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Investigate the possible reduction of mine water ingress by introducing tree plantations: Case study of Cooke 4 mine (South Africa)

Rainier Dennis, Ingrid Dennis, Naziha Mokadem*, Simmone Smit

Centre for Water Sciences and Management, North-West University, 11 Hoffman Street, Potchefstroom, 2531, South Africa

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ABSTRACT

Continuous influxes of groundwater into underground mine workings require a significant financial investment related mainly to the high costs of pumping of large volumes of water ingress, consequently mines become unprofitable. An innovative alternative to pumping methods with the purpose to reduce water volumes, is the establishment of deep rooted, high water-use vegetation covers to act as "artificial pumps". Hydraulic control is one of the leading applications of plant-based strategies for remediating and managing groundwater systems by introducing plantations in selected areas with high ingress potential. This study investigates the impact of plantation introduction on the reduction of effective groundwater recharge. A temperature-based field model was formulated to determine daily ET from measured and observed leaf and air temperature. Results were compared to the FAO (Food and Agricultural Organisation) Penman-Monteith reference crop ET (Evapotranspiration) model and the Shuttleworth-Wallace models in order to validate the predictions of the field model. The developed field model was then used to predict monthly ET values for the Cooke 4 study area (Gemsbokfontein West compartment) to determine the possible reduction of pumping volumes. The area chosen for the proposed plantation was selected based on groundwater levels and the agricultural potential. A water balance for the study area has been developed through the use of the SVF (Saturated Volume Fluctuation) method and inflows to the study area has been modelled as head dependent by using a conductance term.

1. Introduction

Water resources of South Africa are scarce. Whether it is groundwater or surface water sources, the availability and access to water that meets the quality and quantity requirements of people, is a fundamental component of future sustainability. However, factors such as population growth, economic- and industrial development have led to increased constraints on water sources in many areas.

Before the 1970's groundwater was seen as a cheap source of water that required little management, therefore little attention was paid to the management of groundwater resources (Braune, 2000). Unfortunately, due to lack of management of these resources, especially in the mining industry, groundwater was over-exploited and significantly impacted. Today the appropriate management of surface and groundwater resources have become a vital component of mining strategies and is managed through the NWA, 1998. The NWA focuses on the sustainable management of water through demand management of the available resources (Braune, 2000).

Over the past 30 years, significant financial investment has been channelled to environmental research to gain a better understanding of the impact of mining on the environment and its natural resources, and is currently still a continuous field of research. Results from past and current research are applied and utilised to address current problems, and to prevent future recurrence of these problems. Taking into account results from past and current research, several water management strategies have been developed to control influx of water into mines (Hodgson et al., 2001). For example: re-evaluation of extraction mining methods to reduce impacts on geology and groundwater resources, minimising water influx by not undermining highly transmissive aquifers, extensive pumping to holding dams, implementation of barriers and trenches to reduce runoff flow towards faults and ingress points, redesign of mining structures to prevent collapsing and fracturing of strata, construction of evaporation ponds to reduce excess water, sealing of ingress points and fractures, and limiting the size of the mining footprint.

An innovative, "green" alternative to extensive pumping methods with the purpose to reduce water volumes, is the establishment of deep rooted, high water-use vegetation covers to act as "artificial pumps".

* Corresponding author.
E-mail addresses: rainier.dennis@nwu.ac.za (R. Dennis), ingrid.dennis@nwu.ac.za (I. Dennis), 31574343@nwu.ac.za (N. Mokadem), simmone.smit08@gmail.com (S. Smit).

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This bio-drainage strategy is part of a range of phyto-technologies considered as a suitable alternative to conventional engineered-based drainage techniques. The establishment of tree plantations as bio-drainage promoters, can aid in hydraulic control by reducing the effective recharge to shallow groundwater systems. Consequently, the volume of water that is subject to ingress and seepage is reduced. Hydraulic control is one of the leading applications of plant-based strategies for remediating and managing groundwater systems. The reduction of effective recharge to groundwater systems can be achieved by introducing plantations in selected areas with high ingress potential (Ferro et al., 2006).

Many tree species have naturally deep-rooted systems that enables trees to tap into the deep soil layers reaching deeply situated water resources. The establishment of deep rooted trees in such systems function as artificial pumps, thus removing a substantial amount of water from the saturated zone through natural processes including transpiration, plant uptake and precipitation interception of canopy covers. This is achieved by enhancing the transpiration capacity of a landscape by introducing vegetation types with high water use characteristics to large enough areas in order to maintain a balance between recharge and discharge processes below root zones (Schnoor et al., 1995).

Hydrological studies from across the world demonstrated that trees use more water annually than grasslands and shorter vegetation (Farley et al., 2005). Higher water use characteristics of trees are attributed to (a) high aerodynamic roughness of plantations that results in increased annual transpiration rates – twice as much as the rate of short vegetation; (b) the so-called clothesline effect of prevailing trees in rows, substituting for a conventional drain pipe; (c) deep root systems enabling trees to extract water from considerable depths in comparison to short vegetation with shallow root systems and (d) dense canopies with evergreen properties enabling trees to transpire throughout the entire year, in comparison to grasses with seasonal dormant stages (Burgess et al., 2000).

Eucalyptus and Pinus species are considered among tree species with the highest water use characteristics, predominantly driven by high leaf area indices. Desirable traits such as high value timber, growth potential, high water consumption, biomass accumulation and physical parameters of Eucalyptus and Pinus species, has led to increased focus being set on the potential of these commercial hardwood species to be used as efficient bio-drainage species. Catchment-based studies provide evidence of afforestation and deforestation effects on catchment hydrology and stream flow. The impact of afforestation in South Africa is thought to be primarily due to high transpiration rates and productivity of trees, and to a lesser extend due to increased interception losses.

A significant number of researches (Van Lill et al., 1980; Bosch and Hewlett, 1982; Allison and Hughes, 1983; Crombie, 1992; Bacon et al., 1993; Salama et al., 1994; Dye 1996a, b, c); Scott and Lesch (1997); Roberts et al. (2001); Soares and Almeida (2001); Srivastrava et al., 2003; Sikka et al. (2003); Engel et al. (2005); Joshi and Palanisami (2011) have focused their investigation on establishment of Eucalyptus plantations, in different region for example (Argentina, South-Eastern Australia, etc.), showed that Eucalyptus species have the potential to cause recessions of water tables, reductions in stream flow, decrease recharge, increase daily transpiration rates, and complete drying out of soils.

South Africa is classified as a subtropical country with warm temperate conditions. Due to the country's relatively low mean rainfall, the natural vegetation is dominated by non-woody plants. The lack of natural sources of fast growing timber stimulated the introduction and establishment of exotic tree species. Subsequent to years of investment and development, South Africa has become one of the largest cultivated forestry resources worldwide. With a total area of over 1.5 million hectares occupied by plantations, South Africa is categorised as the third largest plantation resource in the southern hemisphere. The majority of South African plantations are comprised of non-native Eucalyptus and Pinus species, comprising 39% and 40% respectively of South African timber plantations (Global Agricultural Information Network, 2014).

In general, the extraction methods applied to obtain minerals from resources have a significant impact on environmental stability and in most cases future sustainability. The disruption or damage to geological features results in the deterioration of subsurface stability, eventually resulting in a serious risk in terms of increased groundwater influx into underground mine workings. It is inevitable that the continuous influx of groundwater into underground mine workings, increase the quantity of water that is exposed to associated mine waste and chemicals which could lead to potential and probable quality deterioration and pollution of valuable groundwater resources (Jarmain, 2003). In addition to the potential deterioration of water quality, the pumping costs associated with high volumes of water ingress could render a mine unprofitable.

Continuous influx of water into mine voids is generally fed by aquifers and leakage from surface water bodies. Since deep mining generally occurs in hard rock formations; fissures, fractures and geological faults present in these formations act as the main conduits of water flow between geological formations and into the underground voids of the mine operating within these geological formations. The fact that groundwater is becoming a scarcer and valued resource, the reduction of impacts on groundwater and ingress of water into mine, depend heavily on effective and sustainable management measures.

In this context, the present study attempts to reduce the influx of water into underground mine workings, in order to minimise pumping costs at Sibanye Cooke 4 Shaft.

It focuses on: (1) formulation of a calibrated field model to assess the ET potential of *Eucalyptus* species growing in the study area, in order to determine the potential of *Eucalyptus* plantations as bio-drainage alternatives for reducing water influx into underground mine workings, (2) comparison of calibrated field model to the reference ET potential as calculated by the Penman–Monteith model; (3) comparison of the calibrated field model to the Shuttleworth-Wallace ET model to predict ET potential for other types of landcovers, (4) evaluate the effect of ET associated with *Eucalyptus* plantations on the volume of mine water ingress.

2. Geography and climatology studies

The Cooke 4 mine (formerly known as Ezulwini gold mine) is located in the Southeast of South Africa, between Latitude 26°15'.0″S to 26°30'.0″S and longitude 27°35'.0″E and 27°50'.0″E. The mine is situated approximately 7 km southeast of the town of Westonaria within the Gauteng Province, and is accessed via the N12 national road between Johannesburg and Potchefstroom (Fig. 1).

South Africa is situated in a warm temperate zone and has a subtropical continental climate. The project area falls within the interior Highveld region of the country, generally characterised by unstable summer conditions with regular rainfall events, and stable winter conditions caused by a dominant high-pressure system resulting in clear skies and pronounced temperature inversions. The region is characterised by cold to mild winters from May to September, and hot to very hot summers from November to March (SAWS, 2015). In general, the mean winter temperatures in Westonaria range between 0 °C and 9 °C in winter, and 21 °C–30 °C during summer months (DWS, 2015). Rainfall in the study area (DWS, 2015) is strongly seasonal, occurring primarily as thunderstorms during summer months (October to March), whilst winter months (May to August) are very dry. An estimated 83% of MAP (Mean Annual Precipitation) occurs during summer months. The average monthly rainfall is 56 mm and the evaporation is around 114 mm/month (data from 2000 to 2015). The maximum relative humidity remains above 60% for the majority of the year, ranging between 57% in November to 72% in March (SAWS, 2015). Wind conditions in the region are highly variable, and is affected by topographic characteristics range between 0.3 m/s to 5.7 m/s (SAWS, 2015).

