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Evapotranspiration to minimise acid mine decant from a decommissioned colliery

ASH Haagner *Agreenco Environmental Projects (Pty Ltd), South Africa*

SJ van Wyk *Agreenco Environmental Projects (Pty Ltd), South Africa*

Abstract

Acidic mine water decant from legacy coal mines presents significant environmental impacts to the Highveld watercourses in South Africa. The costs and logistics for active treatment are often not feasible due to the remoteness of sites, excessive capital and operational costs, lack of infrastructure and complications with brine and sludge disposal. The regulatory authorities currently prefer active pumping and desalinating water from flooded underground compartments, followed by the discharge of treated water into natural watercourses. However, if a sufficient body of monitoring evidence can prove efficacy with a high degree of confidence, then lower-cost and more sustainable water management alternatives may become a reality.

In this project we monitored different tree plantation trial blocks of two species that were established in 2012 to reduce vertical groundwater recharge from rainfall that would report to underground workings. Reducing the ingress rates to below critical levels would eliminate the decant of acidic mine water to receiving watercourses.

Monitoring focussed on establishing water budgets (rainfall, throughfall, soil moisture and moisture extinction, sap flow and groundwater levels) via continuous logging instruments. The monitoring period was four years, from 2018 to 2022, once the trees were nearing maturity. The data were used in building a conceptual site model and then a geohydrological model to estimate draw-down within the trial blocks. A site survey for possible plantation expansion areas followed, after which the geohydrological model was again updated to extend the ingress reduction to a larger area.

The study found that trees survived very well, but that different species were better suited to specific conditions. Water uptake and ingress reduction were very effective in all but the highest rainfall periods. The geohydrological model showed effective draw-down, with the expansion model confirming that the trees could limit vertical groundwater recharge to near zero. However, a residual interflow from deeper aquifers would still result in some recharge to underground workings. During periods of excessive rainfall, this would have to be pumped and used to irrigate plantations to prevent decant altogether.

The establishment of commercial-scale forestry plantations with continuous-cover harvesting could fulfil an important role for local enterprise development, job creation and effective sustainable post-mining land-use, whilst contributing significantly to continuous passive groundwater decontamination, reducing groundwater liability and environmental degradation.

Keywords: *evapotranspiration, phytoevaporation, coal decant, acid mine drainage.*

1 Introduction

Managing the legacy of groundwater issues arising from coal mining is one of the greatest challenges facing the South African coal mining industry (Ochieng *et al.,* 2010). Whilst active collieries operate in a structured and prescriptive legislative environment that requires current and future management of latent and residual groundwater liabilities, legacy mines often do not have the resources or structures to finance long term and adequate interventions. This is particularly prevalent in the South Africa's KwaZulu-Natal coal sector, where many legacy underground operations were mined and now lie abandoned and unrehabilitated (Mintek, 2007). Due to the relatively high rainfall of the KwaZulu-Natal coal belt, many of the underground works are flooded or partially flooded, and decanting (where groundwater becomes surface water) is commonplace

(DME, 2003), with negative impacts to receiving water bodies and terrestrial environments. The high sulphide (particularly pyrite) of the bord-and-pillar mined coal and host rock, coupled with the high oxidation levels provided by oxygen ingress and fluctuating groundwater levels, drives the generation of sulphuric acid, dissolving metals and transporting them to surface (McCarthy, 2011).

As the KwaZulu-Natal coal belt has very challenging and variable structural geology (Mintek, 2007), interventions to mitigate acidic groundwater decant are quite limiting, especially considering that many of the operations are legacy sites that have no or very little funding. Furthermore, the regional Authorities governing protection of water resources require active pumping and treating of the contaminated groundwater as a blanket recommendation, in the absence of proven alternative technologies (DWS, 2015). This situation creates the potential for investigating risk-based, lower cost options, such as nature-based solutions, but within a framework of rigorous scientific experimentation. with robust evaluation of results.

One such lower cost option involves harnessing the evapotranspiration potential of plants to reduce overall water ingress into undermined areas, thus keeping water levels at constant rates and below decant elevations. This simultaneously reduces the oxidation rates for production of acidic groundwater, and prevents the decant of poor quality water, or at least limits the impacts of decant events through effective dilution. The KwaZulu-Natal coal belt is well-suited to commercial forestry and plantations are relatively common and productive.

We considered that using both commercial and indigenous forestry tree species with high anticipated growth rates and total water usage may be a cost-effective means to reduce, or even eliminate, the impacts of acidic decant into the receiving waters. We devised an experimentation framework to provide results on overall efficacy of reducing decant impacts and monitored the results over a period of five years. The key research questions were:

- Do the trees take up enough water to decrease vertical groundwater recharge to acceptable levels, and
- What is the impact of the tree's water consumption on regional groundwater and the existing volumes and quality of decant?

The learnings from this study can be translated to other similar climatological areas of the KwaZulu-Natal coalfields, other southern African coal mining regions, and international regions with similar geochemistry and groundwater conditions.

2 Study background

2.1 Study site

The study site is in between Newcastle and Dundee in the KwaZulu-Natal coal belt of South Africa, which is about 250 km to the southeast of Johannesburg, with an elevation of 1,125-1,440 m above mean sea level (Figure 1). The mining area is situated within the Klip River coal fields (part of the Vryheid Geological Formation), on the eastern escarpment that separates the higher-altitude interior from the lower altitude coastal plain. The landscape appears natural, as most mining activities took place underground. There is no surface discard, and the only remnant surface infrastructure is a single adit, which is used for managing decant volumes.

Annual average precipitation for the study period (2018-2022) was 829 mm per annum and rainfall in the area falls predominantly within the summer months (October to March) with the highest values in December and January, mainly occurring as thunderstorms.

