Impact of changes in water use policy and legislation on mine waste water management infrastructure – A case study of in-line attenuation ponds

Whelan Naidoo
SRK Consulting (South Africa) Pty Ltd, Johannesburg, Gauteng, South Africa

Priscilla Janse van Rensburg
SRK Consulting (Australasia) Pty Ltd, Perth, Western Australia, Australia

ABSTRACT: South Africa is an arid country currently experiencing a drought. Consequently, protection of water resources and responsible water use in all sectors, including the mining industry, has been prioritized. New legislation requires stringent pollution control barriers in mine waste infrastructure. For compliance and to protect the underlying aquifer, the design of a new tailings dam required a barrier system which includes an HDPE liner. Paddock systems are traditionally constructed around South African tailings dams to manage runoff from embankment slopes. The requirement to install a barrier system renders the capital cost of these elements prohibitive. This paper presents a summary of the hydrological analysis, flood routing, and design of an in-line attenuation pond system that combines the functions of traditional paddocks and solution trenches. The solution is cost effective, limits evaporative and seepage losses and complies with legislation. The system was optimized by designing the in-line attenuation ponds to provide attenuation during storm events and conveyance during operational conditions.

1 INTRODUCTION AND SCOPE

Earth is made up of nearly 70 % water, with approximately 3 % of it being fresh water (USGS, 2016). Additionally, the extreme weather patterns and droughts being experienced all over the world are causing severe water stress. Protection of water resources is therefore essential to ensure safe human consumption as well as longevity of aquatic ecosystems. Many countries have imposed strict legislation regarding water resource protection in the mining industry. These are related to separation of clean and dirty water and prevention of groundwater and surface water pollution. These regulations pose new challenges in the design and construction of mine waste infrastructure such as tailings dams as innovative designs are required to ensure project feasibility without compromising safe functionality and operability. This paper presents a design challenge that resulted from changes in water use policy and promulgation of new legislation, and the development of a design solution to meet the requirements.

2 BACKGROUND

Tailings storage facilities (TSFs) in South Africa are predominantly constructed as upstream facilities with a drainage system, decant structure and conveyance, return water dam and associated stormwater management. The primary decant system typically consists of a centrally located penstock through which supernatant pond water is routed and conveyed by a gravity flow outfall pipeline into a solution trench. Most dams are designed to include a drainage system that consists of toe/heel drains, a blanket drain and a curtain drain. The drains collect seepage water and also discharge into the solution trench. The solution trench is an open channel that transports decant water (from the penstocks) and seepage water (from the various seepage drains) to the return water system. It is common for upstream TSFs to be constructed and operated with stormwater management components known as paddocks to manage runoff from the outer TSF embankments. Paddocks are constructed along the perimeter of the facility between the TSF embankment and the solution trench. This is illustrated in the typical perimeter section in Figure 1.

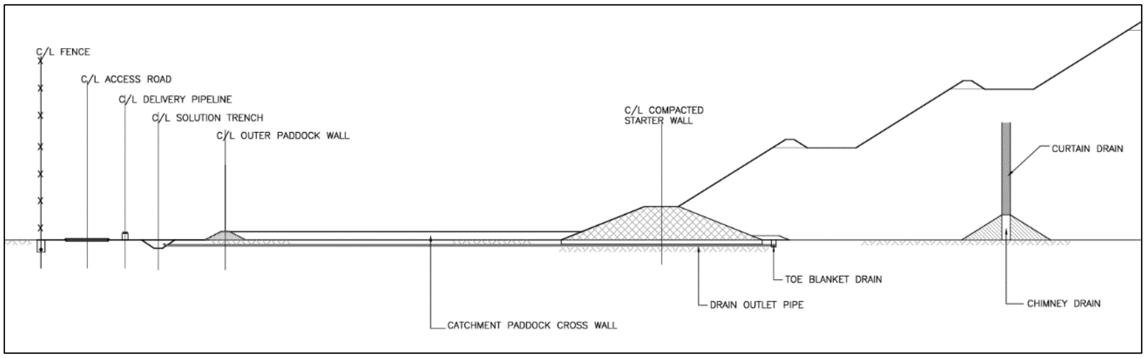

Figure 1. Typical perimeter section schematic through a traditional upstream TSF in South Africa (NTS)

The paddocks are designed to contain and store stormwater runoff from the embankment of the TSF for evaporation and/or seepage into the substrate. Additionally, the individual paddocks serve as intermediate silt traps to contain silt transported by embankment runoff or minor pipeline spills. The disadvantages of the traditional paddock system are as follows:

i) Dirty runoff water can seep into the substrate; however, the contribution from this runoff water is considered far less than the water seeping through the base of the tailings dam into the substrate.
ii) Stormwater runoff is lost and excluded from the water balance on the assumption that it is negligible.
iii) A considerably expansive area around the footprint of the TSF is utilized.

