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TECHNICAL ARTICLE

Applying Practical Hydrogeology to Tailings Storage Facility Design and Management

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Abstract
Hydrogeology plays an important role in tailings storage facility (TSF) design. In this paper, we present hydrogeologic considerations for TSF design and operations and some fundamentals for site characterisation during the design phase that can help reduce the severity of groundwater-tailings interactions. Finally, we present examples of tailings-groundwater interactions from TSF design projects and active mining operations around the globe to illustrate our key points. These examples include successful applications of hydrogeologic principles during design and operations, and unexpected interactions between tailings design elements and groundwater where hydrogeology was not properly considered.

Keywords Groundwater · Embankment stability · Seepage · Pore pressure · Risk mitigation

Introduction

The stability of mine tailings containment structures (embankments typically constructed of tailings/earth/rock), herein referred to as tailings storage facilities (TSFs), depends on the reliability of a multitude of defence mechanisms that should be integrated into the design of the structures to address potential failure modes. Proper design of TSFs and associated defence mechanisms requires detailed understanding of potential interactions between the built and natural environment, including interactions with foundation materials and groundwater systems.

Foundation failure is a common cause of TSF failure, and as a result, extensive foundation investigations are typically undertaken during early design stages. Less understood, historically, are interactions between TSFs and groundwater systems. TSFs are frequently located low in the landscape, so groundwater-tailings interactions are likely, especially in areas with high precipitation rates and shallow water tables. Such interactions may affect pore pressure distributions, with consequent stability or piping (internal erosion) risks to the embankments. Other interactions might involve inadvertent leakage of tailings liquor into the groundwater environment with environmental and regulatory consequences. The potential for these processes, and associated risks to the integrity of TSFs, are key aspects to consider in TSF design and operational management.

Water management is a key aspect of the design and operation of practically all TSFs that deposit fine wastes as a slurry. The importance of proper water management in TSF operation is generally acknowledged, particularly in the areas of management of tailings pond size and location, monitoring and management of pore pressures in embankments in order to minimise the risk of piping (internal erosion), and other phenomena that have the potential to affect structural stability. Operational decisions on water management may manifest as changes to hydraulic gradients in the overall seepage field and elevated phreatic surfaces in

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embankments, and lead to instability. For example, changes in pond position relative to the embankment, use of TSFs for water storage beyond design recommendations, or inadequate seepage collection system operation can lead to increased risks. In a recent review of more than 300 TSF failures, 66 had primary failure mechanisms related to seepage and 63 were a result of embankment overtopping, the latter a clear indication of operational mismanagement (Lyu et al. 2019). This review is consistent both with results published by ICOLD (2001) and the authors' experiences.

The potential for seepage impacts from TSFs has been recognized and considered in the design process for decades (e.g. Klohn 1979), though some TSF designers have considered foundation seepage either as inevitable but acceptable or as a minor issue that could be easily managed with routine engineering controls (i.e. Strachan and Goodwin 2015). Experience has shown that these controls are not always effective. Poorly controlled seepage has caused significant risks and non-compliances with regulatory requirements for many major facilities. Hydrogeologists are increasingly engaged during the TSF operational phase when seepage control and capture systems (if installed at all) have failed, and the owner or design engineer needs to implement measures to contain or mitigate seepage.

Global sustainability principles demand that a closed facility will not bequeath long-term issues to our descendants. Many global mining companies endorse these principles. In common with mine voids and waste dumps, the offsite migration of contaminated groundwater is an issue integral with all aspects of TSFs. The authors' and others' global experience across hundreds of TSFs has shown that interactions with groundwater are frequent, and that seepage prevention and mitigation designs routinely fail to perform as expected. This is often due to poorly understood groundwater systems or unforeseen interactions between the natural and built environment that were not considered properly during the design phase. Potential interactions between groundwater and tailings need to be considered from the process of site selection, through design, construction, operations, and into the post-closure period.

Regulatory and Industry Guidance

The Global Mining Guidelines Group (GMG), part of the Canadian Institute of Mining, Metallurgy, and Petroleum (CIM) has compiled a list of ≈ 30 global guidance documents and standards related to mine tailings (see www.gmggroup.org/tailings, accessed September 2020). These documents are from international groups as well as national associations and committees from Australia, Canada, and the USA. Many of these standards are focused on risk and management frameworks, while only a small number describe design principles or provide guidance in design. For example, the Australian Handbook on Tailings Management (2017) acknowledges the role of hydrogeology in seepage control but does not present design principles or describe the types of field investigations and supporting studies required to assess the groundwater regime as part of TSF design.

A common theme in many tailings guidelines, standards and reviews is a focus on 'failure'. While definitions vary, failure is generally considered as a breach in the integrity of the TSF, resulting in an often abrupt and sometimes catastrophic release of water, tailings, or both. Risk reduction and failure prevention are key components of most guidance documents. Potential interactions between TSFs and groundwater may present risks, do not typically compromise dam integrity, and as such may not be a point of emphasis in global guidance documents.

Industry perceptions regarding the role of hydrogeology in tailings storage design have evolved in recent years, and this is reflected in more recent guidance documents. Major mining companies are taking the lead in making their internal tailings storage and design standards publicly available, and many promote consideration of hydrogeology and potential impacts to groundwater during the design phase.

Examples include the Rio Tinto procedure "D5—Management of tailings and water storage facilities" (2017) referred to as the 'D5 standard', publicly available on Rio Tinto's website, which contains two broad classes of risks, one of which is uncontrolled release of water or tailings. Importantly, Rio considers "contamination caused by uncontrolled subsurface (foundation) seepage beyond design expectations" in this risk category. The D5 standard recommends that expert hydrogeologic studies be considered in TSF design. Rio Tinto (and others) have internal teams of hydrogeologists who assist operational tailings teams with groundwater-related issues.

Similarly, the more recent Anglo American Standards and Technical Specifications for Mineral Residue Facilities and Water Management Structures (V 5.1, 2019), publicly available on their website, specify that design reports must include or make reference to specialist's hydrogeology reports. These standards are the first to require that the independent technical review panel for each facility include specialists in hydrogeology, groundwater, and contaminant transport.

One of the more comprehensive recent guidance documents on this issue is the APEGBC "Site Characterization for Dam Foundations in BC". This document was developed in response to recommendations of the Independent Expert Review Panel report on the Mount Polley TSF breach to 'identify an appropriate standard of professional practice for site characterisation' (APEGC 2016). It is one of the first guidance documents to provide a thorough description of the hydrogeological aspects of site characterisation, typical investigation methods, and the components that should be included in a conceptual model. It includes guidance on designing seepage 'control, conveyance, collection, and mitigation systems' as well as prediction of potential or artesian uplift pressures in the embankment foundation. The Mount Polley failure contaminated a large freshwater lake and was partially the result of a foundation failure in response to increasing pore pressures during tailings deposition (IEEIRP 2015).

