South African Journal of Industrial Engineering Nov 2022 Vol 33(3), pp 248-261

A SIMULATION-BASED WATER MANAGEMENT STRATEGY FOR LIFE-OF-MINE WATER PLANNING

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ARTICLE INFO

Article details
Presented at the 33rd annual conference of the Southern African Institute for Industrial Engineering, held from 3 to 5 October 2022 in Zimbali, South Africa

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DOI
http://dx.doi.org//10.7166/33-3-2787

ABSTRACT

Adequate water distribution in mines is crucial for both cooling and production. As deep-level mines become deeper, the water requirements, and the subsequent dewatering requirements, also increase. Numerous studies on mine dewatering planning exist; however, these studies fail to recognise the integrated nature of the water system, which comprises the service water supply and the dewatering system. These studies also commonly neglect service water distribution and intensity, life-of-mine water planning, and the use of zero-waste baselines. In this study, a generic simulation-based water management strategy is proposed. The strategy should 1) include both service and dewatering water systems, 2) account for dynamic production plans, and 3) allow for life-of-mine modelling. Data from underground audits were used to develop a baseline model along with the mine plans and survey data. Applying the management strategy to a case study mine resulted in predictions that were accurate to within 5% for future plans.

OPSOMMING

Voldoende waterverspreiding in myne is van kardinale belang vir beide verkoeling en produksie. Soos diepvlakmyne dieper word, neem die waterbehoeftes en die daaropvolgende ontwateringsvereistes ook toe. Talle studies oor mynontwateringsbeplanning bestaan; hierdie studies erken egter nie die geïntegreerde aard van die waterstelsel wat bestaan uit die dienswatervoorsiening sowel as die ontwateringstelsel nie. Hierdie studies verwaarloos ook algemeen dienswaterverspreiding en -intensiteit, lewensduur-van-mynwaterbeplanning en die gebruik van nulafvalbasislyne. In hierdie studie word 'n generiese simulasie-gebaseerde waterbestuurstrategie voorgestel. Die strategie moet 1) beide diens- en ontwateringswaterstelsels insluit, 2) rekening hou met dinamiese produksieplanne, en 3) voorsiening maak vir lewensduurmodellering. Data van ondergrondse oudits is gebruik om 'n basislynmodel saam met die mynplanne en opnamedata te ontwikkel. Die toepassing van die bestuurstrategie op 'n gevallestudiemyn het gelei tot voorspellings wat tot binne 5% akkuraat was vir toekomstige planne.

1. INTRODUCTION

1.1. Background

Underground mining involves the strategic extraction of mineral resources from an underground location [1]. An underground mine requires a constant supply of chilled water [2]; however, the quantity of water required varies throughout the day. This variation is primarily the result of various ongoing mining operations conducted throughout the different shifts. The water intensity is also dictated by the depth of the mine. Tertiary cooling, such as underground fridge plants, is often only implemented below depths of 1 500 m. This indicates that the water intensity is directly proportional to the depth of the mine because of its increasing water requirement as the mine develops deeper [3].

The continuous water demand also creates a need for the constant removal of water, known as 'dewatering' [4]. In deep-level mines, dewatering is crucial in removing not only underground service water but also fissure water, which comes from surrounding water deposits and aquifers [5], [6]. Should this requirement not be met, the mine could experience localised flooding [5]. Flooding not only impedes mining activity, but also increases the local ambient air temperatures [6]. Dewatering is essential to any mining operation, with the effectiveness of the dewatering system having a significant impact on the overall operating cost of the mine as well as on the general health and safety of the workers [4]. The supply and dewatering systems form part of the integrated water reticulation system (WRS), which removes the hot water from the mine and returns it as chilled water. This system accounts for around 14% of a mine's energy consumption [7].

As the mine depth increases, so does the water demand [8]. Emphasis should be placed on ensuring that the working environment complies with the legal thermal stress limits stated in the Mine Health and Safety Act, shown in Table 1.

Table 1: Legal thermal stress limits [9]

Parameter	Limit (°C)
Maximum wet-bulb temperature	32.5
Maximum dry-bulb temperature	37

Temperatures above the limits not only pose a threat to the general health of underground workers, but also impact worker productivity. Under extreme temperatures, worker productivity is negatively impacted [10]. Planning for future expansions becomes critical to ensure continuous supply to underground users, as this water supply is crucial for both mining and critical cooling operations.