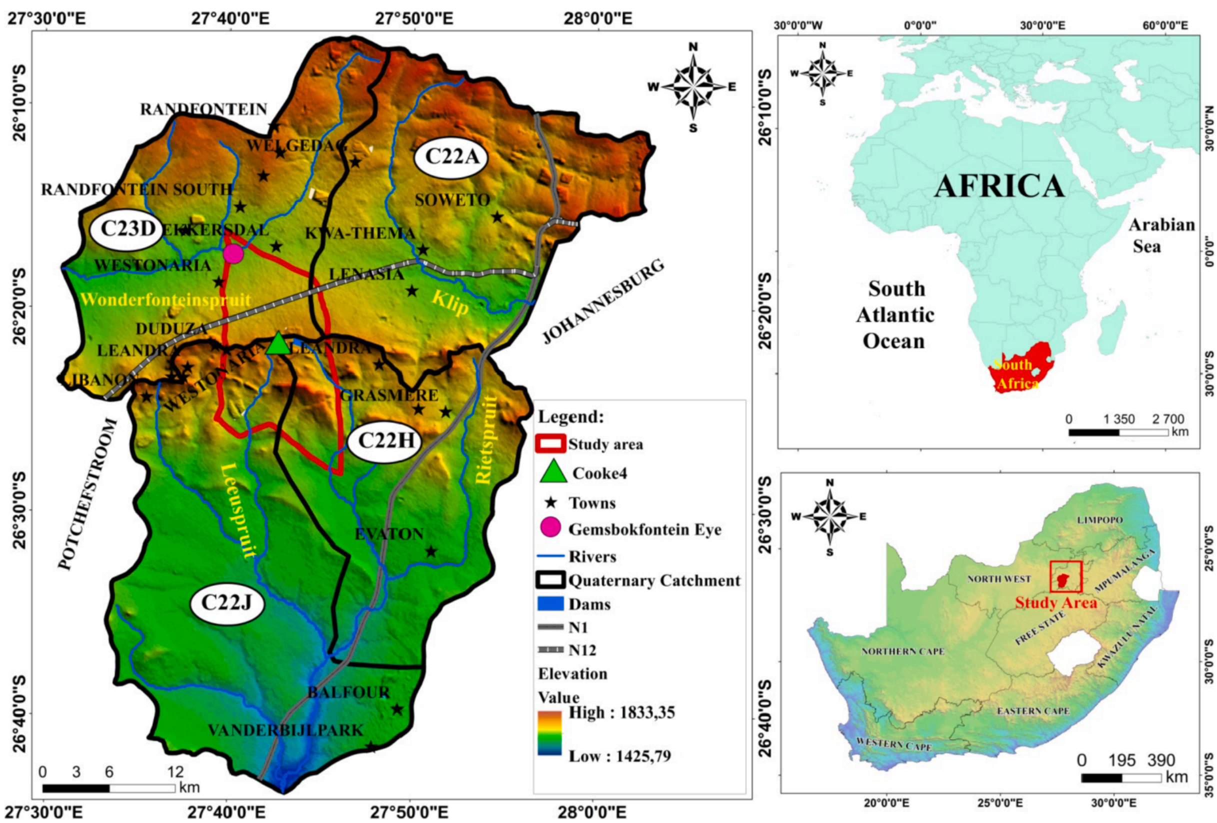

Fig. 1. Locality map of the Cook 4 study area.

3. Geology and hydrogeology studies

3.1. Geology

The study area is situated within the Witwatersrand Basin. This Basin is a well-established gold-mining area with an impressive history of established gold producing mines.

The hydrostratigraphic units in the study area are shown in Fig. 2a. These units consist of three prominent geological groups namely, from the base to the surface.

- Witwatersrand Supergroup
- Ventersdorp Supergroup
- Transvaal Supergroup

Witwatersrand Supergroup: The Witwatersrand Basin is defined as an Achaean sedimentary, characterised by an elongate surface expression with a longitudinal extension of approximately 300 km northeast-southwest and 100 km northwest-southeast (Tucker and Viljoen, 1989). According to Mellor (1917), the Witwatersrand Super Group is divided into two distinct groups; (1) West Rand Group, and (2) Central Rand Group.

(1) The West Rand Group: is divided into three distinct subgroups namely Hospital Hill, Government Reef and Jeppestown. These subgroups are formed by shales with intermittent units of quartzites, banded ironstones, tillite and lava.
(2) The Central Rand Group: is divided into two subgroups namely Johannesburg Subgroup and Turffontein Subgroup. Lithology in these groups is dominated by quartzites with interbedded fragments of conglomerate reefs. The Booysens Shale. Which occurs between the two subgroups, separates the Johannesburg Subgroup from the Turfontein Subgroup.

Ventersdorp Supergroup: The Ventersdorp Supergroup is composed mainly of andesitic lavas and related pyroclastics, however acid lavas and sedimentary intercalations also occur. In addition, the Ventersdorp Supergroup consists of the Platberg Group and the Klipriviersberg Group. The Klipriviersberg group is most prominent in the study area, and consists of the Alberton and Westonaria formations (Tucker and Viljoen, 1989).

Transvaal Supergroup: This Supergroup consist of three main aquifers, namely, from base to surface, lower aquifer, upper aquifer and dolomite aquifer (Malmani Subgroup).

The lower aquifer is associated with less weathered, but fractured sedimentary deposits in the Black Reef formations.

The upper aquifer (Pretoria Group) is mainly restricted to the weathered sedimentary deposits of the Timeball Hill and the lava units of the Hekpoort Formations where rock material is exposed to the surface (Fig. 2b). Although these formations are not considered as sustainable aquifers, high water yields are expected where fractures intersect. Previous studies suggested that open fractures seldom occur deeper than 60 m as the weight of overlaying material will, over time, close deeper fractures that will in return decrease transitivity potential (SRK Consulting, 2013). The aquifer base consists of impermeable quartzite, shale and lava formations, and the top of the aquifer is presented by the surface topography. Although the upper weathered and lower less weather aquifers are hydraulically connected, confining layers of clay and shale often separate the two aquifers, classifying the aquifers as semi-confined.

The Malmani Subgroup dolomite of the Chuniespoort Group (Fig. 2a and b) has a thickness of 200 m–1500 m (Parsons and Killisck, 1985), which dominates the geology at the Cooke Section (Tucker, 1980). The geological setting is complicated by numerous dykes and faults occurring in this area (Tucker and Viljoen, 1989). The Malmani Subgroup contains two formations, (1) the Oaktree formation consists of dark-grey dolomitic units interbedded with carbonaceous shales which decrease in thickness from the base of the formation upwards, (2) the

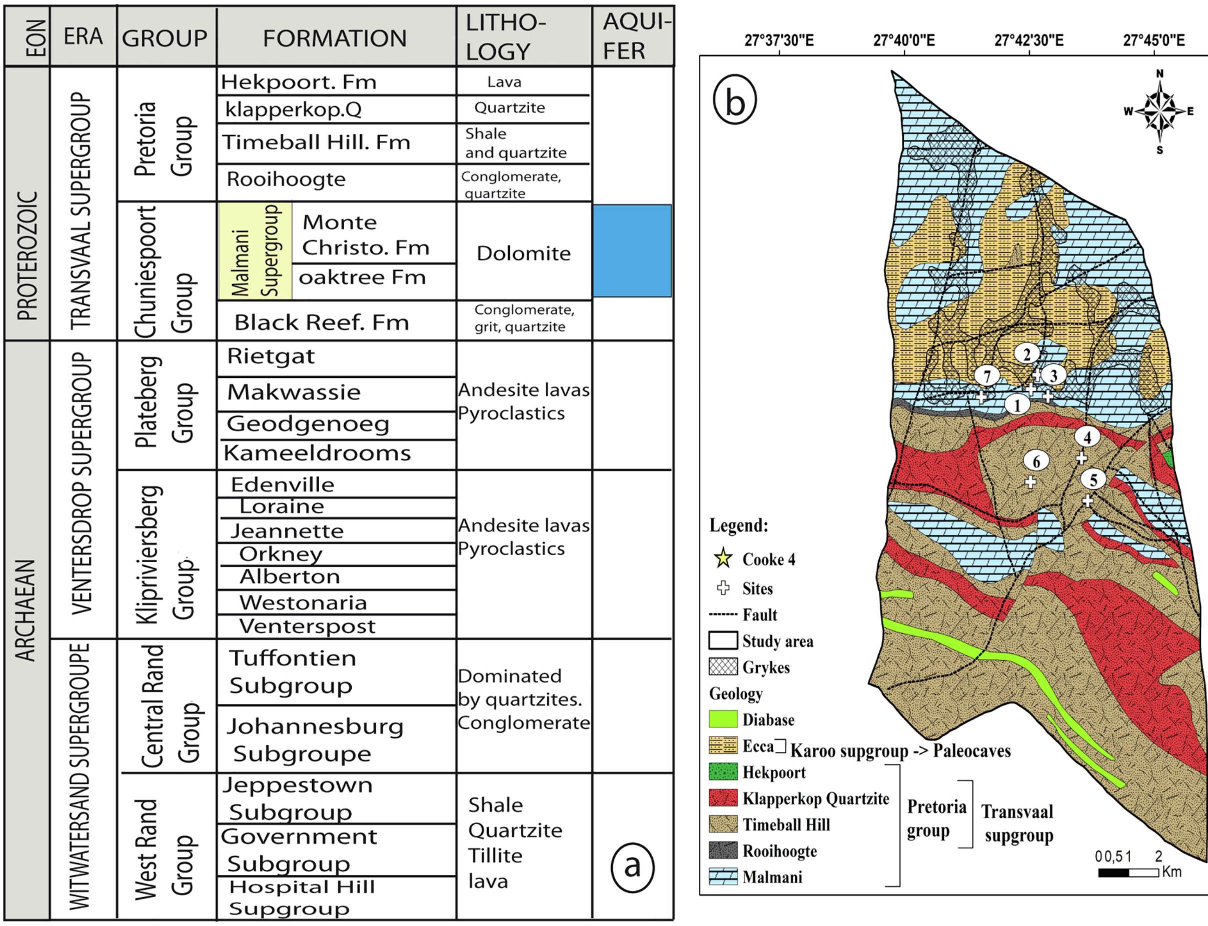

Fig. 2. a: Geology map **b:** Lithostratigraphic column in the study area.