The Global Industry Standards on Tailings Management (GlobalTailingsReview.org 2020) recommends site characterisation that includes hydrogeology, though it is silent on the role of hydrogeology in TSF design and management. In summary, the role of hydrogeology in tailings storage is becoming well-recognized and is generally acknowledged in the design community and industry guidance documents as a key component of TSF design. However, while conceptual hydrogeologic models (CHMs) are routinely developed during the design phase for new TSFs in some jurisdictions, hydrogeologic considerations are not uniformly and globally applied to TSF design and operations.

Overview of Groundwater-Tailings Interactions

Hydraulic Gradients and Flow into Tailings

Most groundwater systems are fundamentally gravity driven, with downward vertical gradients at higher elevations and recharge zones, and convergent or inward (and sometimes upward) flow at valley bottoms and lower elevations. Springs and swamps occur where the water table intersects the land surface or where geological structures act as flow paths, and groundwater pressures are high enough.

Many TSFs are designed as valley-fills, with one or more embankments constructed perpendicular to the valleys. The position of the TSF relative to the regional and local groundwater flow regime will dictate whether water tends to flow into or out of the tailings deposit, and these conditions may change in response to loading and filling of the TSF. Predicted hydraulic gradients have implications for design of drains and seepage collection and capture systems. For example, in an upland valley with regional downward groundwater gradients, the driving force (hydraulic gradient) for vertical seepage migration will be higher when the TSF is operational, and due consideration must be given to foundation permeability to prevent seepage impacts to groundwater. In the absence of low permeability foundation layers, seepage may migrate laterally away from the TSF, regardless of whether collection drains have been installed. In extreme cases, groundwater mounding due to saturated tailings placement may cause localised gradient reversal and seepage flow across natural groundwater divides.

In contrast, where a TSF is cited in a lowland valley with upward vertical gradients, springs, or artesian conditions, groundwater flows into tailings and potential uplift pressures on liner systems must be considered during design. Groundwater (or spring) inflows into tailings may result in significantly higher volumes of seepage to manage, especially in the early phases of TSF filling when pressure from the weight of tailings and embankments are lower. In some cases, excess water inflows may raise the phreatic surface in embankments, with resultant risks to stability. These conditions need to be considered carefully during design.

Foundation Seepage

Seepage impacts occur when fluids in the tailings impoundment migrate through the foundation or through the embankments. Some of this seepage may be captured by engineered drain systems, including under-drain systems beneath liners and pumped wells installed for seepage capture near TSF perimeters. Seepage that bypasses these structures typically discharges to groundwater or surface water, potentially moving offsite in the long term. Such migration may cause water quality changes that exceed regulatory criteria and guidelines, may constitute offsite environmental impacts, and may breach legally enforceable conditions of operational approval.

TSF operations typically (but not always) involve placing high volumes of slurry on a lined or unlined foundation over a very large area. This process indicates a potential risk for foundation seepage losses to groundwater. These risks may be mitigated through use of natural or engineered layers of low permeability foundation materials, such as compacted clay or till or geomembrane liners.

For TSFs with natural low permeability foundation materials, designers generally assume that a base layer of fine tailings of low permeability will be established during the initial phases of TSF filling, which will help prevent vertical migration of fluids to underlying groundwater. However, TSFs may be used for early discharge of slurries with a low percent of solids during the commissioning phase of processing, when tailings slurries do not meet assumptions of TSF design specifications. This early deposition may be associated with high potential for foundation seepage losses by void filling in the unsaturated part of the shallow subsurface.

Even low permeability foundations allow some vertical fluid migration when placed under a high hydraulic head from tailings deposition by slurry. Vick (1990) notes that seepage discharge occurs even when complex liner systems are used. Even where a low permeability layer is successfully established and unit seepage rates are very low, the footprint of the areas involved may be very large. Tailings impoundments typically contain a few tens of thousands to several hundred million cubic meters of variably saturated material stored over areas as large as several square kilometres. For very large tailings storages, even well-constructed conventional liners will delay seepage rather than preventing it. Key questions may be whether the almost inevitable seepage constitutes an environmental threat or risk of non-compliance with regulatory conditions and whether the liner/drainage system will perform adequately for the long term.

Ultimately, the fate of seepage that reaches groundwater will be controlled by the geometry and hydraulic properties of the hydrogeologic system underlying and surrounding the TSF. Layering, heterogeneity, and structural features in the foundation may influence or control seepage transport, and may control the quantity of seepage that reports to, or bypasses, designed seepage collection systems.

Seepage mechanisms are described in more detail by Waterhouse and Friday (2000); as they note, long term seepage rates may be limited by the geometry of the underlying aquifer, and its capacity to impede lateral movement of seepage water rather than the liner (Fig. 1.). The intent here is not to describe all the factors affecting seepage migration, but rather to emphasize that understanding the shallow aquifer system and development of a robust conceptual hydrogeological model is essential for design of effective seepage mitigation measures.

Foundation Pore Pressure

Loading due to embankment construction and tailings placement adds stress to the tailings and underlying materials; in some situations, this can increase pore pressures. The load from embankment construction and tailings placement increases over the life of the TSF. Sustainable TSF design relies on several factors, of which pore pressure dissipation, via drainage, is considered critical to minimize pressure build up within the tailings and the foundation. To achieve desired factors of safety (FoS) for various loading conditions, design slope angle selection relies on stability assessments that consider pore pressure in the tailings, embankment, and foundation beneath the TSF walls and slopes.

Pore pressure dissipation ultimately relies on drainage and pore fluid migration in response to loading. Pressure dissipation in tailings is typically achieved through decant systems, basal drainage layers, finger or toe drains, or other structures designed to encourage dewatering and consolidation. The ability of the foundation materials to dissipate rising pore pressures beneath the TSF is a function of the geometry and hydraulic properties of the underlying shallow groundwater system.

