Development of a proactive surface water management process and adaptive water management for mine operations

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Abstract

It is generally accepted that the majority of slope failures are triggered or at least are contributed to by surface water. As a result, effective water management is a cornerstone of any safe, profitable, and reputable mining operation. The mining-water nexus plays a critical role in environment, social and governance (ESG) frameworks and reporting, currently in high demand with modern investors. Water management at mining operations is typically comprised of several separate strategies and plans which may or may not interact effectively with one another but are generally developed to both function over a longer timeframe and focus on a specific aspect of the water cycle at the operation. Therefore, the current approach to short term operational water risk management can leave operations exposed to risks, such as extreme weather events, due to ineffective resource planning, infrastructure planning that disrupts the operational mine plan (i.e., water management gets in the way of mining) and responses that place unsustainable pressure on the operations teams during these extreme events. This may lead not only to unwanted events such as unplanned discharge, but also to staff turnover and unsafe practices during implementation of management measures.

To address this challenge without incurring unreasonable capital requirements for in-pit water management infrastructure, it is necessary to develop a proactive and adaptive process more able to respond to shocks. Such a process leverages the dynamic nature of open pit mining and a collaborative, narrative-driven approach for proactive surface water management during the rainy season to prevent unplanned impacts on the operation's business plan. This paper presents a detailed description of a representative proactive surface water management process developed for open pit mine operations, which has been tested at active operations with positive results during above average rainfall events in semi-arid environments.

Introduction

It is generally accepted that the majority of slope failures are triggered, or at least impacted negatively, by surface water. Therefore, effective water management is a cornerstone of any safe, profitable, and reputable mining operation, with the mining-water nexus playing a critical role in environment, social and governance (ESG) frameworks and reporting. In their "Top 10 business risks and opportunities for mining and metals in 2024" report, Ernst & Young (2023) list ESG as the biggest risk for the third year in a row, with water stewardship voted as the third most scrutinized ESG factor by investors for 2024. The uncertainty surrounding climate change and its impact on mining operations plays a critical role in ESG for miners, with natural disasters and extreme weather events featuring in the top five global risks in the next two and ten years in the World Economic Forum's Global Risks Report 2023 (WEF, 2023). The role of effective water management in mitigating these risks at mining operations is undeniable, with water playing a large role in economic, social, environmental, and reputational outputs of the operation.

Water management at mining operations is typically comprised of several separate strategies and plans, as shown in Figure 1. These generally interact with one another to a certain extent but are often developed to function over a longer timeframe (i.e., medium to long term) and are focused on a specific aspect of the water cycle at the operation. Short term operational water risk management (i.e., less than 18 months) is usually a secondary consideration that is dealt with by the operational teams as-and-when required. This approach to short term operational water risk management can leave operations exposed to risks such as extreme weather events, due to ineffective resource planning and/or infrastructure planning that disrupts the operational mine plan (i.e., water management gets in the way of mining). This places unsustainable pressure on the operations teams during these extreme events which may lead to unwanted events such as unplanned or unlicensed discharge, staff turnover and unsafe practices during implementation of management measures.

