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A case study for designing and testing a tailings storage facility cover

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Abstract

Due to the extreme and volatile geochemical properties of gold tailings, most tailings storage facilities (TSFs) will need to be clad, capped or covered for final rehabilitation to be effective in the long-term. Without such interventions, groundwater and soil contamination are almost inevitable, and mine closure (with associated liability relinquishment) an impossibility.

We undertook a series of geochemical, pedological and hydraulic tests on potential cover soils for a large (>650 Ha) gold TSF in South Africa. The tests included detailed work on the variability of the tailings material as well. The tailings proved to be acidic and saline, with high concentrations of total and leachable heavy metals. The testing showed that the tailings was net acid generating, with high sulphur content and very low neutralisation potential. Kinetic testing provided unacceptably poor leachate qualities. Hydraulically, the tailings material proved to have ideal store-and-release properties. The range of soils present were also tested and found to have insufficient neutralising potential to combat the acid production from the tailings, but the hydraulic properties appeared promising to support phyto-evaporation. Adequate soil volumes were located and mapped.

The data were used to inform potential cover designs, which were the product of erosion modelling, unsaturated flow modelling, geochemical modelling and geohydrological risk modelling. The model outputs suggested a series of potential phyto-evaporative transpiration (PET) covers that could be suitable to achieve the closure objectives of <5% of mean annual rainfall percolating through the cover and into the underlying tailings and through the foundation of the TSF.

We then built a series of four lysimeters (with a control site), each representing a different potential PET cover configuration. The total cover thicknesses varied from 450 mm to 800 mm. In each, we measured vegetation dynamics (plant density, leaf area, contact cover, species composition), soil moisture depletion and volume, run-off, seepage, and sediment movement. Most of these parameters were measured hourly, via in situ probes, whilst other measurements were recorded monthly during the summer growth season and every second month during the winter.

Measurements continued for five years (2017–2021). The data collected from the lysimeters validates the model predictions and shows that the model outputs are conservative, with lower seepage rates being reported for all trial covers. The thickest and thinnest soil covers yielded relatively poor performance, with the addition of rock not benefitting any of the performance criteria.

Ultimately, the characterisation, modelling and testing of potential covers have allowed us to identify the most appropriate long-term closure cover of the gold TSF and has resulted in a cost saving of ZAR 200 million over the initial cover cost estimates. If the designed cover is implemented correctly, the active post-closure water management costs are substantially lowered, and the contamination plume will start to recede within 25 years of decommissioning.

Keywords: *tailings closure, phyto-evaporative cover, lysimeter monitoring*

1 Introduction

1.1 Background to tailings environmental risks

A principal function of a tailings cover is to accumulate all water received during precipitation and allow the gradual release of the rainwater through transpiration by vegetation, thereby reducing seepage and leaching of toxic materials stored in the TSF (Defferrard et al. 2016). The soil cover should also be thick enough to prevent upward migration of solutes into the vegetation rooting zone.

South African waste legislation (South African Government 2008) requires that tailings storage facilities are capped in accordance with specified cover types, based on their waste classification category. Most of these specified covers are based on limiting moisture ingress through either inducing run-off or limiting infiltration through barrier systems. However, a review of the performance of these specified covers (van Zyl et al. 2022) has shown deficiencies, largely due to the semi-arid climate, very high evapotranspirative coefficients, and constructability issues. The legislation does allow for deviations from the specified covers following a risk assessment methodology where alternative cover systems can be developed.

1.2 Background to cover design process

We completed a risk-based alternative cover design for one of South Africa's largest gold TSFs. It is a down-streamed cyclone facility with batters constructed from tailings underflow. The tailings is sulphidic and saline in nature. The major environmental risks associated with the gold TSF were:

- Sterilisation of previously productive land: area previously used for economically-feasible livestock ranching.
- Groundwater contamination: acidic, saline seepage with concentrations of many heavy metals exceeding threshold values. The TSF has no under-liner but does have a drainage collection system.
- Surface water contamination: acidic and saline surface water run-off or overtopping from the supernatant pond.
- Soil contamination: through shallow seepage, run-off and deposition of wind-blown tailings.

Using the selector for appropriate cover types (Wickland et al. 2006) by climate types shown in the Global Acid Rock Drainage Guide (International Network for Acid Prevention 2009), it was clear that the semi-arid climate and 5:1 potential evapotranspiration ratio required a store-and-release evapotranspiration (ET) cover. Based on cover material availability, a set of conceptual cover scenarios were developed, informed by site observations and experience with similar tailings projects.

A full set of material characterisation and predictive modelling was undertaken to define the environmental risks. Firstly, the tailings and potential cover soils were geochemically analysed (static and kinetic humidity leach cells) and physically evaluated (dry bulk density, foundation indicators, in situ infiltration), along with long-term and event-based erosion modelling. This was followed by a series of unsaturated flow and geochemical models, which predicted the upwards and downwards movement of rainfall infiltration through the vegetated cover, as well as the concentrations of elements of concern (and rising acidity/salinity) over time. These seepage liquor volumes and concentrations were then input into a foundation seepage model (which was calibrated by actual drain delivery volumes) to eventually inform the source terms for a geohydrological risk model. Lastly, the time-staged predictions of the groundwater sulphate concentration plumes were evaluated for risks of exceedances and impacts to surrounding groundwater users and receiving rivers and other surface water bodies.

