QUANTIFYING THE WATER-USE OF DOMINANT LAND USES IN THE MAPUTALAND COASTAL PLAIN

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WATER
RESEARCH
COMMISSION

TT 781/18

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Report to the

Water Research Commission

by

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March 2019

WRC Report No. TT 781/18

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ISBN 978-0-6392-0083-5

EXECUTIVE SUMMARY

BACKGROUND

It is widely accepted that the expansion of commercial forestry using fast growing alien tree species may have negative hydrological consequences. However, it is acknowledged that some alien plants are important contributors to the South African economy. In water-stressed catchments where there is a high demand for the expansion of commercial forestry (new licence applications) there is an urgent need for alternative land-use activities that will provide viable economic and resource outputs while simultaneously achieving an equitable balance in water resource demand. Along the Maputaland coastal plain, plantation forestry, agriculture (mixed cropping, livestock and fruit trees) and expanded human settlement have influenced the ground and surface water in the region. It is therefore important to understand how fast-growing plantation forestry species and natural forest expansion have changed the plant water-use when compared with the more naturally occurring wooded-grassland conditions.

Current models of plantation forestry in Maputaland incorporate water intensive closed stand plantations based on large scale production or smaller community owned woodlots. Less water intensive land-uses derived from agroforestry systems, might include growing plantation species at different row spacings (row cropping), silvo-pasture systems (mixed indigenous species and livestock combinations) or cultivation of indigenous medicinal species. To implement such systems, it is important to understand the key drivers influencing the ecology of natural vegetation in the region and quantify the water-use of characteristic land-use types. We therefore asked the following questions:

1. What was the water-use impact for different land-uses (vegetation types) on the Maputaland Coastal plain?
2. What was the water-use of potential agroforestry species on the Maputaland coastal plain?
3. Could the existing hydrological models aid in the assessment of the agroforestry impact on the aquatic environment?
4. What was the reliability of these models to simulate the impacts of the various species and combination of species under different agroforestry models in Maputaland?

In this study the ModFlow regional groundwater model and SWAT surface water model were used and evaluated as a tool to study the impact of vegetation systems and species on the groundwater dynamics. The models were used to predict the impact of various agroforestry systems on shallow aquifers and dependent aquatic environments in primary aquifers. The research into the groundwater flows was used to clarify the understanding of the geohydrology in this region and contribute to the broader knowledge and management of environmental resources such as the health of Lakes Sibaya, Mgobezeleni, Shazibe, Bhangazi North and the Kosi Lake which are an important component of the iSimangaliso Wetland Park.

AIM and OBJECTIVES

The aim of the study was to understand and quantify the water-use of different agricultural and ecological land-use components of the Maputaland Coastal Plain. These could potentially be developed into an integrated, multiple-use agroforestry system(s), as an alternative to commercial plantation forestry in water stressed catchments.

The objectives of the project were to:

1. Understand with accuracy the water-use of plantation forestry and indigenous species within a commercial, community woodlot and mixed plantation or agroforestry environment in Maputaland.
2. Understand the ecological pattern and water-use of natural vegetation systems that could be incorporated in agroforestry systems in Maputaland.

3. Develop and evaluate groundwater models of the Maputaland Coastal Aquifer to determine the impacts of land-use in context to plantation forestry, natural vegetation systems and a mixed plantation environment.

METHODS

Study sites and species selection.

The Maputaland Coastal Belt has been identified as an important area due to severe water shortages, social and environmental sensitivities, compounded by a lack of knowledge in both ecological and hydrological fields. This is a groundwater driven site that has changed drastically over the last decade with changing land-use.

The main study area was the Manzengwenya plantation north of Lake Sibaya in Maputaland. Vasi Pan which is surrounded by the Manzengwenya plantation, is one of the few peat land areas in the country and potentially holds a high level of biodiversity. It was therefore possible to study the effects of plantation forestry on the Maputaland coastal aquifer, the water-use of plantation trees in commercial and community areas, indigenous forest expansion and community resource use.

To investigate the water-use and ecological pattern of natural vegetation (objective 1 and 2), suitable examples of indigenous forest patches and forest expansion areas were selected.

Ecological suitability

The forest sites chosen for measuring forest ecological processes fulfilled the following criteria:

i) That the forest patches were well distributed across the plantation
ii) That forest patches had a canopy cover of greater than 80 %
iii) That forest expansion sites were in proximity to forest patches
iv) That forest expansion sites were not recently damaged by fire or ongoing timber management activities.

A key focus was to characterise typical hydrological areas in the Vasi landscape through links with moisture regime, landscape position and natural vegetation cover. Observations showed that hygrophilous grasslands were the most productive areas as they contained fertile soil types, were proximate to ground water and supported palatable grass species.

In Manzengwenya plantation, selection of historical localities of these grasslands enabled resource diversification from single crop plantation agriculture to mixed species tree-grass communities suitable for both trees and livestock to be assessed.

Hydrological suitability

To understand the water-use of plantation species within a community woodlot (objective 1), a well-managed woodlot was selected in the adjacent rural area to Manzengwenya in consultation with the Siphesihle Bukhosini Science Centre.

Pine (*Pinus elliottii*) was planted in the surrounding Manzengwenya plantations in the early 1950s. These plantations were subsequently planted to *Eucalyptus.* The surrounding natural areas are covered by a mixture of densely forested areas, interspersed dry grasslands (dominantly palm veld), hygrophilous grasslands and thicket.

Manzengwenya was suitable to meet the hydrological objectives of this study as:

- It had both indigenous and commercial tree species that could be measured for the water-use component;
- It had many different land-uses near one another that would allow for various agroforestry systems to be studied;
- It was an ideal site to develop and test groundwater models, due to the vegetation and the community largely depending on this water resource; and
- It is an important area in terms of social aspects (government interest) as well as hydrological and ecological importance.

Five sites were selected for the long-term monitoring of individual tree sap flow (the volume of sap flowing through a stem per unit of time). The selection of species for this project was motivated by a combination of expert advice, gaps in research areas and from various site visits where common and/or important species were identified within the selected site. Distance from wetlands and groundwater resources were also considered in the selection of groups of species. The selected sites consisted of a range of dominant land uses in the area.

Ecological Sampling of Vegetation Types

The aim of the ecological component of the study was to identify patterns in plant ecological, plant resource and plant water-use relationships that could be incorporated in agroforestry systems in Maputaland.

The composition of natural forest patches were sampled along transects representing a forest chronosequence from the oldest, least disturbed, through to the youngest stands at the forest edge. Sixty forest plots were sampled along 15 transects from three forest patches within the study area.

In the plantation interior, two types of stands were stratified, those containing a dense stand forest regeneration and those with none. Fifteen sites were selected: eight in two pine stands and seven in three eucalypt stands. A paired-sample approach eliminated the effect of site differences.

In the forest edge expansion study, mature and regrowth forest was classified according to indicator species. Importance values were calculated as the mean value between the percentage basal area and percentage stem density of each species per vegetation type.

Grasslands were sampled along a series of dune ridge and interdune depressions in community rangelands at KwaZibi and MvelaBusha, and at Manzengwenya plantation. Five naturally occurring grassland types were identified: Ephemeral wetland depression grasslands, hygrophilous grassland, geo-suffrutex woody grassland, secondary grassland and dune-ridge grassland. Veld condition and grazing capacity for each grassland type was calculated.

Hydrometeorological Studies

The project conducted intensive measurements of individual tree water-use using heat energy balance techniques (Heat Pulse velocity (HPV) and Dynagage) and eddy covariance (EC) techniques. Weather variables, soil water dynamics as well as modelling the potential impact of the plantation forestry and possible agroforestry options was achieved using the SWAT and ModFlow hydrological catchment models. The research focussed on the priority individual indigenous tree species and plantation trees species within the Manzengwenya plantations and Vasi Pan area.

RESULTS

Ecological

Natural forest expansion

- Forest edge expansion

Patterns of variance in species importance across vegetation types was found to occur in dominant and also less important species. Five species namely, *Hymenocardia ulmoides*, *Sclerocroton integerrimus, Albizia adianthifolia, Brachylaena discolor* and *Apodytes dimidiata* were the most common species involved in forest expansion. The absence of well-known forest species from secondary vegetation such as *Schrebera alata*, highlighted which species would not typically be expected in the plantation environment.

- Ecological preferences of indigenous species suitable for agroforestry practices

Species importance value (IVs) were used as an indicator of preference towards either woodland or plantation growing conditions. Forest species that favoured plantation over woodland conditions, were *Hymenocardia ulmoides*, *Albizia adianthifolia* and *Brachylaena discolor*. Another abundant species, *Sclerocroton integerrimus*, had greater IVs in woodland than in plantations or regrowth forest. This indicated the species was a forest pioneer but also tolerant to the fire-regime experienced in woodland. Fire-tolerant savanna species such as *Strychnos spinosa* and *Sclerocarya birrea* were shown to have greater IVs in woodland than in plantations. *Strychnos spinosa, Sclerocarya birrea, Hyphaene coriaceae*, *Vangueria infausta* and *Trichilia emetica* were considered to be disturbance resilient species and suited to open-canopy woodland conditions. These species could be tested in silvopasture agroforestry systems that combine a moderate density of multi-functional trees with pasture for livestock production.

- Forest expansion into the plantation interior

Densely stratified plantation stands contained 3400 ±1630 sapling stems ha^{-1} compared with sparse stands which were found to average 240 ±280 stems ha^{-1}. The species richness for combined dense and sparse stands was 85 species, most of them were herbaceous; 27 woody indigenous species were encountered. The most frequent woody species was *Sclerocroton integerrimus*, contributing towards 73 and 60 percent of the dense eucalyptus and pine stands, respectively.

Environmental differences between the sparse and dense regeneration were examined through variables of stems ha^{-1}, leaf area index (LAI), soil moisture and soil carbon. Eucalyptus and pine over-story trees averaged 720 stems ha^{-1} and did not differ between the sparse and densely sampled forest regeneration plots. Neither did leaf area index, soil moisture and percentage carbon of the upper 10 cm of topsoil. This indicated that stand conditions did not affect whether plantation stands acted as nucleation sites for forest expansion.

Redundancy analysis (RDA) produced an ordination summarising the main patterns of variation of species response explained by variables of stems ha^{-1}, LAI, soil moisture and soil carbon. Plots with increasing LAI tended to be plots with the greatest forest nucleation. Stems ha^{-1}, soil moisture and soil carbon did not appear to have influenced natural forest regeneration. This suggested other non-measured variables such as distance to seed source or biological dispersal influences were responsible for the spatial location of forest clusters. However, forest clusters had similar dominant species (i.e. *Sclerocroton integerrimus*, *Hymenocardia ulmoides* and *Albizia adianthifolia*), and a similar ratio of compositional dominance (i.e. 20 % of species accounting for 80% of abundance) with forest-edge plots. This suggested that once nucleation processes were initiated, they would follow similar compositional patterns to forest-edges. The implications of these results are that manipulation of environmental variables such as stand density, might not necessarily promote natural forest nucleation in stands of planted alien species.

Forest resources

The most common plant products in all four vegetation types were classed as medicinal and construction use, while the least common use-class was fibre. The most common environmental use-class was restoration followed by fodder, the least common was intercrop. Use-classes with median values were fuel, crafts and microclimate.

The species with the greatest number of use-classes was *Sclerocarya birrea* and *Albizia adianthifolia* (n = 10 uses), this was followed by *Dichrostachys cinerea* (n = 9 uses) *Trichilia emetica* (n = 8 uses) and *Dalbergia obovata* (n = 8 uses).

The role that native plants contribute to human health in rural South Africa relates to both medicinal and nutritional aspects. The most frequently cited plant-use from species in secondary vegetation was medicinal plants.

Three alcoholic beverage making species were common. The fruit of *Sclerocarya birrea* is brewed for beer (ubuganu), while a beer product is brewed from the carbohydrate rich sap or ubuSulu of palms *Hyphaene coriacea* and *Phoenix reclinata*. Trees used for traditional crafts generally exhibited high wood density and grain distance.

The environmental use-classes in this study refer to biophysical services that native species could contribute towards improving land productivity. Nutrient poor and acidic sandy soil conditions are a limiting factor for agricultural productivity in Maputaland and therefore the environmental services provided by selected species could be used to optimise agroforestry practices in small-holder or larger agricultural enterprises. Some examples of species cited for agroforestry practices include: *Albizia adianthifolia* for N-fixation and shade, *Commiphora* sp. for living fencing or *Grewia caffra* for browsing.

From an economic perspective the species that appeared to have the greatest commercial potential were savanna species which ecologically supports the argument for their cultivation and/or domestication in association with silvopasture agroforestry systems. Livestock derived income opportunities related to silvopasture could complement the resources available from these tree products.

Veld condition and estimated grazing potential

Grasslands were found to have veld conditions that ranged between 46 and 83 percent. Dune crests had the greatest veld condition score (83 %), followed by hygrophilous grassland (78%), wetland depressions (74 %), secondary grassland (59 %) and geo-Suffrutex grassland (46 %). The grass species that contributed towards the greatest ecological value in dune ridge and hygrophilous grassland was *Themeda triandra*. Wetland depressions and hygrophilous grassland also contained a number of palatable lawn grasses which additionally contributed towards good veld condition scores. These species included, *Acroceras macrum, Digitaria diversinervis* and *Hemarthria altissima*. Geo-suffrutex grassland had the lowest veld condition score, owing to the frequency of shrubs in this grassland type.

The findings from the veld condition assessments showed that, at mean annual rainfall, grasslands had a grazing capacity of between 0.35 and 0.39 LSU per ha^{-1}. Grasslands with the greatest veld condition score and therefore grazing capacity were dune ridge and hygophilous grassland.

Hydro-meteorological Studies

Climate

Meteorological

The mean long-term annual precipitation at Vasi Pan was 926 mm. The area has a distinct dry and wet season. The frequency and size of rainfall events decreased from February, with very little rain falling in the winter period (June to August) during the study period. There were seasonal differences in solar radiation, with a summer peak of 604 MJ in January 2017 and a winter peak of 420 MJ in August 2016. Summer temperatures were hot, with air temperatures exceeding 30 °C, while winters were mild, with maximum temperatures averaging 25.6 °C. The average daily minimum temperatures were 22.4 °C in summer and 14.7 °C in winter. The average monthly daytime vapour pressure deficit (VPD) was low (0.84 kPa), which indicated a low atmospheric evaporative demand, indicative of the humid subtropical climate.

Sap-Flux Density Measurements

Sap-flux density was measured within the dominant land-use types around Manzengwenya. These included indigenous forest, commercial pine, pine that had invaded natural forest, a eucalyptus woodlot and young commercial eucalyptus trees that had been planted within the wetland edge.

Sap flow data for the indigenous forest site were recorded from late July 2016 to early August 2017. The duikerberry (*Sclerocroton integerrimus*) had the highest mean daily water-use (8.76 $L.day^{-1}$); then the white-pear (*Apodytes dimidiata*) (7.75 $L.day^{-1}$) and flat crown (*Albizia adianthifolia*) (6.22 $L.day^{-1}$). The indigenous trees are semi-deciduous, accounting for the low daily water use of ~2 $L.day^{-1}$ in winter. Peak water-use occurred during summer (December 2016), when daily water-use reached a maximum of 15.31 $L.day^{-1}$.

The monthly water-use of the trees varied seasonally, with more water being used in the wet summer months than in the dry winter months. The large eucalyptus trees used the most water per month in March 2017 (735.11 L), while the indigenous trees used the least water per month in July 2016 (46.71 L). In summer, the average daily water used was highest for the small eucalyptus trees (19.24 $L.day^{-1}$) and lowest for indigenous trees (10.02 $L.day^{-1}$). The large and small eucalyptus trees used substantially more water per day (~ 8 $L.day^{-1}$) than the pine and indigenous trees. In winter, all the tree species monitored used significantly less water per day than in summer. The average daily water used was highest for the small eucalyptus trees (7.95 $L.day^{-1}$), and lowest for the invasive pine trees (4.67 $L.day^{-1}$) in winter. The average daily water uses were similar for the commercial and invasive pine sites, the indigenous forest site, and the large eucalyptus site. However, at the small eucalyptus site, the trees used ~ 3 L.day^{-1} more water than the trees at the other sites in winter. The average daily water use of the large and small eucalyptus trees was similar in summer, with a difference of only 1.2 L.day^{-1}. However, throughout the winter, the difference in their average daily water-use was far greater (3.17 L.day^{-1}), with the small eucalyptus using more water. This difference in daily water-use was because the transpiration rate of the large eucalyptus trees was water-limited, while the small eucalyptus trees were energy-limited. The small eucalyptus trees were planted on the fringe of the Vasi North wetland, where the groundwater table was shallow, and the trees could easily access the water during times of low rainfall. The large eucalyptus trees were planted on dry grasslands and the groundwater table was deeper, therefore the large eucalyptus trees were reliant on rainfall as their main source of water.

<u>Eddy Covariance Measurements</u>

Commercial pine stands were identified as a dominant land use in the Vasi area and a 12-year-old stand was identified for monitoring sap flow and actual evaporation (Eta) using the eddy covariance (EC) technique. During the dry winter period of 2017 (June to mid-Aug), ETa peaked in late July (2.14 mm.day^{-1}) and, during this period, the average ETa was low (1.07 mm.day^{-1}) indicating that the trees were conservative water users in winter, despite the presence of a shallow groundwater table.

The ETa from the indigenous forest was monitored from the wet period in February 2017 to the dry period of July 2017.The daily ETa steadily decreased over the monitoring period, with a maximum ETa of 3.7 mm.day^{-1} occurring in February 2017. The average ETa showed distinct seasonal decreases, as the radiation and rainfall decreased from February to March (2.57 mm.day^{-1}), April to May (1.51 mm.day^{-1}) and June to July (1.02 mm.day^{-1}). From June to July 2017, simultaneous measurements of ETa were taken in the indigenous forest and the commercial pine stand. The average daily water-use for the commercial pine stand (1.54 mm.day^{-1}) was higher than the average recorded for the indigenous forest (1.02 mm. day^{-1}), however both forest types were considered conservative water users in winter.

The sap flow and EC data provided an indication of the seasonal water-use of the selected species and comparisons with simultaneous weather data has helped to highlight the relative influence of climatic conditions on the daily sap flow.

The water-use of the pine trees (*Pinus elliottii*) varied seasonally, with the pine trees using less water in the dry season. The timing of the decline in water use, the rapid recovery after significant rainfall, and the presence of a relatively shallow groundwater table, inferred that the water use of the pine trees was dependant on the available water from rain. The pine trees growing in the Vasi Pan area are isohydric, as the latent energy (LE) peaked at 10 am in winter before maximum net radiation and air temperatures were reached, indicating stomatal closure.

Water levels of the nearby Lake Sibhya have dropped by almost 4 m from 2001 to 2010. Apart from the small eucalyptus trees planted on the edge of Vasi Pan North, the results showed that the water-use of the other trees monitored were limited by water availability, suggesting that their roots were not in contact with the groundwater table.

<u>Cosmic Ray Rover (CRR)</u>

CRR survey maps of the hydro-sense soil water measurements demonstrated the inverse relationship between soil water and neutron intensity at the three sites (hygrophilous grassland, commercial eucalyptus and commercial pine. The CRR soil water maps correlated well with the hydro-sense soil water patterns. The CRR discriminated high soil water areas very well. The CRR and hydro-sense maps, when compared to the landcover image, showed that areas of high soil water corresponded to the areas of thicket vegetation.

Modelling

Soil Water Assessment Tool (SWAT)

<u>Initial model simulation and calibration</u>

Initial simulations were undertaken to test the suitability of the SWAT model. The annual water balance showed that a high proportion of water percolated to the shallow aquifer with approximately half of the remainder reaching the deep confined aquifer. A large amount of the water balance was partitioned to total evaporation (669 mm). The streamflow component (surface runoff, lateral flow and return flow) totalled 117 mm. The results showed that calibration is required for the streamflow component and the importance of quantifying the linkage between the surface water and groundwater components was recognised. Through calibration a significant improvement of the simulation from R^2 0.49 to 0.69 was achieved and the SWAT model was considered suitable for scenario modelling.

Scenario testing

The spatial distribution of total evaporation (ET), soil water content and groundwater recharge between the three scenarios (baseline, baseline with 500 m buffer and baseline plus agroforesty) showed that ET was highly variable both within and between land-use types. This was largely due to changes in soil, depth to water table and management. Plantations in the lower lying areas (near or within wetlands) had the highest ET. The spatial distribution of ET at Vasi Pan showed that the commercial forestry areas were the dominant water-users in the catchment. The annual summary showed that *E. grandis* had a high ET (799 mm) with the indigenous forest (582 mm) and the grassland (519 mm) using significantly less water. The use of the Sequential Uncertainty Fitting (SUFI-2) algorithm within the SWAT-CUP programme in this study allowed for the auto-calibration of the SWAT model. The availability of detailed observed streamflow and ET datasets allowed for an assessment of the objective function for a multi-variable calibration.

MODFLOW

The model code selected for evaluating the interaction between the surface-water and groundwater resources is the industry standard MODFLOW from the USGS.

The Vasi Pan focus area lies on a groundwater ridge between the Malangeni drainage system to the north and the Lake Sibaya groundwater catchment in the south. The main purpose of using MODFLOW was to evaluate its potential to predict the downstream impacts of land use changes on the receiving water resources, mainly the groundwater storage. The principle land use types were exotic plantations, mainly Pine and Eucalyptus species, and areas of indigenous grasslands and indigenous forest.

Water table fluctuations and depth to the water table

One of the main factors that distinguish plantations with high water consumption from other species is their ability to mine water at greater depths. In water stressed environments such as Vasi Pan, this can cause severe impacts on the local water resources. The impact will be increased when the plantations can lower the water table below the rooting depth of the natural vegetation.

Results of the simulated evaporation from the groundwater showed the variable abstraction rate by the different vegetation species when the depth to the water table varied due to topographical features. For example, to the east of Vasi Pan, the plantations showed similar abstraction gradients to the depth of the water table.

Model Application

The aim was to investigate various alternatives to monocultures in the water stressed environment near Vasi Pan, with reference to plantations. Since these plantations are considered Stream Flow Reduction Activities (SFRA) and licensed accordingly, the alternative options are based on scenarios relative to the existing conditions.

- ***Scenario 1:*** Removal of all the exotic plantations.

The water table was predicted to rise by over 2 m from existing conditions.

- ***Scenario 2***: Percentage reduction of area under plantations

In this scenario the impact of reducing the area under plantations by replacing the total area with strip cropping was equivalent to a 50% reduction of water-use in the plantation area.

Aquifer Drawdown

The different land use scenarios described above showed a significant change in the water table elevation around Vasi Pan during the simulation period from 2010-2017. The 100 m and 300 m plantation bands were equivalent to a reduction in the plantation's area (assuming the same tree density) of 50% but the impact on the groundwater levels was significantly different. This was ascribed to the difference in the alternate land use applied in the strip between the plantations.

The Sihle monitoring borehole lies to the north of Vasi Pan and the Manzengwenya Plantations. A regional assessment was conducted by plotting the cumulative difference between the simulated water table profiles for the current land use (exotic plantations) and natural vegetation models. The model indicated a cumulative drawdown in the main sections of the Manzengwenya Plantations that can exceed 15 m over the full simulation period.

Stream Flow Reduction

The various scenarios all indicated various levels of stream flow reduction on the Malangeni River due to the different land use options. However, the magnitude of this impact was due primarily to the new wood-lots that have been planted in the Malangeni Catchment.

POTENTIAL SILVOPASTURE SYSTEMS FOR THE MAPUTALAND COASTAL PLAIN

Native species silvopasture

Indigenous silvopasture tree products can be specifically grown for timber, pulp, fruit, nut products or fodder. Natural systems have a greater diversity of tree species than planted systems, and therefore offer a greater variation of indigenous knowledge products. In this regard there are several useful indigenous trees species that could potentially be incorporated into semi-natural or natural silvopasture systems in Maputaland. One of these species is a highly traded medicinal tree, *Warburgia salutaris* while *Sclerocarya birrea* (marula) was another obvious candidate for silvopasture in Maputaland as they grow naturally in disturbed areas, they are deciduous (and therefore do not utilise water resource in the dry season), are fire-tolerant and provide both cultural and commercial value through their fruit and seed products. Indigenous species based silvopasture systems provide many options for genus exchange initiatives which have been proposed at Manzengwenya, being on the account that they utilise less water and are grown in less dense planting arrangements that current plantation methods.

Plantation species silvopasture

Silvopasture systems grown for pulp or timber are a commercially viable land-use option. A suggested integrated method was to rotate livestock during intermediate years of stand development (i.e. during the second, third and fourth years of the cropping cycle). In this way there would be adequate light to for forage production and the trees would be large enough to sustain damage from livestock. This is an area that requires future research.

Livestock and fodder

Livestock management in silvopasture is not well quantified in the literature. Animal production depends on forage availability which is often influenced by the chronology of the tree component, rainfall and soil variables. During sampling, estimated forage mass for each grassland ranged between 3.1 and 9.4 tons ha^{-1}. Veld condition scores of secondary grassland showed that after disturbances by plantation forestry, there were sufficiently available palatable grass species and grass biomass to provide forage for livestock. Lawn grass and tufted grass species that were sampled in secondary grassland which would likely be suitable for silvopasture systems were: *Digitaria diversinervis*, *Panicum maximum, Brachiaria brizantha, Brachiaria arrecta, Cynodon dactylon* and *Digitaria eriantha.*

DISCUSSION AND CONCLUSION

The general aim of this study was to understand and quantify the water-use of different agricultural and ecological land-use components of the Maputaland Coastal Plain. The results can be used to develop integrated, multiple-use agroforestry system(s), as an alternative to commercial plantation forestry in water stressed catchments.

Ecology and Agroforestry

The study found that woody species (mostly forest pioneers) had benefited through changes in fire patterns and disturbance regime brought about through plantation forestry. A similar composition of plant species was observed growing within the sub-canopy of plantation stands (on both forest edges and within central plantation areas), whereas within slightly fire-exposed secondary grassland (which was in clear-felled plantation areas) species composition tended to reflect savanna conditions. The differences in the compositional variation between these vegetation types reflected the relative influence of the environmental conditions between shaded understory and exposed clear-felled land providing an ecological screening mechanism for identifying which indigenous species would be suited to integration with different agroforestry systems, as it highlighted which species were fast growing and easily available, but also which species preferred slightly fire-exposed grassland conditions over shaded forest conditions.

A review of plant use found 193 uses for the 29 woody plant species that occurred in secondary vegetation. The results demonstrated the diversity of plant products and environmental services that were potentially available through forest expansion. The occurrence of five woodland species with commercial development potential namely, *Sclerocarya birrea, Trichilia emetica, Vangueria infausta, Hyphaene coriaceae* and *Strychnos spinosa*, pointed towards the use or development of these species in cultivated silvopasture systems.

The drier, elevated grassland on dune crests had greater gazing potential than lower lying hygrophilous grasslands, however the hygrophilous and wetland depression grasslands would continue to be productive throughout the dry season on account of the greater plant available moisture and soil organic carbon. In areas with a mean annual precipitation of about 1000 mm, the grazing capacity was estimated to be between 0.31 - 0.39 LSU ha^{-1}.

Individual Tree Water-use

The average daily water-use, for all the tree species monitored, was higher in summer than in winter. In summer, the average daily water-use was highest for the small eucalyptus trees (19.24 $L.day^{-1}$) and lowest for indigenous trees (10.02 $L.day^{-1}$). The large and small eucalyptus trees used substantially more water per day (~ 8 $L.day^{-1}$) than the pine and indigenous trees. In winter, the average daily water-use was highest for the small eucalyptus trees (7.95 $L.day^{-1}$), and lowest for the invasive pine trees (4.67 $L.day^{-1}$). The average daily water-uses were similar for the commercial and invasive pine sites, the indigenous forest site, and the large eucalyptus site (Table 6.9).

It was concluded from the long-term HPV results, that tree water-use was affected by climatic variables and soil water retention properties. The VPD in the area was low throughout the year, due to the proximity of the site to the coast. This affected transpiration rates as there was little atmospheric demand to drive transpiration. The sandy soils present at the sites had low water retention properties and therefore, held little water in the soil water profile and drained quickly after rainfall events. During the wet summer months, when the water supply was not limited, the transpiration rates were affected by solar radiation, and on cloudy days, transpiration rates decreased for all species. In the dry winter months, the water-use of the large eucalyptus and pine trees was limited by water availability, indicating that trees close their stomata during extended dry periods to maintain a relatively constant leaf water potential to survive (Klien *et al*., 2011; Lagergren and Lindroth, 2002). The water-use of the indigenous trees was seasonal, as they are semi-deciduous and reduce their water-use with the onset of the dry season. The small eucalyptus site was energy-limited and transpiration rates decreased in response to a decrease in solar radiation. The small eucalyptus trees were planted on the edge of the Vasi Pan North wetland, where the groundwater is shallow. Therefore, it was concluded that the small eucalyptus trees were potentially accessing water from the groundwater table. To assist in verifying these results, soil water content probes need to be placed at the site to determine the interaction between tree water-use and soil water content and addition information from the installation of boreholes would be beneficial.

Landscape Total Evaporation

The ETa measured in the indigenous forest site, using the EC system, indicated that the indigenous forest's water-use followed the same seasonal trend as found in the HPV data, with ETa peaking in the wet summer and decreasing with the onset of the dry season.

In conclusion, the water-use of the tree species that were monitored in this study was low, in comparison to previous studies in South Africa. The daily water-use of the trees was limited by water availability, except for the small eucalyptus stand, which was energy-limited. From this study, it was clear that the placement of plantations, in relation to groundwater levels, is critical for forestry management in the area, as this can determine whether the trees will be energy- or water-limited. Further research is needed to determine whether the small eucalyptus trees are accessing water from deeper in the soil water profile during the dry season.

Soil Water

The use of the cosmic ray rover to map soil water is a promising technique, as the soil water maps produced by the cosmic ray rover correlated well with the soil water maps produced with the hydro-sense data. Overall, the spatial patterns were adequately captured and the cosmic ray rover could identify changes in soil water over the landscape and effectively illustrate the soil water gradients over the three different land uses.

Surface Water Modelling

The SWAT model provided useful results for detailed time series data and spatially explicit data and demonstrated that gains in daily water yield of up to 50% are possible through careful land-use management.

Groundwater Modelling

The MODFLOW simulations showed a significant downstream impact on the water resources due to the expansion of deep-rooted vegetation with high transpiration rates. The model also indicated that the consolidation of these plantations (i.e spatial density) is a contributing factor to the magnitude of the downstream impact.

Silvopasture Opportunities for the Maputaland Coastal Plain

There are opportunities for silvopasture systems at Manzengwenya to function as an income generating buffer around important wetland areas such as Vasi Pan. This would suit former hygrophilous grasslands or dune ridges, using a natural-silvopasture approach with a known economic tree species (i.e. *Sclerocarya birrea*) and, indigenous grasses, browse species and livestock. The development of such an arrangement would use less ground water resources when compared with eucalyptus plantations, while also diversifying income and skills development through livestock management. It is recommended that a eucalyptus or pine based silvopasture system would be more economically realistic in the short term, and warrants testing. These systems should use less water than current plantation systems and provide an economic return through timber, pulp or livestock products. In addition, ecological but also economically active buffer-zones, that provide biodiversity refuges and mitigate biophysical stress, were also proposed. This information provided a basis for a theoretical framework based on the findings related to plant water-use, grassland and forest dynamics. A conceptualisation of a silvopasture framework that could be applied to the hydrologically sensitive areas at Maznengwenya plantation or other similar areas on the Maputaland coastal plain was developed. The framework follows concentric contours of landuse, ranked by potential water-use and distance from nucleated wetland. Core wetland areas such as Vasi pan form the nucleation of the framework. No trees are planted in this central core area, but it would function as a productive pasture for livestock at an estimated stocking density of 0.8 LSU ha^{-1}. Natural silvopasture systems, would form a primary buffer around the wetland. This area could be planted at densities between 100 and 500 stems ha^{-1} with an economically suitable species such as marula, and stocked at between 0.3 – 0.4 LSU ha^{-1} to conceivably produce 2-3 tons of forage ha^{-1} y^{-1}. Plantation based silvopasture would form a secondary land-use buffer around the nucleation wetland and natural silvopasture systems. This could be planted with eucalypts or pine cultivars at a density between 600 – 800 stems ha^{-1}, stocked between 0.2 – 0.3 LSU ha^{-1} and would produce an estimated dry weight forage of 2 tons ha^{-1} y^{-1}. Commercial plantations would be suited to areas furthest from the wetland nucleation area. Commercial plantations are usually planted at 1000 – 1200 trees ha^{-1}. They could be stocked with cattle rotationally between years two and five and thereafter years nine and twelve. Existing natural forest areas would remain as conservation refuges, that conserve genetic diversity of natural forest species, function as a sustainable reservoir for medicinal and cultural products, and act as a seed source for nucleation or edge expansion processes, thereby gradually increasing diversity within natural and semi-natural silvopasture areas.

RECOMMENDATIONS FOR FUTURE RESEARCH

Future ecological studies of this nature should also look at light and nutrient dynamics for forest rehabilitation. The impact of browsers and grazers on the impacts of seedling establishment and survival also needs further investigation. Furthermore, long term trials would be valuable to test many of the techniques explored in this study.

Several factors limit a comprehensive understanding of silvopasture productivity on the Maputaland Coastal plain. Emphasis for further research should investigate natural silvopasture systems, focusing on the production of *Sclerocarya birrea* in combination with livestock and forage combinations. Forage crops could include both natural grass species and palatable woody species. Further, understanding how various tree densities would affect forage composition due to differences in light inception, assessing potential stocking capacity and how this might influence the storage of soil organic carbon would be important research themes. A marula processing plant has recently been installed near the town of eManguzi and could conceivably be a market for this product. In this light, further knowledge regarding yield potential, identifying local cultivars and economic models for natural silvopasture land-use would also be important.

Research into plantation species based silvopasture would be to understand the economic viability of eucalyptus or pine silvopasture systems, test various grass species for optimum silvopasture production, and determine how grass or forage species would be affected by different tree densities (i.e. double row planting) and livestock carrying capacity. The establishment of silvopasture trials would benefit long-term forestry research at Manzengwenya plantation.

Monitoring of the hydrological cycle (groundwater, total evaporation, soil water etc.) is costly and time consuming, which limits the extent, species and components measured. Additional support is required to extend these measurements to larger areas that may provide further insight into the research questions. It is recommended that an existing or future established agroforestry system be monitored which would assist in understanding the interactions between these heterogenous land uses. This would require assistance from ecological studies. Additionally, future research should focus on investigations into alternate monitoring methods such as remote sensing which could result in significant improvements into surface water and its link to groundwater modelling which is closely linked to tree water-use. Remote sensing could assist model inputs, calibration and validation over a larger spatial area.

Surface water modelling requires knowledge of all the vegetation within the modelled catchment. More effort should be provided to accurately depict the land uses which were not measured in this study. In a groundwater driven system such as Vasi Pan, the link between surface and groundwater interactions are important.

Future research should investigate the linkage between surface and groundwater models.

An approach to automatically initiate annual growing cycles using changes in soil moisture rather than heat units should also be investigated. This approach may be more suitable for South African vegetation and would negate the need to define management operations to initiate growth at a fixed date.

SUMMARY OF MAIN FINDINGS

- The eucalyptus plantation used substantially more water per day (~ 8 L.day^{-1}) than the pine and indigenous trees. In summer, the average daily water-use was highest for the small eucalyptus trees (19.24 L.day^{-1}) and lowest for indigenous trees (10.02 L.day^{-1}). In winter, the average daily water-use was highest for the small eucalyptus trees (7.95 L.day^{-1}), and lowest for the invasive pine trees (4.67 L.day^{-1}). The large eucalyptus trees used the most water per month in March 2017 (735.11 L), while the indigenous trees used the least water in July 2016 (46.71 L).

- During the dry winter period of 2017, the commercial pine stands, which were a dominant land-use in the Vasi area, had a low average ETa (1.07 mm.day^{-1}) as rainfall and solar radiation were limiting. The ETa measurements indicated that the trees were conservative water-users in winter, despite the presence of a shallow groundwater table.

- The ecological study identified indigenous tree species that would be suited to integration with different agroforestry systems. *S.spinosa, S. birrea, H. coriaceae*, *V. infausta*, *A. sengalensis* and *T. emetica* were considered to be disturbance resilient species that could be tested in silvopasture agroforestry systems that combine a moderate density of multi-functional trees with pasture for livestock production. Indigenous South African grasses that are suitable silvopasture species are *B. brizantha, B. humidicola* and *P. maximum.*

- One of the concerns of the DEA and DWS is that water levels of the nearby Lake Sibhya have dropped by almost 4 m from 2001 to 2010. One of the critical factors in determining the impact of trees on the ground water table is whether a species is water- or energy-limited, since a species that is water-limited will use less water in a drought. Apart from the small eucalyptus trees planted on the edge of Vasi Pan North, the results showed that the water-use of the other trees were limited by water availability, suggesting that their roots were not in permanent contact with the groundwater table. The lowering of the groundwater table in the recent drought years may account for the trees not abstracting water from the groundwater.

- Model simulations were used to investigate alternatives to monoculture plantations which are classified as SFRAs.
  ***Scenario 1:* Removal of all the exotic plantations**: The water table was predicted to rise by over 2 m from existing conditions.
  ***Scenario 2*: Reduction of area under plantations by strip cropping.** In this scenario the impact of reducing the area under plantations by replacing the total area with strip cropping was equivalent to a 50% reduction of water-use in the plantation area.
  ***Scenario 3:* Clearing wetland buffers and implementing an agroforestry system**. The SWAT model predicted an increase of up to 40 % water yield. Future research on the water-use of the potential agroforestry species and systems identified in this study is therefore recommended.

ACKNOWLEDGEMENTS

The research reported in this document forms part of a project funded and managed by the Water Research Commission of South Africa in the Key Strategic Area on Water Utilisation in Agriculture.

The project team would like to thank the reference group members who provided valuable information and guidance throughout the research period.

Dr G R Backeberg	*Water Research Commission (Chairman)*
Dr S Mapandeli	*Water Research Commission (Chairman)*
Dr P J Dye	*Private/University of the Witwatersrand*
Prof J G Annandale	*University of Pretoria*
Dr E February	*University of Cape Town*
Dr R N Heath	*Forestry SA*
Ms N Fourie	*Department of Water and Sanitation (DWS)*
Ms D Maluleke	*Department of Water and Sanitation (DWS)*
Dr M B Gush	*CSIR*
Dr C Marais	*Department of Environmental Affairs (DEA)*
Ms S J. Janse van Rensburg	*South African Environmental Observation Network (SAEON)*

The following people provided valuable technical assistance and local knowledge to the experiments:
Dr Alistair Clulow, Dr Terry Everson, Dr Piet-Louis Grundling and Mr Sihle Bukhusini.

The SAEON team (Sue van Rensburg, Siphiwe Mfeka and Kent Lawrence) provided essential monitoring equipment, technical, scientific expertise and data as well as assistance through numerous site visits which were invaluable to the implementation, running and completion of this research project. Mark Scharpers (JGAfrika) provided important borehole data for the study area. Local ecological assistants, Xolani Ngubani and Bhekai Mdhuli are also thanked for their guidance and knowledge during vegetation sampling.

Land owners are acknowledged for allowing field work to be conducted on their property. We are very grateful for this and the assistance they provided during the monitoring period. The land owners at Manzengwenya Plantation, the Department of Agriculture, Forestry and Fisheries (DAFF) and Tembe Mbila Mabaso (TMM) trust are thanked. This includes the izinduna of KwaZibi district, Mr. M.E Tembe and MvelaBusha district, Mr. J.M Tembe.

The University of Pretoria Plant Production and Soil Science department and the University of KwaZulu-Natal Centre for Water Resources Research are acknowledged for the use of facilities and equipment.

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Roman Symbols

cp	specific heat capacity of air at constant pressure (approximately 1040 J kg^{-1} K^{-1})
D	deep drainage (mm)
E_s	soil evaporation (mm day^{-1})
ET	total evaporation (mm)
ETEC	total evaporation (mm) from eddy covariance measurements
ET_o	FAO-56 reference total evaporation (mm)
gc	canopy conductance (m s^{-1}) = (1.rs^{-1})
gc_{max}	maximum conductance (m s^{-1})
G	soil heat flux (W m^{-2})
H	sensible heat flux (W m^{-2})
LE	latent heat flux (W m^{-2})
P	precipitation (mm)
Q	streamflow (mm)
R	surface runoff (mm)
R_n	net irradiance (W m^{-2})
spha	stems per hectare
T	transpiration (mm or L)
T_a	temperature of the air (°C)
Tsonic	air temperature using sonic temperature (°C)
Vh	Heat Pulse Velocity (cm hr^{-1})
w	vertical wind velocity (m s^{-1})
W	contribution from water table upward (mm)

Abbreviations

AWS	Automatic weather station
CSIR	Council for Scientific and Industrial Research
DAFF/DOA	Department of Agriculture, Forestry and Fisheries
DWS/DWAF	Department of Water Affairs & Sanitation
EC	Eddy Covariance
FAO-56	Food and Agriculture Organisation, paper no. 56
HPV	Heat Pulse Velocity
HRM	Heat Ratio Method
HRU	Hydrological Response Unit
LAI	Leaf Area Index
LAU	Large Animal Unit
LSU	Livestock Unit
MAP	Mean Annual Precipitation
PAR	Photosynthetically Active Radiation
PAW	Plant Available Water
SWB	Soil Water Balance
TDR	Time Domain Reflectometry
VPD	Vapour Pressure Deficit
WUE	Water-use Efficiency

Terms

Core forest: Generally the oldest portion of a forest patch or specific forest. This may represent climax or mature areas in undisturbed forests or 'old' regrowth areas in younger developing forest.

Forest Cluster: one to several natural forest trees growing on a limited area within an alien plant stand or grassland. A requirement was that within the group there should be at least one reproductively mature tree present that would be able to attract dispersal agents. Three cluster size classes were defined: Small cluster, with one to three trees; Medium cluster with four to nine trees; and Large cluster with 10 and more trees.

Forest Patch: A small or large isolated area of mature or regrowth forest which can act as a seed source for forest expansion.

Invasive Alien Plants (IAPs): Non-native plant species that have naturalized into disturbed or non-disturbed vegetation in the landscape.

Naturalisation: Colonisation of alien or indigenous forest in areas in the landscape which historically did not contain forest e.g. grassland areas.

Regrowth Forest: A patch of regenerating natural forest which is not in a mature ecological condition where natural forest existed before. It may persist as a regrowth forest if located in a frequently disturbed area i.e. river bed or on a successional pathway to mature forest i.e. in a grassland area.

Rehabilitation: Using some of the original species, plus, where necessary, introduced species, to reforest the site. In this case, there is no attempt to recreate the original ecosystem; rather the objective is to initiate the process that would return the forest to a stable and productive condition.

Secondary vegetation: Native species or mixed IAPs growing in areas in which the original composition of natural vegetation has been removed through disturbance.

Self-perpetual cluster expansion: The ability of a new or young forest cluster to expand without the seed source from core or mature forest patches.

Water-use Efficiency: Biomass produced per unit of water transpired, often termed productive green-water-use.

Woodland: An open canopy community of woody tree species growing with disturbed or non-disturbed areas that has a continuous layer of grasses as a component of the understory.

Plantation Woodlot: A small (1 -3 ha) locally established Eucalyptus stand which form a component of outgrower schemes in communally managed areas. These woodlots are typically grown to supply local building material and pulp.

1. INTRODUCTION

1.1 Background and Motivation

It is widely accepted that the expansion of commercial forestry using fast growing alien tree species in South Africa has had negative hydrological consequences on a catchment scale (Le Maitre *et al*., 2002; Marais and Wannenburgh, 2008; Brites, 2013; Kelbe and Germishuyse, 2010; Vaeret *et al*., 2008). However, it has to be acknowledged that some introduced plants are an important contributor to the economy and there is place for them in agricultural systems. For example, afforested commercial plantation forestry in South Africa employs roughly 170 000 people and constituted sales of 20 billion rand in 2013 (Godsmark, 2014). In water-stressed catchments where there is a high demand for the expansion of commercial forestry (new licence applications) there is an urgent need for alternative land-use activities that will provide viable economic and resource outputs while simultaneously achieving an equitable balance in water resource demand. Agroforestry contributes to poverty alleviation, carbon sequestration, tree domestication and payments for ecosystem services (2nd World AF Congress, Nairobi) but in certain areas it can lead to loss of aquatic environments and ecosystem services (Kelbe and Germishuyse, 2010; Kelbe *et al.,* 2014).

