Modelling and water yield assessment of Lake Sibhayi

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Abstract

This study has been undertaken to establish the probable causes of the almost 4 m drop in the level of Lake Sibhayi between 2001 and 2014, to assess the impact of abstractions for domestic water consumption and by commercial plantations on lake levels, and to determine what sustainable yield can be abstracted from Lake Sibhayi. From the analysis and simulations undertaken, it is concluded that the major cause of the drop in the level of Lake Sibhayi was the below-average rainfall over the period 2001 to 2011. However, while the simulation results show that the effect on lake levels of abstractions for domestic usage over this period has been negligible, they do indicate that nearly 1.4 m of the drop in lake level can be attributed to the impact of the afforestation which began in the catchment in the 1990s. A yield analysis of simulated results with historical developments in the catchment for the 65-year period of observed climate record was undertaken using both a fixed minimum allowable lake level or a maximum drop from a reference lake level as criteria for system failure. Results from simulating lake levels using the historical climate record with the area afforested and abstractions levels fixed at 2014 values indicate that no sustainable additional yield is possible because of the sustained decline in both the simulated lake levels and conceptual groundwater store, which would be environmentally, socially and ecologically unacceptable. Preliminary simulated results indicate that the removal of approximately 5 km^2 of forestry is required to release 1 MCM/yr for domestic abstractions. However, these preliminary results require improved verification of input data and a review of the modelling for increased confidence in the results.

Keywords: hydrology of Lake Sibhayi, lake level, abstractions, afforestation and yield.

INTRODUCTION

Lake Sibhayi, or Sibayi or Sibaya as it is also known, is the largest freshwater lake in South Africa (NWU, 2014; Weitz and Demlie, 2014), with a surface area of approximately 69 km^2, and lies in the tropical north-eastern quadrant of KwaZulu-Natal. Lake Sibhayi was once at the mouth of a large river, and was open to the sea, but currently a forested dune land divides the lake from the coastline (SAT, 2016).

Lake Sibhayi, excluding its catchment, falls within the iSimangaliso Wetland Park conservation area, which has World Heritage Site status (Botha and Singh, 2012) and has been declared a Ramsar wetland of international importance (SAT, 2016).

As reported by Weitz and Demlie (2014), the lake is a popular tourist destination and is exploited for timber plantations and for domestic water supply to the scattered rural settlements of the area. Given that South Africa is a semi-arid country where water is scarce, and that legislation requires water to be managed in a conjunctive and sustainable manner, the lake is a vital source of fresh water for the ecology and local community, and is frequently the only source of water for certain animals during periods of drought (Weitz and Demlie, 2014).

The water balance of the lake has historically been in dynamic equilibrium (Weitz and Demlie, 2014). However, human settlement and land use change has resulted in significant development around the lake in recent years (Bruton et al., 1980; Combrink et al., 2011, cited by Weitz and Demlie, 2014). The development in the catchment has primarily been commercial forestry, subsistence agriculture and rural development. In addition, abstraction from groundwater in the lake's catchment and abstractions from the lake for local community water supply are relatively recent developments. These abstractions from the lake and groundwater system will reduce recharge to the lake and will impact on lake levels, and could result in changing the hydraulic gradient of groundwater, with the potential for saltwater migration from the sea into the lake (Weitz and Demlie, 2014).

Abstractions from Lake Sibhayi

Forestry has increased from the mid-1980s in the catchment and is currently estimated to cover approximately 115 km^2 (23%) of the 509 km^2 catchment. The evapotranspiration (ET) from deeper rooted afforestation is expected to be more than the ET from both natural vegetation and dryland agricultural production. For example, Albaugh et al. (2013) report that the ET from natural vegetation ranges from 700 – 900 mm/yr, while deep-rooted commercial plantations, which are characterized by tall, dense, evergreen canopies that maintain a relatively high leaf area index over the entire year, typically

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have ET in the range of 1 100 – 1 200 mm/yr, dependent on rainfall at the site. This will have an impact on catchment water yield (Albaugh et al., 2013) and thus the growth of afforestation in the catchment is expected to impact on lake levels.

In addition to forestry, the abstraction for local community water supply has been estimated to be 1.35 million m^3/yr (NWU, 2014) and may increase in the medium term.

Objectives of this study

Between 2001 and 2014 the level of Lake Sibhayi dropped from close to 20 m above sea level to nearly 16 m above sea level, its lowest level since the commencement of record keeping 50 years ago. Given the comparatively recent changes in land use and commencement of abstractions for domestic water supply, the decline in observed lake levels to historically low levels in 2014 prompted this study to address the following questions:

- What are the probable causes of the nearly 4 m drop in the level of Lake Sibhayi between 2001 and 2014?
- To what extent have abstractions from Lake Sibhayi for domestic water supply and by forestry been responsible for the drop in lake levels?
- What is the sustainable yield that can be abstracted from the lake without long-term over-exploitation of the resource?

STUDY AREA

The location of the study area is shown in Figure 1. The lake and the contributing catchment are located within the W70A Quaternary Catchment and W3E rain zone (Middleton and Bailey, 2008; 2011) and within the Usuthu-Mhlathuze Water Management Area (WMA 6).

Studies by Miller (2001) and Weitz and Demlie (2014) indicate that the surface area of the lake has been significantly reduced and currently averages approximately 55.5 km^2, with a total catchment area of approximately 512 km^2. However, a thorough catchment delineation was undertaken in this study using the latest freely available 30 m digital terrain model (NASA, 2015) and the catchment area and lake extent were increased to 509.23 km^2 and 68.98 km^2, respectively, for use in this study.

The coastal plain, where Lake Sibhayi and its catchment are situated, extends from Mtunzini in the south to the Mozambique border. As detailed by Smithers et al. (2016), the coastal plain around Lake Sibhayi extends for approximately 60 km inland, terminating against the foothills of the north–south trending Lebombo Mountains. The topography of the coastal plain in the vicinity of Lake Sibhayi is characterised by a series of palaeo-dune ridges roughly parallel to the coastline. The lake is separated from the sea by a palaeo-dune that rises in elevation up to 170 m above mean sea level (amsl). In addition to the palaeo-dune topography, this part of the coastal plain is characterised by flat and low undulating topography. Midgley et al. (1994) refer to the area as a local endorheic area, i.e., the surface water drainage does not leave the catchment. A detailed aquifer, geological and hydro-geological description of the catchment is included in Smithers et al. (2016).

