Hydrogeology and Mineral Resource Development

Leslie Smith

THE GROUNDWATER PROJECT

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THE GROUNDWATER PROJECT

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Table of Contents

The Groundwater Project Foreword

The United Nations Water Members and Partners establish their annual theme a few years in advance. The theme for World Water Day of March 22, 2022, is "Groundwater: making the invisible visible." This is most appropriate for the debut of the first Groundwater Project (GW-Project) books in 2020, which have the goal of making groundwater visible.

The GW-Project, a non-profit organization registered in Canada in 2019, is committed to contribute to advancement in education and brings a new approach to the creation and dissemination of knowledge for understanding and problem solving. The GW-Project operates the website https://gw-project.org↗ as a global platform for the democratization of groundwater knowledge and is founded on the principle that:

"Knowledge should be free and the best knowledge should be free knowledge." Anonymous

The mission of the GW-Project is to provide accessible, engaging, high-quality, educational materials, free-of-charge online in many languages, to all who want to learn about groundwater and understand how groundwater relates to and sustains ecological systems and humanity. This is a new type of global educational endeavor in that it is based on volunteerism of professionals from different disciplines and includes academics, consultants and retirees. The GW-Project involves many hundreds of volunteers associated with more than 200 hundred organizations from over 14 countries and six continents, with growing participation.

The GW-Project is an on-going endeavor and will continue with hundreds of books being published online over the coming years, first in English and then in other languages, for downloading wherever the Internet is available. The GW-Project publications also include supporting materials such as videos, lectures, laboratory demonstrations, and learning tools in addition to providing, or linking to, public domain software for various groundwater applications supporting the educational process.

The GW-Project is a living entity, so subsequent editions of the books will be published from time to time. Users are invited to propose revisions.

We thank you for being part of the GW-Project Community. We hope to hear from you about your experience with using the books and related material. We welcome ideas and volunteers!

The GW-Project Steering Committee

March 2021

Foreword

Our modern global economy impacts the environment in many ways, including the groundwater environment, in support of humanity's many essential activities including agriculture, urbanization, and extraction of fossil fuels and minerals. This book: Hydrogeology and Mineral Resource Development is about mining in the groundwater context. There is an expectation that fossil fuel production will soon decline as other forms of energy replace fossil fuels, but with the global population increasing by 2 to 3 billion people in the coming decades, mining will be essential in the long term.

Of these essential activities, mining does not have the most severe impact on groundwater, but the complexities are extreme because a typical mine has a four-phase life cycle, each one much different from the others. First, the exploration phase disturbs the terrain in order to access the site and drill exploratory holes. The next phase is mine construction including excavation of the earth and creation of drainages to dewater the mine zone. This is followed by mining operations with removal of large volumes of rock and earth in order to extract the ore. Finally, the mine is closed, at which time the disrupted, reorganized landscape is left for nature to cope with the disturbed conditions. As recently as the late twentieth century this last crucial phase received little attention. Responsible mine closure is as, or more, challenging than the mining phase because the goal is to arrange the new landscape for minimal environmental harm over the next millennia.

This book presents a broad vision of how mining interacts with groundwater and vice versa to provide the reader with a vision of the issues and challenges, which are exacerbated by the occurrence of mining in all climatic conditions from arctic to tropical, all terrains from mountains to plains, and involving disturbances ranging from small holes in the ground to vast excavations of many square kilometers. Mining impacts are complex due to weathering reactions between water and the earth materials left behind (tailings and waste rock) after the ore is removed. These materials are exposed to geochemical conditions that are much different than conditions throughout the geologic period when the material rested below ground surface before mining.

The author of this book: Dr. Leslie Smith, Professor Emeritus at the University of British Columbia, has participated in leading research concerning the impacts of mining and restoration on groundwater and surface water. As part of his consulting work, he has observed mining impacts at many locations around the globe, hence this book is superbly illustrated with photographs that bring the reality of mining to our attention given that so few of us witness mining in person.

John Cherry, The Groundwater Project Leader
Guelph, Ontario, Canada, March 2021

Preface

The hydrogeological setting of a mineral resource development project is often a central component in mine planning, safe mine operations and sound environmental stewardship. Mining occurs in a wide range of geologic and topographic settings, across a full range of climatic conditions. The objective of this book is to illustrate many of the considerations involved and methodologies applied when assessing the impacts of groundwater on mine operations, on mine water supply, on mineral waste management and in closure of a mine site following resource depletion. In most countries, strict regulation is in place that recognizes the need for management controls to minimize impacts on groundwater systems. This book discusses the principles of hydrogeology that need to be considered to achieve those goals.

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1 Summary

In this book I discuss hydrogeological concepts and analysis approaches to address topics associated with mineral resource development. The focus in this book is principally on physical attributes of the hydrogeological setting that need to be considered in mineral resource developments. This book provides a broad discussion of the role of hydrogeology in mineral resource development but the intent is not to cover all types of mining operations for which the principles of groundwater flow are integral in project development and site closure. For example, one method not discussed is the control of groundwater flow patterns and flow rates in the design of an efficient fluid injection and withdrawal system for in-situ leaching operations. Another topic not discussed is groundwater control measures used for aggregate mining for construction materials, one of the most common mining operations.

In the mining industry the application of principles of hydrogeology is a central component in safe operational practice, water management and environmental stewardship. Characterization of the groundwater regime is required during the planning and development of large open pit mines, in underground and block cave mining, and at in-situ or heap leach facilities. Figure 1 shows many of the physical structures encountered at a large open pit mining operation. Ore is being mined at the active open pit seen in the southeast corner of the photo. Mill tailings produced during processing of the ore are retained in the storage facility seen to the north in the photo. This mine uses an earth-fill dam constructed of waste rock to retain the tailings, with tailings deposited as a slurry discharge from spigots located on the crest of the tailings dam. This facility has an extensive tailings beach, submerged tailings, and a supernatant pond of process-affected water. Pond water is re-used as a water supply for ore processing. A historic open pit seen to the southwest in the photo is slowly filling with water as a consequence of groundwater inflows and precipitation, creating a deep pit lake. A heap leach operation for additional mineral recovery is located to the southeast of the tailings facility and a waste rock stockpile is north of the active pit. A pond is present in a sump on the floor of the active pit, where the local water table has been intersected. This site is a copper mine; but similar structures can be found at coal mines, diamond mines, in oil sand operations, and in many other mineral resource developments. Underground mines typically produce much smaller volumes of waste rock than an open pit operation. However, they too require a management system for disposal of the tailings produced during processing of the ore.

Figure 1 - Key features associated with ore extraction and mine waste management at an open pit mine that require consideration of the hydrogeological regime. For scale, the diameter of the historic open pit seen in the lower left side of the photograph is approximately 1800 m. North is to the top of the photograph.

The primary hydrogeologic issues associated with mineral resource projects are those related to: (i) safe and efficient extraction of ore during mining operations (e.g., dewatering and depressurization controls), and (ii) protection of groundwater and surface water quality. Management of groundwater inflows is required to ensure dry working conditions and groundwater control is often a critical element in ensuring geotechnical stability of pit walls, tunnels and mineral waste containment structures. The presence of elevated porewater pressures can compromise the stability of slopes in an open pit, in structures such as tailings dams and process water storage dams, or the stability of waste rock stockpiles. In block caving mining, the ore zone is undercut by open workings, inducing the rock hosting the ore to fracture and move by gravity toward constructed draw points below for removal. In the presence of groundwater there is a potential for the broken rock to move as a mud rush into work areas below the block cave. A mud rush is a mobile mixture of water and solids equivalent to a debris flow. Generally, the higher the rates of groundwater flow into the subsidence zone around a block cave, the greater the risk of a mud rush occurring. Managing the risk of a mud rush is a key focus of safe mining practice in block caving.

An evaluation of the potential impact of mine operations or post-mining effluent release on the quality of adjacent surface or groundwater is a central component of environmental impact assessments for proposed mining projects. These assessments require an understanding of subsurface fluid pathways to enable quantification of potential impacts in both space and time. The scales at which impacts can occur can range over distances of several hundred meters, to several square kilometers, even to domains hundreds of square kilometers in extent. Evaluation of potential mitigation measures to minimize these impacts requires a robust characterization of groundwater flows within the mine area as well as any adjacent areas that may be impacted. Characterization of the hydrogeological conditions must also be undertaken to manage situations where contaminants of potential concern have been mobilized from mine wastes and a remedial program is to be implemented to ameliorate impacts to the receiving environment.

2 Introduction

2.1 Climatic and Geologic Settings

Mining occurs in a wide range of geologic and topographic settings, across a full range of climatic conditions. There are large mines in production in desert environments such as the Atacama Desert in northern Chile, the Gobi Desert in Mongolia or the Namib Desert in Namibia, in tropical rainforests in equatorial countries such as Papua New Guinea and the Democratic Republic of Congo, at elevations above 4000 m in the Andes Mountains of Peru and Chile, and in polar environments in Canada or Russia where permafrost significantly modifies the character of the groundwater flow regime from that which occurs in more temperate settings. Each setting presents unique challenges in water management.

Water issues differ between areas where the climatic regime is one of water surplus (annual precipitation exceeds evapotranspiration) versus mines located in a climatic regime of water deficit (annual potential evapotranspiration exceeds annual precipitation). At mines located in a region of water surplus, excess water can accumulate in a tailings storage facility if management controls are not in place. Operational flexibility decreases and the geotechnical risk profile increases when excess water accumulates in a tailings storage facility. Similarly, surface water accumulating in an uncontrolled fashion can result in increased risks of water inflows to an open pit, or to underground workings.

At mines located in climatic regimes with a water deficit there are often no available sources of surface water and the water required for ore processing is obtained from nearby aquifers, if present. In an extreme case, mine operations in a desert setting might involve not only mineral resource extraction but also "mining" of a groundwater resource that could take many centuries to recover to the pre-development state. The climatic regime is also a key determinant of natural groundwater recharge rates and seasonal variations in those rates, both factors in determining the rates and time scale at which mobile contaminants in mine waste are released to the surrounding environment. The magnitude of a solute load released from a mine waste facility, and the time scale for release, can vary dramatically when comparing mine sites in arid and wet climates.

Mines are located in many different geologic settings. The geologic units hosting an ore deposit might be igneous, sedimentary and/or metamorphic bedrock in a low-relief ancient landscape or rugged mountainous terrain. An intrusive ore body associated with mineralized ore fluids could have penetrated a sedimentary sequence of shale, limestone, or sandstone or an igneous/metamorphic sequence of granites and gneisses. In glaciated terrain, a hydrogeologic assessment when selecting a site suitable for a mineral waste facility often requires investigation of groundwater flow in glacial deposits such as tills or outwash sands that overlie bedrock. In the humid tropics, site assessments typically require hydrogeological characterization of a thick saprolite soil and highly weathered rock that commonly forms as surficial layers across the landscape above more competent bedrock.

A full understanding of the geologic setting and how it might influence groundwater conditions at a mine site is fundamental to sound operating practice and environmental protection. A common theme in mine operations that do not perform according to geotechnical design expectations is an inadequate appreciation of the influence of the site geology on hydrogeologic conditions. Sites that present particular challenges in defining the role of groundwater flow include mines located in karstic limestone terrain, sites located in steep mountainous terrain when the bedrock groundwater flow system is controlled by the fracture network permeability, or where fault zones or dykes act to compartmentalize the groundwater flow system into discrete sub-basins, with groundwater leakage between compartments.

Mine developments occur in a diverse range of hydrologic settings. A mine site could be located in the headwater region of a small upland catchment, in a small contributing watershed of several square kilometers, or in a downslope area within a much larger surface water catchment of say, several hundred square kilometers. Wetlands may be a dominant feature in a basin and have a close relationship to the groundwater flow system. Groundwater divides may not coincide with surface water divides established by the surface topography. There are a number of instances where an open pit or underground mine is located in one watershed and the tailings storage facility is located in an adjacent catchment, contributing flow to different stream systems. There are even examples of mines located at the continental divide in South America where, depending upon how the mine facilities are positioned, some of the mine seepage discharges to local streams that report ultimately to the Atlantic Ocean, with other waters reaching the Pacific Ocean.

2.2 Types of Mining Wastes

Operational challenges in managing groundwater and mitigation of environmental impacts associated with water release vary with the type of mine waste under consideration. Assessment of the potential environmental impact associated with water infiltration through mine waste requires consideration of physical and geochemical processes, including biogeochemistry. The nature of these processes will vary with the type of mine waste. There are three broad classes of mine waste; mill tailings, waste rock, and spent heap leach.

Mill Tailings

Tailings are produced when rock containing economic grades of ore-forming minerals is crushed to facilitate extraction of those minerals in a mill. The tailings are a granular waste material that is a composite of clay, silt and sand-sized particles (Figure 2). The grain size distribution of the tailings that are produced is a function of the rock type hosting the ore and processing requirements in the mill to optimize ore recovery. Some tailings are sandy material (e.g., 80% fine sands and 20% silt and clay size particles), while other tailings can be very fine (e.g., 90% silt and clay-sized particles and only 10% sand-sized particles).

Figure 2 - A deposit of mill tailings in an active deposition area, showing a zone of fine sands in the left of the photo, and a zone of silt-sized tailings to the right. The ribbons in the deposit with a metallic luster are where sulfide minerals were concentrated during sediment transport. Scale of view is approximately 2 meters laterally.

Waste Rock

Waste rock is the rock mass that must be removed to access ore zones of economic value. It is either barren of the mineral resource being mined or contains concentrations of ore that are not cost-effective to recover and process. Explosives are used to break down the bedrock and then it is loaded onto trucks or carried by conveyor for disposal in nearby waste rock stockpiles. Waste rock produced during open pit mining can have an extreme range in particle size (Figure 3), from clay-size particles to large boulders up to a meter or more in diameter. The particle size distribution of waste rock is highly variable from site to site, and even within a single waste rock facility. A waste rock pile with 70% boulder and gravel-sized particles by weight, 20% sand-sized material, and 10% silt and clay-sized material would be characterized as a coarse stockpile, while if there were on the order of 40% boulder and gravel-sized particles, 30% sand-sized material and 30% fines, the stockpile would be characterized as a finer-grained stockpile. In addition to overall variability in particle size distribution, the process of placing waste rock in a stockpile results in additional segregation of the particle sizes during dumping and/or compaction of the waste rock creating finer textured layers as a result of truck traffic.

Waste rock produced during underground mining has a similar-sized fine fraction of particles to that from open pit mining, but is commonly absent the large boulder fraction. Soft sediments (e.g., saprolite, glacial deposits) removed to access the ore body may also be in incorporated within a waste rock stockpile. General guidance suggests that waste rock piles where more than 20% of the material by weight passes a 2 mm sieve (medium-grained sand and finer) will behave hydrologically as a "soil-like" pile, while if less than 20% of the material has a smaller particle diameter than 2 mm, the structure will respond as a "rock-like" pile (Smith and Beckie, 2003). 'Soil-like' in this context refers to the ability of the waste rock to exhibit capillarity effects including the retention and transmission of water under negative pore water pressures and the concomitant dominance of more "piston-like" infiltration of water. 'Rock-like' in this context highlights that the waste rock has limited capacity to store and transmit water under negative pore pressures and this promotes the tendency for flow of water along preferential pathways in the stockpile.

Some mining operations produce waste piles that are predominantly soil-sized materials and it can be misleading to characterize these stockpiles as waste rock. Examples include open pit mines where the ore is recovered from within a thick saprolite soil or at a coal mining operation where the fines produced by coal wash plants are stacked on the ground surface.

Figure 3 - Waste rock from an open pit operation has a wide range in particle size, and significant variability from one location to the next within the stockpile.

Spent Heap leach

In heap leach mining operations, rock is placed in constructed piles on the ground surface in multiple lifts and a chemical solution is repeatedly passed through the heap to dissolve and mobilize ore-forming metals such as copper or gold (Figure 4). The solution transports those metals to the base of the heap where the leach solution is collected for processing and re-circulation. Heap leach operations use either run-of-mine rock or crushed ore. If crushed, the typical particle size ranges from fine to coarse gravel size material, and particles are angular in shape. Depending upon the leach solution that is used and the mineralogy of the rock, there can be significant chemical degradation of the rock over time, resulting in progressive increase in finer-grained particles over time. Heap leach piles range from tens to a few hundred of meters in height, and are typically built on top of a low-permeability liner to maximize recovery of the metal-carrying leach solution at the base of the heap and to reduce the risk of leach solutions entering the underlying groundwater system.

Figure 4 - A heap leach pile nearing the end of its operational life. The pile is approximately 100 m in height.

2.3 Management of Mine Wastes

Waste Rock

The majority of the rock extracted in an open pit operation does not contain an economic mineral resource and is placed in waste rock stockpiles (Figure 5). These piles commonly have a large footprint and can be tens to hundreds of meters in height. Waste rock piles at large, open-pit operations may contain up to several billion tons of material. Rain or snowmelt that infiltrates and percolates beyond the near-surface zone of the stockpile continues to move down in an unsaturated flow regime towards the base of the pile. If the foundation has low hydraulic conductivity, then a portion of this water will pond on the pre-mining ground surface and move laterally, emerging at the base of the pile as toe seeps around the perimeter of the stockpile. The movement of this lateral flow component is markedly influenced by the topography of the pre-mining ground surface, and it usually determines the locations of toe seeps. Any water that does not discharge at the pile perimeter acts as a source of recharge to the underlying groundwater system. At some mines a basal drainage network is installed beneath the stockpile to reduce the potential for widespread development of a saturated zone at the base of the stockpile, and to facilitate capture of the contact water. Waste rock that contains sulfide minerals such as pyrite (FeS_2) has the potential to release acidic drainage with elevated metal concentrations for many decades after mine closure. In some cases, the outflow may have a neutral pH but carry contaminants of potential concern (neutral mine drainage), or have high salinity due to leaching of soluble salts if present within the waste rock. An assessment of this potential, and a means for mitigation if required, are issues of detailed evaluation in modern mining practice.