Monte Christo Formation consists mainly of dolomitic units with alternating chert. The estimated thickness of these dolomites is 700 m, with a 1.5 m thick chert layer consisting of thin manganese layers towards the base of the formation. According to Parsons and Killisck (1985), layers of crystalline dolomite, calcareous shales and fine white dolomites with chert fragments also occur in the sequence. The dolomite aquifer yields the largest portion of groundwater and is generally associated with sustainable groundwater abstraction.

3.2. Hydrogeology

The project area consists of a series of low lands (valleys), hill slopes and plains with a low relief. The Cooke 4 mine is situated at an elevation of 1600–1650 mamsl (Fig. 1), on the southern slope of the anticline between two prominent ridges of Gatsrand on the Transvaal Highveld (SRK Consulting, 2013).

The study area is situated in the Upper Vaal WMA (Water Management Area) which is the uppermost water management area in the Vaal River catchment. The study area resides on the watershed boundaries of quaternary catchments C22A, C22H, C22J and C23D as shown in Fig. 1. The Wonderfonteinspruit runs through the northern section of the compartment. It has a typical karst morphology in the sense that the river disappears and reappears (Parsons, 1987). Surface water features in the area includes the Kleinwes Rietspruit, Leeuwspruit and the Peter Wright Dam. As Cooke 4 is situated on the southern anticline of the Gatsrand, no significant runoff or discharge occurs to the north of the study area. Therefore, all surface runoff drain south via the Kleinwes Rietspruit and the Leeuwspruit. Runoff emanating from the largest river quaternary catchment C23D, drains in a south-western direction to the Wonderfonteinspruit. Runoff emanating from quaternary catchment C22J drains in a southern direction via the Leeuwspruit, which is a non-perennial stream, but flow is maintained through mine water discharge. Runoff emanating from quaternary catchment C22H drain in a southerly direction via the Rietspruit. The intersection of C22A with that of the study area is considered negligible with respect to the runoff generated in this catchment.

The Gemsbokfontein eye which is not flowing due to mine dewatering is situated in the north-west corner of the compartment. It is expected that spring flow will resume once mine dewatering has ceased (Schrader et al., 2014). Rison Groundwater Consulting, 2011 reported historic spring flows of ± 9 Mℓ/d for the Gembosbokfontein eye pre-1986.

The Grykes identified during a gravity survey in the northern part of the study area are zones where the dolomites are highly weathered and act as preferred flow paths. Based on regional gravity and resistivity surveys that were conducted in 2011, faulting occurs between 0 and 100 m below the surface of the dolomites, with some individual fractures between 100 m and 180 m below the surface of the dolomites (SRK Consulting, 2013).

The study area is underlain by the partially dewatered Gemsbokfontein-West groundwater compartment. Rock material in this aquifer is basically impermeable accounting for practically no effective porosity. Historically, the dolomite strata in the aquifer have been exposed to numerous karstification and erosion periods. Potential groundwater exploitation in this aquifer depends mainly on the extent of groundwater drainage and leaching of percolated rainfall into the aquifer, and the ability of the aquifer to yield large quantities of water and sustain abstraction. During dissolution processes, the carbonates are removed from the dolomite, subsequently leaving silica, manganese, and iron oxides behind. This residual material is compressible

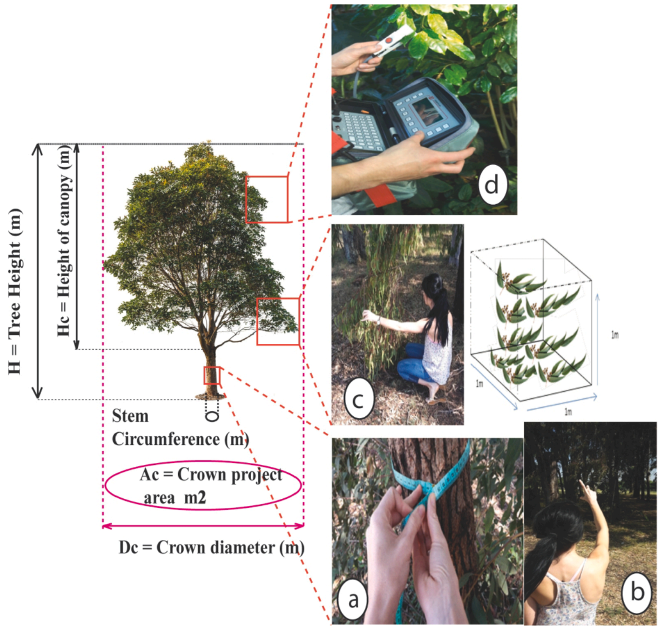

Fig. 3. a: Measurement of stem diameter, b: Measurement of tree height, **c:** Leaf count making use of quadrant count, **d:** Measuring stomatal conductance through Delta-TAP4 leaf Porometer.

with a low density and high void volume – consequently creating the potential of cave formation.

Parsons (1987) mapped the dolomitic outliers to the south of Gatsrand, indicating that dolomitic outliers are hydraulically connected with the Gemsbokfontein compartment as these dolomites are continuous beneath the overlaying Timball Hill rock formations. Previous studies conducted by Johan Fourie and Associates Consulting (2011) concluded that the Gemsbokfontein-West sub-compartment is recharged by various sources including:

- Roughly 15% of MAP (Mean Annual Precipitation);
- Artificial recharge into the aquifer after surface water diversions from Westonaria and Simunye residential areas toward the Wonderfonteinspruit
- Artificial recharge from the Kleinwesrietspruit flowing eastwards from the Peter Wright dam, and the Leeuspruit flowing toward the south west;
- Approximately 6 Mℓ/d leakage from the Magazine Dyke; and
- Approximately 9 Mℓ/d leakage from the Panvlakte Dyke.

The recharge for the Gemsbokfontein is estimated at 27% in 1995 (Bredenkamp et al., 1995). The GRAII (DWAF, 2003) recharge figures for the quaternary catchments comprising the study area present in Fig. 1 varying between 6.2% and 7.4% of MAP.

Water contained in the shallow upper aquifer is attributed to infiltrating rainfall recharge through weathered material, consequently being delayed by the low permeability of underlying dolomite material. According to SRK Consulting (2013) a proportion of the water contained in the upper aquifer still migrates through to eventually recharging the lower aquifer. A significant portion of the groundwater levels were found to lie within the shallow weathered aquifer. The largest volume of water stored in the main dolomitic aquifer occurs in the top 100 m below the water level. The effective base-depth of this aquifer ranges between 150 m and 200 m below the surface. The underlying dolomites have an approximated thickness of 900–1100 m, however it is unlikely that large amounts of groundwater flow occur below this depth, except along intersecting structural conduits to the underground mine workings (Gold One Cook Operations, 2013).

4. Methodology

4.1. Climatic data collection

Hourly temperature data were obtained from the SAWS from the closest weather station to the study area. The regional radiation and vapour data were obtained from the South African Atlas of Agrohydrology and Climatology (Schulze, 2006). This data is required for the development of an evapotranspiration model.

4.2. Field measurements

4.2.1. Representative vegetation assessment

Native vegetation types in the study area consists of open savannah type grasslands, with a sparse distribution of shrubby Karoo and thorn trees, However, the dominating vegetation in the area includes alien Eucalyptus species. In order to include a range of trees pertaining similar characteristics (anticipated to be of similar age groups), tree height and stem diameter measurements were taken. Seven experimental sites were identified, and two representative trees within each site were chosen for measurements and assessments (Fig. 2b).

4.2.2. Tree height, stem circumference and crown diameter

Tree species were identified to ensure homologous data were collected. Following identification, breast height-circumference, mean height and crown diameter was measured (with the use of a reference stick) to include trees of comparable size, thus anticipated to include trees of similar age (Fig. 3a and b).

4.2.3. Canopy volume and crown projected area

Canopy volume was determined using the following volume formulation (Verma et al., 2014).

$$V_C = MH_C D_C \tag{1}$$

where.

V_c = Volume of canopy (m^3), H_c = Height of canopy (m), D_c = Diameter of crown (m), M = Multiplier determined by crown shape.

The crown projected area was determined by the following expression adapted from Verma et al. (2014):

$$A_C = \frac{\pi D_C^2}{4} \tag{2}$$

where.

A_c = Crown projected area (m^2), D_c = Crown diameter (m).

4.2.4. Leaf area and leaf count

Leaf samples were collected and measured in order to determine an average leaf length and width for the estimation of leaf area. Leaf counts were determined by counting the number leaves within a 1 m^3 volume as shown in Fig. 3c. The average measured leaf length was 14 cm with an average leaf width of 1 cm which resulted in an average leaf area of 0.0014 m^2 to be used in the modelling.

4.2.5. Effective leaf area per square meter

The effective leaf area per square meter can be calculated by making use of the following formula:

$$A_{Leff} = \frac{V_C C_L A_L}{A_C} \tag{3}$$

where.

A_{Leff} = Effective leaf area per m^2, V_c = Volume of canopy (m^3),

C_L = Count of leaves per m^2, A_L = Average area of individual leaves (m^2), A_C = Projected crown area (m^2).

4.2.6. Stomatal conductance measurements

Stomatal conductance measurements together with leaf temperature measurements were performed on a set of eight leaves per tree, distributed throughout the outer part of the lower and mid canopy, using a handheld Delta-T AP4 Leaf Porometer as shown in Fig. 3d. Porometer measurements were run until four readings per leaf were obtained. Conductances were measured at 15-min intervals within a 3-h period. The AP4 Leaf Porometer measures the rate of Relative Humidity (RH) increase in a chamber clamped to a leaf surface; as water vapour is released through the stomata during transpiration, the RH in the chamber rises. A rapid rise in the chamber RH is an indication that the stomata are open and provides measurements of water vapour loss from a leaf. The control profile was conducted on 10 December 2015 since peak ET values are expected during the month of December.

4.3. Evapotranspiration modelling

The ET model was formulated based on the field observations of the Eucalyptus trees. Hourly measurements, for a duration of 12 h, were conducted to record leaf temperature and stomatal conductance at a control site. The recorded data was used to determine the relationship between leaf temperature and stomatal conductance and this relationship was used to formulate an evapotranspiration model to predict ET based on air temperature.