Mine water planning should be done in conjunction with the mining development and production plans, as is also the case in mine ventilation planning [11]. The production plan of the mine is a crucial input into a water planning model. Future water flows and pressures should be compared and evaluated against defined acceptance criteria. The outcome should then be used to formulate solutions on the optimal plan.

Owing to the complex nature of deep-level mine WRS, life-of-mine (LOM) planning also becomes increasingly more complex. There is a need for a new water management strategy for life-of-mine water planning in deep-level mines. This can be achieved by using software to conduct thermohydraulic simulations on WRS [12], [13].

The introduction of Industry 4.0 tools in the mining sector is becoming increasingly prevalent [14]. The use of these tools promises increased production along with higher profits [14], [15].

1.2. Purpose of study

The use of simulation software is becoming common for planning in mines [16], [17]. Not only does this allow for adequate future planning, but it also eliminates the 'trial and error' approach that is prevalent in the mining industry [18], [19]. In this study, digital twin (DT) technology was used as a simulation platform. DTs allow for integration between a cyber and a physical environment [20], described by Boje *et al*. [21] as "cyber-physical synchronicity". The DT serves as the digital counterpart of the system [22] which, in this case, is the mine WRS. The use of DTs in industry allows for more informed decision-making about planning, predictions, and optimisation [20].

In mine water planning, DTs using the governing equations for water flow are primarily used. These equations are based on computational fluid dynamics, covering the laws of the conservation of mass, momentum, and energy.

Water management strategies for scenario planning can be found in the literature. However, these studies neglect LOM planning considerations [4], [23]. A distinction should be made when planning for the WRS compared with aquifer dewatering, with many studies focusing on the dewatering of aquifers rather than on a holistic WRS [24]–[26].

This study:

- aims to develop a water management strategy,
- that uses DT technology to predict LOM water requirements accurately,
- using simulation.

A dynamic simulation is required to capture the varying water demand caused by ongoing mining operations.

This study is to be implemented on a deep-level gold mine case study in South Africa. The methodology in the next section expands on the generation of a simulation-based mine water planning and management strategy.

2. DEVELOPMENT OF WATER MANAGEMENT STRATEGY

The methodology implemented in this study is the case study methodology. A case study allows for a comprehensive analysis to be completed on a system [27]. In this study, the principles of a case study methodology are to be applied to a mine. A high-level summary of the case study methodology is shown in Figure 1 [28].

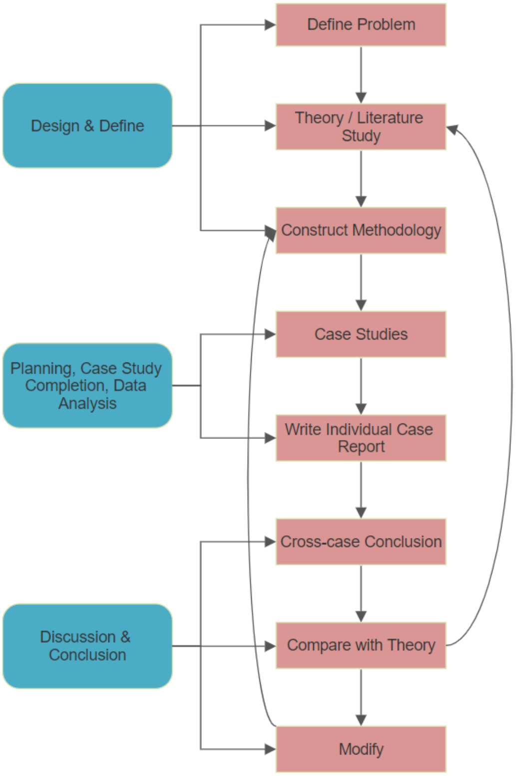

Figure 1: Case study methodology [28]

The need/problem has been identified in the Introduction section. Next, the literature is analysed to inform the development of the simulation-based strategy. This in turn stems from the 'construct methodology' phase.

From this point, the case study (or studies) is/are identified, and the management strategy is applied. The results from the various case studies are to be compared with one another (if applicable), followed by a comparison with the theory that was used to inform the study. It is at this stage where the results can be accepted or modified.

The case study methodology focuses on issues in their real-life context [29]. This is different from experimental case studies such as randomised control trials, in that a case study methodology does not allow the investigator to manipulate variables in the study. In this study, the author has no control over the implementation of the recommendations; instead, the focus is on determining whether the implemented solution naturally concurs with the prediction.

The development of the simulation-based WRS management strategy for LOM water planning in deep-level gold mines is described stepwise below.