Figure 5 - Example of a multi-lift waste rock stockpile.

Mill tailings

Large volumes of mill tailings can be generated over the operational life of a mine. Large mines produce hundreds of millions of tons of tailings that need to be safely contained during operations and following closure of the facility. A mill processing 100,000 tons of ore per day, over a twenty-year period, will produce in excess of 700 M tons of tailings requiring secure disposal. Tailings are commonly discharged into a storage facility as a slurry that segregates to form a settled tailings deposit and a supernatant water pool. A dam, or set of dams, is built to retain both the tailings and the slurry transport water. The elevation of the supernatant pond rises through time as the volume of tailings placed in the facility increases. Over time, the tailings deposit forms an exposed beach near the slurry discharge points (Figure 6). The height of the tailings dam is raised on a regular interval to ensure there is sufficient capacity to hold the volume of tailings to be produced according to the mine plan, in addition to maintaining freeboard requirements to contain the design flood event associated with large rainfall events.

Figure 6 - Photograph showing the interior of a tailings storage facility with an older beach deposit where tailings release is not active (dry sandy area), a current beach deposit forming beyond the slurry discharge points located to the right, and the supernatant pond to the left in this tailings storage facility.

A comprehensive review of tailings management technologies, including numerous case histories, is available in "Study of Tailings Management Strategies", MEND Report 2.50.1, by Klohn Crippen Berger, October 2017. Figure 7 provides a schematic representation of the principal water transfers at a conventional slurry tailings storage facility. This schematic illustrates a tailings facility incorporating a downstream seepage recovery pond, from which water can be pumped back to the tailings facility for re-use. Water enters the tailings facility as direct precipitation, surface runoff from the upstream catchment, with the tailings slurry, and as seepage reclaim. Mine operators remove varying amounts of water from the tailings before it is piped to the tailings management facility, with thickened tailings (or paste) having lower water contents than slurry tailings. Water recovered at a thickener at the mill can be re-circulated to the mill directly, reducing the volume of water lost to evaporation in the tailings pond.

Water leaves the facility via evaporation from open water, evaporation from the tailings beach, seepage through the foundation, and as release of surplus water to the surrounding environment. Evaporation rates differ between an open pond, a wetted beach with active tailings deposition and a dry beach, with the dry beach having the lowest rate of evaporative losses. Water is also retained in the pore space of the settled tailings deposit. Not shown in the diagram is the seepage that reports to the internal drains in the dam that is returned to the tailings pond or released to the environment if not needed for other purposes (with treatment if required). In addition, as the deposited tailings consolidate over time, pore water is expelled into the pond. This diagram highlights the difference between pond seepage that is captured near the toe of the tailings dam at a seepage recovery pond and the unrecovered seepage that bypasses the collection system. Assessment of these seepage pathways is a central topic in environmental permit evaluations. Seepage recovery systems are discussed in Section 7.

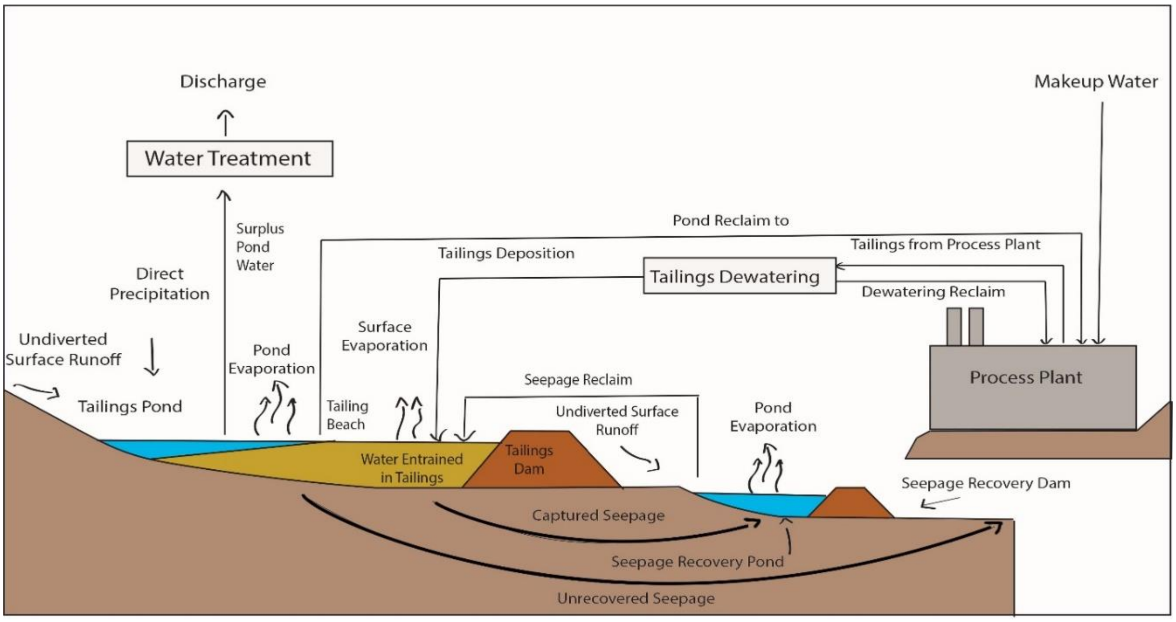

Figure 7 - Schematic diagram of the water transfers at a conventional slurry tailings facility (modified from MEND Report 2.50.1)

An assessment of the rates of process water seepage from a tailings facility requires prediction of both the flow though the dam and its underlying foundation, and an evaluation of the potential for subsurface flow to adjacent valleys through the ridges that form the flanks of the basin in which the facility is located. In areas with little topographic relief, tailings dams are typically constructed as a ring dyke, leading to a radial seepage pattern outward from the facility.

If the ore processed in the mill contains sulfide minerals (pyrite being an example), those minerals will be present in the tailings that are produced unless sulfide minerals are segregated from the bulk of the tailings in a separate mill circuit. Tailings that contain sulfide minerals that are then exposed to atmospheric oxygen on a tailings beach are capable of producing acidic water with elevated dissolved metal concentrations. This process, known as acid mine drainage, requires appropriate controls be in place to minimize contaminant release. Tailings with sulfide minerals but contained under water-saturated conditions are not prone to acid generation because the oxidation of sulfide minerals requires oxygen at concentrations higher than those present in the pore water of saturated tailings. However, dissolution reactions controlled by the redox setting remain a potential concern for impairment of the quality of the water in the facility. Some tailings are geochemically benign with the principal seepage issue then being the chemical characteristics of the process water that is discharged into the pond with the tailings. This is the case at some gold mines where cyanide is used to recover gold from the ore. The concentration of cyanide in the water discharged in the tailings stream could be the principal solute of concern. Management of seepage pathways and mitigation of water quality impacts requires a sound understanding of the groundwater flow system in the watershed hosting the tailings facility.

In some underground mining operations, a proportion of the tailings produced are partially dewatered, amended with binders to increase their strength, and returned underground for disposal in the mine workings. Waste rock is sometimes also placed in abandoned mine workings. This practice introduces a hydrogeologic issue if dissolved metals and other contaminants of potential concern (e.g., nitrates from blast residues) are released from backfill materials and then migrate offsite in the groundwater flow system. These risks are commonly examined with the aid of a groundwater flow model and a coupled solute transport model, developed for the groundwater flow system envisioned to occur following mine closure. This approach allows for prediction of solute concentrations at downstream compliance points.

Spent Heap Leach

Contaminants can be released to groundwater from heap leach facilities should the leach solution migrate through defects in the underlying liner system and bypass any seepage collection system. Modern heap leach facilities often incorporate leak detection systems. Closure of a spent heap leach facility requires consideration of the drain-down time following cessation of the leaching cycle and completion of any fresh water rinsing cycles. In the long-term, meteoric waters that percolate through the spent heap leach can transport chemical contaminants from the heap leach residue to adjacent surface water and groundwater. This risk forms a key element in the evaluation of closure plans at heap leach facilities.

Filtered Tailings

Several failures of large tailings dams in recent years have resulted in the loss of life and the release of large volumes of tailings to the environment. As a result, there has been increasing interest in the option of placing tailings in stockpiles of filtered (partially dewatered) tailings that have a sufficiently low water content to ensure that the tailings will not liquefy and flow. While this approach has a number of geotechnical advantages in comparison to deposition as slurry in a tailings pond, a stockpile of filtered tailings, depending upon the mineralogy of the tailings, can be a potential source of groundwater contamination that requires an assessment of the hydrogeologic regime within and in the vicinity of the filtered tailings stack to assess possible impacts.

2.4 Potential Contaminants of Concern

Potential contaminants of concern in mining and mineral processing include: (i) solutes used in metal recovery such as cyanide at some gold mines; (ii) blasting residuals such as nitrate that enter the mine water circuit or are incorporated as soluble residues within a waste rock facility; (iii) compounds such as arsenic and selenium that can be leached and mobilized from tailings and waste rock under near-neutral pH conditions; (iv) metals released from tailings and waste rock if these wastes contain sulfide minerals that oxidize without subsequent neutralization, producing acidic drainage; and (v) high-salinity pore water released from some types of ores and concentrated during water - recycling through the mill. The geochemical characteristics of impacted mine contact waters can generally be described as acid mine drainage, non-saline neutral mine drainage, and saline neutral mine drainage. Acid mine drainage can occur as a result of the oxidation of the mineral pyrite, if it is present within the mine waste. If there is insufficient chemical buffering capacity within the waste then the effluent becomes acidic which in turns enhances metal mobility resulting in the release of metals such as zinc, copper and nickel. Pyrite oxidation can also occur in the case of non-saline drainage; however, in this case there is sufficient buffering capacity to keep the effluent non-acidic. However, the oxidation process results in elevated concentrations of sulphate, sometimes with concentrations up to several thousand mg/L. In some jurisdictions sulphate is regulated as a potential contaminant of concern in surface water.

Other potential water quality concerns rise in specific geologic settings. For example, in karstic terrain, it is possible that while there may be no specific solute with concentrations in excess of environmental standards, because of the very open nature of the flow pathways in karst, the possibility exists for exceedance of limits on the total suspended solids at emergence points in groundwater springs. In oil sands mining, there is a focus on the persistence in seepage water of naturally-occurring organic compounds such as naphthenic acids present in the supernatant pond water.

Not all mining wastes pose a risk of significant impact to groundwater resources. For example, at some iron ore mines where itabirite (metamorphosed iron-oxide bearing rock) is processed, the mine waste is not chemically reactive and seepage water has essentially the same chemical composition as the background water quality in the watershed.

3 Key Hydrogeological Concepts Applied in Mining Operations

This section provides an overview of key hydrogeological concepts that arise in mineral resource development projects. Application of these concepts in site investigations, dewatering and depressurization of mine workings, seepage assessment and management, and mine closure follow in subsequent sections. Also included is a discussion of representative hydraulic properties of the various types of mine waste materials. Throughout these discussions, it is important to keep in mind the accuracy with which hydrogeological data and calculations should be represented. Mining environments often have complex geology and uncertain spatial and temporal variations in conditions such as recharge rates. There are practical limits on the number of boreholes that can be used to define subsurface conditions at each stage of a site investigation. Field-scale hydraulic conductivity estimates never have accuracy to the second decimal place; some argue using even a single decimal place is not appropriate. This reality should be reflected in the number of digits used when reporting calculations of water flows and solutes fluxes.

3.1 Mine Dewatering and Control of Water Pressures in Mine Workings

The hydrogeologic setting in which a mine is located is a key feature in both the development of a mine plan and its successful execution. There are recent examples in Canada where difficulties in controlling groundwater inflows to underground workings led to a multi-year delay in the startup of operations at one mine and in another case excessive inflow to the underground workings was a key contributing factor in early closure of a mine. High inflows hinder access to working faces and elevated pore pressures decrease rock mass stability. Both of these factors are potential safety issues that require control.

Groundwater control at an open pit mine has two principal objectives: (i) to ensure pore pressures behind the pit walls and beneath the pit floor are sufficiently low so that the pore pressures do not induce rock mass instability, and (ii) to ensure trafficability of heavy equipment on the pit floor is not compromised by either water-saturated sediments or standing water. Wet ground conditions have negative impacts on blasting efficiencies in the open pit. There can also be a risk of flooding of the pit due to an unanticipated inflow of water if a high hydraulic conductivity feature connected to a surface water body or an aquifer is intersected on the pit wall or floor. Figure 8 illustrates an open pit mining operation with effective seepage control, evidenced by the dry condition of the pit floor and walls, with only minor seepage apparent on the walls of the pit and at the pit floor.

Figure 8 - Example of an open pit with effective groundwater control. The pit floor is far below the elevation of the pre-development groundwater table.

With regard to rock mass stability, there are two concerns. First, elevated pore pressures reduce the shear strength of the rock mass. A dewatering system is designed so that for a chosen slope of the pit walls, an acceptable factor of safety against failure of the walls is maintained. Second, uplift pressures immediately beneath the pit floor can be similar in magnitude to the downward force exerted by the rock mass. Uplift pressures are a particular concern when a confined aquifer with elevated hydraulic head is located beneath the pit floor. If the rock ruptures due to the unbalanced uplift forces and the underlying aquifer has relatively high hydraulic conductivity, this could create a pathway for a rapid and substantial inflow of groundwater onto the pit floor. High seepage gradients can also lead to permeability enhancement in bedrock if a higher groundwater velocity mobilizes fine-grained materials infilling fractures.

In geotechnical stability assessments, it is important to recognize the difference between the effects of pressure propagation along a higher hydraulic conductivity zone and a volumetric flow effect where the stratigraphy and flow regime also provides a pathway for higher fluid fluxes. A detrimental pore pressure propagation effect on stability in the foundation of a tailings dam, for example, can occur in the absence of significant fluid flow.

Many of the concepts used in the design of a well field for water supply are applicable in the design of dewatering or depressurization systems at mines even though the geometry of internal boundary conditions imposed by an open pit or underground adit differs from those adopted in well field design for evaluating water supply from an aquifer. The time required to achieve a dewatering/depressurization target is an important design consideration, so these analyses are based on models considering transient groundwater flow. Singh and Atkins (1985) provide a compilation of analytical solutions useful in the estimation of groundwater inflows to mine workings.

3.2 Hydrodynamic Containment

When siting a tailings storage facility and in the assessment of potential seepage pathways beyond the proposed facility, the concept of hydrodynamic containment is important. If the elevation of the water table along the lateral flanks of the valley in which a tailings facility is located is maintained by local groundwater recharge at an elevation well above the ultimate pond level in the tailings facility, there will be an inward hydraulic gradient on the valley flank toward the pond that precludes supernatant water from flowing into the adjacent valleys by passing beneath the bounding ridge line. This situation is referred to as natural hydrodynamic containment. For example, Figure 9 shows a valley that at one time was considered as a potential site for a tailings storage facility. As long as the elevation of the tailings pond was well below the ridgelines in this valley, the only direction of seepage outflow would have been down the valley, at the location of the containment dam. Seepage control measures would need to be implemented only at the foundation and abutments of the proposed dam. During site investigations, water levels measured in piezometers installed along or near the ridgelines are key components in a field program to map the elevation of the water table and define its seasonal variation. If the ultimate pond level in the tailings storage facility is planned to be above the seasonal low elevation of the water table in the bounding ridges, as the pond levels rises to that elevation, conditions are established where natural hydrodynamic containment no longer exists and outward flow through the bounding lateral ridge becomes possible.

Figure 9 - Illustration of natural hydrodynamic containment that would be provided by an elevated water table beneath the lateral ridgelines of this valley.

In flat terrain, the absence of topographic relief precludes reliance on natural hydrodynamic containment for seepage control. The hydraulic gradient is everywhere outwards from the tailings facility. When slurry tailings are placed within a ring dyke, infiltration of water through the base of the facility contributes to the development of a water table mound superimposed on the regional water table profile. The requirements for and design of potential seepage control measures need to be evaluated along the full perimeter of the tailings storage facility. The control measures must be considered in conjunction with the interplay of the induced water table mound and the local and regional scale groundwater flow systems.

3.3 Representative Hydraulic Properties of Mine Wastes

Introduction

Methods for determining the hydraulic properties of mine waste materials are the same as those used in other hydrogeologic studies. Both laboratory apparatus and field techniques have a role to play in measurement of the properties of tailings and waste rock. Tailings are amenable to laboratory-scale measurements due to their grain-size characteristics, however it is important to account for the effect of the applied load as tailings undergo consolidation with on-going deposition in an active tailings storage facility. Flexible wall permeameters with the capability to vary the confining pressure are well suited for this purpose. Mill tailings deposited as a slurry have an anisotropic permeability due to depositional processes, this needs to be considered when undertaking permeameter measurements. In specialized circumstances, standpipe piezometers installed in a tailings beach have been used to estimate in-situ hydraulic conductivity using falling or rising head tests. Although not common in practice, a network of extraction wells can be used to dewater a sandy tailings deposit retained behind a tailings dam to reduce the flowability of the tailings. Efficient design of such a system requires a convention pumping test program be undertaken with one or more pumping wells and nearby monitoring wells to characterize the hydraulic response of the tailings deposit.

Approaches to reliable characterization of the hydraulic properties of waste rock piles are more challenging to implement because of the wide range in grain sizes, the interaction between matrix materials and open voids, preferential flow pathways, and the partially-saturated condition of waste rock piles. Further discussion of approaches to parameter measurement follows in subsections below.