The model results were then compared to the FAO Penman-Monteith reference crop model (Schulze et al., 2006) and the Shuttleworth-Wallace ET model (Zhou et al., 2006) to ensure that the field data model results are realistic and comparable to that of existing models.

The Penman-Monteith model calculates ET from a hypothetical crop with an assumed crop height of 0.12 m, a fixed canopy resistance of 70 s/m and albedo of 0.23, which closely resembles ET from an extensive surface of green grass cover of uniform height, actively growing, completely shading the ground and not short of water.

The Shuttleworth-Wallace model is a variation of the Penman-Monteith model which allows the specification of landcover types based on the parameters as described by (Zhou et al., 2006).

4.3.1. Formulation of the field model

According Campbell and Norman (1998) a correlation can be identified between leaf temperature and stomatal conductance.

Being able to calculate leaf temperature from air temperature facilitates the calculation of stomatal conductance through the relationship established between leaf temperature and stomatal conductance during field observations. The estimation of leaf temperature is calculated using a linearization technique adopted from Campbell and Norman (1998):

$$T_L = T_a + \frac{\gamma^*}{\Delta/_{P_a} + \gamma^*}\left[\frac{R_{ni}}{gH_r c_p} - \frac{D}{P_a \gamma^*}\right] \quad (5)$$

$$\gamma^* = \frac{\gamma g_{Hr}}{g_v} \quad (6)$$

$$g_{H_r} = g_{H_a} + g_r \quad (7)$$

$$g_{H_a} = 1.4 \times 0.135\sqrt{\frac{u}{d}} \quad (8)$$

$$g_v = 1.4 \times 0.147\sqrt{\frac{u}{d}} \quad (9)$$

$$g_r = 0.002T_a + 0.1565 \quad (10)$$

$$e_s(T_a) = 0.6385e^{0.0623T_a} \quad (11)$$

$$e_a = 0.611e^{\left(\frac{17.502T_a}{T_a+240.97}\right)} \quad (12)$$

$$D = e_s(T_a) - e_a \quad (13)$$

$$R_{ni} = R_{abs} - \varepsilon_s B \quad (14)$$

where.

T_L = Leaf temperature in (°C), T_a = Air temperature in (°C), D = Vapour deficit of the atmosphere (kPa), Δ = Vapour pressure gradient (Pa/°C), ε_s = Surface emissivity, P_a = Atmospheric pressure = 101.3 kPa, c_p = Specific heat of air = 29.3 J/mol/°C, $e_s(T_a)$ = Saturation of vapour pressure (kPa), e_a = Vapour pressure of air (kPa), g_{Hr} = Net radiation (mol/m^2/s), g_{Ha} = Net radiation (mol/m^2/s), g_v = Vapour conductance (mol/m^2/s), g_r = Radiative conductance (mol/m^2/s) γ = Psychrometric constant: 6.66×10^{-4} °C^{-1}, d = Characteristic leaf dimension, u = Wind speed (m/s), R_{ni} = Nett radiation (W/m^2), R_{abs} = Absorbed radiation (W/m^2), B = Black body emittance (W/m^2).

Three sampling campaigns were conducted on the following dates during 2015: 22 September, 12 November and 8 December. On each occasion of stomatal conductance measurements, a 3 m ladder was used to gain access to the tree canopies. Stomatal conductance measurements were performed on a set of 8 leaves per tree, distributed throughout the outer part of the lower and mid canopy. Porometer measurements were run until four readings per leaf were obtained. Stomatal conductances were measured at 15-min intervals within a 3-h period.

4.3.2. Converting stomatal conductance to ET

Stomatal conductance measured in mmol/m^2/s were converted to evapotranspiration through the use of the ideal gas law, by calculating the volume of vapour and expressing it as mm/m^2/s. Conversions using the ideal gas law is applicable as stomatal conductance relates to the amount of vapour passing though stomata. The formulation is as follows:

$$V = \frac{nRT}{P} \quad (15)$$

where.

V = *Volume (m^3), n = Number of moles, R = Gas Constant = 0.082057, T = Temperature (K) P = Pressure (atm).*

4.4. Water balance modelling

The impact of ET on effective recharge can be modelled using a groundwater balance model, where the ET component will be used to reduce the effective recharge. The model used is SVF (Saturated Volume Fluctuation) model (Bredenkamp et al., 1995) which translate a change in volume to a change in water level. The SVF model is formulated as follows:

$$h_i = h_{i-1} + \frac{\sum Q_{in} - \sum Q_{out}}{S_y A} \quad (16)$$

where.

h_i = Groundwater level in month i (mamsl), h_{i-1} = Groundwater level in month i-1 (mamsl), ΣQ_{in} = Sum of all inflows to the system e.g. recharge (m^3/month), ΣQ_{out} = Sum of all out outflows e.g. pumping ET (m^3/month), S_y = Specific yield, A = Area (m^2).

Inflows from neighbouring compartments will vary with a change in head and therefore it is required to make use of a conductance term to properly account for these inflows. Conductance of external inflows is formulated as follows:

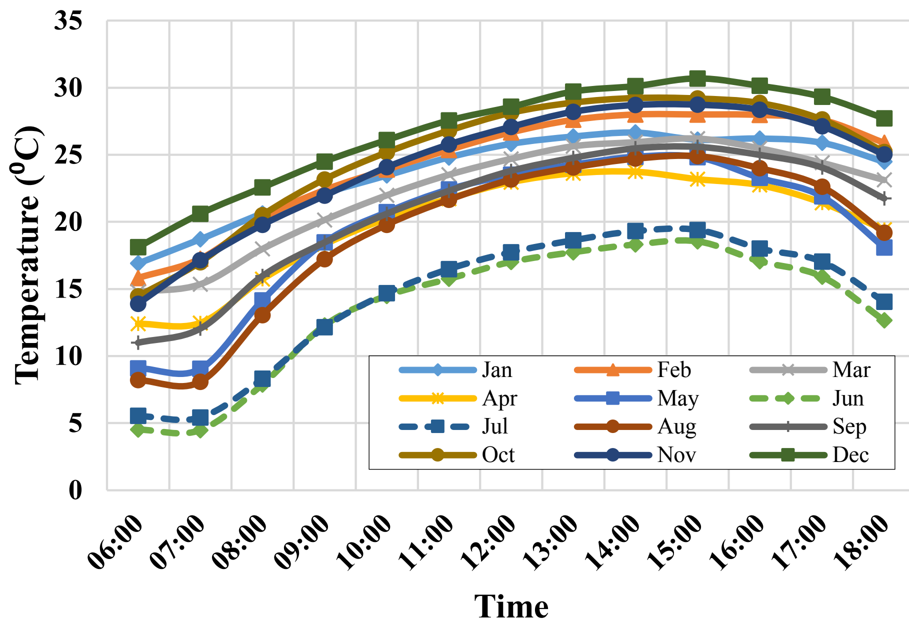

Fig. 4. Monthly air temperature average for Westonaria (2015)

$$Q = KiA = K\frac{\Delta H}{L}A = C\Delta H \quad (17)$$

$$C = \frac{K}{L}A \quad (18)$$

where.

Q = Flow (m^3/d), K= Hydraulic conductivity (m/d), i = Hydraulic gradient (m/m), A = Cross sectional area of flow (m^2), L = Length of flow (m), ΔH = Head loss (m), C= Conductance (m^2/d).

5. Result and discussion

5.1. Result

Fig. 4 displays the same profiles for the temperature curves for all months. Temperature typically peak around 15:00. High temperatures are observed for October, November and December months while low temperatures are observed in May, June and July. The actual vapour pressure and radiation per month for the study area (Fig. 5) obtained from the South African Atlas of Agrohydrology and climatology (Schulze, 2006) illustrated the low radiation vapour are observed for May, June, July and August. Table 1 shows the results of tree heights, canopy height, stem circumferences and crown diameter, which illustrates respectively the averages following, 7.2, 4.3, 74 and 5.9 m. The calculated canopy volumes show a maximum and minimum values of 47 and 231 m respectively and a maximum value of 32.2 m for the crown projected area (Table 1).

The average stem circumference is 74 cm (Table 1). The leaf count figure of 680 leaves per m^3 was used in the modelling. The calculated leaf area per square meter is presented in Table 1. An average of 4.8 m^2 leaf area per square meter on the surface was used in the ET modelling.

Fig. 6 illustrates the measured stomatal conductance together with the relative humidity and leaf temperature. The humidity varied between 20% and 60%. Leaf temperatures during this time varied between 0 and 37 °C. Stomatal conductance was highest between 10:30 and 13:30, while the relative humidity was highest during the morning. As stomatal conductance increased, leaf temperatures decreased. After

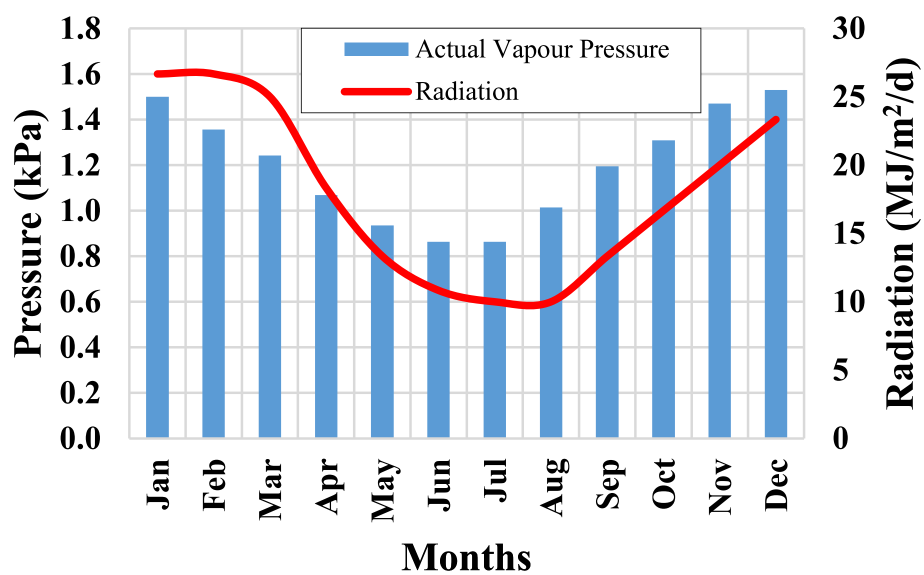

Fig. 5. Actual vapour pressure and radiation per month.