2.1. Baseline modelling

The goal of a simulation model is to produce forward extrapolation for predictive modelling. For forward extrapolation, a very accurate model is required, because the further forward you forecast, the larger the error will become. Thus a calibrated baseline model that is very accurate is required, which forms the first state of the strategy shown in **Figure 2** [11], [30].

According to Nell [31], the first phase when developing a calibrated water model is characterised by an extensive infrastructure survey. During this survey, the following information is gathered:

- Piping routes and location-specific pipe sizes.
- Valve and pressure relief valve locations.
- Booster pump locations and pump specifications.
- Barometric pressure at water network boundaries.
- Skid dam locations and their respective pump specifications.
- Water demands (drill rigs, air cooling units, drills, and cooling cars).

This information is then used in conjunction with the AutoCAD drawing interchange files obtained from the mine's planning department to construct the model. Once the model infrastructure has been built in the DT environment, the next step involves calibration.

Calibration is completed through physical underground audits [11], [30], [31], during which water flow rates and water pressures are logged. These values should then be translated into the simulation model to complete the calibration. The technique for calibrating a chilled water model differs from the calibration of the corresponding return water system owing to the large infrastructure differences between the two models. This varies in accordance with the components of each system that are manipulated during the calibration. These components are given below:

Chilled water:

- Pressure relief valve
- Pipe losses

Return water:

- Pump efficiency
- Pipe losses
- Dam level meters (step controllers)

Pump curves are crucial in calibrating the return water system. The pump curve output in the model depicts an ideal system without large-scale friction loss/flow obstructions. The pump curve output can be verified by manually measuring the pressure drop between the pump outlet and the water destination. This pressure drop is then compared with that of the model. Should there be any discrepancies, the relevant pipeline is reviewed and adjusted in the model.

To manage the irregular nature of the pumps, step controllers are included in the simulation model. The step controller uses the skid dam level as an input and the pump speed fraction as an output. A 'start level' and a 'stop level' are then applied to the step controller, which allows the pump to start when the dam level exceeds a certain level, and stops the pump once the dam level has reduced to below the specified lower bound. This step controller digitally represents the dam level meters that are used underground and that fulfil the same purpose underground.

The baseline model calibration is verified through the comparison of its respective outputs with the audited underground data [32].

2.2. Predictive modelling

Once the calibration has been completed and the simulation model results have been verified and validated, the model is ready to be used for predictive modelling, as shown in **Figure 2**.

With mine water planning, the worst-case scenario should still meet the specified criteria for a given prediction model. In a deep-level mine, the worst-case scenario for water management is the month when the highest number of tonnes of broken rock is removed from the mine. This scenario is not cyclical, and depends on plans from the ore reserve and planning department.

This allows for much higher confidence in the predictive modelling results than in an opencast mine, where the worst-case scenario is the period with the highest average rainfall. Unreliable weather reporting systems mean that one cannot easily schedule periods of high rainfall in advance [33], [34]. It is common for a mine to aim for a specific water intensity or 'tonnes of water/tonnes of rock' ratio [23], [35]. In deep-level mines in South Africa, the average surveyed total water usage per tonne is shown in Table 2.

Table 2: Average water usage per tonne of rock hoisted [36]

Commodity	Total average water usage per tonne rock (m^3)
Coal	0.79
Gold	2.46
Platinum	1.68
Other	1.23

This average water usage is presented with significant variance as a result of variations in data reporting quality as well as variations in individual instrumentation tolerances.

Typical flow requirements for deep-level underground mines are in the range of 200 to 600 L/s, requiring a dewatering rate of 17.2 to 51.8 ML per day [34].

A typical mine blueprint aims for a 'zero' water balance. The water balance is merely the difference between the water flowing into the mining block and the water being pumped out of the mining block. The flows considered in this water balance are as follows:

Inlet flows

- Chilled water
- Drinking water
- Fissure water

Outlet flows

- Total return water

With respect to the inlet flows, both the chilled and the drinking water flows and volumes are often instrumented. The fissure water, however, is difficult to measure, and this flow is highly variable, as it can range from zero to 60 L/s, depending on the surrounding geological conditions and aquifer locations [39].

Knowing the mine-specific water intensity is crucial in mine water planning. This not only directly impacts the requirements of the system, but it creates the need for extensive infrastructure audits to verify the adequacy of the current infrastructure to accommodate the predicted future flows.

The various considerations mentioned in this section should be integrated into a holistic methodology, as shown in Figure 2.