Tailings disposal facilities

The water supply required for the first few months of ore processing is usually accumulated in the tailings storage facility prior to start-up of operations. When tailings slurry (Figure 10) is discharged into the facility, the slurry segregates with coarser-sized particles settling out in closer proximity to the discharge (spigot) point with finer-grained particles transported toward the interior of the facility. Coarser particles that settle near the spigot points eventually develop a tailings beach that stands above the water line of the supernatant pond. The finer-grained tailings deposited underwater are called slimes and consist predominantly of silt and clay-sized particles. Depending on processes that influence sediment deposition and winnowing on the beach, a variable proportion of the finer particles can be trapped above the water line and modify the hydraulic properties of the beach deposit. These deposition processes lead to the tailings forming a heterogenous deposit within the facility, which is commonly also anisotropic, with a higher horizontal than vertical hydraulic conductivity.

Figure 10 - Example of spigot discharge of tailings slurry from the embankment of a tailings storage facility.

Over time, self-weight consolidation of the tailings expels pore water from the deposit and the density of the settled tailings increases. Tailings buried at greater depths have a reduced porosity and lower hydraulic conductivity than the more recently deposited tailings. As a consequence of these processes, a general picture emerges of a tailings deposit with higher hydraulic conductivity near the spigot points, lower hydraulic conductivity in more distal locations from the spigot locations, and a decrease in hydraulic conductivity with depth. Recognition of this overall structure is important when assessing the volume of process water that might leave the facility as unrecovered seepage and enter the surrounding watershed.

At mines with a significant fraction of fine to medium-grained sand particles in the tailings, a beach deposit might have a horizontal hydraulic conductivity as high as 10^{-5} m/s. In more common circumstances, the tailings grid at the mill is finer and a higher proportion of finer particles are entrained in the beach, and a typical hydraulic conductivity is 10^{-8} to 10^{-6} m/s. In the area of the TSF where slimes are deposited, hydraulic conductivity is usually in the range from 10^{-9} to 10^{-8} m/s. The numerical values reported here characterize near-surface conditions. Vertical hydraulic conductivity values are usually assumed to be 5 to 20 times smaller than horizontal hydraulic conductivity, although higher values of the anisotropic ratio can occur. At mines where a very fine grind is required to extract the target minerals in the mill, the entire tailings facility might contain slimes of very low hydraulic conductivity (10^{-10} m/s). Representative seepage rates for a tailings storage facility are discussed in Section 6.

With consolidation, the porosity of a tailings deposit decreases through time as excess pore pressures are dissipated and settlement of the tailings progresses. In the literature, it is common to find the void volume of a tailings deposit expressed in terms of void ratio (e), defined as the ratio of the volume of voids to the volume of solids in a unit volume. The relationship between void ratio and porosity (θ) is $\theta = e/(1+e)$. The void ratio varies with the grain size distribution of the tailings. Therefore, a profile of void ratio versus depth will differ with location inside a tailings facility, in addition to a dependence on the time since deposition. The void ratio of tailings beach deposits is commonly observed in a range from 0.6 to 1.0 (corresponding to a porosity of 38 to 50%), while the finer tailings deposited underwater form deposits with a void ratio commonly observed in the range from 1.1 - 1.2 near surface (porosity of 52 - 55%) to around 0.8 - 0.9 at greater depths (porosity of 45 - 47%).

Waste rock stockpiles

From a hydrogeological perspective, waste rock stockpiles are more complex structures than tailings deposits. The macro-scale properties of a stockpile depend upon: (i) the relative fractions of finer material and cobble/boulder-sized rocks, and (ii) the particle size distribution within the finer size fraction. Stockpiles are built either from the bottom up as a series of thin lifts (with each lift 5 to 10 m in height) or as stockpiles of greater lift height, built by pushing the waste rock down the angle-of-repose slope that forms the perimeter of an advancing dump. In this latter case, individual lifts might be 20 - 50 m in height, and sometimes much higher than that in mountainous terrain. A key factor in both situations, but especially in the second method, is the segregation of particles that occurs during construction, with boulders accumulating toward the bottom of the stockpile and the finer sand and silt-sized particles tending to accumulate closer to the top of the lift (Figure 11). This construction method also imparts a structure to the waste stockpile, with layers forming parallel to the tip face of the stockpile that influence the spatial variation in hydraulic conductivity within the stockpile.

Figure 11 - A 15 m high waste rock test pile built by end dumping, illustrating a broad range in particle size and particle segregation on the tip face.

Over the past 15 years, a number of experimental test piles 5 to 15 m high have been instrumented to better understand physical controls on infiltration through waste rock and the geochemical controls influencing mineral weathering rates and solute release. Summary papers describing these multi-year experiments provide details on test pile construction, monitoring techniques, and interpretations of the data that were collected. These test piles have been constructed in a range of climatic settings, including the Diavik mine in northern Canada (Smith et al., 2013; Neuner et al., 2013; Bailey et al., 2016), Cluff Lake mine in northern Saskatchewan Canada (Nichol et al., 2005), Antamina mine in Peru (Vriens et al., 2019), and Grasberg mine in Indonesia (Andrina et al., 2012).

Three fundamental characteristics of waste rock stockpiles determine the manner in which water moves through these structures.

First, stockpiles have water contents less than saturation with both gravity and capillary suction exerting a control on water flow through the finer-grained materials in the stockpile. A saturated zone can form at the base of the stockpile if the original ground surface has a low hydraulic conductivity that impedes the flow moving downward into native ground. The lateral distribution and pattern of groundwater flow in any basal saturated zone reflects the influence of the original ground surface topography, with flow expected to be channeled toward and along the low points on the ground surface. This process typically controls the locations around the perimeter of the stockpile where toe seeps emerge (Figure 12). Within the stockpile, localized perched zones can also develop above low-permeability impeding layers, such as old traffic surfaces incorporated within the stockpile.

Figure 12 - Toe seepage emerging at the base of a waste rock pile.

Second, waste rock stockpiles are commonly constructed with water contents less than their residual saturation values (field capacity) upon placement in the pile. Therefore, there is a wetting up period following construction in which the initial infiltration component percolating through the pile is taken into storage before the wetting front advances farther into the pile. This process can be prolonged as each lift placed on the stockpile incorporates new material below its residual water content. It can take many years or even decades for the "first flush" of pore water to appear at the base of a large stockpile (excluding the much thinner perimeter zones of the stockpile).

Third, because of the broad range in particle size of waste rock, and particle segregation that occurs during pile construction, flow is often conceptualize as having components of both matrix flow through pathways formed by the finer grain-size fractions and preferential flow occurring through macropores and larger open void spaces between boulders. Figure 13 is a photograph of an excavation in a waste rock pile; the structure observed is characteristic of a matrix dominant system, but there are also a few zones where open void space is retained. Field monitoring programs suggest that for "soil-like piles" the majority of the infiltration passes through matrix materials with the preferential flow component activated only during periods of higher infiltration on the surface of the stockpile. This response has led researchers to develop mathematical models for infiltration through waste rock stockpiles using dual porosity type models of various degrees of sophistication; with domains representing the granular matrix, preferential flow paths, and even stagnant zones not part of the active flow regime.

Figure 13 - Excavation in a waste rock stockpile. Vertical face approximately 3 m in height. In this region of the stockpile, it is anticipated matrix flow would be dominant process, but the photo also shows in the upper center a region of open voids not infilled with finer grained materials where the saturated hydraulic conductivity is likely to be much greater.

In a relatively dry climate with low infiltration rates, the majority of the rainfall and snowmelt that infiltrates the pile moves primarily through granular matrix materials. Due to capillary effects, the matrix has a higher hydraulic conductivity at low flux rates than the coarser macropore pathways where water contents are expected to be low. As infiltration rates increase, there is proportionally increased flushing of the coarser fractions of the matrix materials. At high surface infiltration rates or when surface ponding occurs on the surface of a stockpile, water can flow more rapidly through preferential pathways that develop in the coarsest materials and perhaps, the open voids. In this circumstance, there are shorter rock-water contact times, less interaction with fine-grained materials forming the matrix pathways and the outflow at the base of the stockpile will typically have lower solute concentrations due to dilution of the matrix flow component with the more rapid flow component. This process introduces challenges in characterizing the degree of spatial variability in flushing rates within a stockpile, as the flushing of the mineral surfaces is dependent upon temporal variations in infiltration rates. A "rock-like" stockpile classified as such on the basis of the particle size distribution curve could still behave from the perspective of water flow as a "soil-like" pile in areas with a dry climate. Infiltration rates might be so low that the water is primarily restricted to pathways through the finer grained fraction that is present in the pile (Amos et al., 2015). If the coarse fraction of the waste rock dominates the structure of the stockpile with non-capillary flow governing the behavior, there can be relatively rapid percolation rates through a stockpile, on the order of meters per day, if ponding on the surface of the pile develops.

There are few comprehensive data sets available to characterize the hydrogeological properties of waste rock stockpiles. Relevant properties include: (i) the porosity of the finer grained matrix materials where capillarity influences water flow; (ii) the bulk porosity of the stockpile, which accounts for both the solids forming the matrix materials and the cobbles and boulders; (iii) the water content distribution in the matrix materials of the stockpile; (iv) the saturated hydraulic conductivity; and (v) the soil water characteristic curves of the matrix materials. Infiltration rate is also a key variable that influences solute loads at the base of the stockpile. Given the wide range in particle size distribution of waste rock at different mine sites and the multiple ways in which a stockpile is built, representative values for the site-specific hydraulic properties of stockpiles are challenging to define.

The available data indicate matrix porosity values are generally similar to values for a medium to coarse-grained sand, in the range from 0.25 to 0.35. Bulk porosity values of stockpiles are lower than this range due to the presence of large boulders that do not contribute appreciably to porosity. Field measurements suggest that in most climatic regimes, at depths below the zone of evaporative influence, matrix saturation values commonly fall in the range of 60 - 80% saturation. Water content values are anticipated to be lower where the stockpile has sufficient permeability for advective air circulation within the stockpile, as this provides a means of removing water by an evaporative transfer process. Much lower water contents are expected in "rock-like" piles where there is a smaller matrix component to retain water by capillarity.

Matrix hydraulic conductivity values at saturation often fall in the range from 10^{-6} to 10^{-5} m/s, reflecting the common size of matrix materials in a waste rock stockpile. Soil water characteristic curves for the matrix fraction can be measured in the lab using a Tempe cell, but it is more common in practice that the grain-size distribution curve of the material is determined and empirical equations adopted to estimate a soil water - matrix suction curve. The bulk hydraulic conductivity of a stockpile, where saturated, is several orders of magnitude greater than that of the matrix materials. Pumping tests in re-saturated waste rock backfilled in open pits indicate hydraulic conductivity estimates in the range from 10^{-5} to 10^{-1} m/s, with values at the higher end of the range corresponding to waste rock materials with a low fines content.

Studies of air circulation within waste rock stockpiles also provide insight to the large-scale permeability of a waste rock stockpile, either by direct estimation of air permeability from air injection, or by modeling air circulation in the stockpile and using model calibration to derive a permeability estimate. Air circulation is an important attribute when it provides oxygen re-supply to sustain sulfide mineral oxidation rates in the interior of the stockpile. Because moisture is held in the finer matrix materials, air permeability measurements generally reflect the conductivity of the open, interconnected voids, yielding higher permeability values than the finer-grained matrix material. Air permeability values for stockpiles fall within the general range of 10^{-12} to 10^{-8} m^2. For comparison, these air permeability values would indicate, under saturated conditions, bulk hydraulic conductivity values for water flow of 10^{-5} to 10^{-1} m/s. A number of spatially distributed air permeability tests in the waste rock test pile shown in Figure 11 yielded an average value of air permeability of 1.4 x 10^{-9} m^2 (Amos et al., 2009). Under saturated conditions, this would correspond to a hydraulic conductivity for water of about 1 x 10^{-2} m/s. This value was consistent with estimates of saturated hydraulic conductivity derived using constant head tests carried out in field permeameters two meters in height.

Tracer tests have been used to characterize velocities of water moving downward in a waste rock stockpile after initial wetting. Where the flow is restricted to matrix materials, water velocities of 1 - 10 cm/d have been inferred, although the experimental database is limited in scope. These estimates apply in areas of moderate precipitation, not arid regions. During and following high-intensity rainfall events, where preferential flow through macropore pathways can be initiated in soil-like piles, water velocities up to 1 to 2 m/d have been inferred from tracer tests. Barbour and others (2016) demonstrate the use of stable isotopes to estimate rates of water movement in a waste rock pile at a coal mine in western Canada.

3.4 Contaminant loading to the receiving environment

A key quantity required in the assessment of potential impacts from water infiltrating through mine wastes on surface water quality is an estimate of the solute load when groundwater discharges into a stream or other water body. The solute load L (mg/d) is the mass of solute that enters the water body over a specified time period. The mass load is calculated by multiplying solute concentration by the volumetric groundwater discharge rate, as shown in Equation 1.

$$L = C\,Q \tag{1}$$

where:

C = solute concentration (mg/m^3)

Q = groundwater discharge volume (m^3/d)

Estimates of current loads can be calculated with field measurements, while future loads are often predicted on the basis of a groundwater flow model and a solute transport model. Given an estimate of the solute load delivered to the stream bed, and a mixing model for solutes once they enter the stream, it is possible to estimate the concentration of the contaminant of concern in the stream as it exits a defined mixing zone. This estimate can then be compared, for example, to the aquatic water standard on solute concentration or the water quality standard for use of surface water as a water supply for irrigation.

Figure 14 illustrates this concept, where a set of hydraulic head measurements in piezometers installed in the valley bottom beyond the toe of a waste rock dump have been contoured to provide input to a Darcy law calculation of distributed groundwater discharge along the stream course. The waste rock pile was releasing acidic drainage due to sulfide mineral oxidation. Concentration data from monitoring wells have been contoured to provide an estimate of a dissolved zinc plume at the stream bank. The loading calculation requires an estimate of the hydraulic conductivity of the valley-fill sand and gravels. Values calculated from response tests in individual piezometers, and constant rate pumping tests, ranged over several orders of magnitude. For the purpose of this loading calculation a value of 6×10^{-4} m/s was chosen. Using these data, the estimated zinc loading to the stream in September was 80 kg/d~~,~~ while in November the loading increased to an estimated 400 kg/d. These data demonstrate significant temporal variability in plume geometry and solute loads in this high-permeability system. The data for September reflects conditions at the end of the dry season; the data for November reflects conditions after the onset of winter rains and first flushing of the stockpile since the end of the previous wet season. It is important to acknowledge the uncertainty associated with these estimates arising from the uncertainties in defining the groundwater flow volumes using a contour map of water table elevation, the plume maps derived from a limited number of observation wells, and the challenge in estimating a representative value for the hydraulic conductivity of the sand and gravel deposit.

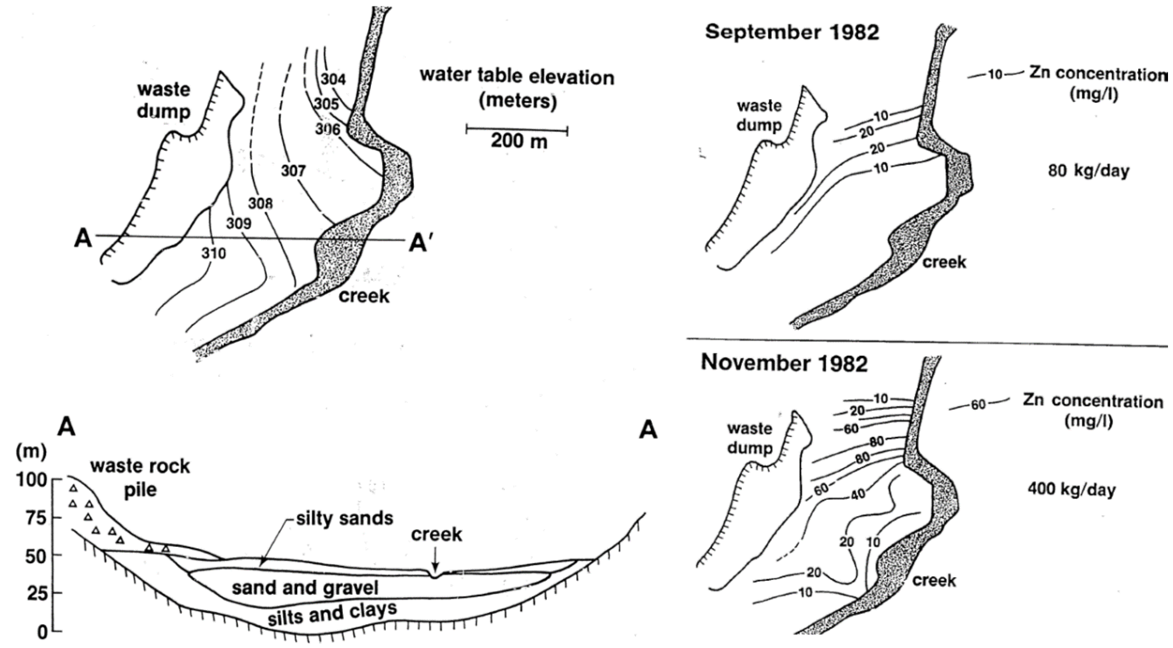

Figure 14 - Example illustrating the estimation of zinc loading from the groundwater system to a creek as it passes the toe of a waste rock facility yielding acidic drainage to the sand and gravel unit.

Contaminant loads to streams are sometimes estimated using synoptic stream sampling (e.g., Byrne et al., 2017). In this approach, estimates of groundwater flow volumes entering the stream are computed by making measurements of stream water velocities and cross-sectional flow area at close intervals along the stream course. At the same time a number of water samples are collected along the stream to record contaminant concentrations. Inflows of surface water along the stream segment being analyzed must also be measured to complete the mass balance calculations to estimate solute loads from contaminant sources distributed along a stream.