Table 1
Measured tree size parameters.

	Tree Height	Canopy Height	Stem Circumference	Crown Diameter	Canopy Volume	Crown Area	Leaf Length	Leaf Width	Leaf Area	Effective Area
	(m)	(m)	(cm)	(m)	(m^3)	(m^2)	(m)	(m)	(m^2)	(m^2/m^2)
Sample 1	6.5	3.0	63	4.1	47	13.2	0.140	0.010	0.0014	3.42
Sample 2	6.0	3.0	48	5.1	73	20.4	0.140	0.010	0.0014	3.42
Sample 3	5.0	4.5	82	5.1	110	20.4	0.140	0.010	0.0014	5.13
Sample 4	5.0	3.0	25	5.7	92	25.5	0.140	0.010	0.0014	3.42
Sample 5	7.0	4.5	46	6.0	152	28.3	0.140	0.010	0.0014	5.13
Sample 6	6.5	5.0	111	6.0	169	28.3	0.140	0.010	0.0014	5.69
Sample 7	8.0	4.0	96	6.0	135	28.3	0.140	0.010	0.0014	4.56
Sample 8	7.0	4.5	46	6.0	152	28.3	0.140	0.010	0.0014	5.13
Sample 9	7.0	4.5	119	6.4	173	32.2	0.140	0.010	0.0014	5.13
Sample 10	9.0	4.0	122	6.4	154	32.2	0.140	0.010	0.0014	4.56
Sample 11	8.5	4.5	29	6.4	173	32.2	0.140	0.010	0.0014	5.13
Sample 12	7.0	4.5	119	6.4	173	32.2	0.140	0.010	0.0014	5.13
Sample 13	9.0	4.0	64	6.4	154	32.2	0.140	0.010	0.0014	4.56
Sample 14	9.0	6.0	64	6.4	231	32.2	0.140	0.010	0.0014	6.83
Average	7.2	4.2	74	5.9	142	27.5	0.140	0.010	0.0014	4.800
Minimum	5.0	3.0	25	4.1	47	13.2	0.140	0.010	0.0014	3.417
Maximum	9.0	6.0	122	6.4	231	32.2	0.140	0.010	0.0014	6.834
Std. Deviation	1.3	0.8	33	0.7	46	5.6	0.000	0.000	0.0000	0.906

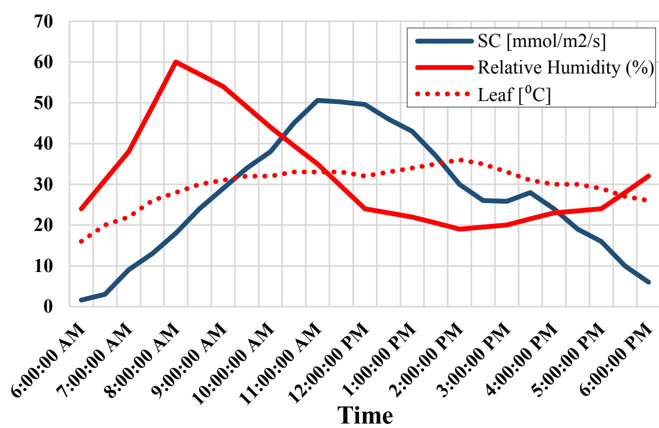

Fig. 6. Measured Stomatal conductance (SC), Measured relative humidity and Leaf temperature.

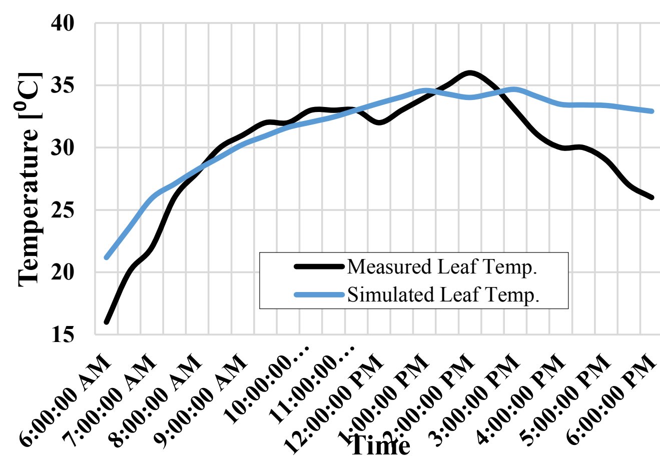

Fig. 8. Measured and simulated leaf temperature.

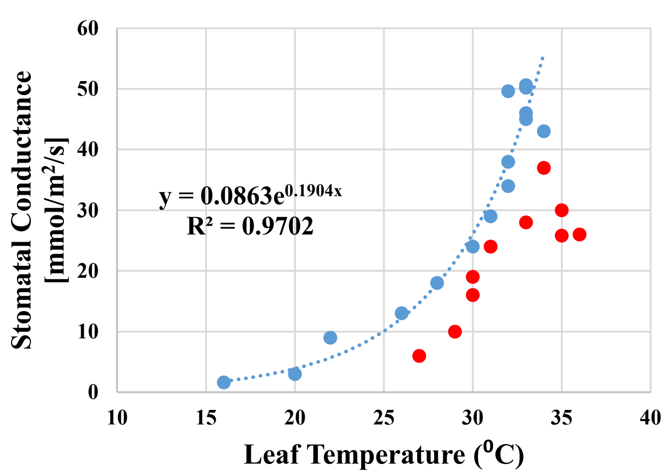

Fig. 7. Stomatal conduction vs. leaf temperature.

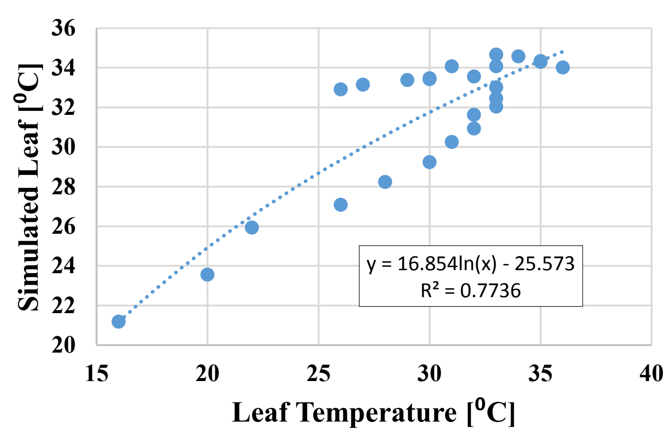

Fig. 9. Correlation between measured and simulated leaf temperature.

16:30 leaf temperatures decreased, and stomatal conductance declined while relative humidity increased.

When considering the behaviour between stomatal conductance and leaf temperature some form of hysteresis is observed; a strong correlation ($R^2 = 0.97$) exists between stomatal conductance and leaf temperature on the rising limb of the graph (Fig. 7), but there is a delay in the drop of leaf temperature on the falling limb when compared to the stomatal conductance.

According Campbell and Norman (1998) leaf temperatures are simulated based on air temperatures. For the purpose of this study Popular leaves with and emissivity of 0.98 and leaf width of 0.01 m were used in leaf temperature modelling. The absorbed radiation R_{abs} was used as a fitting parameter. Fig. 8 shows that a relatively good fit was

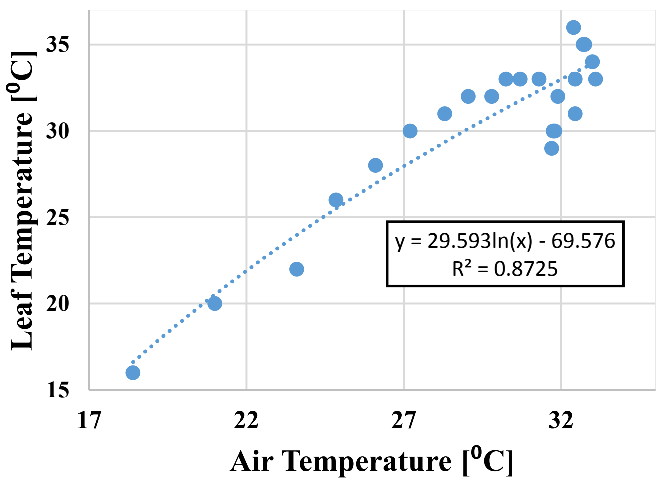

Fig. 10. Correlation between air and leaf temperature.

obtained with the exception of the prediction on the rising and falling limbs of the graph. The measured and simulated leaf temperatures (Fig. 9) show strong positive correlation ($R^2 = 0.77$). Fig. 10 Shows a good correlation ($R^2 = 0.87$) between the air and leaf temperature.

The calibration results are presented in Fig. 11. The simulated values presented in Fig. 11 are based on the hourly air temperature data of the closest weather station for that specific day.

A summary of the calculated ET values per month is presented in Table 2. The high value (9.19 mm/d) was observed during the month of December and the low value (0.79 mm/d) was observed in June. The figures obtained in Table 2 is calculated by multiplying the calculated ET with the average effective leaf area of 4.8 m^2 per square meter (Table 1) as the stomatal conductance is measured per leaf area.

Fig. 12 shows a comparison of the field model results to that of the FAO Penman-Monteith reference crop model and the Shuttleworth-Wallace ET model. The average value for the Shuttleworth-Wallace ET model and the developed field model are basically identical, but the field model exhibits more pronounced minima and maxima compared to the Shuttleworth-Wallace ET model. During the winter months, the developed field model gives similar results to that of the FAO Penman-Monteith reference crop model and this is due to the fact that the model is temperature driven and a sudden drop in winter months is evident (Fig. 4). The Shuttleworth-Wallace ET model assumed an evergreen broadleaf forest landcover with an average tree height of 7.2 m (Table 1).

The model parameters that were used to obtain the best fit as shown in Fig. 13, are the following: Study area = 161 km^2; Specific yield = 0.0043; Effective recharge 7.1% of MAP and Dolomite storage = 28 Mℓ/d. The effective recharge was calculated by assigning a 12.8% (Fleisher, 1981) to the areas where the surface geology is dolomite and a 5.3% (Wolmerans and Guise-Brown, 1978) to the areas where the surface geology is part of the Transvaal group. The study area size was calculated using GIS and the specific yield and dolomite storage were used as fitting parameters in the water balance model. The dolomite storage refers to the amount of water that is released from storage due to the dewatering of the compartment that is taking place.