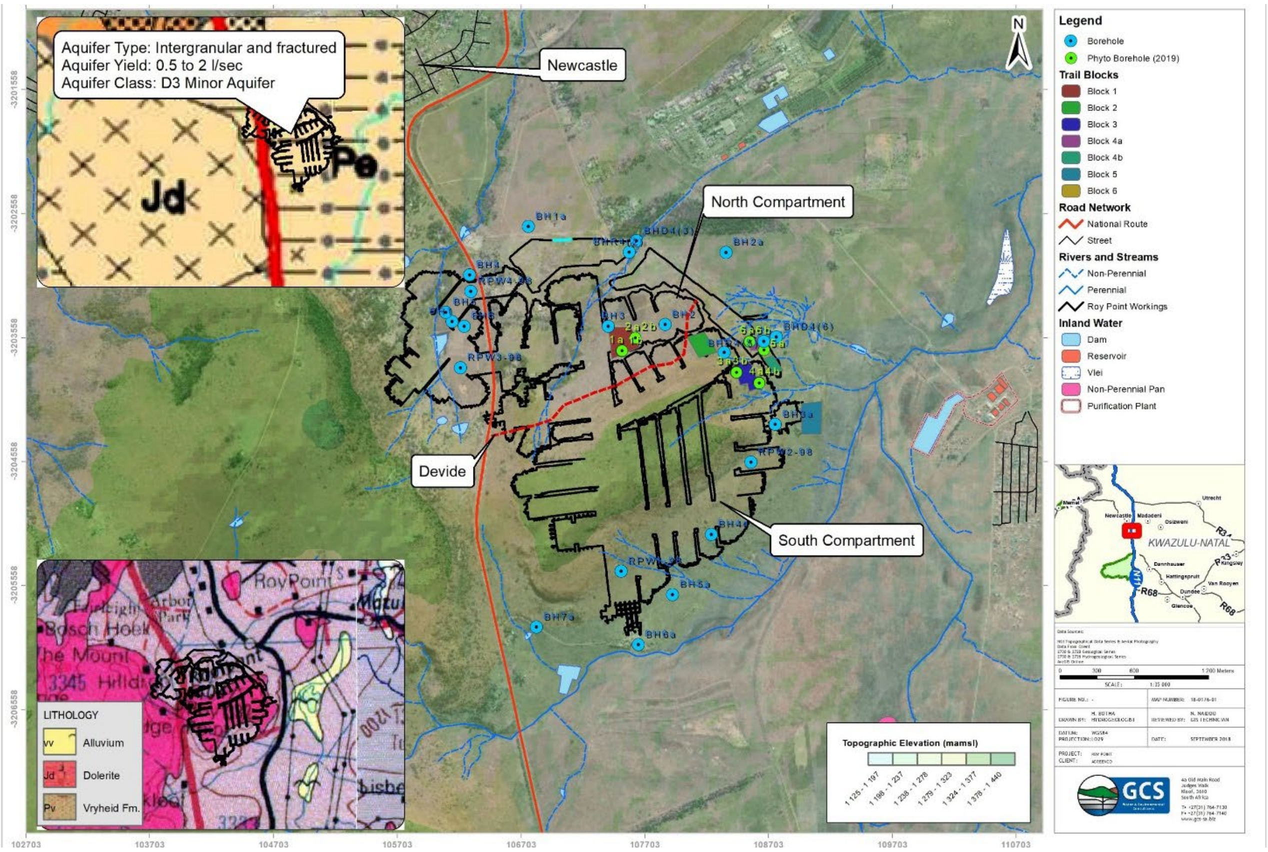


Figure 1 Study area location of the colliery where the evapotranspiration trial is situated

The underlying geology of the site is predominantly Ecca shales and sandstones of the Karoo Supergroup, with the higher elevations comprising Ingogo Dolerite sills (Figure 2) with very low permeability. The underground works is divided into two compartments that drain north and south towards different catchments (Figure 2). Hydrologically, four distinct zones occur:

- Alluvium zone;
- Shallow weathered to semi-weathered confined aquifer zone (varying from 5-15 m);
- Intermediate partially weathered and fractured aquifer zone (to a depth of 50-60 m);
- Confined fractured rock aquifer zone (extending to > 140 mbgl);
- Artificial mine aquifer, with the mine floor separating the old underground workings into two compartments, with interflow between them at an internal decant point (Figure 2).

The soils are predominantly shallow and rocky at the hill-top and slopes, with lower slope sections being comprised of deeper loamy sands, with clay pockets in natural slope seep zones.

The vegetation is mostly natural, comprising mixed grassland and open woodland typical of the KwaZulu-Natal escarpment. The high rainfall yields tall grasses with low grazeability, interspersed with shrubs and small trees in pockets where the terrain prevents excessive frost and fire occurrences.

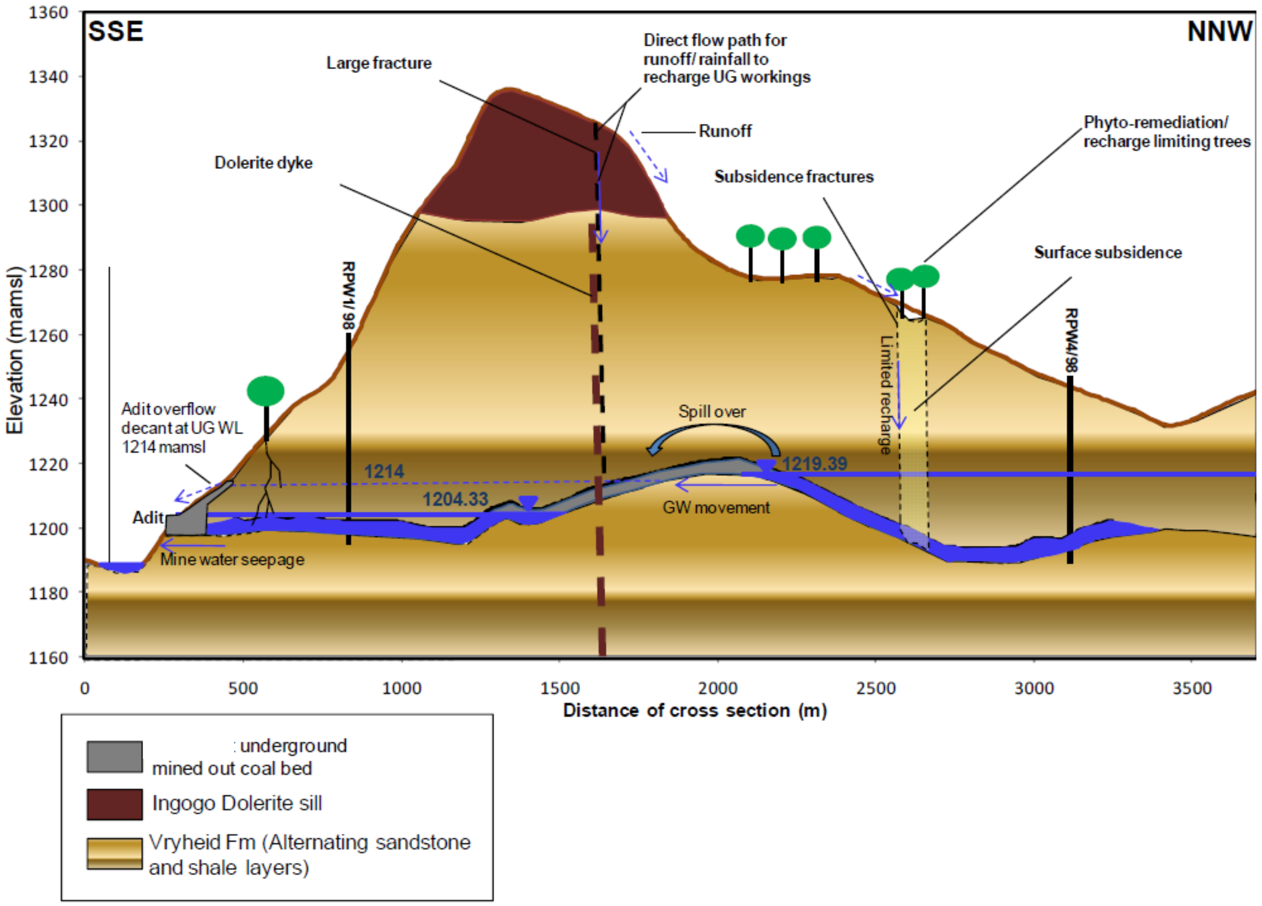


Figure 2 Conceptual model of the study site showing mining compartments and internal and external decant elevations, with evapotranspiration trial blocks

2.2 Evapotranspiration trial block layout

In 2012, six one-hectare trial blocks were established with different tree species to assess the survivability and growth of potential evapotranspiration trees. *Eucalyptus dunnii* (*Eucalyptus*), *Searsia lancea* (*Searsia*) and *Tamarix usneoides* (Wild Tamarisk) (all lycophytic evergreen species) were planted as these species have been reported to have high evapotranspiration potential (McLeroth, 2015). However, the Tamarisk plants failed (fire, grazing and other environmental factors) and only a few stunted plants survived.

Table 1 Details of evapotranspiration trial blocks monitored for the trial

Block	Species	Elevation	Average soil depth	Soil type
1a	*Searsia lancea*	1,263 mamsl	Deep (1.5 m)	Hutton/Bainesvlei/ Avalon
1b	*Eucalyptus dunnii*	1,267 mamsl	Moderately deep (1.2 m)	Hutton/Bainesvlei
3	*Eucalyptus dunnii*	1,260 mamsl	Deep (1.5 m)	Shortlands/Swartland/Bonheim
4a	*Eucalyptus dunnii*	1,237 mamsl	Moderately deep (1.0 m)	Willowbrook/discard
4b	*Searsia lancea*	1,228 mamsl	Deep (1.4 m)	Willowbrook/discard

Table 1 shows the trial blocks that were selected to form part of the four-year monitoring project. A combination of species in a diverse and representative set of soil forms and depths were selected to best represent data for extrapolation and geohydrological modelling. The layout of the trial blocks is shown in Figure 3.