This iterative process allowed for the refinement of the potential cover scenarios and provided a range of potential soil-based covers that were expected to meet the required performance criteria by varying degrees.

2 Methods

Once the concept covers had been designed, the next step was to construct a series of lysimeters to evaluate the performance of the different cover scenarios to inform feasibility. As the appropriate soil materials available were relatively uniform, the main variable between the covers constructed in each lysimeter was the thickness of the soil (four cover designs were considered; 800 mm, 650 mm, 450 mm plus crushed rock and 450 mm monolithic soil), as shown in Figure 1.

The lysimeters could not be constructed directly onto the tailings batters due to the TSF's downstream deposition method. Hence, the construction took place directly adjacent to the TSF on a section of stockpiled topsoil that was reshaped to the appropriate slope angle. A reference monitoring site was also established adjacent to the lysimeters to inform control values. The thinner soil covers' modelling suggested that ameliorated tailings would be required for acceptable hydraulic functioning, hence tailings was also incorporated into construction layers for those lysimeters. Strict construction protocols and material density thresholds had to be followed to simulate the modelled and consolidated cover conditions.

The lysimeters were constructed with geofabric separating the cover soils from the underlying seepage collection system (uniform coarse rock over a filtered coarse sand bed), all sloped to a central seepage collection point (Figures 2 and 3).

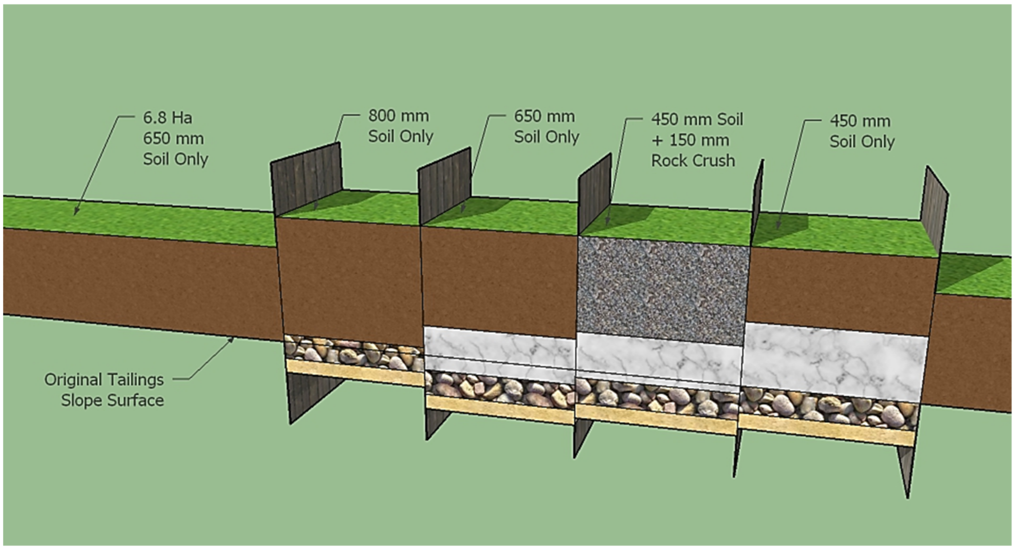

Figure 1 Cover scenarios tested in the lysimeter performance evaluations

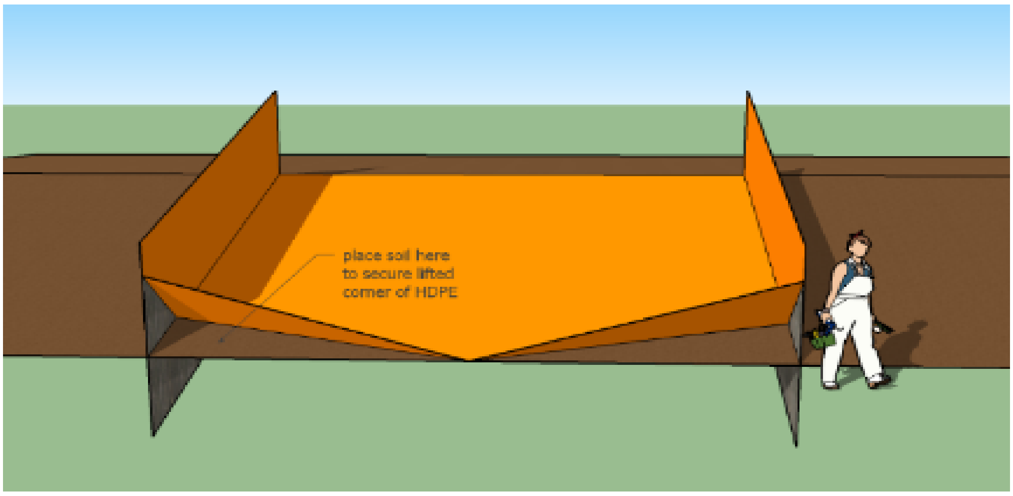

Figure 2 Bottom layers of lysimeter blocks showing impermeable layer over which the seepage collection system was built

