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The Influence of Climate on Seepage from Mine Waste Storages During Deposition and Post-Closure

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Abstract

Surface mine waste storages have the potential to generate contaminated seepage. While exposure to oxygen and the presence of high salinity are primarily responsible for the production of contaminants, the emergence of seepage from stored mine wastes is primarily dependent on the moisture state of the wastes on deposition, the geometry of the waste storage, and the duration of exposure to the climatic setting. Seepage rates are also affected by the extent to which the mine waste storage facilities are lined, whether naturally or by design, and by the effectiveness of any cover placed by way of rehabilitation. During the operation of a surface waste rock dump, oxygen is readily available, and the dump will wet up with rainfall at a rate dependent upon the amount and intensity of rainfall, the height of the dump, and the particle size distribution of the waste rock. On closure of a surface waste rock dump, some attempt may be made to limit both the ingress of oxygen and the net percolation of rainfall infiltration, through the placement of a suitable cover system over the dump. During the operation of a surface tailings storage facility, seepage will occur due to the large volume of water discharged with the tailings, although the ingress of oxygen into the tailings may be limited by their generally high degree of saturation. On closure of a surface tailings storage facility, seepage will diminish as the tailings drain down and will become controlled by rainfall, while desiccation of the tailings will allow greater ingress of oxygen. Some attempt may be made to limit both the ingress of oxygen and the net percolation of rainfall infiltration through the placement of a suitable cover system over the tailings, and the management of rainfall runoff. The paper describes the range of climatic regimes in which mines are located, ranging from arid, net evaporative climates to wet tropical, net infiltrative climates. It goes on to describe the superposition of the water balance of surface mine waste storages on these climatic regimes, both during their operation and post-closure, including the effectiveness of lining and cover systems in mitigating potentially contaminated seepage.

1 Introduction

Natural groundwater recharge rates are a function of the climatic regime and the hydraulic conductivity of the overlying strata. When mine waste is stored on the surface, the recharge regime is dramatically altered from the pre-mine situation. Surface waste rock dumps act as a sponge for rainfall infiltration, facilitating deep drainage beyond the reach of evaporative forces, leading to water storage within the pores of the waste rock, and the emergence of seepage at a rate higher than the natural recharge rate. Initially, the amount of seepage will be a small proportion of the rainfall, and seepage will be dominated by preferred pathway flow. As the dump progressively wets up from rainfall infiltration, its storage capability will become exhausted and the amount of seepage will eventually approach the amount of rainfall infiltration. Depending on the effectiveness of any cover placed on the waste rock dump on closure, and any crusting of the top surface of the dump over time, rainfall infiltration will reduce, as will seepage, as the water stored in the waste rock dump drains down.

During the operation of a conventional surface tailings storage facility involving slurry deposition, considerable water is discharged with the tailings which, depending on the rainfall regime, can be many times the rainfall, causing seepage at a rate many times the natural recharge rate. Deposition of the tailings as a thickened slurry, paste, or filter cake will increasingly reduce the potential for seepage. On closure, the tailings will drain down and the seepage rate will diminish over time.

2 Natural groundwater recharge rates

2.1 Recharge in arid and semi-arid regions

In arid and semi-arid regions, where many of the world's mines are located, the groundwater is typically deep and is overlain by an unsaturated zone of very low hydraulic conductivity. Streams are predominantly ephemeral, often underlain by a perched underground stream in a sand or gravel bed, which itself is underlain by an unsaturated zone above the groundwater table. The base of the underground stream is typically effectively "sealed" by fine sediments, delivering limited water to the unsaturated zone beneath and maintaining its unsaturated state and very low hydraulic conductivity. If this were not the case, all surface and near-surface water would rapidly disappear to the ground, which has ample porosity to store it. There may be a number of perched water tables or aquifers in the profile, and in tight rock of low permeability the groundwater may be restricted to fracture zones.

Groundwater recharge data reported by Beekmann et al. (1996) for arid and semi-arid Southern Africa highlight the effect of climate on recharge rates, as shown in Figure 1. Groundwater recharge in arid and semi-arid areas of Australia still covered by the original native vegetation is close to zero (Cook et al., 2004), since native vegetation has evolved to be particularly efficient at removing the limited available moisture, remaining dormant during droughts and blooming following wet periods. Much of the recharge of the Great Artesian Basin, which covers more than 20% of northeastern Australia, is via outcropping sandstone along the western slopes of the Great Dividing Range, with contributions via leakage from streams and rainfall infiltration (Cox and McKay, 2003).