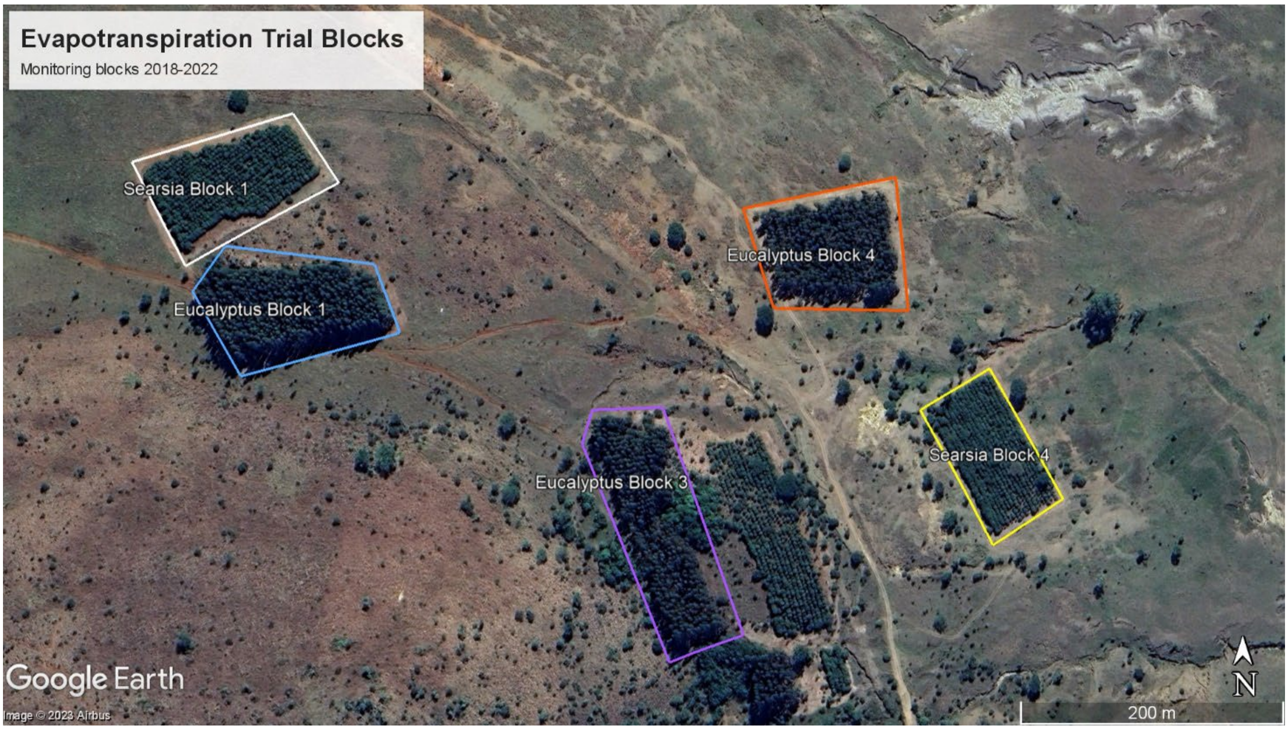


Figure 3 **Location and distribution of evapotranspiration trial blocks**

Deep-rooted *Eucalyptus dunnii* trees are expected to be able to access water in deeper soil profiles and transpire it into the atmosphere. This is a fast-growing species that is known to mature much faster than *Searsia lancea*, and therefore have an earlier impact on groundwater levels. The purpose of the planted *E. dunnii* is to utilize sufficient groundwater to prevent it from rising to a level where it decants from the flooded underground workings to mix with the surface water systems.

Shallow-rooted trees capable of establishment in rocky areas (where soil depth and volume limit commercial forestry species) are also required to intercept seepage and dry out the soil. *Searsia lancea* was selected based on its relatively high water-use and frost tolerance (Dye *et al*., 2017) and tolerance to rocky soils, mine-impacted water and contaminated mine soils. Being an indigenous species, it is more acceptable to regulators and the public than exotic options such as the *Eucalyptus* trees.

3 Materials and methods

3.1 Monitoring and modelling scope

The monitoring project was initiated in May 2018, however, the first year of monitoring was dedicated to the acquisition of instrumentation, calibration, installation, and preliminary test-work. The second year was dedicated to increasing confidence in tree monitoring data output and geohydrology model development for the trial blocks. This was achieved by undertaking rooting depth investigations and installing water level loggers. Additionally, the geohydrological model was expanded to include the wider undermined area. The third year of monitoring was dedicated to further understanding tree water use and the impacts of tree cutting (and coppicing) on tree water use. Further investigations were undertaken to determine the feasibility of expanding the tree plantations to include a wider extent of the mining lease area and the findings were incorporated into the geohydrological model. The fourth year of monitoring was dedicated to further understanding tree water use and the impact of tree coppicing on tree water use, and to increase the confidence of the geohydrology model development. Note that geochemical measurements and modelling were excluded from the study scope and remain an avenue for future investigation.

The following works were undertaken during the monitoring of the trial blocks:

1. Tree Monitoring:
    - ○ Tree growth rates (diameter at breast height) measured,
    - ○ Sap flow probes monitoring tree water uptake,
    - ○ Soil moisture probes measuring soil moisture fluxes,
2. Groundwater monitored using water level loggers;
3. Groundwater modelling:
    - ○ Water balance based on current tree monitoring data;
    - ○ Recharge reduction rates for expanded plantations.

3.2 Monitoring methodology

Two complementary monitoring techniques were followed to monitor tree water uptake. The two techniques were based on water budget measurements and transpiration measurements. Additionally, vegetation performance was also monitored by periodically measuring stem diameter. As part of the monitoring, a borehole level monitoring component was added to the study to provide input into the success of the initial trial testing. All of the data were fed into groundwater models to evaluate the impact of the trial blocks on local recharge reduction, and to evaluate the potential impacts of regional decant reduction if the trial blocks were to be expanded.

3.2.1 Water budget measurements

Water budget measurements were performed using tipping bucket rain gauges and soil moisture probes. The soil moisture probes used were capacitance probes that can effectively measure soil moisture to a depth of 1,200 mm. The probes were installed next to the trees (1-2 m range) and mounted with rain gauges to measure soil moisture and rainfall simultaneously. The probes measured soil moisture content as a millimetre equivalent relative to volume at ten-minute intervals and remotely sent data to the cloud.

3.2.2 Water use measurements

Sap flow was measured by means of thermal dissipation probes (TDPs), which measure the rate at which sap moves through a tree. Sap is the water present in the tracheary cell of the xylem tissue of the tree (Kirkham, 2014). The xylem tissue is one of the two transport tissues present in vascular plants and its basic function is to transport water and nutrients from the roots to stems and leaves. Sap flow, therefore, serves as an indication of the transpiration rate and thus provides good water-use estimates of the trees (Kirkham, 2014).

Sap flow probes work on the principle of thermal dissipation, which the transfer of heat from a heated object to a cool object. To measure sap flow, two probes are inserted into the sapwood, one containing an electric heater (upper heated needle) and the other (lower reference needle) measuring the difference in temperature relative to the time of heating. The probes are specific to a given stem diameter and we opted to use the 30 mm probes for the *Searsia* trees and the 80 mm probes on the *Eucalyptus* trees.