In South Africa, innovative research has been conducted in this field which is based on the premise that indigenous forests can develop within stands of alien tree species and that the natural forest was expanding in many areas (Geldenhuys, 1997; Geldenhuys and Delvaux, 2006). This concept received positive support through recent studies funded by the Water Research Commission (WRC Report No. 2081/1/16). The studies completed at Buffeljagsrivier near Swellendam in the Western Cape, and at New Forest near Fort Nottingham in the KwaZulu-Natal Midlands, and exploratory work in Vasi Pan have contributed important new information on the water-use of indigenous and alien tree species and on the process of natural forest expansion within alien invasive stands. Findings from this study demonstrated that the water-use of different alien tree species and indigenous tree communities needs to be quantified through detailed plant water-use studies since it is not possible to generalise between the different tree species. Ecological studies showed that indigenous forest expansion was influenced by proximity to near-by forest patches, changes in natural fire regime, and the shaded conditions provided by alien timber species. Although findings from this project quantified water-use of indigenous and alien trees, it became apparent through the ecological component of the project that forest regeneration occurred in distinct stages, whereby native and alien trees occur at different densities and size classes. Furthermore, in an agroforestry context different densities, sizes and species of trees (growing in grassland areas) would influence the total evaporation and hence the hydrology of a specific area. The impact of plantation tree species on catchment hydrology is of critical importance in a water scarce country.

Along the Maputaland coastal plain, plantation forestry, agriculture (mixed cropping, livestock and fruit trees) and expanded human settlement has influenced the ground and surface water in the region (Kelbe and Germishuyse, 2010, Vaeret *et al.,* 2008; Kelbe *et al.,* 2014). It is therefore important to understand how fast-growing plantation forestry species and natural forest expansion have changed the plant water-use (transpirational changes) when compared with the more naturally occurring wooded-grassland conditions. This land-use change has likely caused the reduction in water flow through the wetlands, peat deposits and eventually the coastal streams and lake systems. The impacts of the proposed research will be relevant to the total area of the Maputaland coastal plain. Current models of plantation forestry in Maputaland incorporate water intensive closed stand plantations based on large scale production or smaller community owned woodlots. Less water intensive land-uses derived from agroforestry systems might include growing plantation species at different row spacings (row cropping), silvo-pasture systems (mixed indigenous species and livestock combinations) or cultivation of indigenous medicinal species. To implement such systems, it is important to understand the key drivers influencing the ecology of natural vegetation in the region and quantify the water-use of characteristic land-use types. The following questions were therefore asked:

1. What is the water-use impact for different land-uses (vegetation types) on the Maputaland Coastal plain?
2. What is the water-use of potential agroforestry species on the Maputaland coastal plain?
3. Could the existing hydrological models aid in the assessment of the agroforestry impact on the aquatic environment?
4. What is the reliability of these models to simulate the impacts of the various species and combination of species under different agroforestry models in Maputaland?

Various studies to quantify the impact of commercial and community forestry on the coastal plain using numerical models have been attempted (Kienzle and Schulze, 1992; Nomquphu, 2000; Kelbe and Germishuyse, 2000; Vaeret *et al*., 2008; Kelbe and Taylor, 2014). These models have been developed based on many unreliable assumptions and very limited data. Nevertheless, these models are being increasing used for decision making of land-use impacts on aquatic environments (Kelbe *et al*., 2014) including attempts to understand aspects of the regional surface water - groundwater interaction in the primary aquifer (Kelbe *et al*., 2016). There is a need to evaluate these models at the local scale using field data to adequately parameterise the important processes and identify and calibrate the sensitive parameters. To this end, a regional groundwater model was developed to simulate the water table in an attempt to delineate the wetlands using Modflow and coupled hydrological packages (Kelbe *et al*., 2016). Sensitivity analysis and calibration of the regional parameters for this model that simulates the water table profile has been done (Kelbe *et al.,* 2016). It is essential to identify and adequately calibrate sensitive parameters for the recharge and evaporation processes that are an important process in the transmission of hydrological impacts from land use changes to receiving water resources such as streams and lakes.

It is proposed that this regional model is upgraded and evaluated as a tool to study the impact of vegetation systems and species on the groundwater dynamics and then predict the impact of various agroforestry models on shallow aquifers and dependent aquatic environments in primary aquifers. This can be achieved using three-dimensional numerical groundwater models such as ModFlow with coupled unsaturated zone process packages (Niswonger *et al.,* 2006) that have been used to provide a quantitative estimate of anthropogenic impacts on the aquatic environment in the Maputaland region (Kelbe, *et al.*, 2001, 2014, 2016; Vaeret *et al.,* 2008; Rawlins and Kelbe, 1998). Further research into the groundwater flows will clarify the understanding of the geohydrology in this region and contribute to the broader knowledge and management of environmental resources such as the health of Lakes Sibaya, Mgobezeleni, Shazibe, Bhangazi North and the Kosi Lake which are an important component of the iSimangaliso Wetland Park. Water is the most basic of human needs and there is currently a serious water crisis in Maputaland. Quantification of the impact of the different models of agroforestry will assist with management of the regional water resources.

1.2 Aims and Objectives

The aim of the site and species selection process at Vasi Pan was to formulate the project objectives into a practical research framework. This was done by synthesising results from WRC Report No. 2081/1/16, discussions within the project team, stakeholders, consultation with community members, literature review and field work.

The overall aim of the study was to understand and quantify the water-use of different agricultural and ecological land-use components of the Maputaland Coastal Plain, which could potentially be developed into an integrated, multiple-use agroforestry system(s), as an alternative to commercial plantation forestry in water-stressed catchments.

The objectives of the project were to:

1. understand with accuracy the water-use of plantation forestry and indigenous species within a commercial, community woodlot and mixed plantation or agroforestry environment in Maputaland.
2. understand the ecological pattern and water-use of natural vegetation systems that could be incorporated in agroforestry systems in Maputaland.
3. develop and evaluate groundwater models of the Maputaland Coastal Aquifer to determine the impacts of land-use in context to plantation forestry, natural vegetation systems and a mixed plantation environment.

The core of the study area was the Manzengwenya plantation which is north of Lake Sibaya in Maputaland. The area represents excellent examples in which to study the effects of plantation forestry on the Maputaland coastal aquifer, the water-use of plantation trees in commercial and community areas, indigenous forest expansion and community resource use. There were a number of requirements for site selection which varied between the objectives of the study. To investigate the water-use and ecological pattern of natural vegetation (objective 1 and 2), three suitable examples of indigenous forest patches and forest expansion areas were selected. Preliminary investigation into the dominant species in these patches, including a review of the ethnobotanical literature, has guided the initial choice of species for water measurement.

These findings tie into the broader objectives of this project by specifically focusing on outputs suited to (i) water efficient land-use systems and (ii) agroforestry systems. A key focus of the study is to characterise typical hydrological areas in the Vasi landscape through links with moisture regime, landscape position and natural vegetation cover. Observations suggest that hygrophilous grasslands are most productive areas as they contain relatively fertile soil types, are proximate to ground water and support palatable grass species. In Manzengwenya plantation, identifying historical localities of these grasslands will enable resource diversification from single crop plantation agriculture to mixed species tree-grass communities suitable for both trees and livestock.

In order to understand the water-use of plantation species within a community woodlot (objective 1), a safe and well managed woodlot was sought in the adjacent rural area to Manzengwenya. This was done in consultation with the Siphesihle Bukhosini Science Centre which assisted in locating an appropriate site. A review of ethnobotanical literature pointed towards several candidates for potential agroforestry tree species. Of these, *Warburgia salutaris* (pepper bark), stood out as an immediate choice. It is a native tree which was once prolific in the study area and is an important Zulu medicinal plant (Leonard and Viljoen, 2015). Over utilisation of this species has rendered it difficult to find in the wild.

2. KNOWLEDGE REVIEW

An overview of documented ecological and hydrological literature relevant to the Maputaland Coastal Plain and the techniques used throughout this research has been provided in this literature review. This links the overall rationale for the research to the aims and objectives of the study.

2.1 Ecology and Agroforestry of the Maputaland Coastal Plain

2.1.1 Forest-grassland mosaics

Natural vegetation in Maputaland incorporates a transition zone between north east African tropical flora i.e. the Zanzibar-Inhambane regional mosaic, with subtropical flora i.e. Tongaland-Pondoland regional-mosaic (White, 1983). The region contains the southernmost limit of many afro-tropical plant species (Van Wyk, 1996) and is also a centre of plant endemism containing many neo-endemics or recently developed species (Van Wyk and Smith, 2001). The most widely used vegetation classification distinguishes higher rainfall eastern regions as Indian Ocean Coastal Belt (IOCB) and drier western regions as Savanna (SV) as separate biomes (Mucina *et al*., 2006; Rutherford *et al*., 2006). Manzengwenya plantation falls within the coastal IOCB biome (Figure 2.1), which supports azonal Northern Coastal forest (FOz 7), Maputaland Coastal Belt (CB1), Maputaland wooded grassland (CB2), and Subtropical Freshwater wetlands (AZF 6).

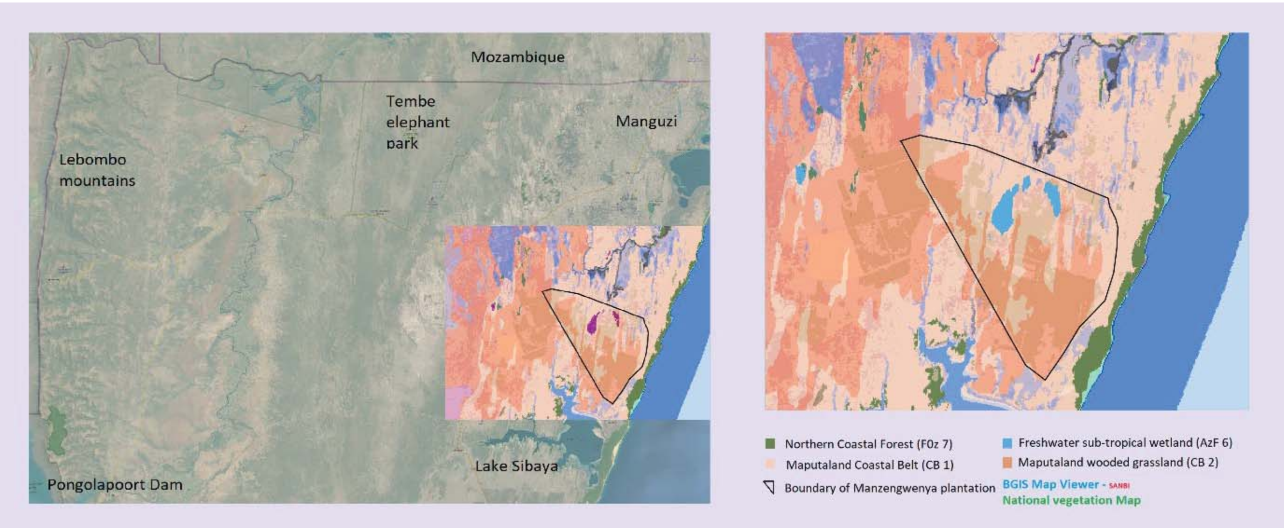


Figure 2.1 National vegetation classification, showing four major vegetation types of the Indian Ocean Coastal Belt in the study area.

Maputaland Coastal Belt (CB1)

The eastern or coastal regions of Maputaland is dominated by Maputaland Coastal Belt and is embedded within (CB1) is Maputaland Woody Grassland (CB2) and Northern Coastal Forest (FOz 7). The patterns within Maputaland coastal belt vegetation are influenced by fire and characterised by forest patches interspersed with extensive grasslands including, palm-veld (containing *Hyphaene coriaceae*), dry tufted grassland, hygrophilus or ephemeral grassland, and thicket (Mucina and Rutherford, 2006).

Important woody species are often pioneer tree and shrub species such as *Syzygium cordatum*, *Bridelia micrantha* and *Acacia koziensis* (Mucina and Rutherford, 2006). Grasslands types vary with landscape position (Van Wyk, 1991a; Matthews *et al*., 1999). Tufted dry grasslands occupy sand dune ridges, whereas, hygrophilous grasslands and ephemeral wetlands occur in depressions or dune slacks (Figure 2.2).

Maputaland wooded grassland (CB2)

Maputaland wooded grassland (CB2) is an azonal (i.e. not restricted to any climate zone) wooded-grassland imbedded within Maputaland Coastal Belt. It occurs in coastal regions from Maputo to Richards Bay at an altitude of 20-120 masl (Mucina and Rutherford, 2006; Siebert *et al*., 2011). It is characterised by a mix of woody herbaceous flora known as geoxyles which have adapted to frequent fire and moisture (Maurin *et al*., 2014) and include species such as *Parinari curatellifolia, Salacia kraussii, Ancylobothrys petersiana, Syzygium cordatum, Diospyros galpinii and Eugenia capensis.* Van Wyk (1991) recognised two woodland-grassland communities (low-lying dwarf shrublands and dune dwarf-shrublands). These vegetation types are found within the study site and their landscape positions are related to localised differences in moisture and soil conditions.

Northern Coastal Forest (FOz 7)

The Northern Coastal Forests (FOz 7) occur as a continuous strip along the seaboard of Maputaland (von Maltitz *et al*., 2003; Mucina and Rutherford, 2006). These forests are represented by vegetation communities with strong tropical affinities which stretch into coastal east Africa (von Maltitz *et al*., 2003). They are separated into two major types: (i) Dune Forests which are a sea facing specialist low canopy forest community (von Maltitz *et al*., 2003) and (ii) Inland coastal forests. The latter form a mosaics within different grassland types and therefore have interesting ecotone communities that are thought to be fire tolerant (Everard *et al*., 1995). In northern Maputaland, Coastal forests may be found up to 30 km inland, good examples are Dukuduku forest, the Sibaya Forest complex and the Sodwana state forest (von Maltitz *et al*., 2003). Coastal forests in northern Maputaland are also thought to share floristic affinities with Sand Forest (FOz8), sharing species such as *Cleistanthus schlechteri*, *Dialium schlechteri and Hymenocardia ulmoides.*

Subtropical Freshwater wetlands (AZF 6)

Subtropical freshwater wetlands can be permanent but are mostly ephemeral in Maputaland. Grassland that integrate with freshwater wetlands are frequently characterised by pan systems and fed through groundwater recharge (Grundling *et al*., 2013). They have been termed hygrophilous grassland and wetland depressions in this study, owing to their distinct localised landscape positions. Grass composition has been shown to relate to a catenary sequence of moisture and soil organic matter from central to outer pan areas (Pretorius *et al*., 2016). These low altitude grassland types are often for agricultural activity because they are more productive relative to sandy dune-crests which are edaphically less productive (Sliva *et al*., 2004).

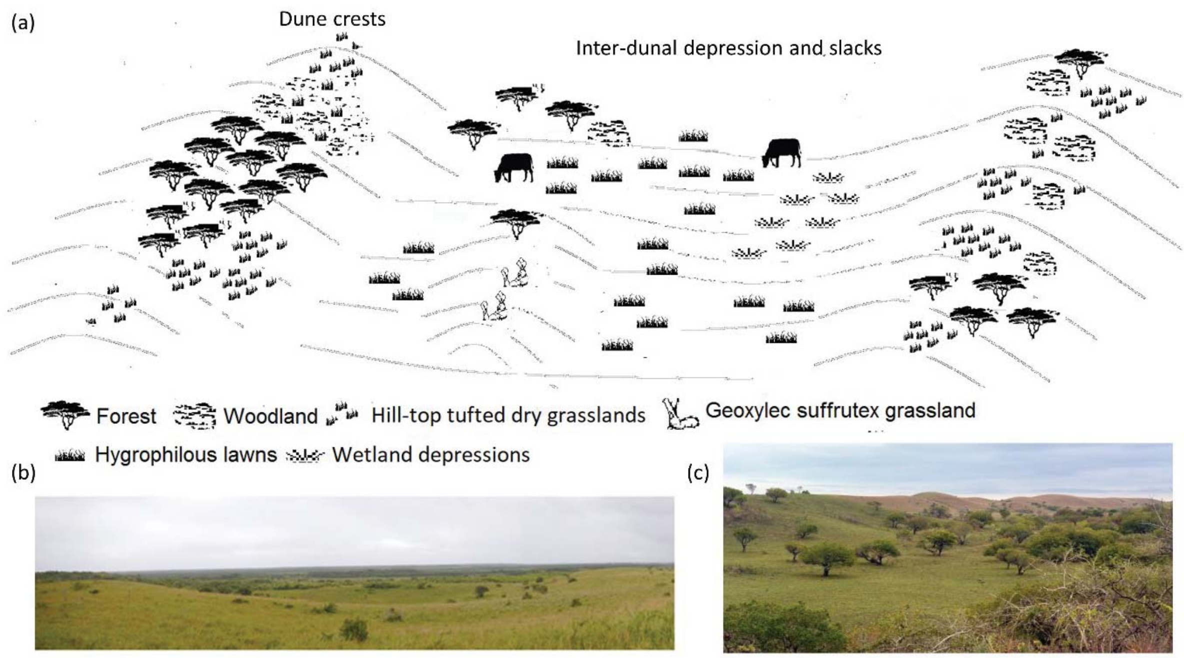


Figure 2.2 (a) Typical landscape layout of northern coastal areas of IOCB vegetation (b) View facing north-west, taken on dune ridge, towards large interdunal slack at Manzengwenya plantation (c) A typical example of fire-climax forest-grassland mosaic vegetation of the IOCB.

2.1.2 Potential species and their uses

Ethnobotany is research at the interface between the disciplines of anthropology, geography, economics and ecology (Cunningham, 2001). It recognises the importance of indigenous knowledge systems by identifying and quantifying the relationship between plants and people. Rural communities in Maputaland utilise natural resources derived from plants to supply them with many environmental goods and services, including wood harvesting for fuel, construction, medicine, spiritual usage, household and food products (Pooley, 1980; Gaugris and van Rooyen, 2009; Corrigan *et al*., 2011; Wet, 2013).

A review of plant usage from literature specific to the Maputaland region showed that 107 species are used as food products, 96 as medicinal species and 68 species for household items (Table 2.1). By mass, firewood is the most utilised plant resource, estimated at about 25.4 m^2 per household covering 29 woody species (Vasicek and Gaugris, 2014). This is followed by building material which is determined by the strength, straightness and resistance to rot, for example *Hymenocardia ulmoides* is commonly used (Gaugris and van Rooyen, 2009).

Many plant species in Maputaland are multi-functional, that is, they provide more than a single product or service. For example, *Sclerocarya birrea* (marula) produces a fruit and an oil crop (Van Wyk, 2011; Vermaak *et al*., 2011), but its bark is also used medicinally (Shackleton *et al*., 2002; de Wet *et al*., 2010). Naturally occurring fruiting species are recognised to be important for diet diversity in rural communities who may not have access to fresh fruit and vegetables (Sunderland *et al*., 2013; Powell *et al*., 2015).

The plant products which are utilised commercially and contribute to household income have the most potential for agroforestry systems. Potentially commercial resources include, fibre collected from the palm species (*Hyphaene coriaceae* and *Phoenix reclinata*) (Pooley, 1980; McKean, 2004), sap from *Hyphaene coriaceae* for brewing beer, seed oil from *Sclerocarya birrea* and *Trichilia emetica* (Vermaak *et al*., 2011) and fruit products from *Strychnos* spp, *Sclerocarya birrea* and *Vangueria infausta* (Van Wyk, 2011). Another potentially valuable agroforestry species is *Warburgia salutaris* (pepper bark). The bark of this tree is one of the popular ingredients for traditional medicine in South Africa and demand is substantial. Overexploitation of *Warburgia* populations suggests there is a potential market for commercial production (Botha *et al*., 2004; Mander, 2004).

Indigenous knowledge systems are increasingly recognised as a tool to strengthen farming practices which are under pressure from global change (Mafongoya and Ajayi, 2017). The plant-use component of this study addresses this subject by quantifying the potential resource benefits that can be supplied by the forest and grassland ecosystems around Manzengwenya plantation.

Table 2.1 A review of the number of species of ethnobotanical value in Maputaland per use-classes of wood products, medicine and household items.

Use Class	No. of Species	Specific Usage *Parts of the plant used	Pooley (1980)	McKean (2004)	Twine (2004)	Gaugris and van Rooyen (2009)	Corrigan *et al.*, (2011)	York *et al* (2011)	De Wet *et al* (2010)	Nciki *et al.*, 2016
Wood products	55	Fuel	x				x			
		Building material	x			x	x			
		Carving	x							
		Trapping	x							
Medicinal	96	Bark*			x		x	x	x	x
		Roots*					x	x	x	x
		Leaves*					x	x	x	x
		Spiritual					x			
Household items	68	Thatching	x							
		Weaving	x	x	x					

Agroforestry is a term used to describe a range of land-uses that combines perennial vegetation with agricultural crop production. It encompasses traditional land-uses (Luoga *et al*., 2000) smallholder (i.e. coffee agroforests; Negawo and Beyene, 2017) and commercial agriculture (i.e. Brazilian silvopasture; Cubbage *et al*., 2012). The term was formalised in 1977 through the formation of (ICRAF) the *International Council for Research in Agroforestry* Research into agroforestry includes agroforestry systems and practices (Nair, 1984; Cubbage *et al*., 2012) agroforestry species (Simons and Leakey, 2004; Chaturvedi *et al*., 2017), biophysical interactions of agroforestry, such as soil productivity (Montagnini and Nair, 2012) and design and evaluation (Raintree, 1987; Erskine, 1991; Ewel, 1999)

Agroforestry combines the components of perennial woody plants with crop and livestock agriculture into three broad agroforestry systems (Nair, 1993), namely, agro-silviculture (crops-trees), silvopasture (trees-livestock-pasture/animals), and agro-silvopasture (trees-crops-pasture). The selection of tree species depends on their ecological preferences, use value, and the potential to grow them cost-effectively. Ideal agroforestry species are those that are readily available, are easy to establish and are multi-purpose. Many indigenous trees that occur naturally in Maputaland are potentially suitable for agroforestry purposes, particularly silvopasture (Table 2.2).

Table 2.2 Summary of potential indigenous tree species suited to agroforestry on the Maputaland Coastal Plain.

Species	Use category	Plant Product	Specific use	Reference
Acacia kosiensis	Fuel, N - Fixation	Wood	Fast growing pioneer legume tree species which is suitable for woodlot applications	(Gush, 2017)
Albizia adianthifolia	Medicine	Bark	Bark used to prepare lotions for itchy skin, love charms and enemas to clear urine for pregnant woman.	(Pooley, 1980; Hutchings *et al*., 1996)
Annona senegalensis	Food	Fruit and roots	Fruit eaten. Roots for stomach problems, infertility, improved sexual performance, pains during pregnancy, fever, or oedema.	(Pooley, 1980; Mahwasane *et al*., 2013)
Antidesma venosum	Food	Fruit	Fruit eaten in field and during famine	(Pooley, 1980; Maghembe *et al*., 1994)
Apodytes dimidiata	Timber	Wood	Wood used for building polls, fire wood and traditional utensils	(Pooley, 1980; Boon, 2010)
Balanites macnaughtonii	Oils	Fruit	Seed oil is flammable	(Pooley, 1980)
Brachylaena discolor	Timber	Wood	Wood used for building polls, fire wood and traditional utensils including baskets	(Pooley, 1980; Boon, 2010)
Coffee racemosa	Coffee	Fruit	Fruit used a commercial coffee variety	(Boon, 2010; de Rezende Maciel *et al*., 2016; Sukkot, 2016)
Craibia zimmermannii	Timber	Wood	Wood used for building polls	(Pooley, 1980; Boon, 2010)
Dialium schlechteri	Timber & Medicinal	Bark & wood, Fruit	Insect resistant wood used for building, bark used for burn treatment, Fruit used as sweets.	(Hutchings *et al*., 1996; Gaugris *et al*., 2006; Boon, 2010)
Dovyalis caffra	Food	Fruit	Fruit eaten and made into jams	(van Wyk *et al*., 2003; Boon, 2010; DAFF, 2013)
Garcinia livingstonei	Food	Fruit	Fruit eaten, cooked in porridge	(Orwa *et al*., 2009; Boon, 2010)
Hymenocardia ulmoides	Timber	Wood and browse	Building polls and firewood, browse for livestock	(Gaugris *et al*., 2006, 2008)
Hyphaene coriacea	Weaving products, Food	Leaves and sap	Leaves used for multiple of products ranging from mats, hats to baskets. The sap is used for brewing wine.	(Pooley, 1980; McKean, 2004)
Inhambanella henriquesii	Food	Fruit	Fruit is harvested and eaten	(Pooley, 1980; Boon, 2010)
Landolphia kirkii	Food	Fruit	Vitamin A supplement	(Pooley, 1980; Fukushima *et al*., 2010)
Mimusops obovata	Food and oil	Fruit and seed	Food supplement and seed contains high levels of oleic acid suitable for oils industry	(Chivandi *et al*., 2016)
Pappea capensis	Food and oil	Fruit and Seed	Food supplement and oils suitable for soap and biodiesel	(Van Wyk and Gericke, 2000;

Species	Use category	Plant Product	Specific use	Reference
				Mng'omba *et al*., 2007)
Phoenix reclinata	Food, Household	Sap and leaves	An alcoholic beverage is brewed from the sap. Leave midribs are used to basketry.	(Pooley, 1980; Orwa *et al*., 2009; Boon, 2010)
Salacia kraussii	Food	Fruit	Vitamin A supplement and fruit	(Pooley, 1980; Cunningham, 1988; Magaia *et al*., 2013)
Sclerocarya birrea	Food & oil	Fruit and seed	Harvestable fruit and oil	(Shackleton *et al*., 2002; Pooley, 1980; Emanuel *et al*., 2005)
Strychnos madagascarensis	Food & Medicine	Fruit	Food supplement, used in the treatment of diarrhoea	(Pooley, 1980; Orwa *et al*., 2009; de Wet *et al*., 2010)
Strychnos spinosa	Food & medicine	Fruit	Food supplement and treatment for snakebite	(Pooley, 1980; Hutchings *et al*., 1996)
Trichilia emetica	Oil & medicine	Bark and seed	Oil is derived from crushed seeds, bark is used medicinally to treat stomach and intestinal complaints	(Pooley, 1980; Hutchings *et al*., 1996; Komane *et al*., 2011)
Vangueria infausta	Food	Fruit	Vitamin A supplement	(Boon, 2010; DAFF, 2013)
Warburgia salutaris	Medicinal	Bark and leaves	Considered one of the most popular medicinal plants in Southern Africa, bark used extensively to treat respiratory illness.	(Maroyi, 2012, 2013; Leonard and Viljoen, 2015)
Ziziphus mucronata	Food & medicine	Fruit	Vitamin A supplement and for respiratory ailments	(Hutchings *et al*., 1996; Boon, 2010; Mokgolodi *et al*., 2011)

2.1.3 Response of natural vegetation to land-use

Afforestation of grasslands by plantation forestry is of concern in Maputaland because of the biodiversity loss incurred to grasslands, and the threat plantation trees pose to wetland functioning (Kelbe *et al*., 2014; Grundling *et al*., 2017). If plantations are established near wetlands or in hydrologically sensitive areas for example, because of illegal woodlots (Figure 2.3), they may reduce the level of the water-table. This can alter the seasonal flux of moisture inundation in ephemeral wetlands or hygrophilous grassland, leading to a change the species composition that favour species suited to drier conditions (Van Wyk, 1991). Plantations can also induce fire-suppression in grasslands through landscape fragmentation (Archibald, 2010). Grasslands depend on frequent fire to maintain them and are replaced by forest in the absence of fire (Bond, 2016). Fire-suppression (i.e. reduction in return-period and intensity of fire) influences tree-grass dynamics in grasslands by favouring trees (both natural species and invasive species) which outcompete grassland species leading to natural forest expansion or woody encroachment (O'Connor *et al*., 2014).

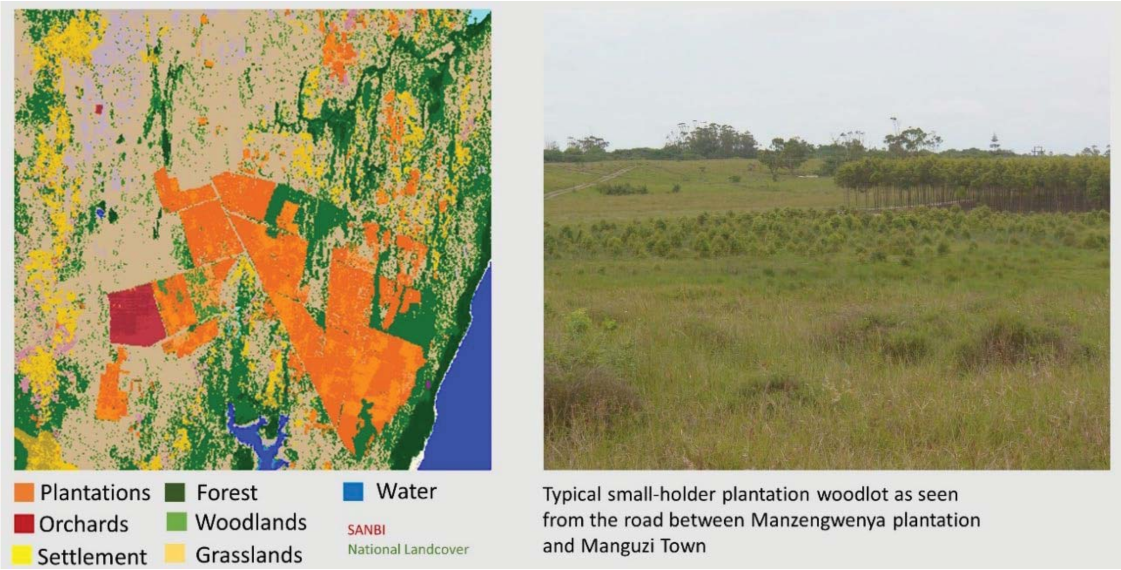


Figure 2.3 Landcover (left) and an example of plantation woodlots in Maputaland (right).

Indigenous tree species generally respond positively to land-use change from natural grasslands to fragmented and fire-suppressed environments such as plantations (Figure 2.4). Several studies, including the ecological component of Project K5/2081, have recorded the effects that fire-suppression have had on natural forest expansion.

Figure 2.4 A *Pinus elliottii* (left) and a *Eucalyptus grandis* (right) stand with a dense stand of natural forest regeneration (background) and a stand with sparse to no natural forest regeneration (foreground).

These studies have looked at the species composition of expanding natural forest in relation to: (i) different plantation species (ii) stand age (iii) distance to forest seed-source (iv) patterns of forest nucleation (v) dispersal effects and (vi) the response native species to self-thinning of plantation species (Geldenhuys, 1997; Geldenhuys and Delvaux, 2006; Everson *et al*., 2016).

At Manzengwenya, various natural forest species occur within the planted stands of *Pinus elliottii* and *Eucalyptus* spp. Planted stands occur in areas that were grassland or wetlands before plantation establishment in approximately 1958 (Bruton and Cooper, 1980). The most frequently encountered areas of natural forest expansion occur in plantation areas which are near established natural forest patches. However, small clusters of natural forest expansion are ubiquitous throughout most of the plantation. In addition, natural forest expansion occurs via a pathway of secondary woodland on the edge of forests (Von Maltitz *et al*., 1996). Forest expansion through secondary woodland in areas that are adjacent to natural forest areas occur at Manzengwenya in clear-cut plantation lands that have been temporally abandoned (Figure 2.5).

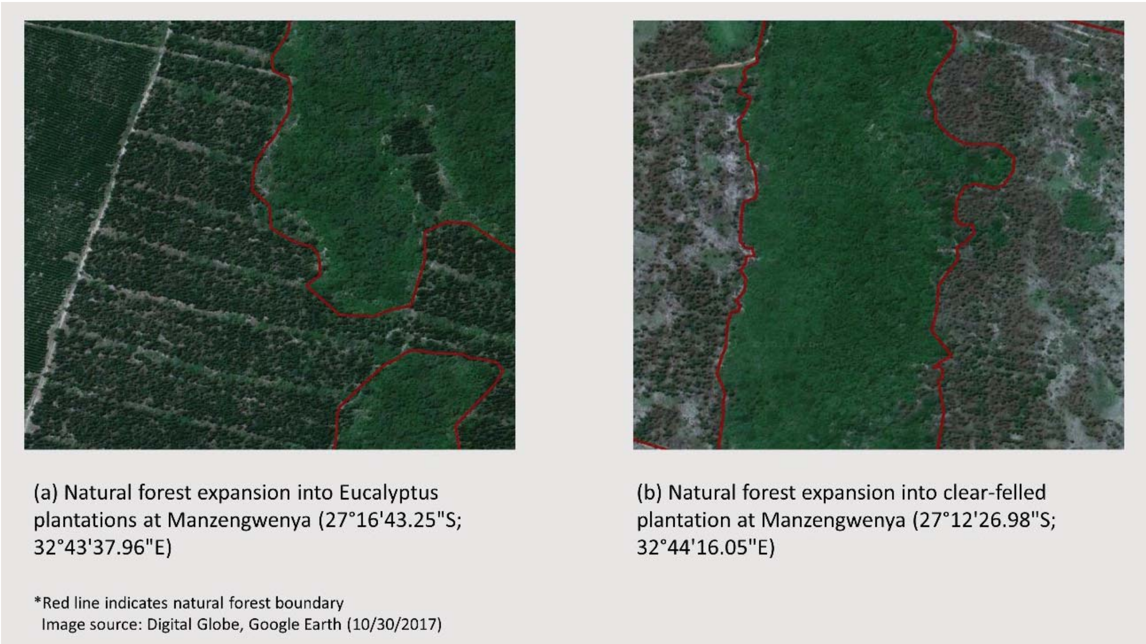


Figure 2.5 (a) Forest expansion on forest edge into plantation (b) Forest expansion on forest edge into woodland (i.e. clear-felled plantation areas)

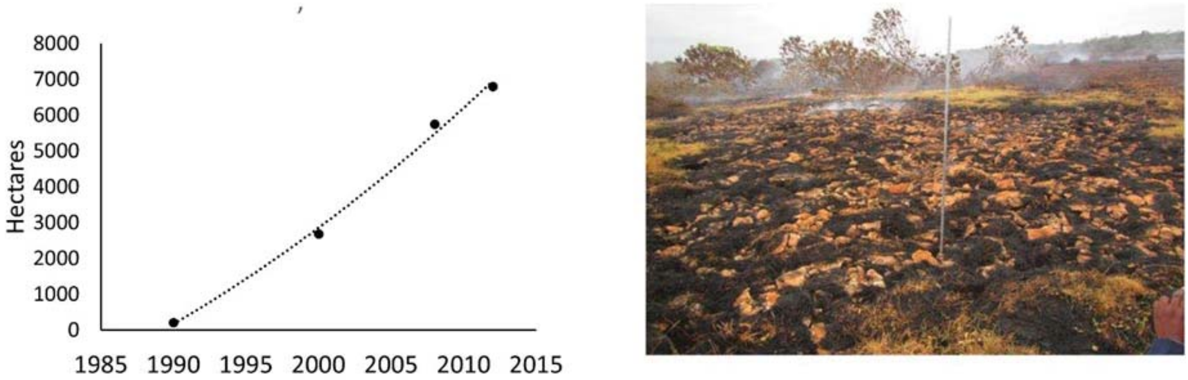
2.1.4 Commercial plantations

The most extensive land-use in the region is commercial and small-holder eucalyptus plantations. The two largest commercial plantations (Mbazwana and Manzengwenya plantations) were government owned, but have recently been handed over to a local tribal authority, Tembe Mibolo Mabaso (TMM) as part of a land-claim process (SA Forestry, 2012). These plantations are extensive, about 8500 ha and 15000 ha respectively. Until the 1990’s *Pinus elliotii* was grown for roundwood but this has changed to eucalyptus hybrids grown for pulp. Eucalyptus hybrids are usually grown in seven-year ratoones at densities of ± 1200 stems ha^{-1}. In addition to commercial plantations, small-holder eucalyptus woodlots are farmed within community managed areas and account for about 6700 ha (von Roeder, 2014). The area of smallholder eucalyptus plantations are expected to have increased since data was collected for this study during 2012 (Figure 2.6 a).

The growth rates of pulp eucalyptus are impressive, with average stem and branch biomass increments of around 15 t ha^{-1} y^{-1} but may reach up to 72 t ha^{-1} y^{-1} (Dye *et al*., 2004). In coastal areas where temperate conditions and solar radiation facilitate year-round growth, trees that have accesses to shallow sandy aquifers have the potential to become high water-users when compared with the natural vegetation (Everson *et al*., 2016).

A combination of drought and land-use change from natural grasslands to plantations is assumed to have contributed towards a general reduction of the groundwater aquifer on the coastal plain (Kelbe *et al*., 2014; Weitz and Demlie, 2014; Smithers *et al*., 2017). This has had negative effects on the peat wetlands at Manzengwenya. In particular at Vasi Pan, where drying out of the peat base layer because of a reduction of the ground water-table, has led to wetland degradation through peat fires (Figure 2.6 b). The issue is recognised and has been the subject of local workshops (van Rensburg, 2018). National government

(Department of Agriculture, Forestry and Fisheries and Department of Water Affairs) and local forestry stakeholders (TMM) are committed to finding a solution to this land-use issue.



(a) (b)

Figure 2.6 (a) Area of small holder Eucalyptus woodlots between 1990 and 2012 (adapted from von Roeder, 2014). (b) Vasi Pan (north) during a peat fire in 2017. Photo: Lulu Pretorius.

2.1.5 Silvopasture systems

Silvopasture combines the use of trees and livestock for agricultural production and can include natural and planted systems. The tree-grass or forest-grassland vegetation matrices of the eastern summer rainfall areas could be referred to as natural silvopasture systems, because they support a combination of indigenous trees and grasses which interact with livestock. These rangeland systems, function as key land-use in rural landscapes, through the products derived from trees and livestock (Hall and Cousins, 2013) and if managed correctly, exert minimal disturbance to natural ecological processes (O'Connor and Kuyler, 2009; Everson *et al*., 2011). Natural rangelands provide multiple products. Grasses provide sustainable high protein feed for livestock production (McGranahan and Kirkman, 2013) while forb and tree species provide products such as food, fuel and medicine (Twine, 2013). Silvopasture agroforestry systems, i.e. a combination of trees, forage and livestock are therefore a potentially sustainable land-use for South Africa, specifically in mesic wooded-grasslands and savannas.

Silvopasture is a sub-class of agroforestry. It applies agroforestry practices, such as alley cropping, fodder-hedges, protein banks, windbreaks, shelterbelts, scattered trees in pastures with intensive management and/or rotational grazing (Nair, 1993; Cubbage *et al*., 2012). The tree species used in silvopasture systems can be alien plantation species, planted native species or adaptions of natural forest systems (Cubbage *et al*., 2012). The type of species and management regimes in silvopasture systems depends on local conditions and markets, however a key element is intensive management through rotational grazing or browsing, rather than opportunistic use of marginal land (Burner and Brauer, 2003). Silvopasture systems are usually composed of tree, fodder and livestock components (Table 2.3).

Table 2.3 Summary of silvopasture components

Silvopasture system (Trees+ pasture and/or animals)	Arrangement of components	Grouping of components	Agro-ecological adaptability
Multipurpose trees on rangeland or pastures	Trees scattered irregularly or arranged according to some systematic pattern	w: multipurpose; of fodder value f: present a: present	Extensive grazing areas
Protein banks	Production of protein-based tree-fodder on rangelands for cut-carry production	w: leguminous fodder trees h: present f: present	Usually in area with high person: land ratio
Production trees with pastures and animals	Local example: cattle under timber or cashews	w: plantation crops f: present a: present	In areas with less pressure on plantation crop land

** Note: Components refer to following codes: w = woody; h = herbaceous; f = fodder or grazing; a = animal*

A key dynamic in silvopasture systems is the effect that tree density and species have on the light availability for fodder crops or grasses. Stem density in silvopasture systems differs widely, ranging from scattered trees in pastures of about 45 stems ha^{-1} to intensive tree systems of 1500 stems ha^{-1}. Depending on tree species, increasing tree density negatively affects forge quantity, but not necessary forage quality (Figure 2.7). A summary of tree spacing per hectare for eight silvopasture systems is shown in Table 2.4 The average planting density in this review was between 250 and 1500 stems ha^{-1}, and was dependent on species, the production objective and bio-climatic region (Cubbage *et al.*, 2012).

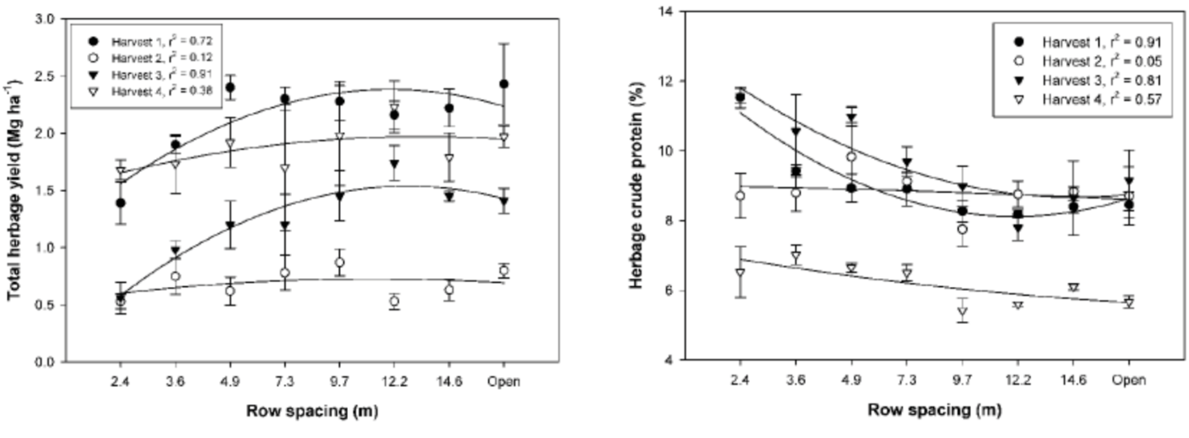


Figure 2.7 *Pinus taeda* density and *Festuca arundinacea* productivity, showing the relationship between row spacing with total herbage yield (left) and protein percent (right) (Burner and Brauer, 2003).

Table 2.4 Examples of silvopasture systems reviewed by Cubbage *et al.* (2012).

Region	Typical tree species	Regeneration	Planting density (trees/ha)	Final density	Pruning	Typical forage species	Grazing
Argentina (extensive cattle ranches)	*Pinus taeda*, *P. elliottii, Eucalyptus sp*. and *Grevillea sp.*	Plantation	700–1,600	150–400	Yes 3-4 times	*Axonopus* sp, *Bracharia* sp	Cattle
	Prosopis sp and Schinus sp.	Natural	n.a.	n.a.	No	*Piptochaetium* and *Digitaria* sp	Cattle:
Southeast, USA (large-scale innovators)	*Pinus elliottii* and *P. taeda*	Plantation	370–1,000	No data	Sometimes	*Paspalum* and *Cynodon* sp.	Cattle
	Nut ochards	Plantation	Rows. Nut orchards: 45	No data	Sometimes	*Festuca* and Lolium sp.	Cattal and goats
New Zealand (Family farms ± 500ha)	*Pinus radiata*, *Cryptomeria japonica*, *Eucalyptus* sp.	Plantation	1,600	300–350	Yes,3 times	*Lolium* sp. with N-fertilization and herbicide	Sheep
Paraguay (Farms of various scales, from humid to dry-lands)	*Tabebuia* sp. and *Cedrela* sp.	Natural	50-100	No data	Yes	*Brachiaria* sp.	Cattle
	Pinus sp and *Eucaplyptus gradis*	Plantation	1333	530	No	*Axonopus* compressus	Cattle
	Prosopsis sp. and Leucauna sp	Natural	45	45	Yes	Native species	Cattle
Uruguay (Large-scale forest industry in conjuction with local cattle ranches)	*Pinus taeda, Eucalyptus grandis*	Plantation	1000- 1100	150-250	Yes	*Paspalum notatum*, *Paspalum* sp.	Cattle (Hereford) and Sheep
	Eucalyptus globulus	Plantation	1300 - 1600	1000 -1300	No	*Paspalum dilatatum*, *Bromus* sp.	Cattle
Brazil: (Large scale forest and agro-forest industry, with livestock)	*Eucalyptus camaldulensis, E. grandis, E. urophylla*	Plantation	250	250	Yes	*Brachiaria brizantha, B. humidicola, Panicum maximum*	Cattle (mainly Zebu), but also Siminental
Chile: (Cattle ranches, farmers of various scales).	*Pinus ponderosa, P. contorta*	Plantation	2000	400	Yes	*Dactylis glomerata, Holcus lanatus, Poa pratensis, Trifolium pratense*	Cattle (Hereford, Black angus)

2.2 Evaporation and Transpiration Measurement Techniques

Evapotranspiration is an important process across a wide range of disciplines, including ecology, hydrology and meteorology (Wilson *et al*., 2001). Based on this multidisciplinary focus, numerous methodologies have been developed to measure evapotranspiration, or components of evapotranspiration (transpiration, soil evaporation and interception), over a range of spatial scales from individual plants and entire watersheds (Wilson *et al*., 2001). The selection of specific methods to obtain the required results is largely dependent on the location of the research to be done, the physical characteristics of the vegetation and the time and funds available to implement such research. Common methods used to measure or estimate vegetation water-use are direct sap flow measurements, micrometeorological methods, various modelling approaches and remote sensing. Each method has advantages and disadvantages which depend largely on the site characteristics and requirements. Micrometeorological methods can provide estimates of flux on an areal basis which allows for direct comparisons with other hydrological components over a site or stand (Hatton *et al*., 1995). *In situ* measurements of tree water-use (i.e. sap flow) enable the role of transpiration in trees to be quantified (Hatton *et al*., 1995). Modelling can provide estimates of vegetation water-use where measurements are not possible or available. However, the accuracy of modelling depends largely on the quality of the input data used and on studies to validate the simulated results.