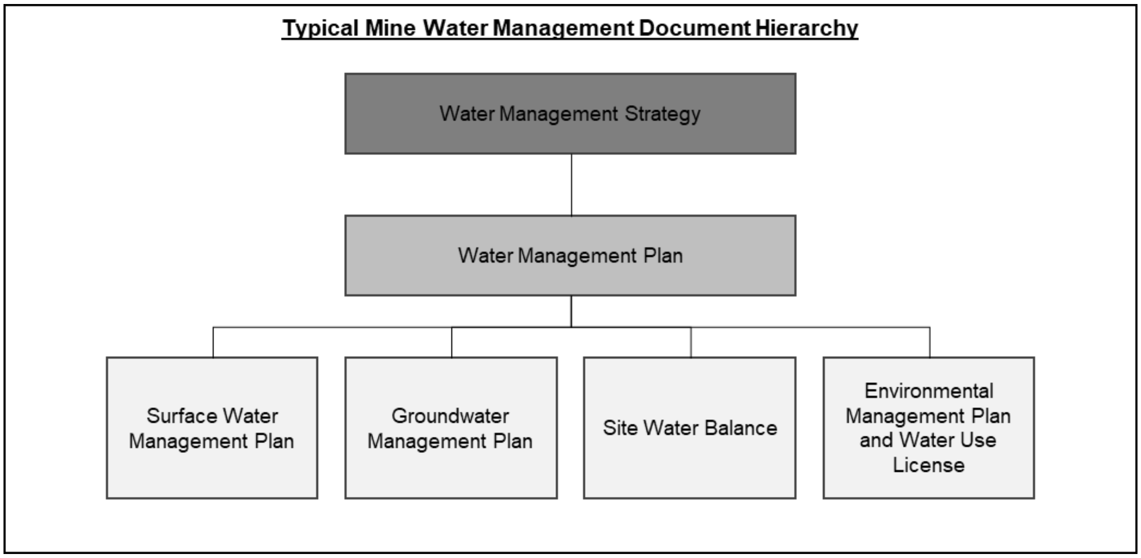

Figure 1: Typical mine water management document hierarchy

Each element of the water cycle at a mining operation has a unique timing profile in terms of their response to extreme events and the duration of the impact following the event, as shown in Figure 2. The timing of the negative impact is dependent on the intrinsic properties of the water cycle element, while the duration of the impact after the event is typically related to the water management capabilities of the operation. The importance of proactive surface water management at a mining operation lies not only in its ability to reduce downtime of the operation, but also in its ability to limit other impacts such as recharge to groundwater systems leading to pore pressure changes in slope faces and overwhelming of water infrastructure.

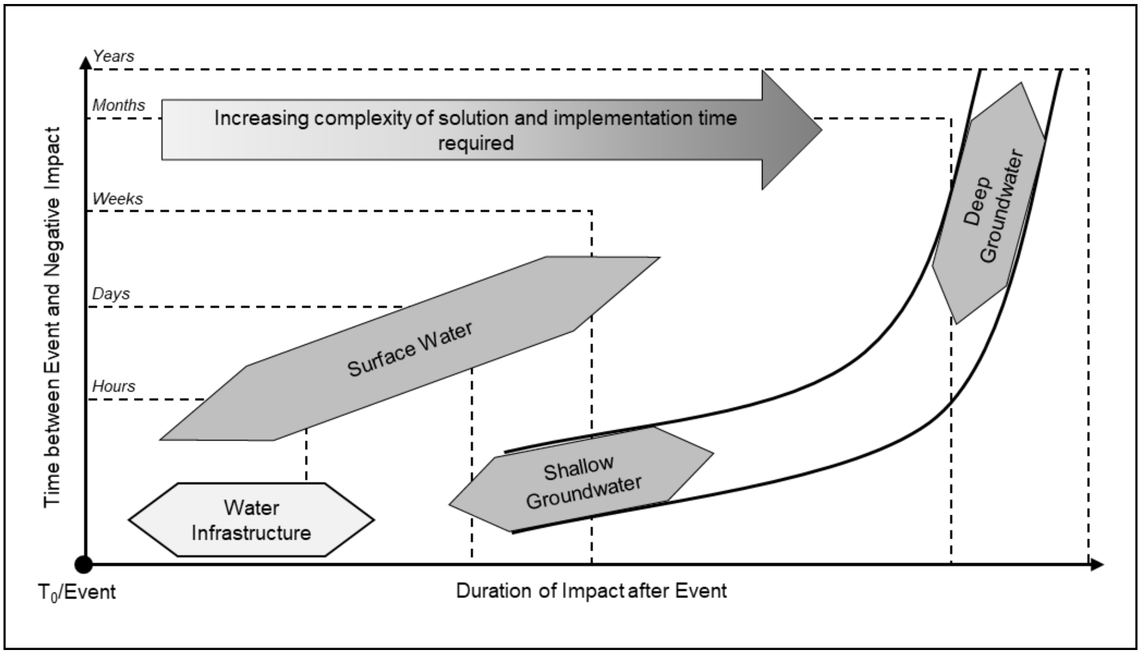

Figure 2: General timing profile of water cycle element responses to extreme events

Traditionally, surface water management at mining operations is focused on static infrastructure such as stormwater canals and dams. These are generally designed to achieve 'clean-dirty' water separation and comply with regulatory requirements. This infrastructure is often also designed for extreme rainfall events such as the 1:50 and 1:100 year events, with the intention to channel, capture and store surface runoff from the design rainfall events. The static nature of this infrastructure limits their application to the mining operations themselves and is often placed around the open pit or within the processing plant area of the site, leaving the active open pit susceptible to flooding during extreme rainfall events.

It is therefore beneficial to an operation to develop a process that leverages the dynamic nature of open pit mining, freely available surface water modelling capabilities, weather forecast datasets and a collaborative, narrative-driven approach for proactive surface water management to prevent unplanned impacts on the operation's business plan. Furthermore, this challenge needs to be addressed without incurring unreasonable capital requirements for in-pit water management infrastructure, that may have a limited lifespan due to the dynamic nature of mining. This paper presents a detailed description of the proactive surface water management process developed for open pit mine operations which has been tested at active operations with positive results during above average rainfall events in semi-arid environments. The rest of the paper presents the guiding principles for proactive surface water management, the process developed for implementation at active operations, and recommendations for risk-based water management practices that can improve operational adaptability to climate change and improve water stewardship at an operation.