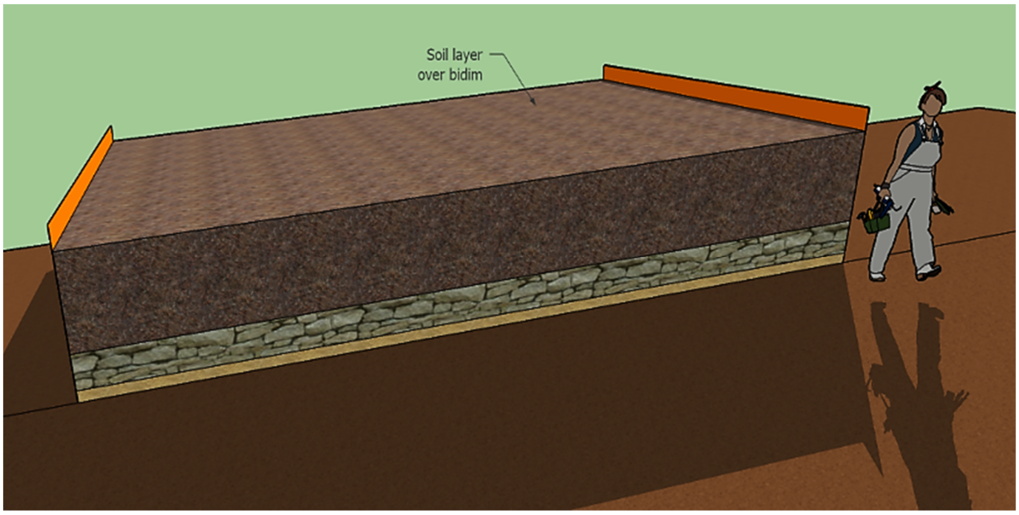

Figure 3 Upper layers of lysimeter blocks showing drainage collection and cover soil layers

The topsoiled lysimeters were then uniformly vegetated using a combination of agricultural lime, compost, NPK fertilisers and a mixture of six pasture grass species. Irrigation was applied when soil moisture levels neared wilting point. The existing, natural grassland vegetation was maintained in the reference site.

The following parameters were monitored:

- Soil moisture and temperature, through soil capacitance sensors.
- Precipitation and irrigation volumes, through tipping-bucket rain gauges.
- Seepage volumes, through the seepage collection system that fed into a tipping-bucket gauge.
- Run-off volumes, through the run-off collection system that fed into a tipping-bucket gauge.
- Erosion, through sediment collection traps.
- Vegetation cover (canopy cover and contact cover), through monthly (growth seasons) or quarterly (dormant seasons) direct measurements.

Most of these parameters were measured hourly, via in situ probes, whilst other measurements were recorded monthly during the summer growth season and every second month during the winter. Data were collected on a continuous basis over four years. The objectives of the monitoring were to establish whether cover performance criteria were being met and whether there were significant differences between the trialled cover scenarios. Key evaluation criteria were the percentages of measured and mean annual precipitation that seeped through the lysimeters.

3 Results

3.1 Precipitation and irrigation

The climate of the trial area is semi-arid, receiving an average rainfall of 453 mm/annum (South African Weather Service 2018), predominantly during the summer months. For the trial, we needed vegetation to establish rapidly and thus irrigated to keep soil moisture levels within the optimal range. Irrigation was maintained for the first 18 months, followed by a six-month gradual withdrawal. Only the trials were irrigated, not the reference site. The irrigation measurements (flow meters) were corroborated by plot-based rain gauges that showed very high correlations. This provided confidence in the records of incident precipitation (Figure 4).

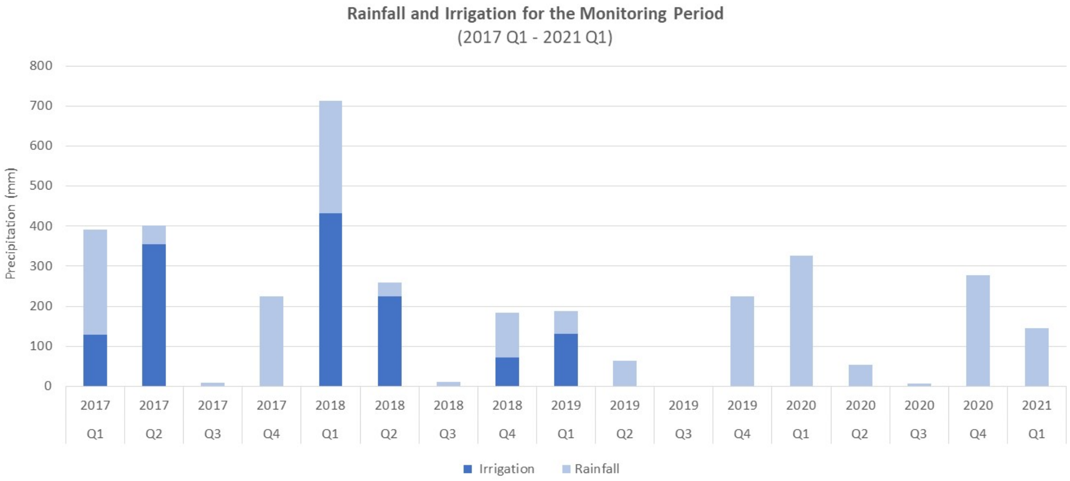

Figure 4 Quarterly total rainfall and irrigation volumes measured over the monitoring period from 2017–2021