3.5 Groundwater as a component of the mine site water balance

Most mining operations rely upon a site-wide water balance to guide their water management strategy. The water balance is usually constructed in the format of a spreadsheet model that quantifies the water transfers illustrated schematically in Figure 7. The model tracks water intake to the operation from precipitation, groundwater withdrawals during pit dewatering and any make-up water for the mill obtained from external water sources. Outflows of water from the site include water consumption, water retained in the tailings pore space, and water releases. Groundwater withdrawals from an open pit or from underground workings are in some instances released directly to the environment if no water quality constraints preclude this option and this water is not required for ore processing at the mill. If there are limitations on the release of the groundwater due to water quality constraints, groundwater withdrawals might be transferred to the tailings storage facility for temporary storage before treatment and release. The inflow and outflow terms balance the change in the volume of water retained in storage. Water balance models can also be run in a dynamic mode, for example, tracking changes in storage on a monthly basis. Commercial software is in common use for this purpose.

It is common to develop a water balance model specific to a tailings storage facility as an aid in planning the schedule for dam raises, to ensure a water supply sufficient to support continuous operation of the mine during dry periods, and to routinely update projections of the required containment volume to safely store the design flood for the tailings impoundment. Groundwater outflows from a tailings facility are a relatively small but nonetheless important component of the water balance, especially in semi-arid to arid climates. Closing the water balance (effectively a check that mass conservation is achieved) provides some assurance the facility is performing according to the design base assumed for the hydrologic system.

The Minerals Council of Australia (2014) has published a helpful accounting tool that guides the development of a mine site water balance. It incorporates groundwater as one of the key elements to be considered in tracking water surpluses and deficits.

3.6 Use of Groundwater Simulation Models in Mining Practice

Groundwater simulation models play an important role in mine design and in the assessment of potential impacts of mine development on the surrounding environment. The most frequent applications at a mine site are in the evaluation of depressurization requirements for an open pit, prediction of underground dewatering requirements and mine inflows, and in seepage assessments at a tailings storage facility. Groundwater models are also applied in geotechnical stability assessments as pore pressures influence of the shear strength of the materials within embankments and in cut slopes. In some jurisdictions, it has become common practice to require the development of a numerical model of the groundwater flow system as part of the process of obtaining a license to construct and operate a mine. Figure 15 illustrates a three-dimensional groundwater model developed to assess groundwater flow paths for a proposed tailings storage facility. Models constructed with more than one million nodes are becoming common.

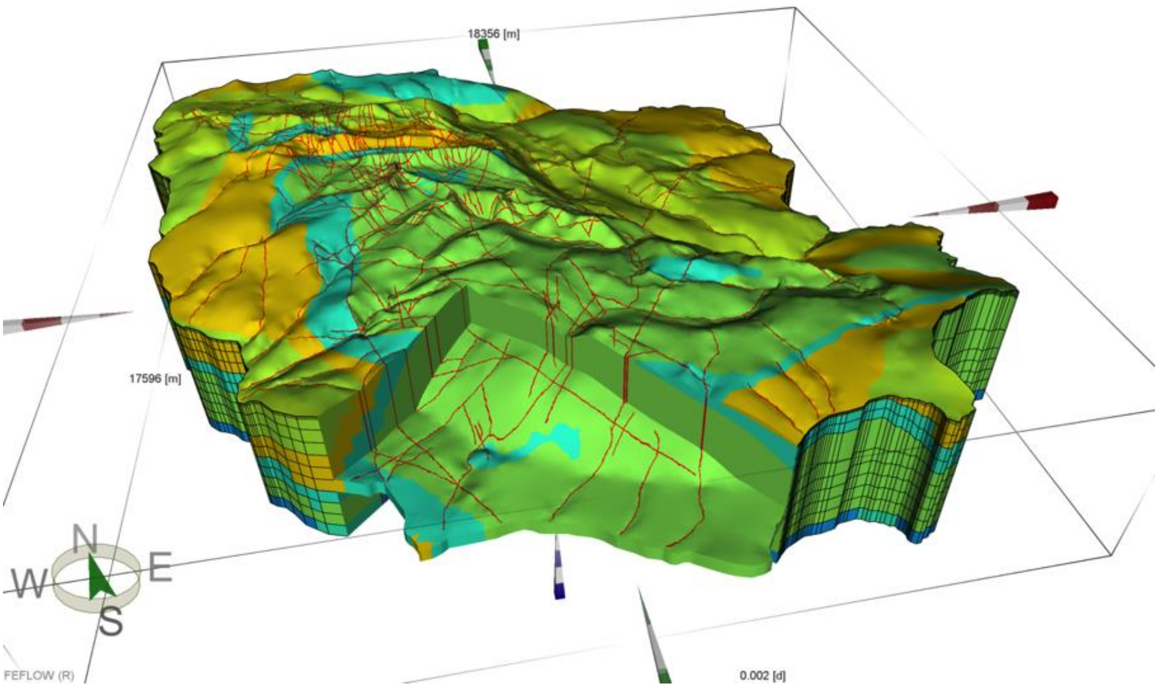

Figure 15 - Example of a finite element grid developed to assess pre-development groundwater flow paths in the vicinity of a proposed tailings storage facility. The tailings facility would be located in the central region of this model domain. The different colors map distinct hydrostratigraphic units identified in the conceptual model of the site. The red traces are inferred faults in the area.

A groundwater model generally serves two functions: (i) as a tool to aid in the interpretation of field data and to refine conceptual understanding of the hydrogeological system and system response to changed conditions associated with mine development; and (ii) a decision support tool to aid in the evaluation of design options. In common with all applications of groundwater simulation models, the issue requiring the greatest attention is the formulation of a sound conceptual model of the hydrostratigraphy and groundwater flow system, which then gets translated into an analytical or numerical simulation model. With sophisticated and user-friendly simulation codes widely available, the tendency in practice is to see reliance on numerical modeling approaches, with simplified analytical solutions oftentimes being applied as first-order checks on the reasonableness of the predictions developed using numerical models. Modeling applications typically focus on the analysis of the groundwater flow system, with particle tracking procedures used to characterize advective transport pathways for mine-contact water (Figure 16). However, it is becoming more frequent to encounter regulatory requirements that solute transport models be applied in the prediction of solute concentrations at prescribed compliance points. These transport models are linked to the groundwater flow model.

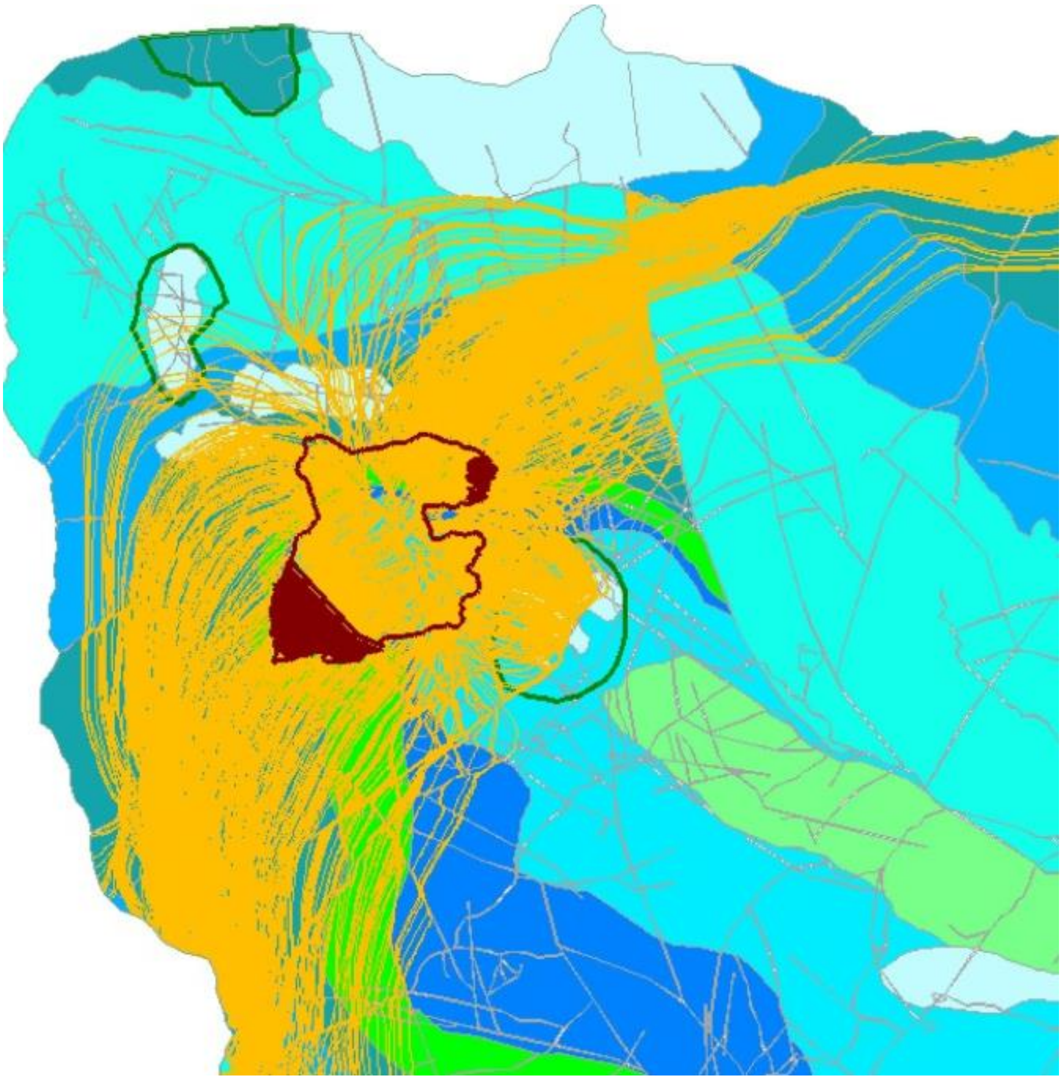

Figure 16 - Example of using particle tracking to characterize groundwater flow pathways (orange traces) from a proposed tailings storage facility (red outline with two containment dams). Particle tracks do not indicate the magnitude of the seepage flux. This figure provides an example of an impoundment, when filled to ultimate capacity, would not have natural hydrodynamic containment around the full perimeter of the facility. Due to the strong influence of geologic structure and compartmentalization on groundwater flow pathways at this site, most of the contact water is predicted to ultimately report to one of two discharge sites.

Simulation models are also used in the design of a management system for a water pool present in flooded underground workings. For example, if the water pool in the mine is contaminated it may be necessary to establish a hydraulic sink using one or more pumping wells to prevent offsite migration. This could be the case if there are near-surface mine wastes that release solutes that are then carried down to the underground workings by groundwater flow. There are numerous sites where the underground workings are used as a water storage facility as part of the mine water supply. Simulation models can aid in identifying an efficient design to operate such a system.

With the widespread adoption of numerical simulation models as an aid in the assessment of mineral resource development projects, several jurisdictions have seen an advantage in formulating practice guidelines to promote sound application of groundwater models. One such example is "Guidelines for Groundwater Modelling to Assess Impacts of Proposed Natural Resource Development Activities", released by the province of British Columbia in Canada in 2012 (Wels et al., 2012). This report provides a comprehensive description of the processes and issues involved in applying numerical groundwater models within the context of mineral resource development. This report includes guidance in conceptual model development, code selection, model setup, model calibration and verification, model prediction, sensitivity and uncertainty assessment, and review. Numerous examples are included illustrating model setup and prediction. A similar-styled document "Australian Groundwater Modeling Guidelines", released in 2012 and intended for a range of applications in addition to mining, is used in the Australian mining industry to establish the expected standard for model applications. Guidance on consideration of uncertainty in hydrogeologic models used for prediction of environmental impacts of mine development and for use of groundwater models in risk assessments can be found in Middlemis and Peters (2018).

4 Hydrogeological Field Investigations at Mine Sites

Field investigations to characterize groundwater conditions at a proposed mine site serve many purposes; studies will be undertaken at several candidate sites for development of a tailings storage facility, at the proposed locations of waste rock stockpiles, in the vicinity of the open pit or underground mine workings, and in the area of the proposed plant site. At the site of a proposed tailings storage facility, hydrogeological studies are usually linked with complementary geotechnical investigations that focus on the definition of the foundation conditions for dam design. Field programs are normally undertaken as phased studies, providing information requirements suited first for conceptual design, and then pre-feasibility study, feasibility design and finally detailed engineering. A similar approach is adopted in the design for a dewatering system at an open pit or in underground workings. An appropriately detailed characterization of the geologic setting is essential in advancing the hydrogeological studies. At each stage of the investigation, decisions on the number and location of boreholes are based on obtaining data required to answer specific questions that underpin the conceptual model of the groundwater flow system, or issues that must be resolved for advancing the design concepts. An inadequate site investigation program can lead to costly re-designs of containment structures, or the requirement in the future to implement perhaps costly mitigation measures.

There is no guidance that defines the number of boreholes that should be installed as part of a site characterization program at each stage of the design process. Each mine site presents a unique geologic setting. For sites with greater geologic complexity, reliable design will require a greater effort to define site conditions at each stage of the site characterization. For large mining projects, it is common that by the time detailed engineering studies are complete, and construction is underway, many tens to several hundred boreholes completed with piezometers will have been installed to meet information requirements.

In comparison to hydrogeologic studies for water supply purposes or at contaminated sites where open standpipe piezometers are common, more extensive use is made in the mining industry of vibrating wire piezometers (VWP) placed in sealed boreholes. A VWP uses a tensioned steel wire and an electromagnetic coil to convert pore pressure on a diaphragm to a frequency signal that can be recorded and related to the pore pressure. Each VWP is connected to a cable that connects to a manual readout or data logger on surface. The use of VWP's reflects a greater focus in the mining industry on definition of subsurface fluid pressures for geotechnical design. In comparison to an open standpipe, they have a rapid response time in lower-permeability soils. Multiple VWP's placed at different depths in a single borehole allow definition of vertical hydraulic gradients, which can be an important attribute in characterization of the groundwater flow system. However, sealed boreholes with VWP's preclude the opportunity to monitor groundwater quality.

Doubek and others (2013) provide a comprehensive description of the site investigation process, hydrogeologic and geophysical testing programs, approaches to data interpretation, and design of monitoring systems used when advancing a design for an open pit from the conceptual phase to detailed engineering. The discussion there is also relevant to field programs undertaken in the siting and design of the tailings and waste rock management systems at a mine site.

Environmental tracers such as oxygen and deuterium isotopes can aid in refining the understanding of a groundwater system and in testing conceptual and numerical model formulations. An overview of the application of environmental tracers in assessment of coal-mining projects can be found at the following website: www.iesc.environment.gov.au/system/files/resources/269a12ba-09a5-424f-bda3-d5f9679317c7/files/environment-water-tracers-factsheet.pdf↗.

5 Dewatering/Depressurization of Underground Workings and Open Pits

5.1 Overview

When mine workings extend below the water table, groundwater inflows to surface and underground mine workings must be managed. Methods range from a basic system of sumps from which water is pumped to surface to the extensive deployment of groundwater extraction wells. Approaches used to estimate inflows and design control systems for both underground and open pit mines are described in this section. In arid climates the regional water table may be many hundreds of meters below ground surface. Apart from minor seepage zones where perched water zones are intercepted, an open pit located above the regional water table will not need groundwater inflow controls.

Open mine workings are effectively a hydraulic sink, drawing in groundwater from the surrounding area and lowering hydraulic head in adjacent areas. Depending upon the hydrogeologic setting, this impact might extend many kilometers beyond the boundaries of the mine site. Mine dewatering carries with it a potential for substantive impacts on groundwater resources in neighboring areas. There could be, for example, a nearby well field supplying potable water for community use. Of similar concern is the potential for a dewatering system to reduce spring flows and base flows in creeks upon which either there is a community use, or this seepage provides critical support to the local ecosystem. In some jurisdictions this impact is regulated by existing water rights to extract groundwater; in other jurisdictions there may be no legal framework in place. There are instances where a proposed mining project did not proceed because impacts on neighboring groundwater users could not be mitigated or the potential impact on a valued ecosystem, even with mitigation, was judged to be unacceptable. Assessments of potential impacts in neighboring areas are evaluated using established field methods and computational tools, such as predictive, three-dimensional transient groundwater models or in some cases coupled surface water/groundwater flow models.

5.2 Underground Workings

A decline tunnel, vertical shaft, horizontal drift and stopes (an open mine void where ore has been removed) act as hydraulic sinks due to the atmospheric pressure boundary condition they impose in the region below the water table. During the planning stage, insight is required to the anticipated flow of groundwater into a tunnel so that this volume of water can be incorporated within the water management plan, and when necessary, measures implemented to control those inflows during and following adit construction. Field observations indicate two flow regimes often characterize the inflow rate; one a diffuse flow through the rock mass with inflow locations determined locally by open joints in the rock mass, and the other (if it exists) a larger focused flow associated with a damaged rock zone along transmissive fault zones that cross the alignment of the tunnel.

The component of diffuse inflow can be estimated to first order from an analytical solution adopting a simply representation of the hydrogeologic setting. The steady state inflow per unit length of the tunnel (Q_O) can be estimated as shown in Equation 2 (Goodman et. al., 1965).

$$Q_O = 2\pi K H_O / 2.3 \log(2\, H_O / r) \qquad (2)$$

where:

K = bulk hydraulic conductivity of bedrock represented as a homogeneous isotropic unit

H_O = depth of the tunnel below the water table

r = radius of the tunnel

By way of example, a 4 m diameter tunnel 200 m below the water table, in relatively permeable bedrock with a hydraulic conductivity of 10^{-6} m/s would have a predicted diffuse inflow of about 20 L/s over a 100 m length of the tunnel. This steady state calculation provides insight to the strong dependence of the diffuse inflow component on the bulk hydraulic conductivity of the rock mass. If the hydraulic conductivity of the bedrock were lower by two orders of magnitude, a reasonable value for sparsely fractured bedrock, the diffuse inflow would be on the order of 0.2 L/s over that same distance. This small flow rate is easily managed by a pumping system. Substantive inflows to underground workings are usually associated with the intersection of discrete fault zones of high transmissivity. If those fault zones are in hydraulic communication with a surface water body, or intersect a near-surface aquifer of high hydraulic conductivity, substantial inflows can be expected.