As a result of the promulgation of legislation, the design and construction of new TSFs must include a pollution control barrier system that includes a high-density polyethylene (HDPE) liner. Interpretation of the legislation suggests that the requirement for a barrier system that includes an HDPE liner may extend to the paddocks, significantly increasing construction costs. A new approach to the design of the paddock and solution trench system of a typical South African TSF was therefore required.

The challenge was addressed by combining the function of two components of the TSF − the solution trench and the paddock system − to in-line attenuation ponds. This paper presents a case study of analysis and design of the in-line attenuation pond system for a new TSF.

2.1 *Changes in legislation*

The National Water Act (NWA) (Act No. 36 of 1998) states that “a person in control of land or occupying of using land and which causes, or is likely to cause pollution of a water resource, must take all reasonable measures to prevent any such pollution from occurring, continuing or recurring”. In addition, the subsequent clause states that reasonable measures shall be taken to comply with any prescribed waste standard or management practice to contain or prevent the movement of pollutants and remedy the effects of the pollution. Regulation 704 of the NWA also prescribes separation of clean and dirty water.

The additional legislation, promulgated in 2013, currently applicable to the design and construction of new TSFs includes Regulation 632 of the National Environmental Management: Waste Act of South Africa (Act No. 59 of 2008). This regulation details the requirements regarding the planning and management of residue stockpiles and residue deposits from prospecting, mining, exploration or production. The regulation states that waste must be classified based on contaminants and an appropriate pollution control barrier system installed as defined by the following regulations appended to the National Environmental Management: Waste Act (Act No. 59 of 2008):

i) Regulation No. 634 - Waste Classification and Management Regulations
ii) Regulation No. 635 - National norms and standards for the assessment of waste for landfill disposal
iii) Regulation No. 636 - National norms and standards for disposal of waste to landfill.

In accordance with these regulations, waste may be classified as one of five types of waste (Type 0 to Type 4) by assessment of the concentration of contaminants contained in the waste material or potential leachate. A corresponding minimum treatment or engineered barrier control system is prescribed in Regulation No. 636 for each waste type (treatment or Class A to Class D). The requirement for a Class C barrier system applicable to a Type 3 waste (comparable to platinum tailings material) is illustrated in Figure 2.

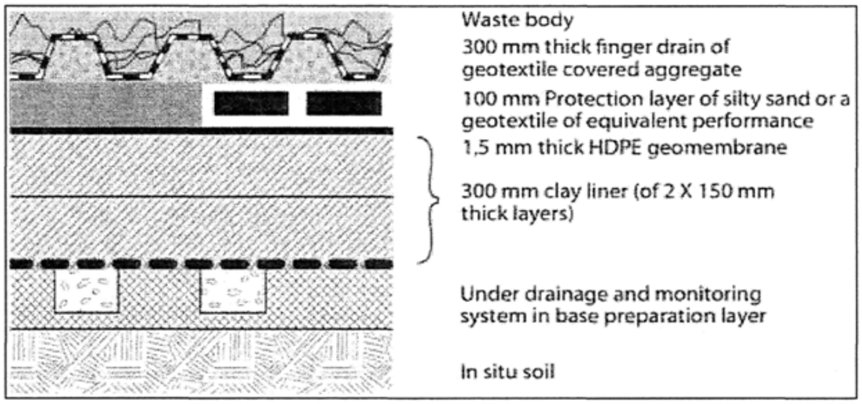

Figure 2. Class C pollution control barrier requirement

Interpretation of the legislation suggests that the requirement for an engineered pollution control barrier system, including the components illustrated in Figure 2, would extend to the construction of the traditional paddock system as the water contained in the paddocks is considered dirty water (i.e. contaminated runoff).

2.2 *Overview of the requirements for a lined system*

Large parts of South Africa are classified as arid by the Köppen Climate Classification system (Kottek, et al., 2006) and it is therefore considered the nation's collective responsibility to use water as efficiently as possible. This is further magnified by the events of February 2018 when South Africa declared a national disaster based on the drought afflicting parts of the country.

This requirement for responsible water use and protection of water resources extends to the mining industry and the design and operation of mine waste infrastructure. Therefore, in addition to the legislative requirements, changes in water use policy influenced the design objectives and requirements for the new lined system which were as follows:

i) Maximize water return
ii) Protect groundwater from pollution
iii) Minimize cost in an already cost-sensitive environment.