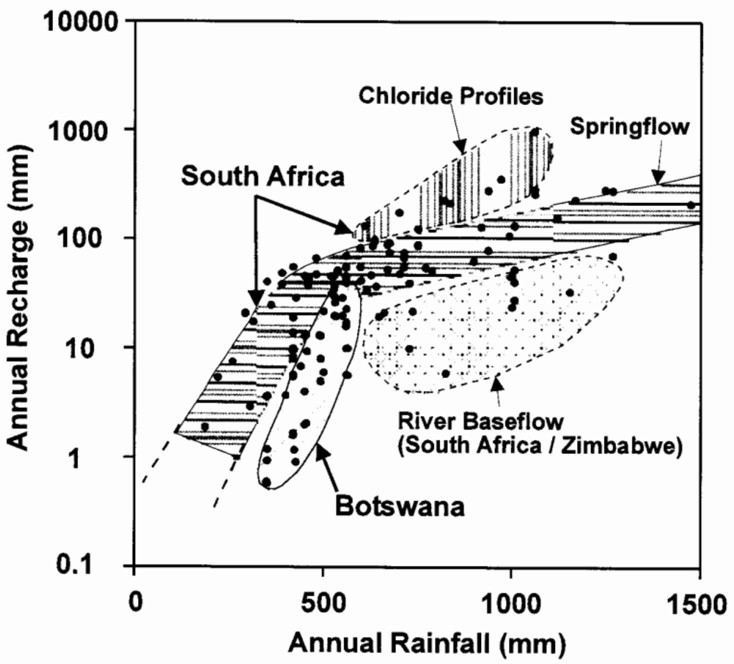


Figure 1 Results of recharge studies from Southern Africa (Beekmann et al., 1996)

Stripping or burning native vegetation for grazing purposes, which vegetation covers about 60% of Australia's land area, may increase recharge rates to between about 1 mm/year and 10 mm/year (Cook et al., 2004). Irrigation for cropping, which covers about 6% of Australia's land area, may increase recharge rates to between about 10 and 100 mm/year, with infiltration rates increasing as continued irrigation wets up the unsaturated zone, rendering it more permeable (as supported by farmers' experiences). The high evaporation rate in Australia's climate concentrates salt at the surface, and the increased net percolation into the ground increases its hydraulic conductivity and captures stored salts, which can later be drawn to the surface by evaporative forces or through the daylighting of groundwater.

2.2 Rainfall versus evapotranspiration

Based on Australian Bureau of Meteorology (www.bom.gov.au) and worldwide climatic data (www.blueplanetbiomes.org/climate.htm/ and www.worldweather.org/) for a range of major mine sites worldwide, the average annual rainfall and evapotranspiration have been compared on Figure 2. Figure 2 shows a threshold average annual rainfall of about 250 mm/year (corresponding to the average annual rainfall of Kalgoorlie in Western Australia), above which net infiltration would be expected and below which net evaporation from the surface would be expected, with no net infiltration. However, below the threshold average annual rainfall, the more extreme rainfall events would induce some net infiltration under natural conditions, and even more due to mine disturbance (including the removal of vegetation, the "sponge" effect of waste rock dumps, and the tailings water added to operational tailings storage facilities).