Overall, the total precipitation was the highest in 2018 when irrigation was also applied to the lysimeters. The average rainfall per year was 475 mm (excluding irrigation) with the highest total annual rainfall in 2020. The lowest total annual rainfall was in 2019 (345 mm). Overall, the highest natural rainfall occurred in Q1 and Q4 (October to March). Irrigation was applied from January 2018 to March 2019. The total irrigation was the highest in 2018 Q1.

3.2 Soil moisture variations

The main soil moisture measurements were focused on recording the hourly moisture ingress and moisture depletion rates at different depths. An extensive dataset exists for the four years of monitoring. A sample of the data outputs is shown in Figure 5, which was from a relatively rainy period in Q1 of 2019, for the 650 mm soil cover lysimeter. The graph shows the rainfall events, and how the soil moisture profile reacted during rainfall, and how it dried out after. The deeper soil horizons (>30 cm) only recharged with higher rainfall events/periods but showed a consistent drying out, even during this relatively wet period. The shallower soil horizons (especially at 10 cm and 20 cm depth) showed rapid wetting in response to rainfall, but with rapid moisture extinction on dry days following rainfall events. The day/night fluctuations in soil moisture are also clear, showing the evapotranspiration effects of the vegetation cover.

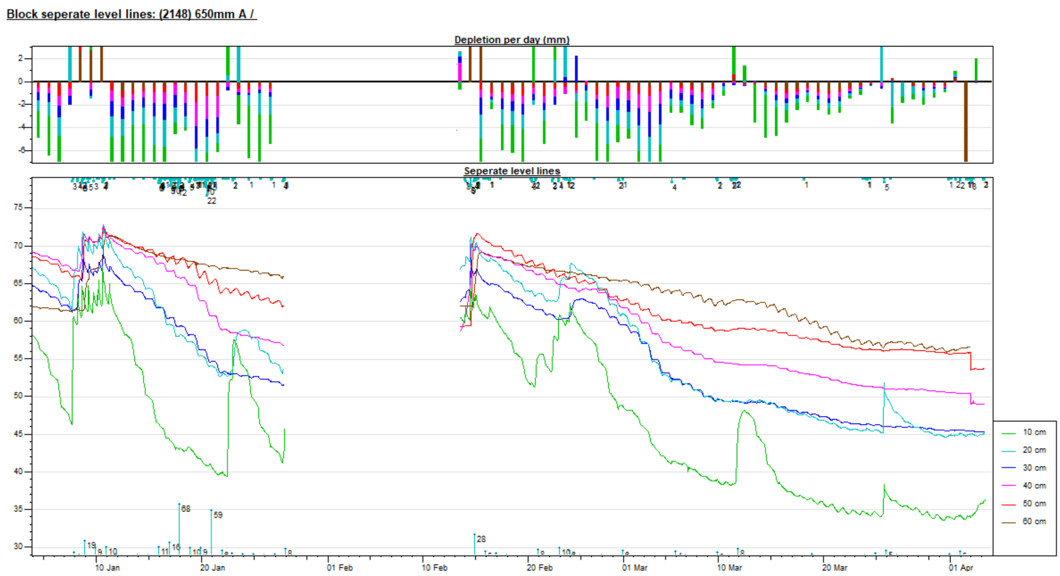

Figure 5 Sample soil moisture movement data from a rainy period in Q1 of 2019 for the 650 mm cover lysimeter

Secondary measurements, especially during the vegetation establishment phase whilst irrigation was used, focused on volumetric water content to ensure conditions between field capacity and wilting point (Figure 6). The annual average soil moisture at all lysimeters was between the optimum range (45–65%). The reference site was above the optimum range (>65 %) in 2019, 2020 and 2021. Soil moisture content was the highest in 2019 and 2020. Over the monitoring period the 450 mm, 450 mm plus rock and 650 mm lysimeters' annual average soil moisture content were the most constant.