Due to the sandy substrate surrounding the lake, the amount of surface runoff is limited and consequently the water levels within the lake are maintained largely by groundwater inflow (Pitman and Hutchison, 1975). The only significant surface drainage feature for the Lake Sibhayi catchment is the

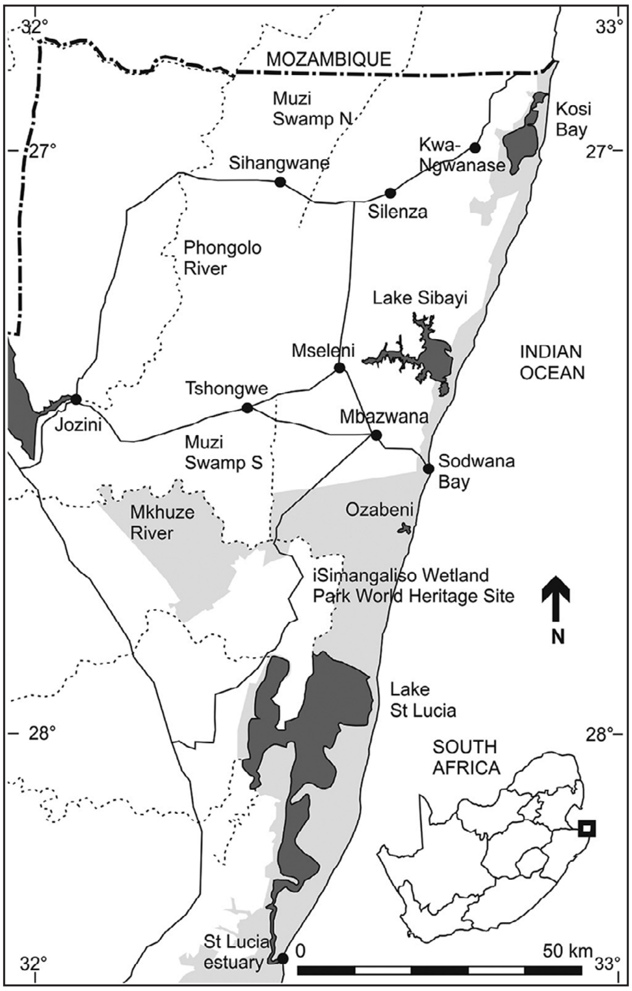

Figure 1
Location of Lake Sibhayi with major roads shown as solid lines, major rivers as dashed lines and light grey shaded area indicating the iSimangaliso Wetland Park World Heritage Site (Weitz and Demlie, 2014)

Mseleni River feeding the western arm of the lake. Several non-perennial streams also drain into the lake. The KuMzingwane and Velindlovu streams feed into the northern arm of the lake, while the Umtibalu and Iswati streams and the Umsilalane stream feed the southern and northern portion of the western arm, respectively. The sandy substrate of the catchment coupled with a relatively flat topography and shallow water table result in a close relationship between surface waters of the lake and the groundwater. This relationship is evident as the lake forms a surface expression of the groundwater (Meyer et al., 2001).

The Zululand coastal plain is characterized by a humid, subtropical climate with a warm summer, dominated by the southern subtropical high-pressure belt. Rainfall in the area is derived from both tropical and mid-latitude weather systems. A strong seasonal precipitation pattern is observed in the region with most of the rainfall occurring during the summer months. The mean annual precipitation (MAP) increases from approximately 700 mm/yr along the western margin of the catchment to approximately 1 000 mm/yr along the coast. Mean monthly temperatures vary between 19°C and 27°C and potential evaporation rates for the Lake Sibhayi area are high, peaking during the summer months (Smithers et al., 2016).

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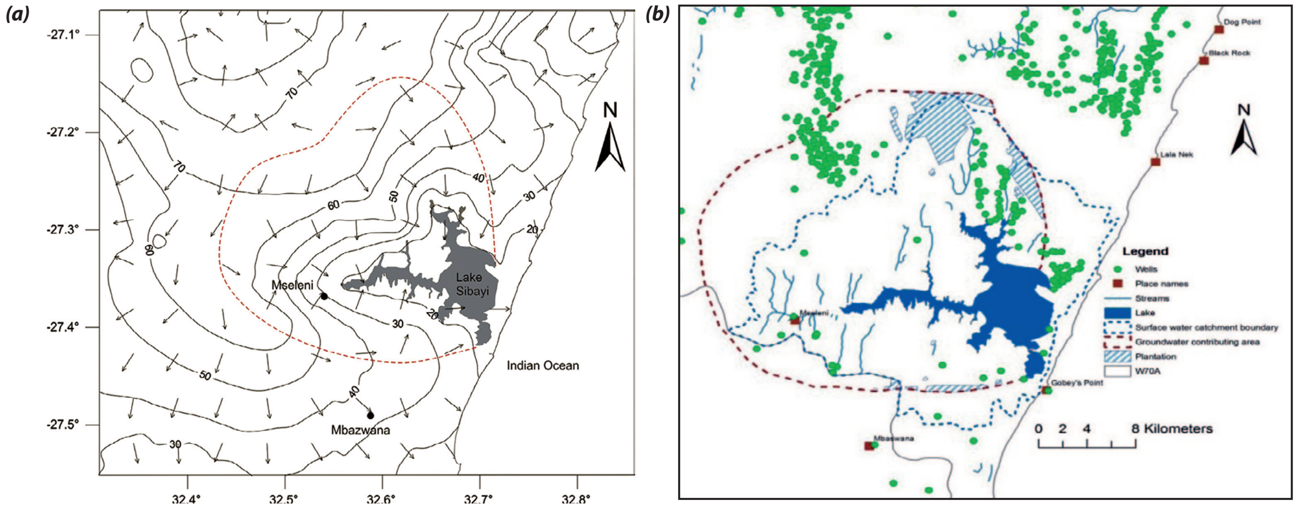

Figure 2
(a) Groundwater flow distribution map showing local flow vectors (groundwater elevation (m) (Weitz and Demlie, 2014); (b) surface and groundwater contributing catchment areas of the lake (Smithers et al., 2016)

Recent isotopic studies within the Lake Sibhayi catchment (Weitz and Demlie, 2014) indicated that not only are lakes, pans and wetlands groundwater fed, but most perennial rivers are also groundwater dependent. One such example is the Mseleni River where groundwater and river stable isotopic signals are almost the same, indicating that the river flow is supported from groundwater discharge.

Weitz and Demlie (2014) used groundwater levels measured within the lake catchment and regional water level data obtained from the Groundwater Resources Information Project (GRIP, 2013) to construct a groundwater-level contour map for the area, shown in Figure 2a. As shown in Figure 2b the surface water divide and groundwater divide do not coincide and the estimated groundwater contributing area to the lake is approximately 569 km^2, which is larger than the surface water catchment area (509.23 km^2).

The area surrounding Lake Sibhayi is covered extensively by commercial plantations. The most prominent of these are the Mbazwana and Manzengwenya plantations situated on the southern and northern side of the lake, respectively. These plantations consist mainly of *Eucalyptus grandis*, *Eucalyptus camaldulensis* (50%) and *Pinus elliottii* (30%), while the remaining 20% of the plantation is clear-felled.

METHODOLOGY

The catchment hydrology was simulated and input to a spreadsheet-based monthly water budget for the lake which was calibrated and used to determine additional yield from the lake and a preliminary forestry:domestic abstraction exchange ratio.

Model selection

There are no gauged streamflow records within the Lake Sibhayi catchment. Hence the use of a calibrated monthly time-step model (e.g. the Pitman Model) was not considered to be suitable for the rainfall-runoff modelling in the catchment. Thus, the conceptual and physically-based daily time-step ACRU agro-hydrological model (Schulze, 1989; Smithers and Schulze, 1995; Schulze and Smithers, 2004) was selected as actual catchment characteristics, such as soil texture, soil depth and site specific vegetation cover, could be used to increase confidence in the rainfall-runoff modelling. In addition, the daily time-step physically-based model was considered a more accurate method of estimating the water requirements from the forestry areas, as the ACRU model has been used in numerous forestry impacts and streamflow reduction activity studies (e.g. Kienzle and Schulze, 1992).