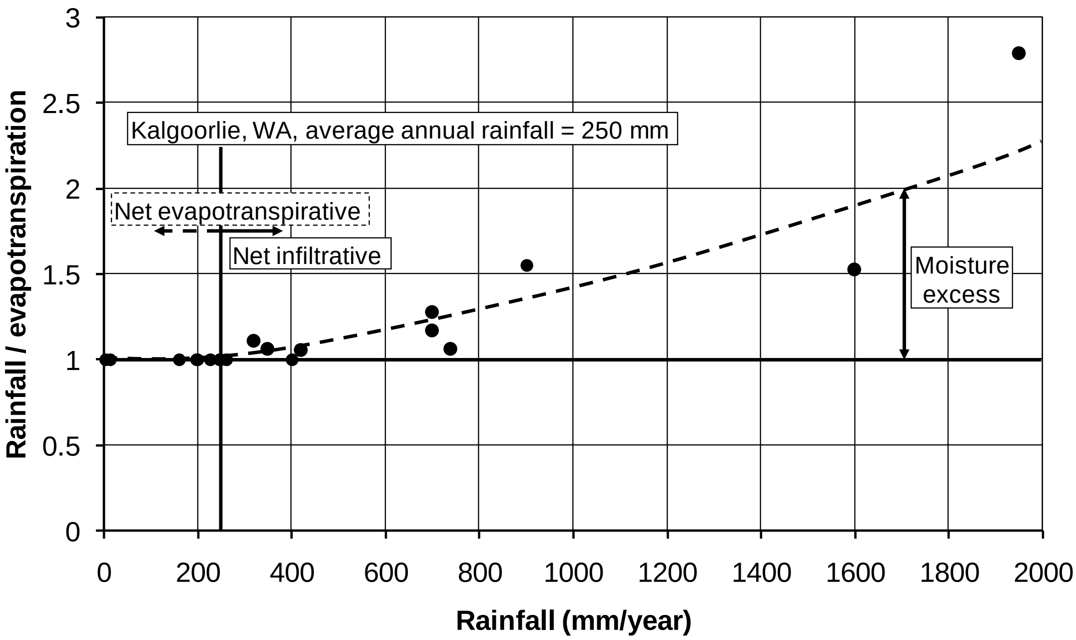


Figure 2 Rainfall/evapotranspiration versus rainfall

3 Impact of surface mine waste storages on recharge

3.1 Waste rock dumps

3.1.1 Conventional construction

Before discussing the mechanisms of rainfall infiltration into surface waste rock dumps and consequent groundwater recharge, it is necessary to examine their typical structure. Surface waste rock dumps are conventionally constructed by loose end-dumping from haul trucks off a series of tip-heads forming a number of lifts, with benches between lifts to allow haul truck movements. From each tip-head, the waste rock ravels down-slope at the angle of repose of the material (35 to 40° to the horizontal, the angle being least for high slopes of weathered rock and greatest for fresh rock). Since the larger boulders (typically up to 1 meter in size) ravel to the toe of the slope, a rubble zone is formed at the base of each lift, which ensures the ready ingress of oxygen (Herasymuik et al., 1995). The bulk of the slope will comprise discontinuous, alternating layers, typically 0.3 to 1 meter thick, of fine and coarse-grained waste rock due to the pattern of raveling caused by the discrete truck dumping operations. The flat tops of each of the lifts, being heavily trafficked by haul trucks and dozers, will comprise compacted, fine-grained, broken rock, typically finer than 100 mm in size, having a thickness of the order of 1 meter. The compacted surfaces will be capable of allowing rainfall runoff to pond temporarily, before it is lost to infiltration and evaporation. Runoff from the top of the dump may be limited by the safety windrows constructed along the crest.

The structure of a conventional surface waste rock dump renders it an oxidation reactor with respect to any reactive materials present. Oxygen will readily enter the dump through the base rubble zone, from which it migrates up the coarse-grained angle of repose layers, before diffusing into the adjacent fine-grained angle of repose layers, driven by the exothermic oxidation reactions. The fine-grained material presents the highest surface area per unit volume, and hence is the most potentially reactive. Oxygen can also enter the dump via its loose side slopes, with limited diffusion of oxygen through the traffic-compacted tops of each lift. Any movement of water through the dump will pick up any oxidation products and potentially deliver them to the environment, either by seepage to the foundation, or from the toe of the dump along buried surface drainage channels.

3.1.2 Rainfall infiltration, storage and seepage during operation

The water balance of a surface waste rock dump includes the initial moisture content of the waste rock (likely to be low), rainfall runoff (if this is allowed), evaporation (both from surface ponding and from storage in near-surface layers), rainfall infiltration and storage, and seepage. The mechanisms of rainfall infiltration include preferred pathway flow and the progressive more broad-scale wetting up of the dump through the storage of rainfall infiltration. Initially, most of the rainfall infiltrating a waste rock dump goes into storage, with only a minor amount (about 2 to 4% of the average annual rainfall beneath the dump top and dumps sides, respectively: Williams and Rohde, 2008) emerging as base seepage via preferred pathway flow along open “pipes” within the dump, triggered by heavy rainfall events or the cumulative storage of rainfall infiltration within the dump over time.

Cumulative rainfall infiltration will cause a wetting up of a surface waste rock dump over time, at a rate dependent upon the amount and intensity of rainfall, the height of the dump, and the particle size distribution of the waste rock. The net infiltration will largely be retained in storage, particularly within the fine-grained angle of repose layers within the dump. Eventually, an uncovered dump will wet up sufficiently that there are continuous water pathways through the partially saturated dump, and any rainfall infiltration will be matched by base seepage, resulting in continuum breakthrough and a far greater potential for contaminant transport to the environment.

3.1.3 Estimated time for continuum breakthrough

Continuum breakthrough corresponds to a degree of saturation of about 60% for weathered waste rock (which is typical of most waste rock exposed for a number of years), at which the rate of seepage from the base of the waste rock dump will match the rate of rainfall infiltration into the top of the dump. Figure 3 provides estimates of the time for continuum breakthrough of waste rock dumps of different heights comprising weathered rock, subjected to different average annual rainfalls, obtained by iteratively distributing rainfall infiltration into the dump (Williams, 2006). It assumes no runoff (a reasonable assumption during the construction of a waste rock dump, when windrows at the crest limit runoff), the ponding of rainfall on the traffic-compacted surface of the waste rock dump, and evaporation from ponded water and the near-surface of the waste rock dump. In developing Figure 3, infiltration and evaporation have both been taken to be about 50% of the average annual rainfall.

In a very dry climate, which will delay continuum breakthrough until well beyond the life of the mine, the surface of the waste rock dump may develop a crust and self-seal over time, further delaying or even avoiding continuum breakthrough and the need for a low net percolation cover. In a very wet climate, a waste rock dump will wet up and reach continuum breakthrough rapidly, most likely during the life of the mine and before a low net percolation cover is placed.

3.1.4 Seepage post-closure

While the placement of a cover on the top of a waste rock dump may reduce net percolation into the dump, the water stored within the dump during its operation and prior to it being covered will continue to seep for many years (Williams et al., 2006), perhaps for as long as the dump was left uncovered. After the construction of an effective low net percolation cover, seepage (and the transport of any contaminants) into the foundation will diminish exponentially over time as the waste rock drains and loses hydraulic conductivity. Seepage from the dump will eventually reduce to the net percolation rate through the cover, which is likely to be higher than the natural recharge rate. Any groundwater mounding beneath the dump will subside over time, eventually trending towards its original elevation.