Applying this equation requires the assumption that there would be a negligible impact of the inflow on the elevation of the water table. Alternative formulations have been presented for the estimation of the transient flow response to emplacement of a tunnel that does lower the water table elevation. The equation above is based on modeling groundwater inflow to a single tunnel and therefore is not directly applicable to the complex adit geometry typical of underground mine workings. Underground mines with a large footprint, and many tens to hundreds of kilometers of workings, can require groundwater extraction rates on the order of 10,000 to 20,000 L/s or higher if located in areas with permeable bedrock.

At sites where appreciable groundwater inflows are anticipated, groundwater control is focused on lowering the water table to reduce inflow volumes and maintaining the lower water levels over time. Cost-effective dewatering designs require a sound understanding of the hydrogeologic setting. Dewatering of underground workings is often undertaken with a combination of vertical wells and collection sumps within the mine workings. At older mines, boreholes might also target abandoned mine works that have been allowed to flood. A potentially important constraint in mine dewatering arises if the groundwater that is produced requires treatment before release to the environment.

At underground operations no longer in operation, after the dewatering systems are shut down, the regional water table slowly rebounds. In historic mining districts where groundwater withdrawals might have continued over periods of 80 to 100 years, the water table could still be rebounding many decades after mine closure. Water table rebound is discussed further in Section 9.

5.3 Open Pits

When the floor of an open pit is excavated below the water table, groundwater enters the pit through seepage faces that form on the pit walls and as upward flow at the pit floor. There are commonly two components to the inflow; diffuse inflow widely distributed through the general rock mass and focused flow where permeable fractures intersect the pit wall (Figure 17). In addition to physical management of the inflowing water, consideration must also be given to the influence of pore pressures behind the pit wall slopes on stability of those slopes. Both issues reflect distinct concerns, but are linked through similar control measures. In this subsection, aspects of seepage interception to control water inflow are first discussed, and then attention is directed to consider aspects of pit slope depressurization.

Figure 17 - Photo on left shows a seepage face near the base of an open pit, as indicated by general wetness of the rock surface. Photo on the right shows water emerging from discrete fractures farther along this same bench.

Groundwater seepage into an open pit initiates a transient hydraulic response in the surrounding bedrock and surficial units that is similar in a number of respects to radial flow toward a pumping well. Where the surrounding bedrock has low hydraulic conductivity, inflow rates will be small and water management can be handled using sumps on the pit floor. If the bedrock has moderate to high hydraulic conductivity, considerable attention is directed to the design and operation of a multi-well network to intercept groundwater before it enters the open pit. If overburden units above the bedrock surface are permeable, it might also be necessary to operate a dewatering system to intercept flows toward the pit in those units.

Groundwater inflow to an open pit can be estimated to first order using analytical solutions based on a simple representation of the hydrogeologic setting and the assumption of radial flow toward a pit penetrating a homogeneous permeable horizon. Marinelli and Niccoli (2000) provide several analytical solutions for estimating steady state diffuse inflow rates to an open pit. Their solutions allow for calculation of flow rates through the pit wall, and the upward flow component through the pit floor. The influence of a pit lake on inflow rates to a closed pit is also incorporated in their solutions.

Insight to the time-varying inflow rate $Q(t)$ can be derived from Equation 3.

$$Q(t) = 4\pi K b S_W / 2.3 \log\left(2.25\, Kbt / {r_p}^2 S\right) \tag{3}$$

where:

K = bulk hydraulic conductivity

b = thickness of the principal geologic unit transmitting groundwater toward the pit

r_p = radius of the pit

S = specific storage of the rock mass under confined conditions

S_W = design drawdown at the pit face

This equation neglects the effects of the regional groundwater flow system, as it solely accounts for water entering the open pit by release of water from storage in the drawdown zone around the pit. By way of example, if the permeable rock mass had a hydraulic conductivity of 10^{-5} m/s and a specific storage of 10^{-5} m^{-1}, with an aquifer thickness of 30 m and a design drawdown of 20 m for an open pit with a radius of 100 m, the inflow 1 month after "instantaneous placement" of the open pit would be approximately 650 m^3/d. After 6 months, the inflow would be predicted to decline to 550 m^3/d. The scenario envisioned here has the floor of the open pit penetrating 20 m into a 30 m thick permeable horizon located at the pit floor.

Dewatering rates vary considerable from mine site to site. Where active dewatering systems using wells are in place, extraction rates might be as low as 500 - 1000 m^3/d and range up to 80,000 m^3/d, or higher when dewatering limestone units in a regional system with karst development. Similarly, the number of wells in operation at a given time varies for site to site; dewatering requirements might be achieved with as few as 3 to 5 wells, while in other cases 20 or more dewatering wells could be in operation. It is normal practice to use vertical or slightly inclined wells. In environments such as the oil sands open pit mines in northern Canada, horizontal boreholes completed with long well screens have proven to be effective in meeting dewatering requirements in a cost-effective manner.

A key question that arises in the design of an open pit dewatering system is the lead time in advance of mining to a particular depth below ground surface that groundwater wells need to be operational so that the depressurization target is achieved in advance of the requirements specified by the mine plan. For example, based on the projected rate of drawdown that can be achieved (e.g., m/month), it might be necessary to have operating wells in place 2 years prior to mining reaching that area of an expanding pit. The lead time required will depend upon the pumping rates achievable at each well, the bulk hydraulic conductivity of the geologic unit and its storage properties (specific storage if a confined aquifer system, specific yield if unconfined), local rates of groundwater recharge, and the regional groundwater flow component.

Rock mass depressurization has the potential to impact groundwater flow in a region well beyond the immediate vicinity of an open pit. A common concern expressed is the extent to which dewatering activities could influence baseflow contributions to nearby streams, or reduce the flow rate at springs used by local communities for potable water supplies. These issues are often addressed using numerical simulation models as this approach allows consideration of the many complex hydrogeologic factors that interact to determine the potential magnitude of an impact. For a simple representation of the rock mass as a homogeneous porous medium without any faults acting as barriers or conduits, and no boundary affects such as the interaction of the cone of depression with a source of groundwater recharge, a preliminary estimate of the time (t) for a head response to be detected at a spring can be estimated as Equation 4.

$$t = L^2 S_S / K \tag{4}$$

where:

L = distance from the pumping wells to the spring

K = hydraulic conductivity

S_S = specific storage

For example, a spring 1000 m distance from the pumping center, in a moderate permeability bedrock with a hydraulic conductivity of 10^{-7} m/s and a specific storage of 10^{-5} m^{-1}, a response time of approximately 3 years is predicted, or 4 months if the bulk hydraulic conductivity were one order of magnitude higher. In a region with karstic limestone, the response time might be measured in hours.

It is often the case that the rock mass in which an open pit is developed is structurally complex. This complexity can reflect, for example, the influence of fault-offset and/or folded stratigraphic units, or through-going faults and dykes. Both factors can lead to the rock mass behaving as a compartmentalized groundwater flow system. Design of an effective dewatering system requires this complexity be understood, at least at a basic level.

Approaches to well-field design can range from applying operational experience and simple analytical methods to the use of detailed three-dimensional groundwater flow models to predict drawdown. It is common to see this latter method be adopted when the bedrock flow system is in a complex geologic setting and/or there are questions concerning potential impacts of the dewatering system on baseflow reductions in nearby streams. The initial designs of many dewatering systems anticipate the eventual need to add additional extraction wells as site experience is gained and the pit is deepened. Pumping wells are either located around the perimeter of the open pit, on mine benches mid-slope on the pit walls, on the floor of the pit, or in some combination of these locations. As the pit is deepened, replacement wells usually need to be installed, which indicates a preference for wells located on the perimeter of the pit where possible.

The geotechnical design of a pit wall slope (overall slope angles, bench widths, see Figure 8) is tied to an evaluation of the requirements for rock mass depressurization. A decision to adopt a steeper pit wall slope often requires a higher degree of pore pressure reduction to achieve a design factor of safety. There is particular interest in prediction of the elevation of the seepage face where it intersects the pit wall. The tradeoff between the design slope angle and depressurization requirements involves consideration of benefits, costs, and risks (e.g., Sperling et al., 1992). A sound understanding of the hydrogeological regime is a key element in design. Changes in recharge rates between wet and dry seasons can exert an important influence on the design of the depressurization system if the change in recharge rate causes significant fluctuations in the water table seasonally.

Another not a common circumstance, hydraulic gradient control might be required in a situation where active mining in an open pit is occurring adjacent to a second pit that has been closed and allowed to fill with water. As the active pit is deepened, the hydraulic gradient across the rock mass between the flooded pit and the active pit will increase, leading to the possibility of particle entrainment and piping by the moving groundwater. This, in turn, introduces a risk of slope instability. Seepage interception wells can be used to manage the distribution of the hydraulic gradient within the rock mass separating the pits.

Beale and Read (2013) provide a comprehensive guide to site investigation, conceptual and numerical model formulation, and the implementation of pit slope depressurization systems, and a discussion of numerous case histories. Challenges specific to mine sites where weak bedrock units are present, such as shales or siltstones, are discussed in Martin and Stacey (2017). Design of the pit wall slopes is commonly based on an assumption of either two-dimensional sectional models for each design sector of the open pit, or a three-dimensional groundwater model when two-dimensional representations of the groundwater flow system are not appropriate. It is more common to see numerical models developed on the basis of continuum approximations of the hydraulic properties of the rock mass rather than the adoption of discrete fracture network models. A current research focus is on better understanding the role of hydromechanical coupling of the groundwater regime, changes in the in-situ stress distribution as mining progresses, and rock mass deformation influencing fracture openings, permeability and the evolution of the pore pressure distribution in the pit walls.

For depressurization of pit wall slopes in the deeper parts of an open pit, where the rock mass hydraulic conductivity might not be sufficient for effective use of pumping wells, the installation of numerous sub-horizontal drains provides an alternative control measure. The drains can be installed at the pit face, or from a drainage gallery driven through the rock behind the ultimate pit face, with drain holes installed from the gallery. The drains yield water by gravity flow, with flow rates that vary with the local connectivity of fracture networks or faults penetrated by the borehole. The effective design of a horizontal drain program depends upon a sound understanding of the structural fabric and jointing in the bedrock. Beale and others (2013) provide an extended discussion of guidelines for the design and implementation of horizontal drain programs.

6 Seepage Assessment for Tailings Storage Facilities

An assessment of the quantity of seepage from a tailings facility, both during operations and in closure, requires insight to the hydraulic properties of the deposited tailings, pond geometry, recharge rates on exposed beaches in the facility, structure of the dam and its seepage control elements, and foundation characteristics. Tailings often form lower-permeability deposits that impede the release of supernatant pond water to the surrounding watershed. Some very large tailings facilities, covering many km^2 in area, report outflows (unrecovered seepage in Figure 7) as low as 10 to 50 L/s. Seepage rates from tailings facilities are lower than those at water storage reservoirs with similar size and foundation conditions due to seepage impedance provided by the tailings. A tailings facility characterized as having a high seepage rate might have outflows of 200 to 500 L/s. Oftentimes, sites reporting these larger seepage rates have a water pond in direct contact with native ground around some portion of the pond perimeter where tailings might not be present to lower the seepage flux. In this latter situation, it is the hydraulic conductivity of surficial sediments and shallow bedrock that influence the magnitude of the seepage fluxes. Seepage volumes exceeding 1000 L/s are a rare occurrence except where karstic limestone is present within the footprint of the facility.

Tailings beaches play an important role in modifying seepage flows. The geometry of a tailings beach is determined by the location of spigot points where the tailings are discharged into the facility, how the water budget for the facility is managed, and the geotechnical properties of the tailings. To aid in reducing seepage rates through the foundation of a dam and at its abutments, there is a preference to develop a wide tailings beach in front of the dam, if operational conditions permit this geometry to be established. A reduction in seepage rates places a lower demand on the seepage interception system and a reduction in the volume of process water pumped back to the tailings facility from the seepage recovery system. Beach length is also a factor in enhancing dam stability by reducing the hydraulic gradient that could initiate internal erosion and piping and creating a zone of non-liquefiable tailings against the upstream face of the dam where the tailings are only partially saturated. Beach lengths vary widely between facilities; some sites operate with a beach 50 m wide, while other sites might have a beach several thousand meters wide. The tailings beach seen in Figure 1 is approximately 1400 m wide.

During project development, estimates of seepage volumes and the design of seepage interception systems are typically based on representative two-dimensional cross-section models or three-dimensional models that incorporate the dam, the tailings facility including a beach zone, engineered seepage control elements, and the surrounding terrain as part of the model structure (see Figure 15, 16). A decision on the extent of the model domain is tailored to the site-specific hydrogeologic conditions that need to be considered to address the question at hand. Because of the scale of a tailings facility and the neighboring basins where a water quality impact might be possible, some of the most detailed and complex models used in hydrogeologic practice today are developed during the assessment of seepage impacts associated with mining projects.

Once in operation, the volume of pond water reporting to the seepage collection systems is often recorded by flow meter or weir. These measurements provide important data in updating a seepage model for the facility, if one has been developed. Reliable estimation of the unrecovered seepage volume is more challenging. It is usually a small component in an overall water balance calculation for the TSF and therefore, uncertainties in the estimation of the other water balance components can mask the volume of unrecovered seepage. Reliance is often placed on either monitoring the changes in baseflow in nearby streams and dry-season flows at springs, or prediction of unrecovered seepage flows derived from a calibrated groundwater model of the local basin in which the facility is located. There are examples of tailings facilities where due consideration was not given to the potential for the geologic setting to lead to unfavorable foundation conditions and the unrecovered seepage volume was a substantial component of the water balance.

7 Seepage Management During Operation of a Tailings Facility

Seepage control measures at a tailings dam serve two critical roles; the first is to ensure the stability of the dam and the second is to reduce the volume of pond water that can pass beyond the dam through the foundation. A tailings dam will often have an internal drainage system and toe drain to maintain a low water table in the downstream shell of the dam; this water is collected by the drainage system and either returned to the tailings facility, treated and released, or directly released to the environment if water quality considerations are met. Depending upon foundation characteristics and dam design, a low-permeability cutoff might be installed to aid in protecting the clay core of the dam from erosion (piping) due to excessive groundwater velocities. This cutoff also has a benefit in reducing the volume of pond water that can pass through the foundation and migrate beyond the downstream toe.

When a cutoff is proposed to reduce seepage bypass through fractured bedrock, a grout curtain is commonly considered. A line of boreholes is drilled to the target depth, usually on a spacing of about 3 to 5 m. In some countries, practice guidelines are established for grout curtain installation. In other jurisdictions, the designer develops a site-specific plan for placement of the grout curtain. Cement is injected into each borehole, first in a short interval at the bottom of the borehole and then moving the injection zone up the length of the borehole. Cement takes (kg of cement per length of injection interval) are recorded as a key matric for identifying the more permeable zones in the borehole. It is often the case that a second row of injection holes, offset from the first, is required to get the specified reduction in permeability. Three and sometimes even four rows of grout holes might be needed to reach design targets for permeability of the cutoff. Check holes orientated at an angle across the curtain are used to confirm the design target for hydraulic conductivity has been met. A grout curtain with an effective hydraulic conductivity of 10^{-7} m/s is usually considered a reasonable target in fractured bedrock. A value of this magnitude, under normal hydraulic gradients, results in low seepage volumes through the curtain if the curtain is laterally continuous.

A second line of defense on water release to the environment is the construction of a seepage collection pond at a location downstream of the toe of the dam (see Figure 7). The seepage collection pond might also incorporate a grout curtain as a cutoff to promote upward flow of contact water to surface where the seepage can then be directed to the collection pond. In permeable soft sediments, a trench backfilled with low-permeable soils amended with bentonite is commonly used to construct a cutoff wall. In this case, the hydraulic conductivity of the cutoff wall, if properly installed, can be as low as 10^{-9} or 10^{-8} m/s. Contact water reporting to the seepage collection pond is usually pumped back to the tailings storage facility or piped to the mill for re-use. Not all tailings facilities incorporate seepage collection ponds beyond the toe of the dam; but their use has become more common as greater attention has been paid to reduction in the risk of potential downstream impacts on water quality.

Tailings deposits have a hydraulic conductivity that will act to limit seepage rates through the base of the facility if the hydraulic conductivity of the foundation unit is higher than that of the tailings deposit. This can occur, for example, when the facility is located on a permeable, sandy till unit or moderately to highly fractured bedrock. At some sites there could be a requirement to further reduce seepage from the tailings facility due to water quality considerations, in which case a geomembrane liner can be placed at the base of the facility. Figure 18 shows a lined tailings storage facility.

Geomembrane liners are not impermeable; installation defects will invariably occur, even with a good quality control/quality assurance program. Experience indicates that the hydraulic conductivity for flow through a geomembrane liner, placed on a properly prepared base, can be expected to be in the range of 10^{-11} to 10^{-10} m/s. As an alternative to a geosynthetic liner, some operations control seepage into the foundation by placement of a compacted, low-permeability soil liner 1 to 3 m in thickness prior to startup of operations. A decision on liner type depends upon soil availability, relative costs of different liner systems, and the required degree of seepage reduction. Construction control during placement of a synthetic or soil liner is key to successful use of this method for seepage management.

Figure 18 - Geomembrane liner installed in a tailings storage facility. At the time of this photograph, water was being accumulated in the facility for startup of mill operations.

The permissible amount of contact water that bypasses a seepage collection system (unrecovered seepage) is regulated under various frameworks. In some jurisdictions, a permissible seepage rate to the environment is specified, such as a value not to exceed 5 L/s. The magnitude of this number is typically determined through studies of the assimilative capacity of the downstream receiving waters. In other instances, the allowable seepage is linked to a requirement to honor a maximum permissible concentration of key elements at specified compliance points. For example, the maximum manganese concentration in surface water at a compliance point several hundred meters beyond the toe of the facility, or in a groundwater monitoring well at a compliance point, cannot exceed, say 2 mg/L. In other instances, the tailings facility might be declared as a zero or de minimis discharge facility. This circumstance requires groundwater interception and monitoring systems be in place at all locations where natural hydrodynamic containment does not exist.