The probes were connected to a data-logger, which has a modem for data transfer on a continuous basis. Data was collected and stored on the data-logger at 15-minute intervals. Additionally, the data were also stored remotely as an added measure to reduce the risk of data losses. A total of five sap flow probes were installed per species in each trial block. Sap flow measurements are presented in $cm^3.hour^{-1}$ and may be converted to L/hour.

By default, sap flow is measured for a sapwood area of 1 m^2 and needs to be recalculated using tree specific sap wood areas. All the calculations for the water use per hectare are based on the current configurations of the trees at one tree per 6 m^2.

3.2.3 Stem diameter and sapwood area estimation

Stem diameter provides an indication of the growth of the trees and is used to calculate sapwood area. Stem diameter is measured just above the sap flow probes. The sapwood area was calculated as follows:

- Total wood area was determined using diameter at breast height;
- Heartwood and bark area (measured from cut trees) was determined;
- Sapwood area was calculated by subtracting total wood area from heartwood and bark area.

3.3 Hydrogeological and geological conceptual model update

The hydrological and hydrogeological conceptual model was updated, studying:

- Groundwater baseflow, on-site water levels, temperature and rainfall;
- Evapotranspiration and tree root update rates;
- Throughfall (i.e. rainfall making it past the tree canopy onto the ground) measurements;
- Estimated groundwater recharge to the groundwater table.

3.4 Hydrogeological modelling

Both analytical and numerical groundwater flow models were developed and were updated periodically with the latest data available for the site. This helped to identify the impacts in terms of:

- Groundwater recharge reduction;
- Groundwater dewatering;
- Implications in terms of the water balances associated with the test block areas.

The impact of evapotranspiration (ET) on groundwater recharge was modelled using a groundwater balance model, where the ET component was used to reduce the recharge. The model used was the SVF model (Van Tonder & Xu, 2000) which translates a change in volume to a change in water level. The limitation in the model is that is assumed that ET directly relates to saturated zone water losses. Based on the positions of the trial blocks, two sub-catchment/drainage areas were delineated. Boreholes that fell within the weathered aquifer zone within the delineated sub-catchments were used to calibrate the model. It is important to note that the boreholes were located far away from the trial blocks, hence dewatering effects were not anticipated in the initial water balance.

The pre-tree model was calibrated with head data for boreholes within the delineated sub-catchments up to the start of 2013. Post-tree settings (where ET was introduced) started from 2013 and ran to 2022. Calibration data for the period 2018 to 2022 is presented, as this is the period where phyto-evaporation monitoring boreholes were installed and for which ET data is available.

4 Results and discussion

4.1 Volume of water uptake to decrease vertical recharge to acceptable levels

For the evapotranspiration project, the target recharge reduction to the underground works was set at ~500 $m^3.day^{-1}$ to prevent decant on average, whilst the remainder of the groundwater influx was from aquifer interflow.

4.1.1 Vertical recharge reduction by trees in the trial blocks

Searsia Block 1: This trial was located on undisturbed, deep loamy soils (Table 1). During rainfall periods there was a less prominent transition from the uppermost zone (20 cm) to the deepest monitored zone (120 cm) in the tree block areas. The vertical recharge data suggested that the trees prevented infiltration into deeper soil zones. The interception of infiltration resulted in less water available for vertical groundwater recharge.

Eucalyptus Block 1: This trial was also located on undisturbed, deep loamy soils (Table 1). It was observed that soil moisture increased with depth from April 2020 to June 2022 (40-80 %). The increase in the soil moisture was due to the increased throughfall. It was considered that the soil was very well saturated and that 50-80 % of the soil pores were filled with water. It was noted that, during the very high rainfall events from December 2021 to April 2022, more water was present in the 100 cm and 120 cm profiles. As such, the trees appeared to not have been effectively able to always prevent percolation, which was likely a result of the high precipitation (over saturation). In general, and observing previous years' data in context to 2022, it was observed that the trees generally prevented infiltration into deeper soil zones. The interception of infiltration resulted in less water available for vertical groundwater recharge.

Eucalyptus Block 3: A good transition from shallow to deep soil zones was observed after and during rainfall events, hence this trial block did not have a major impact on limiting rainfall infiltration. This block was located on a shallow seep zone (Table 1), where more shallow groundwater flowed than the trees could take up. *Eucalyptus* B3 was the best performing block, in terms of water uptake. The higher soil moisture content in this seep zone was highly likely the reason for the better performance of the trees when compared to other tree blocks. However, the high ET caused by the trees will likely decrease vertical groundwater recharge. Although *Eucalyptus* B3 was the best performing block in terms of water uptake, it showed the greatest amount of groundwater recharge.

Eucalyptus Block 4: *Eucalyptus* B4a was situated in disturbed soils associated with the backfilled opencast workings (Table 1). Soil moisture in *Eucalyptus* B4 did not relate well to *Eucalyptus* B1 and *Searsia* B1, but more closely related to *Eucalyptus* B3. Similarly, a good transition from shallow to deep soil zones was observed after and during rainfall events and *Eucalyptus* B4 was shown to have a limited impact on rainfall infiltration. It was noted that during the very high rainfall event from Dec 2021 to April 2022 that more water was present in the 100 cm and 120 cm profiles. As such, the trees appeared to not have been effectively able to prevent percolation which is likely a result of the high precipitation (over saturation) and lower tree cover that could persist on the backfilled opencast.

Searsia Block 4: *Searsia* B4b was situated in disturbed soils associated with the backfilled opencast workings (Table 1). A similar trend in water transfer in the tree block area and at the reference site was noted with regards to *Searsia* B4b to *Eucalyptus* B4a. Reference soil data suggested a moisture deficit in the 20 cm soil zone, which improved to an overall >40 % moisture content in the 120 cm zone. The 40-80 cm soil zones exhibited soil moisture in the same order of magnitude, which suggested the uniform transfer of soil water through these zones. Soil moisture tended to improve during and shortly after rainfall events and the data suggested that pore water was transferred to the deepest zone (100-120 cm) which was also the most saturated. Likely, a similar transfer to deeper soil zones (>100 cm) occurs, which translated to vertical groundwater recharge.

4.1.2 Measured performance of trees over time

Stem diameter is measured as an indication of tree growth and used to calculate sapwood area. It has been found in literature that sap flow increases as sapwood area increases (Delzon et al., 2004). Figure 4 shows the changes in stem diameter measured over time. The data shows that there was an increase in stem diameter in all the trial blocks throughout the monitoring period, correlating positively with the water uptake. The Searsia trees were quite small when compared to the Eucalyptus trees at the start of monitoring in 2018. In the open cast area (Block 4), the Searsia trees had a 50% increase in the stem diameter over the monitoring period. The Searsia trees in the natural soils (Block 1) showed an increase of 150%. The Eucalyptus trees had almost the same stem diameter in the opencast and the natural soils with an average stem diameter of around 12 cm at the start of the monitoring period (December 2018). However, at the end of the monitoring period (June 2022), the Eucalyptus trees in Block 1 (natural soils) increased from 12 cm to 15 cm, (an increase of 25%), those in Block 4 (open cast areas) increased from 12 cm to 16 cm (an increase of 30 %) and the Eucalyptus trees in Block 3 (seep zone) increased from 12 cm to 18 cm (an increase of 50 %) from the initial monitoring period (December 2018). The change in the stem diameter in the Searsia trees increased rapidly in FY22.

