Early Hydrological Monitoring of Cadia's Instrumented Trial Waste Rock Dump[1]

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ABSTRACT

Understanding how rainfall infiltrates, is stored within and is transported through surface waste rock dumps is essential to predicting the release rates of mineral weathering products to the environment. Infiltration is commonly assumed to be 50% of annual rainfall. There are however a lack of field data to confirm this. Further, there is poor understanding of the fate of rainfall infiltration; the proportion that goes into storage within the dump and the proportion that emerges from the base of the dump as seepage. In addition, there is poor understanding of the size of rainfall event necessary to trigger base seepage and the time delay before base seepage emerges following the rainfall event, and how these parameters change as the dump wets-up. Waste rock dumps are heterogeneous in nature, with conventional end-dumping of waste rock from a tip head resulting in a base rubble zone, alternating angle of repose coarse and fine-grained layers within the dump, and a traffic-compacted top surface, creating highly non-uniform pore distributions and preferred flow paths. These preferred flow paths are likely to dominate the transport of water through the dump. A 15 m high trial waste rock dump comprising potentially acid forming material has been constructed at Cadia Hill Gold Mine in New South Wales, Australia. It has been instrumented with two surface lysimeters and 24 base lysimeters to monitor infiltration through the top of the waste rock dump and base seepage beneath the top surface and the side slopes of the dump. The paper describes the design and construction of the trial dump and its instrumentation, and the results of the first 2 years and 8 months of monitoring to 1 September 2008.

Additional Key Words: Acid rock drainage, evaporation, infiltration, lysimeters, preferential flow, runoff, seepage, storage, unsaturated soil mechanics

INTRODUCTION

Rainfall infiltration rates into a surface waste rock dump, storage within the dump and seepage from the base of the dump are not well understood. They are a function of climate, the method of dump construction and resulting dump structure, and the physical and chemical characteristics of the waste rock.

Depending on the sulfide content and reactivity of the waste rock and the availability of oxygen and water, and flow through the dump, acid rock drainage (ARD) can result. Knowledge of waste rock dump hydrology is critical to predicting the rate and quantity of

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ARD (Swanson *et al*., 2000; Williams and Rohde, 2007; Williams and Rohde, 2008a; Williams and Rohde, 2008b). Waste rock dump hydrology is further complicated by the unsaturated nature of the waste rock and the heterogeneous internal structure of the dump.

Conventional waste rock dump construction

The particle size distribution of the waste rock delivered to the dump will depend on the fragmentation of the rock due to blasting and the degree of weathering and hence breakdown on handling of the rock. A waste rock dump constructed by conventional loose end-dumping from haul trucks from a tip-head consists of a trafficked surface layer extending to a depth of approximately 1 m, underlain by discontinuous alternating coarse and fine-grained layers ravelling at the angle of repose of the waste rock, with a base rubble zone of boulders which ravel to the toe of the dump on end-dumping (Herasymuik, 1996). The structure of a conventional waste rock dump renders it an oxidation reactor with respect to any sulfide present. Herasymuik (1996) proposed a conceptual model that accounts for flow and storage of water within waste rock dumps constructed by end dumping. According to the Herasymuik model, the flow of water occurs along layers of finer material under negative pore-water pressures, and the flow of oxygen occurs in layers of coarser material with open pore spaces; i.e. the base rubble zone and coarse-grained angle of repose layers. The fine-grained material presents the highest surface area per unit volume and hence is the most potentially reactive. Oxygen can also enter the waste rock dump through its loose side slopes, with limited diffusion of oxygen through the traffic-compacted top of the waste rock dump (Wilson *et al*., 2000; Williams *et al*., 2003)