Guiding principles of proactive surface water management

The overarching purpose and objective of proactive surface water management is to protect the operational business plan from delays and impacts caused by dynamic surface water during the rainy season. The secondary objective is to improve the adaptive capabilities of the operation's teams in responding to changes in environmental and production conditions. Proactive surface water management is an operational risk management process that leverages existing processes, operating models, and resources at an operation. This maximizes the benefits of existing operational strengths, mitigates weaknesses and threats, and increases the likelihood of realizing opportunities at the operation.

A key enabler to the successful implementation of proactive surface water management is a shared consciousness within the operational teams (both vertically and horizontally), and a striving towards a common purpose set and maintained by the owner of the proactive surface water management plan. To align the multi-disciplinary teams, it is crucial to define a clear vision that the teams can align to when planning and executing their respective tasks. This narrative-driven leadership approach allows multi-disciplinary teams to be empowered to align themselves to the vision and execute their tasks with minimal disruption to the way they do business That is to say that there are not necessarily new work methods or processes introduced to achieve proactive surface water management's vision unless they are essential and agreed to by all stakeholders involved.

This narrative-driven leadership approach to risk management can be coupled with the 'Risk Immune System' concept developed by McChrystal (2021) to form a modified risk immune system approach that forms the basis for proactive surface water management. The risk immune system is comprised of ten dimensions of control that can be monitored and controlled at an operation to remain within the business risk appetite (McChrystal, 2021), namely:

- **Communication**: how information is exchanged at the operation between internal stakeholders and with external stakeholders,
- **Narrative**: how an operation tells others about who they are, what they do and why they do it,
- **Structure**: how an operation and its processes are designed,
- **Technology**: how machinery, equipment, resources, and know-how are applied,
- **Diversity**: how a range of perspectives, abilities and objectives are leveraged in pursuit of a common goal,
- **Bias**: how the assumptions an operation and individuals have influence on decision-making,
- **Action**: how inertia or resistance is overcome to drive a response,
- **Timing**: how the timing of action affects the effectiveness of an operation or individual's response,
- **Adaptability**: how an operation responds to changes in risk profile and/or environmental conditions, and
- **Leadership**: how an operation directs and inspires the overall risk immune system.

To fit with the objectives and principles of proactive surface water management, the risk immune system concept configuration has been modified to drive the individual components via a common narrative (i.e., the objective of proactive surface water management to protect the operational business plan from delays and impacts caused by dynamic surface water during the rainy season). This modification is to improve the adaptability of the operation's surface water management systems and processes by empowering individual stakeholders in the decision-making process. This provides a single, encompassing narrative and two-way communication between stakeholders across multiple levels of work, disciplines, and objectives. The modified risk immune system concept shown in Figure 3 and Table 1 summarises the control dimensions of the system in the context of proactive surface water management.