The initial water balance is modified by introducing the calculated ET over the proposed plantation area of 4.8 km^2. The effect of the proposed plantation is assumed to reduce direct recharge into the compartment and recharge for the plantation area was set to zero for months where the ET exceeded the recharge. The pumping rate of Cooke 3 was assumed to stay constant and the pumping rate of Cooke 4 was reduced until the water level response of the observed borehole and the predicted water level response with the ET delivered the same trend as shown in Fig. 14. The average direct ET of the proposed plantation area is 20 Mℓ/d, but not the whole 20 Mℓ/d is seen as a reduction in pumping rate. The predicted water level dropped a maximum of 2 m and this increase in hydraulic gradient resulted in some increase from inflow sources described by a conductance term (Table 3). Furthermore, when ET exceeds recharge the recharge for the plantation area is set to zero and the effective ET equal the available recharge.

The position of the borehole selected (G1111) to be used in the SVF model is shown in Fig. 15. It is important to note that the borehole selected does not fall within the cone of depression around Cooke 4 shaft, to ensure that a more natural water level response is used in the SVF model.

Table 3 represent inflows and outflows of the system and Fig. 16 shows these flows geographically. The average drop in water level from pre-mining to current water levels is estimated at 27 m (Fig. 17). The results of conductance for each of the inflows are presented in Table 3. A maximum conductance of 315 m^2/d is reached for the Zuurbekom source. The conductance for each of the sources allow for the inflow to change as the head value changes.

Before the calculated ET can be introduced to the water balance, the area where a possible plantation can be introduced must first be identified. The major criteria for establishing a plantation will be the depth of the groundwater level. For the purpose of this study it is assumed that the maximum root depth of the proposed Eucalyptus is 8 mbgl (Nepstad et al., 1994). The reduction in recharge to the area is considered to be through extraction via root uptake only.

The only region where the average groundwater level is 8 mbgl or shallower is shown in Fig. 15. By combining this region with areas with moderate to high agricultural potential, a probable area for the proposed plantation is identified as shown in Fig. 18.

6. Discussion

There exists a correlation between stomatal conductance and leaf temperature even though some form of hysteresis is present. By fitting a curve to the correlated data an expression can be obtained to predict stomatal conductance when the leaf temperature is known.

Existing models can be used to simulate leaf temperature based on air temperature which in turn can be used to predict the stomatal conductance.

Through the use of field measurements, the formulated field model was successfully calibrated to predict stomatal conductance based on air temperature data from a close by weather station. This calibrated model was then used to predict average monthly stomatal conductance on an hourly basis from 06:00 to 18:00.

The calculated ET based on the field model was compared with the FAO Penman-Monteith model for a reference crop ET as well as the Schuttleworth-Wallace model which is a variant of the Penman-Monteith model, but with the flexibility to select a specific type of landcover. On average the field model and the Schuttleworth-Wallace model compared very well, but the field model exhibited more extreme minima and maxima. Overall the comparison seemed realistic.

A water balance for the study area were determined making use of the SVF method under certain assumptions. Inflows to the SVF model were considered as head dependent and were therefore assigned appropriate conductance values. Pre-mining and existing groundwater levels in the area were used to determine the head loss required for head depended inflows.

The assumptions associated with the water balance model can be summarised as follows: (1) all inflows to the system are connected to the mine void via a network of faults within the study area, (2) all dykes are considered impermeable and inflows from adjacent compartments

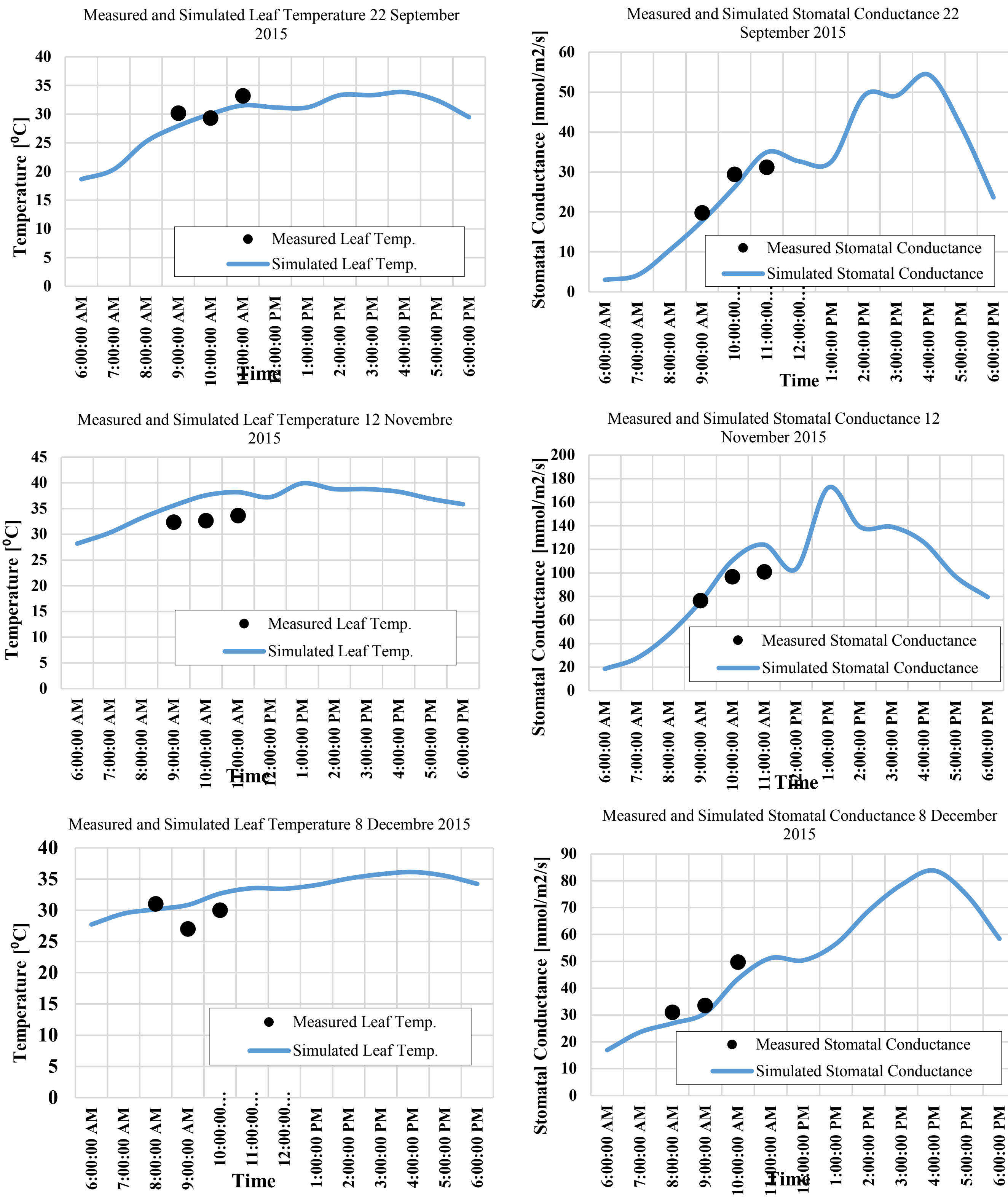

Fig. 11. Field model calibration results.

are head dependent and therefore controlled via a conductance term and (3) all leakage from rivers are also head dependent and controlled via a conductance term.

Water balance model was then modified to account for the ET from the proposed plantation, which were assumed to reduce direct recharge. The most likely area to establish the proposed plantation were determined making use of a combination of where the groundwater levels are 8 mbgl or less and the agricultural potential is moderate to high.

The effective recharge was reduced based on the modelled ET values across the proposed plantation area and the water balance were adjusted so that the predicted water levels will follow the same trend as

Table 2
Summary of calculated monthly ET values.

Month	ET (mm/d)	Month	ET (mm/d)	Month	ET (mm/d)
Jan	6.241	May	1.818	Sep	3.046
Feb	5.595	Jun	0.793	Oct	5.696
Mar	3.686	Jul	0.870	Nov	6.732
Apr	2.148	Aug	2.021	Dec	9.191

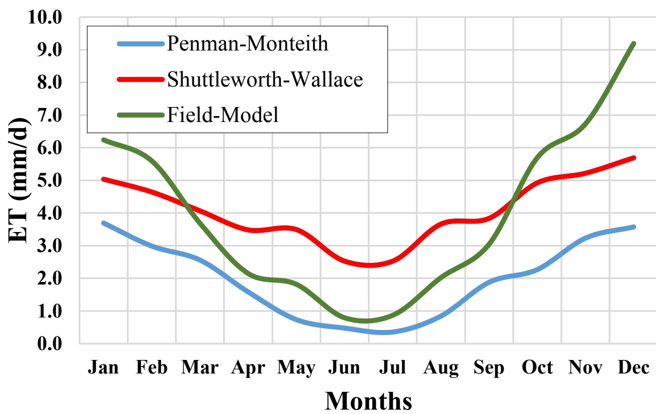

Fig. 12. Comparison of ET model results.

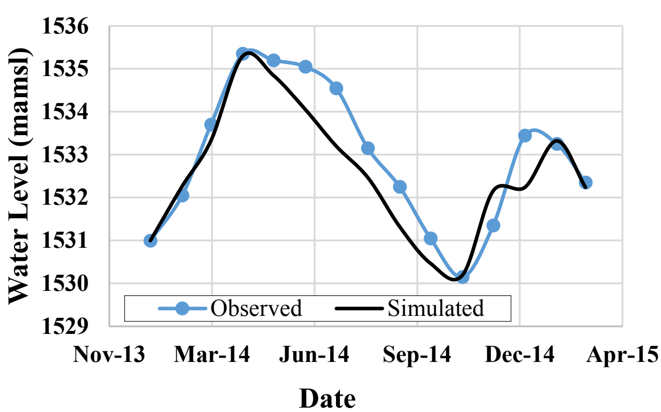

Fig. 13. SVF model fit for borehole G1111.