Pressure dissipation is easily achieved where TSFs overlie unconfined aquifers of sufficient permeability and lateral extent beneath and beyond the TSF embankments, providing a path for lateral pore fluid movement in response to stress. In these conditions, pore pressure build-up is not typically considered a significant risk. In other conditions, achieving

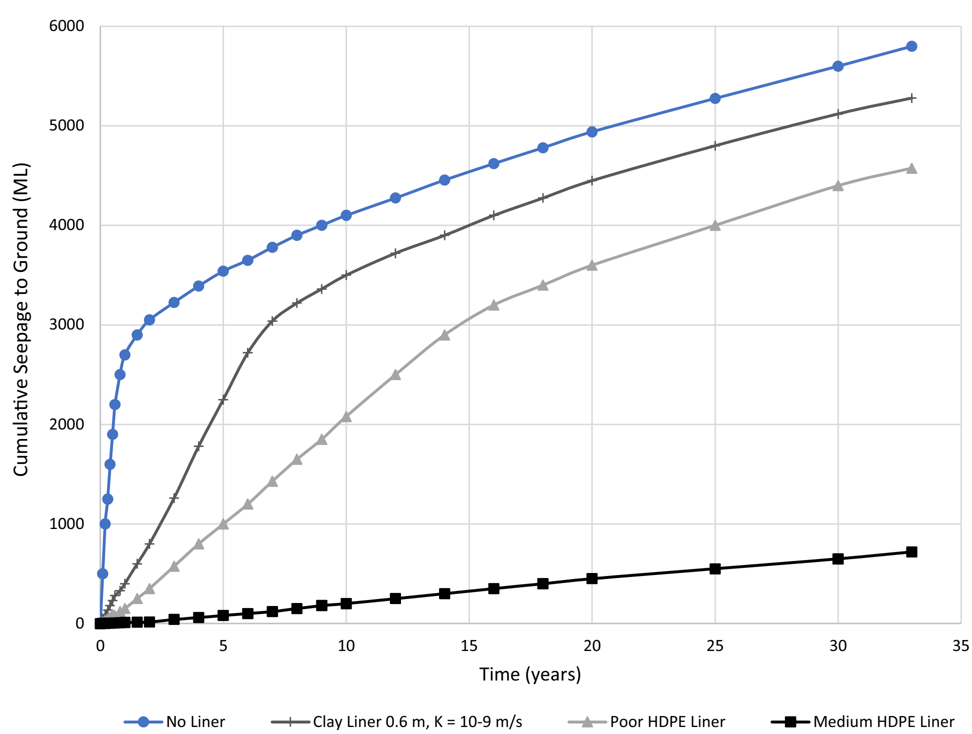

Fig. 1 Seepage volume vs. time for a large TSF and a shallow groundwater system (modified after Waterhouse and Friday 2000)

the desired level of pore pressure dissipation within the foundation may be challenging, especially where the TSF is constructed over a low permeability foundation that effectively confines the underlying water-bearing zones. Where shallow groundwater systems are locally confined, or are narrow or channelized, pressure dissipation potential may be limited by aquifer boundaries.

At some sites, foundation conditions do not allow for effective pore pressure dissipation, and pore pressures respond systematically or irregularly to loading from tailings elevation changes and localised embankment construction activities. When pore pressures are not effectively dissipated, they may exceed ground surface elevation. This is illustrated in Fig. 2 for a vibrating wire piezometer (VWP) located in a foundation layer beneath an embankment, near the toe. In this case, groundwater in discontinuous sandy layers is confined by an overlying clay foundation layer. The channelized and saturated sand layers have limited capacity for pore pressure dissipation.

Designing tailings embankment raises under these conditions requires predicting the likely pore pressure conditions, which may manifest at the ultimate design height of the TSF, which can be challenging due to the non-linear nature of responses. Incomplete pressure dissipation may result in localised artesian conditions. If loading pressures on confined aquifers exceed the strength and confining pressure of the overlying layers, groundwater may manifest at the surface in the form of discharge areas (overflow), discrete springs, or even surface heave.

During TSF operation, if the predicted pressure dissipation cannot be achieved and foundation pore pressures exhibit increasing trends above design trigger levels, pressure mitigation and/or a change in design slopes may be needed to achieve desired FoS and avoid TSF failure. Properly allowing for these factors in design can significantly increase the construction costs of the TSF. If problems of this nature develop during operations, the capacity of the storage may have to be reduced or the rate of tailings deposition decreased, both potentially having a major effect on operation economics that exceed the cost of appropriate design and construction. Knowledge of foundation stratigraphy, aquifer geometry, and hydraulic parameters related to groundwater occurrence and movement are important in assessing the potential risk of failure due to inadequate pore pressure dissipation during construction and operation.

The Role of Hydrogeology in TSF Design and Operations

The main role of hydrogeology in TSF design is to reduce risk and uncertainty in the design process by providing a clear and quantitative understanding of how the TSF is expected to interact with the natural groundwater system.

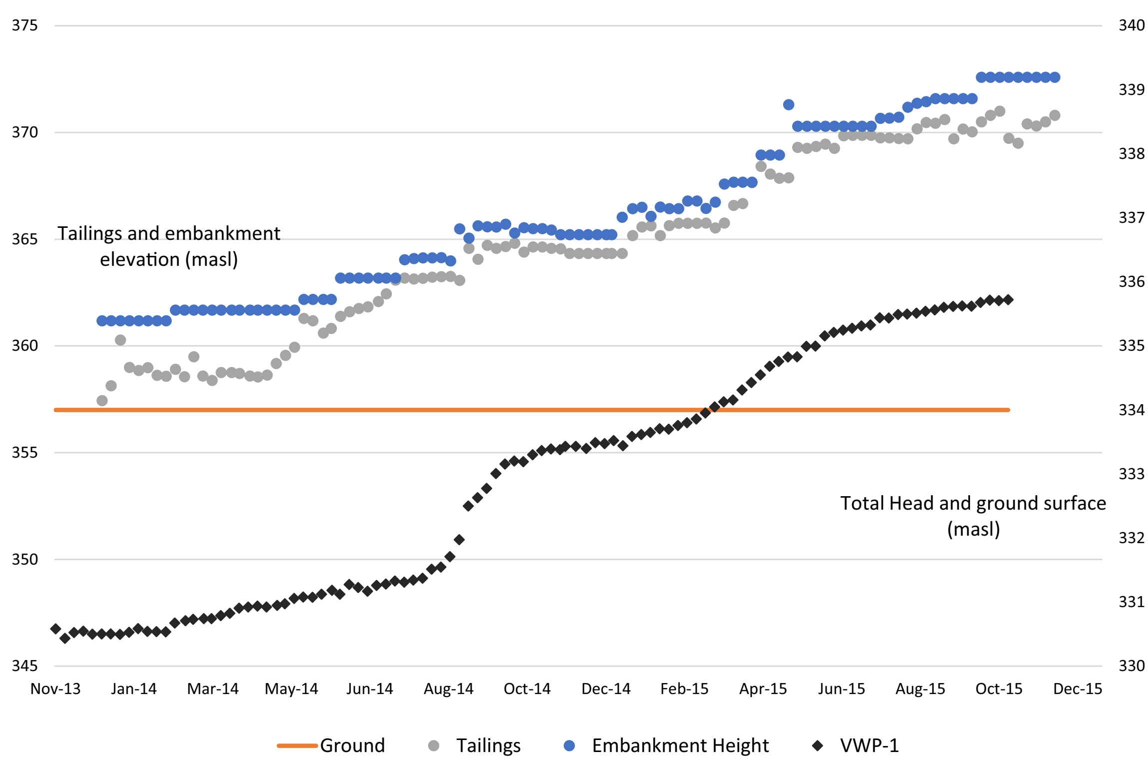

Fig. 2 Example of pore pressure response to loading for a confined shallow groundwater system

For example, a designer might consider what percentage of potential foundation seepage a finger drain system should capture or may seek to design an embankment toe drain with the aim of capturing all of the seepage. These designs often assume seepage will flow from tailings into and towards the most permeable elements—the drainage layers. However, hydraulic gradients in the groundwater system, hydraulic properties of foundation materials, heterogeneity of tailings and natural materials, and the operational performance of engineered drainage systems all influence these outcomes. This is where a well-developed conceptual hydrogeological model (CHM), often combined with numerical modelling, can help reduce design uncertainty and minimize the risk that engineered systems may not perform as desired.