Rainfall infiltration, seepage mechanisms and sulfide oxidation

The water balance of a waste rock dump includes rainfall infiltration, runoff (if this is allowed) and evaporation (both from surface ponding and from storage in near surface layers). The mechanisms of rainfall infiltration include preferred pathway flow and the progressive more broad-scale wetting up of the dump. Nichol *et al*., (2000) and Nichol *et al*., (2003) found that for waste rock placed randomly in an intermediate scale pile (8 m square, 5 m height) flow occurred through the fine-grained matrix, within larger pores and within matrix free areas. Nichol *et al*., (2003) showed that the application of water at a constant rate to the surface of a pile experiment will result in a complex discharge. Tracer testing indicated spatially distinct flow paths with differential wetting velocities and dispersive properties (Nichol *et al*., 2003). Marcoline *et al*., (2003) concluded that the internal pile structure (as described by Nichol *et al*., 2003) appears to dominate flow processes. Li (2000) concluded that infiltration is heterogeneous for unsaturated flow, and homogenous or ubiquitous for flow channelling for waste rock in columns (1.5 m diameter, 2 m height). Therefore, initially any base seepage may reasonably be expected to occur via preferred pathway flow along open channels within the dump, triggered by heavy rainfall events or the cumulative storage of rainfall infiltration within the dump over time. During the early life of a waste rock dump, while base seepage may be relatively high at the localised channels, the total amount of seepage over the area of the dump is likely to be small. In the longer term, cumulative rainfall infiltration will cause a slow wetting up of a waste rock dump over many years, particularly of the fine-grained angle of repose layers within the dump, and will largely be retained in storage.

Eventually, the waste rock dump will wet up sufficiently that there are continuous water pathways through the dump and any rainfall infiltration will be matched by base seepage, resulting in breakthrough and a far greater potential for contaminant transport to the environment.

While waste rock dump structures allow the transport of oxygen and water to interned sulfide material, the duration of ARD is ultimately limited by the mass of sulfide minerals present and can be very long.

CADIA'S TRIAL WASTE ROCK DUMP

A 15 m high trial rock dump covering 0.71 ha was constructed at Cadia Hill Gold Mine in New South Wales, Australia. It was instrumented with two surface lysimeters at its traffic-compacted top to monitor rainfall infiltration, and 24 lysimeters at its base to monitor base seepage beneath the flat, traffic-compacted top surface (14 lysimeters) and the loose, angle of repose side slopes (10 lysimeters) of the dump. A plan showing the layout of the trial waste rock dump and the locations of the two surface and the 24 base lysimeters (numbered 1 to 24) is shown in Figure 1. In addition to the lysimeters, a purpose-built weather station measuring rainfall, air temperature, relative humidity, solar radiation, and wind speed and wind direction was installed on the top of the trial waste rock dump.

