Introduction

Water scarcity is frequently identified as one of the key concerns for mining companies. Mining projects require water at almost every stage of the process, however a large proportion of these projects are located in water-stressed regions of the world such as Africa, Australia and Latin America. The International Council on Mining and Metals (ICMM), in its position document on water stewardship (ICMM 2017), stated that mining projects were encountering increasing levels of social conflict related to water, while the financial cost associated with water related infrastructure accounted for up to 10% of the mining industries capital expenditure. The criticality of water availability is now reflected in the strategic planning of all major mining companies. The Anglo American (AA) CEO, Mark Cutifani, in his 2017 keynote presentation to the Mining Indaba in South Africa stated that "approximately 80% of our operations across the world are in water- stressed areas. This is why we are working towards building the water-less mine", while it was AA's aim to "eliminate, the use of freshly drawn water from our mining processes".

These issues with respect to water availability are at their most extreme in the semi arid to arid regions of the world. At the same time quantification of water resource availability in this type of hydrological environment provides a number of specific challenges, including measurement of highly localised rainfall events and determination of how this rainfall translates to recharge of the groundwater aquifer. These technical requirements need to be properly understood in order to both design an appropriate environmental data collection programme required to underpin the resource evaluation, and to ensure the proper application of analytical approaches to evaluaing groundwater sustainability.

This paper presents the results of a comprehensive study undertaken by the Bisha Mining Share Company (BMSC) at its Bisha Mine in Eritrea, in which it evaluated the data and analytical tools available to the project to underpin sustainable management of its water resources in a challenging semi arid environment.

Background

The Bisha Mine, which has been operating since 2010, is located in an arid to semi-arid area of Western Eritrea. The site lies within the Mogoraib River Basin, an ephemeral tributary of the Gash-Barka, one of Eritrea's five major river systems. Since the end of 2010, raw water supply for mine operations has been primarily derived from a wellfield aligned along the Mogoraib River. This aquifer system also provides water for the local Mogoraib communities as well as baseflow to the regionally important Barka River located 12km downstream of the site.

Water supply from the Mogoraib wellfield has been augmented with pumping from a second smaller wellfield in the alluvial deposits of the Freketetet, a tributary of the Mogoraib,, and from periodic pumping of the closed Harena pit and its associated dewatering boreholes..

As part of effectively managing its water supply BMSC commissioned a comprehensive review of their hydrological monitoring network/data, and the development of both Modflow and GoldSim numerical models, which would support them in the operational management/optimisation of water use, and allow predictive simulation of future impacts of water abstraction. The studies were also used as the basis for identifying any additional environmental data requirements needed to improve sustainable water management in this semi arid environment.

Rainfall

Rainfall has been measured intermittently since 1999 at six locations within the Bisha project area. Measured annual rainfall ranges between 111 mm/yr (2002) and 411 mm/yr (2007). However annual rainfall is observed to differ significantly between rain gauge records across the project area (e.g. in 2005, 146.5 mm was recorded at the Camp rain gauge compared to 220 mm recorded at the Italian Station rain gauge, which are approximately 8km apart). Where rainfall differences between rain gauges are consistent each year, the discrepancy can potentially be attributed to the type of rain gauge being used. However inconsistent annual rainfall differences are likely to be a function of the localized nature of rainfall across the Bisha Project area. For example, in 2012 the Camp weather station recorded nearly 40 mm more rain than the gauge located at the Tailings Management Facility (TMF) weather station which is 2km away. In 2013 this trend was reversed with ~50 mm more rainfall was recorded at the TMF weather station.

The daily rainfall record also reflects the localized nature of rainfall across the Bisha Project area, with significant rainfall recorded at one of the project rain gauges not being detected at the other, or different magnitudes of rain being recorded on the same day (e.g. 26th August 2015, 31 mm at the TMF WS and 74 mm at the Village WS).

This disparity between the magnitude and duration of rain on an annual basis indicates that annual rainfall statistics, a fundamental input parameter to water resource sustainability assessment, must be used with caution when considering site hydrology. Thus a very wet year may not mean a very hydrologically active year, as high rainfall may have occurred over a short period of time e.g. in 2011 when ~26% of the annual rainfall occurred on a single day (2011 annual rainfall was 235 mm of which 61.3 mm occurred on 23rd July). This in turn will strongly influence the percentage of rainfall which may become groundwater recharge.