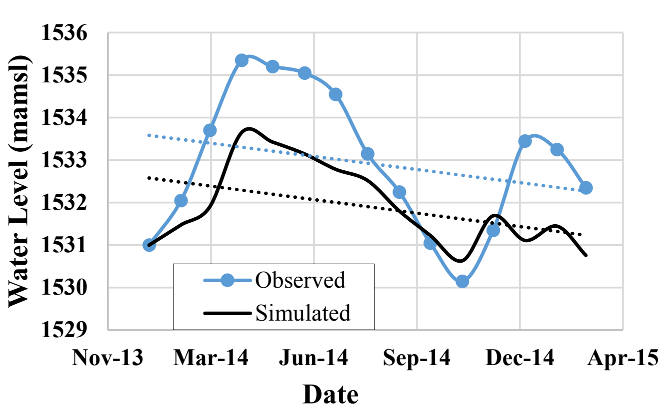

Fig. 14. Predicted water level response with ET of proposed plantation.

the measured water levels. This resulted in an average reduction of 11 Mℓ/d of the pumping at Cooke 4 assuming the pumping of 9 Mℓ/d of Cooke 3 is sustained. This will result in a 16% reduction in the pumping rate at Cooke 4 if all assumptions regarding the water balance model is valid. The average direct ET of the proposed plantation area is 20 Mℓ/d, but not the whole 20 Mℓ/d is seen as a reduction in pumping rate due to

Table 3
Summary of known inflows and outflows, Calculated conductances to the study area.

Inflows	Ml/d	Outflows	Ml/d	Source	Conductance (m^2/d)
Zuurbekom	9	Cooke 4 Pumping	68	Zuurbekom	315
Gemsbok East	6	Cooke 3 Pumping	9	Gemsbok East	210
Leeuspruit	7.5	Gemsbokfontein Eye	0	Leeuspruit	260
Rietspruit	5			Rietspruit	175

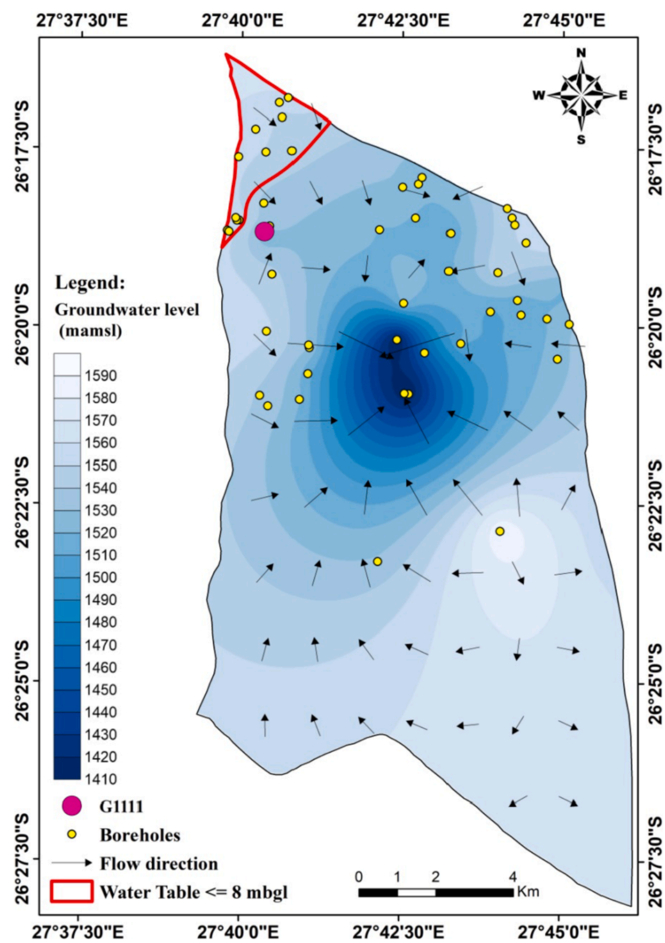

Fig. 15. Groundwater level map of study area, locality of borehole (G1111) used for SVF model and Area where water table are 8 mbgl or shallower.

the fact that the water table drop will increase head dependent inflows and when ET exceeds recharge the recharge for the plantation area is set to zero and the effective ET equal the available recharge.

The water balance model with ET from the plantation are valid under the following assumptions: (1) all assumptions from the initial water balance model, (2) no change in the storage from the dolomite and (3) the water level drop will not affect the ET due to increased root depth requirement. ET is taking place at the predicted rate for each month and is not affected by factors such as the age of the plantation and availability of water.

7. Conclusion

The study showed that a suitable ET estimation can be achieved based on air temperature measurements and making use of an appropriate ET model. By including the ET as a loss component in a water balance model, it is shown that the proposed plantation in an area (3% of the total study area) with high agricultural potential and shallow

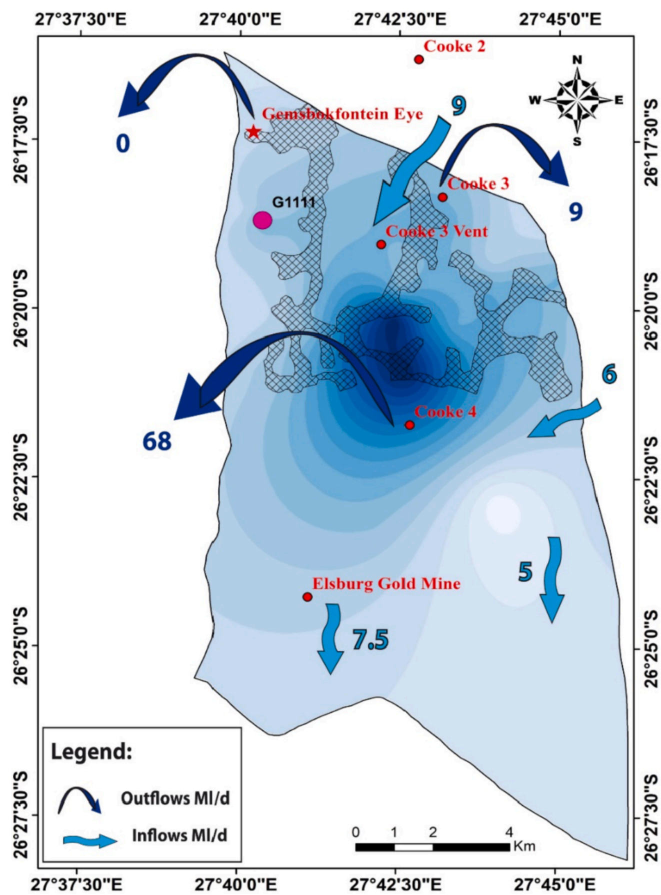

Fig. 16. Inflows and outflows of the study area.

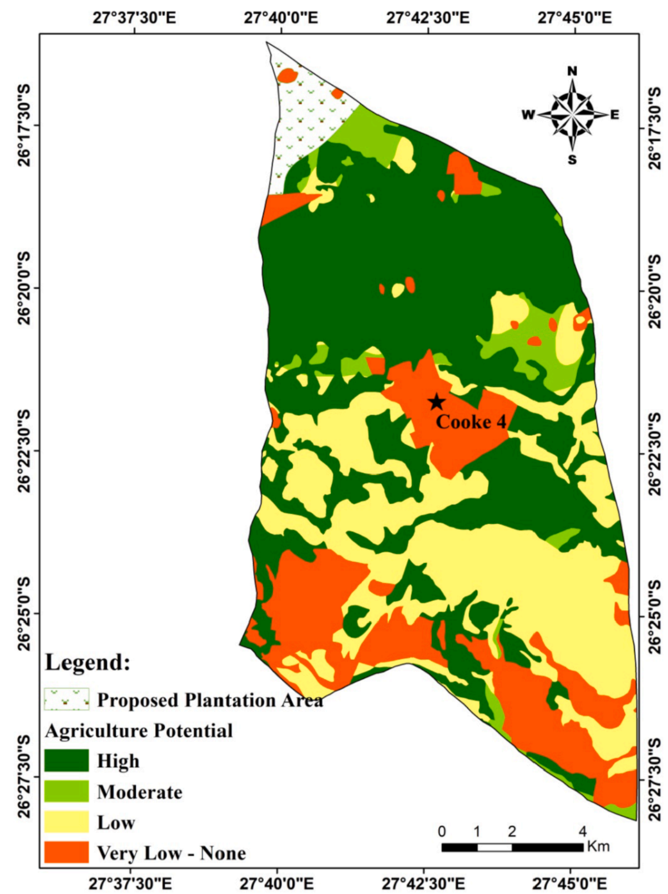

Fig. 18. Proposed plantation area.

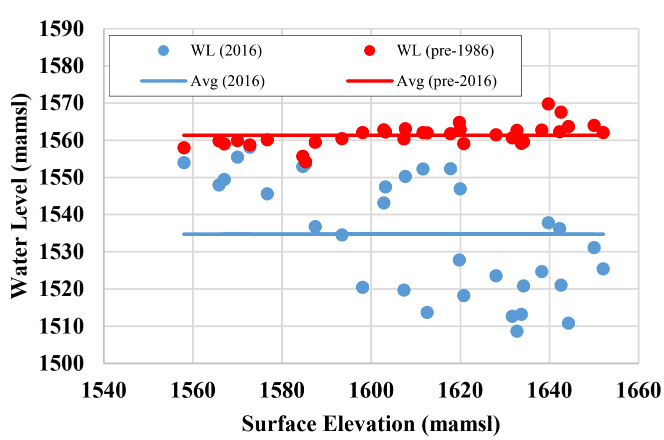

Fig. 17. Comparison of historic and current water levels across the study area.

groundwater levels (< 8 mbgl) can result in a significant decrease of water ingress into mine workings. A possible reduction of 11 Mℓ/d of the pumping at Cooke 4 is predicted, assuming the pumping of 9 Mℓ/d at the adjacent Cooke 3 mine is sustained. However, the 16% reduction in the pumping rate at Cooke 4 is subject to the validity of all assumptions related to the water balance model.

Finally, it is concluded that the introduction of a Eucalyptus plantation, as a bio-drainage option, is worth considering in the Gemsbokfontein West Compartment to reduce mine water ingress within the study area.