Numerous techniques can be used to estimate water vapour exchange rates between the surface and atmosphere, but these techniques often vary in that each technique is only representative within a particular spatial and temporal scale, and either interpolation or extrapolation is necessary to infer evaporation rates outside these scales (Wilson *et al*., 2001). Secondly, the techniques may also differ in whether they measure evapotranspiration or just one or several of its components (e.g. in energy balance techniques the sensible and soil heat fluxes are used to determine the latent heat flux (evaporation). In addition, each of the techniques introduces a unique set of assumptions, technical difficulties, measurement errors and biases (Wilson *et al*., 2001).

A summary of some of the evaporation measurement techniques has been provided in Table 2.5.

Table 2.5 Summary of a selection of techniques used in the measurement or estimation of sap-flux density, sensible heat (H) and/or latent heat flux density (LE) using the surface energy balance (after Savage *et al.*, 2004)

Method	Measurement area, distance or height	Averaging period	Theoretical basis/comment	Comment
Reference evaporation*	Point measurement (2 m above short grass) of solar irradiance, air temperature, wind speed, water vapour pressure	Hourly/daily	Penman-Monteith method for reference evaporation estimation (FAO 56), and use of a crop factor (Allen *et al.*, 2006) for short grass (0.1 m tall) and tall crops (0.5 m tall)	Only reference evaporation and estimated crop evaporation calculated
Heat pulse/sap flow (Stem Heat Balance, SSS)*	In situ measurement (<200 mm)	Sub-hourly/hourly	Dynamax collars allow for the measurement of radial and vertical temperature gradients $C_{st}\frac{dT_{st}}{dt} = P - Q_r - Q_v - Q_f$ (C_{st} is the heat capacity, P is the heat with losses through conduction radially (Q_r), vertically (Q_v) and by convection (Q_f).	Transpiration measurements only. Can be up-scaled to stand transpiration. Woody or herbaceous measurements
Heat pulse/sap flow (Heat Ratio Method)*	In situ measurement (<200 mm)	Sub-hourly/hourly	Rate of movement of stem heat pulse, stem energy balance with continuous heat applied	Transpiration measurements only. Can be up-scaled to stand transpiration
Eddy Covariance (EC) (1 sensor)*	Sonic path length of 100 to 150 mm	20 to 60 min	$H = \rho_a C_P \overline{w'T'}$ (ρ_a is the air density and w' and T' are fluctuations in vertical wind speed and air temperature)	By definition, $LE + H = R_n - G$

**Techniques used in this study*

2.2.1 Sap flux density

In recent years the use of sap flow measurement techniques has increased as a result of on-going technological developments and the recognition that alternative approaches are often inapplicable (Hatton *et al*., 1995). In addition to this, sap flow measurements provide a specific estimate of transpiration *per se*, as opposed to total evaporation measurements (ET), therefore reducing the need for additional measurements and analyses to isolate the transpiration component (Hatton *et al*., 1995). Heat-based sap flow techniques are typically used at stem level and allow for whole-tree water-use measurements without influencing transpiration conditions (Schurr, 1998; Smith and Allen, 1996). Three commonly used sap flux density techniques are Heat Pulse Velocity (HPV), Thermal Dissipation (TD) and Heat Field Deformation (HFD). The HPV technique has been shown to provide accurate estimates of sap flow in both alien tree species such as *Acacia mearnsii*, and indigenous tree species such as *Podocarpus henkelii* (Smith *et al*., 1992; Dye *et al*., 2001; Everson *et al.,* 2007; Dye *et al*., 2008). According to Hatton *et al*. (1995), the HPV method is a practical approach to estimating the water-use of individual trees and heat pulse techniques are often the only reasonable alternative for measuring forest and woodland transpiration in the complex heterogeneous terrain that is often found in riparian areas. A typical HPV installation is provided in Figure 2.8.

Figure 2.8 HPV equipment installed on a *Warburgia salutaris* and a *Eucalyptus grandis*, indicating the thermocouples inserted above and below a heater probe around the tree stem

According to Hatton *et al*. (1995), a major concern of the HPV method is the up-scaling of sapflow estimates from a sample of individual stems (usually measured in litres) to an area basis (usually measured in mm). Without this up-scaling, the measurements may only be compared to other direct *in situ* measurements and cannot be used for broader hydrological interpretations. Up-scaling measurements taken in a plantation of uniform spacing and size is relatively easy and considered to be accurate. According to Wilson *et al*. (2001), difficulty may occur when attempting to extrapolate sapflow measurements from individual stems to a spatial scale comparable to a catchment, due to the large species diversity. The *a priori* determination of the area occupied by a tree in open woodlands or forests, which are particularly non-uniform in riparian areas, is problematic (Hatton *et al*., 1995). Ideally, all the trees in a given area should be measured and then up-scaled. However, due to the high cost and user effort required for this approach, it is not considered feasible.

According to Schwärzel *et al*. (2007), the temporal and spatial scales of transpiration studies are usually extended by modelling. Hatton *et al*. (1995) proposed that an appropriate alternative is to scale the measurements of tree water-use by a scalar of the tree characteristics, where the distribution of this scalar is known for the entire stand. Up-scaling methods have evolved significantly in the past, where Ladefoged (1963) considered a scalar relating crown size and area occupied by each tree to sapflow. Čermák and Kuæera (1987) used allometric relationships, based on tree basal area, while Werk *et al*. (1988) used leaf area estimates. The best relationship, as documented by Thorburn *et al*. (1993), was between the sap flux density and sapwood area and has since been used by Granier *et al*. (1990) and Dunn and Connor (1993). This indicates that more appropriate parameterisations of forest stands are required, to represent variation in site conditions and structural parameters including stand age, stand height, tree density, forest composition and the long-term range of flux rates (Cienciala *et al*., 1999).

2.2.2 Eddy Covariance (EC)

The eddy covariance (EC) method has recently become a valuable tool for evaluating the fluxes of carbon dioxide between terrestrial ecosystems and the atmosphere over a period of time (Baldocchi, 2003). According to Dye *et al*. (2008), the EC system is based on the very high frequency measurements (10 Hz) of water vapour and CO_2 above vegetation canopies. Such frequent measurements describe gas concentrations in eddies of air that are particularly important drivers of gas exchange above aerodynamically rough vegetation (Dye *et al*., 2008). According to Savage *et al*. (1997), this technique is beneficial for determining sensible (F_h) and latent ($L_v F_w$) heat flux densities, because the measurement is absolute. The data obtained from this technique can be checked, by confirming that the net irradiance (I_{net} measured separately with a net radiometer) satisfies the equation $I_{net} = L_v F_w + F_h + F_s$, where F_s is the soil heat flux density. The technique is especially valuable in studies where information on both the water and carbon fluxes are significant indicators of water-use efficiency. These may be compared to similar data obtained over vegetation in other countries. According to Baldocchi (2003), there are four factors which make this measurement technique popular. The first is that it is a scale-appropriate method, as it can provide canopy scale measurements. Secondly, this technique provides a direct measure of net carbon dioxide exchange across the canopy-atmosphere interface (Baldocchi, 2003). The third and fourth factors are that the area sampled by this technique can range from a hundred meters to several kilometers (Schmid, 1994) and that this technique can measure across a range of time scales.

Eddy covariance measurements above the canopy provide estimates of evapotranspiration at the high temporal resolution necessary to examine processes, but also at much greater spatial scales than sapflow (Wilson *et al*., 2001). Simultaneous measurements of sensible heat flux and other trace gas fluxes, such as carbon dioxide, are also feasible. These advantages, *inter alia*, allow for this technique to probe vital links between hydrological and other biogeochemical processes. In addition, simultaneous heat flux and energy balance estimates are used as independent checks on the validity of the measurements (Baldocchi *et al*., 1988).

One major weakness of the eddy covariance technique is that the size and shape of the representative region contributing to the measured flux, is not fixed in time (Horst, 1992). Eddy covariance measurements are sometimes difficult to interpret during weakly turbulent periods, usually at night (Paw U *et al*., 2000 and Baldocchi, 2003). The technique also cannot directly account for advection in areas of significant heterogeneous or complex terrain, limiting its applicability in some locations.

2.3 Cosmic Ray Probe (CRP)

Soil water is a key variable influencing a range of meteorological, hydrological, agricultural and ecological processes (Zreda *et al*., 2012). Understanding the soil water patterns at a range of spatial scales is important. However, this is challenging due to the spatial and temporal heterogeneity of soil water. The cosmic ray neutron method is a new and innovative soil water measurement technique that is capable of measuring area-average soil water (Franz *et al*., 2013). This method therefore fills the measurement gap in observational methods for measuring soil water at intermediate scales between point measurements and satellite pixels.

Cosmic ray neutrons originate in space. These high-energy particles penetrate the earth's surface and interact with atmospheric nuclei, which leads to the generation of fast neutrons (Jiao *et al*., 2014). These fast neutrons travel towards the earth's surface and are moderated primarily by hydrogen. This is due to hydrogens scattering probability or the elemental scattering cross-section, the logarithmic decrement of energy per collision and the number of atoms of an element per unit mass of material, which is proportional to the concentration of the element and to the inverse of its mass number (Jiao *et al*., 2014, Ochsner *et al*., 2013). Since hydrogen at the land surface is mostly in the form of soil water, the fast neutron intensity above the land surface is inversely correlated to the soil water. Therefore, the measured neutron intensity can be used to estimate soil water, if the other sources of hydrogen are accounted for.

The cosmic ray technology currently consists of the cosmic ray probe, which is a stationary instrument that is used for soil water monitoring and the cosmic ray rover, which is an instrument that is placed in a vehicle and driven around the area, for soil water mapping. The cosmic ray neutron probes provide a significant improvement in measuring area-average soil water, but their measurement footprints are still small in comparison to spatial resolution of current satellite soil water instruments. The cosmic ray rover could potentially be used to calibrate and validate satellite soil water products by conducting large scale surveys. The rover could also be used to provide maps to better understand soil water patterns and could potentially be used as a technique to delineate wetlands and riparian areas.

2.4 Surface and Groundwater Modelling

This research covers two models, the Soil and Water Assessment Tool (*SWAT*) and the groundwater driven *MODFLOW* model. The primary focus of the modelling component was the groundwater model (objective 3). However, the surface water model was included to assist in testing agroforestry scenarios.

2.4.1 Soil and Water Assessment Tool (SWAT)

The *SWAT* (Soil and Water Assessment Tool) is a conceptual, continuous time model developed in the early 1990s, to assist in water resource management, in order to assess the impact of management and climate on water supplies and non-point source pollution in watersheds and large river basins (Arnold, 2005). Forest growth, which is a more recent addition to the *SWAT* model, allows for a plant growth component. This model, which is continuously updated, has an improved weather generator, as well as the ability to read in daily solar radiation, relative humidity, wind speed and potential ET (Arnold, 2005). It is physically-based, uses readily available inputs and is computationally efficient to operate on large catchments over extended time periods (Everson *et al*., 2007). The *SWAT* model has an extension to Arcview and ArcGIS, which has increased the versatility of the model, and this spatial component makes it attractive to modelling hydrological components.

Internationally, the Soil and Water Assessment Tool (*SWAT*) model has emerged as one of the most widely used water quality watershed- and river basin–scale models, applied extensively for a broad range of hydrologic and/or environmental problems. The international use of *SWAT* can be attributed to its flexibility in addressing water resource problems, extensive networking *via* dozens of training workshops and the several international conferences that have been held during the past decade, comprehensive online documentation and supporting software, and an open source code that can be adapted by model users for specific application needs (Gassman *et al*., 2014). Although the *SWAT* model has been used in various catchments of South Africa, it has had limited applications as a teaching tool and for consultants. Most of the work undertaken has formed part of bigger research projects. A major reason for the limited use is the lack of available knowledge in South Africa for particular input parameters required by the model and a lack of skills to run the model.

The research undertaken in the modelling component of this project aims to answer the following question:

1. Is the Arc*SWAT* model an appropriate tool to use in a groundwater driven catchment in South African?
2. Can a set of guidelines be constructed to assist subsequent studies in South Africa?
3. What results can we obtain from this model and how could we use them practically?
4. Can Arc*SWAT* be linked to the *MODFLOW* model and should more efforts be provided for this linkage between groundwater and surface water modelling?

Models such as the Agricultural Catchments Research Unit (ACRU), the Soil Water Assessment Tool (SWAT), Système Hydrologique Européen (SHE) model group and WAVES are just some of the models used in South Africa. Due to the available data at the site of interest, the recent development of the ArcSWAT GIS interface and the sediment and nutrient information required for the project, SWAT was chosen as the most appropriate model to use. The input required for ArcSWAT is spatially explicit soils data, land use/management information, and elevation data to drive flows and direct sub-basin routing (Arnold, 2005). ArcSWAT lumps the parameters into hydrologic response units (HRU), effectively over-riding the underlying spatial distribution. These HRUs are grouped according to the topography, soils (type/structure/depth/chemical properties), land use and slope (Figure 2.9).

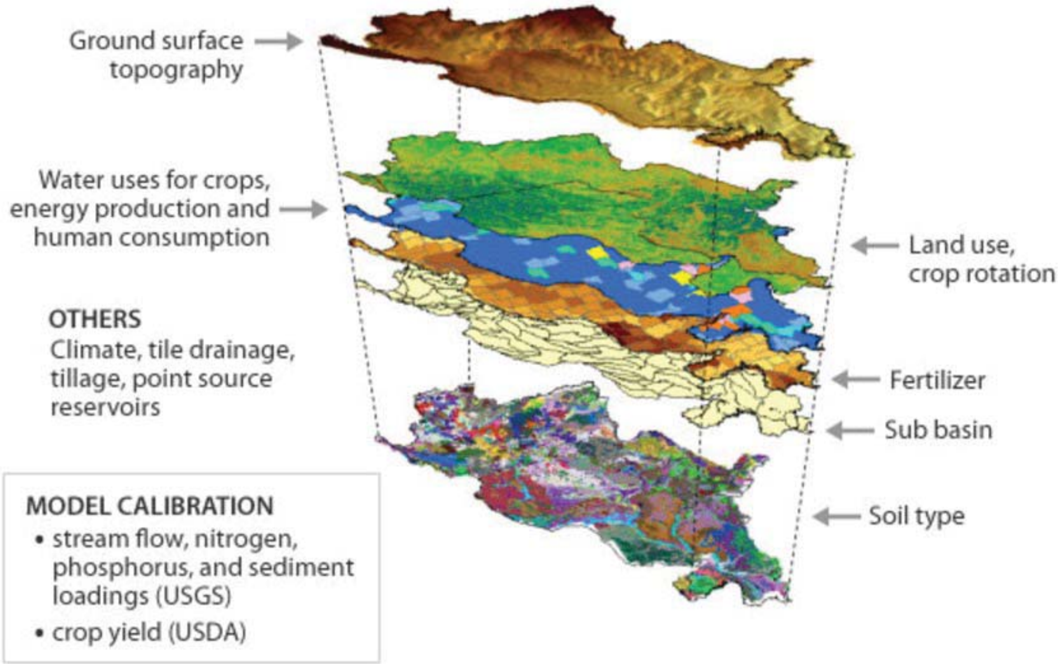


Figure 2.9 Conceptual layout of the ArcSWAT model setup

One of the most important drivers is the meteorological data, which has been vastly improved in this model over recent years. ArcSWAT has options to use measured solar radiation, wind speed, relative humidity and evaporation data. Daily rainfall and temperature data may be generated if unavailable or missing for the simulation period and there are no limitations to the number of rainfall and temperature gauges that can be used in the simulation (Neitsch *et al*., 1999).

2.4.2 MODFLOW

A common approach to hydrological modelling is based on the perception that rainfall impinging on the land surface will flow downhill to the rivers and streams (drainage lines) where it is more rapidly transport to the catchment outlet. In these situations, the steep topography and shallow soils will support surface (Hortonian flow), subsurface (Inter-flow) and saturated overland (Dunnian flow) runoff that is controlled to a very large extent by the topographical gradients (Figure 2.10). Discharge from the rivers is provided by rainfall contained within the topographical catchment (Beven, 2001).

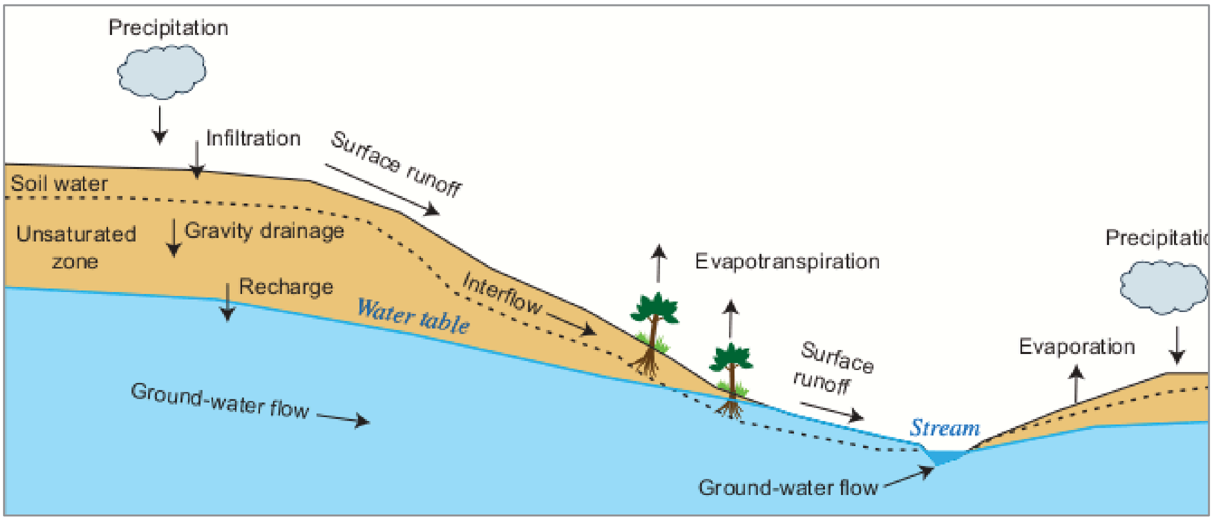


Figure 2.10 Illustration of the conceived hydrological processes under consideration in selection

2.4.2.1 Groundwater modelling in the Maputaland Coastal Plain

The primary aquifer in the Maputaland Coast Plain is characterised by an extensive, veneer of unconsolidated deep sandy deposits overlying an impermeable layer of mudstone (silt and clay) formed during the Cretaceous Period. These deep soils are highly permeable and exhibit little signs of surface runoff. Nearly all effective rainfall, after accounting for interception losses, is perceived to infiltrate the deep soils or pond in shallow depressions and wetlands. The infiltrate will percolate vertically downward under gravity drainage to the saturated zone (water table). This vertical flow will form the groundwater recharge that will then be transported laterally down the groundwater gradient toward discharge boundaries such as rivers, lakes and wetlands where they intercept the water table. Under these conditions the discharge in the drainage lines is derived from the recharge contained within the groundwater catchment rather than the topographical catchment.

The groundwater catchment may be significantly different from the topographical catchment in the coastal plain (Bate *et al.*, 2016). Current studies for the project area indicate a significant difference between the topographical (225 km^2) and groundwater catchments (206 km^2) for the Malangeni River feeding Kosi Bay just to the north of Vasi Pan. The groundwater catchment discharging through a flow monitoring site on the Malangeni River feeding Kosi Bay was derived from groundwater flow vectors and is shown overlying the topographical catchment (light green polygon) in Figure 2.11. Similar differences have been found for Lake Sibaya (also referred to as Sibayi) (Bate *et al.*, 2016) and Lake Mgobezeleni, just south of Lake Sibaya (Bate *et al.,* 2016). This is a crucial issue for impact studies if the anthropogenic activities are located inside the groundwater catchment but are external to the topographical catchment.

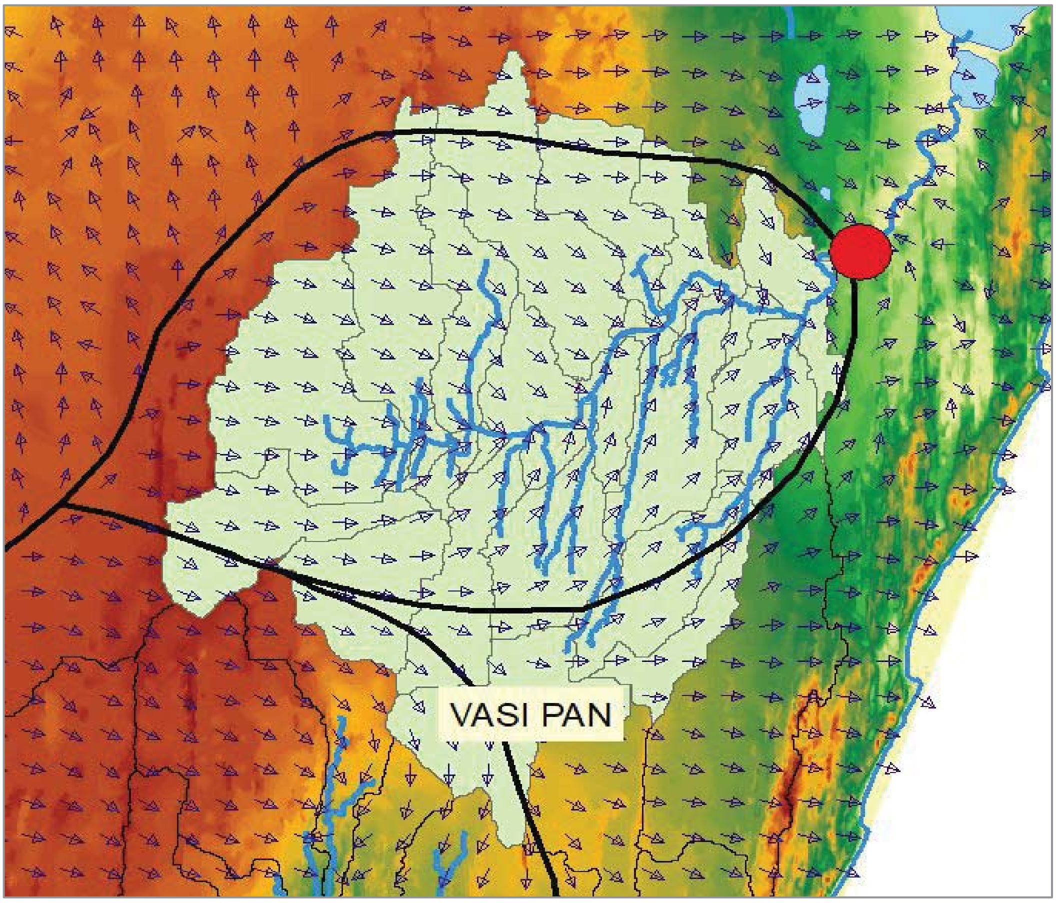


Figure 2.11 Catchment delineation for the study area using MODFLOW

Vasi Pan lies on the groundwater ridge between Lake Sibaya and Kosi Bay (Figure 2.11). Since Vasi Pan has no connected drainage lines (streams) it is difficult to specify a groundwater catchment area for this wetland. However, changes in the groundwater storage in either the Sibaya or Kosi Bay groundwater catchment can have a direct impact on the ridge and hence on Vasi Pan. A drawdown in either catchments can cause a drop in the groundwater ridge and/or its lateral movement. Consequently, the impact zone for Vasi Pan lies in both surrounding catchments.

With respect to the perceived difference in the dominant hydrological processes that are likely to control the movement of water from source (rainfall/recharge) to sink (rivers, lakes and the Indian Ocean), it is proposed that the groundwater dynamics are an essential component of the hydrological modelling of the downstream impacts from anthropogenic activities such as changes in land-use practice. Consequently, hydrological models with limited or no groundwater storage and transport capability are generally not suitable for hydrological impact studies on the Maputaland Coastal Plain.

2.4.2.2 Purpose of the model development

In this study, there is a need to determine the impact of anthropogenic activities on the groundwater storage and downstream resources in the Maputaland coastal plain where there is a very strong surface water-groundwater interaction. There is also a need to identify mitigation measures for the identified impacts. This study aims to evaluate various agroforestry options to reduce the footprint of land use impacts. Numerical models have been identified as a potential tool for an assessment of these management options. Consequently, this study has identified several potential models for application in this region and needs to evaluate their effectiveness in predicting the scale and magnitude of downstream impacts on the aquatic environment.

The impact of plantations and other land types is transmitted via the recharge and evapotranspiration pathways to the groundwater environment where it is slowly discharged through the aquifer into downstream drainage boundaries such as streams, lakes, wetlands and the Indian Ocean. Consequently, these groundwater components of the hydrological process are an essential component of the model selection, development and evaluation. The recharge and evapotranspiration processes operate over characteristic time scales of days while the flow of groundwater to the discharge boundaries can occur over weeks, months and years. Consequently, the model(s) need to simulate hydrological processes over an extended period at appropriate time intervals. This creates complexity in the selection of appropriate processes for inclusion in the model. Sub-daily time steps appropriate for evaporation processes create exceptionally large models simulating impacts over periods of many years. For pragmatic reasons, a daily time step has been chosen for the model development and evaluation.

Climatic changes also have a direct influence on groundwater storage that could mask anthropogenic impacts. The rainfall on the Maputaland Coastal Plain is known to undergo quasi-cyclic trends of about 18 years (Tyson, 1980; Dyer, 1979; Kelbe *et al*.,1983). The recent drought lasting for about 9-10 years conforms to this hypothesis. Consequently, an evaluation of groundwater trends should cover a minimum period of 18 years.

The groundwater model chosen for evaluation is MODFLOW from the USGS. The model features and processes incorporated into the Land Use impact study are described in more detail in the chapter on methodology under Section 5.4.2.

3. THE STUDY AREA

The Maputaland Coastal Belt has been identified as an important area due to severe water shortages, social and environmental sensitivities, compounded by a lack of knowledge in both ecological and hydrological fields. This is a groundwater driven site that has changed drastically over the last decade. Vasi Pan which is surrounded by the Manzengwenya plantation, is one of the few peat land areas in the country and potentially holds a high level of biodiversity.

The Vasi North area falls under the Indian Ocean Coastal Belt Biome and is classified as Maputaland Coastal Belt (CB 1, Mucina and Rutherford, 2006; Scott-Shaw and Escott, 2011). The surrounding natural areas are covered by a mixture of densely forested areas, interspersed dry grasslands (dominantly palm veld), hygrophilous grasslands and thicket. Due to the importance of the site and the abundance of indigenous species, nine tree species were selected to be fitted with the heat pulse velocity systems. The Eddy Covariance technique was chosen to measure total evaporation over various vegetation types. No plant water-use research has previously been carried out in the Vasi pan area. However, research on the groundwater interactions of the peat systems in the area is currently being undertaken (Grundeling *et al.* ongoing).

The Vasi North site is at latitude 27°10’50” S and longitude 32°41’22” E at approximately 68 m above sea level. The pan area is just inland of the greater Isimangaliso Wetland Park protected area, within Quaternary Catchment (QC) W70A and Quinary Catchment (QnC) 5525 (Figure 3.1). The surrounding areas have in the past been exploited for timber uses. Figure 3.2 shows the indigenous fringe area along Vasi North with the Pine species that have invaded the grassland areas.

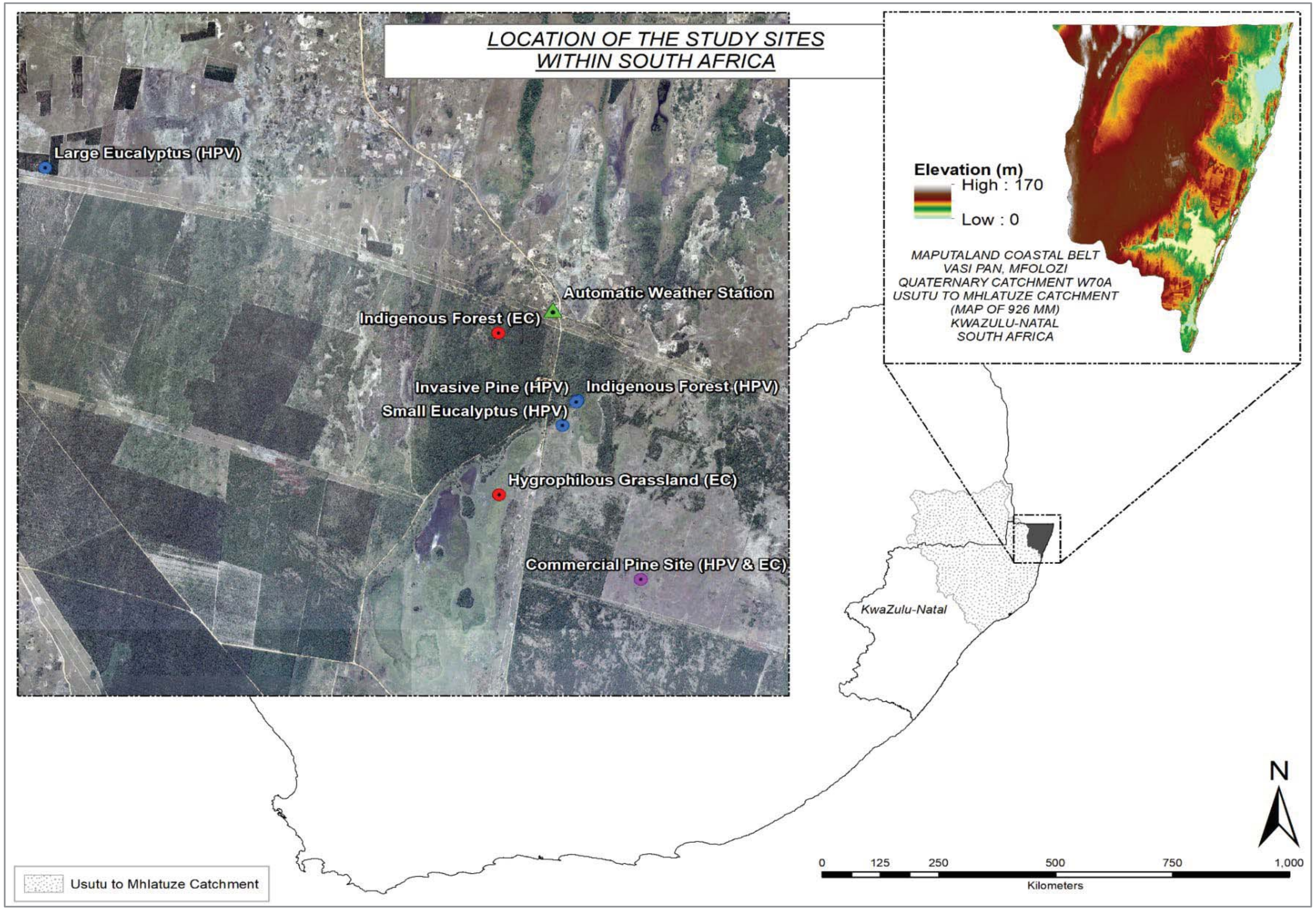


Figure 3.1 Location of the Tree water-use monitoring sites at Vasi Pan

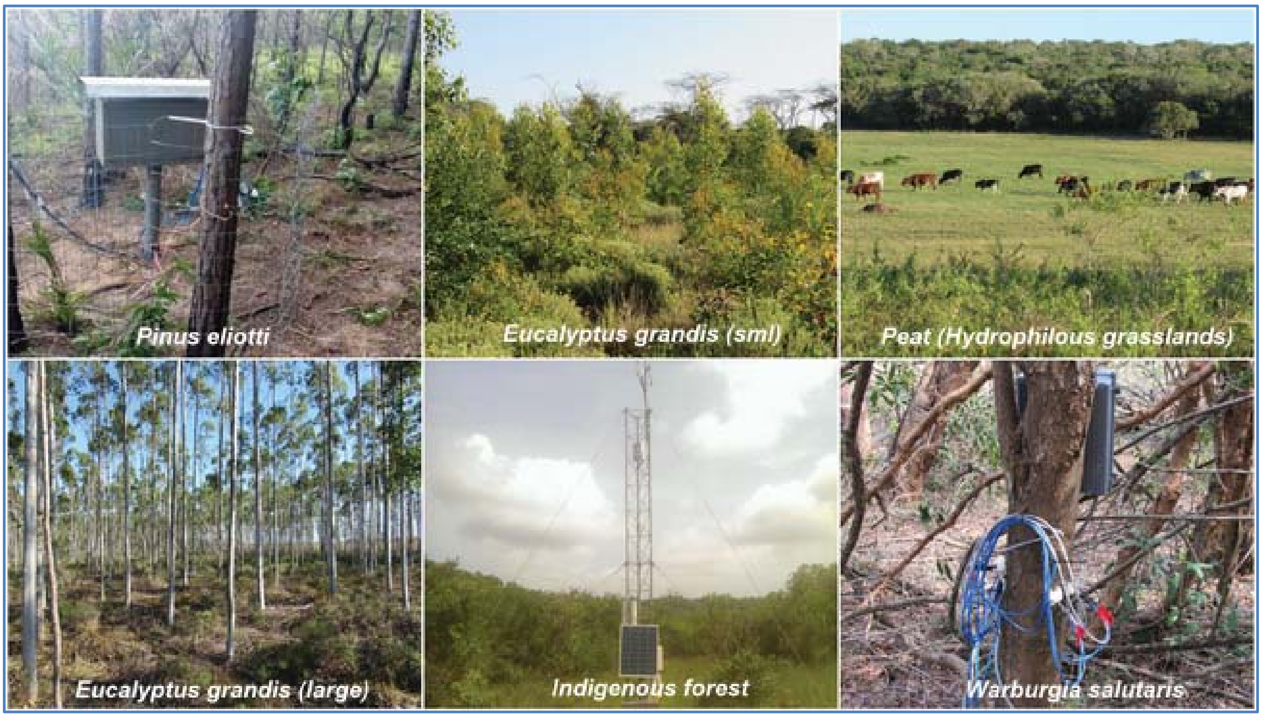


Figure 3.2 Fringe forest at Vasi North showing the presence of Pine species

The soils show evidence of high precipitation and leaching with the deep tertiary sands and pliocene/miocene beds overlaying cretaceous mudstone. The soils in the area are known to be generally infertile and of low agricultural potential. Approximately 80 % of the precipitation occurs in the summer months. The Mean Annual Precipitation is between 750 and 800 mm. There is a distinct dry season from May to August. Average temperatures range from 28.7 °C in the summer to 11.5 °C in the winter.

Groundwater monitoring is ongoing in the area the following resources available:

- SAEON has installed several shallow piezometers in the study area and deployed monitoring loggers that have been surveyed accurately.
- The borehole data from the ARC for a network of shallow piezometers and exposed water surface was surveyed and is assumed to have a high accuracy.
- The borehole data from National Groundwater Database (NGDB) was derived from many different sources over a large period of time and surveyed using very different methods. An accuracy indicator has been supplied and was used as the inverse of the weighting factor for the value reliability.
- The DWS (KZN) also provided a large data base (GRIP) of borehole information obtained from most of the regional drilling contractors. The reliability of the data varies greatly and cannot be used without careful considerations.
- JGAfrika has supplied borehole data for several areas that have been survey with a hand-held GPS with its inherent coordinate inaccuracies.

A correlation analysis of the water table profile and GRIP values in this highly permeable shallow primary aquifer indicated that the spatial covariance of the water table was >0.8 up to a distance of 500 m while the GRIP data showed an equivalent covariance at a distance of less than 50 m. Unless there are (unknown) significant hydraulic structures in the aquifer, it was expected that the GRIP and water table profile should show a similar spatial correlation structure. In a further attempt to use these data, the Altitude value for each site was compared directly to the SRTM raster. This highlighted two regions with very large discrepancies while the majority of the GRIP altitude values were >2 m higher than the SRTM elevation. Very few of these data would have been affected by the SRTM error from tall vegetation (Figure 3.3). These differences were used to modify the water level and provide an error weighting for setting the target values in the model calibration. These data have been used as head target in the relevant aquifer during the model calibration.

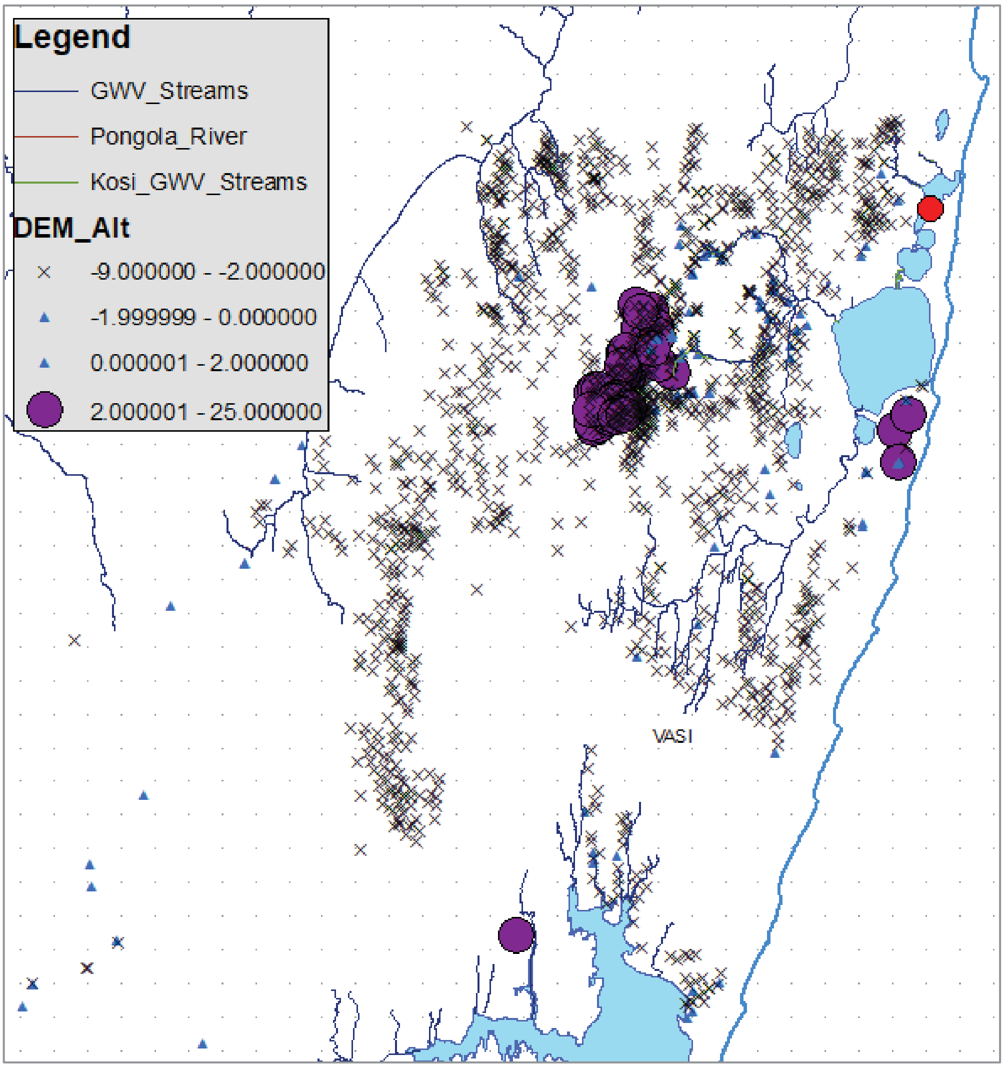


Figure 3.3 Elevation monitoring points in proximity to key water resources

4. SITE SELECTION

In order to determine the suitability of the study area, a number of sites within the Manzengwenya area were visited (Figure 4.1). These sites were assessed based on their ecological and hydrological representativeness and complexity and whether these sites would be able to meet the study objectives.

4.1 Ecological suitability

The forest sites chosen for measuring forest ecological processes fulfilled the following criteria:

(i) That the forest patches were well distributed across the plantation
(ii) That forest patches had a canopy cover of greater than 80 %
(iii) That forest expansion sites were in proximity to forest patches

That forest expansion sites were not recently damaged by fire or ongoing timber management activities. The sites chosen were deemed suitable to meet the study objectives.

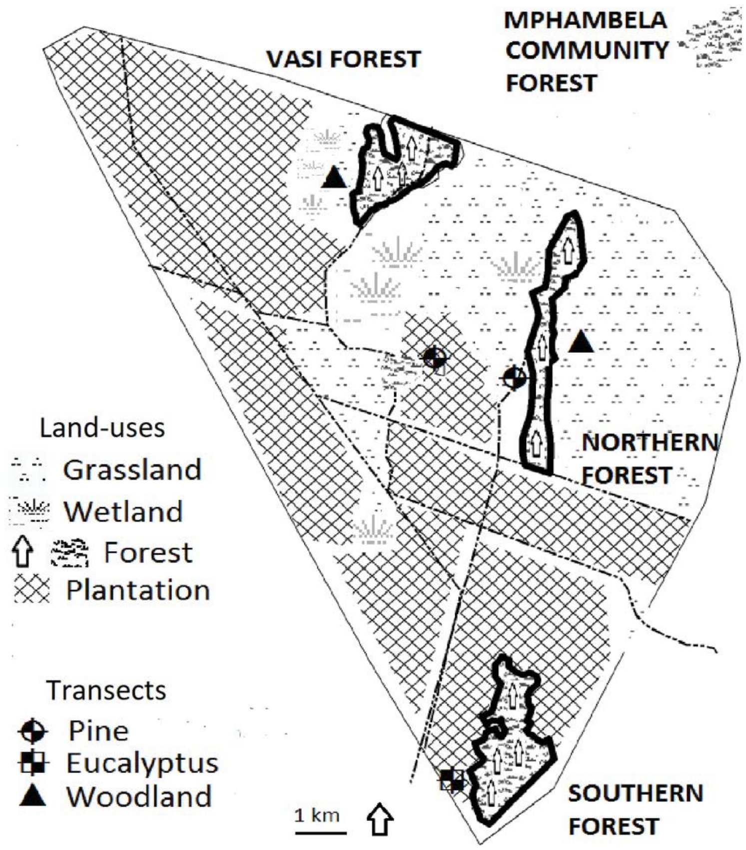


Figure 4.1 A graphic of Manzengwenya plantation, detailing the location of the forest patches and forest expansion sites

4.2 Hydrological suitability

Pine (*Pinus elliottii)* was planted in the surrounding Manzengwenya plantations in the early 1950s. These plantations were subsequently planted to *Eucalyptus grandis* which grew better in the warmer climate. The plantations have been handed over to the Ngonyama Trust which is leased back to the Department of Agriculture, Forestry and Fisheries (DAFF). This transfer is the biggest land reform project in the history of South African forestry (SA Forestry Magazine, 2012) to date. The surrounding natural areas are covered by a mixture of densely forested areas, interspersed dry grasslands (dominantly palm veld), hygrophilous grasslands and thicket.