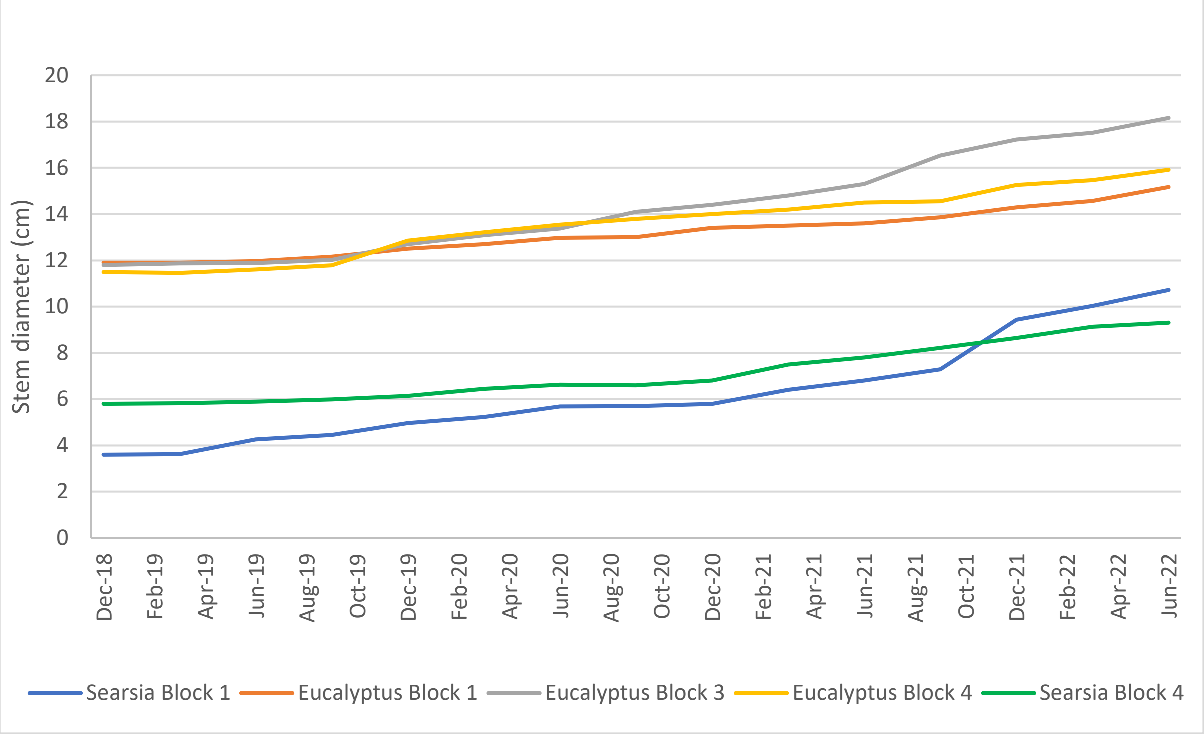


Figure 4 **Changes in stem diameter in the trial blocks over the monitoring period**

One of the aims of establishing tree plantations at the evapotranspiration trial was to investigate whether water uptake by trees would contribute to the reduction in vertical groundwater recharge. It was expected that evapotranspiration by the trees would result in the removal of excess moisture in the soil that was not intercepted, thereby reducing groundwater drainage/percolation. A root development investigation in 2020 indicated that the maximum rooting depth was 2 m, with the bulk root mass in the top 1 m. Water use by trees was measured by taking sap flow measurements and determining the amount of water flowing through the stems hourly and translating that to daily water use. All the calculations for the water use per hectare are based on the current configurations of the trees at one tree per 6 m^2 (1,666 tree density per ha for both tree species). Figure 5 shows water use by the whole trees over time and further demonstrates the changes in water use patterns as influenced by changes in season and rainfall patterns. The *Eucalyptus* trees in trial Block 3 had the highest mean water use amongst all the trees, as the block was located on a seep zone. The figure shows that water use increased during the wet months. This indicates that water use is dependent on soil moisture content. It should be noted that the water use by most of the trees was within the ranges reported in literature (shown as minimum values for *Eucalyptus* and *Searsia* respectively in Figure 5) for similar studies carried out in South Africa (Dye et al., 2008; Dye et al., 2016).

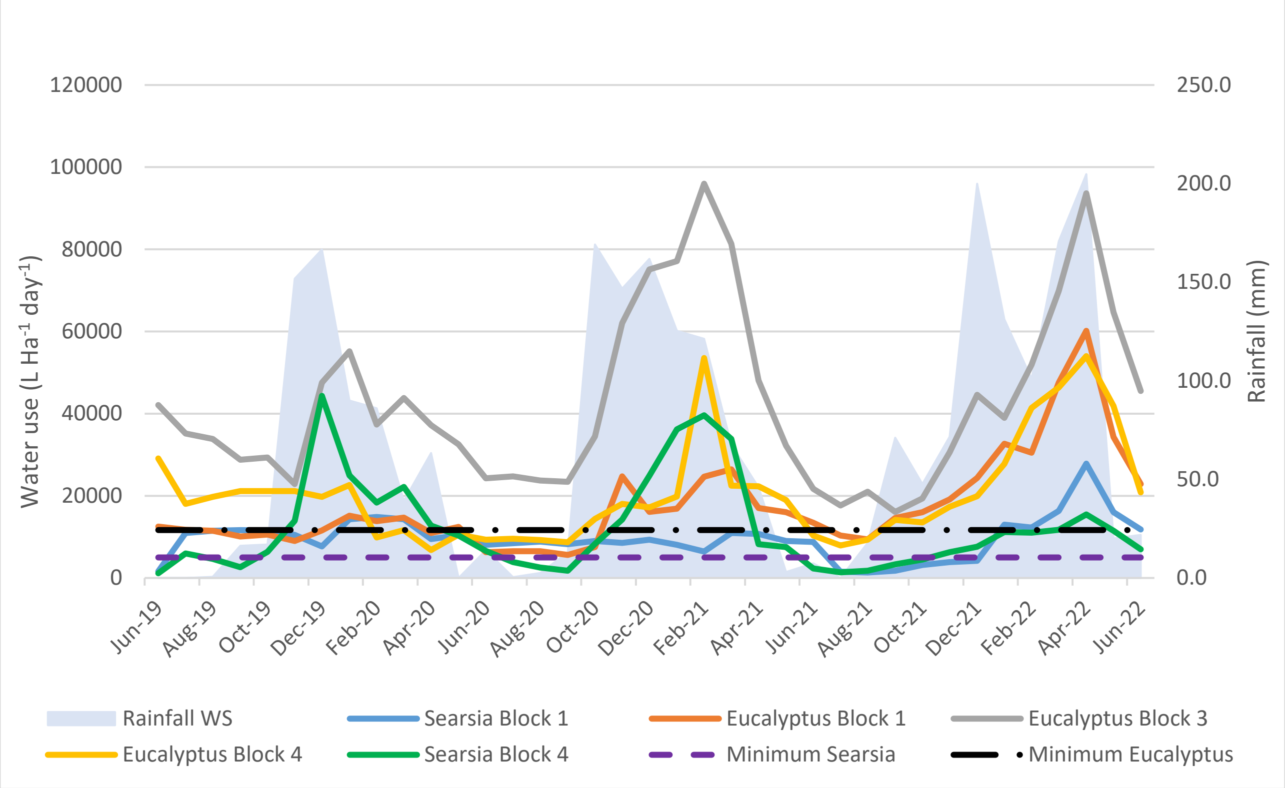


Figure 5 Mean daily water use by trees in the trial blocks compared to similar studies, in relation to rainfall

4.1.3 Estimated throughfall and impact on vertical recharge

Throughfall represents that portion of incident precipitation that is not intercepted by plant foliage in the trial blocks (which is then lost as evaporation). Throughfall was calculated for the period from July 2019 to June 2022. It is important to note that the amount of rainfall that reached the soil was less under/near the trial blocks than for rainfall distributed onto open soil (i.e., due to leaf coverage, pressure drops/increases caused by tree block temperatures and changes in wind directions/windbreaking). Throughfall that permeated the litter layer first needed to overcome the soil moisture deficit before percolation to the aquifer took place.