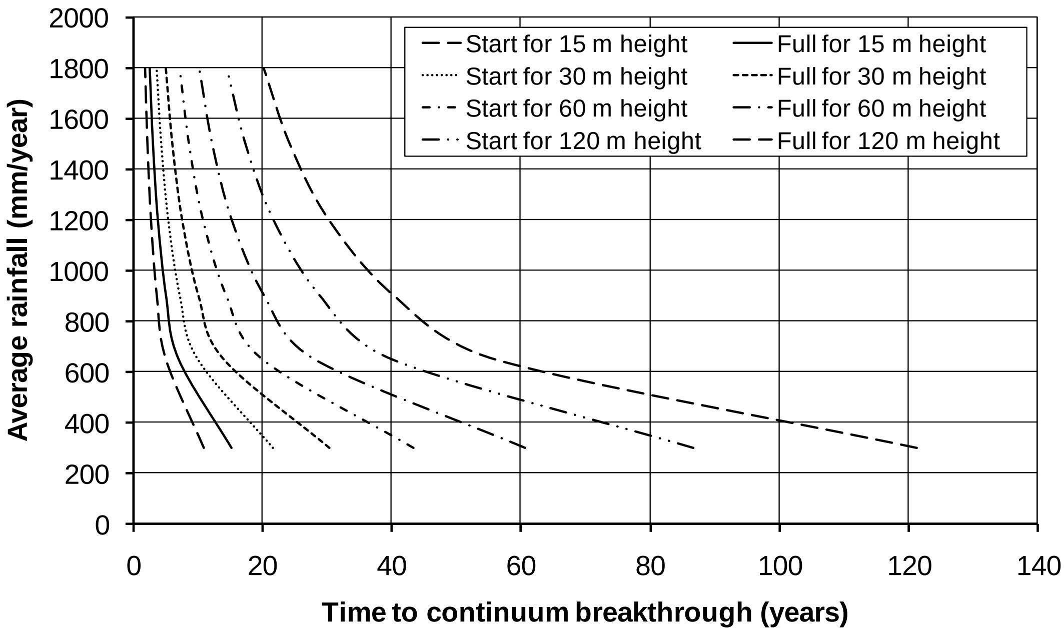


Figure 3 Estimated time for continuum breakthrough of weathered waste rock dumps as a function of average annual rainfall and dump height

For the side slopes of a waste rock dump, the difficulty of constructing a sealing layer, and the potential for erosion of the cover, make the construction of sustainable, low net percolation covers problematic. The side slopes of most dumps may remain prone to infiltration during heavy or continuous rainfall, and it is therefore essential that they be constructed of benign waste rock of sufficient thickness to produce clean runoff and seepage. Further, to limit erosion, the side slopes will generally require a rocky cover.

3.2 Tailings storage facilities

3.2.1 Conventional slurry deposition

The conventional disposal of tailings as a slurry involves ongoing flooding of the tailings surface, with water not entrained within the tailings reporting to the decant pond, or lost to evaporation and seepage. The amount of seepage can be restricted by placing the tailings as dry as possible, and by efficiently removing water from the decant pond. If of suitable quality, tailings water collected in the decant pond could be re-cycled to the processing plant, or may be pumped to an evaporation pond.

Initially, seepage to the foundation is limited by the very low hydraulic conductivity of the unsaturated zone within the foundation. A wetting up front advances downwards, aided by any preferred seepage paths, raising the hydraulic conductivity of the unsaturated zone and causing groundwater mounding, with any contaminants in the seepage able to reach the groundwater. Tailings deposition could be cycled between cells, to allow the tailings to desiccate and to maintain unsaturated conditions within the foundation, and hence limit seepage. The containment walls of surface tailings storage facilities are typically constructed of, or faced with, waste rock, which should be benign and of sufficient thickness to produce clean seepage and runoff.

3.2.2 Drain down and seepage post-closure

Even in an arid or semi-arid climate, the water entrained within the tailings during the operation of the storage facility will continue to seep for many years. Seepage (and the transport of any contaminants) into the foundation will diminish exponentially over time as the tailings drain down and lose hydraulic conductivity. Provided that rainfall runoff is not concentrated locally on the tailings surface but is spread to enhance evaporation, or removed via a spillway, long-term seepage rates will be low and any groundwater mounding beneath the tailings storage facility will subside over time, eventually trending towards its original elevation.

Given the relatively low hydraulic conductivity of tailings, particularly as it desaturates, a cover to limit infiltration may not be necessary in an arid to semi-arid climate, provided the tailings are not allowed to fully resaturate by long-term concentrated ponded water. A net evaporative moisture flux should persist within the tailings, despite periodic re-wetting for short periods following rainfall events. However, a cover may be desirable and necessary for revegetation purposes. Overtopping of the outer slope of the tailings containment should be avoided to limit erosion.

Seepage rates from tailings storage facilities in wet climates may remain high; however, wet climates may offer the potential to maintain tailings underwater to limit oxidation and the production of contaminants.