This site is suitable to meet the hydrological objectives of this study as:

- It has both indigenous and commercial tree species that can be measured for the water-use component;
- It has many different land-uses in close proximity to one another that would allow for various agroforestry systems to be tested and measured;
- It is an ideal site to develop and test groundwater models, due to the vegetation and the community largely depending on this water resource; and
- It is an important area in terms of social aspects (government interest) as well as hydrological and ecological importance.

Five sites were selected for the long-term monitoring of individual tree sap flow, using the heat ratio method (HRM). A vegetation survey undertaken in the Vasi area, identified common indigenous tree species in the area (Starke, pers com., 2016). This research assisted in the selection of the indigenous tree species for monitoring. The species used in local plantations were also selected for monitoring. The selection of species for this project was motivated by a combination of expert advice, gaps in research areas and from various site visits where common and/or important species were identified within the selected site. Distance from wetlands and groundwater resources were also considered in the selection of groups of species. The selected sites consisted of a range of dominant land-uses in the area (Figure 4.2).

Figure 4.2 Land uses selected for HPV monitoring: a) large eucalyptus stand (5-year-old); b) mix indigenous forest invaded by pine; c) small commercial Eucalyptus stand (2-year-old); d) commercial pine stand

The indigenous forest site was a mixed species indigenous forest, in which several of the identified common species were present (Figure 4.2b). This site was located on the edge of Vasi Pan North. The four tree species that were chosen for long-term sap flow monitoring were *Albizia adianthifolia* (Flat Crown), *Sclerocroton integerrimus* (Duikerberry), *Apodytes dimidiata* (White-pear) and *Trema orientalis* (Pigeon wood) (Table 4.1). The sap flow data from each tree provided an insight into the water-use of indigenous tree species growing in competition with one another.

The invasive pine site was located on the fringe of a mixed indigenous forest (Figure 4.2b). At this site, four pine trees (*Pinus elliottii*) were selected for long-term monitoring (Table 4.1). The data provided an indication of water-use differences between introduced and indigenous species, when growing in competition with one another.

In consultation with the local community and the Isibusiso Esihle Education Centre, access was granted to monitor a five-year old eucalyptus hybrid woodlot that is owned by a local community member (Figure 4.2a). The large eucalyptus stand was in a dry and sandy grassland area north of the Vasi Pan (Figure 4.2)

The three trees that were selected for long-term monitoring provided a representation of varying diameter sizes within the woodlot (Table 4.1). The diameter size was determined by measuring the diameter of 30 trees within the woodlot. The measured diameters were sorted into three frequency distribution classes (low, middle, high). The mean diameter size for each frequency distribution class was calculated. HPV sensors were installed in trees with a similar diameter to the mean diameter for each frequency distribution class, to provide a range of sap flow data for trees representing the various size classes.

A stand of two-year old (in 2016) eucalyptus trees was selected for long term tree monitoring of sap flow (Figure 4.2c). This stand was located on the edge of Vasi North and close to the Vasi wetland boundary. At the start of the monitoring, many of the trees were too small for the instrumentation, therefore, three trees that were large enough for the placement of probes in the trunk, with diameters of 7-9 cm, were selected. This site provided an understanding of the water-use of the young introduced eucalyptus trees when planted in the wetland fringe.

A well-established pine plantation (Figure 4.2d) near the Vasi Pan was selected for the long-term monitoring of sap flow. This site was installed late in the study (June 2017) as it was decided that it would be beneficial to have simultaneous measurements of sap flow and ETa, measured by the eddy covariance system, in the commercial pine stand. Three trees, representing various size classes, were selected for installation (Table 4.1). The tree size needed for installation was determined by using the same method as previously described for the large eucalyptus trees. Pine plantations are a common land use in the area, therefore, the water-use data obtained from this site are vital for understanding the impact of pine plantations on the available water resources.

Table 4.1 Species physiology, HPV probe and CS 616 insertion depths at Vasi Pan

Site	Tree No. and Species	Height (m)	Diameter (cm)	HPV Probe Depths (cm)	CS 616 Depth (m)	Comment
Indigenous forest	1. *Albizia adianthifolia* (Flat Crown)*	4.7	11.6	Probe 1: 0.5 Probe 2: 1.0 Probe 3: 1.5 Probe 4: 2.0	Probe 1:0.2 Probe 2:0.5 Probe 3:0.8	Measurements started with HRM and SSS window period in 2015 * *Albizia adianthifolia* trunk damaged. Stopped 15/02/2017
	2. *Sclerocroton integerrimus* (Duikerberry)	5.1	9.6			
	3. *Trema orientalis* (Pigeon wood)	6	13.7			
	4. *Apodytes dimidiata* (White-pear)	5.4	11.2			Started 14/07/2016
Invasive Pine	5. *Pinus elliottii*	5.9	14.2	Probe 1: 0.5 Probe 2: 1.0 Probe 3: 1.5 Probe 4: 2.5		Measurements started with HRM and SSS window period in 2015
	6. *Pinus elliottii*	5.7	14.6			
	7. *Pinus elliottii*	4.6	13.7			
	8. *Pinus elliottii*	5.3	11.2			
Large eucalyptus	9. *Eucalyptus grandis*	16.2	15.5	Probe 1: 0.5 Probe 2: 1.0 Probe 3: 1.5 Probe 4: 2.5	Probe 1:0.2 Probe 2:0.5 Probe 3:0.8	Started 14/06/2016
	10. *Eucalyptus grandis*	15.2	11.3			
	11. *Eucalyptus grandis*	16.1	8.6			
Small eucalyptus	12. *Eucalyptus grandis*	12	8.1	Probe 1: 0.5 Probe 2: 1.0 Probe 3: 1.5 Probe 4: 2.0	N/A	August 2016
	13. *Eucalyptus grandis*	10	9			
	14. *Eucalyptus grandis*	10.6	7.9			
Commercial pine stand	15. *Pinus elliottii*	11.2	16.6	Probe 1: 1 Probe 2: 2 Probe 3: 3 Probe 4: 4	Probe 1:0.2 Probe 2:0.5 Probe 3:0.8	Started 30/05/2017
	16. *Pinus elliottii*	10.4	14.1			
	17. *Pinus elliottii*	15.6	17.6			

5. METHODS

A detailed overview of the ecological and hydrological methods is provided in this section. The set-up of input data for the models as well as initial simulations are also provided.

5.1 Ecological Sampling of Vegetation Types

The aim of the ecological study component in the project was to identify patterns in plant ecological, plant resource and plant water-use relationships that could be incorporated in agroforestry systems in Maputaland.

Table 5.1 Summary of objectives and methods used for the ecological objectives

Objectives	Methods summary
Investigate the response of natural forest to plantation forestry at Manzengwenya plantation and screen forest expansion for ecologically suitable agroforestry species	• Sampling natural forest within Manzengwenya to be used a reference forest for the study • Sampling woody species expansion on forest boundaries within non-harvested abandoned plantation stands and into clear-felled areas which had returned to woodland • Sampling nucleated clusters of forest expansion within central areas of unharvested plantation stands
Determine the rangeland condition and potential of the grassland communities at Manzengwenya and surrounding community managed areas	• Sampling of reference grasslands within relatively transformed community managed areas • Sampling of secondary grassland within clear-felled extant plantation areas • Estimating the veld condition of these grasslands based of comparative studies in the region
Identify the resource opportunities that indigenous woody plant species and grasslands could provide to agroforestry systems at Manzengwenya plantation	• Review of species uses with references to ethnobotanical and agroforesty application of species encountered within the ecological dataset

5.1.1 Natural forest expansion

This study component asked three main questions:

(i) Did the effects of land-use management on natural forest boundary areas (i.e. clear-felling and non-clear-felling of plantation trees) affect the compositional variation of forest species?

(ii) Did plantation stand variables (i.e. stem density, basal area and stem diameter) explain nucleation patterns of natural forest expansion in plantations?

(iii) Could these relationships (i.e. changes in compositional variation of natural species in relation to land-use) be used to screen indigenous species for their ecological preference to different agroforestry systems?

A reference for natural forest in this study was defined as having a closed forest canopy (>80% tree and <5% grass cover; Staver *et al*., 2011), that no historical evidence of plantation activity (e.g. plantation trees stumps were located within plots, and that plots were positioned within the boundary of natural forest or wooded vegetation that existed prior to plantations as determined from geo-referenced aerial imagery in 1947. Composition of reference natural forest patches was sampled along transects aligned perpendicularly to the forest edge using a sequence of plots. This sequence was considered to represent a forest chrono-sequence from the oldest, least disturbed areas, through to the youngest stands at the forest edge (van Wyk *et al*., 1996). Sixty forest plots were sampled along 15 transects from three forest patches within the plantation (Figure 5.1).

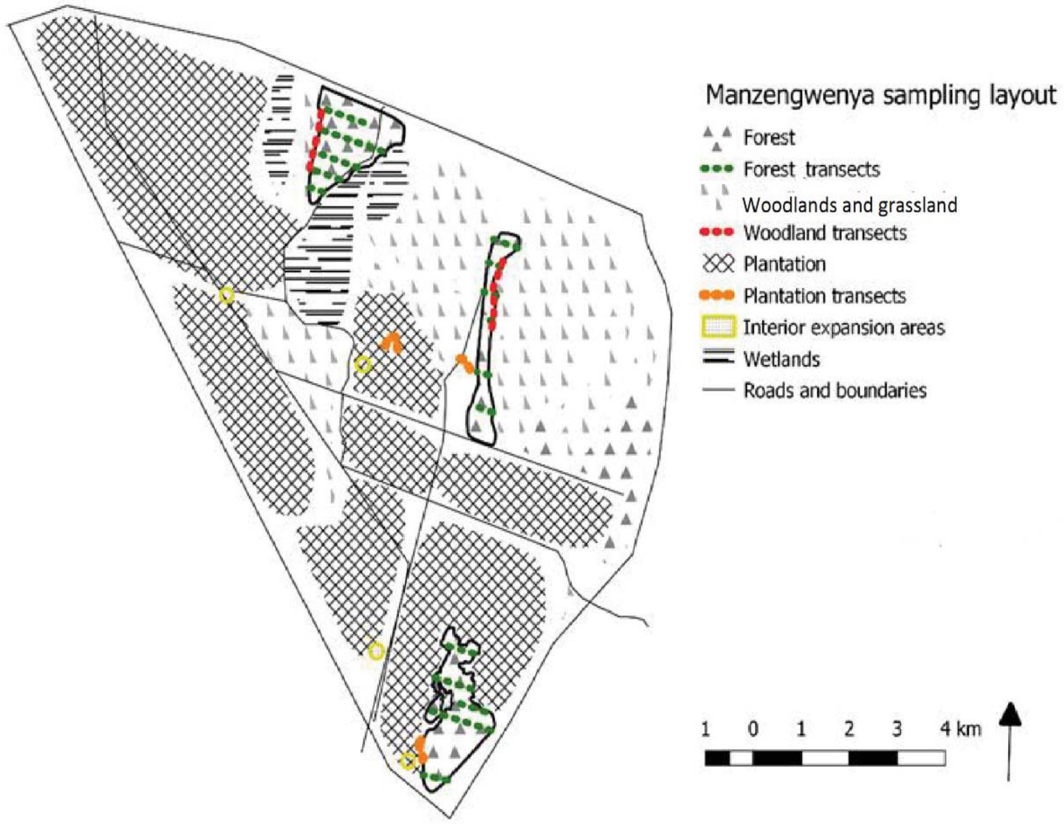


Figure 5.1 Natural forest and forest expansion sampling layout at Manzengwenya plantation. Forest edge expansion was investigated by sampling the selected boundary areas of natural forest, indicated by plantation and woodland transects. Interior or nucleated forest expansion was investigated within the interior of plantation stands (indicated by interior expansion areas).

The design to sample forest expansion on forest boundaries was to select 26 plantation plots and 30 secondary-woodland plots at an average of 150 m intervals along four transects on the edge of the reference forest. Stands on forest edges that represented forest expansion were stratified as either plantation (i.e. indigenous species growing with the understory of plantation stands) or secondary-woodland (indigenous species growing in clear-felled abandoned plantation lands). This was decided based on whether planted timber species were present or not. Forest edge expansion sites were located within <30 m from the reference forest edge (Geldenhuys, 1997) to minimise differences in species dispersal and soil conditions. Fire-return interval of transects was estimated by inspecting Landsat ™ imagery for burn scars between 1995 and 2015. Plots in each transect were assumed to have the same burning history. Burn scars were identified in true-colour by identifying changes in non-vegetated areas (dark hue pixels) to vegetation recovery (green pixels) after fire events in Landsat™ Quickview and geo-referenced images to show plot positions (Verlinden and Laamanen, 2006). Validation of this processes was conducted through maximum likelihood classification in ESRI ArcGIS. Fire-return intervals in woodland and plantation were calculated as:

$RI = \frac{\left(\frac{Y}{T1}\right)+\left(\frac{Y}{T2}\right)}{2}$	*(1)*

where *RI* = estimated fire-return interval;
T = number of burn scars per transect; and
Y = observed number of years.

In the plantation interior, two types of stands were stratified, those containing a dense stand forest regeneration and those with none (Figure 2.4). During the field work 15 sites were selected: eight in two pine stands and seven in three eucalypt stands. Each sample site was sampled with one plot in a dense stand of natural forest regeneration, and a second plot within the adjacent stand with none to sparse natural forest regeneration. This paired-sample approach would cut out the effect of site differences and the expectation is that the observed differences would more likely relate to cluster development as was shown in the Buffeljagsrivier study (Everson *et al*., 2016). The hypotheses to be tested were that there would be no difference in the plantation stand density, vertical stand structure, leaf area index, soil texture, soil water and macro nutrients between the two adjacent stands of dense and sparse natural forest regeneration.

Vegetation sampling for each plot was as follows. Canopy trees (i.e. all trees ≥5 cm stem diameter at breast height, DBH = 1.3 m) were recorded by species and stem DBH within a 400 m^2 circular plot. Sapling plants (i.e. plants with stems between 1-<5cm DBH) were sampled by count within a centrally located 100 m^2 circular sub-plot of the greater 400 m^2 plot. The average canopy height within each plot was estimated using a hypsometer for trees greater than five metres high, or otherwise a measuring pole was used. In plantation interior plots, an index of light interception was provided by five readings of LAI taken using a LICOR LAI-2200 plant canopy analyser during mid-summer. Topsoil samples from each plot were subjected to a standard chemical analysis at the Cedara College of Agricultural laboratories (Manson and Roberts, 2000).

In the forest edge expansion study, two-way indicator species analysis (TWINSPAN; Hill, 1979) was used to classify mature and regrowth forest, through sapling compositional association of forest plots with plantation or secondary-woodland plots. Composition of a plot for the input matrix was described by the number of stems per hectare. Cut levels of 0, 0.02, 0.05, 0.1, 0.2 were used. TWINSPAN was conducted using the Community Analysis Package (Seaby and Henderson, 2007). Importance Values (IVs), a composite measure of species contribution to a vegetation type, were calculated for canopy-sized individuals. Importance value was calculated as the mean value between the percentage basal area and percentage stem density of each species per vegetation type (Lugo and Helmer, 2004). Importance values were compared by Welch's ANOVA, with means compared using Tukey's test (Zaiontz, 2018).

5.1.2 Forest resources

A review of plant-use with respect to the woody species encountered at Manzengwenya plantation was conducted which defined two primary use-categories. (i) plant products and (ii) environmental services. Plant products included cultural and modern uses of plant species. Environmental services included cited agroforestry practices and any other recorded biophysical services. The following nine plant product use-classes were adapted from Pooley, (1980) Cunningham (2001) Nemudzudzanyi *et al*., (2010): fuel, building, fibre, craft, food, beverage, oils/gum/resins, medicinal and spiritual. Environmental service use-classes were: N-Fixation, fodder-bank, integrated pest management (IPM) microclimate manipulation, intercropping, boundary systems (Nair, 1993; Sinclair, 1999). An economic class 'economic potential' was also reviewed for each species, this refers to the species in the literature for commercial exploitation.

The search engines used for the review were: Google Scholar (Younger, 2010), FAO AGRIS (Celli *et al*., 2015), Bielefeld Academic Search Engine – BASE (Bäcker *et al*., 2017), ICRAFs Agroforestry database (AFT; Orwa *et al*., 2009) and Plant Resources of Tropical Africa - PROTA (Lemmens *et al*., 2012). Grey literature was kept to a minimum and every effort was made to cite peer reviewed articles from the closest possible geographic location to the study site. Data relating to physiognomic and chemical classes were not recorded in the species-use matrix.

Each plant species was assigned a resource-value (RV), i.e. the sum use-classes per species. Each use-class was assigned a species value (SV), i.e. the number of species recorded for a given use-class. Descriptive statistics tabulating the mean values and differences of these measures among forest, plantations and secondary-woodland were conducted using Welch's ANOVA with means compared using Tukey's test.

5.1.3 Grazing capacity

The grassland component in this study, asked three main questions: (i) Did the mean value of veld condition and grazing capacity differ across grassland types? (ii) How did this differ according to estimates of other grasslands in Maputaland? (iii) Did grasslands with greater grazing capacity have greater soil clay and carbon mean values?

Grasslands were sampled among a series of dune ridge and interdune depressions in community rangelands at KwaZibi and MvelaBusha, and at Manzengwenya plantation (Figure 5.2) Grassland types were stratified based on landscape position and botanical indicator species following the work of Van Wyk, (1991); Matthews, (2005) and Pretorius *et al*., (2016). Five naturally occurring grassland types were identified: ephemeral wetland depression grasslands, hygrophilous grassland, geo-suffrutex woody grassland, secondary grassland and dune-ridge grassland (Figure 5.2).

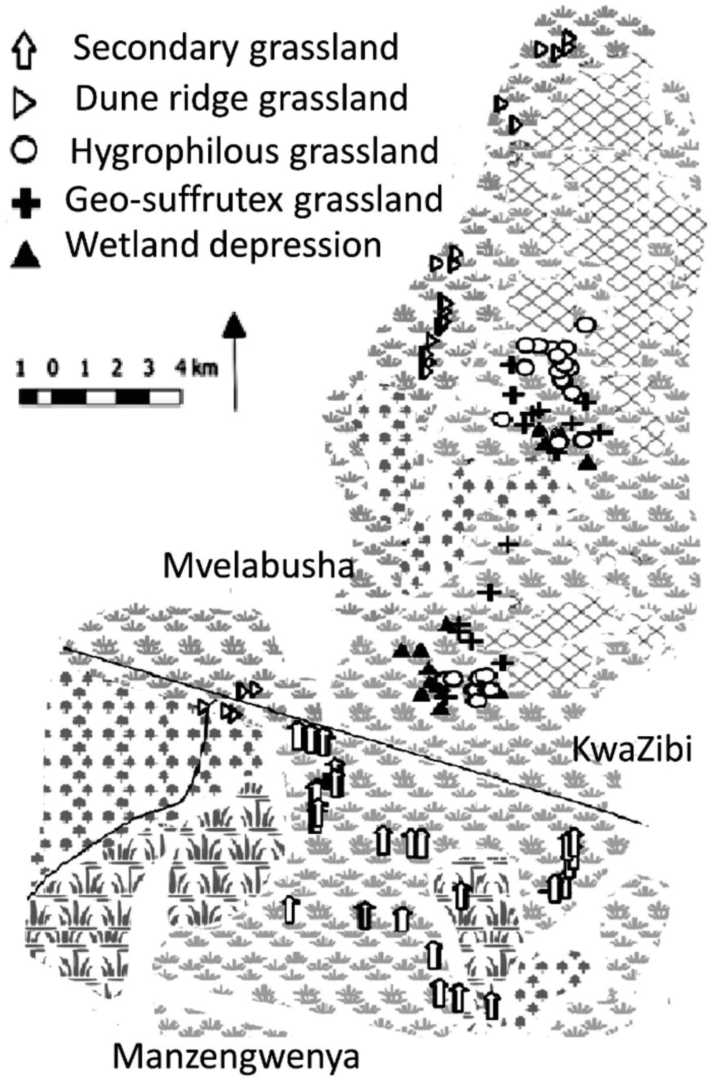


Figure 5.2 Layout of grassland plot on the north east corner of Manzengwenya plantation and the adjacent districts of Mvelabusha and KwaZibi.

The position of each plot was chosen using the sampling design tool in ARC GIS 10. Final plot positions were subject to on-site decisions chosen by random number generation. Species composition for each grassland type was determined by the percentage contribution of each species to the total dry weight. Dry weight was calculated using the dry-weight-rank technique (Mannetje, 1963) and the comparative yield technique (Haydock and Shaw, 1975). The dry-weight-rank technique ranks the three species judged to contribute the most to dry weight while the comparative yield technique was used to apply a forage value to quadrats. The forage value of each grass species was adapted from previous veld condition assessments in Maputaland. Grasses were sampled through a series of 20 x 1 m^2 quadrats along north-south orientated transects in each grassland type. Botanical composition was recorded following Braun-blanquet cover abundance values (Wikum and Shanholtzer, 1978) for each plant species within a 100 m^2 circular plot located in the centre of the transect. Soil samples from the upper ten centimetres of the A horizon were collected for chemical analysis at Cedara College of Agricultural laboratories (Manson and Roberts, 2000). Variables of percentage soil organic carbon (SOC), percentage clay (C) and percentage nitrogen (N) were compared among grassland types using Welch's ANOVA, with means compared using Tukey's test (Zaiontz, 2018).

Veld condition is used to describe vegetation in terms of its long-term potential for livestock production (Tainton, 1999) . The method we used followed an Ecological Index approach, where each grass species is assigned an ecological weighting. Ecological weighting of grass, forb and sedge species were sourced from previous studies conducted in the Maputaland region (Potgieter, 2008). Ecological weighting applies numerical values to the increaser/decreaser classification of grass species (Table 5.2).

Table 5.2 Correspondence between increaser/decreaser and ecological class scoring for veld condition assessments

Increaser/Decreaser Category (Trollope *et al.*, 1989, Potgieter 2008)	**Ecological class (Potgieter, 2008; Bothma, 2004).**	**Ecological Score: (0-10)**
Decreaser: a species which decreases if veld is mismanaged, overgrazed or underutilised	**Class 1:** Valuable and palatable tufted and stoloniferous grass species with a high productivity and a high grazing value.	**10**
Increaser: a species which increases if veld is selectively utilised or underutilised	**Class 2:** Tufted grass species with an intermediate productivity and a moderate grazing value.	**7**
Increaser 2a: grass species that is dominant in poor veld but increases as a result of light overgrazing	**Class 3:** Tufted grass species with a high productivity but a low grazing value.	**4**
Increaser 2b: A grass species that is dominant in poor veld but increases after moderate overgrazing.	**Class 4:** Generally unpalatable and perennial tufted and stoloniferous grass species with an intermediate productivity and a low grazing value	**4**
Increaser 2c: A grass species which is dominant in poor veld and increases after heavy overgrazing.	**Class 5:** Unpalatable annual grass and forb species with a low productivity and a low grazing value	**1**

The veld condition for each grassland type was calculated by multiplying the ecological score of each grass species recorded (between one and ten) with the percentage compositional contribution of that species to a given grassland. This resulted in a potential veld condition score of up to 1000 for each grassland, which was converted to percentage value.

To remain consistent with previous veld condition assessments in Maputaland, grazing capacity was calculated by following equations used by Potgieter,(2008), who compared grazing capacity among Sileza Nature reserve with Tembe Elephant Park and the Tshanini Community areas. The results of these equations were then cross-referenced with suggested long-term grazing norms for the region, as provided by DAFF (Avenant, 2016).

Three equations were used, the outputs of which were reported as Large Animal Units (LAU) per hectare. The equivalent term, Large Stock Unit (LSU) is also used by rangeland scientist. These two terms are based on a 450 kg animal, putting on a mass of 0.5 kg per day when consuming forage which is 55 % digestible (Trollope *et al*., 1990). The first equation (Table 5.3), is a standard empirical equation developed by Danckwerts (1989) and has been used broadly for savanna regions in South Africa. The equation assumes an annual rainfall of 419.7 mm which is then adapted for a given region or scenario using local rainfall inputs. The second equation (Table 5.3), a slightly adapted version of the Danckwerts (1989) equation, was developed by Ezemvelo KwaZulu-Natal Wildlife for the use of veld condition assessments in nearby Tembe Elephant Reserve. The third equation (Table 5.3) was developed by Bothma *et al*. (2004), which considers variables of rainfall, fire, percentage grass cover and accessibility.

Table 5.3 Equations used to calculate grazing capacity

Reference	Equation
(2) Danckwerts (1989)	*Grazing Capacity (in LAU per ha) = [(-0.03 + 0.00289)(X1)] + [(X2 – 419.7)(0.000633)]* (2) *where: X1 = Veld condition %; and* *X2 = Mean annual precipitation.*
(3) Danckwerts (1989) – adapted by Ezemvelo	*Grazing Capacity (in LAU per ha) = 0.7{[(-0.03 + 0.00289)(X1)] + [(X2 – 419.7)(0.000633)]}* (3) *where: X_1 = Veld condition %; and* *X_2 = Mean annual precipitation.*
(4) Bothma *et al*., (2004)	*LAU per100ha (then converted to per hectare) = 0.547 {[c + (r – 419) x 0.23] x a x f (log10g – 1)0.4}* *where:* *c = veld condition %* *r = mean annual rainfall in millimetres* *g = percentage grass cover* *a = accessibility of habitat to plains wildlife on a scale of 0.1 to 1, with 0.1 inaccessible and 1 = totally accessible* *f = fire factor on a scale of 0.8 to 1, with 1 = absence of fire* *419 = standard mean annual rainfall in millimetres for savanna areas*

5.2 Hydro-meteorological Techniques

5.2.1 Meteorological station

The methods used in the study require meteorological data as an input when performing calculations to determine reference total evaporation (ET_o). These data were obtained from the meteorological station located at the Isibusiso Esihle Education Centre near Vasi Pan which was erected on the 20th of November 2014 (Figure 5.3). The station was placed at a flat uniform grassland area to meet the requirements for FAO 56 reference evaporation calculations. Rainfall (TE525, Texas Electronics Inc., Dallas, Texas, USA) at a height of 1.2 m from the ground was measured with additional measurements at a height of 2 m for air temperature and relative humidity (HMP45C, Vaisala Inc., Helsinki, Finland), solar irradiance (LI-200, LI-COR, Lincoln, Nebraska, USA), net radiation (NR-Lite, Kipp & Zonen, Delft, The Netherlands) windspeed and direction (Model 03002, R.M. Young, Traverse city, Michigan, USA). These were measured at a 10 second interval and the appropriate statistical outputs were recorded every hour. The data from the station was downloaded regularly during site visits.

Figure 5.3 Campbell Automatic Weather Station installed at Siphesihle Bukhosini Science Centre

5.2.2 Sap flux density

A Heat Pulse Velocity (HPV) system using the heat ratio algorithm (Burgess, 2001) was set up to monitor long-term sap-flow on all of the selected trees over the monitoring period.

5.2.2.1 Installation of the Heat Pulse Velocity system

HPV systems were installed at five sites, following the principles of the heat ratio measurements, as detailed in Burgess *et al*. (2001). A total of 17 trees were instrumented with HPV sensors for long-term monitoring in the Vasi Pan area. The sapwood depth was assessed, using an increment borer, to determine the depth to which the HPV probes were to be inserted (Figure 5.4a). These depths varied, according to the depth of the sapwood, and were located to represent four different concentric rings of the sapwood area, for scaling to the water-use of the whole tree (Table 5.4), as sap flow velocities can vary radially across the xylem (Wullschleger and King, 2000).

The HPV system consisted of an 18-gauge hypodermic needle, with a 1 cm wound heater of constantan wire at the distal end. The needle with the heater was 1.8 mm in diameter and 35 mm long. The needle heater was inserted into a 2.5 mm outside diameter brass tube, which was inserted into the sapwood area. The thermocouples, made of type T copper-constantan, were embedded in PTFE tubing (outside diameter 2 mm) and were located at equidistant distances (5 mm) from the central needle heater. They were inserted to the predetermined depths per calculated sapwood area. A single tree installation consisted of four pairs of probes (with each set consisting of a needle heater and an upper and lower thermocouple), which were inserted radially to varying depths in the tree stem (Figure 5.4b).

Figure 5.4 HPV installation setup at Vasi Pan, (a) assessment of sapwood depth using an incremental borer, (b) temperature thermocouples placed equidistance above and below the needle heater (c), metal fence to prevent disturbance from cattle and filler foam placed around probes to provide insulation

The system was controlled and data were collected, using a CR1000 datalogger (Campbell Scientific Inc., Logan, Utah, USA) connected to an AM 16/32b multiplexer (Campbell Scientific Inc., Logan, Utah, USA). This system was programmed to measure the hourly sap flow velocity. The selected trees were monitored over a 12-month period, from July 2016 to July 2017, which allowed for an understanding of the seasonal variations in a tree's water-use. To ensure that the data were not affected by outside variables, such as, incoming solar radiation or heat loss, insulation foam was placed around the line heater and temperature probes, which also assisted in holding the probes in place. A metal fence was erected around each tree to prevent any disturbance by cattle (Figure 5.4c).

5.2.2.2 Analysis of HPV data

The HPV data were screened to identify periods of missing data or periods of data showing unrealistically high spikes or low negative values, which is termed 'noisy' data. Noisy data is data that does not follow the trends of the other probes, and/or does not follow any logical relation to the preceding or following values, or environmental changes (Dye *et al.*, 2008). These data are, therefore, considered to be faulty. When patching periods of missing or noisy data for one probe within a tree, good quality data from neighbouring probes in the same tree were used to patch the data. The probe with the highest correlation to the probe being patched was identified through correctional analysis. A simple linear regression was used to patch the data from the functional probe. In some instances, data for all probes in a tree were missing or noisy. In these cases, data from adjacent trees of the same species were used to correlate and patch the affected periods of data. When whole trees were found to have long periods of missing or noisy data, it was best to patch the data with weather station data that were recorded at the same frequency as the HPV data. A correlation between good quality HPV data, before and after bad data, was used to preserve the seasonal variability. ET_o, which was derived by using the Penman-Monteith equation, was used to patch the missing/noisy data. Sap flow is directly related to the availability of energy and therefore, atmospheric conditions. This gives confidence in the accuracy of this technique for in-filling data.

Once the data patching process is complete, it is essential to confirm the "zero flux" value. This value refers to the times of the day when sap flow/transpiration is expected to be zero. It is expected that the lowest values in the diurnal HPV trends will stabilize at around zero; however, a slight misalignment in the position of the thermocouples probes in a tree, cause this not to be the case (Dye *et al.*, 2008). To correct the data, it is necessary to apply an offset to the data, in order to align the lowest values with zero. This offset was calculated by averaging the values from 22h00 to 2h00 each night and applying the offset to the following day.

The raw HPV data were converted to whole-tree sap flow rates in litres, using the following procedures. The area of non-functional xylem (wounding) around the thermocouples was accounted for by using wound coefficient that are described by Burgess *et al*. (2001).

$$V_C = bv_h + cv_h^2 + dv_h^3$$
$$b = 6.6155x^2 + 3.332x + 0.9236$$
$$c = -0.149x^2 + 0.0381x - 0.0036$$
$$d = 0.0335x^2 - 0.0095x + 0.0008 \qquad (5)$$

where
v_c is the corrected heat pulse velocity; and
v_h is sap flow velocity and *b*-*d* are the correction coefficients specific to the size of the wound (*x*).

Following the procedure described by Marshall (1958), sap flux densities were calculated by accounting for moisture content and wood density. The conversion of sap flux density to sap flow was calculated as a product of sap flux density and the cross-sectional area of conducting sapwood (Dye *et al.*, 2008). Sap flow ($L.h^{-1}$) was calculated as the sum of the products of sap flux densities and the cross-sectional area for individual tree stem annuli. Following the work of Dye *et al*. (2008) and Clulow *et al*. (2013), sap flow was assumed to equate to the tree transpiration and tree water-use. Daily water-use ($L.day^{-1}$) was calculated for each site as an average of the individual trees that were monitored.

5.2.2.3 Monitoring of volumetric soil water content

Soil water content probes were placed at each site to measure the hourly volumetric water content (VMC). These measurements coincided with the hourly sap flow measurements of the HPV systems. At each site, a pit was dug and three Campbell Scientific CS 616 probes, connected to channels on the CR1000 datalogger, were inserted horizontally at a 0.2, 0.4 and 0.8 m, respectively, to ensure the soil water profile was monitored. Each site had similar soils of a deep uniform, sandy profile. The VMC measurements assisted in the interpretation of the tree water-use data, supporting the findings with regards to the response of trees to dry and wet periods.

There was an issue with the logger program with regards to data storage and unfortunately, only a week's worth of data was stored on the memory card. The soil water content data for each site was incomplete and therefore, data analysis was limited

5.2.2.4 Tree physiology measurements

To interpret the tree water-use data, tree physiology variables, such as growth measurements, leaf area index, wood density and moisture content, were measured.

The height and diameter of the trees installed with HPV systems were measured pre- and post-study, to provide tree growth increment data. Growth measurements were taken for the plantation species on each field visit (approximately every six weeks). Replicated measurements for the indigenous tree species were not possible, due to the lack of available plants near the setup HPV system. The diameter of 30 trees from each stand in the small eucalyptus, large eucalyptus and pine plantations were recorded three times during the monitoring period. The remoteness of the monitoring site made it difficult to record growth measurements at more frequent and regular intervals.

The Leaf Area Index (LAI) can be defined as "one half of the total surface area of green leaves per unit of ground area" (Woodgate *et al.*, 2015). Only "one half" is considered, since stomata are generally confined to the lower (abaxial) leaf surface. LAI measurements are important for understanding the vegetation structure and functioning in a varying climate. The measurements are directly related to tree water-use, as it is directly related to rate of photosynthesis and evapotranspiration of the canopy (Running, 1984; Running and Coughlan, 1988; Woodgate *et al.*, 2015). Ground-based LAI readings (LAI 2200, LI- COR Inc., Lincoln, Nebraska, USA) were taken at all the sites during each site visit. A measurement sequence of five above the canopy readings, and then 10 below the canopy readings, were replicated three times at each site.

At the end of the monitoring period, measurements of woody density, the moisture content and width of wounded (non-functional) xylem around the thermocouple were recorded, and used to convert heat pulse velocity to sap flux density (Marshall, 1958). The width of wounding was assessed by removing a sample surrounding the thermocouples and line heater, and measuring the width of damaged xylem (Figure 5.5). Three wood samples were extracted from each tree species, using a chisel (Figure 5.5). The samples were sealed in air-tight bags and analysed in the laboratory for density and moisture fraction.

Wood density was calculated as the over-dry mass per unit of the green volume, which was determined by the samples' displacement in water (Malan, 2005). The samples were placed in containers and immersed in water for 30 minutes; they were then used to determine the weight of the displaced water. The container was placed on a scale and a pin was used to fully submerge the wood in the water, without touching the sides of the container, and the subsequent weight of displacement was recorded. The weight of displacement is equal to the green volume of the wood. The samples were placed in an oven at 105 °C for 24 hours, providing a constant mass. The moisture content of the under bark was determined by using the wet mass of the wood, taken before its immersion in water, as well as the oven-dried mass. Table 5.4 summarises the data obtained from these samples.

Table 5.4 Tree specific data required for the calculation of sap flow

Trees species	***Wood density (cm^3g^{-1})***	***Moisture fraction***	***Average wounding (mm)***
Albizia adianthifolia *(Flatcrown)*	*0.6*	*0.91*	*6*
Sclerocroton integerrimus *(Duikerberry)*	*0.6*	*0.91*	*6*
Apodytes dimidiate *(White-pear)*	*0.6*	*0.91*	*6*
Trema orientalis *(Pigeonwood)*	*0.6*	*0.91*	*6*
Pinus elliottii	*0.5*	*0.43*	*6*
Eucalyptus grandis	*0.7*	*0.8*	*6*

Figure 5.5 Assessment of wood density and wounding widths required for the calculation of corrected sap flow

5.2.3 Eddy Covariance

The eddy covariance (*EC*) method provides a direct measure of the vertical turbulent flux of a scalar entity of interest F_s across the mean horizontal stream lines (Swinbank, 1951) providing fast response sensors (~10Hz) for the wind vector and scalar entity of interest are available (Meyers and Baldocchi, 2005). For a sufficiently long averaging period of time over horizontally homogeneous surface, the flux is expressed as:

$$F_s = \rho_a \overline{w's'}$$	*(6)*

where ρ_a is the density of air;
w is the vertical wind speed; and
s is the concentration of the scalar of interest.

The primes in Equation 6 indicate fluctuation from a temporal average (i.e., $w' = w - \overline{w}$; $s' = s - \overline{s}$) and the over bar represents a time average. The vertical wind component is responsible for the flux across a plane above a horizontal surface.

Based on Equation (6), the sensible heat flux H can be expressed as:

$$H = \rho_a c_p \overline{w'T_s'}$$	*(7)*

where c_p is the specific heat capacity of air;
w' denotes the fluctuation from the mean of the vertical wind speed; and
T_s' is the fluctuation of air temperature from the mean.

The averaging period of the instantaneous fluctuations, of w' and s' should be long enough (30 to 60 minutes) to capture all of the eddy motions that contribute to the flux (Meyers and Baldocchi, 2005). The *EC* technique, when properly applied, can be used routinely for direct measurements of surface layer fluxes of momentum, heat, water vapour, and carbon dioxide between a surface and turbulent atmosphere (Savage *et al*., 1997; Massman, 2000; Massman and Lee, 2002; Finnigan *et al*., 2003). Like other micrometeorological methods, an adequate fetch is required for the *EC* method; a fetch to height ratio greater than 100 is usually considered adequate (Wieringa, 1993). The *EC* measurements of w' should ideally be at a height that allows small-sized eddies between the anemometer transducer to be sensed (Savage *et al*., 1995). If the sensor height is too close to the canopy small-sized eddies may not be sensed, resulting in a possible underestimation of the flux. Savage *et al*. (1995) suggested that measurements, under unstable conditions above short turf grass surface, at a height of 1 m above the plant canopy should be sufficient without need of corrections for spectral attenuation of the eddy structures from spatial averaging.

The *EC* method requires sensitive, expensive instruments to measure high frequency wind velocities and scalar quantities. Besides, eddy covariance data need rigorous quality control and filtering, such as anemometer tilt correction (coordinate rotation, planar fit), spike detection, and trend removal (Meyers and Baldocchi, 2005). Sensors must measure vertical wind speed, sonic temperature and atmospheric humidity with sufficient frequency response to record the most rapid fluctuations important to the diffusion process (Drexler *et al*., 2004).

Figure 5.6 Transport and installation of a mobile Eddy Covariance system in the hygrophilus grassland and on a lattice mast in the indigenous forest

5.2.3.1 Selection of Eddy Covariance monitoring sites

Three sites were selected for monitoring the total evapotranspiration (ET_a) of the selected plant communities, using an eddy covariance system. Two EC systems were available for use in this study. One system was a permanent lattice mast, which was left on site to collect continuous data, while the other was a portable EC system on a trailer, which could easily be moved from site to site, to monitor short window periods. The length of the monitoring periods by the portable EC systems was limited by the battery life and the cost of equipment security, as local guards were employed to ensure that the equipment remained undisturbed.

The sites selected for monitoring are representative of the dominant land uses in the area. The natural vegetation in the area is grassland; however, this has changed over time, with the exclusion of fire leading to the increased density of indigenous forests and the introduction of forestry to the area since 1960. The lattice mast was placed in an indigenous forest with a canopy height of 4 m. The site was well-hidden and, therefore, the EC system was left to continuously collect data from the date of its installation in December 2016 until July 2017. This provided an insight into the seasonal changes of the forest's total evapotranspiration. The sites selected for monitoring, using the portable trailer EC system, were a Vasi Pan hygrophilous grassland and a commercial pine stand. The monitoring window for each site was approximately two to three weeks (Table 5.5). The Vasi Pan hygrophilous grasslands provided a reference landscape (seasonally wet grassland) to compare how the changes in land use differed according to the water-use, as opposed to the previous natural landscape. This provided insight into how land use changes in the Vasi area have affected water resources.

Table 5.5 EC monitoring periods (days), where useable data was obtained, for the selected land uses in the Vasi area

EC Sites	*2016*			*2017*							
	Oct	*Nov*	*Dec*	*Jan*	*Feb*	*Mar*	*Apr*	*May*	*Jun*	*Jul*	*Aug*
Indigenous forest					*12*	*31*	*30*	*10*	*30*	*7*	
Commercial pine stand									*30*	*31*	*12*
Hygrophilous grassland		*8*	*14*		*14*	*22*	*10*	*7*			

5.2.3.2 Installation of Eddy Covariance systems in the field

The EC technique was chosen to measure the total ET over the mixed species stand and over grasslands. To do this, an extended Open Path Eddy Covariance system (OPEC) was used to ensure that all the necessary components were measured (Figure 5.7). Both EC systems used in the study were fitted with the following: (a) a net radiometer (NR-Lite), which measured net radiation; (b) Soil Heat Flux plates (HFP01 non-self-calibrating), which measured spatially averaged soil heat flux; (c) the averaging soil thermocouple probes (TCAV-L), which provided the average temperature of the top 60–80 mm of soil; (d) soil water content probes (CS616), which measured the volumetric water content in the soil; and (e) a IRGASON (Campbell) or a Campbell Scientific EC150 system, which measured the fluxes of carbon dioxide and water vapour. The systems were controlled by CR3000 loggers, which were programmed with the EasyFlux™-DL program. This program reduces the post-processing time, as fully-corrected fluxes are processed by the datalogger.

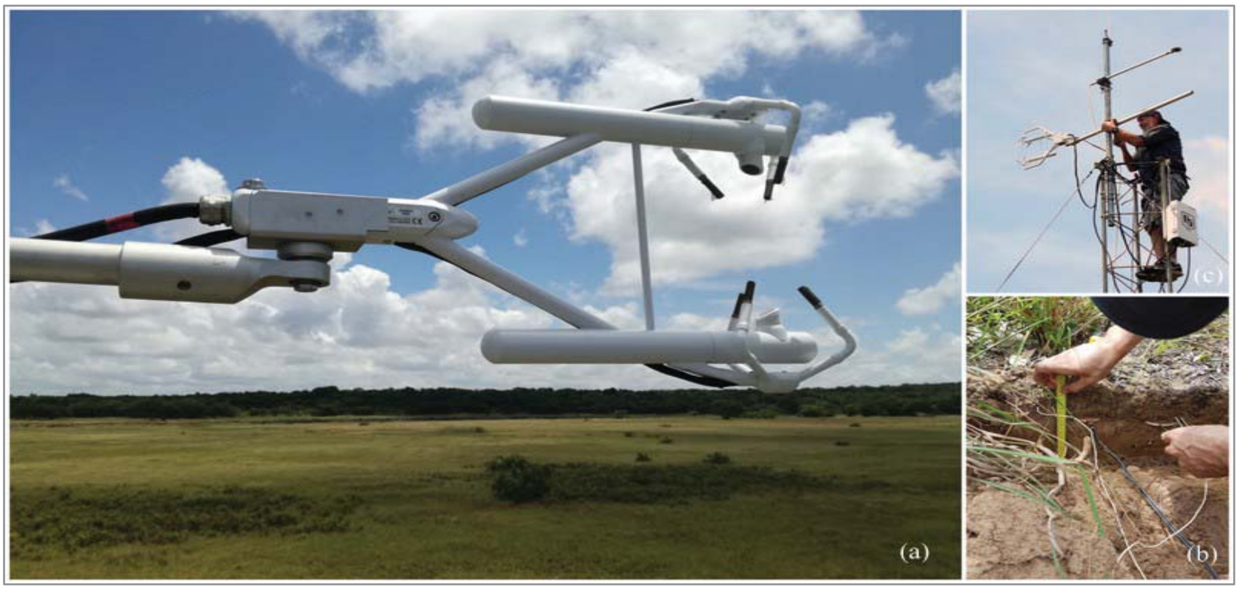


Figure 5.7 Equipment installation of the eddy covariance system in Vasi Pan. a) IRGASON (Campbell) placed on the mobile EC system in the hygrophilous grassland; b) placement of Soil Heat flux plates and Soil Thermocouple probes; c) installation of EC150 CO_2 and H_2O open path gas analyser on the lattice mast in the indigenous forest

A suitable site was found, which represented the local indigenous forest, and a Webb Industries lattice mast was erected (Figure 5.7c). At this site, an EC150 Campbell Scientific EC system was installed at 6 m, which was 2 m above the forest canopy. The system and the previously-mentioned additional system components were installed, following the instructions provided in the Campbell Scientific EasyFlux™-DL manual (Campbell Scientific, 2016).