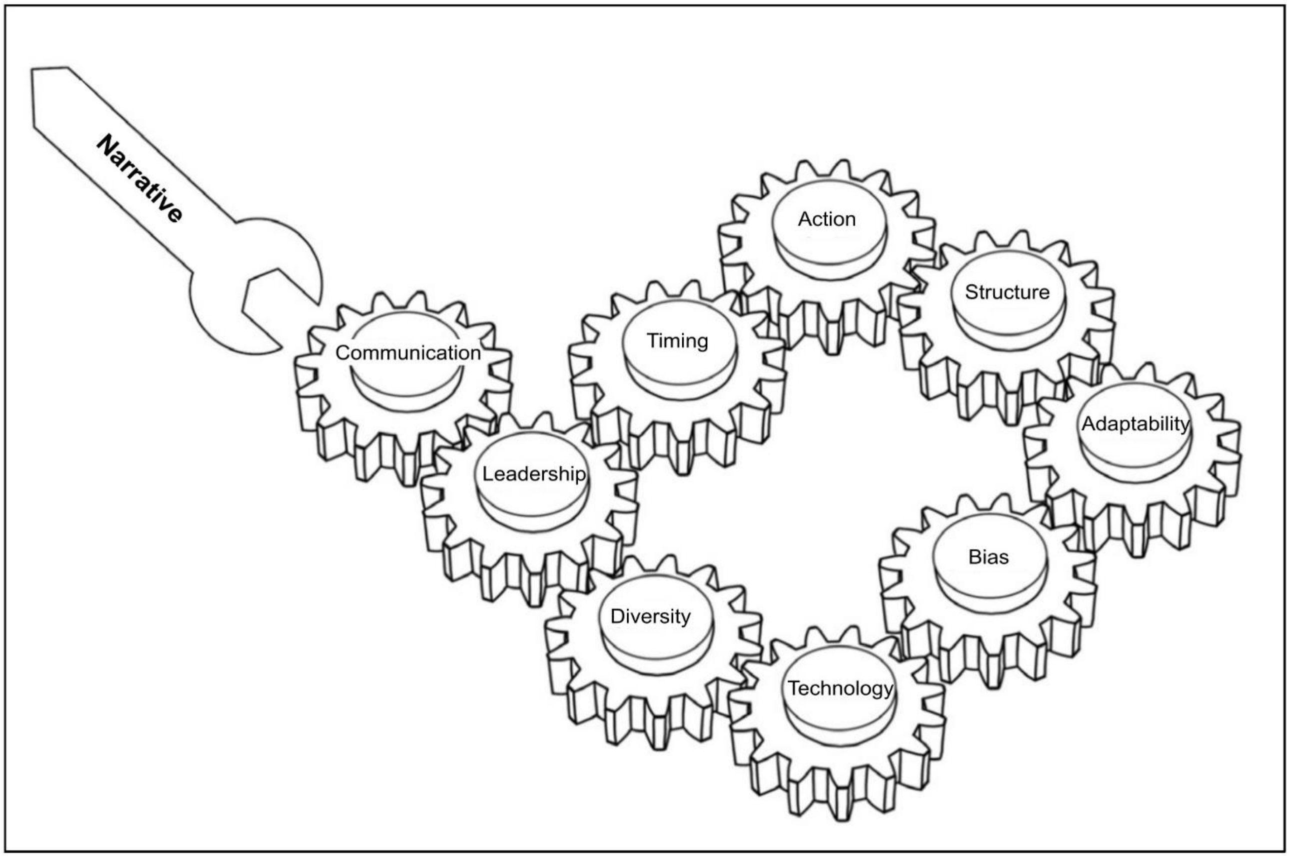

Figure 3: Modified risk immune system concept for proactive surface water management (after McChrystal, 2021)

Table 1: Risk immune system control dimensions in terms of proactive surface water management

Control Dimension	Description
Narrative	The overarching purpose and objective of proactive surface water management is to protect the operational business plan from delays and impacts caused by dynamic surface water during the rainy season at the operation
Communication	The channels and media used for communication, including regular meetings, email exchanges and procedures for communicating monitoring results, incident feedback and adaptive measures
Leadership	The direction of operational teams and resources towards their respective goals and objectives, as well as maintaining alignment with the narrative should be delegated to a single individual to ensure effective coordination amongst team members
Timing	The timing of action, including the required timing of action, should be done in alignment with operational procedures to ensure work is done at the right time using the right resources to ensure effective management of water-related risks and maintaining alignment with the narrative

Action	Action should be taken in alignment with the operational procedures and should be completed not only to address the identified issue at hand, but to maintain alignment with the narrative
Structure	The structure of the operation's proactive surface water management plan should include representation of stakeholders in both the vertical and horizontal direction, as well as have a clearly defined roles and responsibilities document and communication protocol in place
Adaptability	Adaptability should be measured in terms of social learning outcomes, namely: • Stakeholders show a change in understanding, and • The change appears and is practiced between various stakeholders within a social network
Technology	Technology (included specific interpretation and predictive techniques) used in proactive surface water management should be documented and assessed in terms of their relevance and sensitivity to change. Where a technology is deemed irrelevant or sensitive (e.g., only one person can perform the analyses), an appropriate educational/information campaign should be executed to ensure the sensitivity is addressed and the most relevant technology applied in alignment with the narrative
Bias	Individual and organizational biases should be documented, to the extent possible, and leveraged where beneficial or targeted by educational/information campaigns where needed to eliminate bias within the stakeholders and maintain alignment with the narrative
Diversity	A range of both internal and external stakeholders (where applicable) should be engaged in the decision-making process to ensure all aspects of proactive surface water management for the operation are addressed adequately

The proactive surface water management process

The proactive surface water management process uses several sequential steps to achieve its objective and maintain alignment to the narrative set for the operation (i.e., protect the operational business plan from delays and impacts caused by dynamic surface water during the rainy season). Each of these steps contribute towards the risk immune system for the operation, as described in the final section of the paper.

Step 1: Outline expectations

It is imperative that the expectations of the business are aligned to the narrative in a realistic manner to avoid overcommitment of resources and the resultant demotivation of the team members involved in the process. One of the main benefits of proactive versus reactive surface water management is that it enables adaptability at the operation, which in turn reduces the variability of outputs (specifically production outputs) and enables safe, capable, stable and productive operations. The source-pathway-receptor principle should be applied when setting the business expectation for proactive surface water management, as shown in the example presented in Figure 4. This presents the key factors that are being managed (source), how they are managed (pathway) and why they are being managed (receptor). Another benefit of the source-pathway-receptor method of presentation is that multi-disciplinary factors can be highlighted in the process, for example the operational mine plan acts as a pathway to receptors.