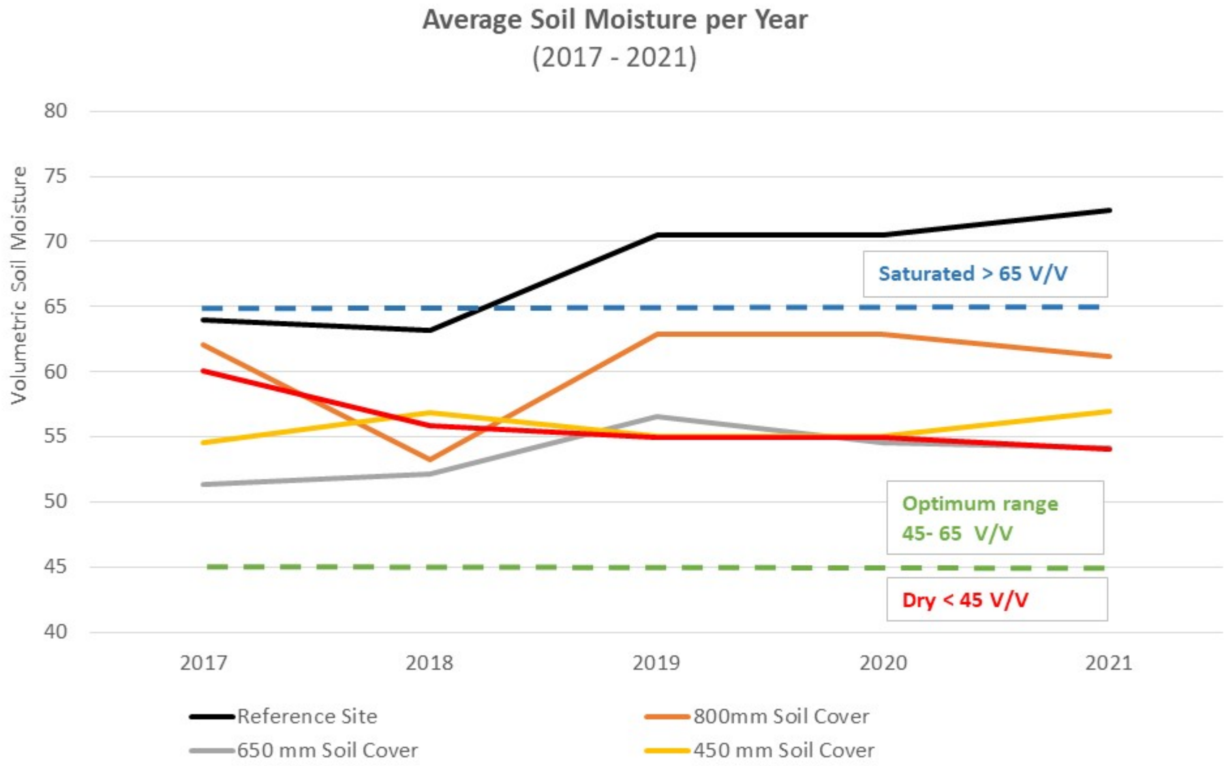

Figure 6 Annual average profile soil moisture content in the different lysimeters from 2017–2021

3.3 Seepage through the covers

The lysimeters were designed and constructed so that all water leaching beyond the plant root zones, and not stored interstitially, would gather and drain towards sealed collection buckets. Tipping-bucket rain gauges recorded the time taken to fill 0.2 mm, so the total seepage volumes and rates of seepage were accurately measured. The annual seepage totals were evaluated against the modelling performance threshold of between 1% and 5% of mean annual precipitation.

Figure 7 depicts the total seepage measured at every lysimeter in L/day. The total seepage was low in 2017, when the lysimeters had not been fully wet throughout but increased at all lysimeters due to irrigation and rainfall. The irrigation was only applied for vegetation growth and establishment in response to drying soil conditions and when no precipitation was expected, hence it did not have a substantial influence on seepage. The soil moisture measurements confirmed this, showing that irrigation events did not percolate to below the 30 cm vegetation bulk root zone.

2018 and 2019 had similar low rainfall (435 mm and 419 mm) with correspondingly low seepage rates. 2020 had very high rainfall (678 mm) and seepage rates in all of the lysimeters increased substantially, which decreased again in the lower rainfall 2021 period. The 650 mm lysimeter had the smallest increase from 2018 to 2021 followed by the 800 mm lysimeter. The thinner covers performed poorer during higher rainfall periods.