4 Worldwide data on recharge from operating surface mine waste storages

4.1 Waste rock dumps

The limited available worldwide data on infiltration and seepage from operating waste rock dumps are summarized in Table 1. For the available data, there is no correlation between rainfall infiltration or seepage and the thickness or age of the waste rock dump. However, it might be expected that seepage, which dictates the potential to impact the environment, would be less than rainfall infiltration, with greatest convergence of the two for thin lifts of waste rock and older waste rock dumps. This is borne out by Figure 4, which shows infiltration or seepage as a percentage of average annual rainfall versus the ratio of dump thickness to age in m/year. The tabulated infiltration ranges from 39 to 100% of average annual rainfall (the higher values corresponding to shallow waste rock dumps, with an average 55% for full-scale dumps of various ages and in a range of climates), and the reported seepage ranges from 2 to 85% of average annual rainfall (averaging 37% for older, full-scale dumps in a range of climates).

4.2 Tailings storage facilities

Limited data on seepage from operating tailings storage facilities have been collected, despite the high seepage rates that occur. Available operational data on seepage beneath tailings storage facilities ranges from 0.5 to 1 times the average annual rainfall, or more, or typically 15% of the water balance (Williams and Williams, 2007). The low end of this range corresponds to wet climates, and/or low rates of rise, and/or tailings discharge at high solids concentrations. The high end of the range corresponds to very dry climates, and/or high rates of rise, and/or tailings discharge at low solids concentrations. These seepage rates would double natural groundwater recharge rates in wet climates, and could be up to 200 times natural recharge rates in dry climates.

The fate of the seepage from a surface tailings storage facility will depend on the relative permeabilities of the tailings at the base of the storage, the foundation beneath the tailings, and the containment wall. A low hydraulic conductivity of the base tailings and/or foundation may force the seepage through the containment wall, while coarse-grained tailings of high hydraulic conductivity underlain by a foundation of high hydraulic conductivity will promote seepage to the foundation. If the base tailings and/or foundation, and the containment wall, all have low hydraulic conductivity, tailings water will remain entrained within the tailings.

5 Effectiveness of liners and covers

5.1 Liners beneath tailings storage facilities

Due to the excess water delivered with slurried tailings, the operation of a tailings storage facility can induce seepage to the foundation and groundwater recharge at a rate at least one to two orders of magnitude higher than the natural recharge rate, and will transport any contaminants present in the tailings or tailings water (Williams and Williams, 2007). Tailings disposal will also create surface ponding on the tailings storage facility, and excess water may be directed to separate evaporation ponds, presenting potential hazards to birds.

Table 1 Worldwide data on waste rock dump infiltration and seepage

Location	Average Annual Rainfall (mm/year)	Age (years)	Thickness (m)	Infiltration (% average annual rainfall)	Seepage (% average annual rainfall)	Source
Australia:						
Argyle, WA	700	20	~ 50	60	60	Wright (2006)
Cadia, NSW, trial	938	1.33	15	50	2 (top) 4 (sides)	Williams and Rohde (2008)
Century, QLD	400	8	50	~ 60	~ 2	Williams (2007)
Kidston, QLD	550	18	Av. 40	~ 50	~ 50	Williams et al. (2006)
USA:						
Questa, NM	226	39	30 to 60	50	-	McLemore et al. (2006) Wilson, pers. comm. (2007)
Canada:						
Whistle, ON, trial	900	3 to 4	6.1	56 to 58	56 to 58	Adu-Wusu and Yanful (2006; 2007)
Northern SA, trials	455	3	5, loose	100	54	Marcoline et al. (2003)
			5, compact	85	14	
		7	5, loose	100	57	Nichol et al. (2005) Wilson, pers. comm. (2007)
		0.42	Trafficked	39	-	Carey et al. (2005)
South America:						
Peru, trial	13	0.33	10	85	85	Wilson, pers. comm. (2007)

Tailings storage facility liners have the potential to greatly reduce the seepage from tailings storage facilities, increasing the volume of surface water that must be handled and the volume occupied by the tailings, but liners are not always effective. Effective liners and associated underdrainage beneath the tailings must be appropriately engineered, and their use must be weighed against the potential environmental benefits in saline and hypersaline groundwater regimes (such as exist in the Eastern Goldfields of Western Australia), the need to handle the increased volumes of tailings water that will report to the surface, and an alternative or additional means of reducing tailings seepage involving thickened or paste tailings.

Consideration may be given to lining tailings storage facilities for a variety of reasons, including a desire to conserve water for re-use, a need to minimize impacts on groundwater, to positively address public (or Regulator) perceptions and concerns, an obligation to comply with corporate policy and/or some other motivation to reduce environmental impacts. The decision to line a tailings storage facility should not be taken lightly, as the cost implications of installing an appropriately engineered barrier to seepage are significant.