The mobile EC system was mounted on a trailer (Figure 5.8) to facilitate the rapid deployment and acquisition of total evapotranspiration data from various land uses. The land uses chosen for monitoring were a commercial pine stand and Vasi Pan hygrophilous grassland. The trailer was fitted with a Clark WT8 pneumatic mast that was capable of being extended to 21 m, using an air compressor. In the pine stand, the mast was set to a height of 14.6 m and to a height of 4 m in the hygrophilous grassland. The system mounted on the mast consists of the Campbell Scientific IRGASON system, which fully integrates the open-path gas analyser and sonic anemometer. This system has been specially designed to increase the accuracy of flux measurements. The system simultaneously measured the absolute carbon dioxide and water vapour, air temperature, barometric pressure, three-dimensional wind speed and sonic air temperature.

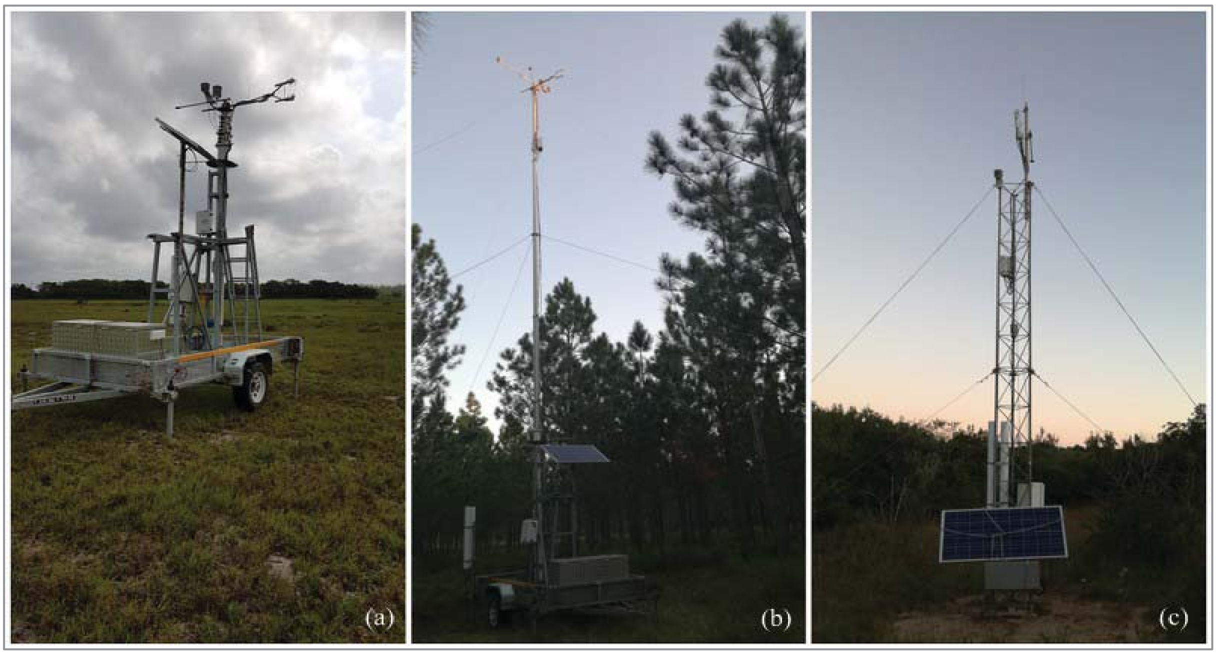


Figure 5.8 Selected EC monitoring sites: a) trailer system in the hygrophilous grasslands; b) trailer system monitoring a commercial pine stand; c) permanent lattice mast in indigenous forest

5.2.3.3 Processing and analysis of Eddy Covariance data

The Easy Flux™-DL software, developed by Campbell Scientific, was installed on the data loggers of the EC systems. It is a CRBasic program that enabled the CR3000 data logger to collect fully corrected fluxes of CO_2, latent heat (H_2O), sensible heat, ground surface heat flux and momentum. Site-specific variables were entered into the program at the start of monitoring, to ensure that the energy fluxes were processed correctly. The program processes the EC data using commonly-used corrections in the scientific literature.

The main correction procedures and algorithms implemented into the program are listed below:

i) Despike and filter 10 Hz data, using sonic and gas analyser diagnostic codes and signal strength and measurement output range thresholds,
ii) Coordinate rotations, with an option to use the double rotation method (Tanner and Thurtell, 1969), or the planar fit method (Wilczak *et al*., 2001),
iii) Lag CO2 and H2O measurements against sonic wind measurements for maximization of CO2 and H2O fluxes (Horst and Lenschow 2009; Foken *et al*. 2012), with additional constraints to ensure lags are physically possible,

iv) Frequency corrections, using commonly-used cospectra (Moore, 1986; van Dijk, 2002; Moncrieff *et al*., 1997) and transfer functions of block averaging (Kaimal and Finnigan, 1989), line/volume averaging (Moore, 1986; Moncrieff *et al*. 1997; Foken *et al*. 2012; van Dijk 2002), time constants (Montgomery, 1947; Shapland *et al*., 2014; Geankoplis, 1993), and sensor separation (Horst and Lenschow, 2009; Foken *et al*., 2012),
v) A modified SND correction (Schotanus *et al*., 1983) to derive sensible heat flux from sonic sensible heat flux, following the implementation, as outlined in van Dijk (2002). In addition, fully corrected real sensible heat flux, computed from fine-wire thermometry, may be provided,
vi) Correction for air density changes, using WPL equations (Webb *et al*., 1980),
vii) Data quality qualifications, based on steady state conditions, surface layer turbulence characteristics and wind directions, following Foken *et al*. (2012); and
viii) The calculation of energy closure based on energy balance measurements and corrected sensible and latent heat fluxes.

The energy flux data was visually checked for outliers. LE fluxes were converted from $w.m^2$ to mm and were summed per day. A monthly Bowen ratio was calculated at a daily time interval for each site. The Bowen ratio is defined as (Bowen, 1926):

$$\beta = \frac{H}{le}$$	*(8)*

for a specific period. It provided an indication on the dominance of LE or H and showed a change in the distribution and weighting of the energy balance components within and between the sites (Clulow *et al.*, 2015).

Monthly crop factors (Kc) were calculated by using ET_a from the EC systems and ET_o from the AWS (calculated using the FAO56 Penman-Monteith model). Kc was calculated at an hourly interval, when Rn >0 and ET_a >0.1 $mm.hr^{-1}$ (Clulow *et al*., 2015), and summed to daily totals, as recommended by Irmak *et al*. (2005). An average of the daily total provided, monthly Kc.

5.3 Cosmic Ray Probe (CRP) Rover

The Cosmic ray rover instrument consists of:

- Six ^3He-filled counters, which are enclosed and shielded by 2.5 cm thick polyethylene.
- Neutron pulse modules connected to the counters, which monitor the neutron counts
- Datalogger, which records the neutron counts.
- A barometric pressure sensor.
- A GPS receiver
- Temperature and relative humidity sensors, which are placed outside the vehicle.

For all rover measurements, the fast neutron counts were totalled each minute and the GPS coordinates, temperature and pressure were recorded at the end of each one-minute interval. The integration time must be short to capture the average soil water with high spatial resolution along the path of the probe. The cosmic ray rover uses the technology of the cosmic ray probe, thus it has the same horizontal footprint (≈300 m radius) and a measurement depth range of 12 -72 cm. The footprint of the cosmic ray rover is the swath with its width equal to the footprint of the stationary cosmic ray probe, and its length equal to the distance travelled during the counting interval.

Cosmic ray rover surveys were conducted at three sites in Vasi. The three sites were a grassland, a eucalyptus forest and a pine forest (Figure 5.9).

Figure 5.9 The cosmic ray rover survey sites

The grassland site is a large open area, which is situated adjacent to a peat land (Figure 5.10 (a)). The mean elevation of the site is 53 metres above sea level. The site coordinates are -27.186167 (latitude) and 32.708122 (longitude). The soils of the site are sandy in texture. Most the site is vegetated with grassland, however there are smaller areas of dense bush (thicket), which are mainly found in the depressions.

The eucalyptus forest site is a young stand, with tree heights not exceeding six metres (Figure 5.10 (b)). The mean elevation of the site is 72 metres above sea level. The site coordinates are -27.18391 (latitude) and 32.72069 (longitude). The eucalyptus site has areas of thicket in the north-western area of the site.

The pine forest site is a stand of pine, with tree heights not exceeding ten metres (Figure 5.10(c)). The mean elevation of the site is 73 metres above sea level. The site coordinates are -27. 192797 (latitude) and 32.715833 (longitude). The pine site has an area of grassland and woodland towards the centre of the site.

Figure 5.10 (a) Grassland, (b) Pine forest and (c) Eucalyptus forest

The cosmic ray rover was placed in the bed of the van (Figure 5.11) and driven in the three sites in a pre-defined pattern, depending on the shape and size of the site. The temperature and pressure sensors were mounted to the van's roof rack. Subsequent volumetric soil water measurements were taken with the hydro-sense during the surveys. The hydro-sense volumetric soil water data is required to calibrate the cosmic ray rover data. The survey used a one-minute interval with a three-minute averaging window. Therefore, the vehicle covered 100 metres every three minutes, which resulted in longer survey times for the three sites. The three-minute averaging window was used to obtain more accurate estimates of soil water, as the sites had low neutrons counts.

Figure 5.11 Cosmic ray rover in the bed of the van

The observed neutron intensity depends on the total hydrogen in the system, as well as the intensity of the incident neutron radiation, which depends on external forces. To isolate the pore water signal, the other sources of hydrogen need to be assessed independently. These include solar activity, barometric pressure, atmospheric water vapour pressure, lattice water, soil organic matter and vegetation. Once the rover surveys were complete, the data was opened and filtered in excel and then processed in Matlab©. The output of this Matlab© processing is the corrected neutron counts.

These corrected neutron counts are used to obtain the ‘no value’, which is the neutron count over dry soil, under the same reference conditions. A calibration curve developed by Desilets *et al*. (2010) relates the corrected neutron intensity to the volumetric soil water.

$$No = \frac{N}{\frac{0.0808}{\theta t + 0.115} + 0.372} \qquad (9)$$

where N is the corrected neutron counts;
Θt is the total water, which consists of the volumetric soil water (Θ_p);
Θ_{lw} is the lattice water; and
Θ_{soc} is the soil organic carbon.
The output of the equation is a map of the ‘no values’ of the surveyed area. The output ‘no map’ is then used to determine the VWC by rearranging the calibration equation.

$$\theta p = \left(\frac{0.0808}{\frac{N}{No} - 0.372} - 0.115\right) - (\theta lw + \theta soc)Pb \qquad (10)$$

where *Pb* is the bulk density.

5.4 Surface and Groundwater Modelling

A detailed overview of the approach for surface and groundwater modelling in the Vasi Pan area has been provided.

5.4.1 Soil Water Assessment Tool

Given that a model can only be as good as the data used for its input, a large amount of time and effort was spent collecting and translating the input data. Additionally, a calibration was performed to test the suitability of the model for this site. Scenario testing was then undertaken to provide a prediction on the potential hydrological gains from clearing around wetlands and incorporating an agroforestry system.

5.4.1.1 Model input

Catchment information was collated for the Vasi Pan site and Quaternary Catchment (QC) W70A. A large amount of manipulation was required for modelling outside of the United States. Therefore, much of the time spent during this modelling exercise was translating data into suitable input data. An overview of the core input variables has been provided in Table 5.6.

Table 5.6 Summary of key SWAT input variables (after Arnold *et al*., 2012)

File name	Description
File.cio	*Watershed file that names catchment levels for output parameters*
.fig	*Watershed configuration file*
.pcp	*Precipitation input file (up to 300 stations)*
.tmp	*Temperature file with daily minimum and maximum temperatures*
Crop.dat	*Land cover/plant growth database file containing plant growth parameters*
.hru	*HRU level parameters*
.sol	*Soil input file*

A digital elevation model (DEM) was used to configure the catchment by dividing it into a sub-basin or sub-catchments. The automatic watershed delineation tool allows for the creation and selection of outlet nodes and the determination of sub-catchment properties and river reach attributes. Subsequently, the sub-catchments were divided into HRUs which were derived from the land use and soil information. The methods followed for the baseline (current state scenario) were as follows:

- The 30 m Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global DEM was used at the starting point. The resolution of this DEM is 30 m by 30 m. However, this DEM does not provide accurate heights in areas of tall vegetation. Verified point and contour data was used to correct these errors and interpolate a higher resolution model. WGS 1984 UTM Zone 36S was used as the projection for this area (ArcSWAT requires all layers to be projected uniformly and UTM is the most commonly used projection for hydrological studies);
- An HRU analysis was undertaken using:
    - Land Use data – a combination of existing databases and user defined boundaries. This data was reclassified using a look up table to be recognizable by the *SWAT* model;
    - Soils data were extracted from existing databases containing hydrological soil attributes. The *ArcSWAT* database (.mbd) was modified to allow for user defined soils to be accepted by the model. These soils were again reclassified using a look up table to match the unique identification codes in the modified database;

    - Slope classes were reclassified into five classes using the DEM;
    - HRUs were subsequently created, each with unique attributes (487 HRUs for Vasi Pan).
- Weather Data Definitions were modified to allow for user defined data to be included. A table was created for each rainfall station including the Station ID, location and altitude. This was edited into the *SWAT2012*.mbd. Individual text files containing daily rainfall, temperature, solar radiation, relative humidity and wind speed were created that could be linked to the modified database. Historical data (1979 – 2014) was synthesised with the measured climate data to provide a long-term climate record for the model.
- The Land Use Update (.LUP) model was used to add land-use components for the various scenarios. Soils and Land-use attributes were checked and/or modified according to the scenarios as per the tables below;

An important addition to this component was land uses that are either different in South Africa or that do not exist in the SWAT database. In this case, new land uses can be added to the SWAT database. This can be done either through the Access database file or through the GIS user interface. Table 5.7 provides a summary of some of the important land use input attributes and the additional land use attributes added to the SWAT database. The following changes have been made to the model database (further described in Table 5.7) to match South African condition:

- *Eucalyptus grandis* and *Pinus elliottii* have been modified and included in the database;
- A new parameter for invaded wetlands with commercial species has been included; and
- A new parameter for cleared wetlands (natural grassland and sedge in this area has been included with pine and eucalyptus removed).

Land management is important for hydrological simulations as it can have a significant impact on the hydrological responses to land use. The management operations were modified in ArcSWAT to specify the initial growing state and periods during harvest, fallow lands and planting (Figure 5.12). Depending on the simulation period and the type of crop growing, initial land cover was set as already established. Depending on the vegetation type, a management period was applied allowing for the complete removal of the vegetation at specified intervals.

This approach is important as it captures the impacts that management has on hydrological responses. Additionally, if a new land use is introduced (e.g. an agroforestry system or an alternative crop), this can be changed and managed through the model at a specified date, providing a dynamic component to this model.

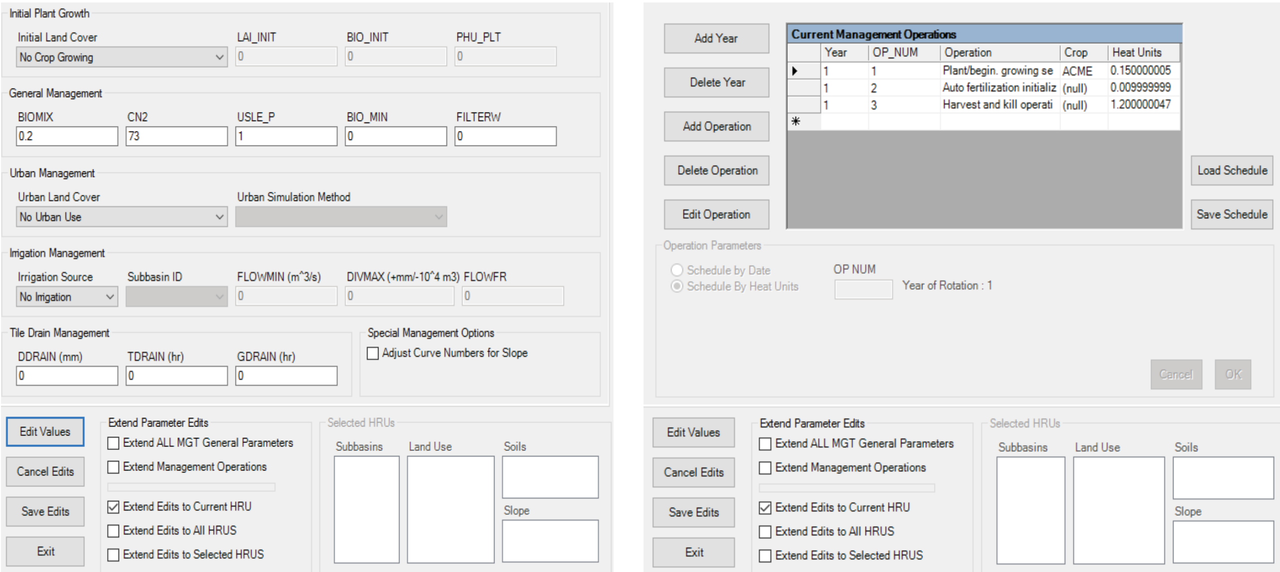


Figure 5.12 Modification of management input variables

Table 5.7 Summary of modified land use input variables

Crop Name	**Crop Code**	**Units**	**Modified Land Use**						
			Wetlands-Invaded	**Wetlands-Cleared**	**Pasture**	**Summer Pasture**	**Winter Pasture**	**Gum (*Eucalyptus grandis*)**	**Pine (*Pinus elliottii*)**
Crop Code	CPNM	N/A	WETF	WETN	PAST	SPAS	WPAS	EUCA	PINE
Radiation-use Efficiency	BIO_E	MJ/m2	15	47	35	35	30	15	15
Harvest Index	HVSTI	Frac	0.76	0.9	0.9	0.9	0.9	0.5	0.76
Maximum Potential LAI	BLAI	m2/m2	5	6	4	4	4	2.5	5
Fraction of Growing Season Leaf Decline	DLAI	m2/m2	0.99	0.7	0.99	0.99	0.8	0.99	0.99
Maximum Canopy Height	CHTMX	m	6	2.5	0.5	0.5	1.5	20	20
Maximum Root Depth	RDMX	m	3.5	2.2	2	2	2	3.5	3.5
Optimal Temperature for Plant Growth	T_OPT	C	30	25	25	25	15	20	30
Minimum Temperature for Plant Growth	T_BASE	C	10	12	12	12	0	0	0
Lower Harvest Index	WSYF	kg/ha	0.01	0.9	0.9	0.9	0.9	0.05	0.6
Minimum USLE C	USLE_C	Unitless	0.001	0.003	0.003	0.003	0.003	0.001	0.001
Maximum Stomatal Conductance	GSI	$m\ s^{-1}$	0.002	0.005	0.005	0.005	0.005	0.012	0.002
Vapour Pressure Deficit on Stomatal Conductance Curve	VPDFR	kPa	4	4	4	4	4	4	4
Fraction of Maximum Stomatal Conductance	FRGMAX	Frac	0.75	0.75	0.75	0.75	0.75	0.75	0.75
Decline in Radiation-use Efficiency	WAVP	g/MJ/kPa	8	8.5	10	10	8	3	8
Elevated Co2 Efficiency	CO2HI	uL Co2/L	660	660	660	660	660	660	660
Biomass Energy Ratio	BIOEHI	Ratio	16	54	36	36	39	20	16
Minimum LAI During Dormancy	ALAI_MIN	m2/m2	0	0	0	0	0	0.75	0.75
Years Until Full Development	MAT_YRS	Years	30	0	0	0	0	10	50
Maximum Biomass	BMX_TREES	tons/ha	1000	0	0	0	0	800	1000
Management Schedule	OpSchedule	N/A	WETF	WETN	PAST	AGRR	AGRR	AGRR	AGRR

Soil properties that influence runoff potential are those that impact the minimum rate of infiltration for a bare soil after prolonged wetting and when not frozen (Govender and Everson, 2005). These properties are depth to seasonally high-water table, saturated hydraulic conductivity, and depth to a very slowly permeable layer. Soil may be placed in one of four groups, A, B, C, and D, or three dual classes, A/D, B/D, and C/D. These are tabulated in Table 5.8.

Table 5.8 Soil hydrological group for ArcSWAT input

Group	Description
A	(Low runoff potential). The soils have a high infiltration rate even when thoroughly wetted. They chiefly consist of deep, well drained to excessively drained sands or gravels. They have a high rate of water transmission.
B	The soils have a moderate infiltration rate when thoroughly wetted. They chiefly are moderately deep to deep, moderately well-drained to well-drained soils that have moderately fine to moderately coarse textures. They have a moderate rate of water transmission.
C	The soils have a slow infiltration rate when thoroughly wetted. They chiefly have a layer that impedes downward movement of water or have moderately fine to fine texture. They have a slow rate of water transmission.
D	(High runoff potential). The soils have a very slow infiltration rate when thoroughly wetted. They chiefly consist of clay soils that have a high swelling potential, soils that have a permanent water table, soils that have a claypan or clay layer at or near the surface, and shallow +soils over nearly impervious material. They have a very slow rate of water transmission.

The steps taken for the development of the final HRUs can be seen in Figure 5.13.

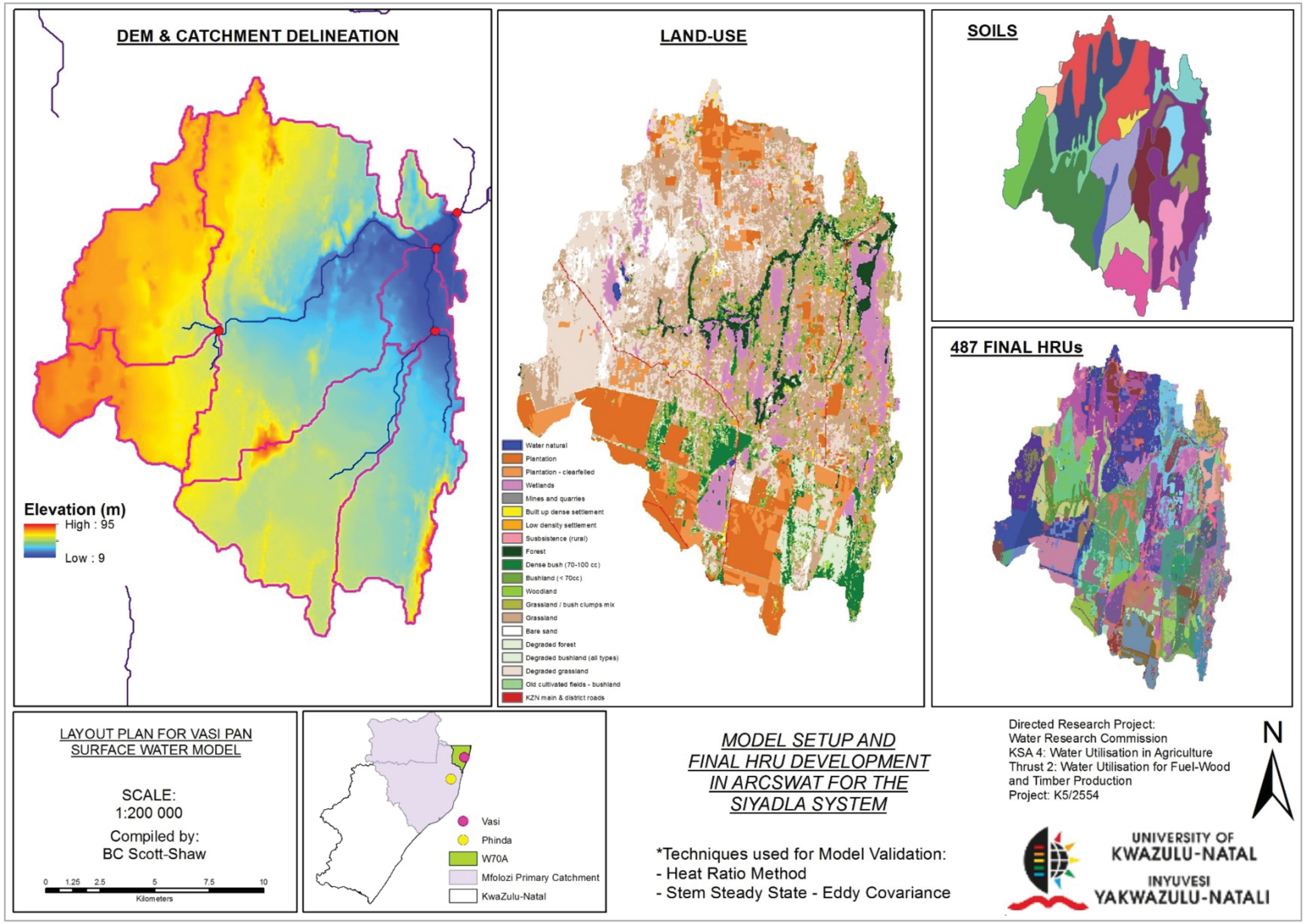


Figure 5.13 Set-up of the Vasi Pan catchment using ARCSWAT

5.4.1.2 Model calibration

The model calibration and validation were undertaken on the catchment using observed streamflow data from Military Bridge (Figure 5.15). SWAT-CUP was used to perform this process using observed streamflow (Figure 5.14). Sequential Uncertainty Fitting is being used as the statistical tool. This process reduces the uncertainty from the model outputs.

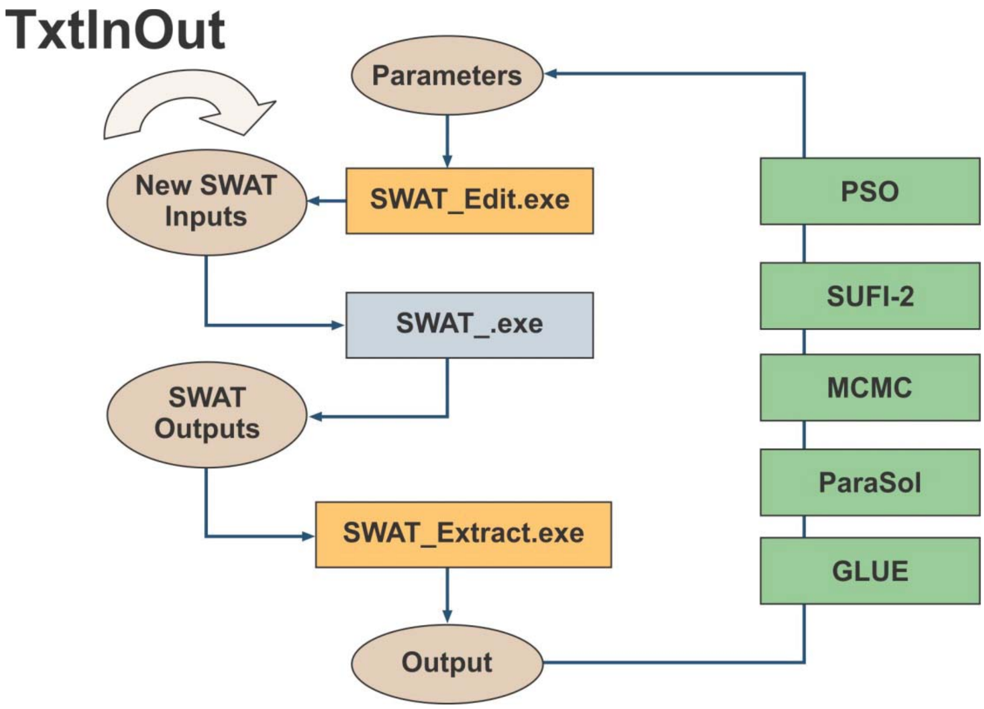


Figure 5.14 SWAT-CUP process for the optimization of the models (Abbaspour, 2015)

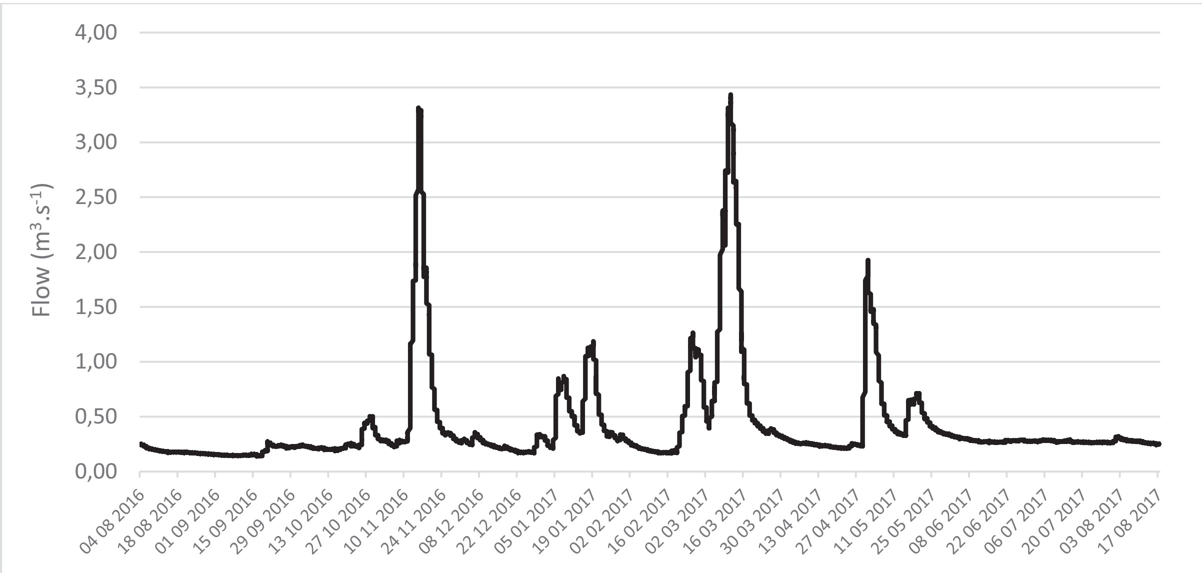


Figure 5.15 Military Bridge flow data recorded near Vasi Pan

5.4.1.3 Scenario testing

The catchment area, as defined by the model set-up, was modelled using three different scenarios. These scenarios were based on input from the ecological component of the study. Details of each scenario has been provided in Table 5.9 and Figure 5.16.

Table 5.9 Modelling scenarios identified to meet the project objectives

Scenario	Description	Area of plantation
1	Current/baseline state defined by the latest landcover intersected with wetland boundaries (NFEPA) and forestry layers from industry GIS.	4 775 ha
2	Baseline landcover with a 500 meter buffer applied to wetland areas. Any plantation areas within this boundary were converted back to natural grassland.	2 929 ha
3	Baseline landcover with all plantation areas converted to an agroforestry system of grassland and plantation rows (3 m plantation and 12 m grassland).	1 732 ha

**Note: the plantation area is only the area within the defined model boundary*

The Hydrological responses to be assessed for each scenario need to provide a spatial and temporal variance due to a change in land use/landcover. These include:

- Daily streamflow;
- Total evaporation (ET) variations;
- Water yield variations; and
- Groundwater recharge.

Furthermore, from a land management perspective, it is important to determine potential gains of water which can then be translated to a monetary gain. Additionally, areas of greatest hydrological sensitivity can be identified through the high spatial resolution of the model and prioritized for rehabilitation (e.g. through planting an agroforestry system).

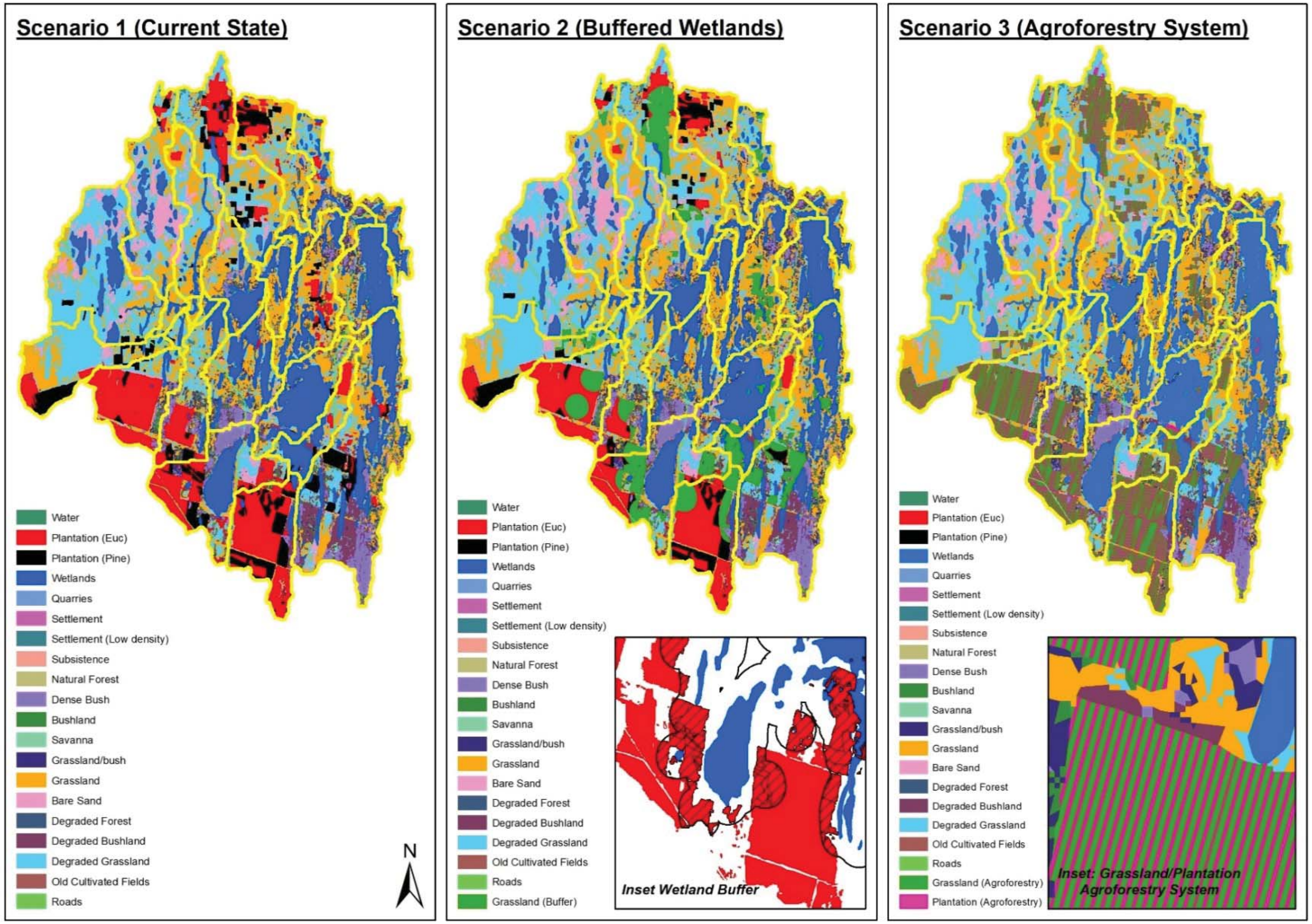


Figure 5.16 Each model scenario applied around Vasi Pan

5.4.2 MODFLOW

The driving variables for the groundwater model include the rainfall and evaporation series for the simulation period that were obtained from the sources listed below. The main sources of data acquired for the model development are also listed below:

- The rainfall and A-Pan measurements for Kosi Bay (W7E004-MET) were extracted from the Department of Water and Sanitaiton (DWS) website.
- The borehole data (water level) used for calibration targets were extracted from various sources but mainly from the following organisations: SAEON, DWS (NGBD), DWS (KZN), ARC (Grundling) and JG_Afrika.
- The lake level measurement for Kosi Bay (W7T003/4/5 and W7R003/4/5)) were extracted from the DWS website and used to specify the lake water levels in the Regional model.
- Water level and flow measurements for the Malangeni River at two sites were provided by SAEON for the period since August, 2016.
- Land use maps and LAI were provided by ARC from a previous project (Grundling,pers com)
- The 1:250 000 geological map from SA Geological Survey was used for the initial estimates of the spatial distribution of the hydraulic properties.

The borehole data and stream flow measurements are crucial in the calibration of important and sensitive parameters in the groundwater model. SAEON has taken ad hoc. streamflow measurements and continuous monitoring of the corresponding water level at the Military Bridge just upstream of the Malangeni river outflow into the Kosi Bay Lake system. These data provide a sufficient record for calibration of the model recharge parameters. Similarly, the available borehole monitoring data has provided a sufficient data for calibrating the groundwater storage. The location of the borehole monitoring sites (calibration targets) are shown in Figure 5.17 by the blue circles.

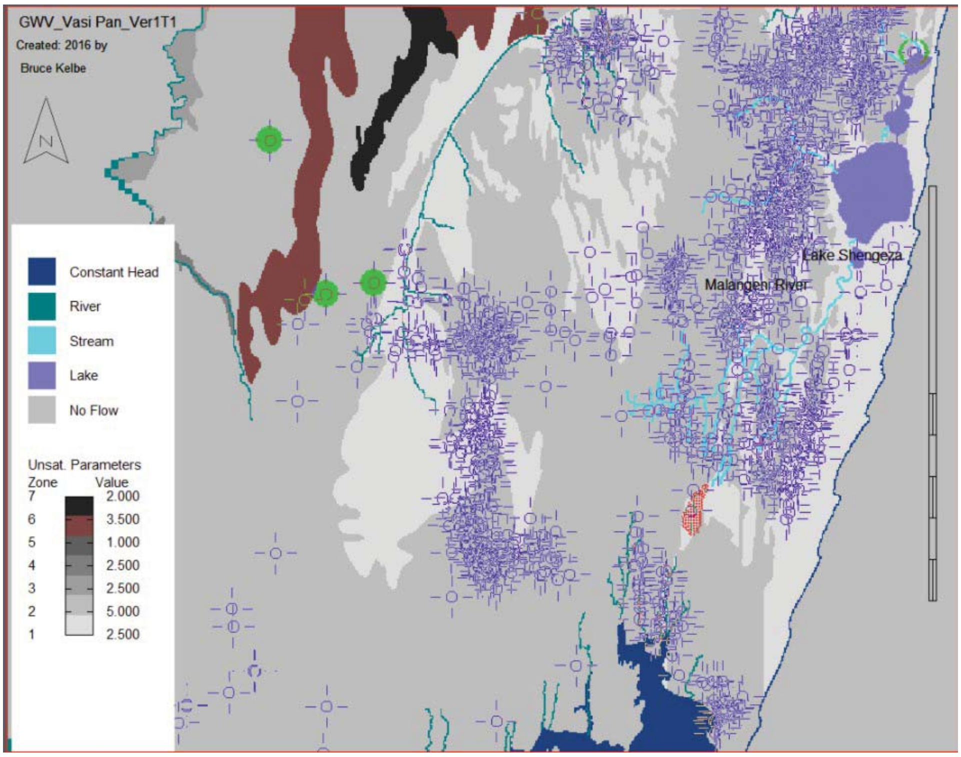


Figure 5.17 The groundwater head calibration targets from DWS, SAEON, ARC and JGAfrika

5.4.2.1 MODFLOW model components

The groundwater model chosen for this study is MODFLOW 2005, a quasi-three-dimensional numerical code, that was first developed in 1986 and has been constantly updated by the US Geological Survey (USGS) with advanced sub-models of the unsaturated zone and surface-ground water interaction processes that links the aquifers to surface water resources. The latest version of the model (MODFLOW6 and MODFLOW-USG) are undergoing testing by the team but have not been used in this project.

The primary aquifer in the study area comprises stratigraphic layers of sandy deposits overlying the assume impermeable St Lucia Formation (aquiclude) comprising fine clay/mudstone deposits of mainly marine origin that forms the base of the primary aquifer covering most of the study area. The St Lucia Formation outcrops along the western edge of the study area along the Pongola River valley and slopes at about -3^{o} to the east reaching depths of <100 mMSL near Lake Sibaya creating a primary aquifer that varies in thickness from a few meters to over 100 m.

The initial (regional) model was configured with one layer and a grid of 100x100 m rectangular nodes and the external and internal drainage boundaries shown in Figure 5.17 to establish the groundwater catchment for the local (Vasi Pan) Model that was extracted from the regional model using Telescopic Mesh Refinement Technique. This was necessary to improve the model performance at the required temporal and spatial scales. The regional model was calibrated for recharge and hydraulic properties before the Vasi Model was extracted.

The drainage line formed by the Indian Ocean was configured as a constant head boundary with an elevation of 0 mMSL. All the external rivers were configured as head dependent boundaries with a bed elevation derived from SRTM elevation data. The internal rivers were all configured as head dependent boundaries with the bed elevation extracted from SRTM elevation data and all other hydraulic properties (width, bed roughness and conductance) were estimated from site visits and aerial imagery.

5.4.2.2 Calibration technique

Modflow is a quasi-3D model that is constrained by the mass balance of an open system where the difference between the inflow (recharge) and the outflow (discharge) control the change in the groundwater storage ($\delta S=I-O$) as shown in Figure 5.18. These three variables of the system are crucial components of the model that need to be adequately represented for the successful application of the model. Under specific conditions the discharge can be measured directly but the recharge and change in the storage volume are unknown and not measurable. Consequently, the parametric models that represent these processes need to be calibrated for a reliable estimate of the model simulations. This section describes the parameters and calibration process adopted for this study.

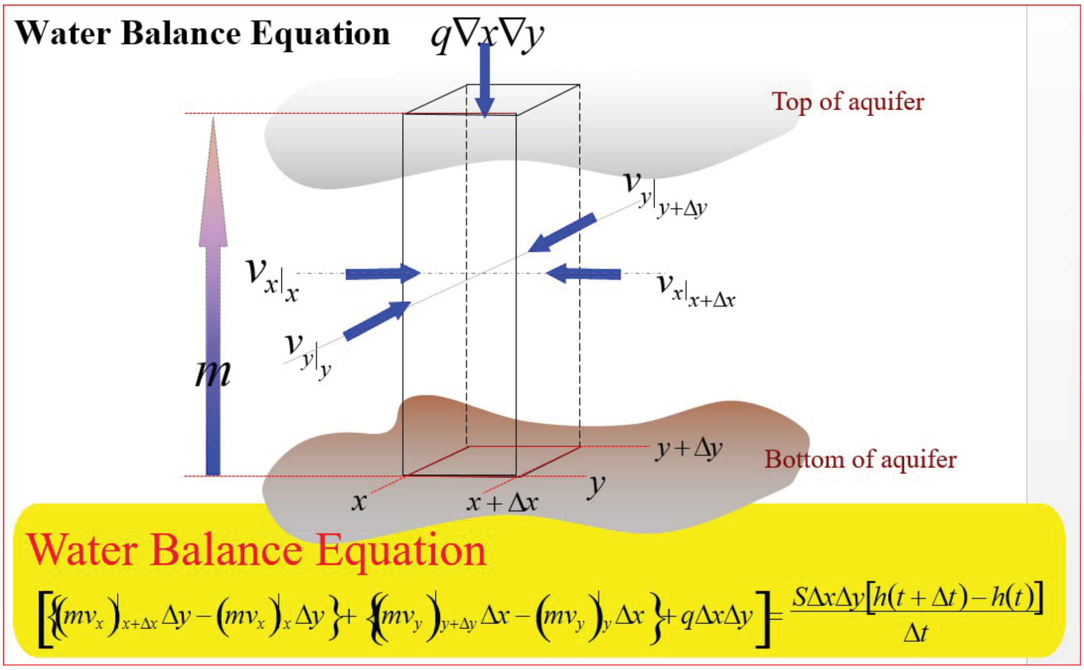


Figure 5.18 The mass balance components of the groundwater model

The recharge is represented by a vertical flux that is mainly derived from the difference between the rainfall and evaporation rates integrated over appropriate time intervals. It varies temporarily and spatially in a way that depends on hydro-meteorological, soil and land use conditions of the catchment. SWAT is an example of the complex processes involved in estimating the recharge to groundwater. Various options are available in the Modflow suite of models for simulating the recharge rate through the surface layers. In this study, that aims to investigate the impact of vegetation types (land use) on the downstream water resources, it is an important process that needs to be included in the model.