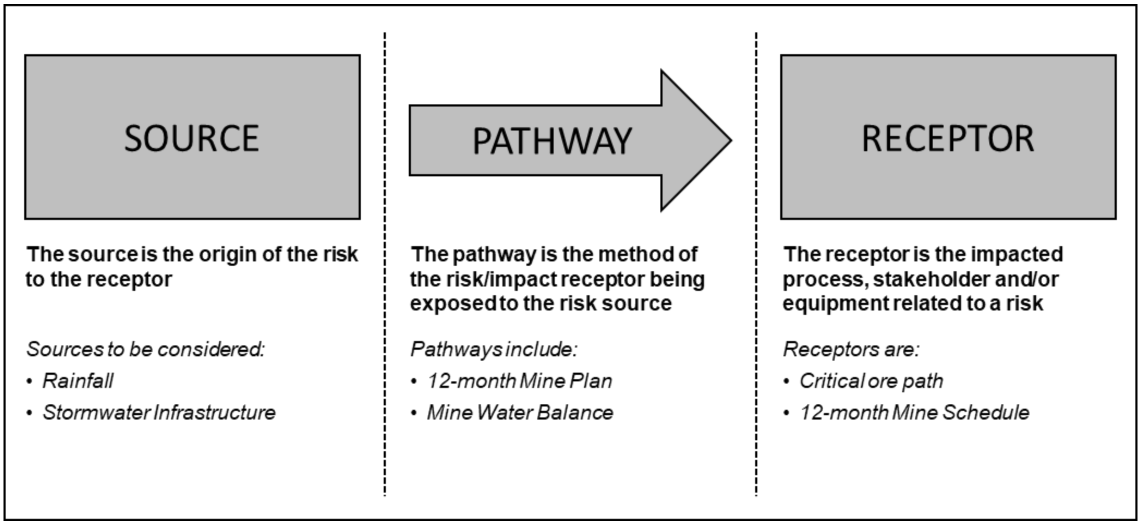

Figure 4: Source-Pathway-Receptor characterisation process

Step 2: Define the operational context

The operational context includes aspects related to the business plan during the coming rainy season, as well as the expected characteristics of the rainy season based on long term forecasts. This is a critical step to ensure work is planned, scheduled, and resourced adequately to enable the right work to take place at the right time.

Long term forecasts

Coupled with historical rainfall records for the operation, long term forecasts provide a view of potential rainfall expected at the operation and the level of preparedness required to effectively manage potential dynamic surface water during the coming rainy season. The Columbia Climate School's International Research Institute for Climate and Society (Columbia Climate School, 2023) provide probabilistic seasonal climate forecasts monthly.

These long term forecasts should be used in the interpretation of the operation's rainfall record to identify rainfall events that could be expected during the coming rainy season and to plan accordingly. For example, when long term forecasts indicate normal to below normal conditions for the rainy season, the proactive surface water management plan should be designed to accommodate and manage those rainfall events between the 25% and 75% quartile range and not necessarily the low probability events such as the 1:50 or 1:100 rainfall events. This is important in managing business expectations and minimizing unnecessary expenditure and resource allocation at the operation.

Identification of critical mining areas for prioritization

Critical mining areas are to be identified based on the annual business plan for the operation. These areas should be those where the most value is expected to be mined during the quarter of the rainy season onset and the quarter of the rainy season end, for example quarter 4 of the current year and quarter 1 of the following year. These critical mining areas should be framed as priority receptors in the proactive surface water management process in addition to the overall business plan for the operation (i.e., the overall business plan should be protected, but critical mining areas should be protected as a priority).

Step 3: Assess the operation's vulnerability status

Surface flood risk modelling

Surface Flood Risk Modelling (SFRM) is a powerful tool in the decision-making and design process for proactive surface water management as it provides an overview of the operation's response to rainfall events and highlights those areas most vulnerable during the rainy season that need to be prioritized in the design of the proactive surface water management plan.

It is recommended that 2D rain-on-grid modelling is conducted for the operation using the current surface topography and planned surface topography for the six month period that falls within the rainy season. Several rainfall events over 24-hours, 3-days and 5-days should be selected from the site rainfall record, aligned with the long term forecasts (i.e., normal, or above/below normal conditions) and the simulation results used to compile an inundation risk map for the current and future operation during and following rainfall events.