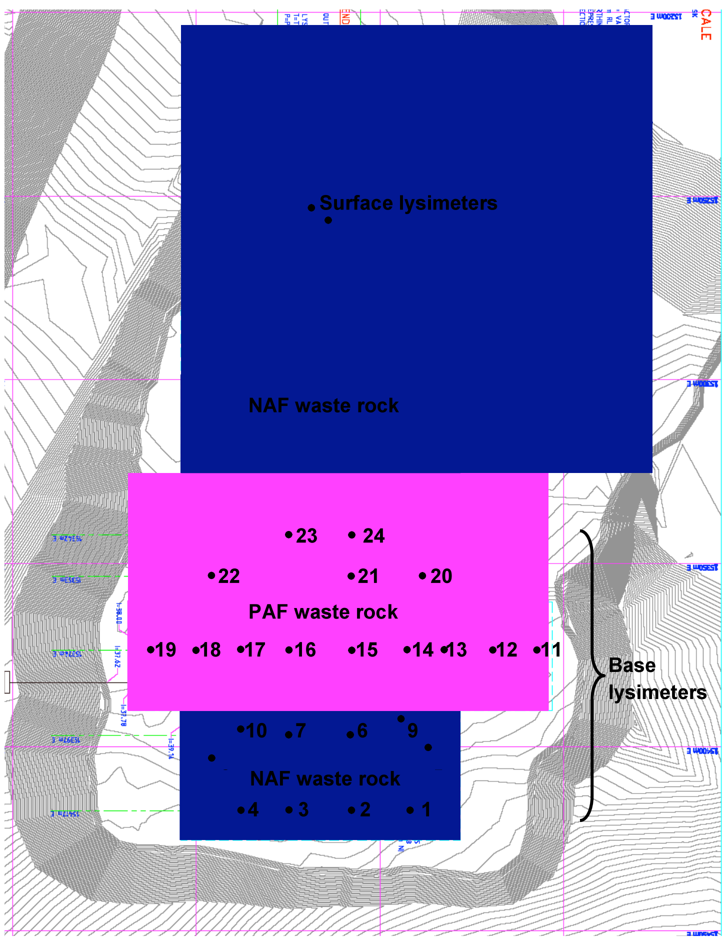

Figure 1. Plan of Cadia's trial rock dump and lysimeter locations.

The sloping site for the trial waste rock dump was built up using 540,000 tonnes of non-acid forming (NAF) rock to form a 1.56 ha base platform, and the trial dump itself was constructed of 110,000 tonnes of NAF waste rock (at each end, shaded blue in Figure 1) and 90,000 tonnes of potentially acid forming (PAF, shaded pink in Figure 1) waste rock in between. The base area of the trial rock dump is 0.71 ha and the top area of the dump is 0.21 ha, of which 0.12 ha is PAF waste rock. The NAF base platform was constructed by end-dumping from haul trucks between October and December 2005, and the trial dump itself was constructed between December 2005 and January 2006.

Heavy rainfall occurred during the construction of the trial dump, resulting in an average volumetric moisture content for the placed rock of about 0.11 (gravimetric moisture content of 6.2%, for a measured specific gravity of 2.65), saturating about a third of the porosity of about 0.33 (corresponding to an initial dry density of 1.78 t/m^3).

Lysimeter design, construction and monitoring

Lysimeter design principles

Lysimeter design for non-atmospheric (that is, buried) conditions creates an elevated water boundary condition at the base of the lysimeter and therefore the hydraulic gradient within the lysimeter is different to that surrounding the lysimeter (Bews *et al*., 1997; O'Kane and Barbour, 2003). To ensure that this difference does not cause "wicking" of water from the wetter lysimeter backfill to the drier surrounding material, the lysimeter wall height must exceed the height of capillary rise above the elevated water boundary condition within the lysimeter. This condition is met when the applied flux is equal to the hydraulic conductivity of the backfill material. The lower the hydraulic conductivity of the backfill material (that is, the more unsaturated and/or fine-grained it is), the higher the required lysimeter wall height.

For the backfill and surrounding materials available for the Cadia trial rock dump base lysimeters, this condition required a "worst case" wall height of 0.1 m. A wall height of 1 m was selected, providing a very large factor of safety against wicking. For the surface lysimeters, atmospheric conditions apply and the wall height required is a function of constructability and the need for the lysimeter backfill to replicate the undisturbed state. A wall height of 2.3 m (the highest available) was selected for the surface lysimeters. All lysimeters were connected by 25 mm tubing to tipping buckets designed to flow under gravity.

Base Lysimeters

The 24 base lysimeters were constructed in the base platform for the trial waste rock dump, distributed over the footprint of the future trial waste rock dump to intersect seepage beneath its top and sides. The base lysimeters comprised open-topped HDPE water tanks measuring 2.4 m in diameter by 1 m in height. They were located in holes dug to a depth of about 0.6 m into the base platform using a tracked excavator. The rock excavated was stockpiled for later backfilling around the lysimeters, with the excess rock removed. A uniform, coarse-grained aggregate termed "crusher dust", having a maximum particle size of approximately 10 mm, was placed to a depth of about 100 mm in the base of each lysimeter hole to act as bedding for the lysimeter tank and to slope the base at 0.5% towards the lysimeter outlet, leaving a hole about 0.5 m deep. Once installed, the lysimeters protruded about 0.5 m above the surface of the base platform. This ensured that no sub-lateral flow across the base platform could enter the lysimeters.