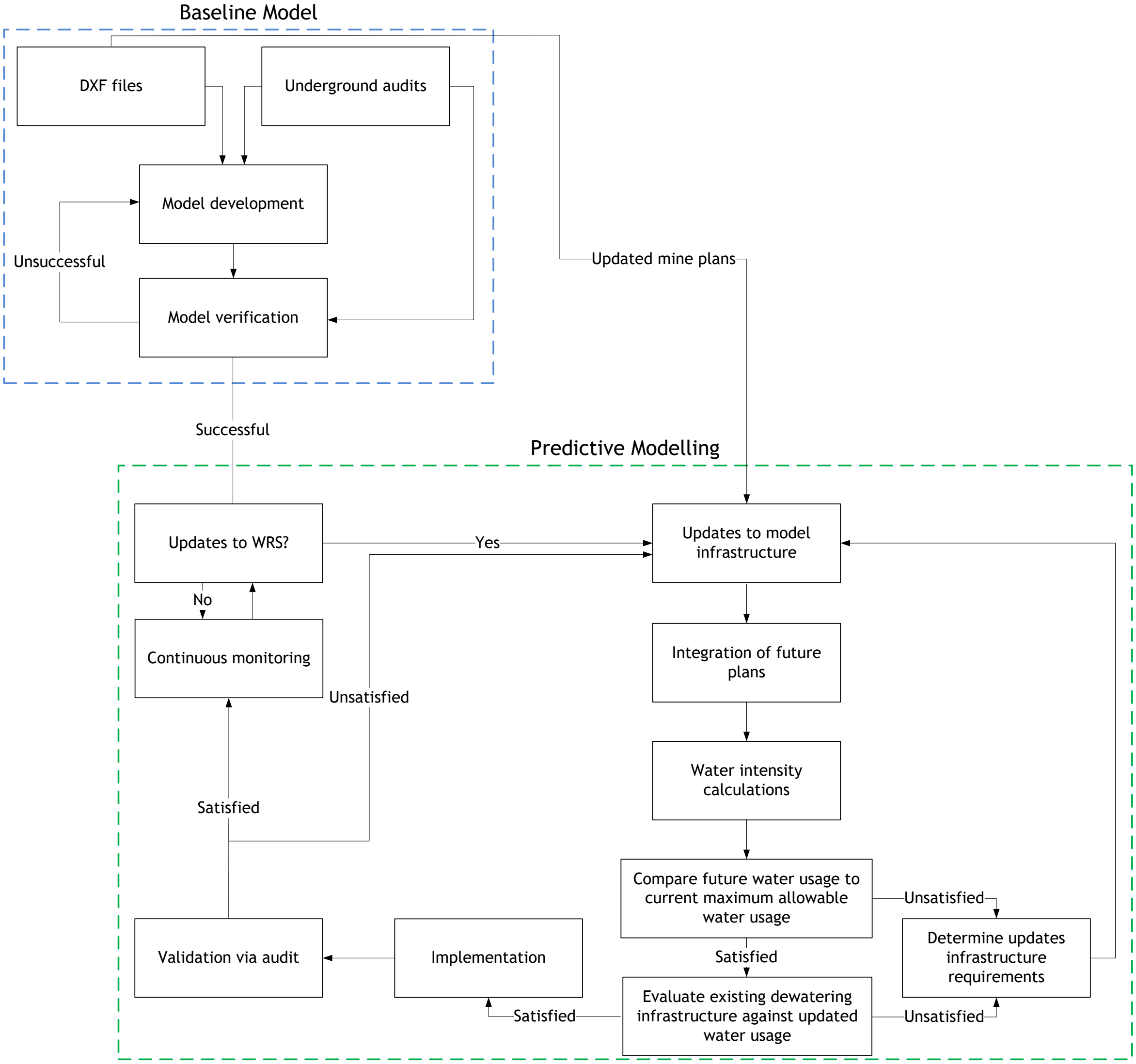

Figure 2: Water reticulation system (WRS) simulation methodology for deep-level gold mines

3. RESULTS AND DISCUSSION

3.1. Case study background

The proposed water management strategy (Figure 2) was applied to a case study involving a deep-level mine, 'Mine Z'. Mine Z is a partially mechanised mine situated in the Free State Province, South Africa.

The mechanised mining method used in Mine Z resulted in a unique mine layout. When planning the mine in 2002, an objective was to ensure the effective movement of the various mechanised machines. This resulted in ramps, declines, and spirals being used to allow for adequate vehicle access. This unique layout is shown in Figure 3.