Over the monitoring period, the recharge reduction for Searsia Block1, Eucalyptus Block 1, Eucalyptus Block 3, Eucalyptus Block 4 and Searsia Block 4 was 57 %, 54 %, 63 %, 46 % and 53 % respectively. Groundwater recharge (using the chloride mass balance method for aquifer recharge of 3.54 %, which relates to the pre-tree model developed) decreased to 1.5 %, 1.6 %, 1.3 %, 1.9 % and 1.7 % respectively. These values, however, only take canopy cover into consideration. This is then further reduced when root uptake is considered.

Figure 6 shows the mean monthly throughfall recorded from July 2019 to June 2022. Monthly throughfall recorded shows how trees respond to seasonal changes in rainfall. An analysis of the monthly throughfall data indicated a positive correlation between rainfall and throughfall. However, the correlation was not as good in 2022 with the extreme rainfall that was recorded on site. The figure shows that rainfall was much higher in 2022, with slight decreases in the volume of throughfall.

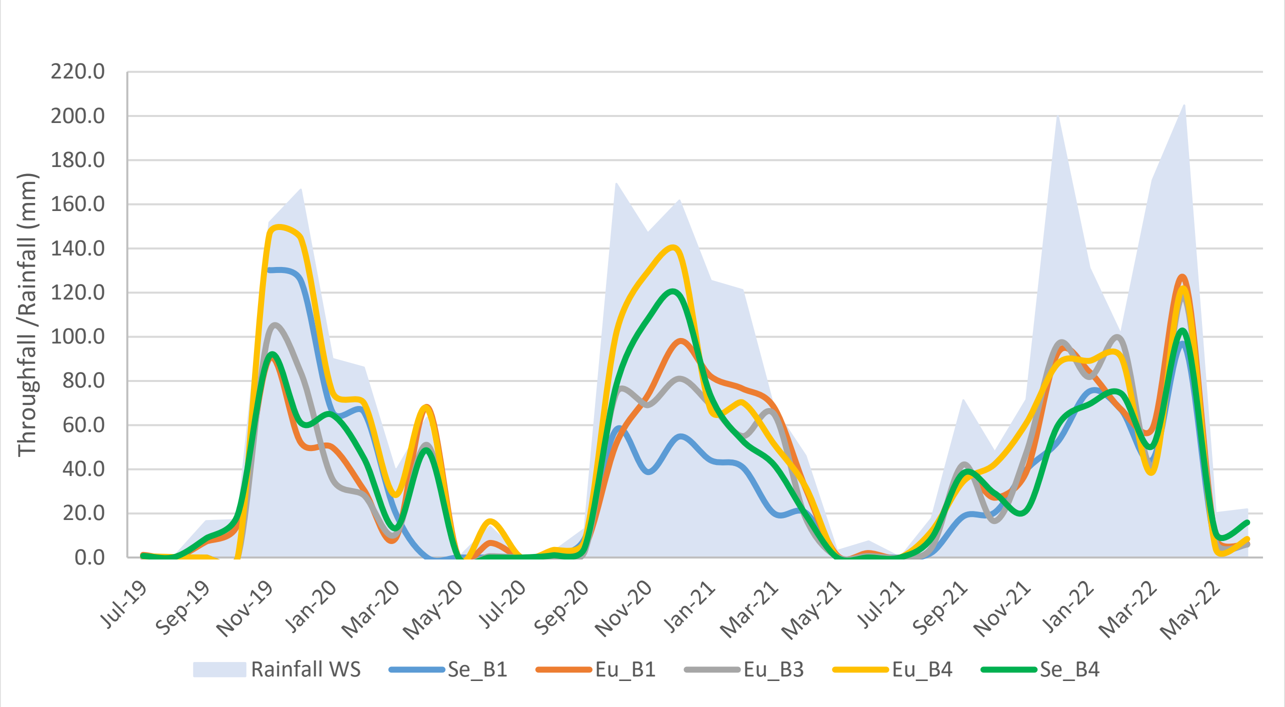


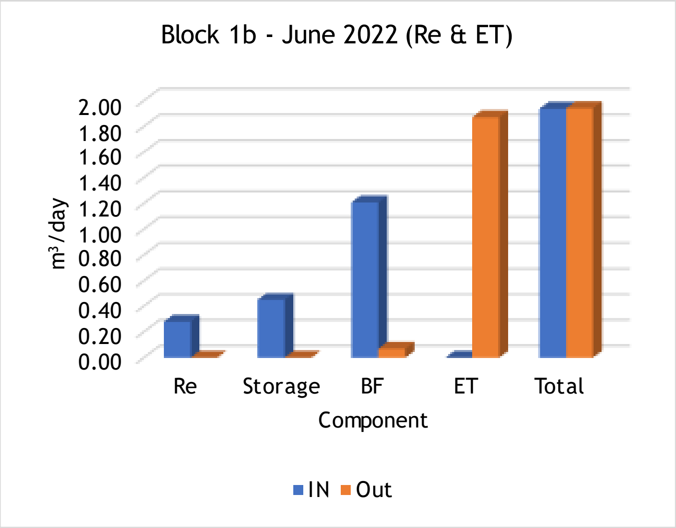
Figure 6 Throughfall recorded for the trial blocks, compared to rainfall

4.2 Water balance in the trial blocks

The water budgets apply to the trial block areas only, thus focussing on the saturated zone. From the water budgets obtained, the following was noted:

<u>*Searsia* Block 1:</u>

- The initial water balance (pre-trees) suggested that recharge (Re) and aquifer base flow (BF) from the surrounding aquifer contributed to the total water budget.
- The water balance for the end of June 2022 (Figure 7) suggested that Re decreased by approximately 41% and that the aquifer was compensating for the ET loss by drawing water from storage. ET accounted for 33% of the total balance loss. BF out of the tree block was reduced (by 28%) as ET drew water from the saturated zone.



	Block 1b (m^3/day)		
S-2022	Re	0.28	0.00
	Storage	0.45	0.00
	BF	1.21	0.07
	ET	0.00	1.87
	Total	1.94	1.94

Figure 7 Water balance for Searsia Block 1, indicated as an example

- It was observed that the total water balance increased, as more water was taken from storage and BF to compensate for ET.

Eucalyptus Block 1:

- The initial water balance suggested that Re and BF from the surrounding aquifer contributed to the total water budget.
- The water balance for the end of June 2022 suggested that Re decreased by 43% and BF into the block area has improved by 88%. ET accounted for 96% of the total balance loss. It was further observed that there was a significant loss in storage from the surrounding saturated zone, suggesting that the Re & BF into the block was not sufficient to maintain water levels in the block area.
- It was observed that the total water balance increased, as more water was taken from storage and BF to compensate for ET.

Eucalyptus Block 3:

- The initial water balance suggested that Re and BF from the surrounding aquifer largely contributed to the total water budget.
- No impact in terms of ET was observed in this test site, this was due to the water level depth. The effect of ET and Re reduction showed how BF into the block had been depleted (interflow out of the block did not report to storage). Recharge decreased by as much as 53%.
- The total water balance for the tree block area was reduced.

Eucalyptus Block 4:

- The initial water balance suggested that Re and BF from the surrounding aquifer largely contributed to the total water budget.
- The water balance for the end of June 2022 suggested that Re decreased by approximately 54% and BF into the block contribute as major components to the water budget. ET accounted for 67% of the total water balance.
- It is observed that ET reduced the BF out of the block, as well as drew water from storage. The net result was a lowering of the water table.

Searsia Block 4:

- The initial water balance suggested that Re and BF from the surrounding aquifer largely contributed to the total water budget.
- The water balance for the end of June 2022 suggested that Re had decreased by approximately 48 % and the remainder was made up of BF and storage. It was observed that ET reduced the BF out of the block. ET accounted for 28 % of the total water balance.