River stage and flow data

Hydrological data has been collected manually at five locations across the project site in order to assess both surface water management requirements at the Bisha Mine site, and to determine the potential for surface water to provide a mine water supply source. Stage-discharge relationships were determined for each monitoring station based on the estimates of flow and the associated river stage. These data have been further analysed to try and quantify runoff coefficients for each of the gauging station catchments. Derived coefficients ranged between 0.01 and 0.71 with the majority falling between 0.01 to 0.3 [Coefficients were derived for the Shatera gauging station which exceeded 1 (suggesting more runoff was generated than rainfall) however these have been excluded from the data set]. The huge range of derived run-off coefficients indicates the difficulty in relating spot rainfall measurements to rapid flood flow generated in this type of environment. Wheater and Brown (1989) presented an analysis of a 597 km^2 subcatchment of the wadi Yiba in Saudi Arabia, where runoff coefficients derived using data from 5 rain gauges within the catchment varied from 0.059 to 0.79 (similar in range to those derived for Bisha), with the greatest runoff volume being associated with the smallest measured rainfall event, suggesting that even this relatively high density of rain gauges was not sufficient to capture the rainfall events which were giving rise to specific events at the flow gauging stations. Their conclusion was that application of rainfall depth-area-frequency relationships in this type of climate, beyond the area of storm coverage, was difficult due to the limited spatial area of storm rainfall events, the complex channel routing within wadi systems, and the impact of transmission losses, where runoff flow dissipates through infiltration into the wadi bed.

Significant flow has been observed in the Mogoraib during a period when no rainfall was recorded at the project rain gauges. Additionally no flow was measured in the Freketetet or Shatera Rivers at the same time, indicating that rain falling in the upper reaches of the Mogoraib catchment, and outside the project area, was responsible for this observed flow. Entire river flow events are also observed on a sub-daily time period. Water levels have been observed at the Upper Mogoraib gauging station to have increased from 0 m, peaking at 2.96 m before receding back to 0 m over a 21 hr period. In addition, a stage as high as 1.57 m has been observed over a period of 9 hours between zero flow conditions. This indicates that monitoring of rainfall and flow data on a sub-daily frequency is required in order to accurately de-

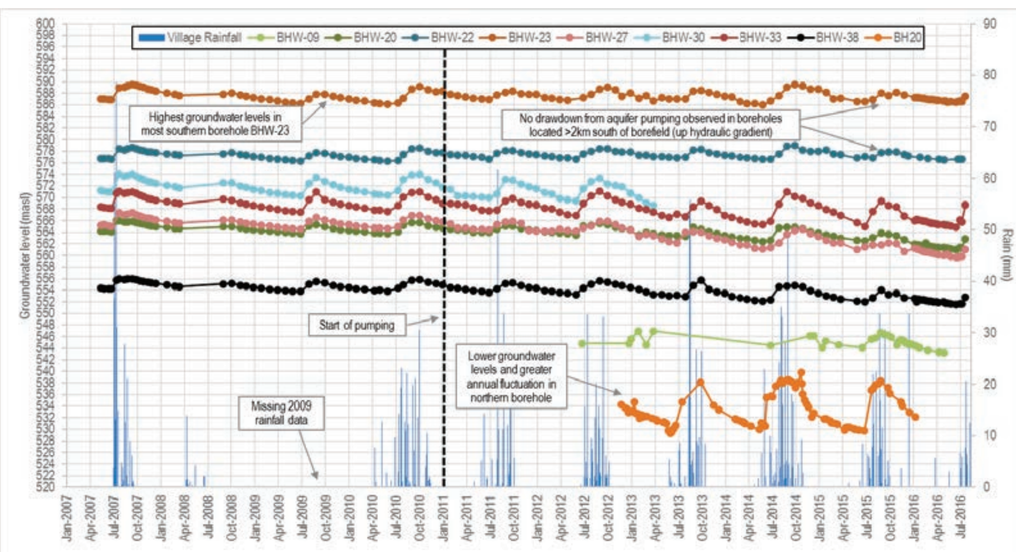

Figure 1 *Groundwater levels in selected boreholes along the Mogoraib River*

fine rainfall-runoff processes for this type of project area.

Mogoraib Aquifer

Groundwater levels have been recorded in the Mogoraib aquifer boreholes since June 2004. A plot of selected groundwater levels, together with rainfall data from the Camp(Village) rain gauge, is presented in Figure 1. Groundwater levels follow a seasonal trend consisting of rapid increase as a result of wet season recharge from ephemeral flow in the Mogoraib River followed by natural recession through the dry season.

Boreholes with thicker layers of high storage alluvium (such as BHW-22 and BHW-18) show subdued response to the early rainfall events as the field capacity of the unsaturated sediments takes time to be reached. Once the field capacity is reached, the individual responses become more noticeable and show larger changes in water level. Boreholes in areas of very thin to no alluvium which penetrate directly in to the low storage transition zone, show much greater changes in groundwater level.