The only package available in MODFLOW that incorporates the unsaturated zone processes directly involving the vegetation as an impact on the recharge and evapotranspiration (crop factor and rooting depth) is the UZF package (Figure 5.19) developed by (Niswonger *et al.,* 2006). Unfortunately, it does not include interception losses that must be applied manually from the incident rainfall to derive an effective rainfall for application in the UZF package. The UZF package simulates the infiltration, percolation and distribution of excess infiltrate based on soil properties (Kv, β, porosity) of the unsaturated zone. It also incorporates the evaporation losses (vertical discharge) that are based on vegetation type (crop factor and rooting depth) and the atmospheric demand. There are also situation where there may be transmission losses from the drainage boundaries and injection wells that would contribute to groundwater recharge.

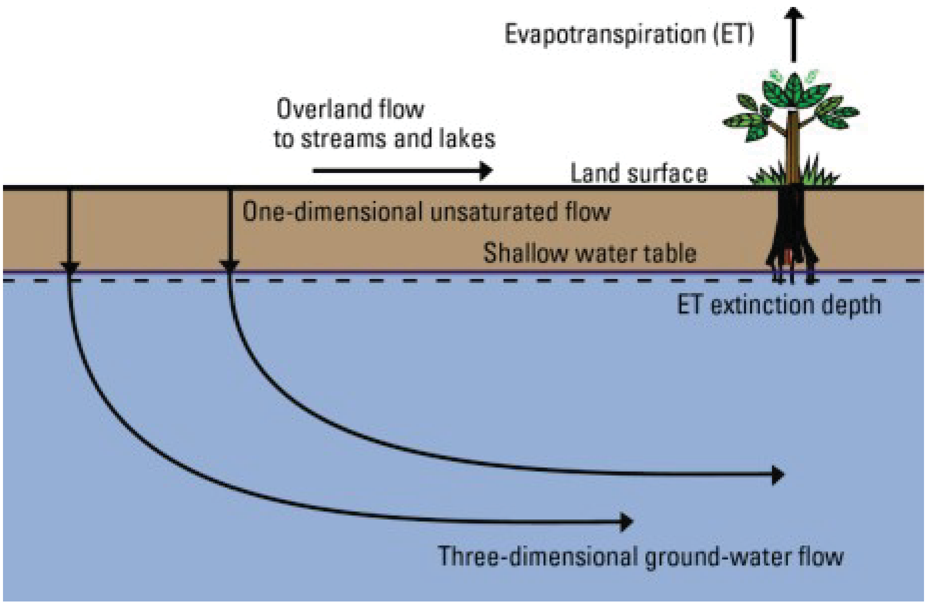


Figure 5.19 The conceptual model for the UZF package (Niswonger *et al*., 2006)

The discharge is represented by lateral flow from the groundwater though drainage boundaries that take on many forms such as rivers, lakes, oceans, boreholes and catchment divides (no flow). The rivers, lakes, ocean and boreholes are all specified boundaries. However, the groundwater catchment divide is generally unknown but can be simulated in the model if the appropriate external drainage boundaries are specified, as has been done in this study. The discharge rate through the various drainage boundaries depends on the type of boundary. The Ocean does not vary over the model time steps (>1 day) and can be represented by a constant head value. Lakes require a specialised model (LAK) that incorporates all the inflow and out flow contributions to the lake water balance provided the entire catchment is incorporated into the model domain.

The river and stream flow rates are generally an order of magnitude greater than the groundwater discharge rates so they can be model in various ways. The Stream Flow Routing (SFR1) package (Prudic *et al.,* 2004) has been used in this study in order to simulate the actual runoff and depth of flow from the rivers for calibration purposes. There are no known historical gauging stations on any of the coastal streams so a monitoring site was established in conjunction with SAEON at the old Military Bridge on the Malangeni River feeding into the Kosi Bay lakes. The model domain was selected to incorporate the necessary drainage boundaries (streams) that contained the relevant groundwater catchment. The ongoing logging at the flow gauging site has played a crucial role in the calibration of the recharge.

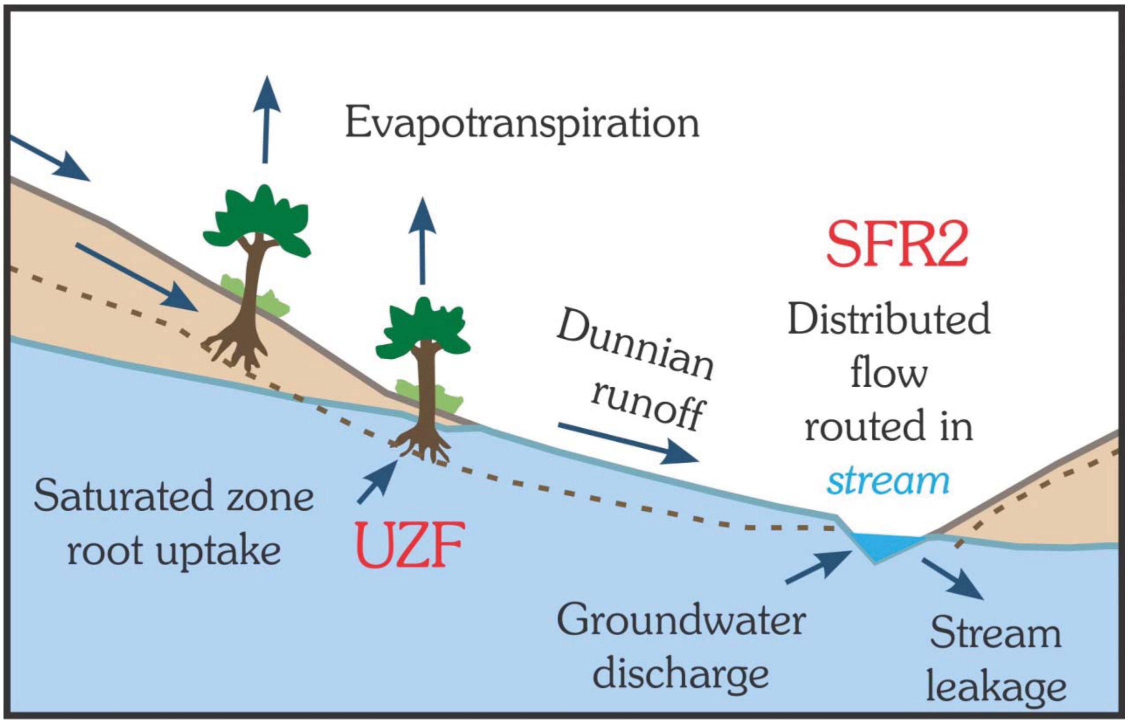


Figure 5.20 The hydrological components included in the model development for a groundwater dominated system

The groundwater storage is represented by the water table profile between the drainage boundaries in unconfined aquifers and the piezometric head in confined aquifers. Both these surfaces vary in time and space and need to be monitored by strategically located boreholes and piezometers. The variability in the storage is directly related to the recharge and discharge as well as the hydraulic properties of the aquifer(s). The hydraulic properties of the aquifer(s) are generally unknown and need to be determined from geological exploration and geophysical surveys. However, there are few observations for the study area so it was considered necessary to use calibration methods to derive the spatial variation of the hydraulic properties in this study based on the available water level record. The available water level record has been described for the study area. The more recent supplementary shallow drilling and logging by SAEON has provide transient data for the main area of interest that has played an important role in the model calibration.

The calibration of the hydraulic properties of the model aquifers is generally based on establishing a good correlation between the predicted and measured groundwater storage based on the assumption that the recharge and discharge to the groundwater storage are known or can be reliably determined. Since a change in the recharge rate will change the storage if there is no corresponding change in the discharge, it is essential to calibrate both the recharge and the aquifer properties simultaneously to achieve the best estimate of these properties. An arbitrary change in the recharge rate will require a corresponding change in the hydraulic properties to achieve the required calibrated parameters (Figure 5.21).

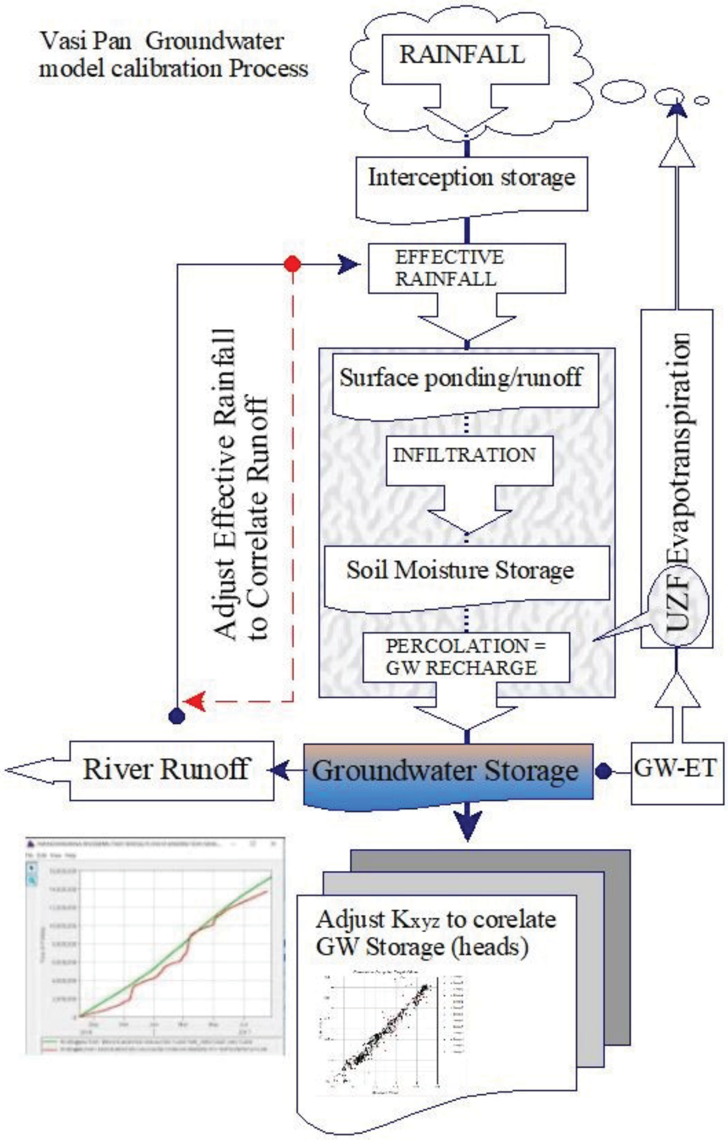


Figure 5.21 The calibration protocol used in this study.

While the groundwater storage can be reliably determined from a suitable network of monitoring piezometers/boreholes, it is not generally possible to directly measure the recharge so appropriate methods are required to derive the best estimate of the recharge rate. In this study, the underlying assumption in the calibration of the numerical model is that the inflow (net recharge) into the groundwater storage is subsequently lost to discharge through all the drainage boundaries comprising the rivers, lakes and the Indian Ocean shoreline within the groundwater catchment shown in Figure 5.17 provided the groundwater storage is constrained by the water balance of the system. However, the discharge can only be measured directly from appropriate boundaries that directly drain the groundwater storage zone (aquifers) such as the rivers, provided that the entire drainage boundary (catchment) is incorporated into the model to support the mass balance assumption. For groundwater dependent system, such as the study area, it is necessary to incorporate the groundwater catchment in preference to the topographical catchment. This further requires that the external drainage boundaries provide a reliable estimate of the catchment as described in the study area.

The calibration protocol chosen for this study assuming the basic model configuration of the aquifers, land-use and drainage boundaries have been specified in the model.

1. Apply a RELATIVE interception factor (*i.e.* LAI) to the rainfall series for each vegetation type to obtain the effective rainfall series for direct application to the UZF recharge.
2. Apply a RELATIVE crop factor and rooting depth for each vegetation type to obtain the effective EP rate for direct application in the UZF evaporation.
3. Apply estimates of the steady state infiltration rate, Kv (unsaturated), Saturated water content of unsaturated zone, and the exponent (ß) in the relationship between Kv and water content.
4. Apply INITAIL estimates of the hydraulic conductivity and storage coefficients from published studies.
5. Import all head and flow observations with relevant weights for their reliability/accuracy
6. Run the model under steady state and transient conditions to resolve all issues of instability.
7. Conduct a sensitivity analysis of all-important parameters for all the various spatial zones with variable properties and identify the most sensitive parameters for model calibration.
8. Conduct steady state model runs and manually adjust the sensitive parameters, with a particular focus on the recharge and aquifer properties to achieve improved correspondence between the simulated and measured heads and stream flow rates.
9. Apply inverse modelling using PEST SDV to obtain the best estimate of the aquifer properties and recharge.
10. Evaluate the derived parameters as suitable values for the model simulations.

6. RESULTS

Pine was planted in the surrounding Manzengwenya plantations during 1958. These plantations were subsequently planted to *Eucalyptus grandis* which grew better in the warmer climate. The plantations have been handed over to the Ngonyama Trust which is leased back to the Department of Agriculture, Forestry and Fisheries (DAFF). This transfer is the biggest land reform project in the history of South African forestry (SA Forestry Magazine, 2012) to date. The detailed findings on water-use, ecological dynamics and modelling are presented.

6.1 Ecology of the Maputaland Coastal Plain

Table 6.1 Summary of results for the ecological component of the study

Objectives	Results summary
Investigate the response of natural forest to plantation forestry at Manzengwenya plantation and screen forest expansion for ecologically suitable agroforestry species	• Five species namely, *Hymenocardia ulmoides*, *Sclerocroton integerrimus*, *Albizia adianthifolia, Brachylaena discolor* and *Apodytes dimidiata* were the most common species involved in forest expansion, as they contributed towards more than half the IV of all sampled secondary vegetation. • The composition variance of species that had expanded into the understory of plantations and woodland differed significantly, showing that savanna species such as *Sclerocarya birrea* and *Strychnos spinosa* were more likely to occur clear-felled plantations than abandoned but non-harvested plantations • Species IV and their ecological preferences are summarised in Table 6.2
Identify the resource opportunities that indigenous woody plant species and grasslands could provide to agroforestry systems at Manzengwenya plantation	• The most cited agroforestry species occurred in woodlands, and would likely suit silvopasture agroforestry systems. These include: *Sclerocarya birrea, Strychnos spinosa, Annona senegalensis, Hyphaene coriaceae* and *Trichilia emetica* • Small scale, hardwood timber resources may be derived from natural species growing within the understory of plantations, for example *Hymenocardia ulmoides*. • Forest expansion into plantations and secondary woodlands could be used as repository for medicinal plant species and other cultural products
Determine the rangeland condition and potential of the grassland communities at Manzengwenya and surrounding community managed areas	• Grassland grazing capacity was slightly greater but comparable with previous regional studies and with the DAFF guidelines for region • However, the equations used were empirical, and therefore did not account for relative edaphic and moisture variation within the landscape • These differences were found to challenging to quantify and should be a specific objective for future research

6.1.1 *Natural forest expansion*

The results from the investigation of natural forest expansion, with a strong focus on the statistical relationships has been provided. The forest edge, indigenous preference and expansion into plantations are documented in the section.

6.1.1.1 Forest edge expansion

A classification that differentiated regrowth forest (i.e. potentially young forest expansion or regeneration) from compositionally mature forest using TWINSPAN was conducted (Table 6.2). This was an important step in the analysis, because we wanted to assess which plant species were associated with disturbance and would therefore be suited to agroforestry as a land use. Conducting this analysis provided a basis to derive 'a measure of importance' for certain plant species in relation to different forest development stages.

The left-side (or negative TWINSPAN division) grouped most of the known forest expansion plots (i.e. secondary vegetation) with about half of the naturally occurring reference forest plots. This particular group of reference forest plots was compositionally associated with secondary vegetation and thereafter termed regrowth forest. Indicator species for the 'left TWINSPAN division' were *Sclerocroton integerrimus and Dichrostachys cinerea*, these species are known to be related to disturbance and savanna environmental conditions (Von Maltitz *et al*., 1996; Rutherford *et al*., 2006). The right-side of the TWINSPAN classification contained the remainder of reference forest plots. The indicator species for this division were known mature forest species such as *Tricalysia delagoensis* and *Isoglossa woodii* (Tsvuura, 2009). The forest plots on the right-side of the TWINSPAN division were thereafter classified as mature forest.

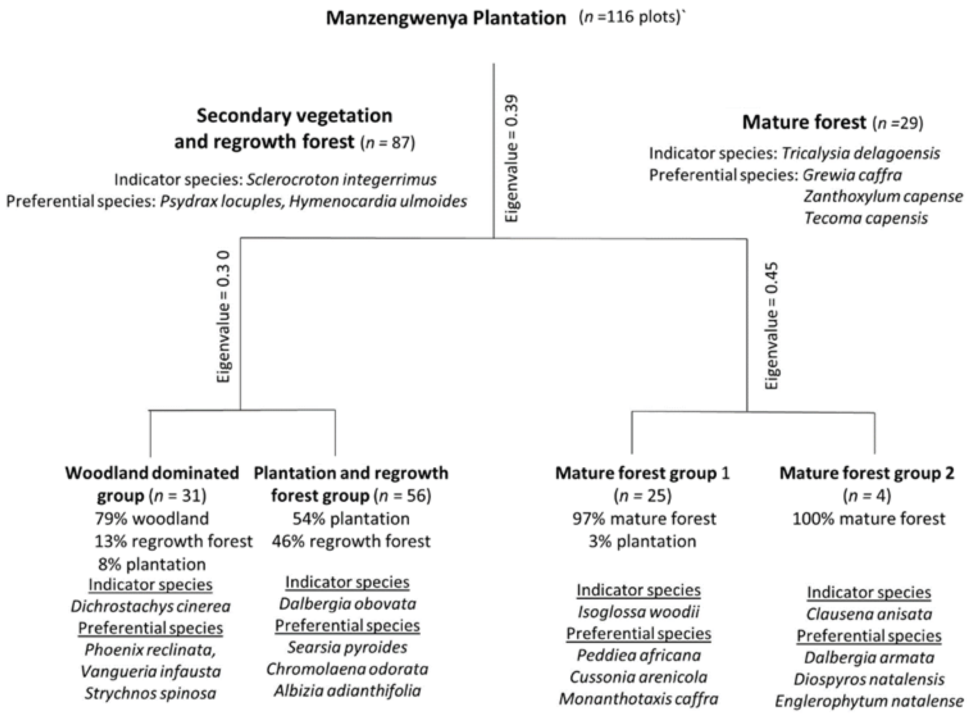


Figure 6.1 TWINSPAN classification representing understory sapling plot composition. The left-side of classification contained most woodland and plantation plots. Forest plots that integrated on left-side of classification were classified as 'regrowth forest'. Forest plots on the right-side, were classified as 'mature forest'.

Based on the classification of these plot groupings, IVs of forest species were calculated for mature forest, regrowth forest, plantation and secondary vegetation. Analysis of variance (ANOVA) among species that occurred in all four vegetation types was conducted to asses if mean IVs were significantly different or not (Table 6.2).

Table 6.2 Importance values (IVs) of plant species across four vegetation types sampled in study.

(a)

Species	Natural forest		Secondary vegetation		Welsh's
	Mature forest	Regrowth forest	Plantation	Woodland	ANOVA [1]
Hymenocardia ulmoides	29.02_a	21.49_a	28.82_b	15.87_a	**10.4**
Albizia adianthifolia	10.03_a	10.95_a	28.65_b	10.01_a	**4.3**
Brachylaena discolor	9.20_a	5.25_a	12.30_b	2.02_a	**4.7**
Apodytes dimidiata	8.13	3.80	3.05	3.23	0.12
Ficus burkei	6.05	-	-	-	-
Sclerocroton integerrimus	5.11_a	15.75_{ab}	16.26_b	26.75_b	**8.2**
Dalbergia obovata	3.66	0.35	-	0.28	0.3
Trichilia emetica	3.07_a	1.37_a	2.24_b	0.45_{ab}	**18.6**
Canthium inerme	2.48	2.97	0.62	0.94	2.6
Clausena anisata	2.28_a	0.40_b	-	-	**5.6**
Syzygium cordatum	1.88	5.53	0.53	0.13	7.6
Strychnos madagascarensis	1.68	0.58	-	0.48	0.06
Celtis africana	1.57	-	-	-	-
Strychnos spinosa	1.57_a	4.37_{ac}	0.12_a	10.20_{bc}	**9.04**
Schrebera alata	1.26_a	2.78_a	-	-	**0.15**
Vitellariopsis emarginata	1.12	0.03	-	-	1.2
Zanthoxylum capense	1.06	0.51	-	-	1.8
Dialium schlechteri	0.97	6.13	-	3.46	1.1
Manilkara discolour	0.95	-	-	-	-
Trema orientalis	0.84	0.87	1.29	-	1.7
Antidesma venosum	0.80	1.64	0.49	2.41	0.5
Strelitzia nicolai	0.77	3.81	-	-	0.5
Tabernaemontana elegans	0.73	1.38	0.37	0.49	0.5
Rhoicissus schlechteri	0.53	0.54	-	-	0.4
Mimusops obovata	0.51	0.12	-	-	0.3
Strychnos gerardii	0.44	-	-	-	-
Psydrax locuples	0.42	0.18	0.34	-	1.5
Vepris lanceolata	0.40	0.52	-	-	0.3
Combretum molle	0.30	0.15	-	-	0.6
Suregada zanzibarensis	0.27	0.06	-	-	
Phoenix reclinata	0.26	2.08	0.78	2.87	3.1
Teclea gerrardii	0.25	-	-	-	-
Grewia caffra	0.22	0.03	-	-	**23**
Clerodendrum glabrum	0.21	0.23	-	-	0.25
Commiphora zanzibarica	0.16_a	0.75_a	0.42_a	1.91_a	27
Erythroxylum emarginatum	0.15	-	-	-	
Vangueria infausta	0.14	0.32	0.54	1.44	2.9
Englerophytum natalense	0.12	-	-	-	-
Chaetachme aristata	0.12	-	-	-	-
Vitex ferruginea	0.11	-	-	0.12	0.007
Canthium inerme	0.10	0.21	0.12	-	
Tricalysia delagoensis	0.09	0.75	0.51	-	0.4
Ozoroa obovata	0.09	0.11	-	-	0.01
Xylotheca kraussiana	0.07	0.03	-	-	0.3
Manilkara concolor	0.07	0.06	-	-	0.15
Searsia pyroides	0.07	0.16	-	-	0.08
Blighia unijugata	0.06	0.28	-	-	0.5
Pappea capensis	0.06	-	-	-	-
Commiphora neglecta	0.06	-	-	-	-
Scolopia zeyheri	0.05	0.09	-	-	0.12
Maytenus undata	0.05	-	-	-	-
Sideroxylon inerme	0.04	0.30	-	-	0.7
Sclerocarya birrea	0.04	0.06	-	5.29	4.49
Terminalia sericea	0.04	-	-	-	-
Allophylus africana	0.03	-	-	-	-
Euclea natalensis	0.03	-	-	-	
Adenia gummifera	0.03	-	-	-	-
Casearia gladiiformis	0.03	-	-	-	-
Mystroxylon aethiopica	0.03	0.03	-	-	-
Dalbergia armata	0.03	-	-	-	-
Dichrostachys cinerea	0.03	0.34	0.84	0.92	2.6
Hippocratea delagoensis	0.03	-	-	-	-
Rothmannia globosa	0.03	-	-	-	-
Bridelia carthartica	-	0.47	0.24	-	0.3
Croton gratissimus	-	0.14	-	-	-
Euclea capensis	-	0.03	-	-	-
Hyperacanthus amoenus	-	0.08	-	6.11	0.9
Hyphaene coriaceae	-	0.04	-	2.69	0.9
Lagynias lasiantha	-	0.05	-	-	-
Mimusops caffra	-	-	-	0.11	-
Psychotria obovata	-	1.73	1.50	1.82	0.35

Differences of species IVs among vegetation types was found to occur in dominant and also less-common species. Five species namely, *Hymenocardia ulmoides, Sclerocroton integerrimus, Albizia adianthifolia, Brachylaena discolor* and *Apodytes dimidiata* were the most common species involved in forest expansion, as they contributed towards more than half the IV of all sampled secondary vegetation. The absence of well-known forest species from secondary vegetation such as *Schrebera alata*, highlighted which species would not typically be expected in a plantation environment. Species such as *Sclerocarya birrea*, which contributed towards woodland but was largely absent in plantations and forest, pointed towards its preference for disturbed conditions as encountered after plantation trees have been clear-felled.

The analysis of burn scars from the forest expansion sites, suggested secondary woodland experienced a shorter fire return interval, estimated at 2.8 – 6.6 years, than plantations, which was estimated at 6.8 – 8.4 years.

6.1.1.2 Ecological preferences of indigenous species suitable for agroforestry practices

Species importance value (IVs) were used as an indicator of preference towards either woodland or plantation growing conditions. For example, forest species that favoured plantation over woodland conditions, were *Hymenocardia ulmoides*, *Albizia adianthifolia* and *Brachylaena discolor.* These were assumed to be quick growing and early successional plants in their natural environment (as indicated by their importance in the reference regrowth forest), but also general pioneers into plantations and less so in woodland. Another abundant species, *Sclerocroton integerrimus,* had greater IVs in woodland than in plantations or regrowth forest. This indicated the species was a forest pioneer but also tolerant to a fair variation of the fire-regime experienced in woodland. Savanna species such as *Strychnos spinosa* and *Sclerocarya birrea* are fire-tolerant and were shown to have greater IVs in woodland than in plantations. Based on the classification of these plot groupings, IVs of forest species were calculated for mature forest, regrowth forest, plantation and secondary vegetation. Analysis of variance (ANOVA) among species that occurred in all four vegetation types was conducted to asses if mean IVs were significantly different or not (Table 6.2).

A strong case for testing native species in agroforestry systems was on account of the structural (mean DBH 6.4 ± 1.2; stems ha^{-1} 400 ±183 and basal area ha^{-1} 3.2 ±2.1) and the floristic nature of woodland, which supported at least five multi-functional species with potential for commercial agroforestry application (Van Wyk, 2011; Vermaak *et al*., 2011). *Strychnos spinosa, Sclerocarya birrea, Hyphaene coriaceae, Vangueria infausta, Annona senegalensis* and *Trichilia emetica* were considered to be disturbance resilient species and suited to open-canopy woodland conditions. These species could be tested in silvopasture agroforestry systems that combine a moderate density of multi-functional trees (± 50 – 500 stems ha; Cubbage *et al*., 2012) with pasture for livestock production. This could conceivably be achieved through cultivation, domestication or through managing secondary vegetation, such that it functions as a repository for cultural plant-use and biodiversity conservation. Some examples could include ethnobotanical uses of medicinal species such as *Adenia gummifera* (Corrigan *et al*., 2011), food products from species such as *Strychnos spinosa* (Cunningham, 1988), or seed oils extracted from species such as *Trichilia emetica* (Vermaak *et al*., 2011).

6.1.1.3 Forest expansion into the plantation interior

Densely stratified plantation stands contained 3400 ±1630 sapling stems ha^{-1} compared with sparse stands which were found to average 240 ±280 stems ha^{-1}. The species richness for combined dense and sparse stands was 85 species, most of them were herbaceous; 27 woody indigenous species were encountered. The most frequent woody species was *Sclerocroton integerrimus*, contributing towards 73 and 60 percent of the dense eucalyptus and pine stands, respectively (Table 6.3). Other frequently encountered woody species were *Hymenocardia ulmoides* (but this species was absent in pine stands), *Canthium inerme*, *Tricalysia delagoensis* and *Trichilia emetica.* Pine and eucalyptus saplings within their respective overhead stands were more abundant in sparse than in dense stands (27 and 29 %, respectively). In dense stands, the five most common species (or about 20 % of species richness) accounted for over 80 percent of total woody abundance. Sparse plots shared a more equal distribution of total abundance, with about 46% of species accounting for 80% of abundance. Sparse and dense stands did not differ by relative species composition, suggesting no dominant compositional differences of woody species existed amount the stratified vegetation units.

Table 6.3 Importance values of woody species across six stratified vegetation types

Species	Sparse (Pine and Eucalyptus	Dense (Pine and Eucalyptus)	Eucalyptus (sparse)	Eucalyptus (dense)	Pine (sparse)	Pine (dense)
Albizia adianthifolia	2.22	2.37	3.70	5.82	-	-
Apodytes adianthifolia	-	2.17	-	-	-	3.67
Brachylaena discolor	-	0.79	-	1.94	-	-
Bridelia carthartica	-	0.79	-	-	-	1.33
Canthium ciliatum	-	0.98	-	-	-	1.67
Canthium inerme	13.33	5.13	-	3.39	33.33	6.33
Clausena anisata	2.22	-	3.70	-	-	-
Clerodendrum glabrum	-	0.98	-	-	-	1.67
Commiphora zanzibarica	2.22	5.92	-	14.56	5.56	-
Dalbergia obovata	-	1.97	-	0.48	-	3.00
Dichrostachys cinerea	2.22	-	3.70	-	-	-
Eucalyptus grandis	17.77	-	29.63	-	-	-
Grewia caffra	-	0.19	-	-	-	0.33
Hymenocardia ulmoides	13.33	18.18	22.22	44.66	-	-
Landolphia kirkii	-	0.59	-	-	-	1.00
Ochna natalensis	-	0.39	-	-	-	0.67
Pinus elliotii	11.11	0.19	-	-	27.78	0.33
Psidium guava	4.44	-	-	-	11.11	-
Psydrax locuples	-	0.98	-	2.42	-	-
Sapium integerrimum	17.77	44.26	25.93	12.13	5.56	63.00
Sideroxylon inerme	-	0.19	-	0.48	-	-
Strychnos spinosa	-	1.38	-	-	-	2.33
Tricalysia delagoensis	4.4	4.74	7.41	1.94	-	6.67
Trichinella emetica	6.66	0.19	-	-	16.67	0.33
Vangueria infausta	-	0.79	-	0.97	-	0.67
Xylotheca kraussiana	-	4.74	-	0.48	-	6.33
Zanthoxylum capensis	2.22	1.97	3.70	3.88	-	0.67

**Importance Values are the relative stem density per species to each vegetation type*

Environmental differences between the sparse and dense regeneration were examined through variables of stems ha^{-1}, LAI, soil moisture and soil carbon (Table 6.4). Eucalyptus and Pine overstory trees averaged

720 stems per hectare and did not differ between the sparse and densely sampled forest regeneration plots. Neither did leaf area index, soil moisture and percentage organic carbon of the upper 10 cm of topsoil. This indicated that stand conditions did not affect whether plantation stands acted as nucleation sites for forest expansion.

Table 6.4 Environmental variables did not differ between stratified dense and sparse plantation stands.

Plot stratification class	**Dense** i.e. natural species at 3400 stems ha^{-1} ±1630	**Sparse** i.e. natural species at 240 ±280. stems ha^{-1}	F-stat
Environmental variables			
Plantation stems ha^{-1}	721.66 ±216.89	713.33 ±209.13	0.06
Leaf area Index (LAI)	2.38 ±0.94	1.9 ±0.50	4.22
Soil moisture percentage	1.72 ±1.71	1.63 ±1.50	0.001
Soil Carbon percentage	0.76 ±0.49	0.64 ±0.18	1.04

The RDA analysis produced an ordination summarising the main patterns of variation of species response explained by variables of stems ha^{-1}, LAI, soil moisture and soil carbon. Leaf Area Index was the only probable variable ($p = \leq 0.05$) accounting for 17% of species variance. Plots with increasing LAI tended to be plots with the greatest amount of forest nucleation. Stems ha^{-1}, soil moisture and soil carbon did not appear to have influenced natural forest regeneration. Reasons for why stands with greater native species density seemed to increase with LAI could have been due to shading from native species themselves or because plots with less disturbances (i.e. plantation fires) had slightly greater crown cover. A Monte Carlo test run at 10 000 replicates suggested there was a slight probability ($p = \leq 0.06$) that the eigenvalues generated in the model were by chance. The species most likely have to correlated positively with increasing LAI were *Canthium ciliatum, Sapium integerrimum* and *Strychnos spinosa*, whereas, *Commiphora zanzibarica* was the only species with a probable negative association ($p = \leq 0.05$). The results of the analysis suggested other non-measured variables such as distance to seed source (Duncan *et al.*, 2000) or biological dispersal influences were responsible for the spatial location of forest clusters.

Nucleated forest clusters had similar dominant species with forest-edge plots, for example, *Sclerocroton integerrimus, Hymenocardia ulmoides* and *Albizia adianthifolia*. This suggested that once nucleation processes were initiated they followed similar compositional patterns to forest-edges. The implications of these results are that manipulation of environmental variables such as stand density, might not necessarily increase the amount of forest nucleation in stands of planted alien species.

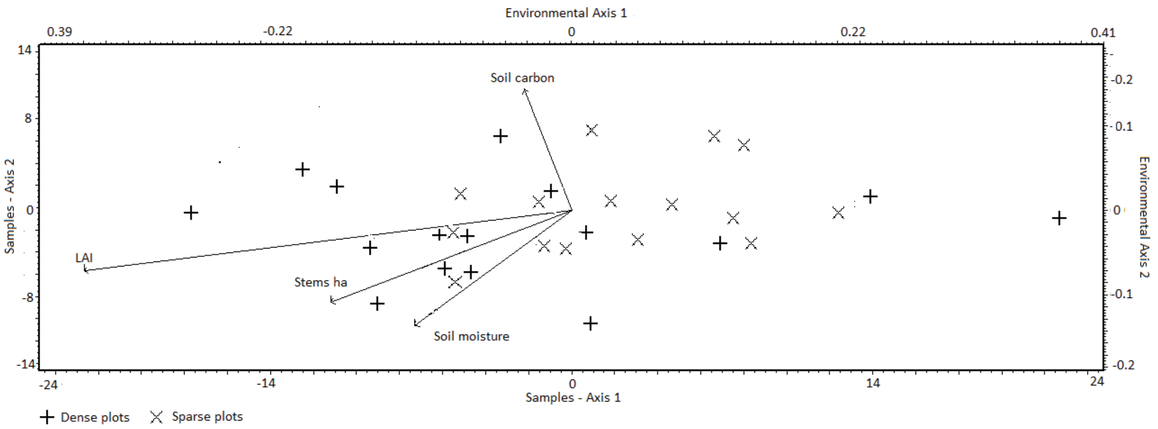


Figure 6.2 Redundancy analysis of plots in relation to environmental variables

6.1.2 Forest resources

This component of the study quantified the range of available resources available from indigenous woody species growing at Manzengwenya. Resources potential was investigated in natural forest (i.e. in mature and regrowth forest) and forest-edge expansion (i.e. in plantation and woodland). Results showed that mature forest (*n* = 263 uses) and regrowth forest (*n* = 269 uses) offered the greatest diversity of resources, followed by woodland (*n* = 175 uses) and plantation (*n* = 193 uses). The most common plant products in all four vegetation types were from medicinal and construction use classes, while the least common use-class was fibre (Figure 6.3). The most common environmental use-class was restoration followed by fodder, the least common was inter-cropping. Use-classes with median values were fuel, crafts and microclimate.

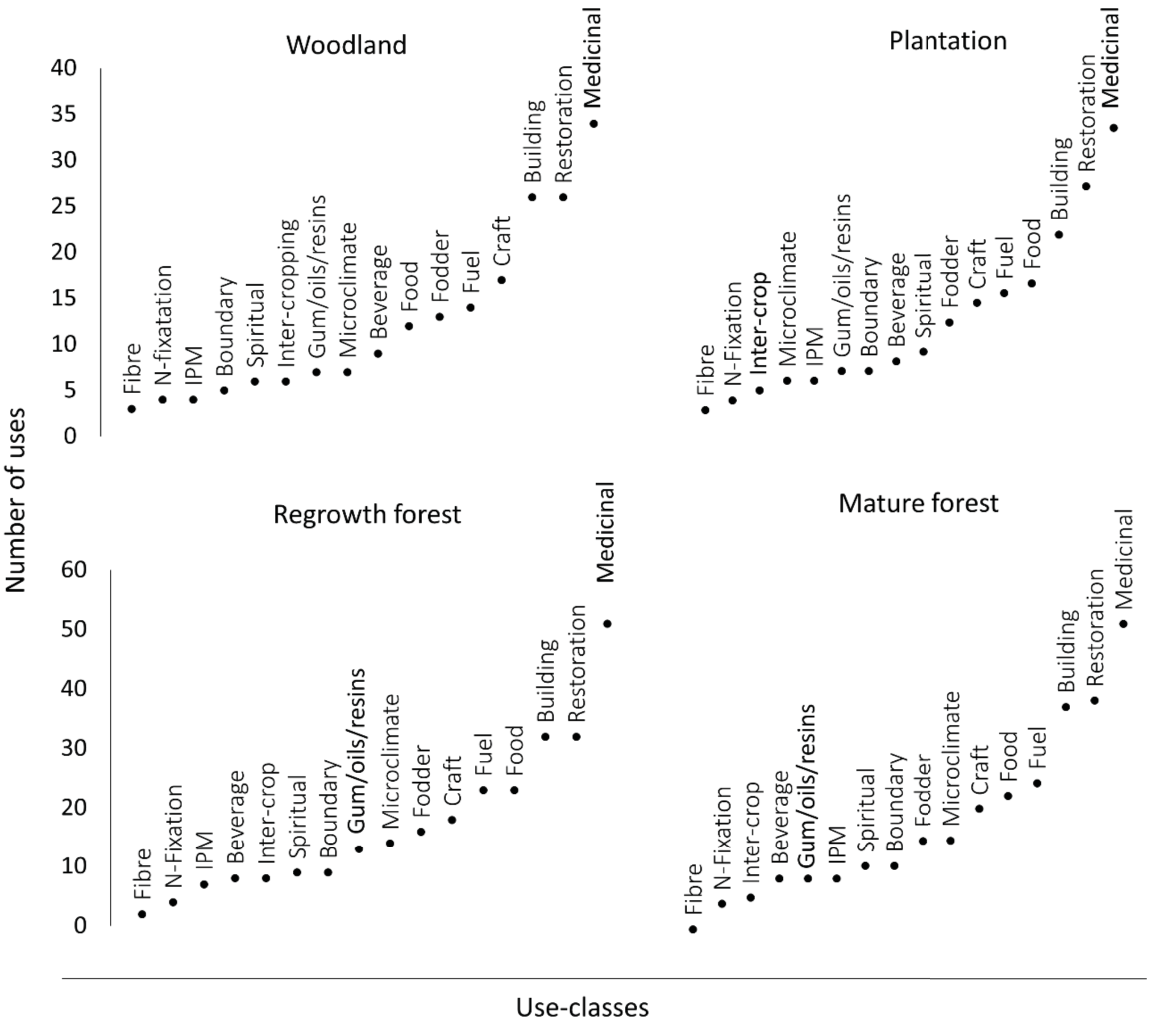
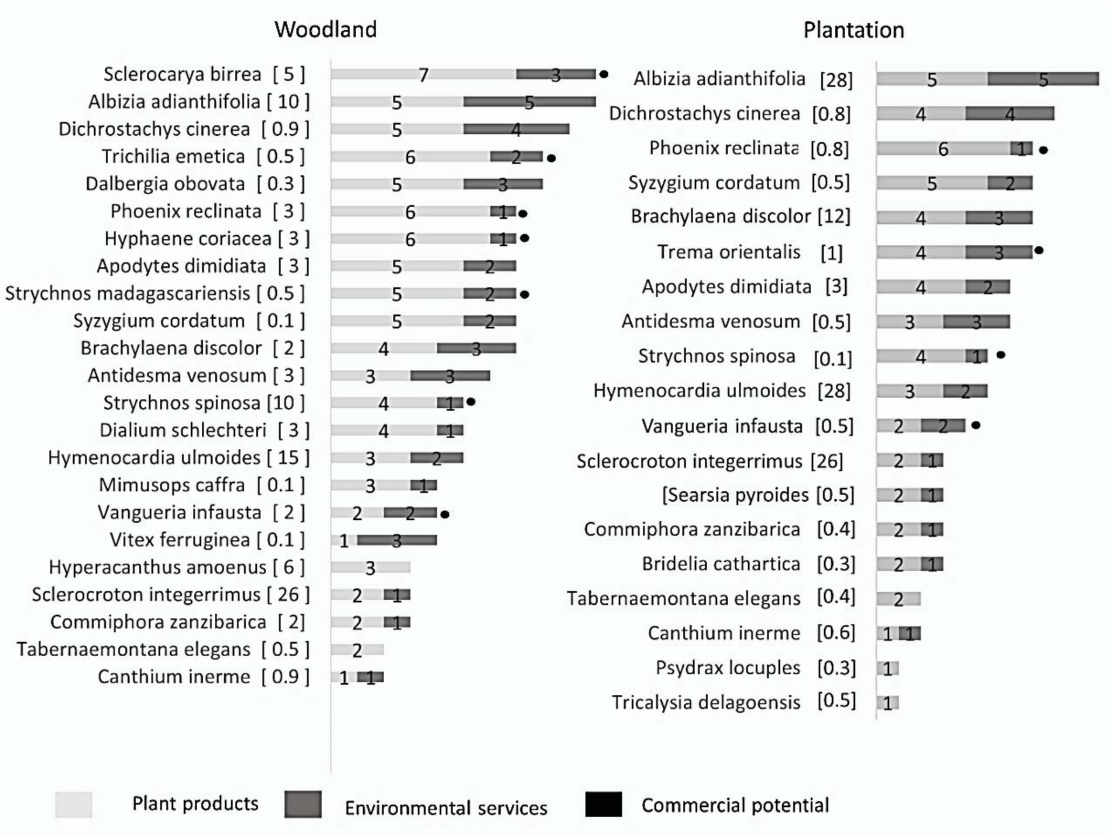


Figure 6.3 Ranking of the number of species per use-class across four woody vegetation types at Manzengwenya.

The species with the greatest number of use-classes (i.e. multi-purposeness) was *Sclerocarya birrea* and *Albizia adianthifolia* (*n* = 10 uses), this was followed by *Dichrostachys cinerea* (*n* = 9 uses) *Trichilia emetica* (*n* = 8 uses) and *Dalbergia obovata* (*n* = 8 uses). On average plant species in woodland and plantations (4.7 ± 2.4 and 4.1 ± 2.4 uses respectively) had more cited uses when compared with mature (3.1 ±2.1) or regrowth forest (3.5 ±2.4) and demonstrated that species responsible for natural forest expansion bought with them a variety on plant-uses suited to humans.

Not all quantitively abundant species had the most uses. For example, *Sclerocroton integerrimus* had a high IV in both woodland and plantations (Table 6.5) but was not considered specifically valuable in terms of resource provision. While in contrast, a specifically useful species such as *Sclerocarya birrea*, was encountered but not too common in woodland and absent in plantations. Other commercially prospective multi-purpose trees found in woodland were *Strychnos spinosa* (fruit); *Vangueria infausta* (fruit); *Hyphaene coriaceae* (fibre and beverage) and *Trichilia emetica* (oils). These species are ecologically fire-tolerant and have strong cultural links in Maputaland (Pooley, 1980; Cunningham, 1988). In plantations, *Hymenocardia ulmoides* accounted for a fair proportion (28 %) of stand importance in plantations. The species has insect resistant wood properties and occurred between 250 and 300 stems ha^{-1}, which suggested it was a possible candidate for sustainable hardwood lath harvesting.

Table 6.5 Selected tree species in secondary vegetation, showing IV, number products cited, number environmental services cited and citation for commercial potential.



The role that native plants contribute to human health in rural South Africa relates to both medicinal (Corrigan *et al*., 2011) and nutritional aspects (Cunningham, 1988). The most frequently cited plant-use in secondary vegetation was medicinal plant species. This was found to cover ailments including: Respiratory disease (i.e. *Brachylaena discolor*; York *et al*., 2011), Skin diseases (*Tabernaemontana elegans*; Nciki *et al*., 2016), Sexually transmitted diseases (*Syzygium cordatum*; Naidoo *et al*., 2013) and Diarrhoea (*Trichilia emetica*; de Wet *et al*., 2010). Only *Adenia gummifera* (Passifloraceae) was deemed to be of conservation concern (Declining red data status; Williams *et al*., 2013). This species is known in cultivation (Nichols, 2005) and is a therefore a candidate for enrichment planting in plantation areas.