The base lysimeters contain a three-stage filtration system, designed to satisfy the empirical filter design criteria given in Cedergren (1977). The lysimeter outlet was covered by a 100 mm high geotextile sock filled with screened filter sand, the base of the lysimeter was filled with screened filter sand to a height just in excess of 100 mm, covering the filter sock, and 100 mm of screened gravel was placed over that. The remainder of the lysimeter was backfilled with coarse gravel comprising crushed NAF rock. This material was placed over and around the base lysimeters to a height and lateral extent of 2 to 3 m to protect the lysimeters during subsequent end-dumping of the trial waste rock dump material. The air-entry value (capillary rise) of the crushed NAF rock would be equal to or greater than the very low air-entry value of the surrounding coarser-grained rock so as to not create a capillary barrier to downward flow. Figure 2 shows the installation sequence for the 24 base lysimeters.

Figure 2. Base lysimeter installation sequence (a) installed base lysimeters; (b) base lysimeters after backfill.

Surface lysimeters

The two surface lysimeters were constructed in the traffic-compacted top surface of the trial waste rock dump. The lysimeters comprised open-topped HDPE water tanks measuring 2.4 m in diameter by 2.3 m in height. They were located in holes dug to a depth of about 2.4 m into the top surface using a tracked excavator. The rock excavated was stockpiled for later use in backfilling around and within the lysimeters, with the excess rock removed. Crusher dust was placed to a depth of about 100 mm in the base of each lysimeter hole to act as bedding for the lysimeter tank and to slope the base at 0.5% towards the lysimeter outlet, leaving a hole about 2.3 m deep, so that the lysimeters could be installed with their tops flush with the surface. Surface runoff was directed away from the lysimeters.

The surface lysimeters contained a three-stage filtration system as described for the base lysimeters. The remaining lysimeter volume above the filter and the surrounding holes were then backfilled to approximate the stratigraphy and density of undisturbed traffic-compacted top surface of the trial waste rock dump. Recompaction was achieved by a sheep-foot roller to within 0.5 m of the final surface. The remaining 0.5 m was compacted in 100 mm lifts using a vibrating compaction roller outside of the lysimeters, and a vibrating plate for waste rock placed inside the surface lysimeters. Density was monitored using neutron probe density testing. Replication of in situ conditions within and around the lysimeters is imperative for ensuring that the measured surfaces fluxes are representative of the actual fluxes (Bews *et al*., 1997; O'Kane and Barbour, 2003).

Rainfall

Figure 3 shows the daily rainfall over the 2 years and 8 months of monitoring to 1 September 2008. The single largest rainfall event occurred on 18 October 2006, with 73.8 mm recorded in 24 hours. The cumulative rainfall to from 1 January 2006 to 1 September 2008 was about 2,050 mm, averaging about 770 mm/year.