Rainfall-runoff conceptual model

The hydrology of the Bisha project area is typical of arid and semi-arid climates. River flow is generated from highly localized, high-intensity short-duration convective rainfall events that generally occur during a distinct wet season. Annual evaporation is recorded to be far in excess of recorded rainfall. Sparse vegetation, clay rich soils and soil crusting limits infiltration rates. Water generated from rainfall events is therefore dissipated as sheet run-off or lost via evaporation. In parts of the catchment sheet run-off is concentrated by topography and delivered to the river systems, which are otherwise dry as they receive little to no baseflow. Rainfall is therefore the primary hydrological input to river flow. Studies have also shown that there is potential for sheet run-off to decrease following a wet year due to enhanced vegetation cover (Wheater 2010).

The sporadic, high-intensity short-duration rainfall events lead to sub-daily hydrograph responses with steeply rising and falling limbs. Stream flow is not continuous with individual rainfall events generating peak river flow with short lag times (potentially sub-hourly) before quickly dissipating back to zero. Flow in the larger catchments, such as the Mogoraib River, may result from many unrelated localized storms occurring away from the project area. Conversely smaller catchments (e.g. Freketetet) only flow after very local rainfall events and will not receive run-off from storms of limited spatial extent. Studies have shown that river flows in these environments often move down channels as a "flood wave", as rainfall events are localized, short duration and intense and short, while the river catchments are extremely responsive. This type of flow dominates in the Mogoraib River and explains the large differences in flow recorded at the Upper and Lower Mogoraib stations, as manual measurement of stage/flow may not have been at a high enough frequency to capture the flood wave, and related flow may not have been measured simultaneously at both stations.

Surface water - groundwater interactions

As distributed infiltration of rainfall through catchment soils is limited due to soil crusting and high evaporation rates, channel bed infiltration will be the dominant process of groundwater recharge in the project area. Recharge will occur as flood flows lose volume to bed infiltration during downstream propagation. This conceptualization is supported by monitored groundwater levels which show seasonal fluctuations close to river channels and almost no response away from areas of drainage.

Recharge to groundwater underlying river channels will be a function of the time in which the river is flowing. Two dimensional numerical experiments in similar environments have shown that "infiltration opportunity time" (duration and spatial extent of surface wetting) is more important than high flow stage in controlling infiltration to groundwater. Thus antecedent moisture conditions are a key control on unsaturated zone flow with the expectation that higher moisture contents within the unsaturated zone will increase infiltration rates. Moisture content will increase with longer periods of river flow. Maximum groundwater recharge will occur from frequent river flow events of large areal extent, and therefore "hydrologically active" years may be more important than "wet years".

Conventional hydrological modelling approach

The conventional approach to quantifying recharge to the Mogoraib aquifer would be to determine the relationship between rainfall and run-off and then to establish the relationship between the resulting stream flow and recharge. However, as has been outlined in the preceding sections, accurately modelling these processes in semi-arid and arid climates is complicated given the challenges in recording both the necessary rainfall and flow data. These challenges include:

- Highly localized rainfall events: Flow may be generated in project rivers from rainfall events that are not accurately recorded at project rain gauges. A study at Walnut Gulch in Arizona which has a similar climate and wet season indicated that a rainfall correlation of r^2=0.9 between rain gauges would require a gauge spacing of 300 – 500 m apart (i.e. at distances further than this, recorded rainfall at each station becomes less likely to reflect the same rainfall event).
- Frequency flow/stage measurements: Flow rates in the Bisha environment can vary significantly on a sub-hourly time period and therefore a dataset collected on a longer frequency than this will not accurately reflect river conditions.
- Dynamic channel morphology: Each flow event has the potential to significantly change the channel morphology at each gauging station. This means that derived stage-discharge relationships may not remain valid over time, as the relationship can change, even between successive flow events. Therefore flow records calculated from stage are likely to be inaccurate and may result in large difference between two calculations of river flow.
- Inaccuracy of flow measurement: High flows are challenging to measure accurately and will likely be inaccurate where estimates have been made using channel cross sectional areas and Manning's n.

Given the uncertainty in the rainfall and flow data, conventional methods of rainfall-runoff assessment are not considered applicable, as reflected in previous calculations of run-off coefficients for site ranging from 0.01 to 0.71 (and in excess of 1 at the Shatera rain gauge).