The CHM is an important part of all phases of TSF development, including site selection, design, operations, and closure. Hydrogeologic investigations and CHM development can often be coupled with geotechnical investigations in the early design stages. When utilized at the design stage, a good CHM can help mitigate the risk of water-related issues during TSF operation. Design decisions that rely on the CHM may include the selection of a liner system, if required, design of seepage collection and control systems, and design and optimisation of the site monitoring program. Importantly, the CHM should be updated throughout the life of the TSF as new information and data become available.

Site Selection

Hydrogeological factors are often critical in the successful design and operation of TSFs. A key part of site selection is understanding the hydrogeological conditions at the different sites that may be considered for further investigation. Recognising and avoiding sites where groundwater-related risks to the TSF cannot be practically or economically controlled by engineering design is critical. If complex engineering design is required to limit seepage rates to groundwater, it raises the question of whether the structure will perform adequately without future intervention after closure.

As discussed briefly in previous sections, the natural state of the groundwater system and pre-construction gradients will provide clues to potential tailings-groundwater interactions. Sites with shallow water tables, springs, and upward gradients can help with respect to seepage control, but may also result in higher quantities of water inflow to be managed and potentially a greater risk of elevated phreatic surfaces in embankments.

In contrast, sites with deep water tables and downward hydraulic gradients may present the risk of seepage loss, particularly if foundation materials are highly permeable. Some sites may be unsuitable for conventional tailings deposition by slurry if the seepage potential is high enough. In such cases, perhaps the only viable approach is dry stacking of the tailings or conversion of the tailings slurry to a low moisture content, low hydraulic conductivity paste, both methods followed by robust capping at closure.

TSF site selection is a complicated process often driven by several factors, including location relative to ore processing facilities, property or mining lease boundaries, project economics, and many others. Development and consideration of a CHM during site selection may help the owner understand potential risks at each site and inform the design controls that would be required to mitigate future tailings-groundwater interactions.

Site Investigation during Design

During TSF design, extensive geotechnical investigations are typically undertaken to assess foundation materials and their properties in the vicinity of embankments, including the ability of these materials to limit potential seepage impacts to groundwater. These studies provide input into foundation preparation requirements and selection of natural or synthetic liner materials, where required. Hydrogeologic site investigations should focus on identifying and understanding any additional groundwater-related risks in design, including:

(1) the presence of springs and upward hydraulic gradients that have the potential to cause liner uplift pressures or excessive flow into the TSF and engineered drains,
(2) the presence and geometry of any preferential pathways that may allow for transmission of seepage beyond the TSF footprint to downgradient receptors, and
(3) the ability of the shallow groundwater systems to mitigate elevated pore pressures that may be generated by loading due to tailings and material placement.

The site investigation program should include a review of available geological and geotechnical data to aid in scoping and design of supplemental investigation locations. Field investigations should be integrated with geotechnical programs and generally focus on:

(1) Groundwater occurrence, identification of water bearing zones, and whether aquifers are present;
(2) Hydraulic characteristics and hydraulic properties of any identified aquifers;
(3) Establishment of an appropriate, site-specific groundwater monitoring network;
(4) Understanding the geometry of the groundwater system below and around the TSF, including the presence of geological structures and features that may serve as preferential seepage flow pathways; and
(5) Collection of water levels and background groundwater quality data.

More detailed recommendations are summarized in APEGBC (2016) (pp 33–35).

Coupling hydrogeologic field work with geotechnical field work during early design phases presents a unique opportunity to obtain some of the data and information necessary for development of a preliminary CHM, although extra drilling locations and testing are typically required. As noted by Waterhouse and Cooper (1994), hydrogeologic investigations utilize techniques similar to those used in geotechnical investigations, but they are typically applied over a larger area and at a different scale of intensity.

Opportunities to leverage geotechnical field programs at this stage of design include hydraulic testing of planned geotechnical bores (i.e. through falling head tests), the conversion of some planed geotechnical boreholes to groundwater monitoring bores for sampling and testing, and conversion of some boreholes to piezometers in key materials. For proper characterisation of the hydrogeologic system, additional groundwater monitoring bores away from the embankments are usually needed, though subsequent hydraulic testing and water quality sampling of the established monitoring network can often provide sufficient information for CHM development.

Design of Groundwater Monitoring Systems

The CHM is key to successfully designing groundwater monitoring systems. Often monitoring programs are designed around monitoring bore networks installed during design phase investigations. In complex geology, reliable prediction of seepage flow pathways and rate of migration can be challenging, and additional piezometers and groundwater sampling wells may be required as understanding of the CHM evolves over the life of the facility.

At many operations, the responsibility for groundwater monitoring, evaluation and reporting lies outside the tailings team. Monitoring is often conducted by the environmental team as part of a compliance monitoring program. Typically, compliance monitoring is focused on seepage impacts and relies on water quality data from a subset of bores located downgradient of the TSF.

It is important to recognize that the type and amount of groundwater data required for compliance purposes can be significantly less than the data required to support operational decisions by the tailings team. For example, if areas of elevated pressures develop in foundations or embankments, water level records for the underlying and surrounding groundwater systems are required to understand pressure dissipation processes. A robust TSF instrumentation and monitoring program should always include routine water level monitoring of all available groundwater bores in the area.

The Role of Numerical Groundwater Modelling

Numerical groundwater modelling, when conducted during the design phase, can provide key insights into potential interactions between the groundwater system and design elements. Numerical modelling can also be used to test the performance of or optimize the configuration of design structures such as drains and cut-off walls. However, this modelling is only credible when there is enough information to develop a robust CHM for use in model development. Where insufficient data is available during the design phase, hydraulic calculations, analytical models, and other interpretive techniques can help inform understanding of the groundwater system and identify key data gaps to be addressed to advance the CHM.

Preliminary numerical modelling should be updated and validated during the operational phase when more information is typically available for this purpose. Data not typically available during the design phase includes VWP sensor data from TSF embankments, water levels from monitoring bores, seepage rates or volumes from drain systems, and information on foundation pore pressures from piezometers. Model updates and recalibration is particularly important if the TSF configuration changes, as when TSF raises beyond initial design assumptions are contemplated.