Three alcoholic beverage making species stood out in the review. The fruit of *Sclerocarya birrea* is brewed for beer (*ubuganu*), while a beer product is brewed from the carbohydrate rich sap or *ubuSulu* of palms *Hyphaene coriacea* and *Phoenix reclinata* (Cunningham, 1988; Cunningham and Wehmeyer, 1988). Trees used for traditional crafts generally exhibit high wood density and grain distance (Dyer *et al*., 2016). Fast growing less dense species found in secondary vegetation such as *Brachylaena discolor* have been recoded for uses such as basket rims (Cunningham, 1987), while harder wood species (i.e. *Hymenocardia ulmoides*) are used for fencing and building or as grain stampers (i.e. *Apodytes dimidiata,* Ngubani, pers. comm.). Trees preferred for curio carving were encountered but were not abundant, and include *Trichilia emetica* and *Ekebergia capensis* (both Meliaceae) for the softness and ease of the wood on hands (Jacobsen, 2004),

Nutrient poor and acidic sandy soil conditions are a limiting factor for agriculture in Maputaland (Cunningham, 1988; Jury *et al*., 2008) and the environmental use-classes in this study referred to biophysical services that may improve land productivity. Some examples of species cited for agroforestry practices include: *Albizia adianthifolia* for N-fixation and shade (Orwa et al., 2009) *Commiphora sp.* for living fencing or *Grewia caffra* for browsing (Mkhize *et al*., 2014).

From an economic perspective the species that appeared to have the greatest commercial potential were savanna species. This supports an ecological argument for their cultivation and/or domestication in association with silvopasture agroforestry systems (Nair, 1993; Noordwijk and Ong, 1999). Livestock derived income opportunities related to silvopasture could complement the resources available from these tree products (Tonucci *et al*., 2011; Balehegn, 2017).

6.1.3 Veld condition and estimated grazing potential

The grassland study component asked three main questions:

(i) How did veld condition vary among grassland types?

(ii) What was the estimated grazing capacity and how did this compare with other grasslands in Maputaland?

(iii) Did grasslands with greater potential grazing capacity have soils with a greater percentage carbon, clay and nitrogen within the upper levels of the A-horizon?

The veld condition of the grasslands ranged between 46 and 83 %. Dune crests had the greatest veld condition score (83 %), followed by hygrophilous grassland (78 %), wetland depressions (74 %), secondary grassland (59 %) and geo-Suffrutex grassland (46 %), (Table 6.6). The grass species that contributed towards the greatest ecological value in dune ridge and hygrophilous grassland was *Themeda triandra*, a well-known palatable species, which generally indicates good condition veld. Wetland depressions and hygrophilous grassland also contained a number of palatable lawn grasses which additionally contributed towards good veld condition scores in these grasslands. Typical species in these included, *Acroceras macrum*, *Digitaria diversinervis and Hemarthria altissima.* Geo-suffrutex grassland had the lowest veld condition score, owing to the frequency of shrubs in this grassland type. Secondary grassland had a surprisingly high veld condition score. This was attributed to disturbance tolerant indigenous lawn grasses (i.e. *Digitaria diversinervis, Brachiaria brizantha* and *Ischaemum fasciculatum*) in addition to palatable pioneer grasses such as *Andropogon eucomus* and *Digitata eriantha.*

Estimates of grazing capacity varied from 0.11 LAU ha^{-1} (under 750 mm MAP, in suffrutex grassland) to 0.74 LAU ha^{-1} (under 1250 mm MAP, in dune ridge grassland) (Table 6.7). This was comparable, though slightly greater in some cases, with the long-term grazing capacity norms as recommended by DAFF, which was between 0.28 – 0.35 LAU ha^{-1}.

Veld condition of the hygrophilous grassland (74 %) was greater than reported for Sileza reserve (63.3 %; Potgieter, 2008), however at a similar rainfall bracket (± 750 mm MAP) the grazing capacity was slightly lower than reported by Potgieter (2008). Comparison with the Department of Agriculture, Forestry and

Fisheries (DAFF) spatial data (Figure 6.4), showed long-term grazing capacity of all sampling sites were between 0.28 – 0.35 LSU ha^{-1}. This was comparable with the grazing capacity of the dune-ridge (0.40 LSU ha^{-1}), hygrophilous and wetland depressions (0.39 LSU ha^{-1}) of Danckwerts (1989) (*Tembe*) and Bothma *et al*., (2004) equations, under mean rainfall conditions (i.e. ±1000 mm). Recommended grazing capacity for the different grasslands are presented in Table 6.7.

Table 6.6 Contribution of grassland species to percent frequency (f) and percent veld condition score (v) of five grassland types: Hygrophilous grassland, Wetland depression, Dune ridge, Geoxylic suffrutex grassland and Secondary grassland.

Species	**Hygrophilous**		**Wetland**		**Dune ridge**		**Geo-Suffrutex**		**Secondary**	
Veld condition score		**78**		**74**		**83**		**46**		**59**
	f	v	f	v	f	v	f	v	f	v
Acroceras macrum	8.1	8.1	13.7	13.7	1.3	0.3	1.7	1.7	0.9	0.9
Andropogon eucomus	0.2	0.1	0.1	0.0	0.6	0.3	0.2	0.1	4.9	2.4
Andropogon gayanus	0.0	0.0	0.5	0.4	1.7	1.2	0.2	0.1	0.1	0.1
Andropogon shirensis	0.5	0.4	0.4	0.3	7.2	5.0	1.1	0.7	1.3	0.9
Aristida stipitata	-	-	-	-	-	-	-	-	0.2	0.0
Bewsia biflora	-	-	0.0	0.0	0.7	0.3	-	-	0.2	0.1
Brachiaria arrecta	1.6	1.8	14.6	3.3	1.1	-	0.9	0.4	3.6	-
Brachiaria brizantha	1.8	1.1	3.3	10.2	-	0.8	0.4	0.6	-	2.5
Chloris gayana	-	-	-	-	1.0	0.7	0.1	0.1	0.0	0.0
Cymbopogon nardus	0.3	0.2	0.3	0.2	2.7	1.9	2.0	1.4	0.8	0.5
Cynodon dactylon	0.5	0.4	0.0	0.0	0.4	0.2	0.2	0.2	4.6	3.2
Dactyloctenium geminatum	5.6	0.6	2.3	0.2	0.8	0.1	2.8	0.3	11.2	1.1
Digitaria debilis	0.6	0.0	2.0	-	4.9	0.0	1.1	-	2.6	0.4
Digitaria diversinervis	9.8	6.9	-	4.3	0.0	2.4		1.4	29	20.3
Digitaria eriantha	0.6	0.6	6.1	-	3.5	-	1.9	0.3	0.6	0.0
Digitaria natalensis	0.6	0.2	-	0.7		0.3	0.3	1.2	0.0	0.8
Digitaria sanguinalis	0.2	0.1	0.7	-	0.3	0.1	1.2	-	0.8	0.1
Digitaria swaziensis	0.5	0.1	-	0.0	0.5	-	-	-	0.5	-
Diheteropogon amplectens	0.3	0.6	0.0	2.0		4.9		1.1	2.6	2.6
Eragrostis ciliaris	0.0	0.0	-	-	-	-	0.0	-	-	-
Eragrostis curvula	0.0	-	-	0.0	-	-		0.2	-	-
Eragrostis inamoena	-	1.6	0.0	0.8	-	0.4	0.4	0.3	-	0.7
Eragrostis lappula	3.9	3.5	2.0	0.4	0.9	0.6	0.8	0.2	1.8	1.7
Eulalia villosa	8.7	0.0	0.9	2.6	1.4	-	0.5	0.2	4.2	-
Eustachys paspaloides	0.0	1.3	2.6	2.3		0.5	0.2	0.5		0.5
Forbs	1.3	16.1	2.3	10.6	0.5	25.6	0.5	23.1	0.5	8.9
Hemarthria altissima	15.9	2.9	10.9	4.3	17.9	1.0	65.0	0.8	11.2	1.0
Heteropogon contortus	2.9	-	4.3	-	3.4	0.0	1.7	0.0	1.0	-
Hyperthelia dissoluta	-	0.2	-	0.5	0.0	6.8	0.1	0.1	-	0.3
Imperata cylindrica	0.2	0.0	0.8	0.0	9.7	0.0	0.2	0.1	0.4	0.0
Ischaemum fasciculatum	1.6	1.2	8.0	5.6	1.1	0.8	0.7	0.5	5.6	3.9
Leersia hexandra	0.3	0.1	9.5	2.8	0.3	0.1	0.2	0.1		-
Melinis repens	0.3	0.0	0.1	0.0	0.2	0.0	0.1	0.0	0.0	0.0
Panicum dregeanum	-	-	-	-	-	-	0.0	0.0	-	-
Panicum maximum	-	-	0.0	0.0	0.6	0.6	1.0	1.0	0.2	0.2
Panicum natalense	0.0	0.0	-	-	0.2	0.2		-	0.1	0.1
Panicum repens	2.7	1.9	7.6	5.3	2.2	1.5	1.1	0.8	3.0	2.1
Perotis patens	0.3	0.0	0.1	0.0	0.4	0.0	0.4	0.0	0.1	0.0

Species	Hygrophilous		Wetland		Dune ridge		Geo-Suffrutex		Secondary	
Sacciolepis curvata	0.1	0.0	-	-	0.3	0.1	-	-	0.5	0.2
Sedges	1.7	0.3	2.4	0.3	0.6	0.1	0.7	0.1	0.9	0.3
Setaria sphacelata	1.3	1.3	1.4	1.4	0.3	0.3	0.8	0.8	0.7	0.7
Sporobolus subtilis	0.4	0.0	0.1	0.0	0.6	0.1	1.9	0.2	4.7	0.5
Themeda triandra	26.6	26.6	2.0	2.0	20.1	20.1	4.9	4.9	2.2	2.2
Trichoneura grandiglumis	-	-	0.1	0.0	-	-	-	-	-	-
Triraphis schinzii	0.6	0.0	0.2	0.0	7.7	0.0	3.9	0.0	0.9	-
Tristachya leucothrix	0.2	0.4	0.1	0.1	0.2	5.4	0.1	2.7		0.6
Urelytrum agropyroides	0.0	0.0	0.3	0.0	3.3	0.3	0.0	0.0	0.4	0.0

Table 6.7 Estimates of grazing capacity in LSU per hectare of five grassland types under three rainfall scenarios using equations derived by Danckwerts (1989) and Bothma *et al*., (2004).

	Depression grassland	Hygrophilous grassland	Dune ridge grassland	Suffrutex grassland	Secondary grassland
Rainfall 1250 mm					
Danckwerts (1989)	0.71	0.72	0.73	0.63	0.63
Danckwerts(1989) *Tembe*	0.50	0.50	0.51	0.44	0.44
Bothma *et al*., 2004	0.48	0.48	0.50	0.39	0.43
Rainfall 1000 mm					
Danckwerts (1989)	0.54	0.56	0.59	0.47	0.51
Danckwerts (1989) *Tembe*	0.39	0.39	0.40	0.34	0.36
Bothma *et al*., 2004	0.38	0.39	0.39	0.33	0.35
Rainfall 750 mm					
Danckwerts (1989)	0.23	0.24	0.26	0.15	0.19
Danckwerts (1989) *Tembe*	0.16	0.17	0.18	0.11	0.13
Bothma *et al*., 2004	0.17	0.17	0.18	0.11	0.14

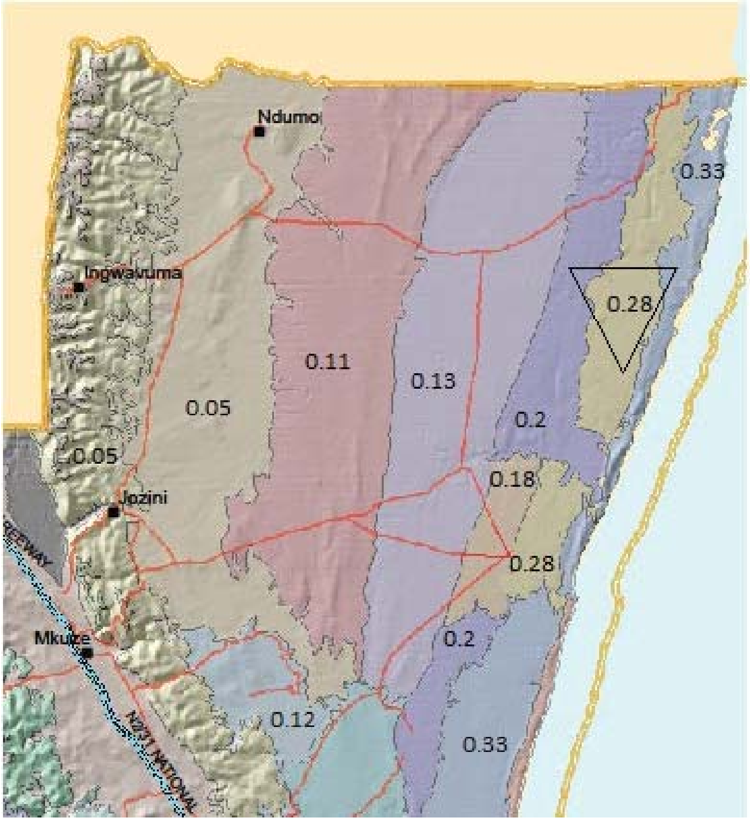


Figure 6.4 Long-term grazing capacity map produced by the Department of Agriculture Forestry and Fisheries (Avenant, 2016) for the Maputaland region. Numbers within coloured polygons indicate recommended LSU ha^{-1}. The eastern section of Manzengwenya plantation (indicated by the black polygon) has greater stocking potential (0.28 LSU ha^{-1}) than the western section (0.2 LSU ha^{-1}). LSU values recommended by DAFF (0.28 LSA ha^{-1}) were slightly less than the mean LSU for all grasslands using Bothma's equation (0.36 LSU ha^{-1}) at an annual precipitation of 1000 mm, but slightly greater than 750 mm MAP (0.15 LSA ha^{-1}).

Soil organic carbon (SOC), nitrogen (N) and clay differed significantly (p = <0.001) among grassland types (Table 6.8). Wetland depression grasslands had the greatest mean percentage SOC, N and clay followed by hygrophilous grassland and then secondary grassland. The clay content in dune ridge grassland was greater than expected and did not differ from lower lying grassland types such as wetland depressions and hygrophilous grassland. However, in wetland depressions and hygrophilous grasslands values of SOC and N were greater than in dune ridge grassland (p <0.001; Tukey post-hoc test). Mean values of SOC, clay and N in secondary grassland did not differ with hygrophilous grassland, suggesting that secondary grassland was naturally hygrophilous grasslands before plantation disturbance ($p \leq 0.001$; Tukey post-hoc test).

The decreasing rainfall gradient from coastal to inland areas in Maputaland as reflected in the decreasing carrying capacity. The grazing capacity of the grasslands around Manzengwenya were some of the highest in the region (Figure 6.4). The veld condition assessments showed that grassland composition supported a grazing capacity of between 0.11 and 0.72 LSU ha^{-1}, depending on the rainfall input of the equation. The grassland with the greatest veld condition score and therefore grazing capacity was dune ridge grassland. However, this value did not account for temporal variations in grassland productivity, which is known to vary seasonally. The amount of SOC in wetland soils correlates positively with soil moisture as a result of less mineralisation under saturated conditions (Pretorius *et al*., 2016). We therefore assumed that wetland depressions and hygrophilous grasslands were likely to be more productive during dry-season periods (May – Oct) than dune ridges, on account of having greater SOC and therefore moisture.

Veld condition varied among grassland types. Dune ridge, wetland depressions and hygrophilous grasslands all had an average veld condition score of above 75%, while geo-suffrutex grassland had the lowest score and therefore the lowest potential grazing capacity. The calculation of the grazing capacity of the sampled grasslands (using the mean annual rainfall for the area) was slightly greater than the long-term values estimated by DAFF (Figure 6.4), but at below average rainfall they were considerably lower. Soils with the most SOC, clay and N did not necessarily have the greatest grazing capacity, but our calculations did not take overall productivity into account i.e. the ability of lower lying more fertile grasslands to produce dry season forage.

Table 6.8 Comparison of soil variables (percent SOC, clay and N) across five grassland types.

Grassland Type	Wetland depression	Hygrophilous grassland	Dune Ridge	Geo-Suffrutex	Secondary grassland	F-stat
% Soil Organic Carbon	11 (3.5)	5.01 (3.14)	0.72 (0.40)	0.86 (0.64)	4.46 (4.75)	41.5
% Nitrogen	0.81 (0.30)	0.34 (0.21)	0.06 (0.03)	0.09 (0.06)	0.29 (0.32)	33.3
% Clay	7.50 (0.3)	4.96 (4.62)	4.24 (2.25)	0.16(0.47)	5.08 (5.68)	41.6

** Brackets indicate standard deviation from the mean*

We estimated the grazing capacity of grasslands to range between 0.3 and 0.4 LSU ha^{-1}, though this would vary depending on the amount of rainfall received during any given season. Owing to lawn grass composition and environmental conditions of hygrophilous and wetland depression grasslands, it is likely that lower elevation grasslands areas would sustain a greater amount of grazing pressure than those grasslands situated on sandy dune ridges. Further research into a more accurate assessment of how wetland depressions and hygrophilous grasslands could function as 'key resource areas' would likely benefit livestock management practices in the region.

6.2 Meteorological

The rainfall measured at Vasi Pan was added to the long-term data record for the study. Any inconsistencies between these data and the data recorded at the nearby sites were corrected using a relationship derived between the overlapping data of the historical records. These data were used for the modelling component of the study, as well as to link the tree growth (determined from anatomy analysis) to the last 30 years of rainfall.

The mean annual precipitation observed since 1914 at Vasi Pan was 926 mm (Figure 6.5). As little as 427 mm and as much as 1689 mm has been observed in a hydrological year (high variation). The current study was carried out in an abnormally dry period (drought). Therefore, the historically seasonal wetlands were dry.

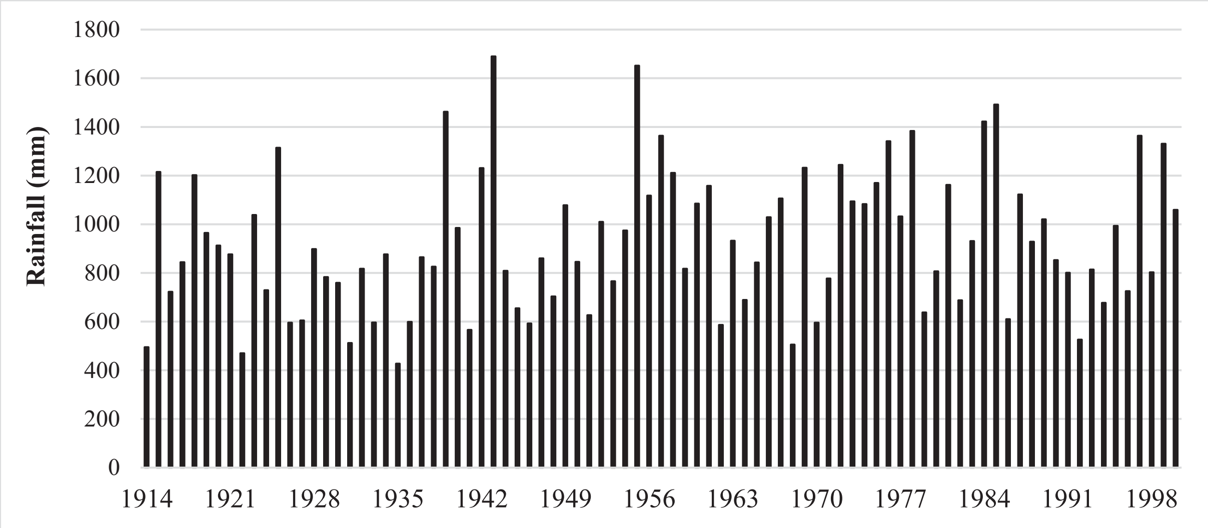


Figure 6.5 Annual precipitation recorded at rainfall stations near Vasi Pan

The Vasi Pan area has a distinct dry and wet season. The wet season begins in September, with peak rainfall occurring in summer from November to January (Figure 6.6). The frequency and size of rainfall events decreased from February, with very little rain falling in the winter period (June to August).

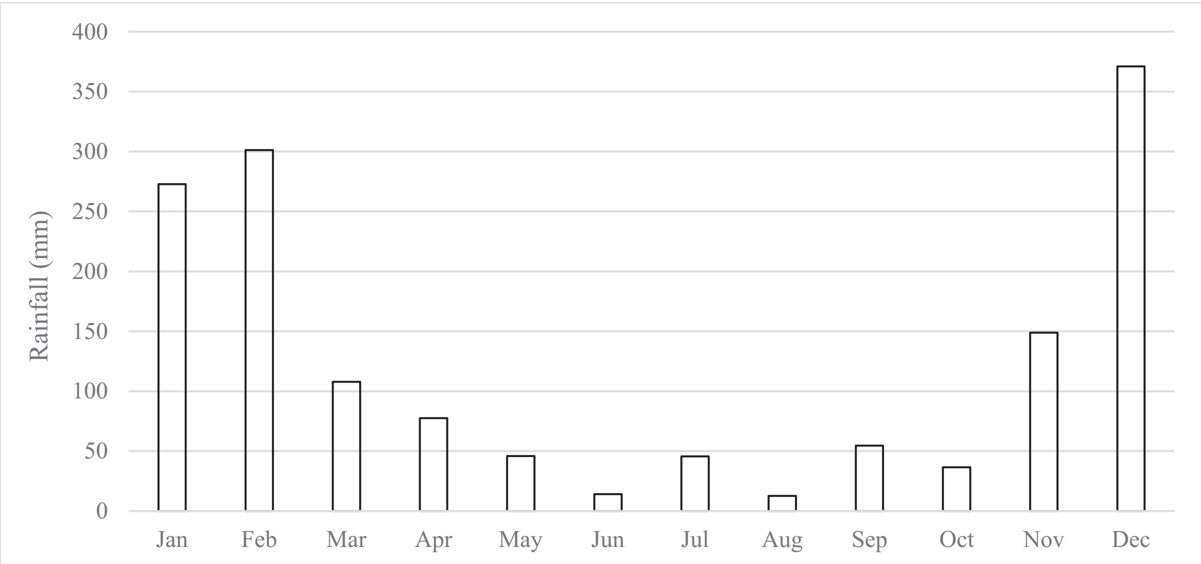


Figure 6.6 Total monthly rainfall averaged over a three-year period at Vasi Pan

There were seasonal differences in solar radiation, with a summer peak of 604 MJ in January 2017 and a winter peak of 420 MJ in August 2016 (Figure 6.7). Solar radiation varied, due to cloud cover, with higher solar radiation occurring on clear days. It is important to note the influence that cloud cover had on solar radiation, particularly in summer, as tree sap flow responses to energy are well documented (Landsberg and Waring, 1997; Meiresonne *et al.*, 1999; Granier *et al.*, 2001; Williams *et al.*, 2001; Wullschleger *et al.*, 2001; Meinzer *et al.*, 2004).

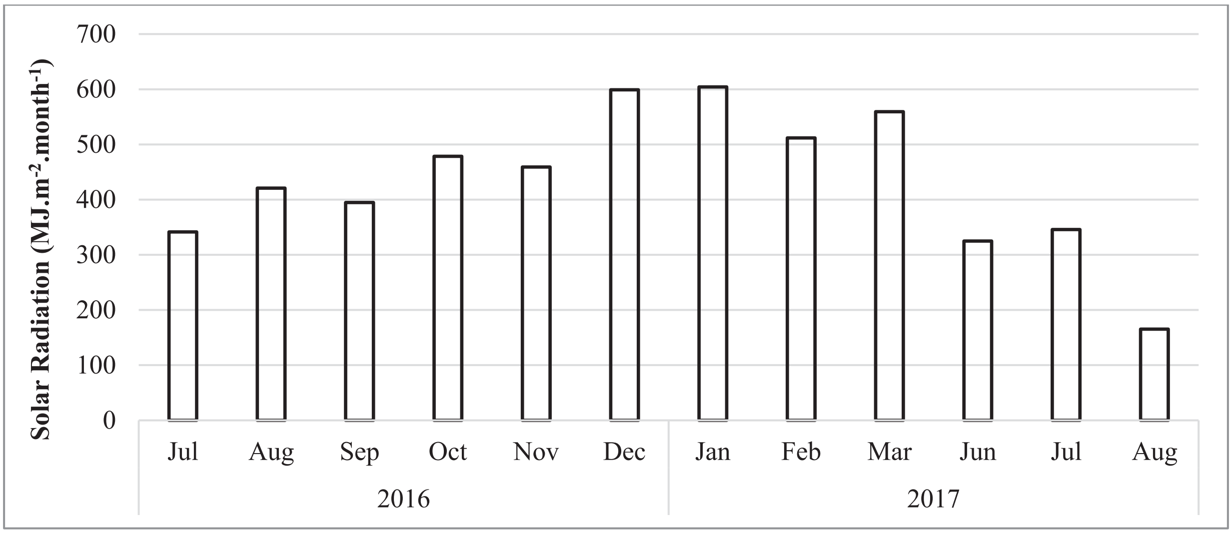


Figure 6.7 Total monthly solar radiation observed at Vasi Pan

The warm Mozambique current from the north has a warming influence on the Maputaland coastal areas. The Vasi Pan area has a temperate climate, experiencing hot summers and mild winters. There were small differences in the daily and seasonal maximum and minimum air temperatures. Summer temperatures were hot, with air temperatures frequently exceeding 30 °C, while winters were mild, with maximum temperatures averaging 25.6 °C (Figure 6.8). The average daily minimum temperatures were 22.4 °C in summer and 14.7 °C in winter.

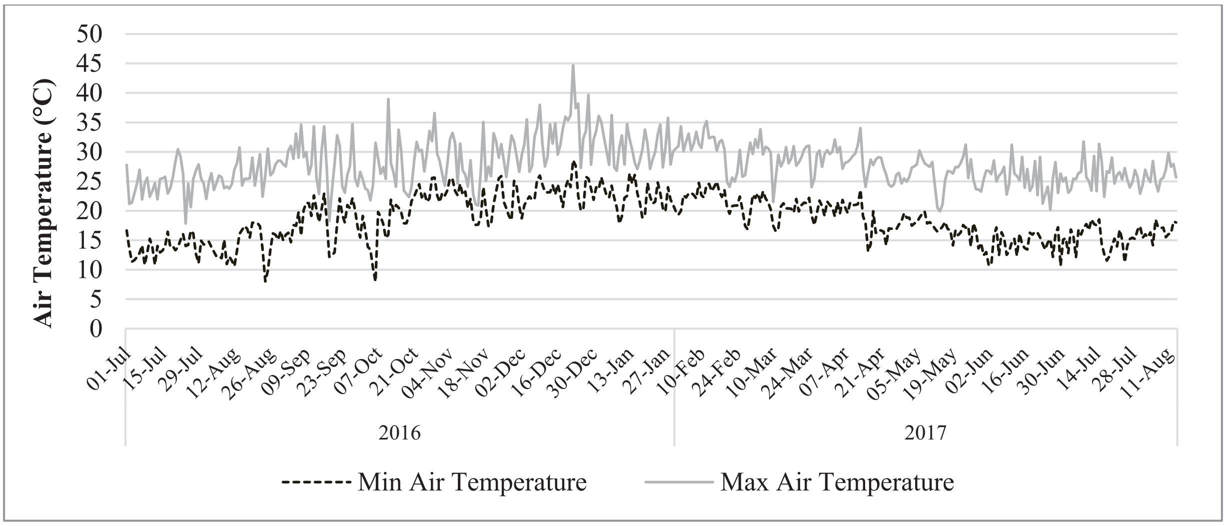


Figure 6.8 Maximum and minimum air temperature observed at Vasi Pan

A vapour pressure deficit (VPD) was recorded from November 2016 to July 2017; however, data for the month of January 2017 was unavailable. The average monthly daytime VPD was low (0.84 kPa), which generally indicates a low atmospheric evaporative demand (Figure 6.9). The Vasi Pan area has a humid subtropical climate, which accounts for the low VPD values. Maximum daily VPD occurred at midday and peak VPD was lower in the summer months (November to February) than in the winter months (June to July), as summer was more humid.

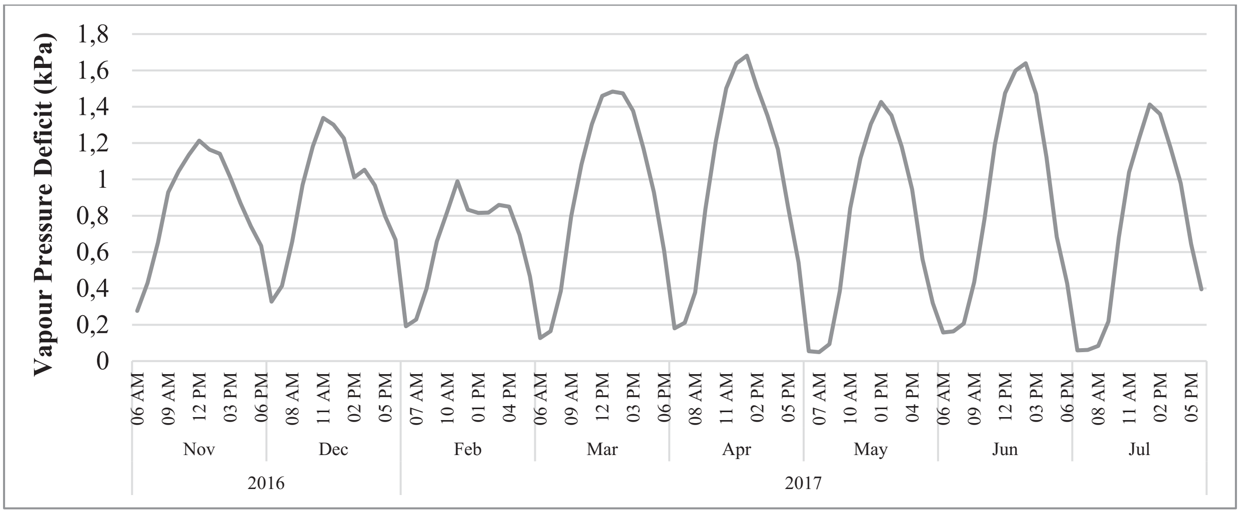


Figure 6.9 Monthly daytime (Rn >0) vapour pressure deficit measured in the Vasi Pan area

The soils in the Vasi Pan area had a deep, uniform sandy profile and held little water. The VMC was generally low, between 2 and 13 % (Figure 6.10), due to the low water retention properties of sandy soils. After rain, the VMC for all three probes rapidly increased and steadily decreased during the subsequent period of no rainfall, as the water drained quickly through the soil.

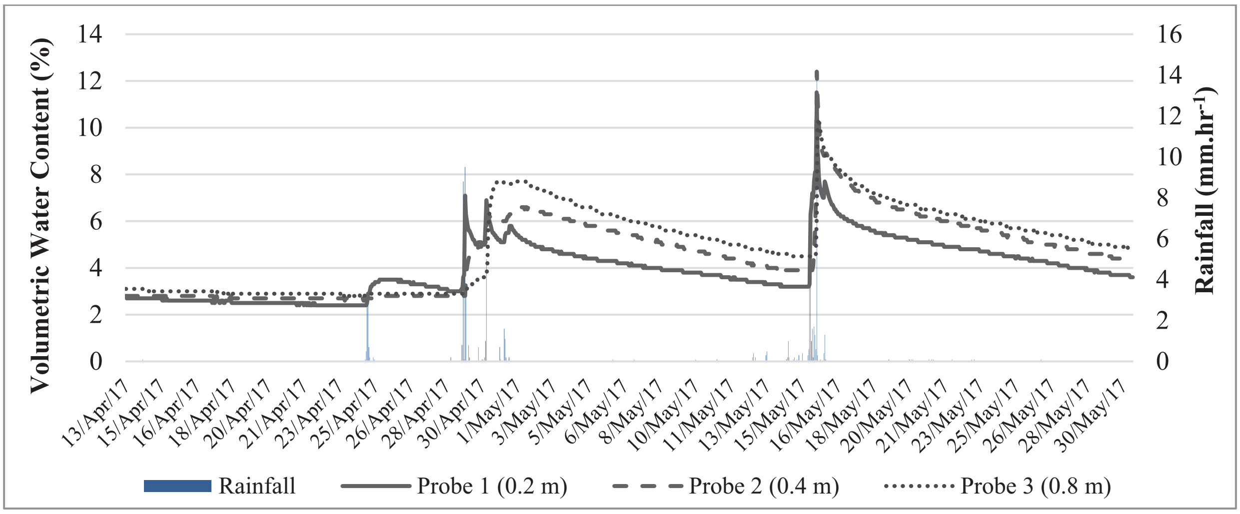


Figure 6.10 Hourly volumetric water content measured at the indigenous forest site

6.3 Sap-Flux Density Measurements

Sap-flux density was measured within dominant land-use types around Manzengwenya. These were the indigenous forest, the commercial pine stand, pine that had invaded natural forest, a *Eucalyptus* woodlot and young *Eucalyptus* trees that had been planted within the wetland edge.

6.3.1 Indigenous forest

Sap flow data for the indigenous forest site were recorded from late July 2016 to early August 2017, providing an insight into the annual seasonal variability of indigenous tree water-use. The duikerberry (*Sclerocroton integerrimus*) had the highest mean daily water-use (8.76 L.day^{-1}) of the indigenous species monitored, then the white-pear (*Apodytes dimidiate*) (7.75 L.day^{-1}) and flat crown (*Albizia adianthifolia*)

(6.22 L.day^{-1}). Unfortunately, the pigeon wood (*Trema orientalis*) only gave a week's worth of good data and was therefore not included in the study. The water-use data from the individual indigenous species followed similar tends which allowed for the daily water-use of each species to be represented as an average for all three trees (Figure 6.11).

The indigenous trees are semi-deciduous in winter, accounting for the low daily water-use of ~2 L.day^{-1} from July 2016 to late September 2016 (Figure 6.11). The start of the wet season in spring (October 2016) and the flush of new leaves on the trees coincided with increased daily water-use, as transpiration resumed (6-14 L.day^{-1}). Peak water-use occurred during summer (December 2016), when daily water-use reached a maximum of 15.31 L.day^{-1}. The water-use of indigenous trees was low during rainfall events in summer. For example, in mid-February, water-use declined from ~14 L.day^{-1} to ~4 L.day^{-1}, coinciding with a decrease in solar radiation from ~25 MJ.day^{-1} to ~11 MJ.day^{-1}, due to the high cloud cover (Figure 6.11). Thus, during the summer wet periods, the trees were energy dependent.

From March to July, there was a steady decline in radiation from ~20 MJ.day^{-1} to <10 MJ.day^{-1}, as solar altitudes declined with the onset of winter (Figure 6.11). Following two weeks of no rainfall, the water-use of indigenous trees increased from 7 L.day^{-1} to 12 L.day^{-1}, in response to the small rainfall event (0.5 mm. day^{-1}) on 15th April 2017 (Figure 6.11). This was despite the continued decline in radiation during this period.

The daily water-use in winter 2017 steadily decreased from early June, from ~11 L.day^{-1} to ~5 L.day^{-1}. This decline coincided with the start of the dry season and the loss of some leaves from the trees. During the winter months, when the trees were inactive (June to late September), the daily water-use was not noticeably affected by rain or changes in solar radiation (Figure 6.12). From the results, it was evident that water-use of indigenous trees responded to the seasonal variability in the trees' physiology. However, in the trees' active growing season, their water-use was limited by the rainfall and available energy, depending on the prevailing climatic conditions.

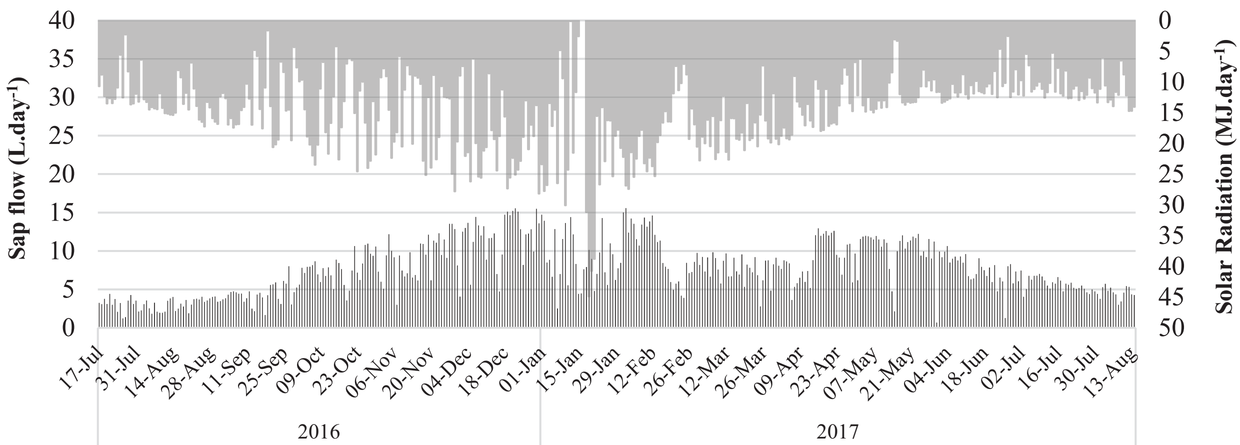


Figure 6.11 Mean daily water-use (L.day^{-1}) of the indigenous forest spp. monitored located within a mix indigenous forest on the fridge on Vasi Pan North compared with solar radiation (MJ.day^{-1})

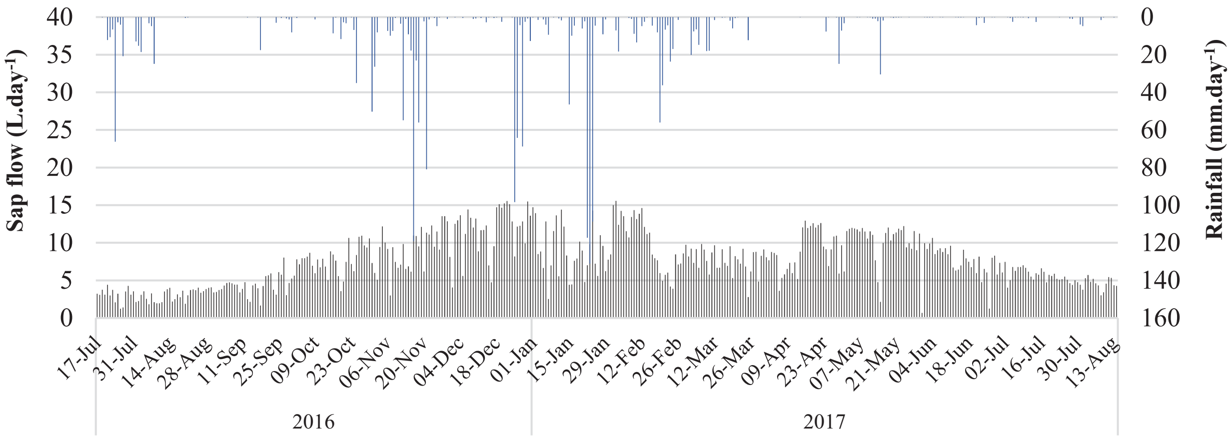


Figure 6.12 Mean daily water-use (L.day^{-1}) of the indigenous forest spp. monitored located within a mix indigenous forest on the fridge on Vasi Pan North compared with daily rainfall (mm.day^{-1})

6.3.2 Invasive Pine

Sap flow data for the invasive pine site were collected from late July 2016 to early August 2017. The total daily water-use for the invasive pine site, shown in Figure 6.13, was an average of the four pine trees monitored.

In the 2016 winter months (July to October), daily water-use reached a low of <2 L.day^{-1} and a maximum of 11.2 L.day^{-1} (Figure 6.13). This variation in daily water-use was in response to the rainfall. For example, daily sap flow rapidly increased from ~2 L.day^{-1} to ~11 L.day^{-1}, in response to the five-day rainfall event in late July. During the subsequent five-week dry period, the daily water-use steady decreased from ~ 9 L.day^{-1} to below 1.55 L.day^{-1} (Figure 6.13). It took approximately three weeks, from the time of the last rainfall, for the water-use values to return to values similar to those before the rainfall event (i.e. ~2 L.day^{-1}). This pattern in daily water-use was repeated during small rainfall events in late September 2016. Solar radiation over this period continued to steadily increase by ~ 10 MJ day^{-1} from 17 July to 31 October 2016. However, the daily water-use showed no response to the increased solar radiation. This implied that the water-use of the invasive pine trees was limited by water availability.

In the wet summer period (November 2016 to February 2017), rainfall occurred regularly and the invasive pine trees had access to a more stable supply of water. Daily summer water-use reached a maximum of 21.2 L.day^{-1}, with an average of 5.8 L.day^{-1}. As water availability was not limiting during this wet period, the availability of energy became a limiting factor that affected the transpiration rates. This was evident from the 14 February to 25 February 2017 (Figure 6.13), when a drop in solar radiation (~25 MJ.day^{-1} to ~8 MJ.day^{-1}) coincided with a decrease in the daily water-use (~10 L.day^{-1} to <5 L.day^{-1}).

The results showed that the daily water-use of the invasive pine trees was largely dependent on water availability, providing a possible indication that the invasive pine trees were obtaining water predominantly from the vadose zone. This also implied that the pine trees at the indigenous site were not in regular contact with the groundwater table, as the water-use was close to zero in the dry periods, despite being evergreen.

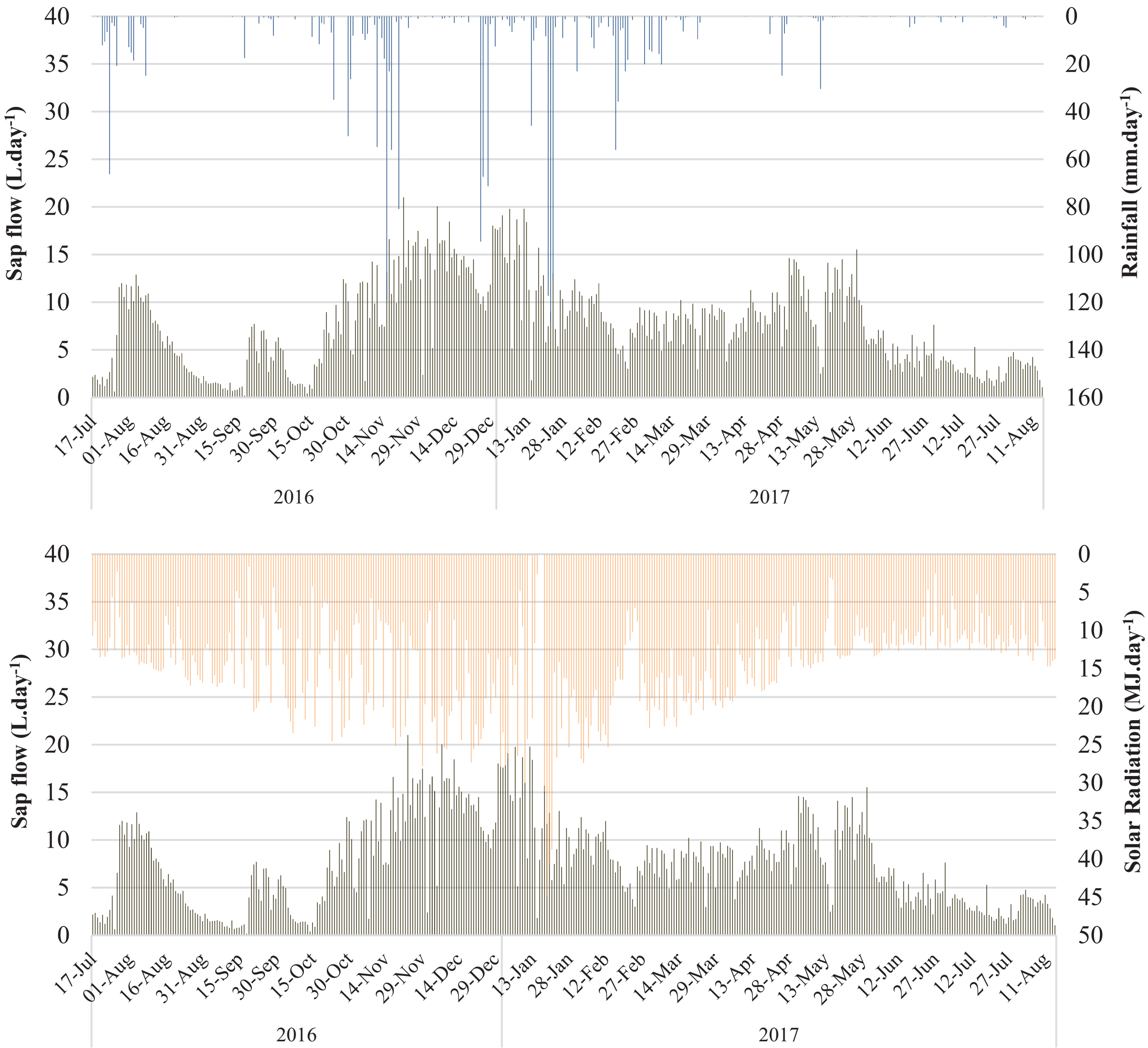


Figure 6.13 Mean daily water-use (L.day^{-1}) of the invasive pine trees monitored located within a mix indigenous forest on the fridge on Vasi Pan North compared with daily rainfall (mm.day^{-1}) and solar radiation (MJ.day^{-1})

6.3.3 *Commercial Pine*

Due to the shortage of sap flow equipment, monitoring at the commercial pine stand was restricted to a short period from June 2017 to mid-August 2017. This corresponded to the dry winter season. During this period, the average daily water-use was 5.32 L.day^{-1}, with a maximum of 12.73 L.day^{-1} and minimum of 3.44 L.day^{-1} (Figure 6.14).