3 CASE STUDY

3.1 *Overview of the project*

The TSF at a platinum mine located in the Limpopo Province of South Africa is approaching the end of its design life. Life of mine (LOM) is planned to proceed for at least another 20 years and therefore an alternate tailings disposal option was required. Following an extensive options analysis and risk assessment phase, construction of a second TSF was determined to be the best option for the mine. The second TSF was designed as an abutment to the existing facility with a footprint constrained by the current surface lease area and environmental authorisation. A general arrangement of the planned facility is illustrated in Figure 3.

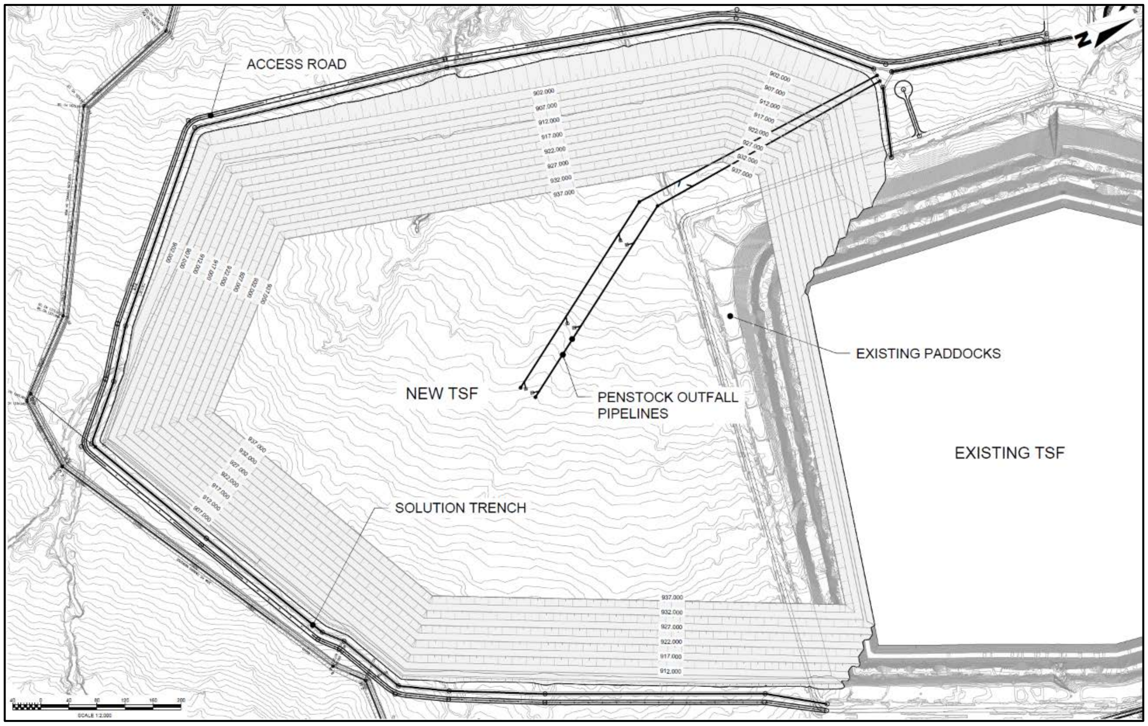

Figure 3. General layout of new TSF

In accordance with the applicable legislation, samples of the waste were obtained and tested to classify the waste type and subsequently the barrier system requirement. The resultant waste type classification (Type 3) prescribed the design of a pollution control barrier system that comprised a 1.5 mm thick single layer HDPE geomembrane over a 300 mm thick clay layer, an above and below liner drainage system and protection to the liner from damage (Class C). In addition, the local communities' main source of water in the area is groundwater and potential contamination of the groundwater may affect the community health and social well-being, further reinforcing the requirement for stringent pollution control.

Conveyance of the stormwater runoff from the eastern and southeastern flanks of the facility posed a challenge as the site is located within a valley and the abutment of the new facility to the existing facility prevents the possibility of open channel flow around the northern perimeter. The solution trench is therefore required to collect and convey the runoff generated by the TSF embankments in addition to the operational flow rate in a single direction for the length of the perimeter of the new facility. To provide the required hydraulic capacity for a storm event by means of a single conveyance feature was considered impractical and attenuation was deemed necessary.

The design and construction of the traditional paddock system was not considered feasible due to the surface area constraint, the increased cost of installing the pollution control barrier to the paddocks and the loss of runoff/ stormwater to evaporation which could otherwise be harvested. The design approach was therefore to develop a solution trench that combined the conveyance function of a traditional solution trench with the attenuation function of the traditional paddock system.

3.2 *Design criteria and considerations*

The design criteria were split into operational and storm event design criteria. Operational flow consists of flow from the seepage drains (above and below liner, blanket drain and toe drains) and water decanted from the supernatant pond by the penstock and outfall pipeline.