If unrecovered seepage is moving down valley beyond the seepage collection pond with concentrations of one or more solutes above natural background values, then additional groundwater interception measures might be required. This will commonly involve the installation of one or more groundwater wells to capture the process-affected water. Beyond the normal design considerations for the interception wells and associated monitoring wells, a key point of discussion becomes what the capture efficiency of the interception well system will need to be in order to meet environmental standards. For example, is it necessary to capture 90% of the impacted groundwater in the well system, or will the efficiency need to be greater than, say 98%? A prerequisite to achieving high capture efficiency is the identification of secure seepage collection points in the basin downstream of the dam. This step requires reliable definition of preferential seepage pathways. In this regard, seepage interception in a basin underlain by limestone with karst development is prone to a much higher degree of uncertainty than is the normal circumstance because of the inherent difficulty in identifying all the potential pathways.

Seepage interception systems are generally implemented within the framework of an adaptive management plan, with monitoring data used to guide refinement in the interception well network through time. The more heterogeneous the hydrogeologic setting, the more challenging it becomes to design and operate a system at high capture efficiency. Verification of capture efficiencies is challenging. It is often based on concentration measurements in receiving surface waters rather than from subsurface concentration data obtained from monitoring wells.

8 Seepage Assessment for Waste Rock Stockpiles

Following initial wet up of a waste rock stockpile, the principal determinants of the volume of contact water reaching the base of a stockpile are the amount of infiltration that passes beyond the zone of evaporative losses at the crest of the stockpile (sometimes called net infiltration or percolation) and potential losses due to air circulation within the stockpile removing water by evaporation. Evaporative losses at the crest of a stockpile are dependent upon seasonal variations in climatic conditions and solar radiation, the temporal distribution of rainfall and snowmelt, and material properties of the matrix. Average infiltration rates are commonly reported in the range from 10 to 50% of the annual precipitation. At a given site, infiltration totals can vary widely from one year to the next due to differences monthly rainfall totals, the characteristics of individual storm events, and in the factors that control evaporative losses. For example, in northern high latitude sites, a daily rainfall of 5 to 10 mm that occurs during the peak month for incoming solar radiation in July might lead to little or no infiltration to the stockpile, while the same event occurring in mid to late Fall could lead to a significant infiltration event due to significantly lower levels of solar radiation and a consequent small evaporative loss.

Molson and others (2005) provide an early example of a numerical model developed to obtain improved insight into the nature of interacting processes controlling water movement through a waste rock stockpile and the geochemical evolution of the pore water. They represented the waste rock stockpile as a layered system responding as a granular porous medium. Lahmira and others (2017) provide a recent example of a model-based investigation of water infiltration and air circulation through a waste rock pile represented as a heterogeneous porous medium. Current state-of-the-science models are not widely applied in practice due to questions of whether the effort required to formulate and develop a numerical model adds significant value in the decision process. There remains considerable uncertainty in the quantitative description of the material properties of a waste rock stockpile and in obtaining field measurements of the key parameters to inform site-specific applications of these advanced numerical models. When they are used, it is less in a predictive mode than a "what-if" mode to explore design concepts.

A key issue of concern in evaluation of potential environmental impacts of a waste rock stockpile is the prediction of solutes loads at the base of the stockpile. As noted in Section 3.4, solute loads are determined by time-varying water fluxes and solute concentrations. The many geochemical processes that must be considered in prediction of solute loads at the base of a waste rock stockpile are reviewed in a number of papers (e.g., Amos et al., 2015; Wilson et al., 2018) and these processes are not addressed here. There is, however, a key hydrogeological factor that needs to be considered in prediction of the solute load for each potential contaminant of concern. Geochemical predictions are frequently based on estimates of geochemical weathering rates derived from standardized leaching tests carried out in the laboratory on samples where the maximum particle size is 6 mm. These weathering rates are then up-scaled to apply in the field over pile heights of 10's of m or more. One of the scaling factors used describes the proportion of the rock mass with surface area sufficient to contribute meaningfully to release of metals and other solutes. The reactive surface area is several orders of magnitude greater for the finer particle-size fraction when compared to larger particles. A second scaling factor is the proportion of the rock mass that is flushed by water infiltrating through the stockpile. The former factor is often taken as the fraction of the waste rock that is less than 6 mm in diameter, corresponding to the upper bound particle size specified in laboratory leaching tests. The latter factor is referred to as the water to solid ratio or the water-solid contact area. The water to solid ratio is an empirical ratio between 0 and 1. This factor is difficult to estimate in practice because it varies with nature of the unsaturated flow regime within a stockpile; including how the fraction of immobile water, granular matrix zones, and preferential flow paths interact, and how that interaction varies in time. Values used in practice are usually in the range from 0.2 to 0.4, but there is considerable uncertainty in identifying an appropriate value. This topic continues to be an active subject of research (e.g., Blackmore et al., 2018; Wilson et al., 2018).

9 Hydrological Considerations in Mine Closure

In most jurisdictions, mining companies are required to provide a conceptual closure plan for a proposed mine as part of the environmental assessment submitted for initial project approval. Good practice involves regular updates to the closure plan and costs of closure during the life of the mine, with the greatest granularity added to the closure plan toward the end of the life of the mine as ore reserves approach depletion. Closure objectives that accommodate the character of the hydrogeologic regime are an important part of the planning process. From a hydrogeologic perspective, the main objectives of the closure plan are to: (i) address the risk that at some future point in time changes in the hydrogeologic regime could influence stability of geotechnical structures, and (ii) minimize the risk of water quality impacts to receiving waters in nearby watersheds. In addition, in some circumstances mining-induced subsidence of the land surface can alter surface water drainage patterns and groundwater - surface water interactions. Such a possibility needs to be considered in establishing the closure plan.

9.1 Underground Mines

Following cessation of operations, dewatering systems at an underground mine are shut down and the workings allowed to flood as the water table rises toward a new equilibrium condition. The rate at which the water level will recover depends upon the hydraulic conductivities of the subsurface geologic units and the specific yield of the units in the region where the bedrock was dewatered and the specific storage of the deeper bedrock that was depressurized but not dewatered. Groundwater enters storage in the rock mass, the open mine voids, and in any backfill materials placed in the mine workings. While the changed hydraulic conditions in the subsurface will modify the flow regime on a local scale from that existing prior to mine development, it is usually assumed that the post-closure flow system would have the same general configuration as that prior to mine development. However, this is not always the case as groundwater flow divides can shift with subsurface disturbance and groundwater that prior to development reported to one valley might report to an adjacent valley and discharge to surface after mine closure.

An assessment of recovery rates in hydraulic head and water table elevation, changing flow paths during the recovery period, and the ultimate geometry of the post-recovery flow system is usually undertaken using a three-dimensional, transient groundwater flow model. Underground mine workings are more complex than can normally be incorporated in a numerical model grid; simplified representations of the workings must be adopted. In mines that have been operated for decades, early mining records might not have been retained and access to older workings not safe, so there can be significant uncertainty in defining the geometry of the mine workings and the open void volume, and thus accurate quantitative predictions may not be achievable.

Dewatering of the underground workings creates a zone of drawdown centered about the mine workings. This drawdown cone may be somewhat circular but more commonly has a roughly elliptical shape due to the influence of geologic structure and geometry of the mine workings. A common question asked when evaluating mine closure plans concerns the time period over which the drawdown cone will be in place to maintain an inward hydraulic gradients toward the mine workings. If the walls of the mine workings hold soluble salts generated from mineral weathering, or if reactive waste rock stockpiles are located above the footprint of the drawdown cone, then for the duration of the recovery period there will be hydrodynamic containment of mine-affected waters. However, once the drawdown cone has dissipated, groundwater flow through the mine workings becomes part of the regional groundwater flow regime and contaminants might eventually move beyond the boundaries of the mine site. Surface outflows from mine adits carrying elevated concentrations of metals may require a collection and treatment system that must be operated for many decades after mine closure.

The rate of mine re-flooding will depend on the total drawdown that developed during mine operations, the void volume of the mine workings, and the hydraulic conductivity, specific storage and specific yield of the geologic units, and groundwater recharge rates in the area. The recovery rate is greatest in the initial period after dewatering wells are shut down. The recovery rate decreases through time in the same manner observed in the water level recovery curve following the termination of a pumping test. Mine workings located in semi-arid to arid climatic regimes will generally require longer recovery periods than at mine sites located in higher rainfall areas. On one hand, hydrodynamic containment in the vicinity of the mine workings might be maintained for decades to many hundreds of years following mine closure. On the other hand, if the hydrogeological conditions lead to the drawdown cone dissipating relatively quickly, off-site migration of solutes in the groundwater system could become a concern early in the closure period.

9.2 Open Pit Mines

At the end of an open pit operation, sump pumps and/or dewatering wells are decommissioned. The geometry of the pit and the void volume may be modified if partially backfilled with mine waste. Following cessation of pumping, in most climatic regimes, both surface water and groundwater will inflow to the pit, creating a pit lake (Figure 19). These pit lakes become part of the closure landscape and attention must be directed toward their hydrology and especially, water quality trends in the lake. Golder Ltd. (2017) provides a literature review of pit lakes in a number of different geographic settings. This report includes discussion of numerous case histories.

Figure 19 - Pit lake forming at a closed mine site. The pond level was rising at a rate of several meters per year, with the water level below the elevation of the subsurface spill point for the pit.

Figure 20 illustrates the water balance for a closed open pit; in this case a situation is depicted in which waste rock has been placed back in the pit as part of the mine closure plan. If rates of evaporation exceed rates of groundwater inflow, precipitation, and runoff of surface water into the pit, then the open pit remains in a dry state or perhaps a small seasonal pool of water forms on the pit floor. This situation ensures hydraulic containment of contaminated water. If the cumulative inflow rates exceed evaporation rates, a pit lake develops and the water level rises over time. The long-term equilibrium condition determines the ultimate elevation of the pit lake. One of three possible conditions occur: (i) if the water level stabilizes at an elevation everywhere below the level of the water table in the bedrock surrounding the pit, a permanent hydraulic sink is created; (ii) if the water level in the pit rises to a "spill point elevation" where at one or more locations on the pit perimeter the water level in the pit exceeds the water table elevation in the surrounding terrain, subsurface outflow of pit water commences once the spill point elevation is reached; and (iii) if the inflows exceed the outflows to the extent that the water level rises to a topographic low point on the pit rim, then a flow-through lake is established with surface water outflows.

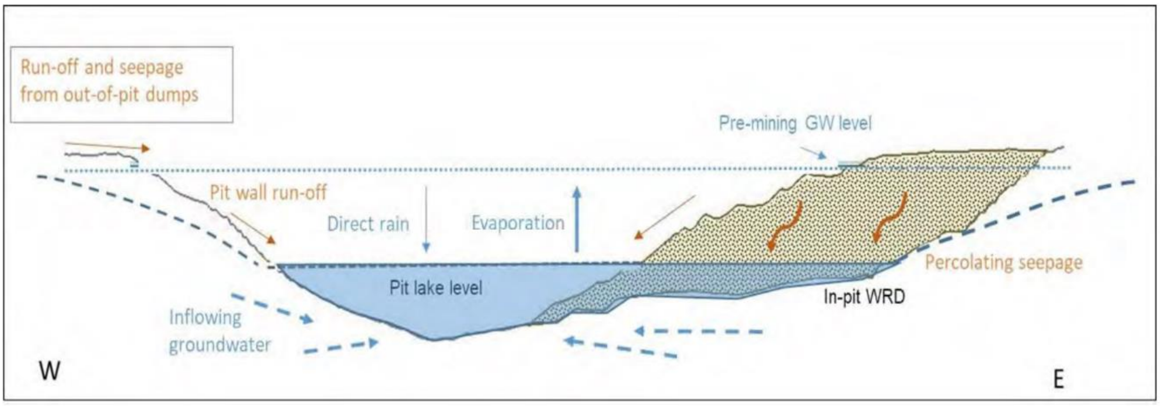

Figure 20 - Schematic of the water balance for a closed open pit. From Linklater, C., et al., (2017), published by Sustainable Mineral Institute, University of Queensland Brisbane.

It often takes many decades or more for a pit lake to approach a dynamic equilibrium level if the controlling factor on the rate of rise of the lake level is the rate of groundwater inflow to the pit rather than surface water inflows. Groundwater inflow rates to the pit diminish over time as the hydraulic gradient driving groundwater toward the open pit decreases as the pit fills with water. When the dynamic equilibrium condition is established, lake levels fluctuate with annual changes in the climate cycle. Solute concentrations could exceed permissible standards if the quality of the water in the pit is impacted by sulfide mineral weathering on the walls of the pit exposed above the water line, or solutes are released from any mine waste placed in the pit before or at closure.

The assessment of the time for a closed pit to re-flood, impacts on the surrounding hydrologic regime, and groundwater flow paths to offsite receptors, is commonly developed using a transient, three-dimensional numerical groundwater flow model in conjunction with a surface water hydrology model (e.g., Linklater et al., 2017). For pits where the water level rises above the groundwater spill point, particle-tracking techniques can be used to identify the groundwater pathways, the eventual receiving surface water bodies, and to estimate solute travel times by advection. At some mine sites, decisions have been made that require a commitment to long-term pumping and water treatment following mine closure to prevent the water level in the pit lake from rising to the spill point elevation where hydrodynamic containment would be lost. It is also necessary to assess the risk of the pit lake exceeding the spill point elevation during extreme rainfall events.

Figure 20 also points to a calculation sometimes undertaken to determine the region around the open pit that contributes to groundwater entering the open pit (labeled "seepage from out of pit dumps"). Loadings released from any mine waste stockpiles contained within this area will eventually report to the open pit. This seepage is considered within the water management plan for the open pit. Stockpiles located outside this region have solute loads reporting elsewhere on the site. This calculation is equivalent to identifying the capture zone of a contaminant interception well or a water supply well. Figure 21 shows such a calculation for a mine located in a semi-arid region (Birch et al., 2006). Solute loads generated by mine waste stockpiles located within the red contour (capture zone of the open pit) report to the open pit. Loadings to groundwater from any stockpiles outside this zone would be projected to report to other drainages.

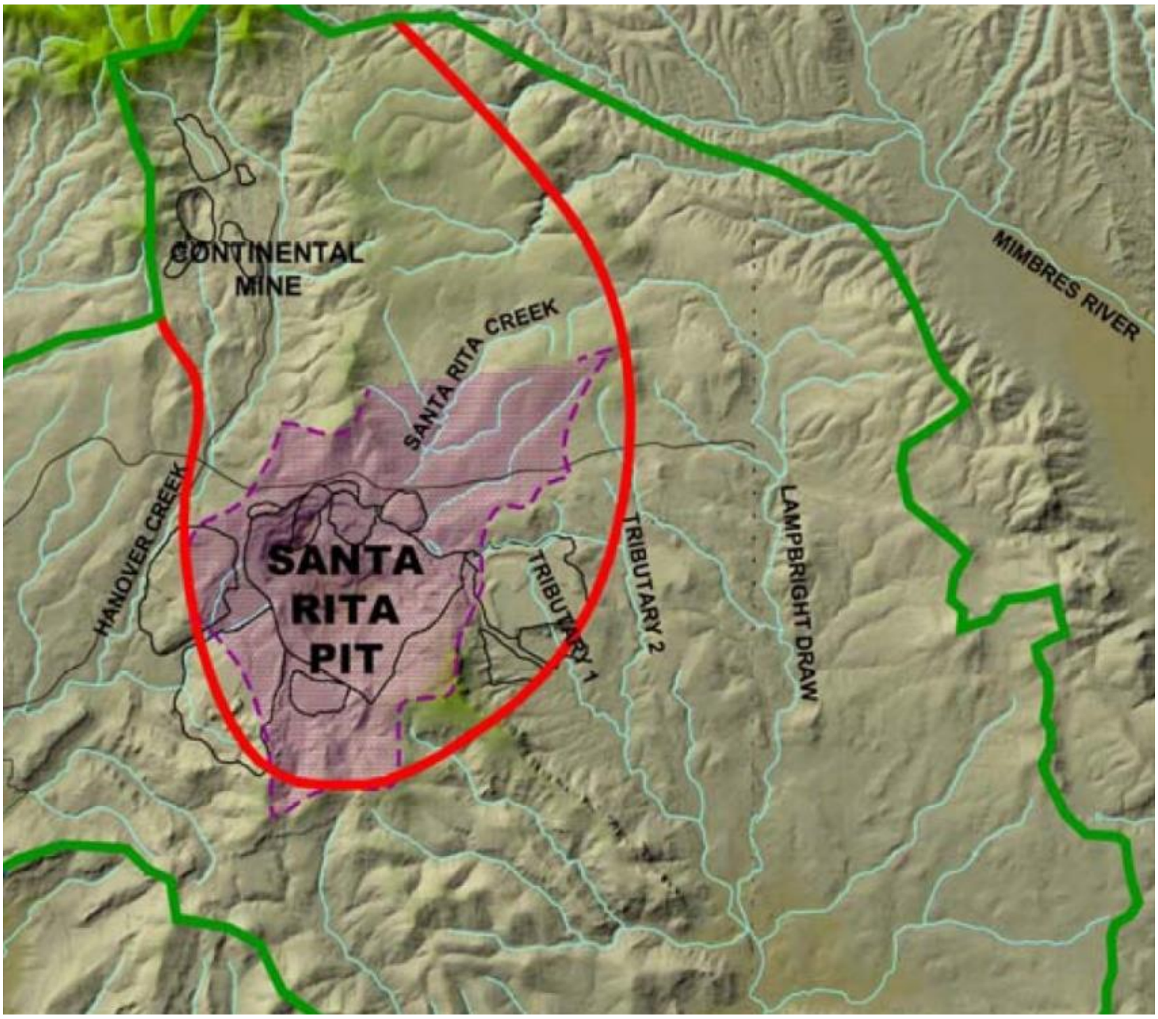

Figure 21 - Projected capture zone of groundwater reporting to an open pit. Groundwater recharge occurring within the region mapped by the red contour is predicted to report to the pit. The capture zone shaded purple accounts for the local-scale flow systems around the pit while the green contour represents the surface water drainage boundary. Modified from Birch et al., 2006).