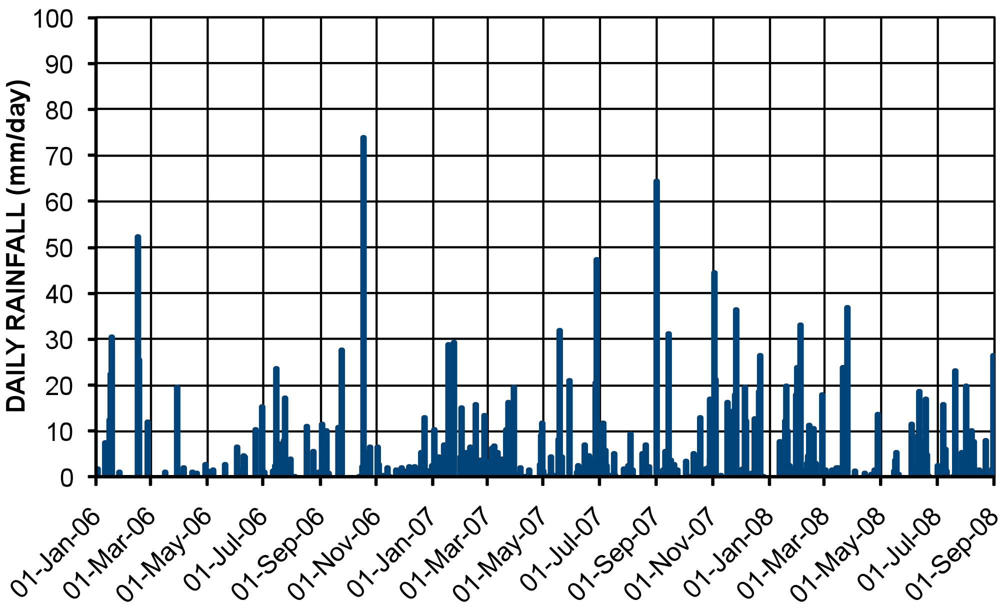

Figure 3. Daily rainfall at Cadia's trial waste rock dump.

The 30-year average rainfall data for the Australian Bureau of Meteorology (#063254) weather station located nearest to Cadia at the Orange Agricultural Institute (NSW), show that all but four average monthly rainfall totals exceed those recorded at the trial waste rock dump over the monitoring period. The largest shortfalls occurred between March and May 2006 and between November 2006 and May 2007. Further, of the months below the 30-year average, seven of them fall below the driest 10%. The average annual monitored rainfall is about 82% of the 30-year average annual rainfall of 942 mm.

Top surface infiltration

Surface infiltration into the flat top of the trial waste rock dump has been monitored from 1 June 2006 onwards, following the construction of the dump and the installation of the two lysimeters on its traffic-compacted top surface. The lysimeters responded within

24 hours, building up to an average peak infiltration of 86% of cumulative rainfall in mid-August 2006, followed by a gradual decline since, with little further infiltration recorded after 1 December 2006, as seen in Figure 4. Differential settlement and hard-panning of the surface of the dump and the concentration of infiltration at sink holes not intersected by the surface lysimeters are the main factors behind the lack of recorded infiltration. The patterns of infiltration vary markedly across the dump and with variations in rainfall over time. The average infiltration recorded by the two surface lysimeters over the monitoring period from 1 June to 1 December 2006 was 445 mm or about 62% of the cumulative rainfall of 720 mm to that date. This is equivalent to an average (unsaturated) hydraulic conductivity for the dump surface as a whole of about 2×10^{-8} m/s between 1 June and 1 December 2006.