4.3 Aquifer drawdown modelling

The aquifer drawdown output of the combined Re & ET transient state model is shown in Figure 8, below. It can be seen that the drawdown was localised to the test block areas and that the maximum drawdown was in the order of 2.8 m, with greater drawdown observed at the middle of the tree bocks and lower drawdown away from the tree blocks (where the calibration boreholes were situated).

Figure 8 Transient state Re & ET model visual output (drawdown in the test block areas)

4.4 Projected expansion performance (modelled)

The drawdown model was expanded to all areas deemed suitable for tree planting (based on grid-auguring of soils and observations of surface rock content. Root excavations done in 2020 showed *Searsia* trees performed better in shallow soil, with the bulk root volume in the upper 0.3 m. The bulk of the root volume for the *Eucalyptus* trees was in the top 0.8 m of the soil. Areas with high potential for tree planting amounted to 198.8 ha, whilst areas with very high potential for tree planting amounted to 118.2 ha. *Eucalyptus* trees, with higher overall water uptake, were used for the expansion modelling.

Table 2 Recharge parameters and efficiency of trees in reducing vertical recharge

Recharge parameter	Modelled data
Average daily vertical recharge	500 $m^3.day^{-1}$
Efficiency of tree planting to ~324 ha to reduce vertical recharge	67 %
Residual recharge to be managed	165 $m^3.day^{-1}$
Deep aquifer baseflow	183 $m^3.day^{-1}$
Effective residual recharge liability (deep aquifer baseflow + vertical recharge)	183 $m^3.day^{-1}$
Efficiency of trees to reduce vertical recharge	100 %

A summary of the findings of the tree planting feasibility assessment is presented in Table 2. The geometric means of the observed ET and recharge reduction for the existing tree plantation areas were applied in a prediction modelling scenario. The prediction modelling aimed to:

- Describe the impact on the groundwater flow system if phyto-evaporation is rolled out to the greater project area; and
- Evaluate aquifer drawdown and the total model water balance for maturity (eight years after tree planting) and 20 years after tree planting.

The predicted spatial impact as a result of the application of the phyto-evaporation for the feasibility area is shown in Figure 9 and Figure 10. From the model outputs, the following was noted:

- At maturity, the drawdown in the underlying aquifer was predicted to be limited to the phyto-evaporation application area. Drawdown in the saturated zone was estimated to range from 0.5 m to 5.5 m. Greater drawdown was observed in areas where the water table is shallow, as opposed to higher elevation areas such as at the dolerite cap.
- After 10 years a larger impact was observed for the greater project area, and the average drawdown in the underlying aquifer was observed to range from 1.5 to 6 m.
- After 20 years the extent of dewatering further increased, and the average drawdown in the saturated zone was predicted to drop by as much as 2.5 to 8 m.

From the prediction modelling undertaken it is predicted that the total recharge to the underlying aquifer for the full high potential planting area will decrease by as much as 67 % just based on rainfall interception. The modelling from maturity to 20 years after maturity suggested that initially, ET loss will be greater due to shallower water levels (i.e., root interception rate will be greater), and will decrease as the water table decreases.

The net result of the planting of trees will induce a pseudo-steady-state flow regime, where the portion of recharge that makes it to the aquifer zone is allocated to aquifer storage replenishment or flow to the surrounding aquifer. The planned areas for expanding the trial blocks amount to 317 ha and have been modelled to reduce vertical recharge to an average of 213 m^3.day^{-1} with an efficiency of 100 % (no vertical recharge) (Table 2).

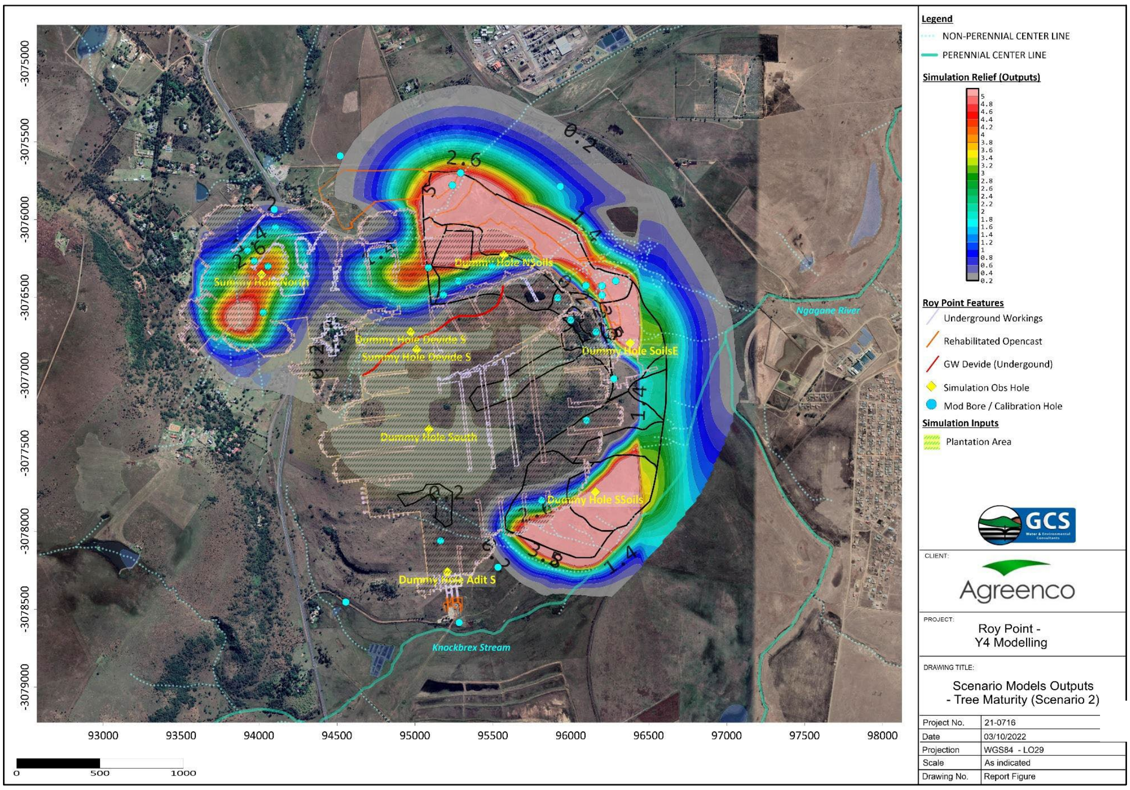


Figure 9 Predicted drawdown at the onset of monitoring (at tree maturity, eight years in)