It is important to note that the model is to be used only as a decision-making tool, along with other tools as applicable, and should not be constructed to be a standalone model (i.e., calibration of the model is not required, and the model should be built to be fit-for-purpose). Representative results were achieved at Piteau client operations using a single Manning's coefficient for the entire operation and a model grid cell size of 5 m. As a rule, the model for the operation should not take longer than two (2) working days to construct (excluding computational time for topography) and should not take longer than one (1) hour to run. Barring computational limitations, if modelling takes longer than these indicator times it is recommended that the model is simplified to be fit-for-purpose.

Step 4: Develop an action plan

Dynamic Surface Water Management Infrastructure Design

Based on the SFRM results, appropriately placed and sized sumps should be designed and incorporated into the mining schedule. The sumps should ideally be placed in the original mining path to minimize disruption to the mining schedule and impacts on future mining activities. The sizing of the sump should consider the mining equipment fleet capabilities and current blasting practices at the operation to avoid designing unrealistic sumps (e.g., sump blocks that are more than two benches deep).

The sump dimensions should ideally be based on typical mining block dimensions and bench heights, with the effectiveness of the sump more dependent on pump and pipeline equipment used to evacuate water from the operationally active areas. This is recommended as it causes the least disruption to the mining process at the operation and does not introduce any additional safety risks to the operation. Once the sump positions have been identified and agreed to with the relevant stakeholders at the operation, the SFRM exercise should be repeated using the newly generated future topographies (which include sump blocks), and the results evaluated in terms of their effectiveness in inundation risk reduction in active mining areas.

Following the finalisation of sump positions at the operation, the existing pipelines that can be used to evacuate surface water from active mining areas should be mapped and catalogued in terms of their potential use in the current proactive surface water management plan. Where additional pipelines are required, these should be designed, and the required material procured timeously for installation.

The current surface pumping fleet (if available) should be catalogued, and the appropriate pumps placed at each of the sumps across the operation. The efficiency of the pump should be evaluated using the pump's pumping curve and its ability to evacuate water from the sump within the required time (as defined by the operational teams). Where resourcing shortfalls are identified within the existing pump fleet, an options analysis should be conducted to identify internal transfer opportunities between sumps to reduce pumping head requirements while remaining within the risk appetite of the operation. If this is not achievable, a business case should be developed to the appropriate level and submitted to procure the required resources. It is recommended that operation-specific procedures and standards are developed which, as a minimum, specify material stock levels to be maintained at the operation and availability targets for pumping equipment.

Baseline Implementation Schedule and Vulnerability Dashboard Development

A baseline, ideal schedule for implementation of the proposed sumps, pipelines and pump equipment placement should be developed and the timeline constructed to include both the ideal start date and absolute latest start date. The schedule scenarios should be compared with the onset of the rainy season and the peak period of the rainy season, where implementation should be near completion before the onset of the peak period of the rainy season. Figure 5 shows an example of an ideal start date schedule and absolute latest start date schedule compared to the rainy season distribution trend.