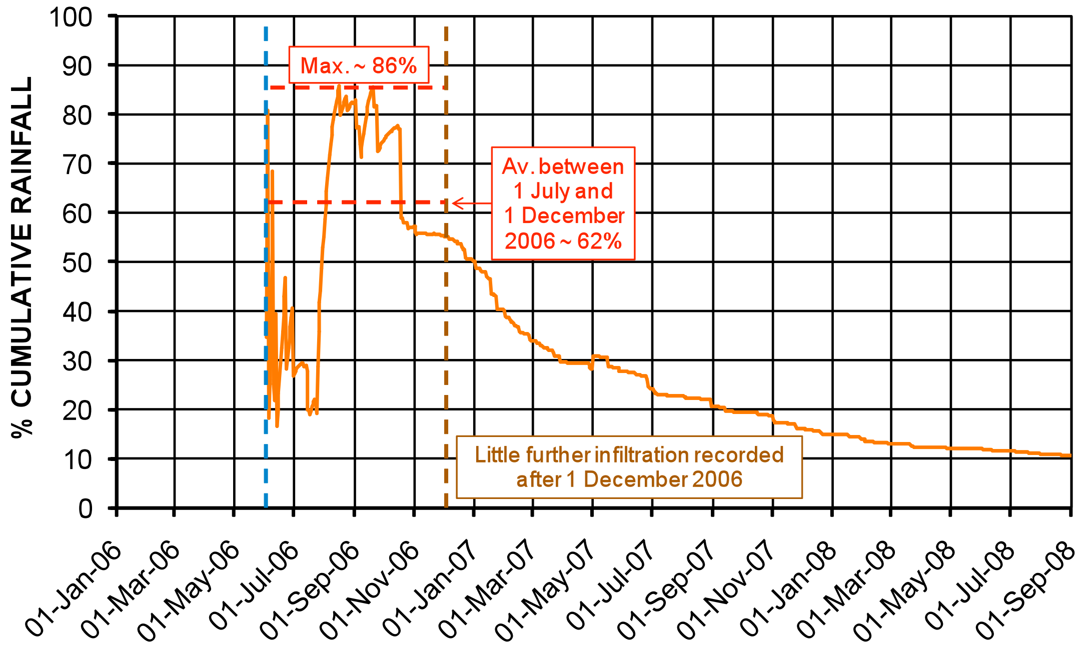

Figure 4. Average cumulative top surface infiltration into Cadia's trial waste rock dump over time, as a percentage of cumulative rainfall.

Base seepage

When base seepage has been recorded, lysimeters beneath the flat top of the trial waste rock dump have flowed for about twice as long (40 to 120 days, implying an average hydraulic conductivity during drain-down of 4.3×10^{-6} to 1.4×10^{-6} m/s) as those beneath the angle of repose slopes (20 to 60 days, implying an average hydraulic conductivity during drain-down of 8.7×10^{-6} to 2.9×10^{-6} m/s), due to the greater height of waste rock involved.

Figure 5 shows the average cumulative base seepage (expressed as a % of cumulative rainfall) recorded by lysimeters beneath the flat top and the angle of repose (AOR) slopes of the trial waste rock dump. The base seepages responded broadly to rainfall, increasing over time as the dump wet up. Initially, more base seepage reported beneath the angle of repose slopes of the dump compared with that beneath the flat top, due to the reduced storage capacity of the lower height of waste rock beneath the slopes. However, this reversed over time, possibly due to the preferred pathways beneath the flat top being fed by greater surface ponding and developing further, which is not the case beneath the angle of repose slopes.

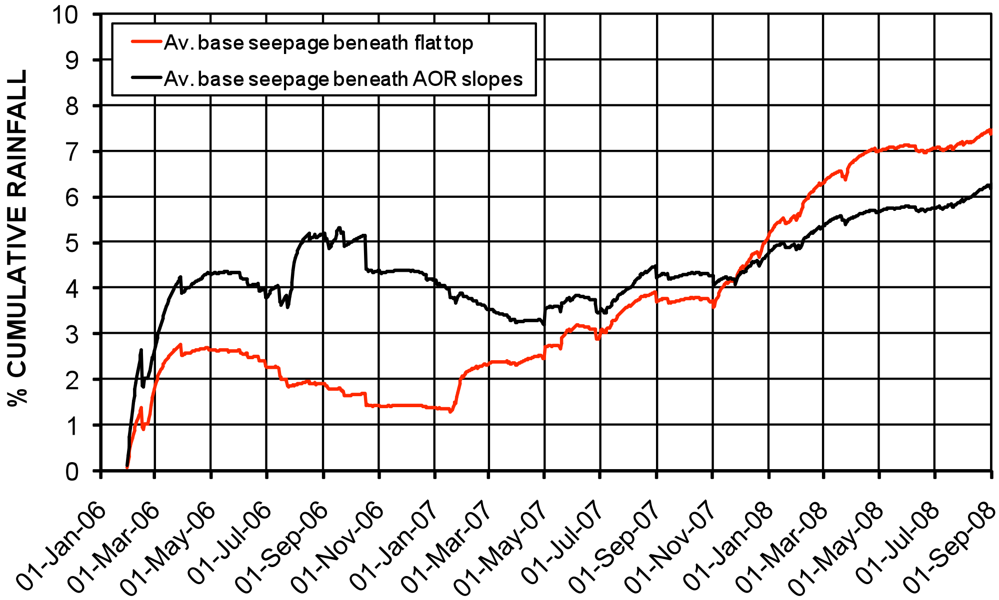

Figure 5. Average cumulative base seepage beneath flat top and angle of repose slopes of Cadia's trial waste rock dump over time, as a percentage of cumulative rainfall.