Numerical modelling during operations may be undertaken for several purposes. Three-dimensional numerical groundwater modelling can be used to assess and predict changes in seepage with increasing tailings and pond elevation (e.g. Levenwick et al. 2009). If seepage impacts have occurred, models can be used to assess possible migration pathways and travel times to potential receptors.

Models can also be used to help understand operational risks. For example, elevated pore pressures in embankments that develop during TSF operations may pose stability-related risks. Engineering solutions to stabilize embankments, like buttresses, are costly. Where elevated foundation or embankment pore pressures are present, TSF-groundwater models can help elucidate mechanisms and processes responsible and can be used to test pore pressure mitigation measures. Phreatic surface levels and two- or three-dimensional pore pressure distributions obtained from these models are often used in slope stability assessments to help assess risk.

Hydrogeology during the Operational Phase

During operations, most TSFs are raised periodically to accommodate increasing tailings volumes. At some sites, foundation pore pressure increases may by dynamic and rapid, even after years of consistent and previously acceptable pressure levels. These reasons for these changes are not always apparent but are sometimes linked to the performance of the hydrogeologic system. For example, if a partially saturated zone becomes fully saturated and confined, the ability of that zone to dissipate pore pressure increases from loading is diminished. Well-designed monitoring systems are important, as is regular and critical review and interpretation of the collected data.

Arguably, the most common role of hydrogeology in TSF operations is related to the effects of seepage on the environment. If seepage bypasses the engineered seepage cut-off or capture systems and travels beyond the footprint of the TSF, hydrogeologists may be engaged to help understand the fate and transport of seepage in groundwater and potential impacts to downgradient receptors. These investigations are complex and costly and there is no standard qualification for a "tailings hydrogeologist," so approaches and results vary.

Distinguishing TSF seepage impacts from already poor-quality groundwater can be particularly challenging at mines that have been in operation for a long period of time, in arid climates with saline groundwater systems, and at sites where the TSF is in close proximity to large disturbance footprints or waste rock storage areas –conditions commonly encountered at mine sites in Australia and Chile, among others. In these conditions, exploratory data analysis (EDA) and machine learning (ML) techniques, when applied to physical and water quality data sets by an experienced tailings hydrogeologist, are invaluable in understanding source-pathway-receptor relationships (Ezzy and Fortuna 2020). EDA and ML assessments of existing surface water, TSF decant water, and groundwater quality data can help distinguish seepage contributions of the TSF from naturally saline background aquifers or previously impacted groundwater.

Hydrogeology for Closure Planning and Design

Finally, as operations begin to transition towards closure, tailings hydrogeologists and TSF-groundwater models have a key role to play in assessing the potential for long-term seepage effects on the environment and in predicting drain down rate of the phreatic surfaces and pore pressure distributions in TSFs. The evolution of the phreatic surface in the TSF under different closure or cover scenarios may inform overall landform stability evolution over time, and aid in selection of closure options. Predictive models calibrated to long operational data sets can inform future expectations for seepage rates and control measures.

Finally, selection and evaluation of closure options for TSFs need to consider the long-term stability of the landform, which is related to the post-closure evolution of the pore pressures in the tailings and embankments. Evaluation of cover types and options and landform design need to consider their potential effects on the rate of drain down in the TSF. Numerical modelling of the TSF and underlying groundwater system can inform the potential for long-term seepage impacts to the environment and can be used to test potential mitigation systems.

Practical Examples of Hydrogeology in TSF Design and Management

This section presents examples of successful applications of hydrogeology to TSF design and management, as well as examples of issues that can arise when hydrogeology is not considered properly. Schematics are used to illustrate lessons learned from site experience, instead of actual site information, which is often confidential.

Effective Use of Hydrogeology in Seepage Collection Design

At a large gold development project in South America, an experienced tailings hydrogeologist was engaged during the preliminary design phases of the TSF. The CHM indicated that the mostly fine-grained foundation saprolite (extremely weathered in-situ rock) was heterogenous, with some coarse-grained zones of higher permeability.

Preliminary groundwater modelling was undertaken to assess the effectiveness of the proposed toe drain design, and to assess the effectiveness of planned seepage collection pumped wells. Modelling included simulation of anisotropy in the underlying saprolite, which was a key factor controlling seepage from the tailings through the foundation of the TSF.

Model sensitivity analysis revealed that an order of magnitude change in the anisotropy of horizontal to vertical hydraulic conductivity ratio (Kh:Kv) resulted in the preliminary toe drain design capturing ≈ 95% vs 17% of expected seepage, with higher anisotropy resulting in significant seepage bypass (conceptually illustrated in Fig. 3). Uniform materials allow for gradient distributions that are downwards beneath the TSF, transitioning to upward at the embankment toe. In contrast, materials with Kh:Kv anisotropy may result in higher horizontal hydraulic conductivity beneath drain systems, allowing significant seepage bypass.

These results of conceptual and numerical hydrogeologic models were used to help refine preliminary designs and to develop a site field investigation approach to collect the data needed to reduce uncertainty and improve design of seepage collection and capture systems.

Change in Groundwater Conditions due to Design Elements

At a copper project in South America, a grout curtain was installed as a cut-off wall in fractured bedrock beyond the toe of a valley fill TSF to prevent downgradient seepage