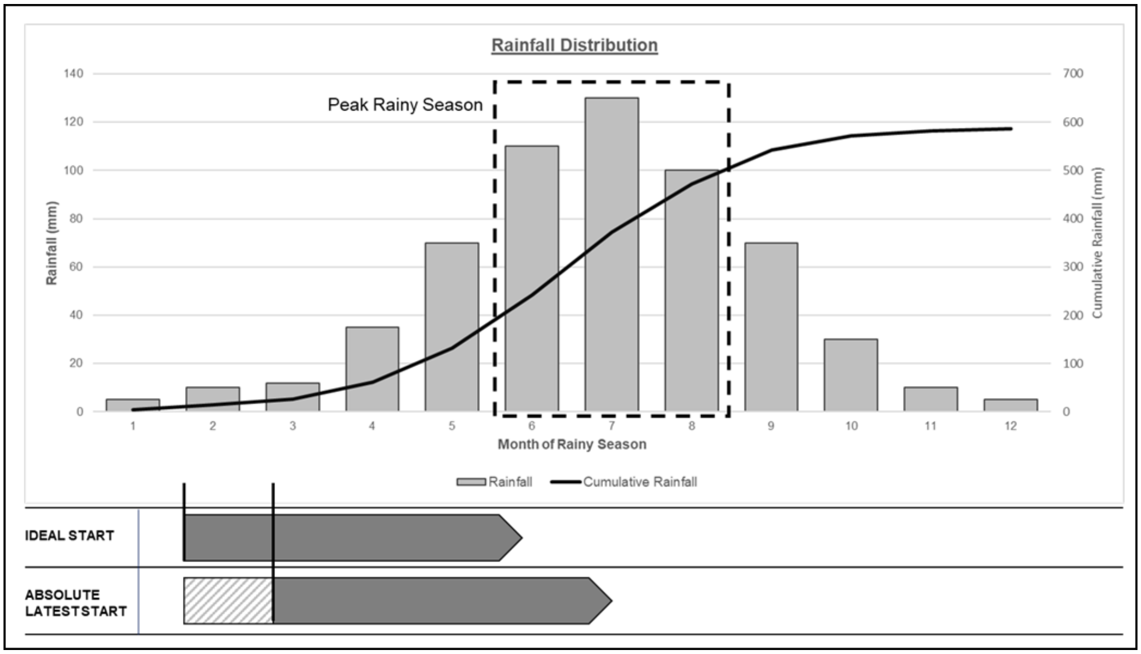

Figure 5: Example of implementation schedule scenario evaluation

Using the sump completion dates from the selected schedule scenario, final SFRM should be completed using the most probable rainfall events for the period and the effectiveness of the sumps simulated and the SFRM risk map updated and shared with stakeholders for comment.

Step 5: Set measures and metrics

Operation-specific vulnerability index definition

The Vulnerability Index per mining area being managed is a critical component of proactive surface water management as it enables tracking of implementation progress and the prioritization of work, and provides a mechanism for identifying additional resourcing requirements within teams across the implementation process. It is important to note that vulnerability is reported as an index only, meaning that an area is relatively more vulnerable compared to an adjacent area.

The general formula for the vulnerability index is shown in Equation 1, where **Receptor Tasks (R)** are those tasks performed in the execution of the business plan and should not be disrupted and **Proactive Surface Water Management Tasks (PSM)** are those tasks that form a part of the proactive surface water management plan for the operation.

Equation 1: General Vulnerability Index Formula

$$Vulnerability\ Index = \left(\sum Rating_{PSM\ Tasks}\right) \times \left(\frac{\sum Rating_{R\ Tasks}}{Number\ of\ R\ Tasks}\right)$$

When selecting the tasks to be tracked as part of the vulnerability index for the operation it is recommended that the SMART principle for KPI development is followed, as shown in Figure 6.

S	Specific	Define clearly what needs to be achieved
M	Measurable	Define how achievement will be measured
A	Achievable	Is the goal realistic?
R	Relevant	Does the goal align to the narrative?
T	Time-constrained	Define key milestones and delivery dates aligned to the overarching narrative and objective

Figure 6: The SMART KPI principle

Representative receptor tasks (R) for the vulnerability index should be those tasks most vulnerable to dynamic surface water and a binary rating assigned (e.g., Yes = 5, No = 0). Representative PSM tasks should be selected based on the work planned and each of the teams involved in implementation of the proactive surface water management plan should be represented in the tasks. When assigning ratings to the PSM tasks it is recommended that a sliding scale be used which is linked to the completion status of the task (e.g., 100% = 0, 50% = 3, 0% = 5, etc.).

Step 6: Develop feedback and response tools

Operational vulnerability dashboard

A baseline vulnerability dashboard should be set up using the identified work tasks required and their respective target completion dates. This dashboard should include all relevant tasks and the responsible and accountable team members for their implementation. It is important to remember that the dashboard is a visualization of the input sheet data which includes the factors required to calculate the vulnerability index per area considered. Each operation is split into evaluation areas differently based on their configuration and mining method. However, it is important when splitting the operation into subareas for evaluation, to ensure that the areas are both realistic in their management and representative of conditions at the operation.

Daily weather forecasts and rainfall measurement reporting

A 6-day weather impact forecast for the rainy season period (from onset to end) should be developed using the most reliable weather forecasting application available for the specific site in question. This forecast should be maintained at the operation and submitted daily to senior management and the operational teams and stakeholders. If moderate to high-risk wet weather events are identified on the 6-day forecast the following actions should be taken as a minimum:

- Communication of event potential to internal stakeholders at the operation as early as possible, ideally during morning start up meetings,
- Visually identify vulnerable mining areas and opportunities for deployment and/or diversion of resources to minimize the impact of wet weather events on the overall mining schedule,
- Prepare adjusted work plans for execution when called for, and
- Prepare appropriate recovery plans for the mining operations to speedily recover production rates following impacts from wet weather events.

During the rainy season, or after any rainfall event, the water management team at the operation should record the measured rainfall depths at the operation's rainfall stations and update the central master rainfall database and submit the updated daily rain tracking dashboard to senior management and the operational teams and stakeholders. There is significant value in being able to link forecasted events to previous events, especially where previous events have been unusually intense or disruptive. This provides documentation of institutional memory relating to such events and can aid in the communication of urgency or magnitude of disruption expected.