The ACRU model has been widely verified in South Africa and it has a high level of process representation with physically-based input parameters/variables (Schulze, 1995; Schulze and Pike, 2004). The ACRU model was therefore configured for the Lake Sibhayi catchment and was used to simulate evapotranspiration (ET), surface runoff into the lake and deep percolation to groundwater.

Shallow groundwater modelling

In addition to utilising the standard ACRU model as described above, the shallow groundwater sub-model documented by Kienzle and Schulze (1995), and which was used to investigate the impacts of afforestation on ground water resources in Northern Zululand by Kienzle and Schulze (1992), was also utilised in this study. The concepts used in the shallow groundwater model are illustrated in Figure 3. Deep-rooted forests can have access to water below the subsoil horizon in the intermediate zone and capillary fringe. Additional refinements were made by linking the water extracted for transpiration below subsoil to a conceptual groundwater store as described below. The shallow groundwater sub-model was thus used to model the impact of deep-rooted forestry on deep groundwater recharge and on surface runoff.

Model inputs

The ACRU model is linked to the Southern African National Quinary and Quaternary Catchments Databases (Schulze et al., 2005), which provided extensive default inputs for the model. Additional inputs regarding current land cover were sourced from the National Landcover Database (Thompson, 1999) and confirmed through site visits to the catchment area.

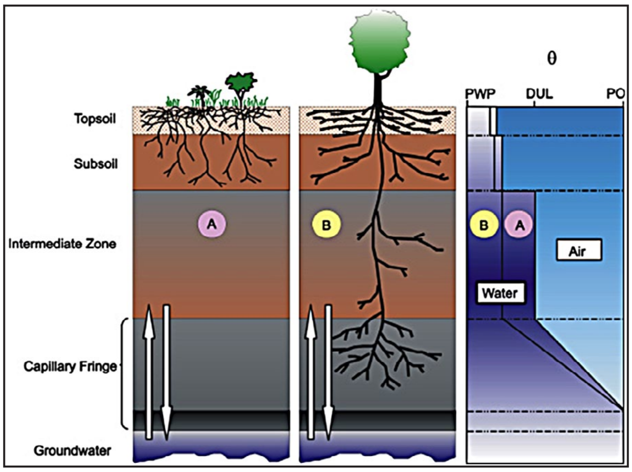

Figure 3
Conceptualisation of typical root and soil water distribution under (A) shallow roots and (B) deep-rooted conditions (θ = soil water content, PWP = permanent wilting point, DUL = drained upper limit, PO = total porosity) (Kienzle and Schulze, 1992)

A summary of the distribution of land use in the catchment is provided in Smithers et al. (2016).

Given the very flat topography, the delineation of the contributing surface runoff catchment was not trivial and the catchment area obtained (578.48 km^2, including the lake surface area) is slightly larger than the catchment area reported in other studies (Miller, 2001; Weitz and Demlie, 2014). The increase in contributing catchment area was considered to be as a result of using a more detailed digital elevation model (DEM), i.e., the SRTM 30 m DEM), which was not available in the previous studies. Thus, the increased topographical resolution in such a flat, and often endorheic, area resulted in an increased contributing catchment area in this study.

In the ACRU model, reference potential evaporation may be estimated by a number of equations, or from evaporation pan data, depending on the availability of input information. The information available for this study was daily maximum and minimum temperature values for the period 1950 to 2007. Based on this, the Hargreaves and Samani (1985) equation was used to calculate evaporative demands and losses. Temperature data was obtained from the South African Weather Service (SAWS) Climate Station 0412180 W.

An important input into the ACRU model is information pertaining to soils in the catchment. The dominant soil texture of the Lake Sibhayi catchment was classified as 'sandy'. The top soil depths are generally 2 m deep while the subsoil depths are 12 m, based on anecdotal evidence from geohydrological studies in the catchment area. The textural characteristics of the soils at the study site were validated at a high level (i.e. assessment of cuttings and other exposed soil profiles) during a site visit.

Evapotranspiration from forests

Literature-based estimates of ET by forests in Zululand have been widely reviewed by NWU (2014), who report ET for forests to range from 1 200 to 2 700 mm/yr, with an average of 1 800 mm/yr. This exceeds the MAP for Zululand (Lynch, 2004) which indicates that the trees are utilising shallow groundwater. In addition, NWU (2014) also report that measured ET per tree in different studies ranges from 2 to 270 L/d which, for a tree density of 1 600 trees/ha, is equivalent to 117 to 15 768 mm/yr. The maximum transpiration from vegetation is 9 mm/d (Schulze, 2015), which is equivalent to 3 285 mm/yr or 56 L/d for a tree density of 1 600 trees/ha. Given the range of ET rates reported for forestry, NWU (2014) used 6.5, 16 and 20 L/d to model ET from forestry, which is equivalent to 380, 934 and 1 168 mm/yr for a tree density of 1 600 trees/ha.

The conventional ACRU model configured for forestry simulated ET values ranging from 600 to 800 mm/yr, i.e., which is less than the MAP for the study area. Using the ACRU shallow groundwater sub-model, the average annual ET from the deep-rooted (12 m) forestry was approximately 1 300 mm/yr, which falls into the range of values reported by NWU (2014) and confirms that the ACRU shallow groundwater model is making use of water below the subsoil horizon.

Environmental flows

In order to determine the yields that could potentially be abstracted from the lake, the environmental water requirement (EWR) for Lake Sibhayi needed to be considered. Therefore, an approach was adopted that allowed for the inclusion of an EWR requirement in this study, albeit at a desktop level.

In this predominantly groundwater-driven system, quantifying the environmental flow component was not straightforward. The approach adopted was to use the total inflow into the lake (i.e. from both surface water and groundwater sources) to simulate the required EWR volume, which cannot be abstracted from the lake during the same month of inflow. Furthermore, when modelling the yield, selected minimum lake levels and maximum drawdown from a reference lake level were adopted as proxies for a range of ecological flow requirements.

EWRs were determined as part of this investigation using the Desktop Model within the SPATSIM Framework (Hughes, 2005). The monthly distribution of low flows was determined in SPATSIM using regional parameters for Type T: S.Natal. Furthermore, since the catchment upstream of the lake contains significant forestry, some agriculture and numerous groundwater and surface water abstractions, an ecological management class (EMC) of C (i.e. moderately modified) was adopted for the assessment.

Once EWRs were generated, hydrological and streamflow yield analyses were conducted to determine streamflow yields from the lake under current-day land use conditions. This also served as an indication of the impacts that current land use has on the catchments when compared to natural conditions.

Lake bathymetric data

The most recent bathymetric data of the lake was reported by Miller (2001) and a maximum depth of 41 m was measured, as shown in Figure 4. In addition to the data obtained from Miller (2001), a detailed Lidar strip survey was available from 16 – 20 m amsl, which was at the time, and still is, above the lake levels. The resultant survey data highlighted that a full Lake Sibhayi retains a significant storage volume, i.e., more than the capacity of the Midmar, Albert Falls and Inanda Dams combined, or approximately 44% of the Pongolapoort Dam.