The storm event hydraulic capacity consists of stormwater (within the basin decanted by the penstock and runoff from the TSF embankments captured directly by the solution trench) in addition to the operational flow. The design storm event for stormwater conveyances in and around a mine is a 1 in 50-year 24-hour storm event in accordance with the recommendations by the Chamber of Mines (1996).

In addition to hydraulic capacity, practical design considerations include cleaning and maintenance and the limitation of a single flow path around the TSF towards the return water dam.

3.3 *Hydrologic analysis*

The catchment contributing to the solution trench was divided into five subcatchments, as indicated in Figure 4. During operation of the TSF, berms will be constructed on each bench/step-in containing stormwater runoff. Each bench will therefore act as an effective paddock attenuating runoff and enabling evaporation and infiltration into the dam. Runoff from the lowest bench only therefore contributes to the assessment of the in-line attenuation ponds. The respective catchment characteristics determined are summarized in Table 1.

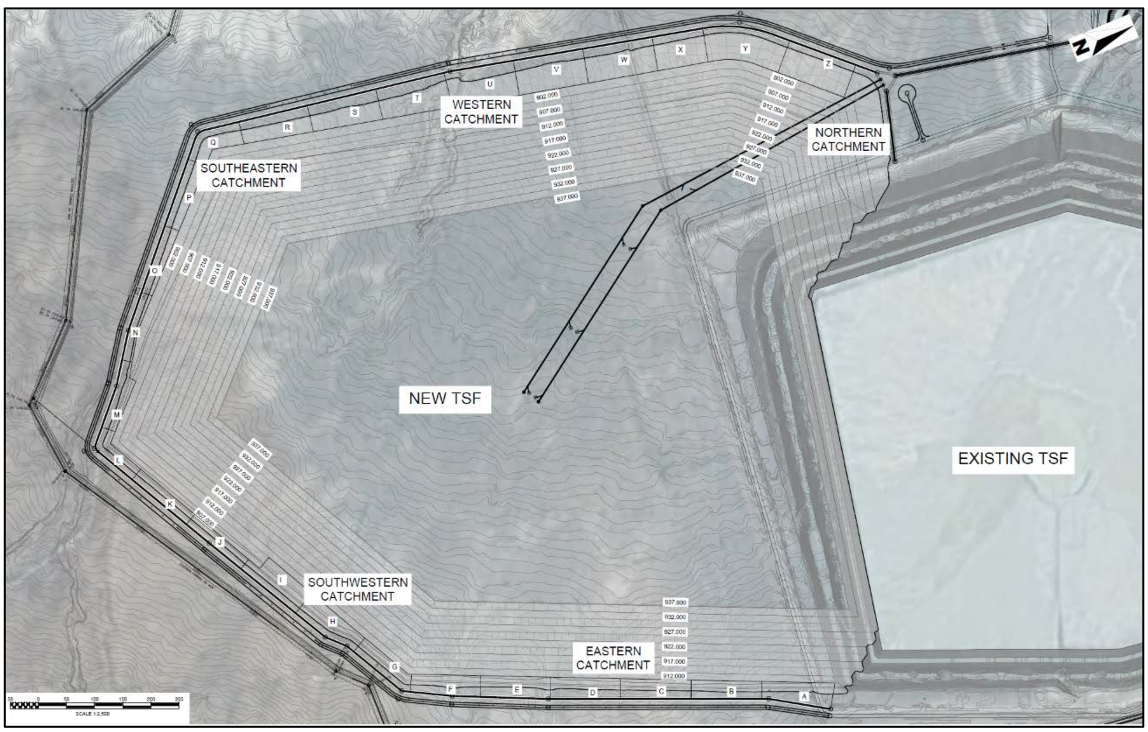

Figure 4. Subcatchment areas

Table 1. Catchment characteristics

	Area (m^2)	Hydraulic length (m)	Average catchment slope (%)
Eastern	17,500	24.3	39
Southeastern	11,919	10.8	27
Southwestern	9,752	40.0	24
Western	44,560	67.5	28
Northern	6,100	71.0	28

The design storm (24-hour, 1 in 50-year annual exceedance probability (AEP)) depth was determined as 127 mm by fitting 98 years of daily data to a log-normal distribution. The Soil Conservation Service South Africa (SCS-SA) method of runoff estimation was used to determine stormflow runoff for each catchment as recommended by Smithers and Schulze (2002). No flow and/or depth gauge records were available to calibrate the coefficients and runoff values from the slopes of the TSF embankment and therefore reasonable assumptions were made based on vegetation condition and soil type. A curve number of 75 was considered appropriate as the embankment slopes are designed to be well vegetated which will result in some infiltration despite the steep catchment slopes. The resultant runoff depth was determined as 69.1 mm.