The 14 base lysimeters located beneath the flat top of the trial waste rock dump have all recorded seepage. They first recorded seepage between about 30 days and 175 days after the completion of the trial waste rock dump. The cumulative flows to 1 September 2008 have varied over five orders of magnitude, from 0.001 to 175 mm. The flows recorded by base lysimeters located beneath the flat top have been between 0.0001% and 20% of cumulative rainfall to 1 September 2008. The cumulative base seepage rose to a maximum of about 7% of cumulative rainfall at the end of the monitoring period, as shown in Figure 5. A reducing majority of rainfall infiltration (about 86% to 1 September 2008) went into storage within the dump.

All but one of the base lysimeters located beneath the angle of repose slopes of the trial waste rock dump have recorded seepage. The responding lysimeters first recorded seepage between about 30 days and 195 days after the completion of the trial waste rock dump. The cumulative flows to 1 September 2008 have varied over four orders of magnitude, from 0.0003 to 85 mm. The flows recorded by the base lysimeters located beneath the angle of repose slopes have been reasonably constant over time, ranging between 0.0003% and 9% of cumulative rainfall to 1 September 2008. The cumulative base seepage rose to a maximum of about 6% of cumulative rainfall at the end of the monitoring period. Again, a reducing majority of rainfall infiltration (about 82% to 1 September 2008) went into storage within the dump.

The observed base seepage occurred under a range of conditions:

i. high intensity and low cumulative rainfall (February 2006);

ii. low intensity and low cumulative rainfall (May 2006 to July 2006);

iii. low and medium intensity with moderate cumulative rainfall (August 2006 to December 2006); and

iv. low and medium intensity and high cumulative rainfall (January 2007 to September 2008).

The base lysimeter data suggest that there is a relationship between rainfall intensity, the available water storage capacity of the trial waste rock dump (expressed as a percentage of cumulative rainfall), and the lysimeter response time and flow, following rainfall events. As the trial waste rock dump wets-up over time and the available storage capacity is depleted, the size of the triggering rainfall event and the response time before base seepage occurs both reduce exponentially.

At 100 mm cumulative rainfall, the rainfall event required to trigger base seepage beneath both the flat top and angle of repose slopes of the trial waste rock dump was of the order of 30 mm and base seepage occurred in about 10 days, as seen in Figure 6. At 10 days, the equivalent hydraulic conductivity for the preferred pathways is 1.7×10^{-5} m/s beneath the flat top of the dump and 8.7×10^{-6} m/s beneath the angle of repose slopes. Beyond about 750 mm cumulative rainfall, the triggering rainfall event asymptotes towards about 2.5 days and the time for base seepage to appear asymptotes towards about 2.5 days (Figure 6). At 2.5 days, the equivalent hydraulic conductivity for the preferred pathways is 4.4×10^{-4} m/s beneath the flat top of the dump and 2.2×10^{-4} m/s beneath the angle of repose slopes.

CONCLUSIONS

The paper presents in detail the design, construction and monitoring of an instrumented trial waste rock dump constructed at Cadia Hill Gold Mine in New South Wales, Australia to monitor rainfall infiltration and base seepage. The Cadia trial waste rock dump is on a scale comparable to a conventional waste rock dump lift, and has demonstrated the following key points:

- The average annual rainfall recorded over the 2 year and 8 month monitoring period of 770 mm is about 82% of the 30-year average annual rainfall for the site.
- Surface infiltration into the trial waste rock dump peaked at 86% of cumulative rainfall, followed by a gradual decline, with little further infiltration recorded after 1 December 2006. Differential settlement and hard-panning of the surface of the dump and the concentration of infiltration at sink holes not intersected by the surface lysimeters are the main factors behind the loss of recorded infiltration. The average infiltration recorded over the monitoring period from 1 June to 1 December 2006 was 445 mm or about 62% of the cumulative rainfall of 720 mm to that date. This is equivalent to an average (unsaturated) hydraulic conductivity for the dump surface as a whole of about 2×10^{-8} m/s between 1 June and 1 December 2006.