Using data from Miller (2001), the lake level : surface area relationship shown in Figure 5 and the volume: lake level relationship shown in Figure 6 were derived and used in the

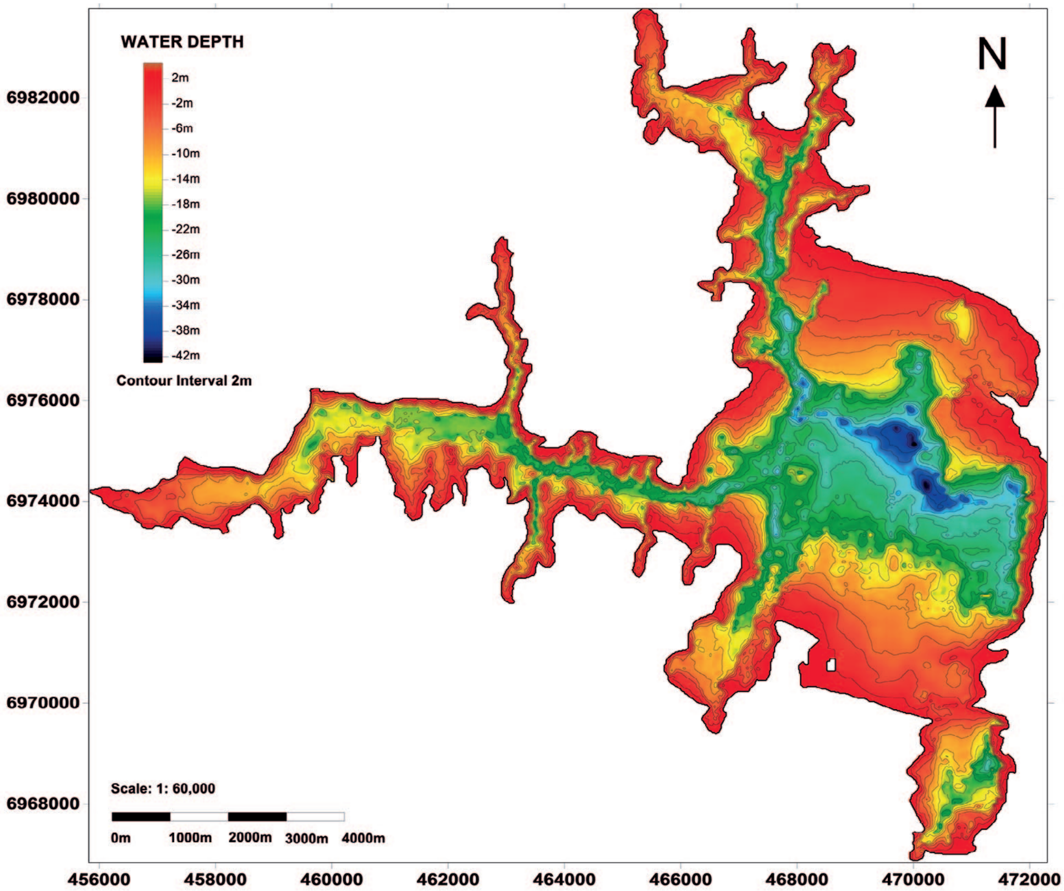

Figure 4

Bathymetric map of Lake Sibhayi (data from Miller, 2001)

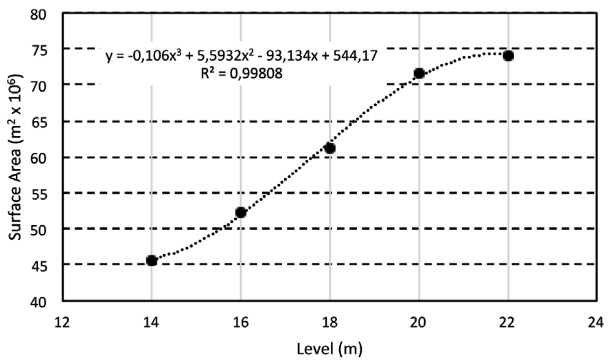

Figure 5

Surface area: lake level relationship for Lake Sibhayi

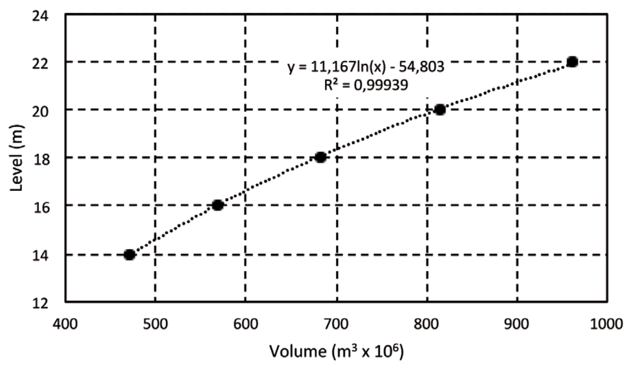

Figure 6

Lake level : volume relationship derived for Lake Sibhayi

water budget calculations for the lake. The equations shown in Figure 5 and Figure 6 were derived for the range of levels shown and should not be applied outside of these ranges (i.e. 14 to 22 m).

Lake levels

The primary lake level data for Department of Water and Sanitation (DWS) Station W7R001 is shown in Figure 7 and indicates that an adjustment to the data was necessary prior to 1981. Adjusted lake levels were used prior to September 1980, and thereafter the DWS primary data was used to calculate the monthly average lake levels used in the study. Some inconsistencies are apparent in the DWS primary data levels, e.g., from November 2013 to the end of the record. Given the inconsistencies in the observed lake level and rainfall, the lake levels for this period (i.e. November 2013 to December 2014) were excluded from the study, as shown in Figure 8.