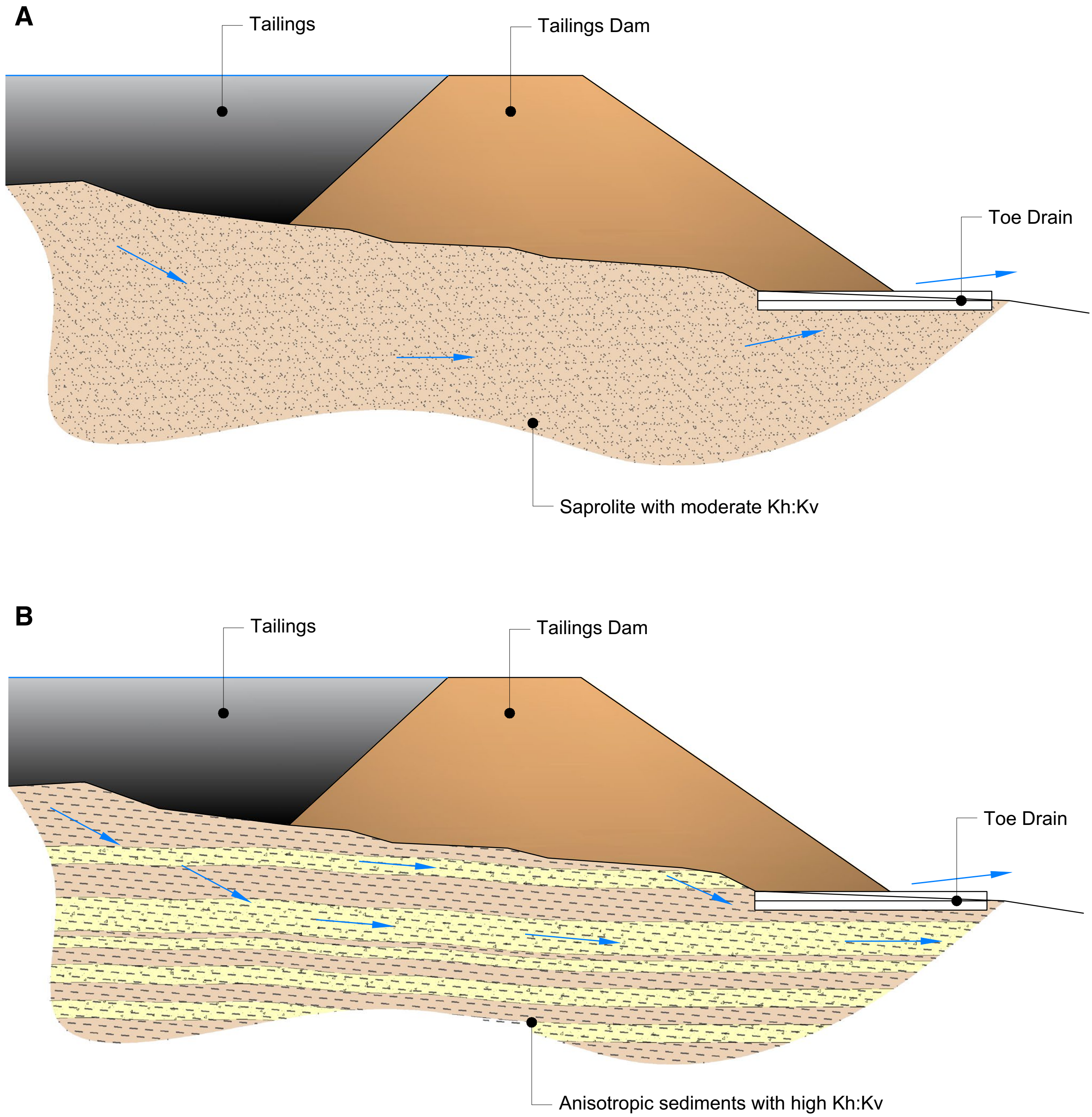

Fig. 3 Schematic showing effect of Kh:Kv ratio on drain discharge: **a** Anisotropic saprolite with moderate Kh:Kv ratio and **b** Sediments with high Kh:Kv ratio, leading to partial drain bypass

migration. A small collection drain was included in the center of the cut-off wall at the base for seepage collection. Unfortunately, the fracture systems in the valley were not fully connected hydraulically to this drain, resulting in incomplete drainage and build-up of hydraulic head behind the cut-off wall. Eventually, rising hydraulic head levels resulted in seepage finding alternative pathways around the cut-off wall through faults and fractures in valley abutments. This is illustrated schematically in Fig. 4. This caused down-gradient impacts to water quality via fracture flow in patterns that were not easy to understand or interpret. Establishing seepage flow pathways through abutments is difficult and elevated pressures in fractured rock abutments can be challenging to mitigate.

In this case, the cut-off wall and drain designs did not properly consider principles of fractured rock flow like the

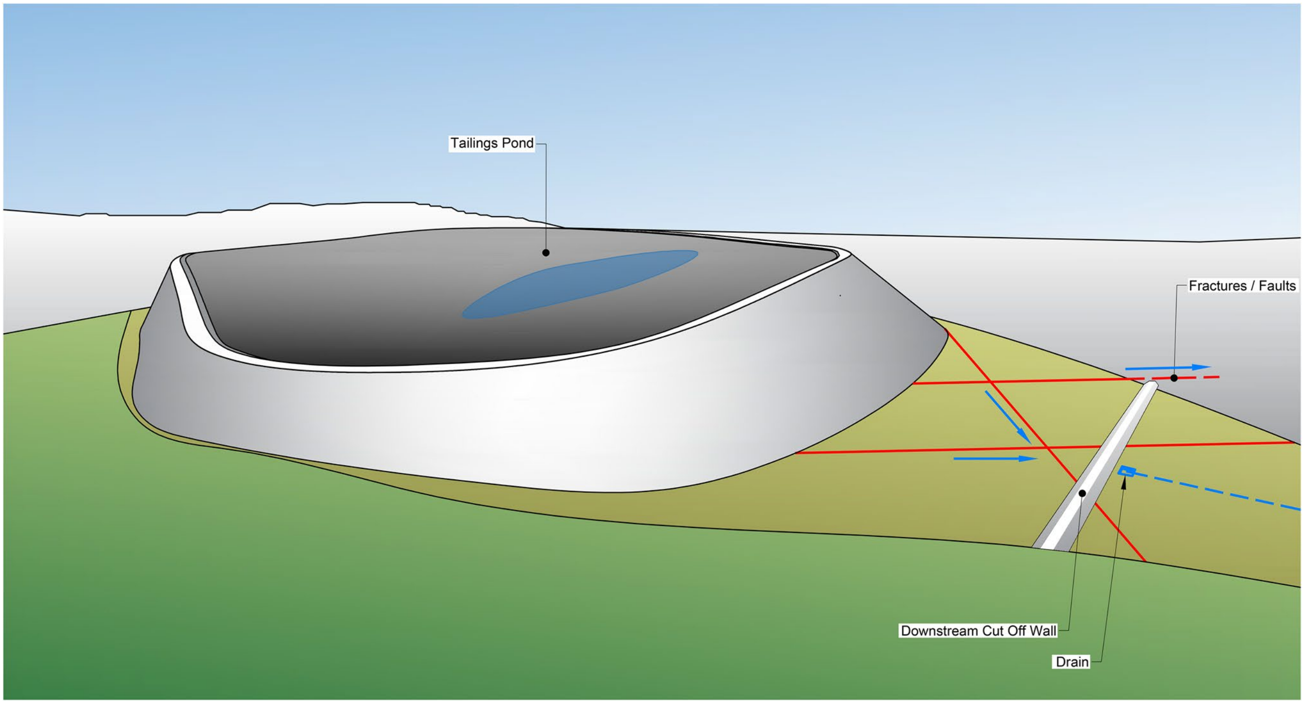

Fig. 4 Schematic illustrating fracture flow around a cut-off wall through abutment

heterogeneity of the factures and their continuity or future interactions between the natural and built environments. A restriction in seepage flow was assumed (and achieved), but the potential for hydraulic head build-up was not anticipated by the designers. Development of a robust CHM during TSF design and simple modelling of cut-off wall impacts would likely have predicted these effects, and led to a more effective and efficient seepage mitigation design and avoidance of later issues and mitigation expenses.