Peak flow determinations would ideally be conducted using calibrated runoff models; however, limited hourly rainfall records are available in South Africa. The peak discharge was therefore estimated according to the South African National Roads Agency Limited (SANRAL) Drainage Manual (SANRAL, 2013) using SCS techniques based on the triangular unit hydrograph concept. The unit hydrograph represents the temporal distribution of stormflow for an incremental unit depth of stormflow, ΔQ, that occurs in a unit duration of time, ΔD. By assuming a time to peak of 3/8 of the total hydrograph duration, the peak discharge for a storm with a uniform temporal rainfall distribution is given by Equation 1.

$$q_p = \frac{0.2083\,AQ}{D/_2 + L} \tag{1}$$

In Equation 1, q_p is the peak discharge in m^3/s, A is catchment area in km^2, Q is the stormflow depth in mm, D is the effective storm duration in hours and L is the catchment lag in hours. The effective storm duration is related to the catchment response time (or the lag) and therefore the denominator of Equation 1 can be simplified to 1.83 L. The stormflow runoff volumes and peak discharge values estimated are summarized in Table 2.

Table 2. Catchment runoff volume and peak discharge

	Runoff volume (m^3)	Peak discharge (m^3/s)
Eastern	1,210	17.6
Southeastern	824	19.1
Southwestern	674	5.2
Western	3,081	16.8
Northern	422	2.2

Hydrographs for each subcatchment were generated using the method developed by Haan (1994) and are shown in Figure 5.

3.4 *Hydraulic design*

The solution trench was divided into attenuation ponds by including concrete walls at 100 m intervals along its alignment. The hydraulic design of the in-line attenuation ponds was divided into two components, i.e. the solution trench conveyance during normal operational conditions and the attenuation ponds for the storm condition. While the larger constraint is the storm event flow condition, the outlets between the attenuation ponds must be sized to allow unrestricted flow during the operational condition. The sizing of the solution trench channel and outlets was an iterative process described in the sections below.

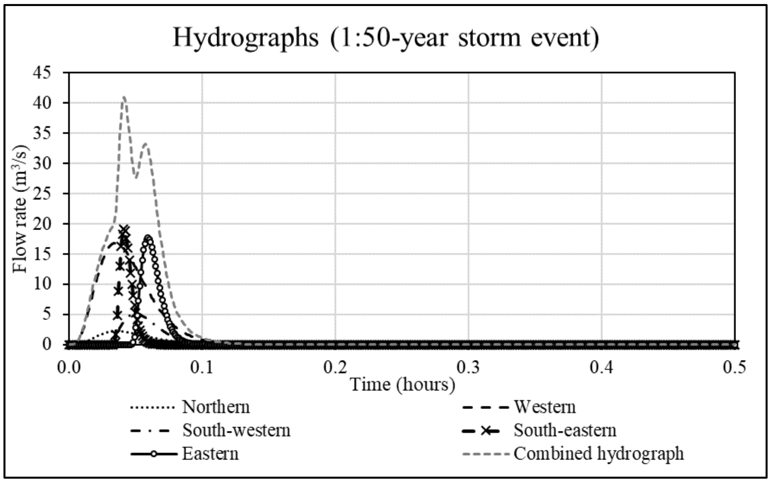

Figure 5. Hydrographs for each subcatchment

3.4.1 *Operational conditions*

The operational flow rate was quantified by considering the drain flows measured on the existing facility, outputs from the seepage model (for the above and below liner drain designs) and operational penstock decant flow rates estimated for the facility.

Under free surface flow conditions, the hydraulic capacity of the solution trench and outlets was determined by Manning's equation for open channel flow which is described by Equation 2.

$$Q = \frac{1}{n} \times A \times R^{\frac{2}{3}} \times \sqrt{S} \tag{2}$$

In Equation 2, Q represents the flow rate in m^3/s, A represents the cross-sectional flow area in m^2, n represents the Manning's roughness coefficient of the channel surface in $s/m^{1/3}$, R the hydraulic radius in m and S the slope of the channel in m/m. The slope of the solution trench varies along the perimeter of the facility due to undulation of the natural topography and therefore the hydraulic capacity of the solution trench and outlets under free surface flow conditions is not constant.