An option sometimes considered as part of the closure plan for an open-pit mining operation is re-location of waste rock or deposition of tailings into the open pit following completion of mining. In other cases, an in-pit waste rock stockpile developed during operations may be feasible (see Figure 20). Several of the advantages gained in this approach are a reduced footprint of mine waste in the closure landscape and submergence of some of the waste rock or tailings below the re-bounding water table, which can have a long-term geochemical benefit. However, the quality of the water in the pit might be degraded in the near-term if the waste rock contains secondary mineral products that formed while the waste rock was stored on the ground surface, which may then mobilize upon re-wetting. To obtain permit approval, it may be necessary to document the potential impact of backfilling the pit on groundwater flow patterns in the nearby area, to assess impacts to the receiving environment, and to confirm the final landscape is stable. This is normally undertaken using a three-dimensional groundwater model of this closure scenario, combined with particle tracking to delineate the capture zone.

9.3 Tailings Storage Facilities and Waste Rock Stockpiles

A common step during the closure of tailings facilities, waste rock stockpiles, and spent heap leaches is to place a soil cover on top of the mine wastes. Two types of soil covers are considered based on the design intent; isolation covers and infiltration covers. The main intent of an isolation cover is to prevent contact with the mine wastes by humans and wildlife, to minimize long-term mobilization of mine wastes by either wind-blown erosion or surface runoff, and to provide a substrate for re-vegetation of the disturbed landscape. Figure 22 shows an example of an isolation cover in a semi-arid environment, placed on a re-contoured waste rock stockpile. The surface topography created includes consideration of surface drainage patterns for large run-off events.

Infiltration covers provide isolation but they also have as their design basis the intent to reduce the amount of infiltration that enters the underlying tailings or waste rock. Soil covers can be as thin as 30 cm, or up to 2 m in thickness, depending on design intent and availability of suitable soils. Cover design draws heavily on concepts of unsaturated flow through soils and quantifying the exchange of water and energy at the soil - atmosphere boundary.

Figure 22 - Example of an isolation cover placed on a re-contoured waste rock pile.

A number of factors are considered when evaluating the potential benefits of cover placement on mine wastes. A soil cover can be designed to enhance storm runoff in comparison to that occurring on the tailings surface or waste rock stockpile if it were left uncovered. If surface runoff does not come in contact with underlying mine wastes, it is likely to be of suitable quality to allow direct release to the environment, without need for water treatment. Tradeoff studies are sometimes undertaken to assess the benefits of a higher level of cover performance relative to an anticipated reduction in requirements for water collection and costs of water treatment after mine closure.

If mine wastes yield solute loads to groundwater that present a concern for water quality, or the anticipation is that at some point in the future solute loads will increase as mineral weathering progresses, an infiltration cover design might be adopted that decreases solute loads reporting to the base of the facility. The timing for placement of a soil cover during closure activities is often based on geochemical assessment of the length of time before the neutralization capacity of the tailings or matrix materials in waste rock is consumed and acidic conditions begin to develop. A second design consideration for reactive mineral wastes is the extent to which a soil cover might reduce the rate of oxygen resupply into interior regions of a stockpile, thus reducing the rate of sulfide mineral oxidation. In this latter case, the porosity of the soils used in the cover and the water content within the cover that is retained over the climate cycle determines the oxygen flux into the mine waste. Soil covers also suppress preferential flow through waste rock stockpiles due to the reduction in net infiltration and their more uniform surface characteristics when compared to uncovered waste rock. The pore water flux entering the underlying waste rock is more likely to be transmitted through granular matrix materials due to capillary pressure effects, contributing to more uniform flushing of the stockpile with a consequent influence of the spatial and temporal variability in solute loads.

An excellent review of the function, design and monitoring of single layer or multi-layer soil cover systems is provided in a guidance document developed by the International Network for Acid Prevention (2017). Several of the principal design concepts for infiltration covers are noted here. From the perspective of modifying the amount of infiltration passing through mine waste, soil covers are designed as water storage and release systems, barrier systems, or they may incorporate both elements. The design intent of a store and release cover is to have sufficient capacity to store wet-season precipitation within the root zone of the soil cover and then to rely on evapotranspiration to remove that water during the dry season. Over the annual cycle, net infiltration through the cover is reduced. A barrier system is designed to promote surface runoff and interflow within the cover system as the means of reducing downward percolation into mine wastes. In barrier systems, use is made of low-permeability compacted soils such as clays or geosynthetic (geomembrane) liners. Unlike a liner system place beneath a tailings facility, which has hydraulic head acting across the liner, a geosynthetic liner incorporated within a soil cover is less prone to leakage through installation defects due to a much-reduced water head. Experience suggests that for an effective store and release cover system, a net infiltration in the range of 5 - 10% of the annual precipitation would be considered an excellent outcome in more humid climates, with a net infiltration of 20 - 30% of annual precipitation being a reasonable estimate of performance for many sites. Net infiltration through a cover would be lower in an arid climate. If a geomembrane is incorporated in the liner system, net infiltration is usually expected to be on the order of 1 - 2% of annual precipitation.

In projecting cover performance into the future, the influence of multi-year climate cycles needs to be considered, rather than the average annual precipitation and temperature condition. Because potential environmental risks can exist long into the future following mine closure, it is becoming more common that cover performance is also evaluated (modeled) for various climate change scenarios.

9.4 Spent Heap Leach

Development of a closure plan for a heap leach facility involves consideration of the unsaturated hydraulic properties of the spent ore materials, as this data is key to prediction of the time frame over which residual leach solutions will be released at the base of the pile. This drain down time of the leach solution often determines the length of time that active management of the pile is required. Estimates of this time period can be derived using simulation models of saturated - unsaturated flow. This presents a challenging application of unsaturated flow concepts because of the size of the system to be considered and the heterogeneous nature of the spent ore in the leach pad. Attention is also directed to the long-term release of other potential contaminants of concern from the leached ore in the pile, as this can also determine the long-term management requirements for the heap leach. Soil covers to reduce infiltration of precipitation through the spent heap leach, and to isolate the spent ore from the terrestrial environment, are also considered as part of the closure process. Cover concepts discussed in Section 9.3 are applicable here. The ultimate requirement in closing heap leach facilities is a demonstration that the strategies adopted for closure are protective of the underlying groundwater resource over the long term.

9.5 Landscape Restoration

Hydrogeologic processes play an important role in landscape function when planning landscape restoration (re-construction) following closure of a mine site. For example, the hydrogeologic component of the water cycle is key in planning for eventual closure of the oil sands operations in northern Alberta or at strip mines where land disturbance can cover many tens of km^2. Wetlands are an important element in landscape function in many climatic regimes and it is common to see wetlands included as an integral design element in the land surface. Local scale groundwater flow in a constructed landscape needs to be considered as the local systems oftentimes serve to sustain a wetland during dry season conditions. Consideration of groundwater flow paths is also required in evaluating salt loads and potential soil salinization in a restored landscape. The role of hydrogeology in landscape restoration in the oil sands mining area of northern Alberta in Canada is discussed at length in the report "Guidelines for Wetlands Establishment on Reclaimed Oil Sands Leases", published by the Cumulative Environmental Management Association in 2014. As an illustrative case study, a comprehensive discussion of the closure plan for the Ranger Uranium Mine in northern Australia, including the role of hydrogeology and application of hydrogeologic models in the design of the plan, can be found at the website http://www.energyres.com.au/sustainability/closureplan↗.

10 Wrap Up

This book has provided an overview of the ways in which the hydrogeologic setting forms an integral component of mineral resource development projects and how the hydraulic properties of mine waste materials influence the potential impact of mine wastes on the surrounding environment. An understanding of the site geology and groundwater regime is fundamental in ensuring safe operational practice, rock mass stability, stability of tailings dams and waste rock stockpiles, and sound environmental stewardship. Issues related to groundwater arise in project development and permitting, in day-to-day operations, in closure planning, and in the post-closure period.

Reliable prediction of groundwater inflows to mine workings and potential water quality impacts in the surrounding environment are challenging due to the complex nature of the geologic setting in which mines are often developed. Advances in site characterization methodologies and the development of powerful computational tools are contributing in a significant way to more reliable forecasts of water flows and potential impacts. Governing processes are generally well understood, as are protocols for collection of field data and approaches to data synthesis. There remains a need for improved insight to the means for using measurements made at a small scale to forecast system response at a larger scale. For example, characterization and quantification of infiltration pathways through a waste rock stockpile, if needed to make a prediction of solute loads at the base of the stockpile, largely remains an empirical exercise in practice.

Recognition of the limits to predictability needs to be appreciated by all stakeholders in mineral resource developments. For example, it may be that there are wide error bars on prediction of the time for a pit lake to reach an equilibrium position or the spill point elevation if groundwater inflow rates are the controlling factor. While a base case analysis may indicate a time say, of 250 years, uncertainties in defining the hydrogeological system could lead to bounds on the prediction of as few as 100 years or more than 500 years. Another example of the limits to predictability is provided by mineral resource developments in terrain with karstic limestone; which reflects the difficulty in determining the nature of the interconnected flow pathways through karst and where all the outlet locations could occur. There is also the general challenge in prediction of solute arrival times, and concentration values even for a non-reactive solute, if no data are available to calibrate the solute transport model, which is the common circumstance during the project development stage.

11 Suggested Reading

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12 Exercises

Exercise 1 – Solute Loading

The shaded zone in the Figure Exercise 1-1 below identifies the location of a small waste rock stockpile on an upland slope, some 200 m away from a stream channel in the valley floor. The stockpile is releasing sulphate to an underlying unconfined aquifer. The depth to the water table at the topographic divide is 10 m. The contours present the vertically averaged sulphate concentration across the saturated thickness of the aquifer. Given the data provided below: (1) Estimate the mass of sulphate entering the stream channel each day that originates from the waste rock stockpile; and (2) List the key assumptions you have made to develop this loading estimate.

For ease of calculation, assume the aquifer is composed of a homogeneous sand with a hydraulic conductivity of 5×10^{-4} m/s. Assume the aquifer averages 10 m in thickness. Assume the highest sulphate concentration observed at any depth in the monitoring well indicated by the star is 310 mg/L. For ease of calculation, assume a background sulphate concentration in the aquifer less than 5 mg/ L.

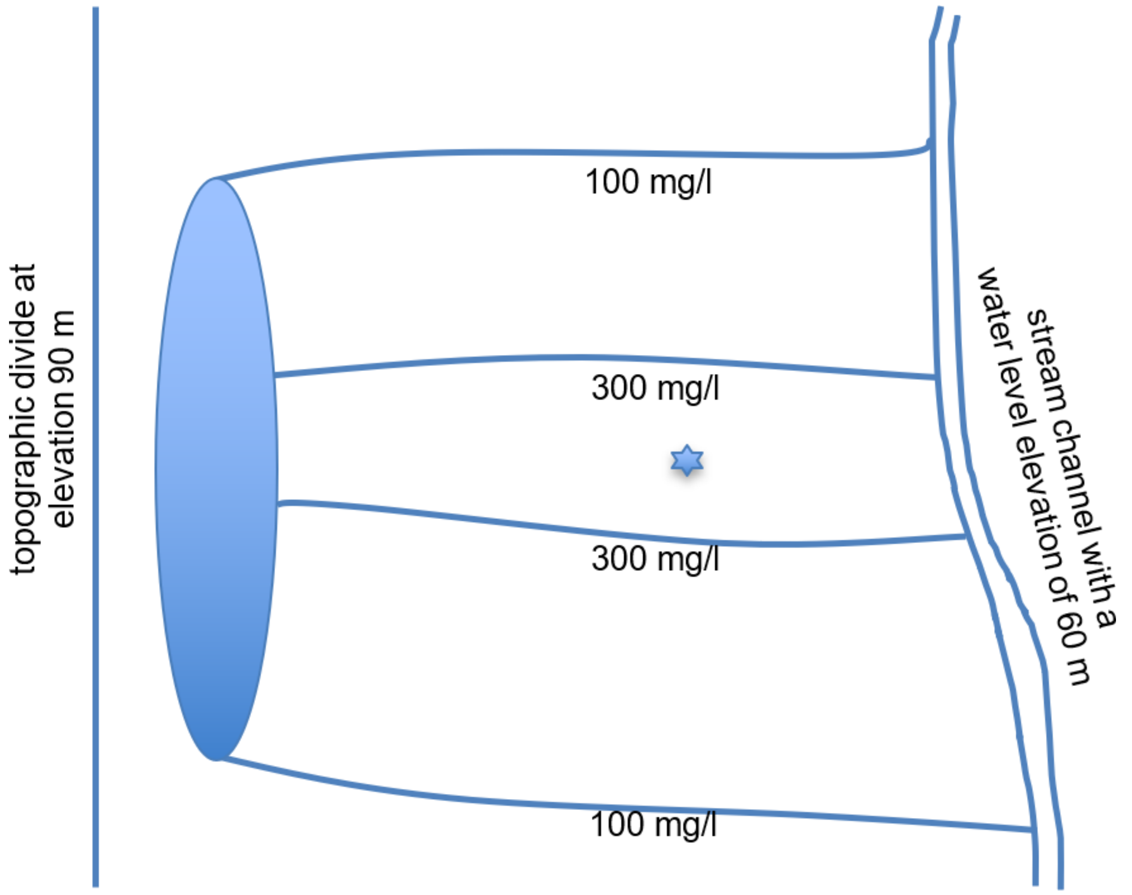

Figure Exercise 1-1 – Schematic of Exercise 1.

Click for solution to exercise 1

Exercise 2 - Inflow Prediction to Open Pit Mine

An open pit for extracting ore is to be excavated through a thick section of low permeability till to the base of the fractured bedrock horizon, as shown in the cross section below (the schematic diagram is vertically exaggerated, thus not drawn to true scale). The till, which acts as a confining layer to the underlying more permeable fractured bedrock, is 15 m thick with a hydraulic conductivity of 1×10^{-8} m/s. The fractured bedrock horizon is 30 m thick, with an effective hydraulic conductivity of 5×10^{-6} m/s and specific storage of 1×10^{-5} m^{-1}. Below the fractured horizon, the bedrock has a hydraulic conductivity of 1×10^{-9} m/s. Assume a depressurization system (e.g., horizontal drain holes) will be put in place to maintain the hydraulic head at the toe of the pit wall at an elevation 5 m above the pit floor. The pit will be roughly circular in geometry, with an ultimate diameter of 400 m.

1. Estimate the diffuse inflow to this open pit three years after it reaches full depth, assuming instantaneous development of the pit. Standard practice would be to develop a three-dimensional numerical model that simulates the incremental construction of the open pit through time and the resulting groundwater conditions within the till and fractured bedrock. An analytical solution is useful for providing initial insight to the magnitude of flow into the pit over time. Given the minimal time required to calculate an analytical solution, the results are valuable to a numerical modeler who can compare the values and, while qualitatively compensating for the simplifications of the analytical solution, can investigate the numerical model setup more carefully if the analytical and numerical results are strikingly different. One would expect the initial flow to be much higher in the analytical solution and the steady state value to be roughly the same between solutions.
2. Develop a second estimate of inflow for a case where the water table is near the top of the fractured bedrock, the till is unsaturated, and the fractured bedrock unit responds as an unconfined aquifer with a specific yield (S_y) of 0.03. Explain why the inflow is significantly higher for one case relative to the other.

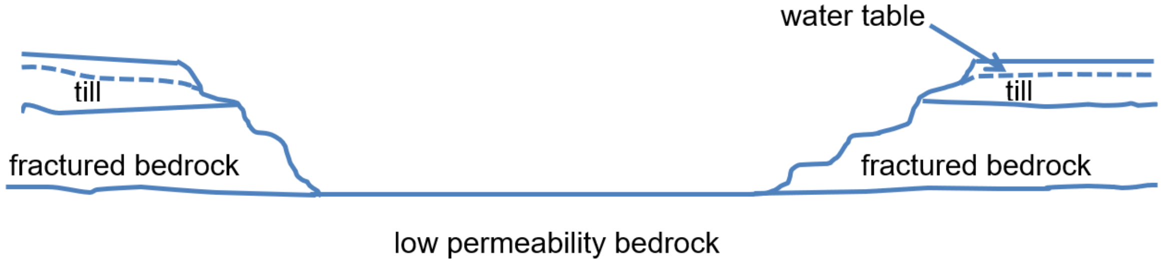

Figure Exercise 2-1 – Open Pit Mine Schematic for Exercise 2.

Click for solution to exercise 2

Exercise 3 - Water Balance for a Tailings Storage Facility

Express, in equation form, the water balance of the tailings storage facility shown in Figure 7 of the main text, and repeated here as Figure Exercise 3-1.