Unexpected Interaction between Groundwater and Design Elements

At a large copper project, extensive foundation investigations were undertaken for a planned multi-cell TSF in relatively level terrain, but a robust CHM was not developed for the groundwater system. During construction of the initial cell, one embankment of the TSF was placed over a natural alluvial drainage channel, while the remainder of the TSF was constructed over clay soils and underlying bedrock. The alluvial channel is several meters deep, hosts a localised shallow aquifer, and conveys storm flows from overland runoff during episodic wet season storm events. An engineered clay cap was constructed over the alluvial channel where it underlies the embankment and TSF footprint as a seepage prevention measure, effectively confining the previously unconfined shallow aquifer. Cut-off walls were installed adjacent to the decant pond and downgradient of the TSF embankment to prevent downstream seepage migration through the alluvium and allow for seepage collection and capture. This is shown schematically in Fig. 5. This design has proven effective for limiting foundation seepage and downstream seepage migration.

However, because the engineered elements effectively prevent groundwater migration, the confined alluvial channel aquifer could not effectively dissipate pore pressures caused by the TSF operations due to its limited lateral extent. Over time, the increasing weight of the rockfill embankments and tailings resulted in localised artesian pressures in the shallow alluvium and excess pore pressures in the overlying clay foundation at the embankment toe. Pressure build up under the embankment requires active pressure mitigation and consideration during slope stability analysis and design of raises. Extra rockfill has been added to maintain slopes to increase stability and achieve the desired FoS, resulting in increased construction costs that were not anticipated in earlier budgeting.

There are many hydrogeologic challenges to proper design of a TSF over a channel aquifer, and these have been described previously (Stephens et al. 2006). Involvement of an experienced tailings hydrogeologist in the siting studies, planning, and early design phases of this TSF could have prevented this condition and the considerable expense of subsequent control measures. For example, installation of upstream cut-off walls combined with flow diversion around the perimeter would have effectively dewatered the shallow

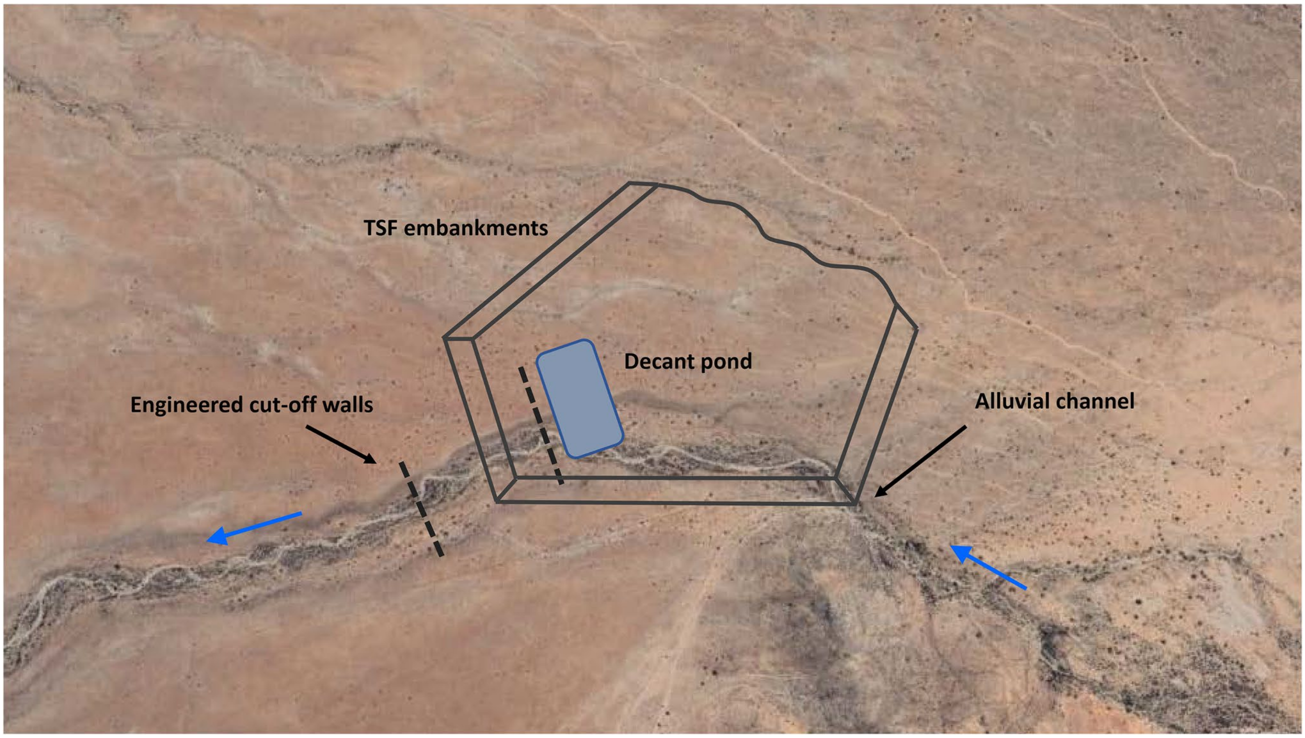

Fig. 5 Schematic showing plan view configuration of TSF embankments, alluvial channel, and engineered structures. Blue arrows represent natural surface water/shallow groundwater flow prior to construction

aquifer under the TSF and allowed for significant improvements in the ability of the natural system to dissipate pore pressures, with corresponding improvements in slope stability and avoidance of the costs of control measures.

Failure to Consider CHM during Operations

At a large copper project in South America, seepage migration beneath the TSF is controlled by fracture systems. Seepage is recovered through several groundwater extraction wells installed at and beyond the toe of the embankment. The wells have a wide range of sustainable pumping rates, depending on location. Initially, seepage recovery was very effective. However, when downstream embankment raises were implemented, pushing out the downstream toe, the most productive extraction bores had to be abandoned. Replacement wells were installed, generally in a similar configuration. This is illustrated schematically in Fig. 6.

The subsequent extraction network was not able to capture similar seepage flow volumes or control seepage migration, resulting in impacts to downstream receptors and seepage emergence into nearby creeks. In this instance, lack of documentation of major fracture orientation during the design phase combined with failure of the operations team to consider the CHM during pumping well replacement contributed to seepage management failures. To mitigate this issue during the operations phase, field investigations (i.e. geophysical surveys) could be undertaken downstream of the embankment toe to identify the orientation of the transmissive fault zones and aid in selecting appropriate locations for replacement pumping wells.