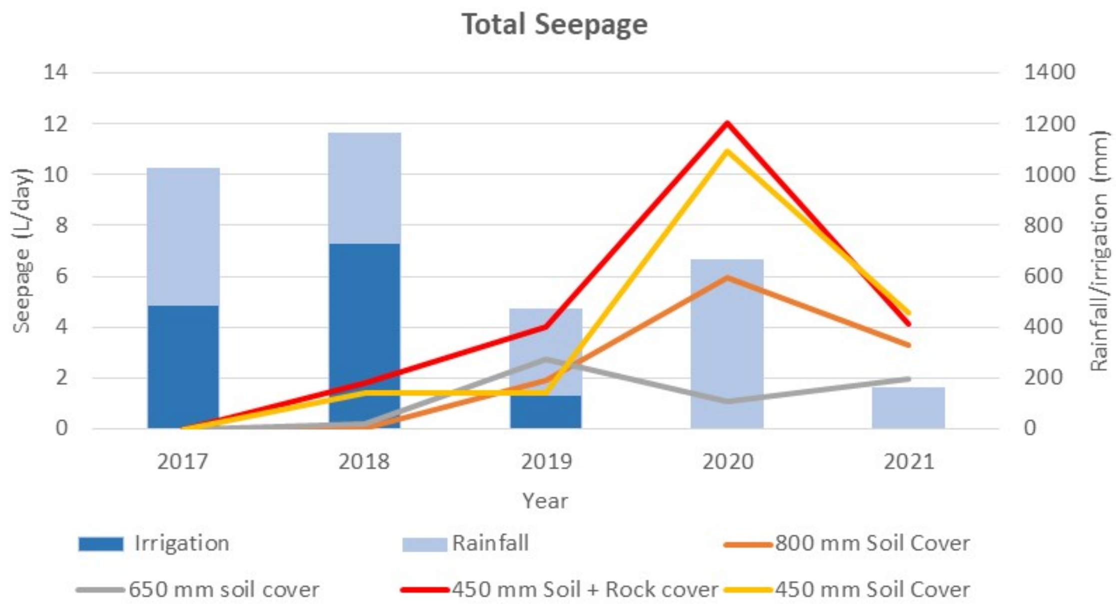

Figure 7 Total annual seepage rates in the different lysimeters from 2017–2021

3.4 Run-off and erosion

No specific thresholds were set for run-off; hence measurements were focused to compare between covers in the lysimeters. Figure 8 depicts the total run-off for the monitoring period. The run-off was high in 2017 and 2018 compared to other years when the vegetation had become established and the soil surface had consolidated. The 450 mm plus rock lysimeter had the highest run-off in 2018, however, decreased and was the lowest in 2021, as expected. The total run-off over the monitoring period was the lowest at the 650 mm lysimeter.

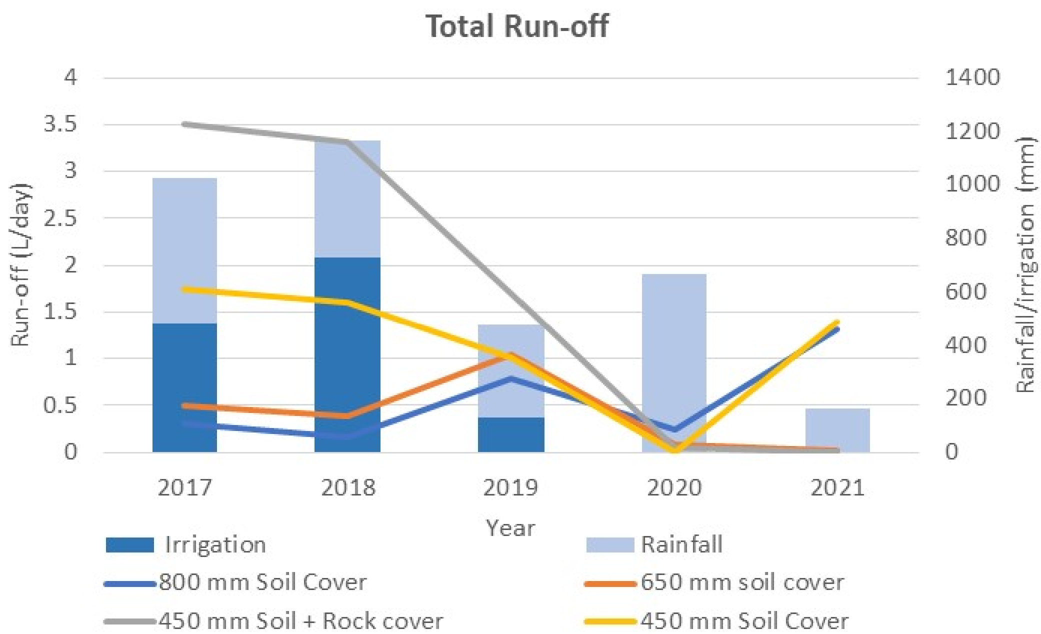

Figure 8 Total annual run-off rates in the different lysimeters from 2017–2021

For erosion, the models showed that an acceptable initial average annual soil loss would be below 10 tons/Ha. Once per quarter, the run-off captured within the sealed drums was measured and the sediment filtered out, dried and weighed. The measured erosion at every lysimeter was well below the threshold (Figure 9). This indicates that the covers were stable enough to maintain acceptable erosion rates.

The highest erosion was measured at the 800 mm lysimeter in 2019 (0.11 ton/ha/year) and the lowest at the 650 mm. There was no erosion measured in 2020 at the 800 mm lysimeter due to an excavator damaging the lysimeter barrier resulting in an excess erosion, which would not be an accurate representation of the erosion.