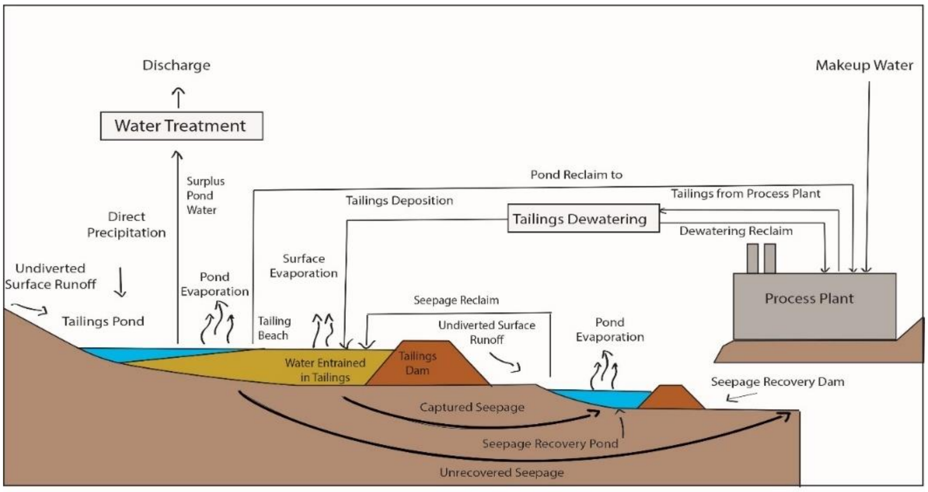

Figure Exercise 3-1 – Tailings Storage Facility.

Click for solution to exercise 3

Exercise 4 - Hydrodynamic Containment

The cross section below shows a proposed tailings impoundment in a central valley with higher terrain to the west and east, and the dry season, pre-development position of the water table.

The dashed line indicates the planned height of the tailings pond at the end of mine operations. Estimate the highest elevation of the pond for which there would be full hydrodynamic containment in the central valley (based on analysis of this section).

Explain why at the final proposed height of the tailings pond, the valley to the west is not expected to be impacted by water that seeps through the valley walls containing the pond, but the valley to the east can be anticipated to have a potential impact on groundwater quality.

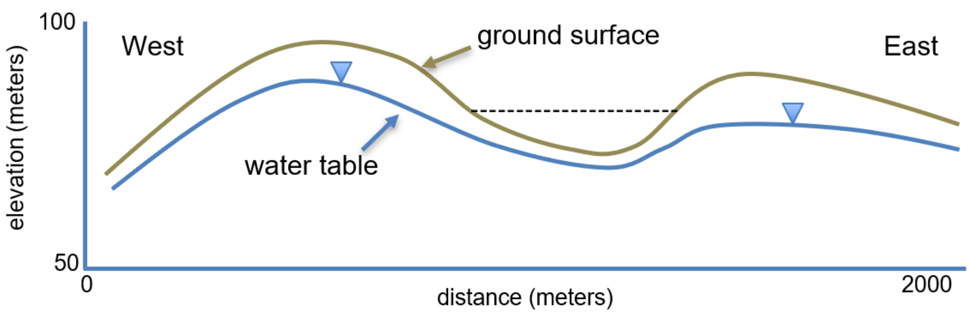

Figure Exercise 4-1 – Cross section of proposed tailings impoundment for Exercise 4.

Click for solution to exercise 4

Exercise 5 - Impact of Rock Mass Depressurization on Regional Flow

The cartoon below illustrates a proposed depressurization system for an open pit mine located in a limestone formation in mountainous terrain. A local community in the nearby valley relies on springs that discharge within the community property boundary for their potable water. Assume there are no dominant structural or dissolution features in the limestone that could control the pattern and rate of groundwater flow.

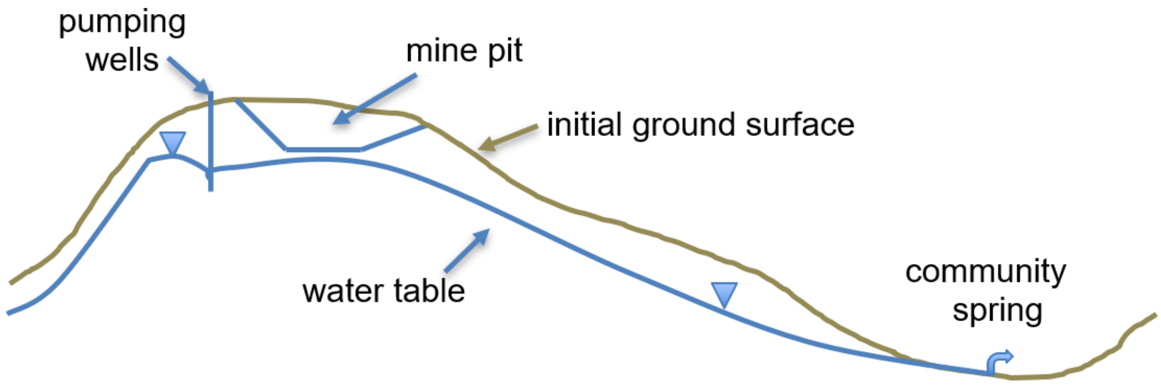

Figure Exercise 5-1 – Proposed depressurization system for open pit mine.

1. Derive a first-order estimate of the time it takes to observe a reduction in the hydraulic head in the vicinity of the springs due to the operation of the depressurization wells.

2. Assuming solute transport occurs only by advection, estimate the travel time of a solute that is mobilized by sulfide mineral oxidation on the pit walls, bypasses the capture zone of the production wells, and migrates to a discharge point at the springs.

The distance from the pumping wells to the springs is 3000 m. The distance from the open pit to the springs is 2800 m. Assume the effective hydraulic conductivity of the limestone is 5×10^{-6} m/s, the specific storage is 1×10^{-4} m^{-1}, and its effective porosity is 0.05. Assume the elevation difference between the floor of the pit and the springs is 200 m.

Click for solution to exercise 5⤵

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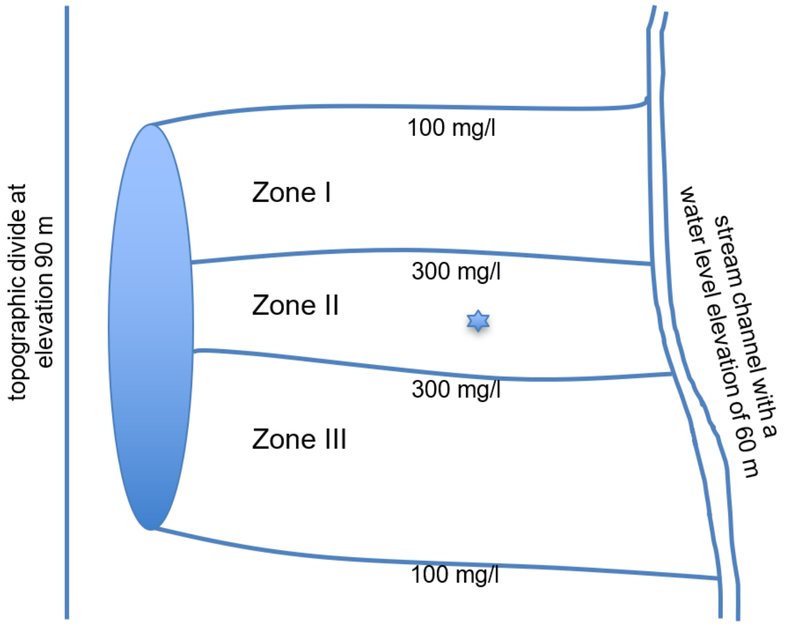
14 Exercise Solutions

Solution Exercise 1

1. *Loading calculation*

Estimate of the hydraulic gradient in aquifer: (80 m - 60 m) / 200 m = 0.1

Divide the sulphate plume into 3 zones, as shown below.



Zone I

Assume average sulphate concentration in Zone I of 200 mg/L

Given the distance from the divide to the stream, estimate the width of Zone I as 53 m

Cross-sectional area of flow at the stream: 53 m x 10 m = 530 m^2

Zone II

Assume average sulphate concentration in Zone II of 300 mg/L

Given the distance from the divide to the stream, estimate the width of Zone II as 33 m

Cross-sectional area of flow at the stream: 33 m x 10 m = 330 m^2

Zone III

Assume average sulphate concentration in Zone III of 200 mg/L

Given the distance from the divide to the stream, estimate the width of Zone III as 63 m

Cross-sectional area of flow at the stream: 66 m x 10 m = 660 m^2

Loading to stream is the product of the volumetric discharge (q=Kai) and concentration

Loading to stream in Zone I =

$$(5\text{x}10^{-4}\ \text{m/s})\ (530\ \text{m}^2)\ (0.1)\ (200\ \text{mg/L})\ (1000\ \text{L/m}^3) = 5300\ \text{mg/s} \cong 460\ \text{kg/d}$$

Loading to stream in Zone II =

$$(5\text{x}10^{-4}\ \text{m/s})\ (330\ \text{m}^2)\ (0.1)\ (300\ \text{mg/L})\ (1000\ \text{L/m}^3) = 4950\ \text{mg/s} \cong 430\ \text{kg/d}$$

Loading to stream in Zone III =

$$(5\text{x}10^{-4}\ \text{m/s})\ (660\ \text{m}^2)\ (0.1)\ (200\ \text{mg/L})\ (1000\ \text{L/m}^3) = 6600\ \text{mg/s} \cong 570\ \text{kg/d}$$

Total sulphate load carried to stream is approximately 1460 kg/d

2. *Key assumptions*

A number of simplifying assumptions have been made to derive this estimate. Other than those related to the reliability of the hydraulic conductivity estimate and the contouring of the sulphate plume, the key assumptions are:

- The hydraulic head gradient in the direction of groundwater flow within this unconfined aquifer is linear between the topographic divide and the stream.
- There is no bypass flow beneath the stream course, all the groundwater moving in this section of the aquifer discharges into the stream bed.
- To compute a representative concentration value for each zone, it was assumed there is a linear concentration profile across the width of each zone, between the contours. Because the maximum concentration in the monitoring well was only slightly higher than the bounding concentration contours defined by the vertically-averaged concentration, an average concentration of 300 mg/L was adopted for Zone II.
- The spread of contaminants beyond the 100 mg/L contours is minimal and can be neglected, some compensation for that is provided by ignoring the background concentration of the aquifer.

Return to Exercise 1↥

Solution Exercise 2

1) *Confined response*

Assume the hydraulic conductivity of the till is so much lower than that of the fractured bedrock that horizontal flow from the till into the pit is negligible, but vertical leakage downward into the fractured bedrock keeps the fractured bedrock fully saturated, thus the fractured bedrock responds as a confined unit. In this case, the time-varying inflow rate Q(t) can be approximated by the equation:

$$Q(t) = (4\pi K b s_w) / (2.3 \log (2.25Kbt / r_p^2 S))$$

where:

K is the hydraulic conductivity of the fractured bedrock horizon (5×10^{-6} m/s)

b is the thickness of the fractured bedrock horizon (30 m)

S_w is the design drawdown at the pit face (30 m - 5 m) = 25 m

r_p is the radius of the open pit (200 m)

S is the specific storage (1×10^{-5} m^{-1})

After a period of 3 years, the calculated inflow is approximately 360 m^3/d.

2) *Unconfined response*

For the case where the water table is near the top of the fractured bedrock, the pores of the fractured bedrock will drain so it responds as an unconfined unit, with $Q(t)$ approximated by:

$$Q(t) = (4\pi K b s_w) / (2.3 \log (2.25Kbt / r_p^2 S_y))$$

S_y is the specific yield (0.03).

After a period of 3 years, the calculated inflow is approximately 1240 m^3/d.

The predicted inflow is higher for the case where the fractured bedrock acts as an unconfined aquifer because of the greater volume of water released from storage for a unit decline in hydraulic head when the fractured bedrock unit dewater, in comparison to the case where water is released only from elastic storage.

This comparison highlights the fundamental importance of the conceptual model used to characterize the hydrogeologic system, even when using simplified analytical models for order-of-magnitude estimates.

Both calculations assume a negligible inflow to the open pit from the underlying low-permeability bedrock. This is a reasonable approximation given a hydraulic conductivity value of 10^{-9} m/s. If there were a permeable fracture zone within the deeper bedrock that intersected the pit flow, then higher flows could be anticipated if that fracture zone was itself connected to a more permeable hydrogeologic unit.

Return to Exercise 2↥

Solution Exercise 3

The water balance for a tailings storage facility is calculated by comparing all the volume inflow for a given time period with all the volume outflows. The difference between these volumes corresponds to the change in the volume of water held in the tailings storage facility over that time period. The water balance can be calculated either for the free water in the tailings facility, or the total volume of water, which includes the volume of water entrained within the tailings solids.

The water balance equation for the free water in the facility shown in the Figure can be written:

Inflows

Q_p	volume added from direct precipitation
Q_{runoff}	volume added by undiverted surface runoff in catchment
Q_{ts}	volume of water transferred in with the tailings discharge
Q_{rc}	volume of water returned from seepage collection pond

Outflows

Q_{pp}	water volume sent to process plant
Q_{wt}	water volume released to environment, after treatment (in any)
Q_{ent}	water volume entrained with tailings solids
Q_{ep}	water lost to evaporation from pond
Q_{eb}	water lost to evaporation from beach
Q_s	seepage to groundwater, recovered
Q_{snr}	seepage to groundwater not recovered

Change in Storage

ΔS	Change in volume of water held as free water in the pond

The water balance equation for free water in the pond would be:

$$\Delta S = (Q_p + Q_{runoff} + Q_{ts} + Q_{rc}) - (Q_{pp} + Q_{wt} + Q_{ent} + Q_{ep} + Q_{eb} + Q_s + Q_{snr})$$

Many of these quantities can be measured directly (e.g., volumes of water pumped between facilities) while other quantities can be estimated using climate data (e.g., evaporation). Seepage losses to groundwater are sometimes back-calculated after conducting bathymetric surveys of the tailings pond to calculate the change in pond volume over a given time period, and using the water balance equation to estimate seepage loss.

Return to Exercise 3↥

Solution Exercise 4

Recharge on the eastern flank of the valley maintains a minimum water table elevation at the drainage divide of approximately 80 m. On the western flank of the valley, recharge maintains a water table divide at an approximate elevation of 92 m. Therefore, if the elevation of the tailings pond rises above an elevation of 80 m, there will be an outward hydraulic gradient driving groundwater flow from the pond to the valley to the east of the tailings impoundment. Groundwater recharge on the west side of the valley maintains a water table elevation significantly above the proposed pond elevation, so a hydraulic gradient toward the pond is maintained, as is hydrodynamic containment. On the eastern side of the facility, an outward hydraulic gradient is established as the water table comes into equilibrium with the rising pond level, hydrodynamic containment is overcome, with flow toward the valley to the east. If the pond elevation were limited to a height of say, 75 m, then both sides of the valley would provide hydrodynamic containment.

It is useful to note that an assessment of this nature needs to be based on water table elevations in the dry season, because they reflect the lowest elevations and so, represent the most vulnerable condition.

Return to Exercise 4↥

Solution Exercise 5

1. *Impact Time for a Hydraulic Head Change at the Community Spring*

The time to observe a hydraulic head response at the community springs can be approximately by:

$$t = (L^2 S_S)/K$$

where L is the distance from the pumping center to the springs, S_s is specific storage of the limestone and K is hydraulic conductivity.

$$t = (3000\ m)\ (3000\ m)\ (1x10^{-4}\ m^{-1})\ /\ 5x10^{-6}\ m/s) \cong 6\ years$$

2. *Solute Arrival Time to the Community Spring*

The time for a solute released in the pit, which then bypasses the capture zone of the pumping wells, and migrates to the springs can be approximated using the equation for groundwater velocity (v):

$$v = (K\ /\ \theta)\ dh/dL$$

where θ is the effective porosity and dh/dL is the hydraulic gradient. The hydraulic gradient can be estimated in a simple way as the vertical distance between the pit floor and the springs divided by the distance from the pit to the springs. The water table at the open pit will likely be controlled by pumping at an elevation a small distance below the pit floor.

$$v = [(5x10^{-6}\ m/s)\ /\ 0.05]\ *\ [200\ m\ /\ 2800\ m]$$

$$v = 7x10^{-6}\ m/s$$

The solute arrival time by advective transport, assuming a linear horizontal flow path to the springs (that is, 2800 m) and steady state flow, travel time is distance/velocity.

time = distance/v = 2800 m / ($7x10^{-6}$ m/s) thus, the estimated travel time is about 12 years.

The calculation of both the head response time and the travel time should be viewed as initial estimates. If more accurate values were required in an impact assessment, standard practice would be to construct a three-dimensional hydrogeological simulation model to take into proper account the influence of domain geometry on pressure propagation and groundwater flow paths. Given the minimal time required to calculate an analytical solution, the results are valuable to a numerical modeler who can compare the values and, while qualitatively compensating for the simplifications of the analytical solution, can investigate the numerical model setup more carefully if the analytical and numerical results are strikingly different.

Return to Exercise 5↥

15 About the Author

Dr. Leslie Smith is an independent consultant and Professor Emeritus in the Department of Earth, Ocean and Atmospheric Sciences at the University of British Columbia in Vancouver. He was a professor in that department from 1981 until his retirement in 2016; between 1997 and 2016 he held the Cominco Chair in Minerals and the Environment. His field of specialization is groundwater flow and contaminant transport, and includes an emphasis on hydrologic aspects of mine waste management (tailings and waste rock) and surface water – groundwater interactions. He is a Fellow of the Royal Society of Canada and the American Geophysical Union. He currently serves on a number of Independent Geotechnical and Tailings Review Boards, for companies both in Canada and internationally.

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Modifications from Original Release

page iii, number of pages was changed from 67 to 69

page iv and v, the Table of Contents was updated

at a number of locations, the volume unit "liter" was abbreviated as "l" and was changed to "L"

at a number of locations, the time unit "day" was replaced with "d"

page 20, 1st paragraph, the expression e/1+e was changed to e/(1+e)

page 52, last sentence of section 9.5, the link was changed to www.energyres.com.au/sustainability/closureplan

page 54, third item (International Network for Acid Protection, 2017) link was changed to www.inap.com.au/wp-content/uploads/global-cover-system-design.pdf

page 63, and equal sign (=) was added after "Loading to stream in Zone II" and "Loading to stream in Zone III)"

page 64, a) and b) were changed to 1. and 2. to be consistent with Exercise 2