The initial configuration selected for the system was a trapezoidal concrete solution trench, with a base width of 1.5 m and provision for four 200 mm nominal diameter PVC pipes to serve as outlets. As part of the iterative process and to facilitate cleaning and maintenance, the outlets included in the final design are two rectangular box-outs of 450 x 200 mm in the concrete wall of each pond at the invert level of the solution trench. The minimum capacity of the solution trench and rectangular outlets exceeds the maximum flow rate under operational conditions and was therefore deemed satisfactory for operational conditions.

3.4.2 *Storm event conditions*

During the design storm event with a 1 in 50-year AEP, the runoff generated on the slopes of the TSF is collected by the in-line attenuation pond system and attenuated, while the rate of discharge between ponds is controlled by the outlet. Based on the maximum head determined, the concrete walls that form the in-line attenuation ponds are sized to be 1.20 m high at intervals of 100 m, and the initial proposed solution trench is deemed acceptable as the dimensions enable maintenance and operation as well as 0.43 m of channel freeboard (as a minimum). A partial plan view of the in-line attenuation ponds is illustrated in Figure 6.

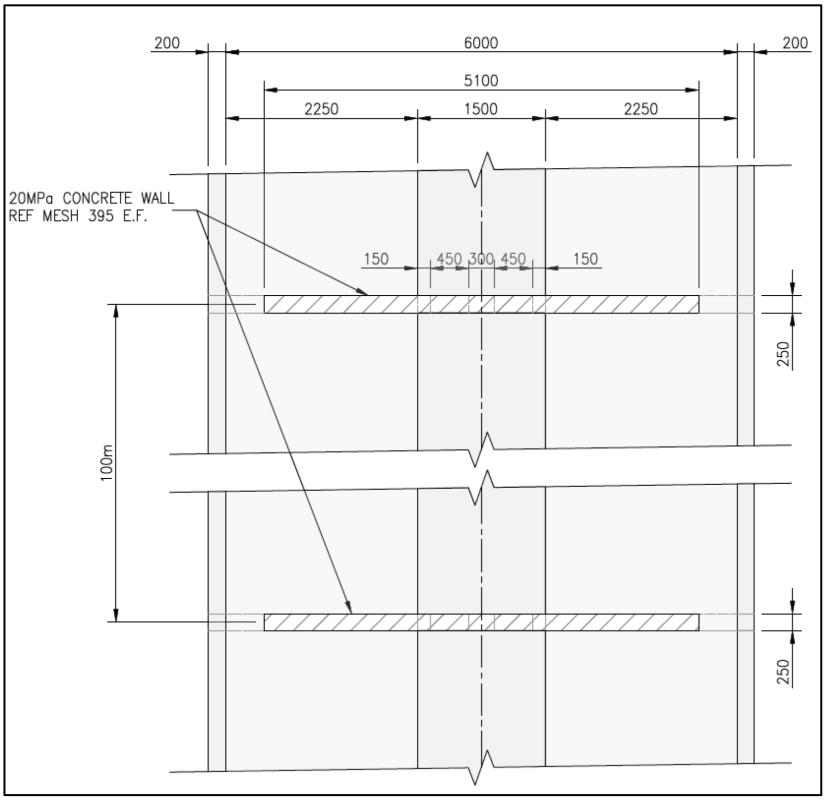

Figure 6. Partial plan view of in-line attenuation pond system

As a result of the location of the outlets at invert level, the outlets will be submerged after/ during a storm event and the orifice discharge formula described by Equation 3 is applicable to determine the rate of discharge.

$$Q = C_D \cdot A_o \sqrt{2g\mathrm{H}} \tag{3}$$

In Equation 3, C_D represents the discharge coefficient, A_o is the cross-sectional area of the opening of the outlet in m^2, g represents gravitational acceleration, H is the vertical height of water (head) at the outlet wall measured in m relative to the invert level of the outlet measured.

The range of the anticipated flow rates through the various compartments at the outlets using Equation 2 was determined as approximately 0.33 m^3/s (for the maximum head) and 0.24 m^3/s (for the minimum head). The area provided by two box-outs of 450 x 200 mm each provide sufficient control of the discharge rate resulting in the desired attenuation. A typical cross-section of a division wall within the solution trench forming an in-line attenuation pond is illustrated in Figure 7.

To ensure effective operation of the in-line attenuation pond system, any accumulated silt within the ponds must be cleared regularly and the outlets must be kept clean and clear of debris. To ensure that maintenance and cleaning is as easy to carry out as possible, the pipe outlets specified during the preliminary design were replaced with rectangular section outlets to enable the use of a broom during cleaning.