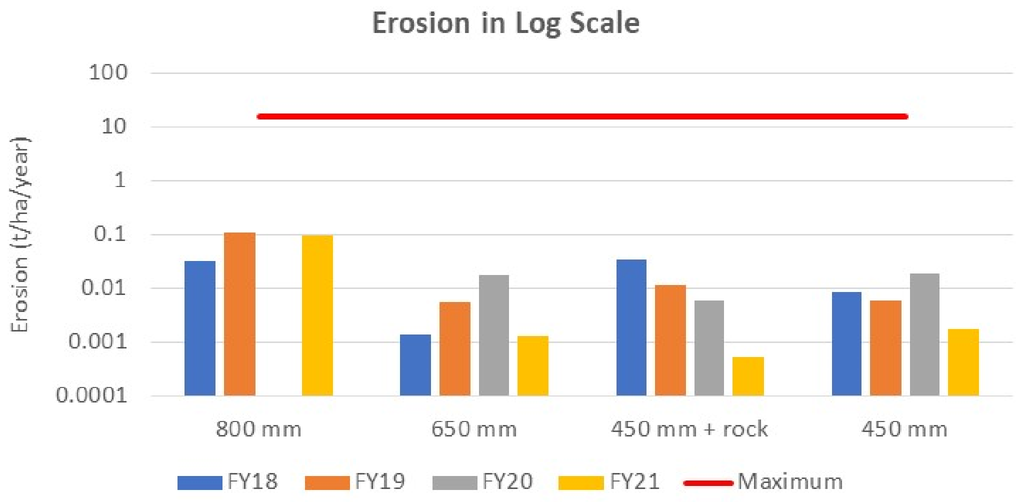

Figure 9 Total annual erosion rates in the different lysimeters from 2017–2021

3.5 Vegetation performance

Vegetation performance was considered one of the most important variables to controlling rates of seepage. Specific vegetation cover and leaf area thresholds were identified during modelling that would enable sustained seepage interception at the required rates over time. For simplicity, three cover categories are used for reporting in this paper, namely poor (<22%), fair (23–55%) and good (>56%) (Figure 10). Vegetation cover of at least fair cover was required to suit model predictions.

The annual average cover shows that all lysimeters were above the minimum threshold (22%). The reference site, however, decreased in 2019 and 2021 and was below the minimum threshold with poor vegetation. From 2018 to 2020 the 650 mm lysimeter had the highest percentage cover but by the end of the trial (at which final performance was measured) all of the cover lysimeters had comparable vegetation cover that met the target thresholds for evapotranspiration requirements.

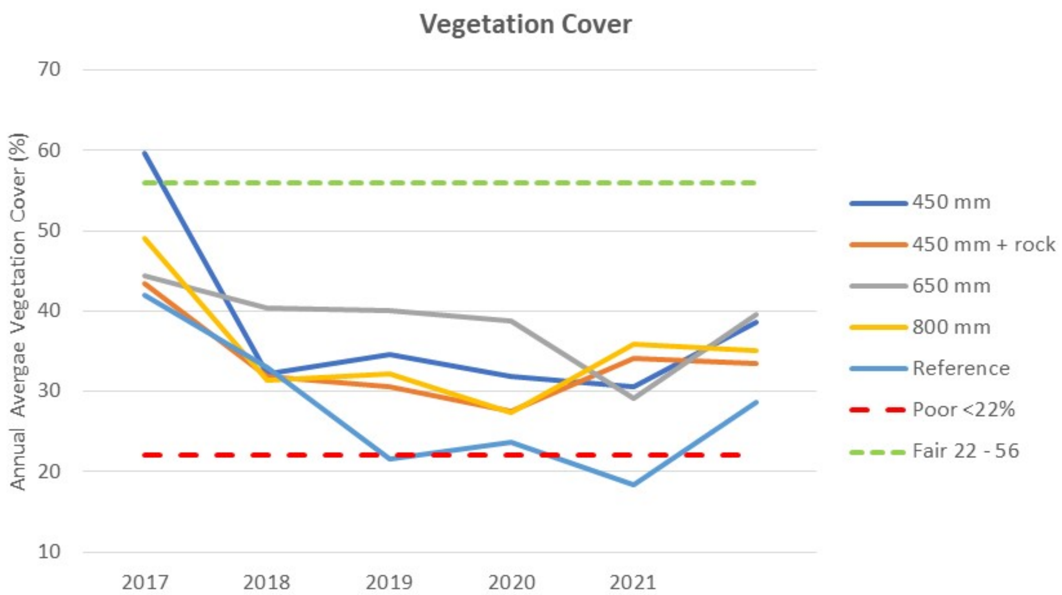

Figure 10 Annual average vegetation cover in the different lysimeters from 2017–2021

3.6 Overall cover performance

The summarised results, compared to the cover performance or design specifications, are shown in Table 1.

Table 1 Summarised cover performance over the monitoring period

Parameters	Design specifications	Reference site	800 mm soil cover	650 mm soil cover	450 mm + rock soil cover	450 mm soil cover
Mean soil moisture (%)	45–65	72.445	61.23	54.10	54.07	56.90
Mean seepage (L/day)	–	N/A	3.31	2.01	4.15	4.61
Mean run-off (L/day)	–	N/A	1.33	0.01	0.01	1.40
Mean canopy cover (%)	<22 = Poor 22–56 = Fair >56 = Good	18.31	35.90	29.09	34.15	30.59
Mean contact cover (%)	<16 = Poor 16–26 = Fair >26 = Good	12.22	24.15	19.06	23.55	21.34
Erosion (t/ha/year)	15	N/A	0.09	0.00	0.00	0.00
Annual seepage (% precipitation)	0–5%	N/A	6%	4%	8%	9%
Annual seepage (% of MAP)	0–5%	N/A	2%	1%	2%	2%

Most of the cover lysimeters met the design specifications in most aspects, however only the 650 mm cover lysimeter was able to control seepage in above average rainfall years as well as average and below-average years. The different covers were scored on a relative scale of 1–4 (2–8 for seepage), based on annual averages and totals. A greater score represents better relative functionality. The relative ranking of the cover material performance is presented in Table 2.