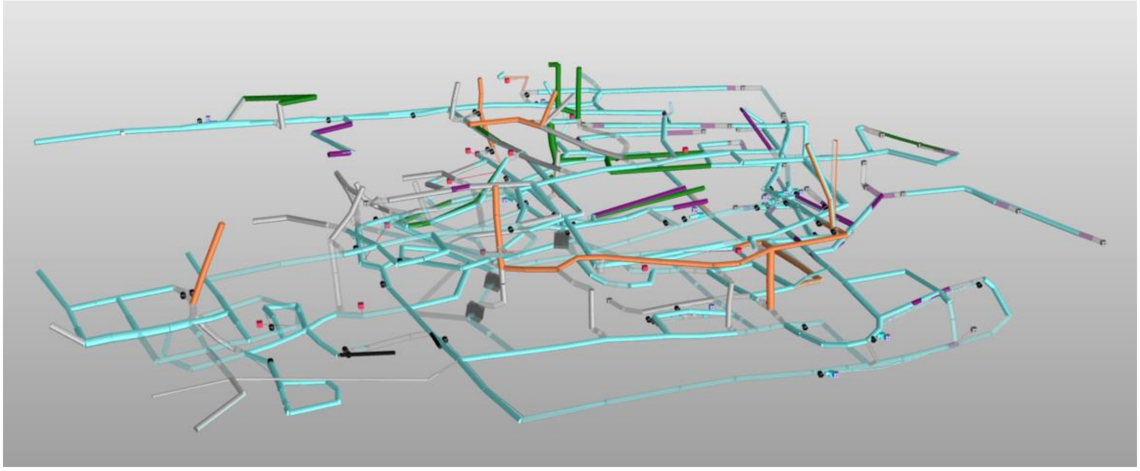

Figure 3: Mine Z layout

3.2. Application of water management strategy

3.2.1. *Baseline model*

Underground audits initiated the baseline simulation model's development. For the purposes of the study, these audits were divided into two segments:

- infrastructure and layout investigation and
- flow investigation.

The infrastructure and layout investigation was conducted first. This, along with the DXF plans, allowed for the system's frame to be developed.

The simulation model was broken up into two regions: the mining block and the old mine. The mining block is the region where the production levels and current mining activity are found. The old mine is now used as part of the mine's holistic dewatering system, where the larger pumping stations are situated. These pumping stations have no impact on the WRS in the mining block, as their sole function is to return water to the surface.

The mining block was identified as the most complex region, as well as the region that is more dynamic. The dynamic nature of the mining block's WRS forced the simulation model to be built from a snapshot of the mine. This snapshot had to be a two-week-long period, as agreed upon between the mine and the DT developer, so that the infrastructure audit could be carried out without changes being made to the system.

The infrastructure audit allowed for an ideal flow-per-level as well as an ideal zero-waste baseline to be developed. This infrastructure breakdown per level is shown in Table 3.

Table 3: Current mining block infrastructure

Level	# of drill rigs	# of drills	# of air-cooling units	# of bulk air coolers	Inline coolers	Cooling cars	Bolter	Solos	Total flow (L/s)
1		**10**	**2**						**12.00**
2				**1**					**25.00**
3		**20**						**1**	**6.00**
4	**1**	**5**			**3**				**12.55**
5	**4**			**1**			**1**		**37.20**
6			**1**			**2**			**25.00**
Total # of Components	**5**	**35**	**3**	**2**	**3**	**2**	**1**	**1**	
Total Flow (L/s)	**12.75**	**7.00**	**15.00**	**50.00**	**9.00**	**20.00**	**2.00**	**2.00**	**117.75**

Water requirements per component:

- Drill rig = 2.55 L/s
- Narrow reef mining drill = 0.2 L/s
- Air cooling unit = 5 L/s
- Inline cooler = 3 L/s
- Cooling car = 10 L/s
- Bolter = 2 L/s
- Solo = 2 L/s
- Bulk air cooler = 25 L/s

The above infrastructure was used in the baseline model to determine the ideal flow-per-level. These flows were entered as inputs into the baseline model.

The flow investigation was completed over a period of 14 days. During this time, nine underground audits were conducted at the various levels to obtain comprehensive data for the water flow in the various networks. The errors between the underground audit data were then compared with the baseline model outputs. This is shown in Table 4.