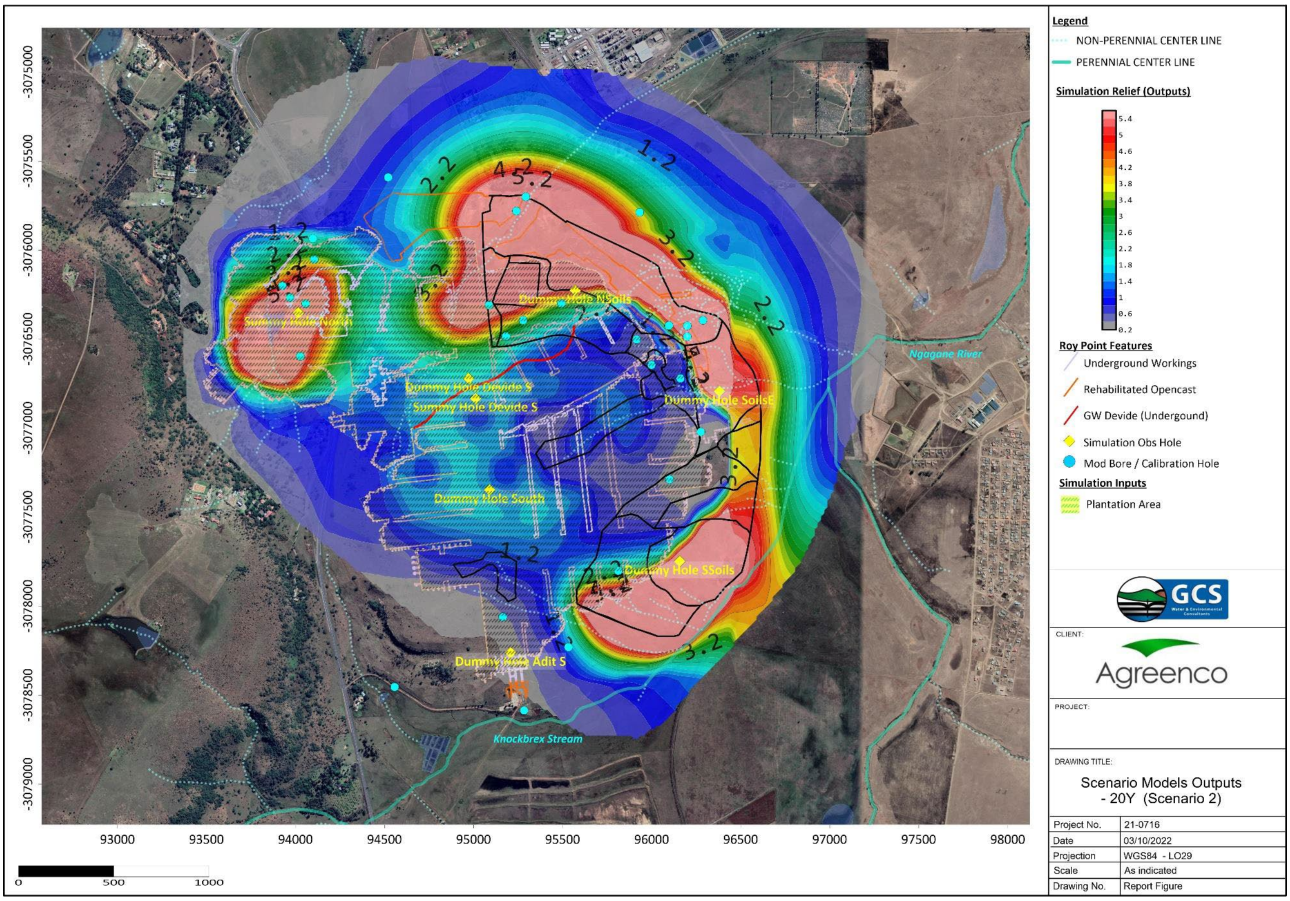


Figure 10 Predicted drawdown 20 years after planting

5 Conclusion

One of the main objectives for the tree plantations was to reduce vertical groundwater recharge through rainfall interception and water uptake by the trees. The groundwater recharge percentage in the trial blocks (Re) was determined using the effective recharge range calculated for the regional aquifer and the estimated throughfall for the tree plantation areas. According to DWAF (2006), the study area falls in a natural groundwater recharge area ranging from 5 to 6 % of the Mean Annual Precipitation (MAP, in the order of 712 mm.yr^{-1}) – regional recharge to the aquifer.

The prediction modelling shows how rolling out the evapotranspiration trials to the greater project area has the potential to further decrease recharge, and a gradual lowering of the water table with time can be expected. Considering the target recharge mitigation required and the simulated recharge reduction as per the scenario model, the trees highly likely have the potential to reduce vertical recharge to the underground workings by 55 % (if planted and successfully established as per the scenario modelling). The numerical model developed for this study suggests a value in the order of 183 m^3.day^{-1} (about 15 % of the total recharge to the workings). Based on the data provided for the simulations and simulation results it is expected that expanding the evapotranspiration plantation trials to 317 ha of the mining lease area will greatly influence both groundwater recharge rates and groundwater levels in the area. Reducing the amount of water in the weathered aquifer zone, which receives water via the unsaturated soil zone associated with the plantation areas, will reduce the effective recharge to the underground workings. The current model indicates that recharge reduction of 500 m^3.day^{-1} is required, hence, planting and successfully establishing trees as per the scenario modelling will have the potential to decrease the decant significantly. To further decrease decant from the underground workings, drilling a borehole with a drip irrigation system may help to reduce the mine water balance. Extending the tree planting to areas with low potential with *Searsia* trees will further decrease the vertical recharge, though not as much as *Eucalyptus* in the high potential areas.

This project did not specifically look at the impact on the regional groundwater users, and also the impact of decreased recharge on the actual changes in volumes in the receiving streams, which are avenues for further study.

There are direct mine closure benefits of rolling out the project to the full area. Initial calculations suggest that forestry as a post-mining land-use has the potential to not only decrease the overall water management liability, but also to generate income through timber harvesting, leading to sustained economic activity, including job creation. These funds can be used to supplement additional water treatment that may be required to eliminate the negative impacts of decant entirely.

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References

Delzon, S, Sartore, M, Granier, A, Loustau, D. 2004. Radial Profiles of Sap Flow with Increasing Tree Size in Maritime Pine. Tree Physiol. Vol 24, pp. 1285–1293.

Department of Minerals and Energy (DME). 2003. Potential Government Intervention to Significantly Reduce the Amount and Impact of Discard Coal. Viewed 22 June 2023. https://www.energy.gov.za/files/esources/coal/coal_discards.html

Department of Water and Sanitation (DWS) 2015. Mine Water Management Policy Position. Viewed 22 June 2023. https://www.gov.za/sites/default/files/gcis_document/201707/40966gon568.pdf

Department of Water Affairs (DWAF), 2006. Groundwater Resource Assessment II. Viewed 22 June 2023. https://www.dws.gov.za/groundwater/GRAII.aspx

Dye, P. et al., 2008. The Potential of Woodlands and Reed-beds for Control of Acid Mine Drainage in the Witwatersrand Gold Fields, South Africa.

Dye, P, Clulow, A, Prinsloo, E, Naiken, V, & Weiersbye, I. (2016). The Annual Pattern of Sap Flow in two Eucalyptus Species Established in the Vicinity of Gold-mine Tailings Dams in Central South Africa. Southern Forests: a Journal of Forest Science. Vol 78, pp. 307-313.

Dye, P, Naiken, V, Clulow, A, Prinsloo, E, Crichton, M, & Weiersbye, I. (2017). Sap Flow in Searsia pendulina and Searsia lancea Trees Established on Gold Mining Sites in Central South Africa. South African Journal of Botany. Vol 109, pp. 81-89.

Kirkham, M. 2014. Principles of Soil and Plant Water Relations. Kansas State University Press. Pp. 375.

McCarthy, T.S. 2011. The Impact of Acid Mine Drainage in South Africa. South African Journal of Science. Vol 107, pp. 1-7.

McLeroth, 2015. Soil Survey, Land Capability, Wetland Delineation, Present Land-use, Broad Vegetation Communities, Findings and Recommendations for Indigenous Tree Woodland Plots. Internal Report, South32.

Mintek. 2017. Assessment of KwaZulu-Natal Province’s Coal Mining and Coal Resources. Trade & Investment KwaZulu-Natal.

Ochieng, G, Seanego, E, & Nkwonta, O. 2010. Impacts of Mining on Water Resources in South Africa: a Review. Scientific Research and Essays. Vol 5(22), pp. 3351-3357.

Van Tonder, G & Xu, Y. 2000. A Guide for the Estimation of Groundwater Recharge in South Africa. Water South Africa. Vol 27,(3), pp. 341 – 343.