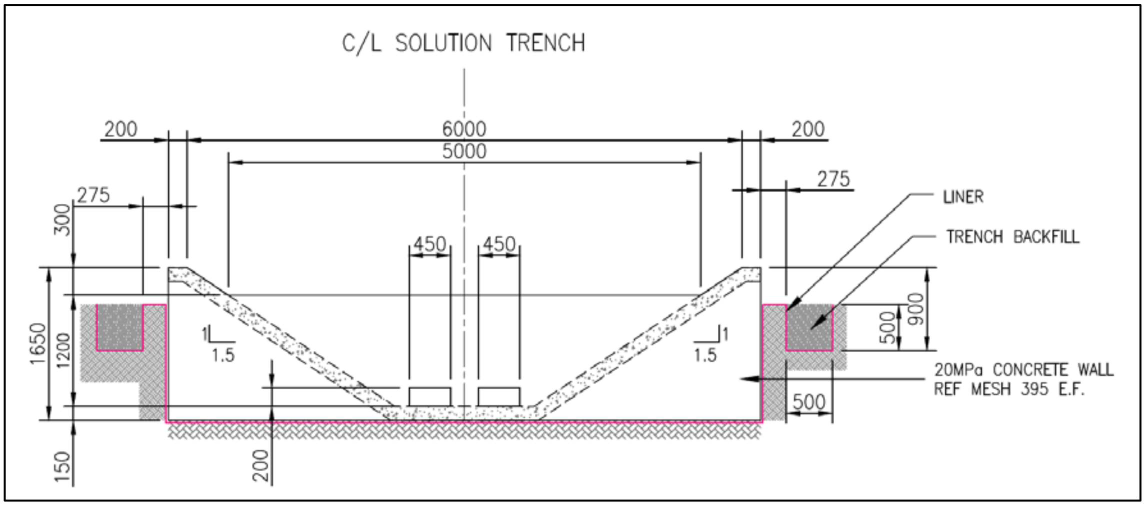

Figure 7. Typical section of outlet of in-line attenuation pond system

The attenuation provided within the ponds is limited to the height of the concrete walls and therefore the in-line attenuation ponds have the potential to spill. Due to this, storms with greater return periods (other than the 1 in 50-year AEP storm event) were evaluated. As the volume contained within the attenuation pond exceeds the storage volume, the walls are overtopped and will function as broad-crested weirs. The discharge rating of the weirs is determined by the relationship described by Equation 4.

$$Q = C_D \cdot L\, H^{\frac{3}{2}} \quad (4)$$

In Equation 4, C_D represents the discharge coefficient, L represents the length of the weir and H represents the head of water above the elevation of the crest of the wall. While the freeboard during storm events of a greater return period is reduced, the weir has sufficient hydraulic capacity to convey the required flow rate (the 1 in 100-year AEP storm event) without spillage.

3.5 *Evaluation of design*

To further evaluate the performance of the in-line attenuation pond system by simulation, a routing model was compiled using the EPA Stormwater Management Model (SWMM) software. The stormwater was routed through the in-line attenuation pond system for the required storm condition and the results evaluated for performance.

A series of 26 in-line attenuation ponds were modelled to route flow resulting from the hydrograph determined for each contributing catchment and flow received from preceding attenuation ponds in the series. The outlet condition from each basin is specified as a cumulative function which consists of the free surface flow condition (operational condition), orifice flow (for attenuation of a storm) and weir flow (when a storm with a greater return period than the design storm occurs).

The design objectives for the in-line attenuation ponds were to maximize water return, protect groundwater from pollution and minimize costs. Results of the evaluation in the SWMM model indicated that the in-line pond system is successful in attenuating the stormwater to the extent that the resultant runoff is safely discharged to the silt trap and return water dam with no spillage. A cost comparison between a more traditional system which includes independent lined paddocks (approximately 8.5 Ha) and solution trenches and the in-line attenuation pond solution was completed. The cost saving on the liner and ground preparation is approximately ZAR 10 million (approximately 5 % of the total project capital expenditure).

3.6 *Construction and maintenance consideration*

The walls that divide the solution trench into the attenuation ponds are designed for construction using 20 MPa reference mesh-reinforced concrete. The openings could be cast in a concrete wall as box-outs without difficulty. The openings were also sized to ensure ease of cleaning in the event of siltation or blockage by debris. Siltation of the ponds is anticipated over time and therefore an essential part of the operations and maintenance considerations will be the ongoing maintenance and care of the in-line attenuation ponds.

4 CONCLUSIONS

The impact of water stress caused by drought conditions and water scarcity is a growing concern across the world in all sectors, including the mining industry. Innovative solutions are therefore imperative to optimize the management of mine waste water.

To design optimized systems or structures for the collection, attenuation and conveyance of stormwater runoff from the embankments of TSFs in future, reducing the uncertainty in quantifying stormwater runoff rates and volumes is required.