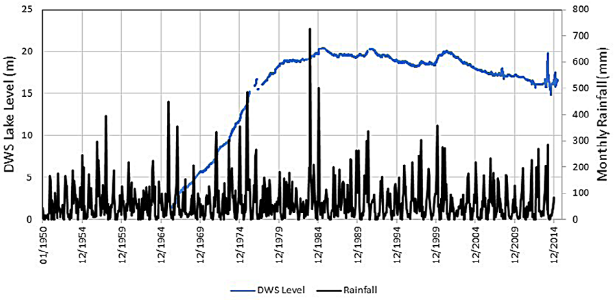

Figure 7
Primary DWS lake level data and monthly rainfall

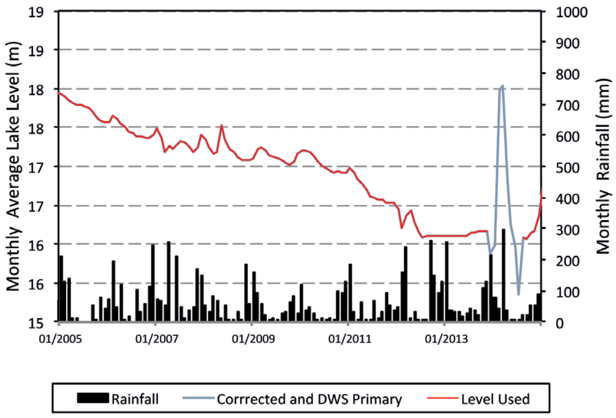

Figure 8
Lake levels used in the simulation

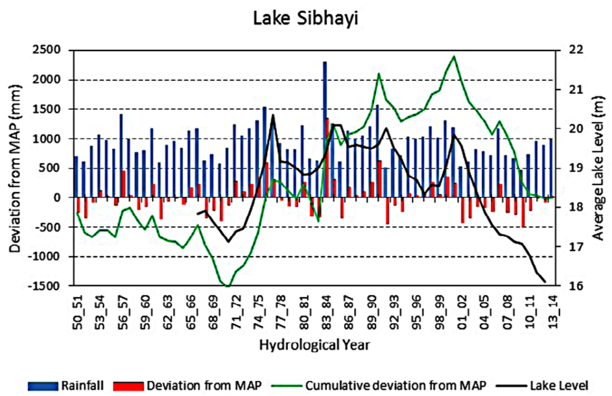

Figure 9
Annual rainfall and lake level, and deviations of rainfall from MAP

Rainfall and lake level response

As shown in Figure 9 the observed lake level has been declining since 2001. The mean water level for December 2014 was 16.22 m amsl, significantly lower than that measured in April 2001 which was 19.56 m amsl.

Annual rainfall, average annual lake level and both annual deviations of annual rainfall from the MAP and the cumulative deviation of rainfall from MAP are shown Figure 9. The results indicate a strong correlation between average lake level and cumulative deviation of annual rainfall from MAP. Hence the decline in lake level since 2001 is linked to the number of consecutive below-average rainfall years that have occurred from 2000 to 2010.

Lake water balance modelling

The daily surface runoff and drainage to groundwater simulated by the ACRU model were accumulated into monthly totals and used as input to the lake water balance model as detailed below. The monthly storage in the lake was computed using (1).

$$V_{(i)} = V_{(i-1)} + RFL_{(i)} + SW_{(i)} + GW_{(i)} - EVAP_{(i)} - SEEP_{(i)} - ABS(i) - TS\_ABS_{(i)} \quad (1)$$

where:

$V_{(i)}$	=	lake volume ($m^3 \times 10^6$) at end of month = *i*
$RFL_{(i)}$	=	rainfall on lake ($m^3 \times 10^6$) during month = *i*
$SW_{(i)}$	=	surface runoff ($m^3 \times 10^6$) into lake during month = *i*
$GW_{(i)}$	=	groundwater contribution ($m^3 \times 10^6$) to lake during month = *i*
$EVAP_{(i)}$	=	evaporation from lake ($m^3 \times 10^6$) during month = *i*
$SEEP_{(i)}$	=	seepage from lake to sea ($m^3 \times 10^6$) during month = *i*
ABS	=	fixed monthly abstraction ($m^3 \times 10^6$) from the lake and which used to determine the yield of the lake
$TS\_ABS_{(i)}$	=	additional abstraction from lake for month = *i* derived from monthly abstractions time series ($m^3 \times 10^6$)

The above variables were estimated as described below:

(i) The depth of rainfall falling on the lake was converted to a volume using the surface area derived from the relationship shown in Figure 5.

(ii) The monthly evaporation from the lake was estimated from the accumulated daily reference A-pan evaporation for the month computed in the ACRU model and the monthly total was converted to open water body evaporation using monthly lake: A-pan factors derived from Smithers and Schulze (1995).

(iii) The daily surface runoff depth simulated by the ACRU model was converted into a monthly volume flowing into the lake using the contributing surface catchment area.

(iv) The water draining below the root depth in the ACRU model was conceptualised to flow into a groundwater store and a fraction of the groundwater store was released as the monthly groundwater flow into the lake. Both the initial value of the groundwater store at the start of the simulation and the fraction of the store released on a monthly basis to the lake were determined by calibration of these values to fit the simulated lake levels to the observed lake levels. In order to include the impact of deep-rooted afforestation on groundwater, the groundwater store was reduced by the transpiration simulated by the ACRU shallow groundwater model from the intermediate zone and capillary fringe, as shown schematically in Figure 3.

(v) The seepage from the lake through the dunes to sea was simulated using the differences in the hydraulic heads of

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the two water bodies and the hydraulic conductivity of the sand, as shown in (2).

$$Q_i = \frac{KL_s(h_i^2 - h_c^2)}{2L_p} \tag{2}$$

where:

Q_i = volume ($m^3 \times 10^6$) of ground water outflow to the sea in month = i

K = is the permeability of the medium (m/d)

L_s = is the length of the seepage face (m)

L_p = is the length of the flow path (m)

$h_i - h_c$ = head difference (m) between the lake stage and the sea surface above the impermeable cretaceous layer

Mean values for K in the study area have been reported to range from 4.30 to 5.00 m/d (Meyer and Godfrey, 1995; Jeffares & Green, 2012) and a value of K = 4.5 m/d was used in this study. The length of the seepage face (L_s) was assumed to be 12 km and the length of the flow path (L_p) was estimated to be 2.5 km. The depth of the impermeable cretaceous layer was estimated by Meyer et al. (2001) to be approx. 100 m and hence h_c = 100 m was used in this study.

The registered water abstractions with DWS, excluding forestry, were used as the $TS\_ABS_{(i)}$ values in (1). The abstractions used in the simulations increased from 0.5 ML/d in 1990 to 3.1 ML/d in 2004 and remained constant thereafter.

Impact of afforestation on hydrological responses: shallow groundwater model

The simulated impact of afforestation on surface runoff and deep drainage are shown in Figure 10 and Figure 11, respectively. Thus, for a known surface runoff simulated for natural vegetation, the surface runoff from an afforested area was estimated using the results shown in Figure 10. With the catchment 100% afforested, the shallow groundwater model simulates no deep drainage. Hence, the results in Figure 11 show the impact of increasing the area of deep-rooted forestry on recharge to the groundwater storage.

Afforested areas

Numerous sources of data were assessed to quantify the historical change in forestry within the catchment. Initially, the WARMS database (DWS, 2015) and the National Land Cover Database (Thompson, 1999) were used as they were the only available data. These two datasets yielded differing results, with WARMS reporting larger afforested areas of 142.58 km² when compared to the 85.64 km² from Thompson (1999). However, the different dates of the two datasets may explain some of the difference. Additional information was obtained from DWS on afforested areas and is included in Figure 12. The forestry area used in this study was derived using the following assumptions, which are based on the best current (though still limited) understanding of the history of afforestation in the area:

- Planting started in 1986 but only one ninth of the total area was planted per year.
- Harvesting started 9 years after planting, and thereafter there was an even spread of trees, age-wise, across the full planted area.
- In 1999 harvesting stopped and by 2007 all trees are large and the area under large trees stabilises at 115.9 km².