Scheduling and Tracking

The owner of the proactive surface water management plan at the operation should be integrated into the normal schedule tracking process for the operation to obtain information for input into the operational vulnerability dashboard, such as task completion status and active mining areas. The responsible operational team should inspect and test the existing pumping fleet on a quarterly basis and ensure that maintenance is done when needed to ensure a recommended minimum of availability as determined by the operation to be realistic is consistently maintained across the surface dewatering pump fleet.

Summary: operational risk immune system

A key enabler to the successful implementation of proactive surface water management is a shared consciousness within the operational teams (both vertically and horizontally) and striving towards a common purpose which is set and maintained by the owner of the proactive surface water management plan. The proactive surface water management process can best be summarised in the context of the operation's risk immune system, Figure 7 shows the risk immune system control dimensions and the elements of the surface water management process that support these control dimensions.

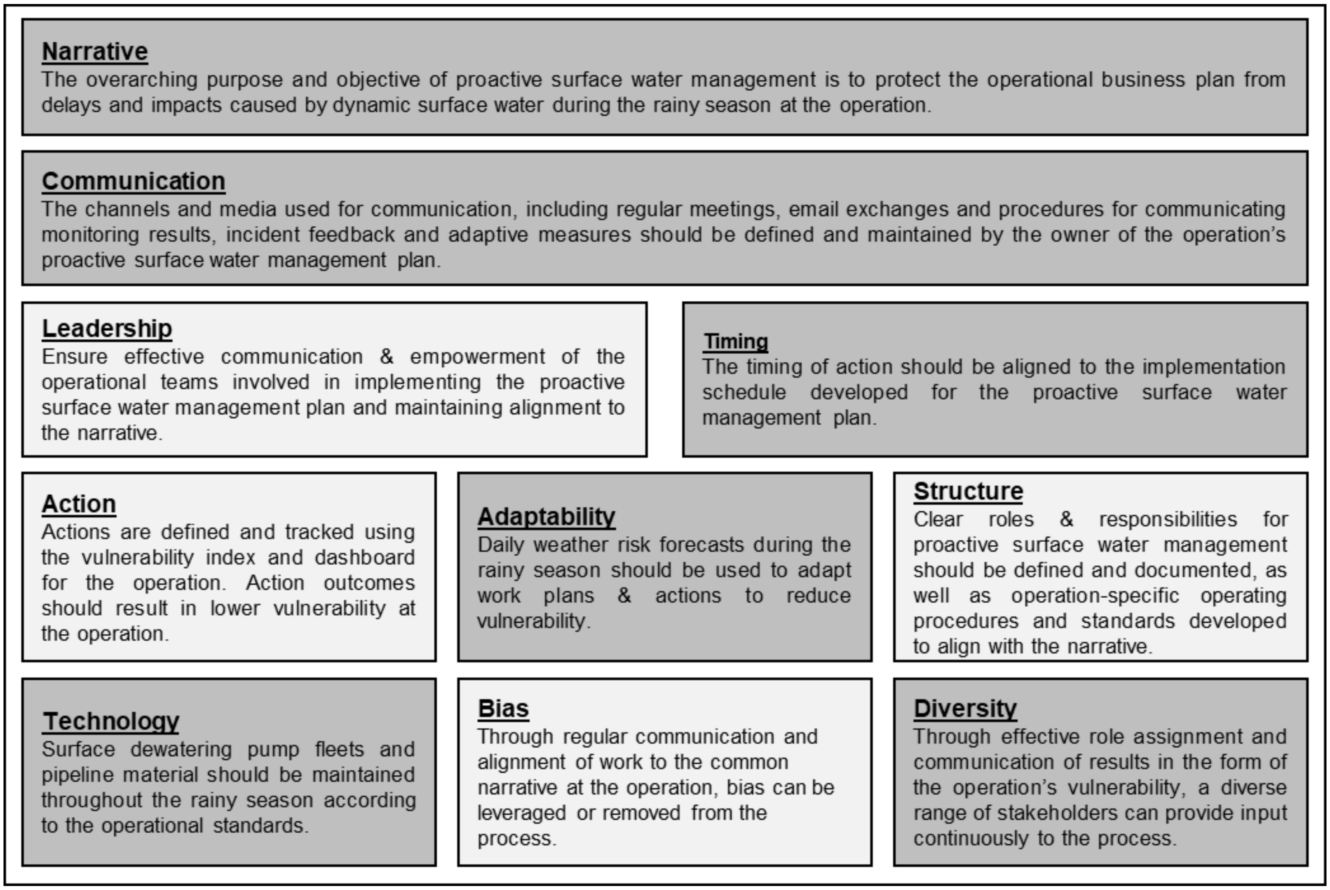

Figure 7: Proactive surface water management risk immune system

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