Quantification of groundwater recharge from water level data

In order to define an initial groundwater recharge rate as the basis for numerical flow modelling a recharge volume was calculated based upon selected wells along the Mogoraib River using:

- the increase in water level in the alluvium occurring during wet season periods of recharge;
- an estimated alluvial aquifer storage of 6%. This value was estimated based on an analysis of groundwater level decrease against measured pumping rates;
- the rate of groundwater recession at different groundwater elevations based on recorded dry season rates of recession.

The estimated annual recharge rates are presented in Table 1.

The best recharge record available is for BHW-39 where a good correlation has been identified between groundwater recharge and daily rainfall events over 3.5 mm at the Camp (Village) WS. The strength of the correlation however decreases if the threshold rainfall event for inclusion in the analysis is increased or decreased (Figure 2), while the derived relationship does not show a linear increase between recharge and wet days from a zero value. This suggests that recharge from initial flow events is less than recharge occurring from subsequent events (e.g. recharge from 15 wet days is roughly double the recharge from 10 wet days), an observation that is consistent with the conceptualisation that increased recharge occurs as a result of increased unsaturated zone moisture content.

Mogoraib aquifer abstraction sustainability assessment

A two layer Modflow groundwater flow model was developed to look at the long term sustainable yield from the Mogoraib aquifer system. The first layer corresponds to the Mogoraib and Freketetet alluvial aquifers, while the second layer represents the underlying bedrock. Although the conceptual model suggested that recharge in the study area largely reflected seasonal flood water which

Table 1. Preliminary estimates of groundwater recharge (mm)

	BHW39	BHW32	BHW24	BHW33	Average
2007	280	275		372	309
2008	129	111	114	84	110
2009	157	154	147	297	189
2010	289	276	226	405	299
2011	167	152	131	213	166
2012	255	259		384	299
2013	237	153		235	208
2014	313			373	343

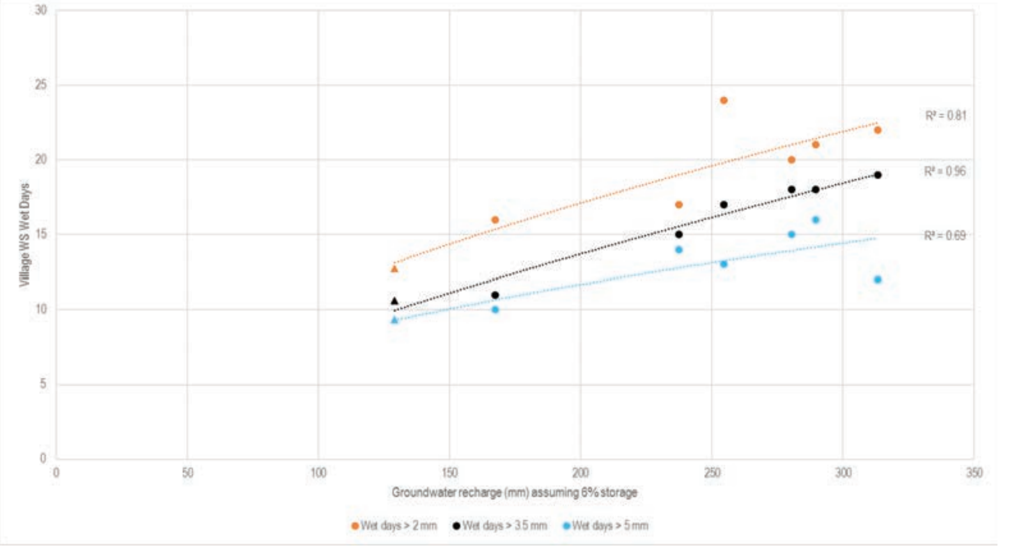

***Figure 2** Estimated wet season groundwater recharge as a function "wet day" rainfall magnitude*

infiltrates through the bed of ephemeral river channels, with little infiltration of distributed rainfall, an initial groundwater model with no distributed recharge could not be calibrated to observed groundwater levels. Therefore an initial starting point of 0.7% of MAP was used, indicating that recharge probably does occur away from the wadiis, in response to local ponding of water from intense rainfall events and/or the occurrence of concentrated flow due to localized steep topography e.g. the toe of hillsides. This represented an important conclusion in terms of "harvesting" runoff for water supply.

The groundwater model predicted that the alluvial aquifer unit alone does not receive sufficient recharge to supply all water demand, and that groundwater flow from the underlying fractured bedrock is required to sustain the required water supply. The drought simulations showed that the increased drawdown would reduce the efficiency of the pumps and therefore the achievable yield. In order to maximize the water that is recoverable, additional boreholes should be drilled so that individual well abstraction rates can be reduced whilst still meeting required volumes under groundwater stress conditions.

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