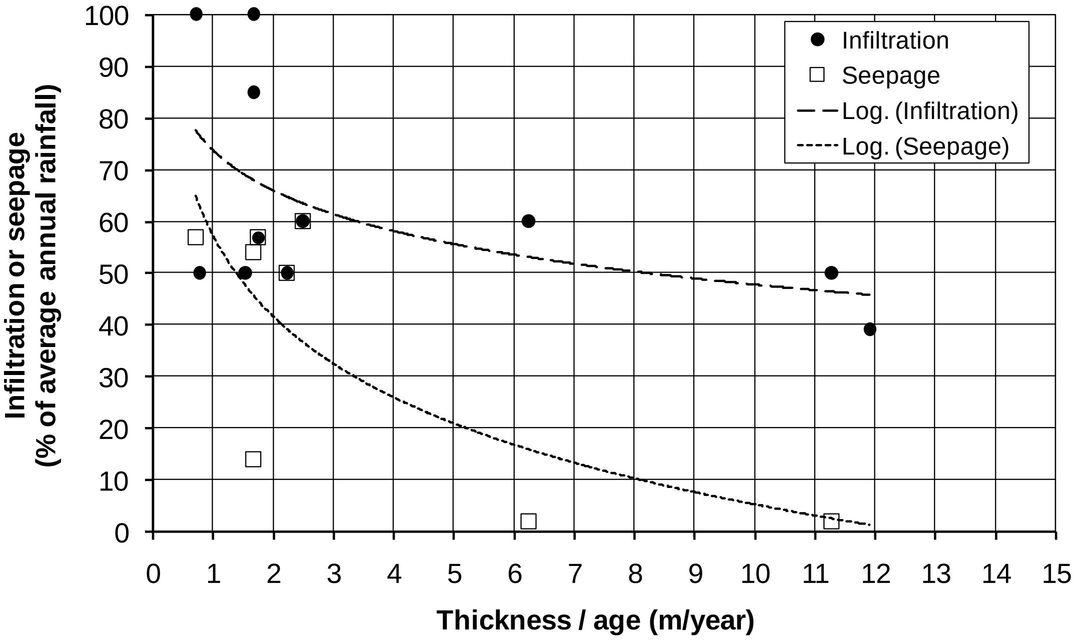


Figure 4 Infiltration into and seepage beneath dump tops versus waste rock dump thickness/age

5.1.1 Lining alternatives

The effectiveness of liners depends on their integrity, which in turn depends on the materials used and the construction and maintenance methods employed. Their effectiveness also depends on the hydraulic gradient to which they are subjected, which in turn depends on whether underdrainage is provided and how effective it is, the applied hydraulic head, and the thickness of the liner. Liners can comprise natural earthen materials, geomembranes (e.g. HDPE) and composite such as geosynthetic clay liners (GCLs). The potential effectiveness of various liners is summarized in Table 2. In Table 2, typical saturated hydraulic conductivity values are given in the usual "m/s" and also in "mm/year", the latter enabling ready comparison with average annual rainfall.

Table 2 Potential effectiveness of liners

Material	**Saturated Hydraulic Conductivity (unit hydraulic gradient)**		**Liner Thickness**	**Leakage Rate (10 m head)**
	(m/s)	(m/s)	(mm)	(m/s)
Geomembrane:				
Intact	10^{-14}	0.0003		
In practice	10^{-10}	3	1.5	7×10^{-7}
GCL	10^{-10}	3	5	2×10^{-7}
Natural, unfissured clay	10^{-9}	32	3	3×10^{-9}
Well compacted clay	10^{-8}	315	0.3	3×10^{-8}
Poorly compacted clay	10^{-7}	3,150	0.3	3×10^{-7}
Tailings	10^{-7}	3,150	10	10^{-7}

The saturated hydraulic conductivity represents the leakage rate through the liner for a unit hydraulic gradient, corresponding to effective underdrainage. While intact geomembranes are practically impermeable, in practice a geomembrane liner will have imperfections resulting in a much higher effective permeability (Rowe et al., 2002). Also given in Table 2 are the leakage rates for a 10 meter hydraulic head applied to each liner, assuming no, or ineffective underdrainage. While an HDPE or GCL liner is clearly the most effective where underdrainage is fully functional, the high hydraulic gradient applied to thin liners in the absence of fully functional underdrainage renders them among the least effective.

The foregoing discussion highlights the potential pitfalls of tailings storage facility liners. For a tailings storage facility liner to be effective, a liner of low saturated hydraulic conductivity must be selected, the integrity of the exposed liner must be ensured, and the hydraulic head on the liner may need to be managed through the installation of underdrains beneath the tailings.

For evaporation ponds, reliance must be placed largely on the effectiveness of the liner and foundation to limit seepage to the groundwater, and on maximizing evaporation and limiting the hydraulic head by employing shallow ponds. However, this increases the area of the ponds, increasing the potential hazard to birds.