Throughout the duration of the audit period, level 3 was closed owing to a fall of ground and a return fan failure, which made the area unsafe. Level 5 also experienced production problems during the audit period, with development drilling coming to a halt while additional tertiary cooling was added to the level. An average error of 4.2% was identified with the baseline model. Although only certain levels could be verified, the gathered data proved adequate to calibrate the model to within 4.2%. After calibration, the model could be trusted to predict the levels where the verification could not take place.

Table 4: Audit data vs simulation outputs for baseline model

Level	Component	Simulated flow	Audit flow	% difference
1	Air-cooling unit 1	11.5	12.0	4.2
	Air-cooling unit 2	3.3	3.7	10.8
	Narrow reef	1.95	2.0	2.5
4 West	Inline cooler	4.9	4.7	4.3
	Peak level flow	5.4	5.6	3.6
4 East	Peak level flow	10.8	10.5	2.9
6	Cooling car	10.04	10.35	3.0
Decline	Peak flow	114.0	117.0	2.6

3.2.2. Predictive modelling

Historical tonnage and water usage were used to calculate the water intensity for the mine. This water intensity was then used in conjunction with future production plans to predict future water requirements. For Mine Z, this is shown in Figure 4.

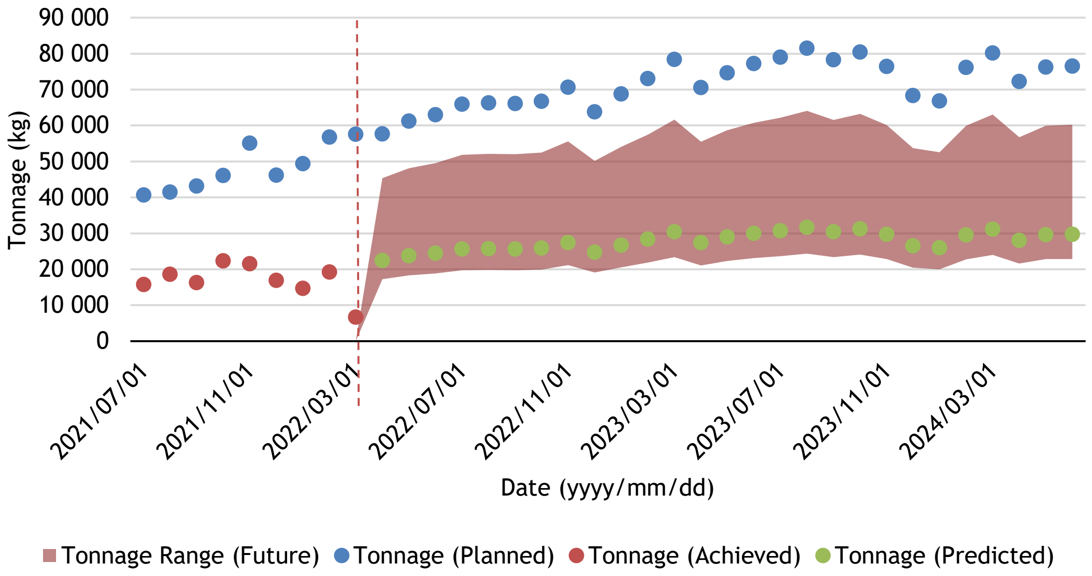

Figure 4: Tonnage profiles of Mine Z for a two-year period

Figure 4 shows the deviation between the planned tonnes and the achieved tonnes to the date when this research ended. The achieved tonnes fell significantly short of the initial plan; the factors impacting this were not engineering-related, but were often the result of human factors such as inefficient work and the poor upkeep of equipment. This deviation, whether the achieved tonnes exceeded or were less than the planned tonnes, should be determined. If the achieved tonnes fell short of the planned tonnes, as in the case study mine, a safety factor was not required on the predicted water usage derived from the planned tonnes. This was because of the assumption that the achieved future tonnes were not expected to surpass the planned tonnes, but rather were expected to fall short. This suggested that the water requirement derived from planned tonnes would be a significant overestimate.

The average water intensity for Mine Z was determined to be in the order of 1.17 kL/Ton – or that, for every 1 ML of water sent into the mine, 855 kg of mined reef and waste was extracted. Figure 5 below gives an indication of the predicted supply of water required to achieve the planned production figures.