Successful Seepage Control Design

At a large polymetallic mine in South America, a robust CHM was developed during TSF design. The CHM indicated potential for seepage migration through the fractured rock foundation. Groundwater modelling was undertaken to assess seepage control and predict potential impacts, both for the original TSF design and subsequent design of several operational lifts. Modelling indicated the potential for seepage migration through fractures. To prevent seepage migration, foundation and abutment fractures were pressure grouted in several rounds prior to rockfill embankment construction. The result is that after many years of operation and several embankment raises, downstream water quality remains unaffected, despite the ever-increasing hydraulic head behind the embankment.

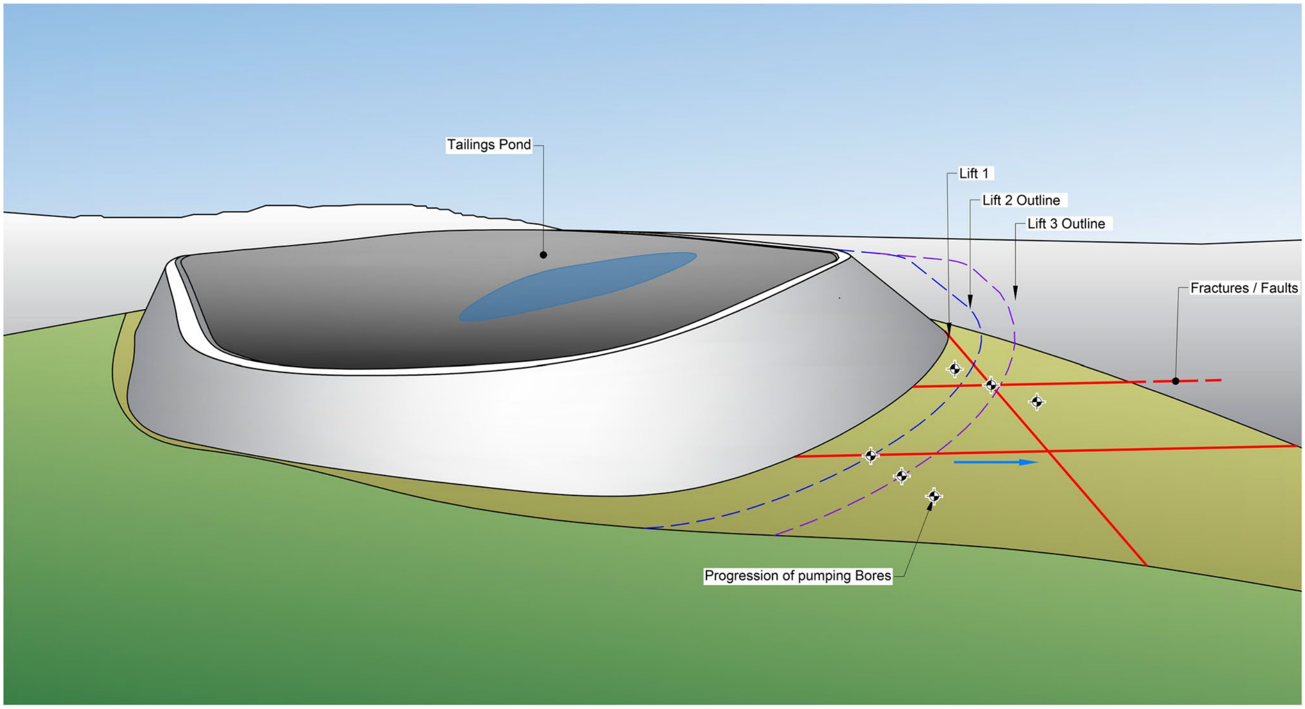

Fig. 6 Schematic showing progressive locations of successive recovery wells relative to fracture systems controlling flow as the embankment is raised and previous recovery wells are destroyed

Use of Advanced Analytical Techniques

At a coal mining project in Australia, it was difficult to distinguish seepage impacts from the TSF from poor groundwater quality associated with previous mining activities and saline waters in the deeper bedrock aquifer. Previous assessments had suggested widespread, slow leakage from the TSF along a substantial perimeter. The proposed seepage collection and capture system, using cut-off trenches or extraction and pump-back wells, was both extensive and expensive. A third party review of the remediation system design indicated that a CHM update was required. We revaluated the existing water quality data sets, applying EDA and ML techniques, including principal component analyses, K-means clustering, and support vector machine models to the full water quality data set, including surface water samples, decant pond samples, and shallow and deeper groundwater. When combined with revaluation of geologic data, we were able to update the CHM cost-effectively to identify source-pathway-receptor relationships. Results of this assessment indicated that seepage pathways were in fact quite limited in extent, reducing the footprint of the planned remediation system by more than 60%, with substantial capital cost savings (i.e. > $1 M). The hydrogeological assessment was completed in about three weeks at modest cost.

Use of CHM During Operations

At a copper project in South America, the original CHM described the presence of karst terrain in nearby lithologic units. During a planned TSF raise, the design team recognised that the tailings elevation increase would place tailings near newly recognized karst features in one of the valley walls. Supplemental hydrogeologic studies were conducted to evaluate the distribution of karst features and assess whether the identified features could serve as a seepage conduit to downgradient receptors. The updated CHM confirmed the potential for piping of tailings into karst features and subsequent seepage transport. To mitigate this risk, designers implemented a management strategy that included: (1) removal of topsoil and sediments to identify surface karst features and cavities in bedrock; (2) grouting of identified karst features; and (3) installation of a drainage layer followed by a low permeability blanket of compacted clayey soil between the tailings and bedrock to minimize the potential for piping and seepage. The employment onsite of a karst hydrogeology specialist was critical in early recognition of the features of concern.

Summary and Conclusions

The critical role of hydrogeology in tailings storages is now generally acknowledged by TSF designers as a key component of TSF design, but input from groundwater specialists is not uniformly applied to the design and operation of TSFs globally. We hope this review will increase awareness of groundwater-TSF interactions and the potential issues associated with these interactions. The aim is to highlight the importance of proper consideration of hydrogeology during TSF design, operation, management, and closure.

This paper presents some fundamental concepts and practical examples of hydrogeologic considerations for TSF design and operation. Proper and timely application of hydrogeology can help avoid failures, off-site contamination, and unbudgeted remediation expenses. TSF design and operation teams are encouraged to:

- Engage a qualified tailings hydrogeologist as a key member of the design and investigation team from the beginning, through operations, to closure.
- Identify groundwater occurrence, key hydrogeologic features, and aquifer geometry early in the design phase and develop a conceptual hydrogeologic model of the groundwater system.
- Evaluate how preferred design elements may interact with the natural groundwater system.
- Using models as appropriate, use these hydrogeologic assessments to feed into the design and operation of the TSF.
- Consider how TSF-groundwater interactions will change over the life of the facility as loading increases and hydraulic gradients change, and then also after closure

In summary, design, construction, and operation of TSFs are best approached by multi-disciplinary design, management, and review teams, with hydrogeology being an important discipline that needs to be appropriately applied.

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