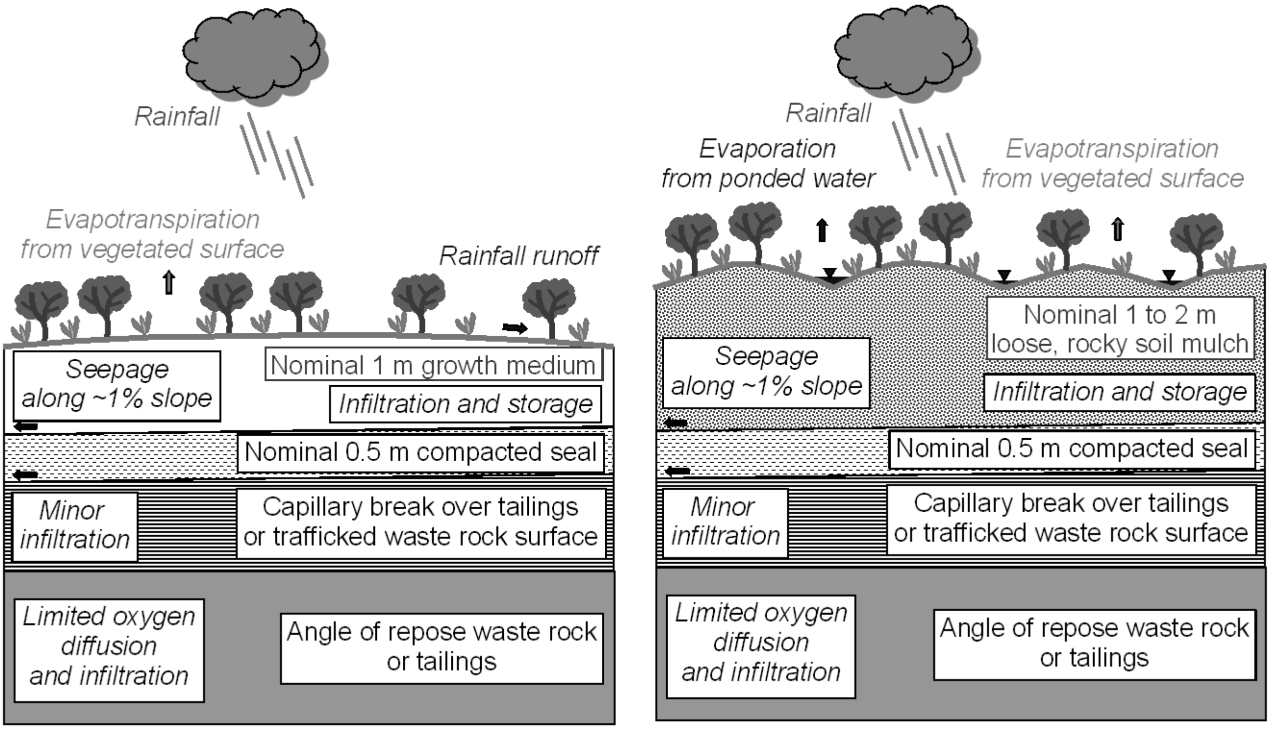
5.2 Covers

The two most common cover types applied to mine wastes are: (a) rainfall-shedding or barrier covers, and (b) store/release covers (Williams et al., 1997; 2006), as shown schematically on Figure 5. Rainfall-shedding covers were developed for landfills, partly to limit the net percolation of rainfall into the potentially contaminating landfill, but also to accommodate the inevitable large total and differential settlements of the landfill. The key element of a rainfall-shedding cover is a barrier or sealing layer, comprising compacted clayey soil, a geomembrane or a composite of the two, which is generally overlain by a growth medium. Rainfall-shedding covers are applied in wet climates, in which a vegetative cover can be sustained to limit erosion.

The key elements of a store/release cover developed for seasonal, dry climates are: (i) a thick loose rocky soil mulch layer with an undulating surface to store the wet season rainfall without inducing runoff, (ii) an effective sealing layer at the base of the cover to “hold-up” rainfall infiltration and, (iii) the appropriate choice of sustainable vegetation to release the stored rainfall during the wet season, through evapotranspiration. The required thickness of rocky soil mulch will depend on the wet season rainfall pattern and the rooting depth of the vegetative cover, and is typically 1 to 2 m thick. The sealing layer needs to ideally achieve a saturated hydraulic conductivity of less than 10^{-8} m/s, so that in its usual unsaturated state its hydraulic conductivity will be less than 10^{-10} to 10^{-9} m/s (less than 3 to 30 mm/year). The cover should cycle annually between wet and dry states without a net wetting up (which would lead to net percolation) or drying out (which would cause vegetation die-back and subsequent rainfall-induced erosion). In Australia’s generally arid to semi-arid climate, a eucalyptus tree cover represents the only sustainable means of achieving the required evapotranspiration rates from a store/release cover in the long-term. Since the rocky mulch layer is loose and granular, the trees are unlikely to promote cracking and the development of preferred seepage pathways.