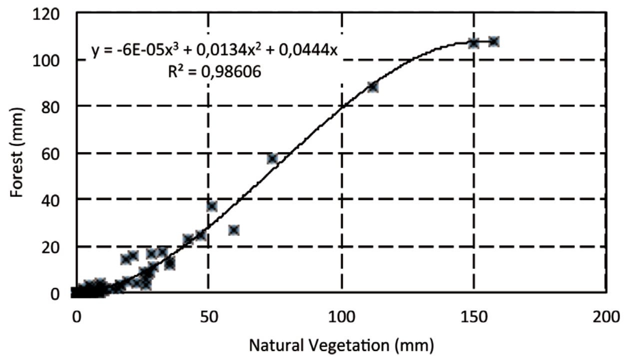

Figure 10
Simulated impact of forestry on monthly surface runoff

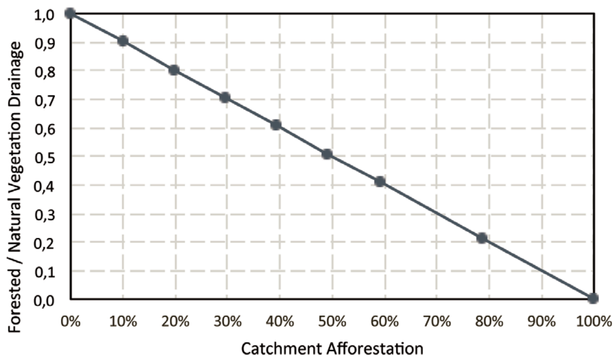

Figure 11
Simulated impact of forestry on deep drainage

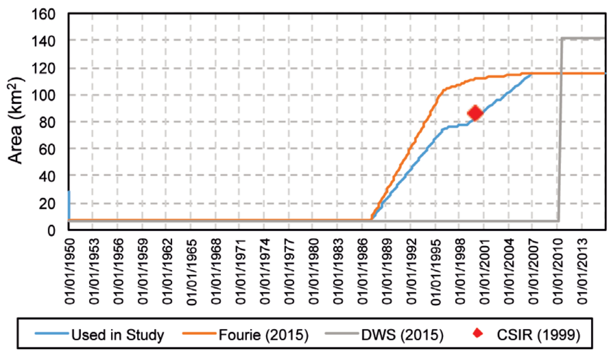

Figure 12
Area of forestry simulated

Yield determination

Traditionally water yield, or assured supply for a given level of risk, from a catchment in South Africa is determined from a water budget of annual failures, defined as any monthly failure within a year resulting in an annual failure. The disadvantage of using annual failures to determine catchment yield is that while a single monthly demand may not be met, there may be prolonged periods within the year where the demand is met. Thus, in this study the yield from the lake system was determined using the number of monthly failures of the system

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Figure 13
Graphical depiction of available water for abstraction using a desired lake level

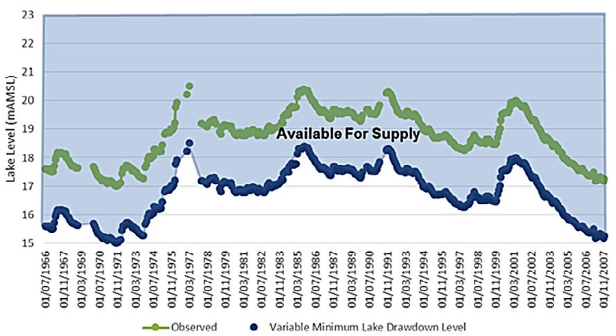

Figure 14
Graphical depiction of available water for abstraction for specified level of drawdown

to meet a demand, i.e., when the available monthly value did not meet the demand, with the required level of assurance calculated from the number of months with failure divided by the total number of months within the total simulated period.

Two approaches to determining system failure were used. In the first approach, the minimum desired level of the lake was set (e.g. 16 m amsl) and the additional abstractions above historical abstractions that can be made were determined such that the lake level was above the desired minimum level for the assured percentage of the time. For example, if the system was only allowed to fail 2% of the time, then 98% of the months should not have a lake level lower than the minimum desired level of the lake. The rationale behind this scenario was to allow for a minimum lake level for ecological purposes. This was included to prevent the system from being drawn down too far, which would reduce ecological habitat and could have significant environmental impacts. A graphical depiction of the lake storage available for yield in this scenario is shown in Figure 13.

In the second approach, the additional abstractions were determined such that the level of the lake does not decrease by more than a selected depth from the levels simulated for historical conditions. Thus, the lake was simulated for historical conditions with no additional abstractions and these simulated levels were used as a reference to determine the maximum drawdown level for each month, as depicted in Figure 14. The assured yield was then the volume abstracted such that the minimum level does not drop below the maximum drawdown allowed, i.e., the monthly lake levels must remain above the allowed drawdown from the reference level for the assured percentage of the time. For example, if the lake level is only allowed to drop 1.0 m below the reference level for 2% of the time, then the simulated level with the additional abstraction must remain above the maximum drawdown level for 98% of the time. The rationale behind this scenario was similar to the first approach; however, in this case, a varying requirement was imposed using historical lake levels as a reference. This was done as, without a detailed Reserve determination of the lake, the selection of a minimum acceptable lake level may not sufficiently account for the complexities of the system.

RESULTS

Lake model calibration

All simulations were started in January 1950 with the average lake level (i.e. 18.4 m) for the period for which lake levels have been observed (i.e. since 1966). Calibration of the spreadsheet-based Lake Water Budget Model was done by adjusting the initial groundwater store and groundwater store release coefficient in order to meet the following objective function as closely as possible:

(i) Minimise the differences in the simulated lake level and observed lake level for the period used in the calibration.
(ii) The simulated lake level should be equal to the observed level of 17.6 m amsl in July 1966 (start of the observed lake level record).

The calibration process was impacted by the large observed rainfall depth from October 1983 to September 1984 recorded at the rain gauge (0412180 W) selected for the lake catchment. A comparison of rainfall recorded at daily rain gauges within 50 km of the selected rain gauge was undertaken, as shown in Figure 15, which clearly indicates that the rainfall measured at Rain Gauge 0412180 W was significantly larger than the rainfall at the surrounding rain gauges, particularly for January 1984. Furthermore, a particularly large rainfall depth (2 668 mm) was recorded at Rain Gauge 0412180 W for the period from January 1984 to February 1985, and this period of the record may be of doubtful accuracy. It was, therefore, probable that the rainfall used in the lake water budget simulations may not be reliable for January 1984, and possibly not reliable up to February 1985. Thus, different periods were assessed in the calibration process in order to reduce the influence of these potentially erroneous rainfall data, and to include or exclude the impacts of afforestation and abstractions. The calibration parameters for the period from January 1986 to December 2014 were deemed to be the most representative for the available information and were used in the study. The simulations with afforestation levels shown in Figure 12, and the model calibrated for the period from January 1986 to December 2014, are shown in Figure 16. The impact of the large rainfall depth in January 1984 is also evident in the large over-simulation for the period from January 1984 to March 1984. In order to improve the comparison of the simulated and observed levels after the large potentially erroneous observed rainfall during 1984 and 1985, the simulated lake level was adjusted to the value of the observed level in October 1985, as shown in Figure 16.