The methods currently employed in determination of the stormwater runoff flow rates and volumes are sensitive to the selection of a series of runoff coefficients. These runoff coefficients are selected on the basis of land use, vegetation condition and soil type (characterised by hydrologic soil groups). The runoff coefficients which may be considered applicable to partially vegetated TSF embankments require calibration and/or validation.

Climate monitoring stations on site are currently maintained and operated by the operator on the facility. In addition to measurement of the rainfall depth, measurement of the stormwater volumes accumulated within the paddocks at facilities that use the traditional paddock system (or recording of the depths resulting in the in-line attenuation ponds) is recommended. Monitoring of water levels within the paddocks at existing TSFs and water facilities will enable calibration of the runoff coefficients resulting from the storm depth as measured.

Furthermore, the impact of drought and extreme weather patterns may affect the type and rate of establishment of vegetation. Many TSF embankments in South Africa are currently irrigated to suppress dust and encourage and sustain vegetation establishment. This practice may prove unsustainable in future due to the volumes of water consumed and alternate vegetation and/or erosion protection measures may be required, altering the stormwater runoff generation potential.

The in-line attenuation pond system optimizes the footprint of the facility, and reduces capital cost and water losses. Exclusion of a paddock system lined with the required pollution control barrier system resulted in a footprint that was reduced by approximately 8.5 Ha and an estimated capital cost saving of more than ZAR 10 million. Following construction, with effective maintenance, the efficacy of the in-line attenuation pond system can be evaluated and potentially applied to the design and construction of other facilities that are subject to similar constraints.

REFERENCES

Chadwick, A., Morfett, J. & Borthwick, M., 2004. *Hydraulics in Civil and Environmental Engineering.* Fourth Edition ed. New York: Spon Press.

Department of Water Affairs and Forestry, 1999. *Regulation No. 704 on Use of Water for Mining Related Activities Aimed at the Protection of Water Resources*, Pretoria: National Water Act, 1998 (Act No. 36 of 1998).

Department of Environmental Affairs, 2013a. *Regulation No. 634: National Environmental Management: Waste Act (59/2008): Waste Classification and Management Regulations*. Government Gazette of the Republic of South Africa, 578(36784), pp. 3-21.

Department of Environmental Affairs, 2013b. *Regulation No. 635: National Environmental Management: Waste Act (59/2008): National norms and standards for the assessment of waste for landfill disposal*. Government Gazette of the Republic of South Africa, 578(36784), pp. 22-33.

Department of Environmental Affairs, 2013c. *Regulation No. 636: National Environmental Management: Waste Act (59/2008): National norms and standards for disposal of waste to landfill*. Government Gazette of South Africa, 578(36784), pp. 34-45.

Department of Environmental Affairs, 2015a. *Regulation No. 632: National Environmental Management: Waste Act (59/2008): Regulations Regarding the Planning and Management of Residue*. Government Gazette of the Republic of South Africa, 601(39020), pp. 4-14.

Department of Environmental Affairs, 2015b. *Regulation No. 633: National Environmental Management: Waste Act (59/2008): Amendments to the List of Waste Management Activities that have, or are likely to have, a Detrimental Effect on the Environment*. Government Gazette of the Republic of South Africa, 601(39020), pp. 15-16.

Haan, Barfield & Haynes, 1994. *Design Hydrology and Sedimentology for Small Catchments*. London: Academic Press Inc.

Kottek, M., J. Grieser, C. Beck, B. Rudolf, and F. Rubel, 2006: *World Map of the Köppen-Geiger climate classification updated*. Meteorol. Z., 15, 259-263. DOI: 10.1127/0941-2948/2006/0130.

Parliament of the Republic of South Africa, 1998. *National Water Act (36 of 1998)*, Cape Town: Parliament of the RSA.

SANRAL, 2013. *The Drainage Manual*. Sixth ed. Pretoria: The South African National Roads Agency SOC Ltd.

Smithers, J. C. & Schulze, R. E., 2002. *Design Rainfall and Flood Estimation in South Africa*, Pietermaritzburg: Water Research Commission.

SRK, 2017. *Marula Tailings Dam No. 2 – Preliminary Design Report – Engineering Analysis and Design of Tailings Dam*, Johannesburg: SRK Consulting (South Africa) (Pty) Ltd.

The Chamber of Mines of South Africa, 1996. *Guidelines for Environmental Protection: The Engineering Design, Operation and Closure of Metalliferous, Diamond and Coal Residue Deposits*. Johannesburg: Chamber of Mines of South Africa.

United States Geological Survey (USGS), 2016. *How much water is there on, in, and above the Earth?* [Online] Available at: https://water.usgs.gov/edu/earthhowmuch.html [Accessed 24 June 2018].