Table 2 Weighted scoring of cover performance

Cover	Vegetation cover	Seepage	Run-off	Erosion	Final score
800 mm	2	6	3	1	**12**
650 mm	4	8	4	4	**20**
450 mm + rock	1	2	1	2	**6**
450 mm	3	4	2	3	**12**

4 Conclusion

The initial modelling suggested, based on various models, to construct a minimum 450 mm thick (thicker if possible- 800 mm preferred) soil-only cover and to establish good vegetation growth on the cover. We decided to test the modelling predictions in-field. The aim of the cover lysimeter study was to investigate the efficiency of various (800 mm, 650 mm, 450 mm plus rock and 450 mm thickness) store-and-release covers in minimising seepage and run-off from the slopes. Monitoring of vegetation cover, soil moisture content, seepage, run-off and erosion was undertaken from February 2017 to April 2021. Generally, the modelled results were over-predicting compared to the actual measurements at the lysimeters. Seepage monitoring measured lower values (between 0.005–0.07 mm/year) compared to the modelled seepage, which was predicted to be between 5–10 mm/year for fair to good vegetation cover at the 650 mm lysimeter. Erosion was also well below the threshold (10 ton/ha/yr) predicted by the modelling.

During the monitoring period, irrigation (initially applied from 2018 until March 2019) was stopped to determine how the lysimeters would respond to dryland conditions. The monitored parameters are discussed separately below.

4.1 Vegetation cover

The vegetation cover was dictated by rainfall, but largely remained above the minimum prescribed levels from the design specifications following the dry season and cessation of irrigation. Furthermore, vegetation cover in the lysimeters was higher than that in the reference site and showed little variation from one year to the next. This indicates that the covers were able to maintain stable vegetation cover, despite the transition from irrigated to dryland conditions. There was, however, a lag in vegetation response to seasonal changes, which impacted seepage and run-off control. The addition of shrubs or evergreens to the vegetation cover may compensate for this seasonal lag.

The contact cover was 'poor' at all lysimeters after establishment in 2017 and increased to 'fair' in 2018. The 650 mm lysimeter had the best contact cover overall. Therefore, based on vegetation cover, the 650 mm had the best performance over the monitoring period. It is recommended that the 'fair' vegetation cover be used in calibrating models for future predictions.

4.2 Soil moisture

The results indicate that, although there was less precipitation in 2019 (due to discontinuation of irrigation), the different covers were able to maintain acceptable soil moisture levels to sustain plant growth. The average soil moisture per year for all lysimeters was within the optimum range. Only the reference site had soil moisture above the optimum range. The soil moisture extinction data showed that all of the cover lysimeters encouraged effective evapotranspiration of the bulk of incident rainfall, which corresponded well with modelled predictions and the seepage data.

4.3 Seepage, run-off and erosion

Although soil cover thickness is an important factor in seepage control, the seepage data collected suggests that slight changes in vegetation cover may also have had a substantial influence on the efficiency of the covers in controlling seepage, particularly in the thicker covers. Contrary to model predictions, the thickest cover (800 mm) was not the most efficient in seepage control but rather the 650 mm cover, which had marginally greater vegetation cover. The current rehabilitation prescriptions set by the TSF engineers limit vegetation species selection to grasses. Including trees and shrubs, especially evergreens can overcome seasonal lags and perhaps allow for thinner soil covers, with the added benefit of being more resilient to seasonal changes.

Vegetation cover was also found to have a substantial influence on the efficiency of the covers in minimising run-off and limiting erosion. The data shows that erosion was highest in the 800 mm and 450 mm plus rock lysimeter, which, had low vegetation cover. This further demonstrates the need for vegetation that grows before the first rainfall and vegetation that functions all year round (evergreens). Although soil losses through water were relatively high in the 800 mm lysimeter, erosion was below the minimum prescribed targets in the specifications.

4.4 Overall cover performance

In 2017, the 450 mm lysimeter was the best-performing cover based on canopy and contact cover, and soil moisture content. As the lysimeters developed, the 650 mm lysimeter improved to the best-performing cover in 2021. The 450 mm plus rock decreased in performance and was the worst-performing cover by 2021.

Based on the scoring system for overall best-performing cover, the 650 mm cover maintained fair vegetation cover, as well as low seepage, run-off and erosion and was therefore the best-performing cover, whereas the 450 mm plus rock was the worst-performing. Going for the thickest 800 mm cover proved to have no benefits over the 600 mm cover, nor the 450 mm cover. The total cost savings by applying 150 mm less soil cover amounts to ~ZAR 200 million for total construction of the TSF.

This paper highlights the benefits of following a structured process in overall cover design, starting with in-field and laboratory material characterisation, through numerical modelling and thorough field testing, prior to construction.

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