The same calibration parameters were then used to simulate the lake level with no abstractions or afforestation, also shown

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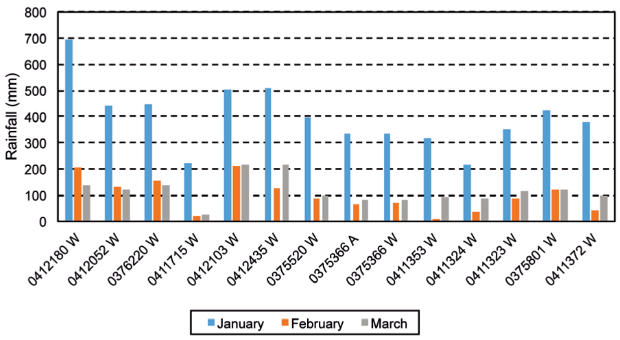

Figure 15
Comparison of rainfall for January to March 1984

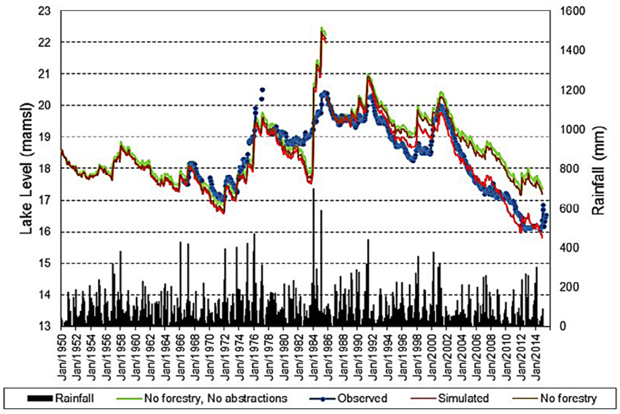

Figure 16
Observed and simulated lake levels calibrated for January 1986 to December 2014

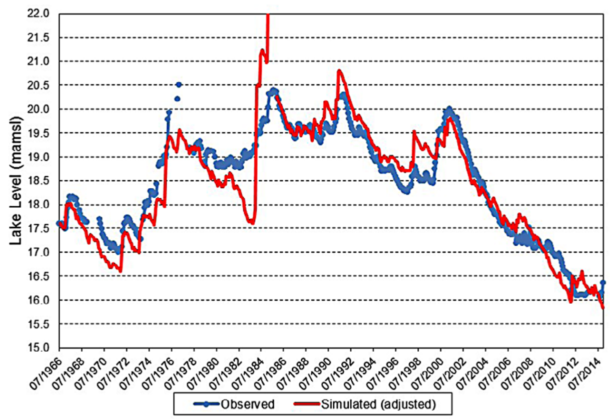

Figure 17
Simulated lake levels with minimum level = 16.0 m amsl exceeded in 98% of the months: historical catchment development

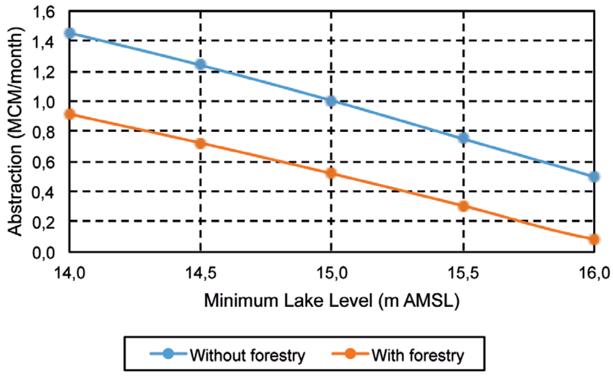

Figure 18
Maximum monthly abstractions for lake levels exceeded in 98% of months: Historical catchment development

in Figure 16. Given the limitations in the model, input data and information on abstractions, the results in Figure 17 are deemed to be the best simulation of the lake level with no anthropogenic influences. The results indicate that the abstractions simulated in the model had very little impact on the simulated lake levels. The increasing impact of afforestation development on the lake levels over the period simulated is evident in Figure 16, where afforestation is shown to reduce lake levels over the period by nearly 1.4 m.

Yield scenarios: historical development

The results of determining the assured yield for the two approaches used to determine system failure are presented in this section. Results for the historical forestry growth shown in Figure 12, and with no forestry, were simulated. The yield was initially simulated for historical developments in the catchment and for both the specified minimum lake level and maximum drawdown from reference level approaches.

Specified minimum lake level

With historical levels of afforestation and abstractions as input to the model, and for a specified minimum lake level of 16.0 m amsl and with a 98% assurance of supply, the maximum additional monthly abstraction that can be made is 0.085 $m^3 \times 10^6$ per month, which equates to approx. 2.8 ML/d. The results of the simulation are shown in Figure 17, which indicates that the failures occur between January 2012 and December 2014. The maximum monthly abstractions for varying minimum lake levels exceeded in 98% of the months are shown in Figure 18, which indicates that the impact of the afforestation is to reduce the yield by approximately 0.5 $m^3 \times 10^6$ per month.

Specified maximum drawdown

Reference lake levels were simulated with the historical levels of afforestation and abstractions. Additional abstractions were then simulated such that a user-specified drawdown

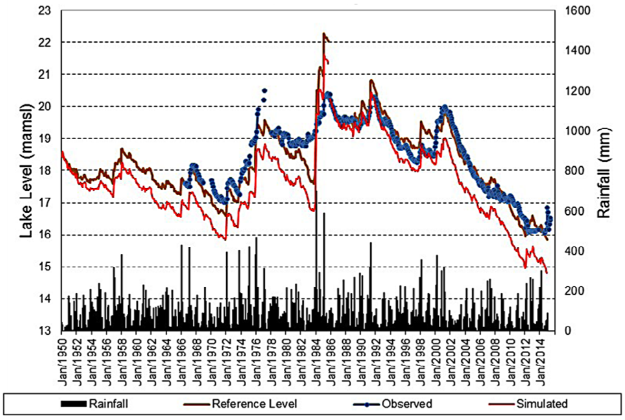

Figure 19
Lake levels for drawdown not exceeding 1.0 m from the reference level in 98% of months: historical catchment development

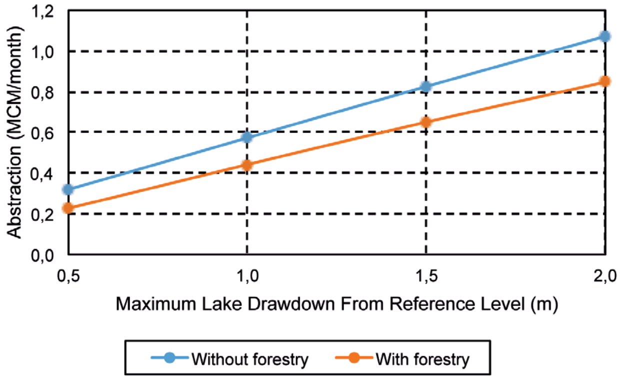

Figure 20
Maximum monthly abstractions for the maximum drawdown level not being exceeded in 98% of months: historical catchment development