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References

Allison, G.B., Hughes, M.W., 1983. The use of natural tracers as indicators of soil-water movement in a temperate semi-arid region. J. Hydrol. 60, 157–173.

Bacon, P.E., Stone, C., Binns, L., Leslie, D.J., Edwards, E.W., 1993. Relationship between water availability and Eucalyptus camaldulensis growth in a riparian forest. J. Hydrol. 150, 541–561.

Bosch, J.M., Hewlett, J.D., 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. J. Hydrol. 55 (1–4), 3–23.

Braune, E., 2000. Towards comprehensive groundwater resource management in South Africa. In: Sililo, O. (Ed.), Proceedings of the XXX IAH Congress on Groundwater: Past Achievements and Future Challenges. Cape Town, South Africa. 26 November to 1 December 2000. AA Balkeme, Rotterdam, pp. 7–16.

Bredenkamp, D.B., Botha, L.J., Van Tonder, G.J., Van Rensburg, H.J., 1995. Manual on Quantitative Estimation of Groundwater Recharge and Aquifer Storativity. WRC Report TT 73/95 Water Research Commission, Pretoria.

Burgess, S.S.O., Pate, J.S., Adams, M.A., Dawson, T.E., 2000. Seasonal water acquisition and redistribution in the Australian woody phreatophyte, Banksia prionotes. Ann. Bot. (Lond.) 85, 215–224.

Campbell, G.S., Norman, J.M., 1998. An Introduction to Environmental Biophysics (2nd Eds). Springer-Verlag, New York, United States of America.

SRK Consulting, 2013. Independent Technical Report: Gold One Cooke Four Underground Operation. Gauteng, South Africa.

Srivastrava, R.J., Kumar, A., Prasa, K., 2003. Studies on Soil Moisture Variations under Eucalyptus Plantation. XII World Forestry Congress, 2003, Quebec City, Canada.

Crombie, S.D., 1992. Root depth, leaf area and day time water relations of Jarrah (Eucalyptus marginata) forest over storey and understorey during summer drought. Aust. J. Bot. 40, 113–122.

DWAF, 2003. Department of Water Affairs and Forestry. Groundwater Resources Assessment Phase II Database. Retrieved from. www.dwaf.gov.za/Groundwater/

GRAII.aspx.
DWS, 2015. Department of Water and Sanitation. Hydrological Services. Retrieved from: http://www.dwaf.gov.za/Hydrology/.
Dye, P.J., 1996a. Response of Eucalyptus grandis trees to soil water deficits. Tree Physiol. 16, 233–238.
Dye, P.J., 1996b. An investigation of sub-soil water penetration in the Mokobulaan research catchment, South-eastern Transvaal. S. Afr. For. J. 161, 31–34.
Dye, P.J., 1996c. Climate forest and streamflow relationships in South African afforested catchments. Commonw. For. 75, 31–38.
Engel, V., Jobbagy, E.G., Stieglitz, M., Williams, M., Jackson, R.B., 2005. Hydrological consequences of Eucalyptus afforestation in the Argentine pampas. Water Resour. Res. 4, 1–14.
Farley, K.A., Jobbagy, E.G., Jackson, R.B., 2005. Effects of afforestation on water yield: a global synthesis with implications for policy. Glob. Chang. Biol. 11, 1565–1576.
Ferro, A., Cassada, J., Berra, B., Tsao, D., 2006. "Phytoremediation of TPH-Contaminated Groundwater," Presented at the Annual International Conference on Soils, Sediments, and Water. University of Massachusetts, Amherst.
Fleisher, J.N.E., 1981. Geohydrology of the Dolomite Aquifers of the Mamani Subgroup in the Wouthwestern Transvaal. RSA. Department of water Affairs and Forestry Technical Report GH3169.
Johan Fourie and Associates consulting, 2011. Ezulwini Mining Company (Pty) Ltd Strategic Water Management Plan. Paardekraal, South Africa. Report No.: JW043/17/F925 - Rev 3.
Global Agricultural Information Network, 2014. Update on the South African Lumber Industry. Retrieved 11/24/2014 from. http://www.unece.lsu.edu/marketing/documents/2015Mar/gme15-03.pdf.
Gold One Cook Operations, 2013. Underground Operation, Gauteng, South Africa. (Independent Technical Report).
Hodgson, F.D.I., Usher, B.H., Scott, R., Zeelie, S., Cruywagen, L.M., De Necker, E., 2001. Predictive Techniques and Preventative Measures Relating to the Post Operational Impact of Underground Mines in the Quality and Quantity of Groundwater Resources. pp. 272 WRC Report no. 699/1/01, ISBN no. 1868451828.
Jarmain, C., 2003. Potential for Using Trees to Limit the Ingress of Water into Mine Workings: A Comparison of Total Evaporation and Soil Water Relations for Eucalyptus and Grassland. University of Natal. (Thesis – MSc Agric), Pietermaritzburg.
Joshi, M., Palanisami, K., 2011. Imapct of Eucalytpus Plantations on Ground Water Availability in South Karnataka. ICID 21st International Congress on Irrigation and Drainage. pp. 15–23 October 2011, Tehran, Iran.
Mellor, E.T., 1917. The geology of the Witwatersrand: and explanation of geological map of the Witwatersrand goldfield. Nature 100 156-156.
Nepstad, D.C., Carvalho, D.E., Davidson, E.A., Jipp, P.H., Lefbvre, P.A., Negreiros, G.H., Da Silva, E.D., Stone, T.A., Trumbore, S.E., Veira, S., 1994. The role of deep roots in the hydrological and carbon cycles of Amazonian Forests. Nature 372, 666–669.
NWA, 1998. National Water South African Government Gazette. Act No. 36 of 1998.
Parsons, C.F., 1987. Lnterpretation of Standard Colour Aerial Photographs of Gemsbokfontein Dolomitic Groundwater Compartment Phase 2. Confidential Report. JCI Research Unit. Report No.223.
Parsons, C.F., Killisck, A.M., 1985. The Surface Geology of Part of the WAGM: Property and Environs. Retrieved from. https://dspace.nwu.ac.za/handle/10394/613.
Rison Groundwater Consulting, 2011. Groundwater Monitoring Borehole Installation: Ezulwini Mining Company (Pty) Ltd Tailings Storage Facility. Krugersdorp, South Africa.
Roberts, S., Vertessy, R., Grayson, R., 2001. Transpiration from Eucalyptus sieberi (L. Johnson) forests of different age. For. Ecol. Manag. 143, 153–161.
Salama, R.B., Bartle, G.A., Farrington, P., 1994. Water use of plantation Eucalyptus camaldulensis estimated by groundwater hydrograph separation techniques and heat pulse method. J. Hydrol. 156 (1–4), 163–180.
SAWS (South African Weather Services), 2015. Annual Report 2014/2015. Retrieved from. http://www.weathersa.co.za.
Schnoor, J.L., Licht, L.A., McCutchein, S.C., Wolfe, N.L., Carrerira, L.H., 1995. Phytoremediation of organic and nutrient contaminants. Environ. Sci. Technol. 29, 318–323.
Schrader, A., Winde, F., Erasmus, E., 2014. Using impacts of deep-level mining to research karst hydrology — a Darcy-based approach to predict the future of dried-up dolomitic springs in the Far West Rand goldfield (South Africa). Part 2: predicting inter-compartmental flow and final groundwater. J. Environ. Earth Sci. 72, 2583–2595.
Schulze, R.E., 2006. Solar radiation: background. In: Schulze, R.E. (Ed.), 2006. South African Atlas of Climatology and Agrohydrology. Water Research Commission, Pretoria, RSA, WRC Report 1489/1/06, Section 5.1.
Schulze, R.E., Maharaj, M., Moult, N., 2006. Reference crop evaporation by the Penman-Monteith method. In: Schulze, R.E. (Ed.), 2006. South African Atlas of Climatology and Agrohydrology. Water Research Commission, Pretoria, RSA, WRC Report 1489/1/06, Section 13.3.
Scott, D.F., Lesch, W., 1997. Streamflow responses to afforestation with Eucalyptus grandis and Pinuspatula and to felling in the Mokobulaan experimental catchments, South Africa. J. Hydrol. 199 (3), 360–377.
Sikka, A.K., Samra, J.S., Sharda, V.N., Samraj, P., Lakshmanan, V., 2003. Ow flow and yield response to converting natural grassland into bluegum (Eucalyptus globulus) in Nilgiris watersheds of South India. J. Hydrol. 270, 12–26.
Soares, J.V., Almeida, A.C., 2001. Modelling the water balance and soil water fluxes in a fast growing Eucaluptus plantation in Brazil. J. Hydrol. 253, 130–137.
Tucker, R.F., 1980. The Sedimentary and Mineralogy of the Composite Reef on Cooke Section, Randfontein Estates Gold Mines, Witwatersrand, South Africa. Unpublished M.Sc. Thesis), University of Witwatersrand, Johannesburg, South Africa, pp. 335.
Tucker, R.F., Viljoen, R.P., 1989. The geology of The West Rand Goldfields, with special reference to the southern limb. In: In: Anhauesse, C.R., Maske, S. (Eds.), Mineral Deposit of South Africa, vol. 2. Geological Society of South Africa, Johannesburg, pp. 649–688.
Van Lill, W.S., Kruger, F.J., Van Dyk, D.B., 1980. The effect of afforestation with Eucalyprusgrandis Hill ex Maiden and PinuspatulaSchlecht. Et. Cham. on streamflowfrom experimental catchments at Mokubalaan, Transvaal. J. Hydrol. 48, 107–118.
Verma, N.K., Lamb, D.W., Reid, N., Wilson, B., 2014. An allomeric model for estimating DBH of isolated clustered Eucalyptus trees from measurements of crown projection area. For. Ecol. Manag. 326, 125–132.
Wolmerans, J.F., Guise-Brown, F.H., 1978. The Water Hazard in Deep Gold Mining of the Far West Witwatersrand- South Africa. SAIMOS-7, Granada, pp. 329–346.
Zhou, M.C., Ishidaira, H., Hapuarachchi, H.P., Magome, J., Kiem, A.S., Takeuchi, K., 2006. Estimating potential evapotranspiration using Shuttleworth-Wallace model and NOAA-AVHRR NDVI data to feed a distributed hydrological model over the Mekong River Basis. J. Hydrol. 327, 151–173.