• When base seepage has been recorded, lysimeters beneath the flat top of the trial waste rock dump have flowed for about twice as long as those beneath the angle of repose slopes, due to the greater height of waste rock involved.

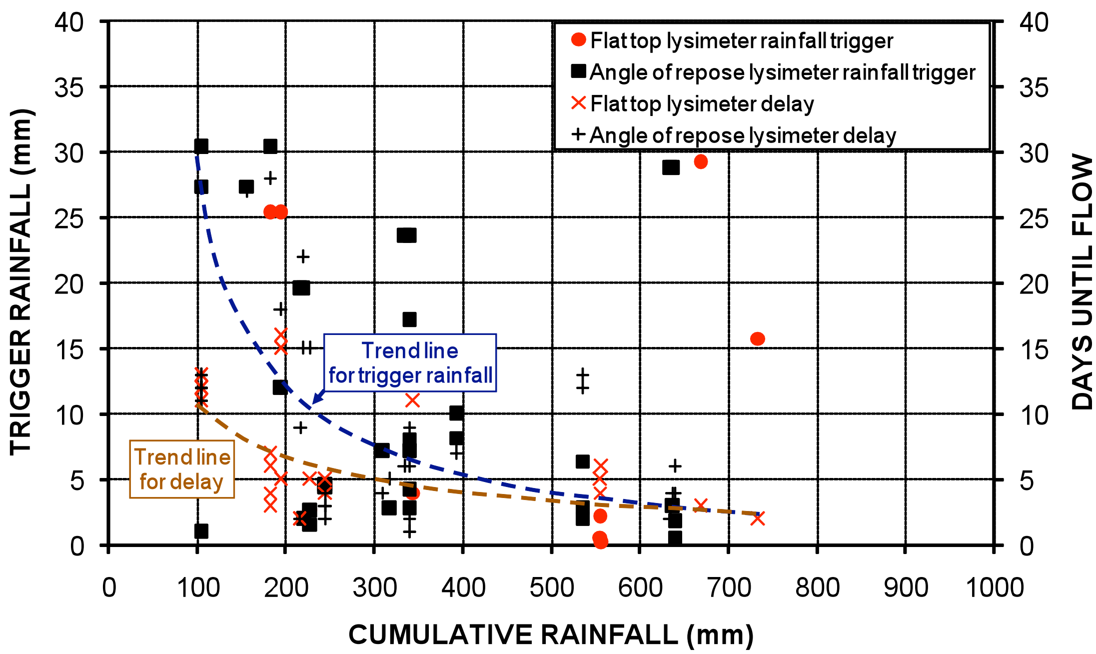

Figure 6. Reducing trigger rainfall and base seepage delay with increasing cumulative rainfall at Cadia's trial waste rock dump.

• Initially, more seepage reported beneath the angle of repose slopes of the dump compared with that beneath the flat top, due to the reduced storage capacity of the lower height of waste rock. However, this reversed with time, possibly due to the preferred pathways beneath the flat top being fed by greater surface ponding and developing further, which is not the case beneath the angle of repose slopes.

• The cumulative base seepage beneath the flat top of the trial waste rock dump was about 7% of cumulative rainfall to 1 September 2008.

• The cumulative base seepage beneath the angle of repose slopes of the trial waste rock dump was about 6% of cumulative rainfall to 1 September 2008.

• As the trial waste rock dump wets-up over time and the available storage capacity is depleted, the size of the triggering rainfall event and the response time before base seepage occurs both reduce exponentially, towards 2.5 mm and 2.5 days, respectively.

The Cadia trial waste rock dump will be monitored for a number of years to confirm the trends recorded to date and to investigate when saturated breakthrough occurs (estimated to be after about 5 years). Data are required from other sites under a range of conditions to improve understanding of waste rock dump wetting-up and seepage phenomena.

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