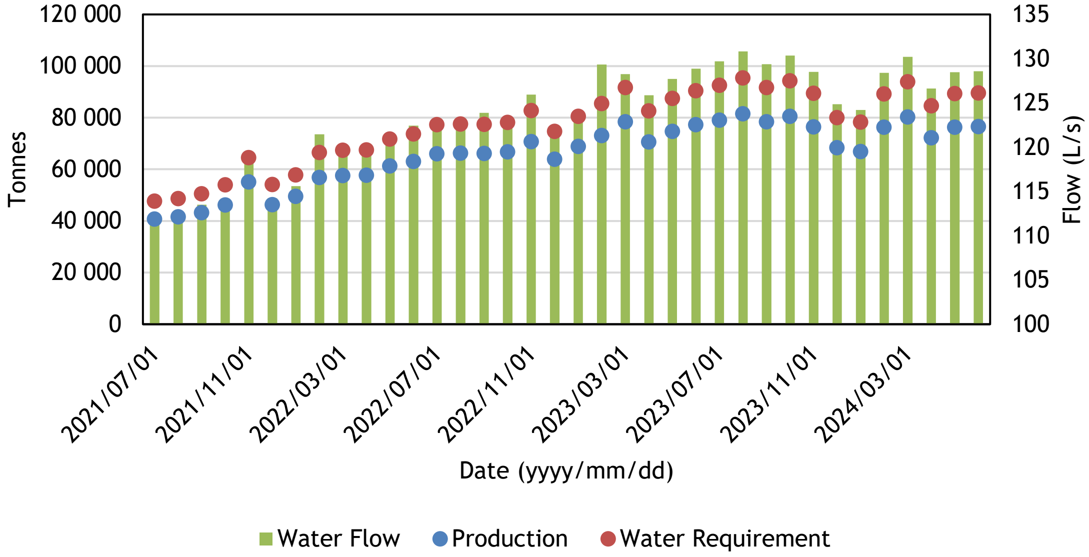

Figure 5: Predicted water usage

The supply water requirement had a proportionate relationship with the planned tonnes in the case of Mine Z; the increased production figures resulted in an expected 10 to 15 L/s increase in the supply water required flow. The infrastructure needed to be audited to investigate whether the existing infrastructure could adequately accommodate this increase, or whether new infrastructure might be required.

With the predicted supply of water flows on hand, the infrastructure analysis was completed to determine the adequacy of the current infrastructure to accommodate future requirements safely. In Mine Z, the existing central dam was flagged for review. While the dam and its associated pump stations were able to accommodate future flows, the increased required flow caused the pumps to operate under high stress. This resulted in the need for a new, larger dam and pumping station. The comparison between the existing and proposed systems is shown in Table 5 below.

Table 5: Infrastructure comparison

System	Dam volume (m^3)	Pump flow (L/s)	Number of pumps	Pump power (kW)
Existing system	400	105	3	210 (per pump)
Proposed system	1 200	170	1	750

The proposed system shown in Table 5 proved superior to the existing system in every way. It boasted a dam with three times the capacity of the existing system. In addition to the dam capacity, the higher-powered pump reduced the required number of pumps from three to one, all while the water flow rate out of the dam was increased.

To predict the conditions of the proposed pumping system in the mine, the baseline model had to be adjusted to include the proposed system. This involved inserting the new dam and pumping station, as well as re-routing the return water pipes towards the new system as opposed to the existing system. Once this was complete, the model was simulated to establish the baseline operating conditions of the new system. The system was then implemented, and the actual data obtained from the implementation was compared with the simulated prediction.

The future model was updated with the conditions for the day when the audit took place, which involved:

- adjusting the simulated supply water flow to match the measured flow and
- using the measured pumping volume to determine the quantity of additional water included in the return system (fissure water, water from previous water build-ups).

Figure 6 below shows the predicted flow pattern for the future model.

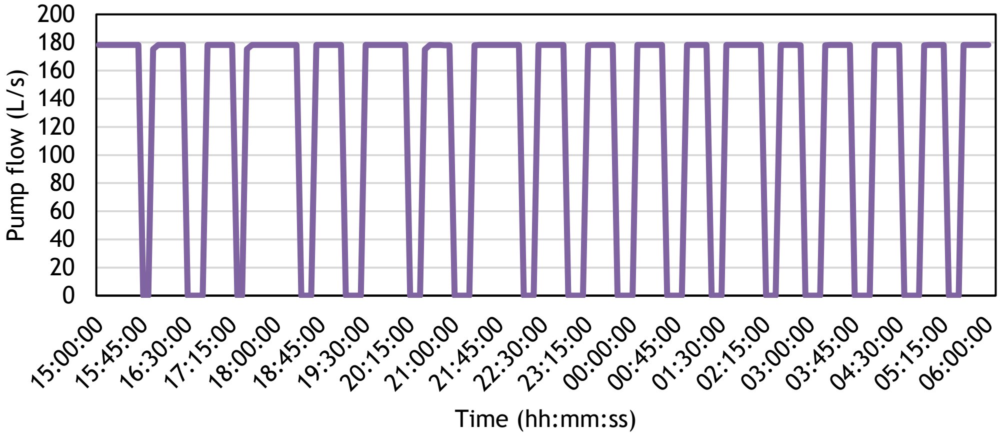

Figure 6: Baseline predicted pump flow pattern

This was compared with the data gathered from the audit period when the new system was operational, shown in Figure 7 below.