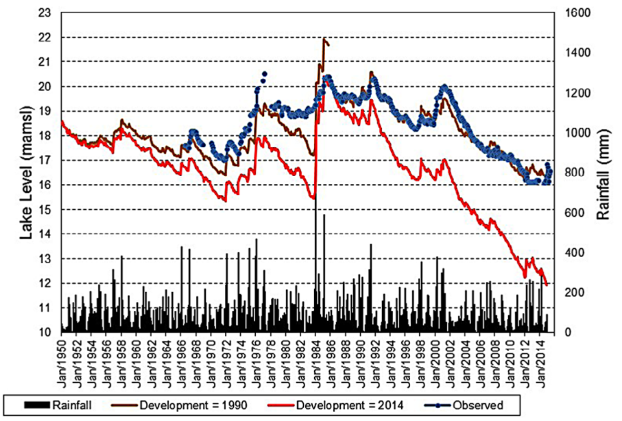

Figure 21
Simulated lake levels with afforestation and domestic abstractions fixed at 1990 and 2014 development levels

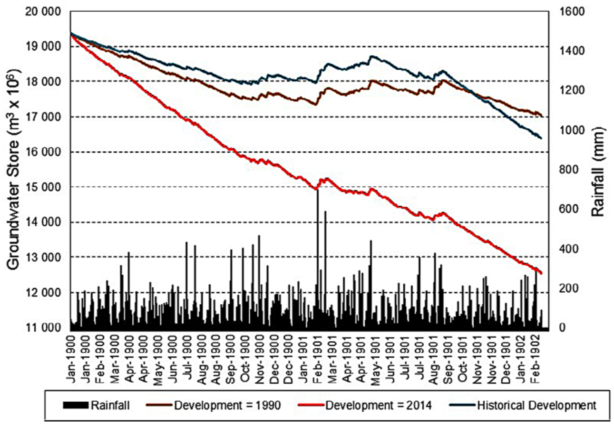

Figure 22
Simulated conceptual groundwater stores with afforestation and domestic abstractions as historical growth and fixed at 1990 and 2014 development levels

from the reference lake level was not exceeded in 98% of the months simulated. For example, Figure 19 shows the results of specifying a maximum drawdown level of 1.0 m from the reference lake levels. The maximum monthly abstractions for varying drawdown levels not exceeding the maximum specified drawdown in 98% of the months are shown in Figure 20, which indicates that the impact of afforestation is to reduce the yields by approximately 0.2 $m^3 \times 10^6$ per month.

Yield scenarios: fixed development

The results from simulating lake levels using the historical climate record with the area afforested and abstractions levels fixed at 1990 and 2014 values are shown in Figure 21. From Figure 21 it is evident that the 2014 level of development in the catchment is not sutainable for the historical climate and hence no sustainable additional yield is possible, based on the assumption that lake levels below 15 m would be environmentaly, socially and ecologically unacceptable.

Similarly, as shown in Figure 22, the conceptual groundwater store which releases groundwater into the lake (cf. $GW_{(i)}$ in (1), using the calibrated groundwater release coefficient, is relatively stable for the historical and 1990 development scenarios, but decreases over the simulated period for the fixed 2014 development scenario. Thus, based on the simulated results, the current levels of development are not sustainable and further scenarios should be simulated to explore strategies to return to a sustainable system.

Preliminary forestry: domestic abstractions ratios

Given the small impact that the domestic abstractions have on the lake levels relative to afforestation, as shown in Figure 16, simulations were performed with no afforestation in the catchment and with fixed levels of domestic abstractions ranging from 1 to 5 times the 2014 abstraction (1.13 MCM/yr) and the final lake level was noted. With no domestic abstractions simulated, the area of forestry was then increased from zero until the final lake level was the same level as for each of the domestic abstractions simulated. The results shown in Figure 23 indicate that the removal of approximately 5 km^2 of forestry is required to release 1 MCM/yr for domestic abstractions.

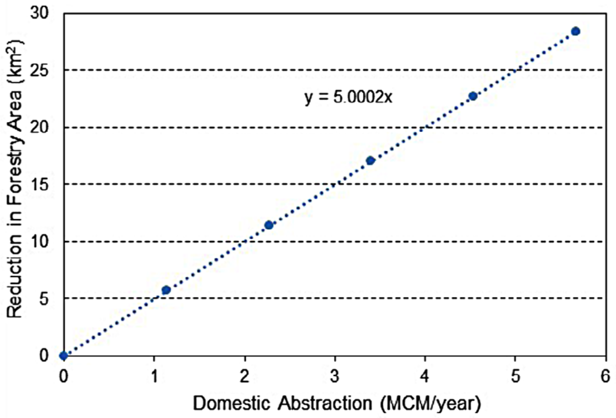

Figure 23
Reduction in forestry area required and increase in domestic abstraction to achieve the same final lake level

DISCUSSION AND RECOMMENDATIONS

Lake Sibhayi is one of the major features of the iSimangaliso Wetland Park conservation area, which has World Heritage Site status. It is South Africa's largest freshwater lake and when full it holds more water than can be stored in all three large dams on the uMngeni River. However, the lake is almost completely dependent on groundwater for recharge and the assessment of how much water can be abstracted from the lake on a sustainable basis is complex.

This study has been conducted in order to obtain a better understanding of Lake Sibhayi's hydrology, to establish the probable causes of the almost 4 m drop in the level of Lake Sibhayi between 2001 and 2014, to assess the impact of abstractions for domestic water consumption and commercial plantations on lake levels, and to establish what yield can be abstracted from Lake Sibhayi on a sustainable basis.

Although modelling the groundwater-driven catchment hydrology has been difficult, a good fit between observed and simulated lake levels was obtained for the period that is most relevant to the present day, i.e., 1986 to 2014. The simulation results indicate that approximately 35% of the drop in lake levels since 2001 can be attributed to the impact of afforestation, although it must be noted that there is some uncertainty regarding the exact history, extent and impact of afforestation in the catchment. In contrast, the results indicate that the impact of domestic abstractions on lake levels has been negligible.

The major cause of the drop in the level of Lake Sibhayi since 2001 is postulated to be the 10-year period of significantly lower than average rainfall which lasted from 2001 to 2011. The reduced rainfall over this period was significant and the plot of cumulative annual rainfall deviation from the MAP correlates very well with rising and falling lake levels over the 50-year period during which rainfall and lake level records have been kept.

A yield analysis of simulated results with historical developments in the catchment for the 65-year period of observed climate record indicates that domestic abstractions could be increased by 0.22×10^6 m^3 per month, which is a 233% increase on 2015 abstractions, without affecting lake levels by more than 0.5 from historical levels m in 98% of the months simulated. Similarly, domestic abstractions could be increased by 0.09×10^6 m^3 per month with historical developments simulated in the catchment, which is a 90% increase on 2015 abstractions, in order to maintain simulated lake levels of more than 16.0 m for 98% of the months simulated.

However, results from simulating lake levels using the historical climate record with the area afforested and abstractions levels fixed at 2014 levels indicate that no sustainable additional yield is possible with sustained decline in both the simulated lake levels and conceptual groundwater store, which would be environmentally, socially and ecologically unacceptable.

Preliminary simulated results indicate that the removal of approximately 5 km^2 of forestry is required to release 1 MCM/yr for domestic abstractions. However, these preliminary results require improved verification of input data and a review of the modelling to have more confidence in the results.

Given the ecological importance of the lake, the value of the water abstracted and the levels of uncertainty inherent in aspects of this study, further refinement and verification of the hydrological study is strongly recommended.

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