5.2.1 Performance of covers on waste rock dumps

Available worldwide data on the performance of uncovered dumps, and rainfall-shedding and store/release covers over waste rock dumps are summarized in Table 3, and cover performance is plotted on Figure 6. For relatively young covers in wet climates, or subjected to particularly wet years (greater than about 450 mm of rainfall), both cover types show relatively high net percolation as a percentage of average annual rainfall (up to 61% for rainfall-shedding covers and up to 13% for store/release covers). The highest net percolation corresponds to rainfall-shedding covers on slopes that do not incorporate a compacted sealing layer. In dry climates, rainfall-shedding covers show a general exponential deterioration with time, due to the loss of cover integrity. In dry climates (less than about 550 mm average annual rainfall), store/release covers incorporating a sealing layer show good performance up to at least 10 years (the maximum age reported), with net percolation of generally less than 2% of average annual rainfall. There is a paucity of data on the performance of covers on tailings storage facilities.



(a) (b)

Figure 5 Most common cover types applied to mine wastes: (a) rainfall-shedding and, (b) store/release

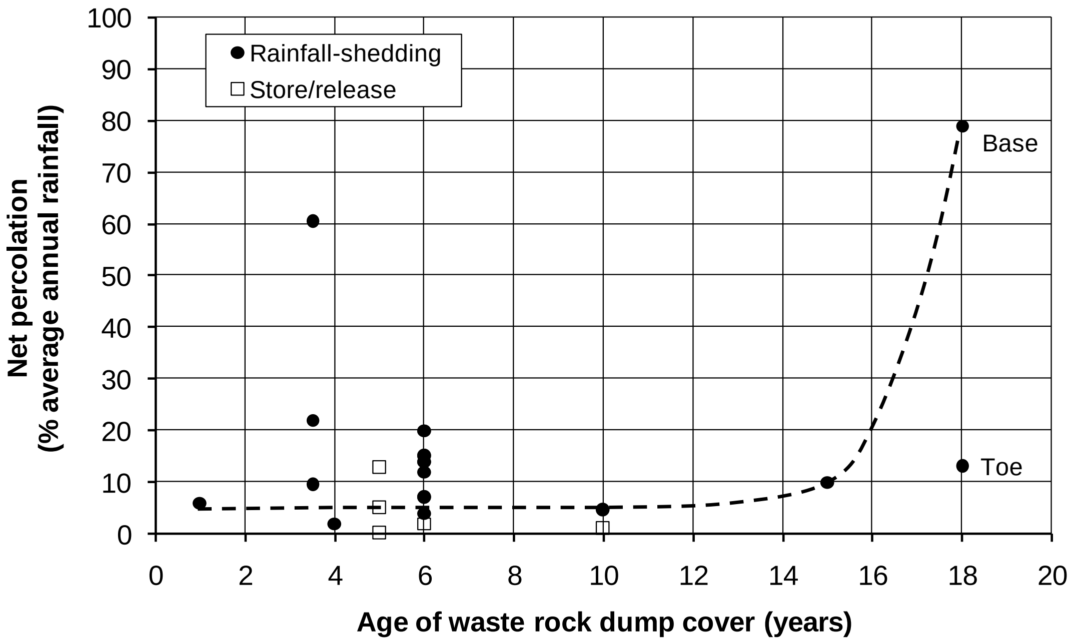


Figure 6 Performance of: (a) rainfall-shedding and, (b) store/release covers over time

Table 3 The performance of covers on waste rock dumps in Australia, America and Canada

Location	Cover Type	Age (years)	Net Percolation (% average annual rainfall)	Source
Australia:				
Kidston, QLD	Store/release (2.5 m)	10	< 1	Williams et al. (2006)
Mary Kathleen, QLD	Rainfall-shedding (1.5 m)	18	79 (base) 13 (toe)	Lottermoser et al. (2003)
Mt Whaleback, WA	Store/release (2 m) Store/release (4 m)	5 5	5 to 13 0	O'Kane and Waters (2003)
Rum Jungle, NT	Rainfall-shedding (0.75 m)	0 to 10 18	2 10	Kuo et al. (2003) Taylor et al. (2003)
USA:				
Goldstrike, NV	Store/release (1.8 m)	6	2	Zhan et al. (2006)
Canada:				
Equity, BC	Rainfall-shedding (0.8 m)	10	5	Swanson et al. (2003)
Whistle, ON	Uncovered	3 to 4	57	Adu-Wusu and Yanful (2006)
	Rainfall-shedding:			
	• 1.36 m incl. bentonite	3 to 4	22	Adu-Wusu and Yanful (2007)
	• 1.5 m incl. clay	3 to 4	61	
	• 0.9 m incl. GCL	3 to 4	10	
Northern SA, trials	Uncovered Rainfall-shedding (0.25 m compacted)	8 8	50 6	Marcoline et al. (2006)

6 Conclusions

Surface mine waste storages have the potential to generate contaminated seepage, depending on the moisture state of the wastes on deposition, the geometry of the waste storage, and the duration of exposure to the climatic setting. Seepage rates are also affected by the extent to which the mine waste storage facilities are lined, whether naturally or by design, and by the effectiveness of any cover placed by way of rehabilitation. For waste rock dumps, seepage rates will inevitably increase as the dump wets up due to rainfall infiltration, until or unless an effective cover is placed. For tailings storage facilities, seepage rates will be at their highest during the operation of the facility, and will decrease as the tailings drain down post-closure, particularly if an effective cover is placed to limit further net percolation.

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