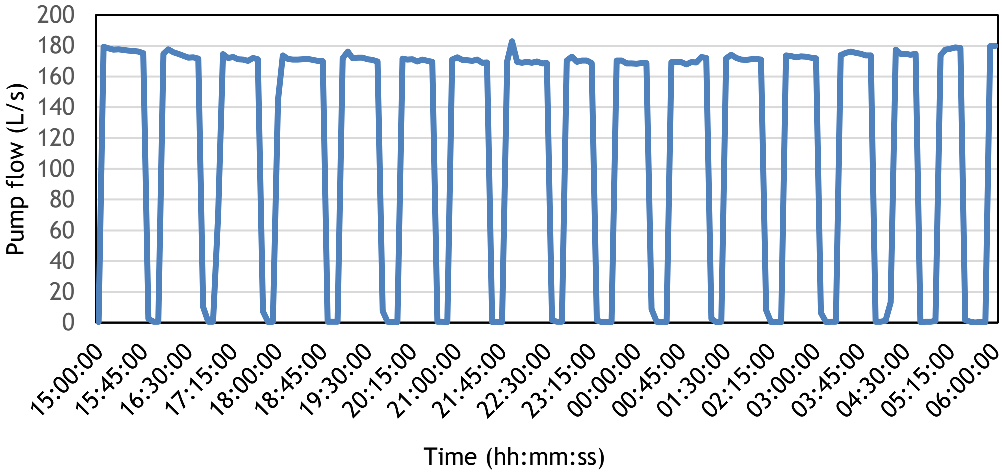

Figure 7: Audited pump flow pattern

The differences between Figure 6 and Figure 7 were then analysed to determine the accuracy of the prediction made during the predictive modelling phase. The comparisons are shown in Table 6 below.

Table 6: Data analysis

Metric	Measured data	DT model prediction	% error
Pump flow (L/s)	170	178	4.7
Quantity pumped in period (kL)	6 353	6 570	3.4
# of pump starts	17	18	5.9
Average			4.7

Only three criteria – those shown in Table 6 - could be used for the comparison between the predicted model output and the measured data: pump flow, the quantity of water pumped, and the number of pump starts in the measured period. The average error between these different metrics was 4.7%, which was slightly higher than the baseline model error of only 4.2%. However, with both errors falling below 5%, the future model could be accepted for use in predictive modelling [32].

3.3. Discussion

The successful implementation served as the validation of the water management strategy shown in **Figure 2**, and thus the use of the simulation for predictive modelling. It is recommended, however, that the accuracy of the future model be constantly reviewed in every instance when the future model is used in planning, as this allows for an average error to be established. Included as a recommendation is the need for periodic recalibration of the model to prevent the compounding effect on the error that changes (predictive modelling, updates, etc.) to the model might induce.

4. CONCLUSION

Introducing simulation by means of digital twins to mine water planning ensures greater confidence in future water plans. A holistic methodology was proposed, first, to create the baseline model, and second, to adapt the baseline model to be used for predictive modelling on a mine's WRS.

The water management strategy was successfully applied to the case study mine, Mine Z, a gold mine in Free State, South Africa. The baseline modelling phase of the strategy proved successful, and showed an average error of only 4.2%, allowing the model to be accepted and thus used in the predictive modelling phase.

The predictive modelling segment of the strategy was used to predict the impact of a new return water pumping station in the mine's return water system, as the existing pumping station proved unsuitable for the predicted future water flows.

The results indicated that the proposed water management strategy was successful in predicting the real-life operating conditions of the new pumping station, with the maximum error being 5.9%. This allowed for the model to be accepted for use for predictive modelling in the mine's WRS.

4.1. Acknowledgements

This work was sponsored by ETA Operations (Pty) Ltd, South Africa. The author also thanks JJ Swanepoel for his mentorship and Tanielle Pettitt for her assistance in proofreading and reviewing the document.

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