The daily water-use of commercial pine trees did not show any consistent trends, in response to rain or solar radiation. Solar radiation remained low (<12 MJ.day^{-1}), with little daily variation. In addition, the daily rainfall events over this time were small (<5 mm.day^{-1}) and infrequent, which is expected in the dry winter period. These factors may account for the lack of response from the trees, in terms of their daily water-use. A longer monitoring period was needed to determine the effects of these climatic variables on the seasonal water-use of commercial pine trees.

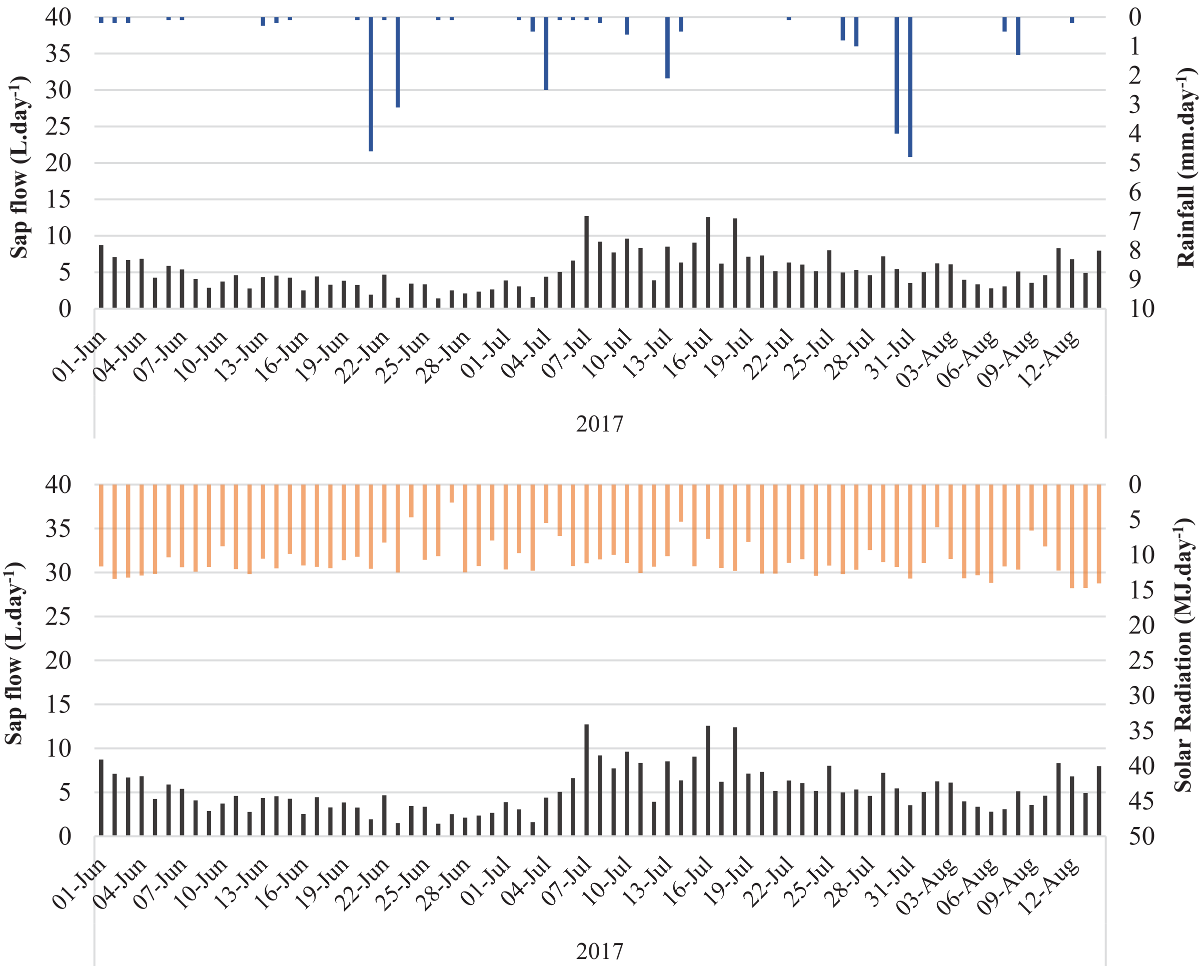


Figure 6.14 Mean daily water-use (L.day^{-1}) of the pine trees monitored located in a commercial pine stand compared with daily rainfall (mm.day^{-1}) and solar radiation (MJ.day^{-1})

6.3.4 Young Eucalyptus

Water-use at the small eucalyptus stand (2-year-old) was monitored from the beginning of the wet season in September 2016 to the dry season in August 2017. The daily water-use (Figure 6.15) was calculated as an average of three trees.

The daily water-use was high during the wet months (Figure 6.15), with a maximum of 35.32 L.day^{-1} and an average of 19.28 L.day^{-1} (November 2016 to February 2017). During the wet period, the daily water-use responded to changes in solar radiation. For example, from the 8-9th of November 2016, a decrease in solar radiation (20.07 to 9.31 MJ.day^{-1}) coincided with a decrease in daily water-use (18.42 to 9.52 L.day^{-1}).

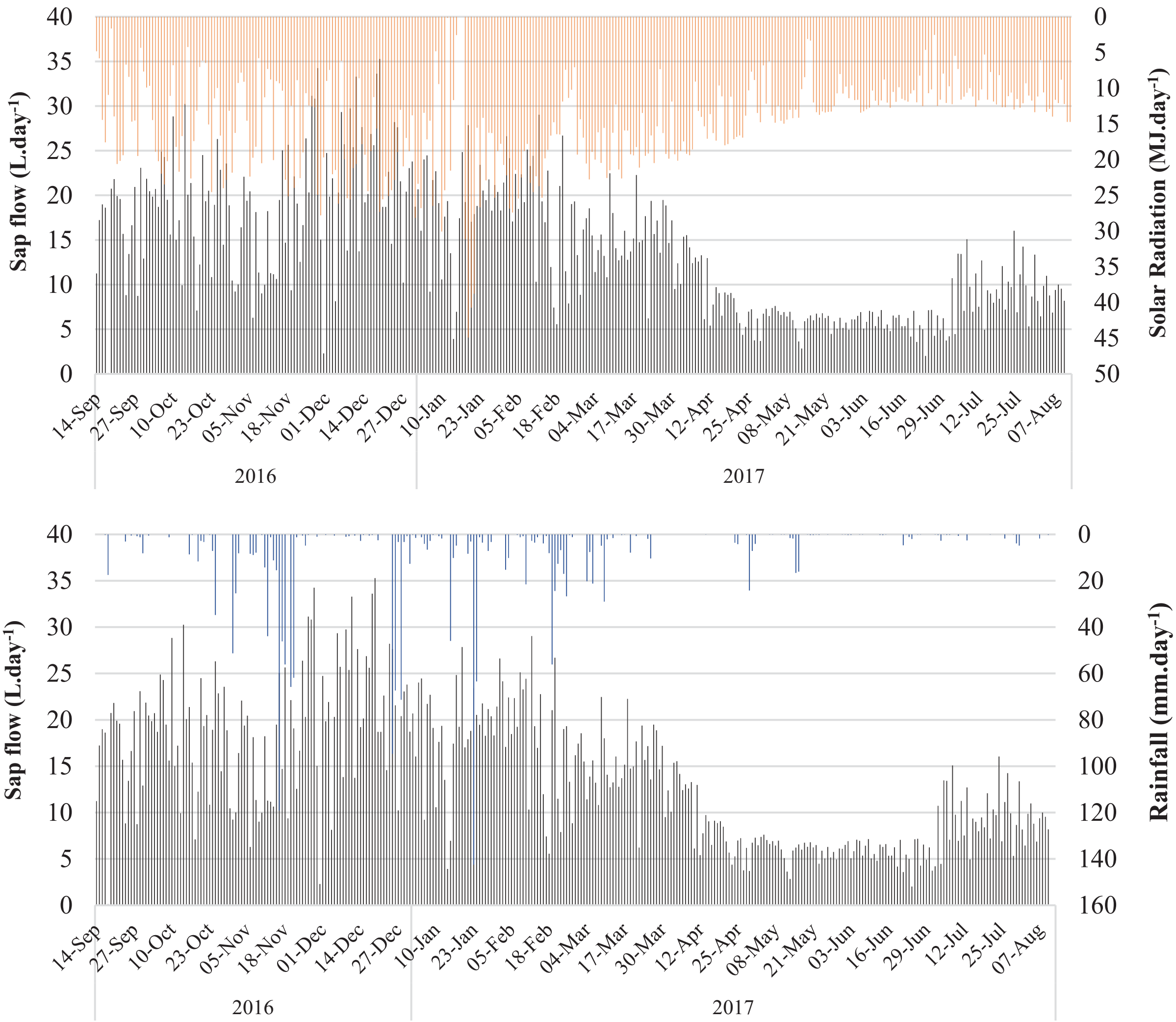


Figure 6.15 Mean daily water-use (L.day^{-1}) of the small eucalyptus trees monitored located on the edge of Vasi Pan North compared with daily rainfall (mm.day^{-1}) and solar radiation (MJ.day^{-1})

The daily water-use of the small eucalyptus trees decreased from the end of the wet summer season (March 2017) into the winter season. This decrease was in response to a decline in solar radiation, with the onset of winter. During the dry winter season, the average daily water-use was 7.95 L.day^{-1} (June- July 2017) and the trees' water-use did not response to rainfall events. The lack of response to infrequent rainfall events and the high average water-use during the dry season, indicated that the water-use of the small eucalyptus trees was limited by available energy and not by water availability. The small eucalyptus trees were not reliant on rain, but were potentially obtaining the water they used for transpiration from the shallow groundwater zone, as the trees were planted on the fringe of a wetland (Vasi Pan North).

6.3.5 Eucalyptus woodlot

The large eucalyptus trees (5-year-old) were monitored from the wet season (November 2016) into the dry season (August 2017). Daily water-use during the wet season was high, with an average of 18.04 L.day^{-1} (November 2016 to February 2017) and a maximum of 35 L.day^{-1} (Figure 6.16) During the wet season, when rainfall occurred frequently, daily water-use responded to changes in solar radiation, decreasing as the solar radiation decreased.

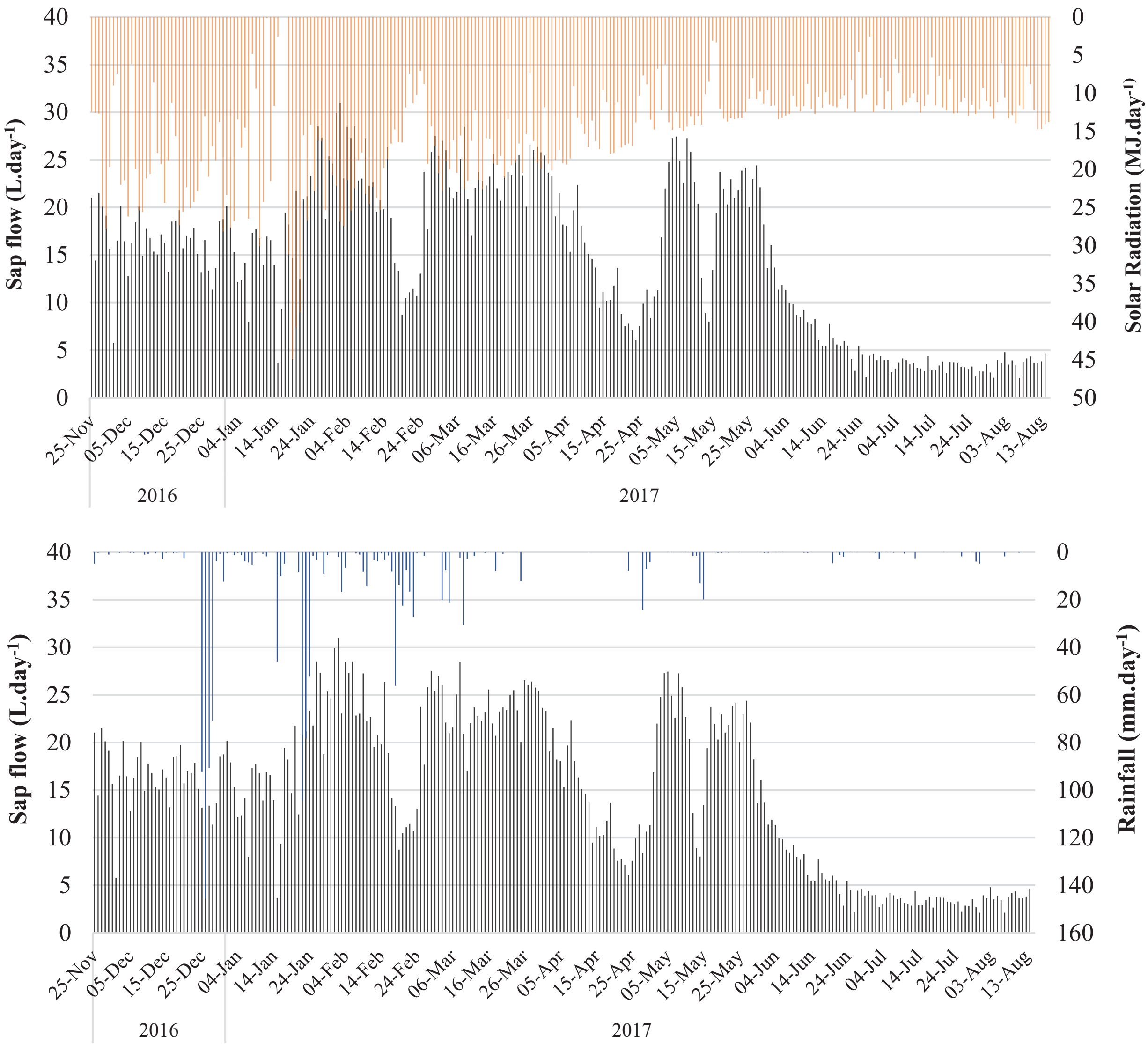


Figure 6.16 Mean daily water-use (L.day^{-1}) of the large eucalyptus trees monitored compared with daily rainfall (mm.day^{-1}) and solar radiation (MJ.day^{-1})

Four weeks with no rainfall, from the 25 March to 25 April, resulted in the daily water-use of large eucalyptus trees decreasing from 26.41 to 7.76 L.day^{-1} (Figure 6.16). Their water-use increased from ~4 to ~12 L.day^{-1} after two large rainfall events (>20 mm) in May. During the dry season (June to August 2017), average water-use remained low (4.78 L.day^{-1}), as restricted water supply and solar radiation limited transpiration (Figure 6.16). The water-use of the large eucalyptus trees in summer was therefore limited by water availability. This relationship between soil water availability and tree water-use indicated that the large eucalyptus trees relied on rain as their primary source of water.

6.3.6 Discussion

The monthly water-use of the monitored trees varied seasonally, with more water being used in the wet summer months than in the dry winter months (Figure 6.17). The large eucalyptus trees used the most water per month in March 2017 (735.11 L), while the indigenous trees used the least water per month in July 2016 (46.71 L). The length of the monitoring period for the selected species varied according to the installation date, therefore, cumulative water-use was not calculated, as the results would not be comparable between species.

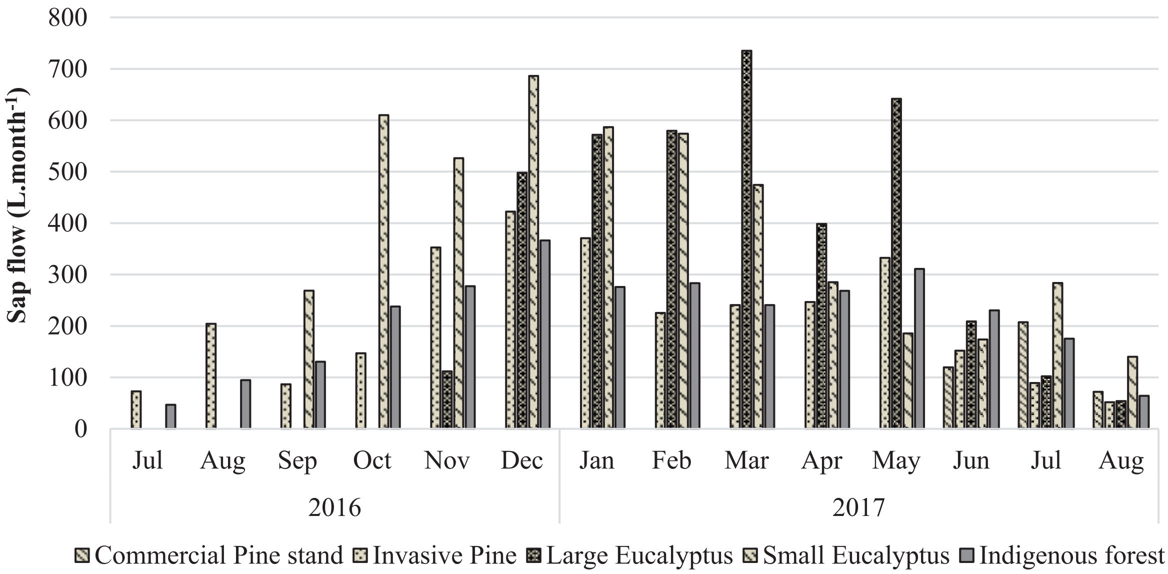


Figure 6.17 Total monthly water of the tree spp. monitored around the Vasi Pan area

The average daily water-use, for all the tree species monitored was higher in summer than in winter (Table 6.9). In summer, the average daily water-used was highest for the small eucalyptus (19.24 L.day^{-1}) and lowest for indigenous trees (10.02 L.day^{-1}). The large and small eucalyptus trees used substantially more water per day (~ 8 L.day^{-1}) than the pine and indigenous trees.

In winter, all the tree species monitored used significantly less water per day than in summer. The average daily water-used was highest for the small eucalyptus trees (7.95 L.day^{-1}), and lowest for the invasive pine trees (4.67 L.day^{-1}) in winter (Table 6.9). The average daily water-uses were similar for the commercial and invasive pine sites, the indigenous forest site, and the large eucalyptus site (Table 6.9). However, at the small eucalyptus site, the trees used ~ 3 L.day^{-1} more water than the trees at the other sites in winter. This difference in average water-use is of particularly interest for the large eucalyptus, as their water-use averages were similar in summer.

The average daily water-use of the large and small eucalyptus trees was similar in summer, with a difference of only 1.2 L.day^{-1} (Table 6.9). However, throughout the winter, the difference in their average daily water-use was far greater (3.17 L.day^{-1}), with the small eucalyptus using more water. This difference in daily water-use was because the transpiration rates of the large eucalyptus trees are water-limited, while the small eucalyptus trees were energy-limited. The small eucalyptus trees were planted on the fringe of the Vasi North wetland, where the groundwater table was shallow and the trees could easily access the water during times of low rainfall. The large eucalyptus trees were planted on dry grasslands and the groundwater table was deeper, therefore the large eucalyptus trees were reliant on rainfall as their main source of water.

Table 6.9 The average daily water-use for the tree spp. monitored in the Vasi Pan area

	Average water-use (L.day^{-1})	
	Wet summer (Nov-Feb)	**Dry winter (June-Aug)**
Indigenous forest	10.02	4.67
Commercial pine stand	N/A	5.32
Invasive pine stand	11.42	4.67
Large eucalyptus	18.04	4.78
Small eucalyptus	19.28	7.95

6.4 Eddy Covariance Measurements

6.4.1 Hygrophilous grassland

Energy fluxes for the hygrophilous grassland were recorded during November 2016, February, March and April 2017 (Figure 6.18a). During the monitoring period, latent energy (LE) peaked at approximately 280 W.m^{-2}, with the sensible heat flux (H) peaking at 240 W.m^{-2}. The average monthly Bowen ratio was >1, indicating that H dominated the energy balance (Figure 6.18a) in winter. The average Bowen ratio increased from June (1.27) to August 2017 (2.68), indicating that less energy was available to evaporate water.

6.4.2 Indigenous forest

Energy fluxes for the indigenous forest were measured from the end of summer (February 2017) to mid-winter (July 2017). The noticeable dips in Rn, for the months of February, June and July, were due to cloud cover (Figure 6.18b). The balance of energy between two of the three components shifted during the monitoring period. G remained low (<50), while the partitioning of energy between LE and H varied (Figure 6.18b). For the months of February, March, May, and June, LE dominated the energy balance, with an average Bowen ratio of < 1. During these months, more of the available energy was being used for the evaporation of water. The average monthly Bowen ratio was close to one for April (0.97) and July (1.09), indicating that the available energy was being equally partitioned between evaporating water (LE) and heating up the atmosphere above the soil (H).

The energy balance closure, calculated from the direct hourly energy flux daytime values, was poor for each land use (indigenous forest 43.79 %; commercial pine stand 66.06 %). These discrepancies may be a result of an overestimation of LE and/or H, an underestimation of the available energy (Rn - G) and unaccounted energy, such as advection or storage in the canopy biomass.

6.4.3 Commercial Pine

Energy fluxes for the commercial pine stand were recorded over the 2017 dry season and the data followed the expected energy balance relationship, where LE and H were less than Rn (Figure 6.18c). During the monitoring period, LE peaked at 10 am (~100 w.m^2) and was lower than H, which peaked at midday (~200-300 w.m^2). The LE peaking at 10 am indicated that there was stomatal closure to control water loss. The average monthly Bowen ration was >1, indicating that H dominated the energy balance (Figure 6.18b) in winter. The average Bowen ratio increased from June (1.27) to August 2017 (2.68), indicating that less energy was available to evaporate water.

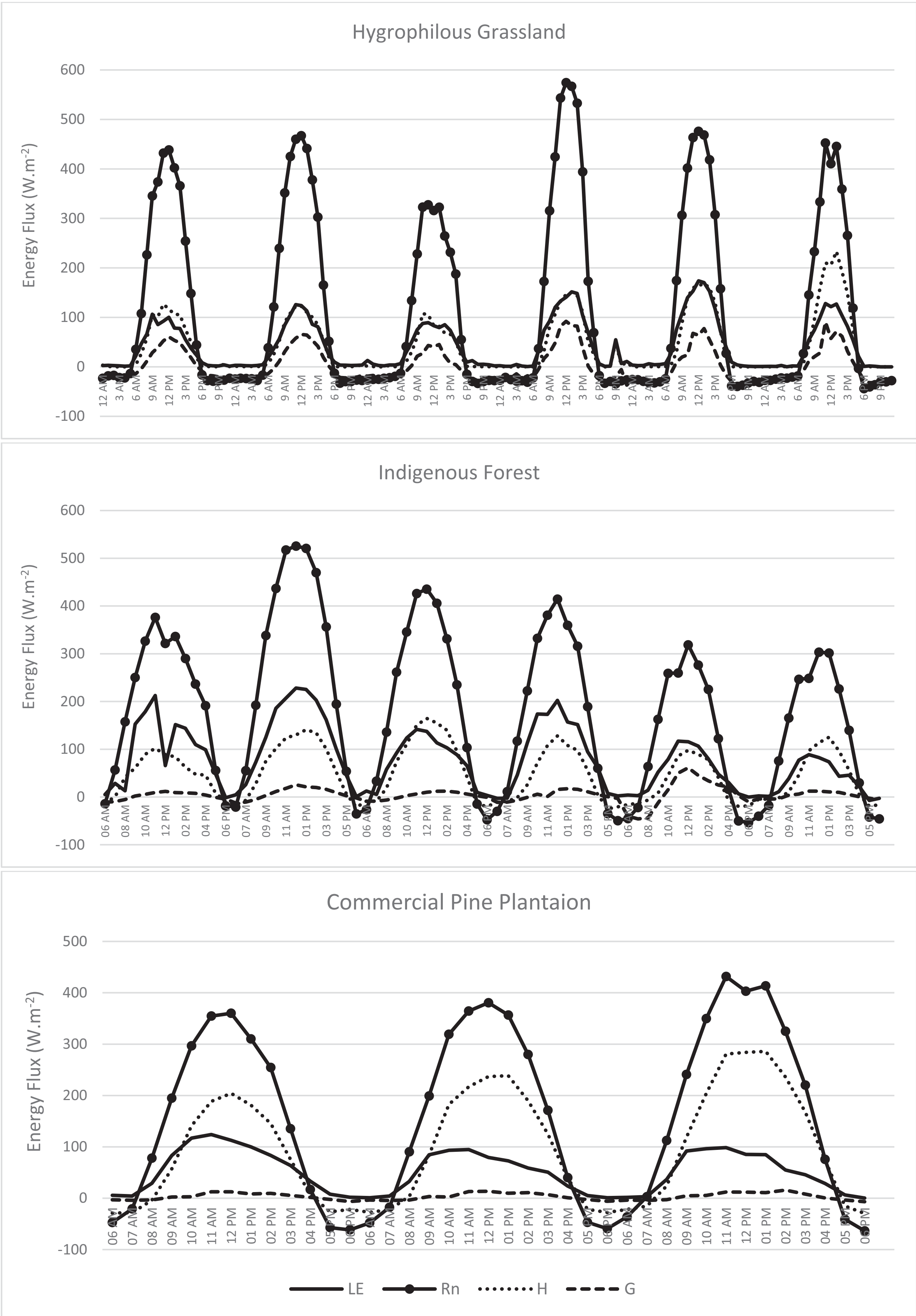


Figure 6.18 Average hourly energy fluxes measured at each monitoring site

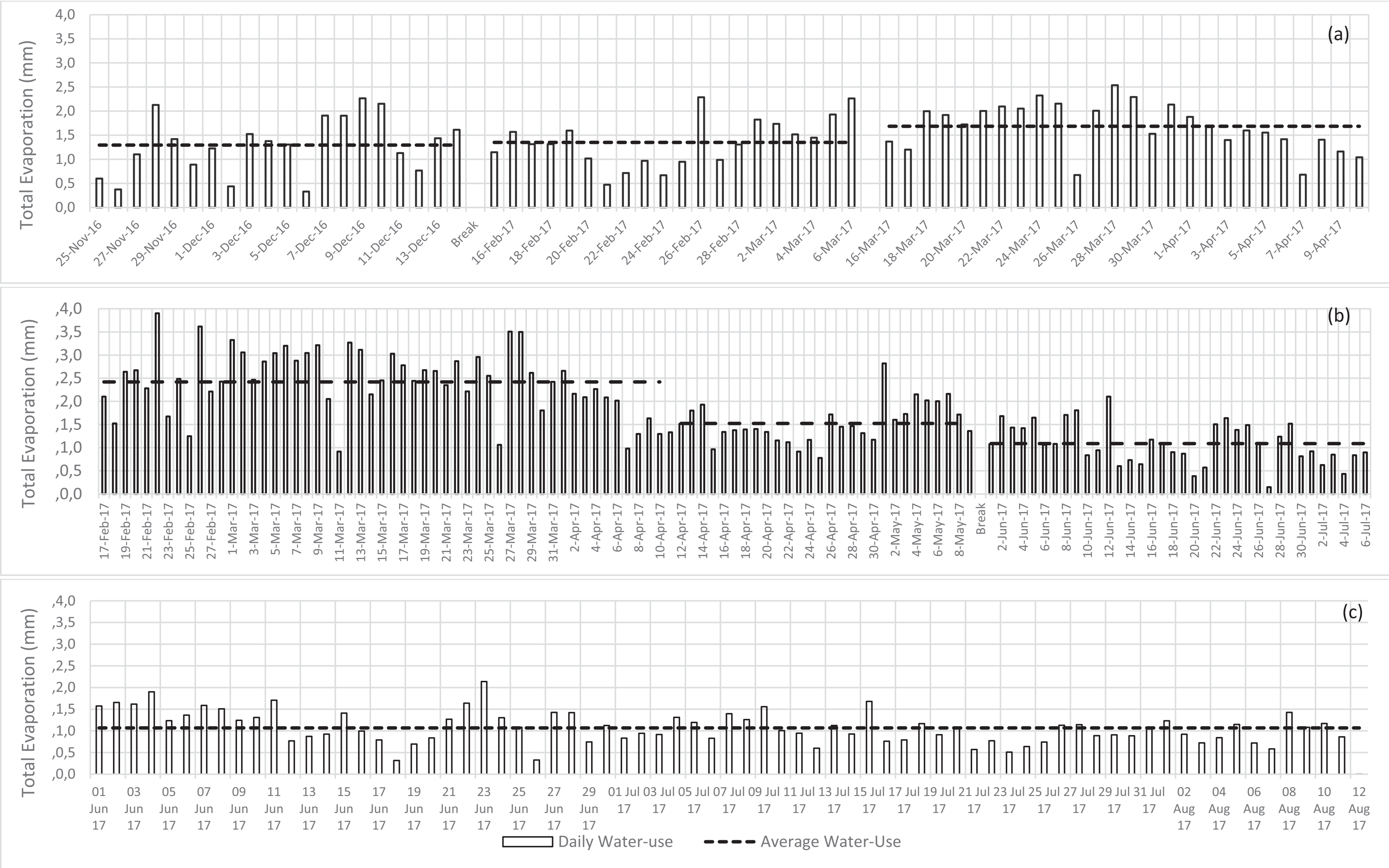


Figure 6.19 Daily total evaporation of the hygrophilous grassland (a), the indigenous forest (b) and the commercial pine stand (horizontal dotted lines are means for the relevant periods).

Commercial pine stands were identified as a dominant land use in the Vasi area and a 12-year-old stand was identified for monitoring sap flow and ETa monitoring, using an EC system, during the dry winter period of 2017 (June to mid-Aug). The ETa peaked in late July (2.14 mm.day^{-1}) and, during this period, the average ETa was low (1.07 mm.day^{-1}), as rainfall and solar radiation were limiting (Figure 6.20). The ETa measurements indicated that the trees were conservative water-users in winter, despite the presence of a shallow groundwater table.

During the winter period both Eta and transpiration were low with daily rates generally < 1.0 mm day^{-1}. The average transpiration (1.75 mm.day^{-1}) was similar to the average ETa (1.1 mm.day^{-1}) (Figure 6.20). Although Eta is usually expected to be greater than transpiration (i.e. it includes other sources of evaporation such as the plant sub-canopy and bare soil). These results are not surprising as the understory was dormant (winter) and the differences small in relation to the resolution of both techniques.

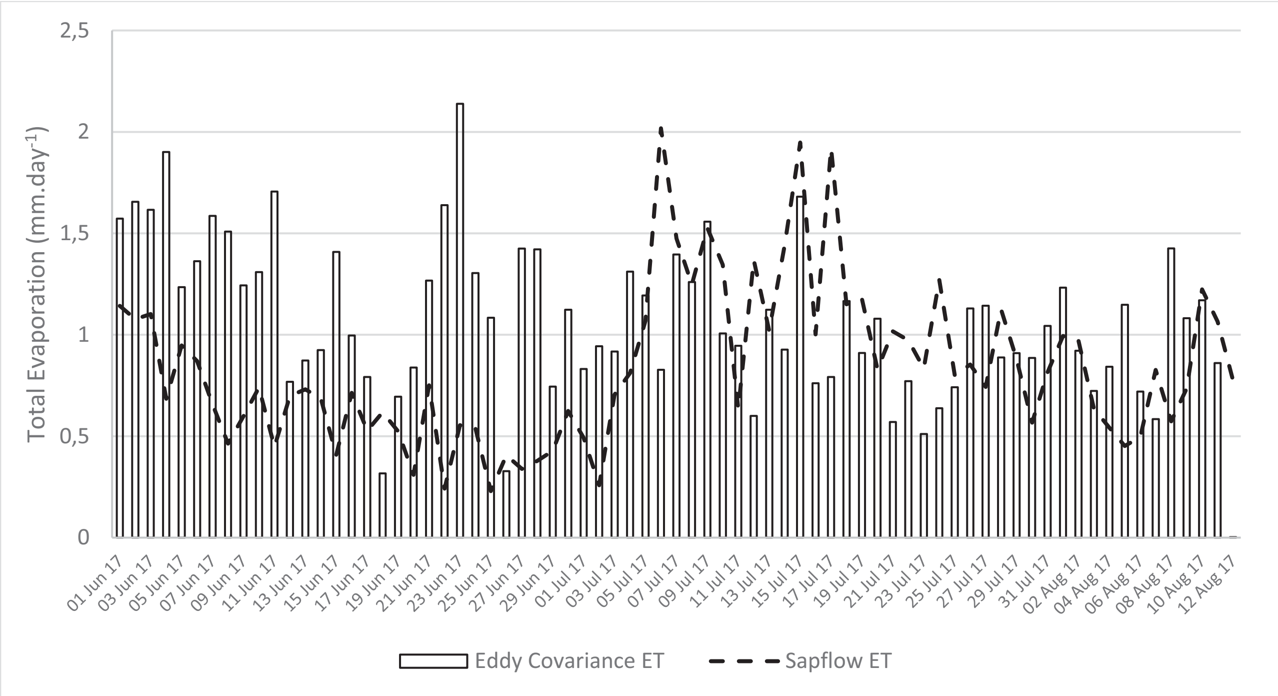


Figure 6.20 Daily total evaporation of the commercial pine stand measured using EC and sap flow techniques

The ETa from the indigenous forest was monitored from the wet period in February 2017 to the dry period of July 2017.The daily ETa steadily decreased over the monitoring period, with a maximum ETa of 3.7 mm.day^{-1} occurring in February 2017 (Figure 6.21). The average ETa showed distinct seasonal decreases every two months, as the radiation and rainfall decreased from February to March (2.57 mm.day^{-1}), April to May (1.51 mm.day^{-1}) and June to July (1.02 mm.day^{-1}). This indicated that the total evaporation of the indigenous trees was responding to the seasonal changes in climate and tree physiology.

From June to July 2017, simultaneous measurements of ETa were taken in the indigenous forest and the commercial pine stand. The average daily water-use for the commercial pine stand (1.54 mm.day^{-1}) was higher than the average recorded for the indigenous forest (1.02 mm. day^{-1}) (Figure 6.21). Although the commercial pine stand used slightly more water than the indigenous forest, both forest types were conservative water-users in winter.

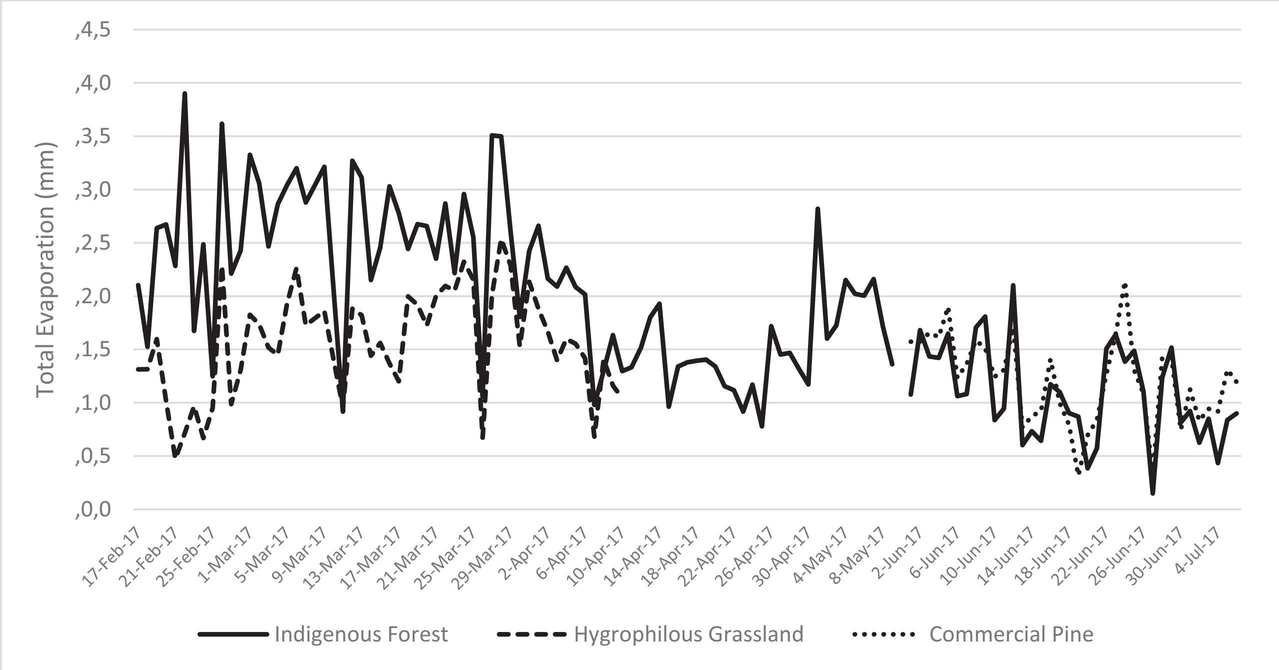


Figure 6.21 Daily total evaporation measured above the indigenous forest, the hygrophilous grassland and the commercial pine stand

The monthly Kc factors calculated for the indigenous forest and commercial pine stand followed the same trends as the HPV and EC data. For the indigenous site the Kc was the highest in February 2017 (0.93) and the lowest in July 2017 (0.4). High Kc values are typical when the vegetation is actively transpiring, which is associated with high incoming solar radiation and water availability. These conditions were present during the summer months in the Vasi Pan area. The Kc values decreased from February to July 2017; however, an increase from April (0.5) to May (0.69) was due to the late rains that occurred in May. In the commercial pine stand, Kc was the highest in June (0.55) and the lowest in August (0.32). The values decreased monthly during the dry season. The Kc for June and July were similar for the commercial pine stand and the indigenous forest, with values of ~0.5.

The Kc values in winter were generally much lower than one, indicating that the ETa was much less than the ETo. In summer, the values were just less than one, indicating that ETa was nearly equal to ETo (evaporative demand).

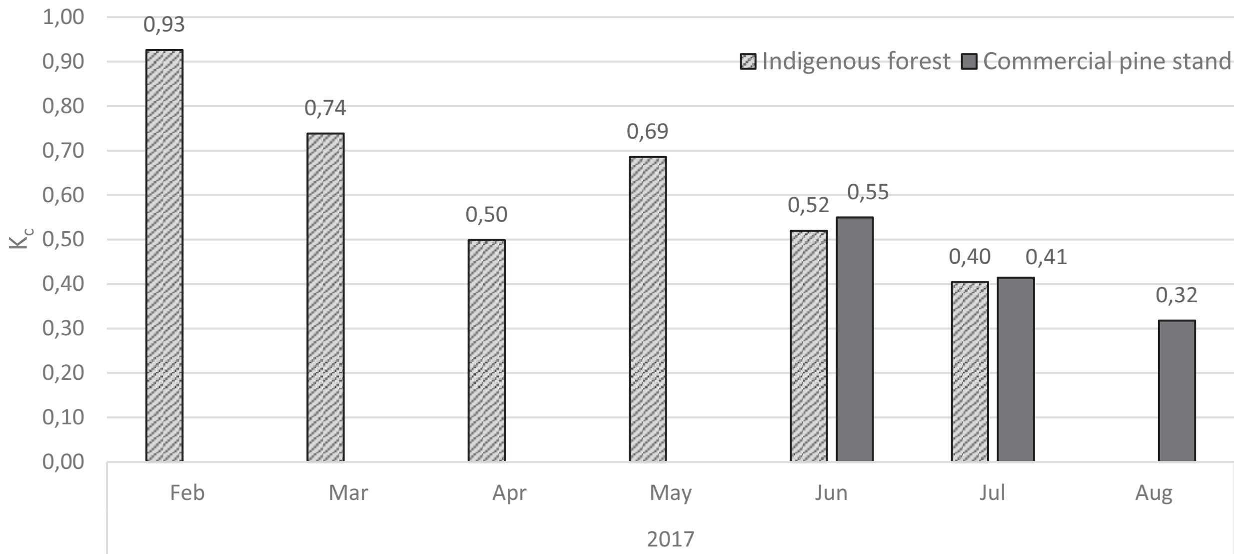


Figure 6.22 Monthly crop co-efficient (K_c) for the selected land uses in the Vasi Pan area

6.4.4 Discussion

The sap flow and EC data provided an indication of the seasonal water-use of the selected species and comparisons with simultaneous weather data has helped to highlight the relative influence of climatic conditions on the daily sap flow.

The water-use of the pine trees (*Pinus elliottii*) varied seasonally, with the pine trees using less water in the dry season. The timing of the decline in water-use, the rapid recovery after significant rainfall, and the presence of a relatively shallow groundwater table, inferred that the water-use of the pine trees was dependant on the available water from rain. In South Africa, several studies have reported sap flow data for *Pinus spp;* however, no comparable study on the water-use of *Pinus elliottii* in the Zululand region was found. A study measuring the water-use of invasive pines in riparian zones in the Western Cape showed similar trends in water-use (Dzikiti *et al.*, 2013). The results from this study, and that of Dzikiti *et al*. (2013), showed a substantial decline in water-use in the dry periods, despite the presence of shallow groundwater. This was because most pine species are isohydric, which means that they close their stomata, as soil and atmospheric conditions become dry, to maintain a relatively constant leaf water potential (Klien *et al*., 2011; Lagergren and Lindroth, 2002). The pine trees growing in the Vasi Pan area are isohydric, as the LE peaked at 10 am in winter before maximum net radiation and air temperatures were reached, indicating stomatal closure.

From the comparison between ET_a and transpiration data for the commercial pine stand, it was concluded that the HPV method was not underestimating daily water-use of the pine trees, as transpiration rates regularly exceed ET_a rates. The average daily water-use for pine trees (~16 year-old, diameter 14 cm) growing in the Vasi Pan area was ~11 L.day^{-1} in summer and ~5 L.day^{-1} in winter. These values were significantly lower than values recorded in previous studies undertaken in summer rainfall areas throughout South Africa (Dye *et al.*, 2001; Gush *et al.*, 2011). The daily average water-use of *Pinus patula* trees, located in Karkloof, KZN midlands, were found to be ~50-100 L.day^{-1} in summer and ~25-30 L.day^{-1} in winter (Dye *et al.*, 2001; Gush *et al.*, 2011). This difference in water-use can be attributed to the differences in soil water holding capacity between the two regions. The pine trees in the KZN midlands are planted on shale and sandstone soils, which have a greater water holding capacity than the sandy soils located in the Vasi Pan area.

The semi-deciduous nature of the monitored indigenous species accounts for the seasonal variation in water-use. The trends in daily water-use conformed to the patterns from other single-tree water-use studies in South African indigenous tree production systems (Gush and Dye, 2009; Gush 2011; Mapeto *et al*., 2017). Similar results were found in a moist southern Cape forest, as ET_a varied from season to season (Dye *et al*., 2008). The seasonal variation in transpiration rates is an adaptation that allows the trees to survive in conditions with limited soil water storage and regular dry periods. A comparable study by Clulow *et al.* (2013) measuring the water-use of indigenous species growing in dune forest in Zululand, found that the indigenous species used ~25 $L.day^{-1}$ in summer, which was considerably higher than the values recorded in this study (~10 $L.day^{-1}$).

The water-use of the small (2-year-old) and large eucalyptus (5-year-old) (*Eucalyptus grandis*) trees monitored in the Vasi Pan area were lower than the values recorded in a previous study monitoring eucalyptus spp. in Zululand (Dye *et al.*, 1997). Dye *et al.* (1997) measured the water-use of three eucalyptus hybrids (6- to 8-year-old) growing on sandy soils in Kwambonambi, Zululand. Their daily water-use peaked between 50-70 $L.day^{-1}$ in mid-summer, which was far greater than the peak summer rates recorded at Vasi Pan (25-35 $L.day^{-1}$). The sap flow rates exhibited a similar seasonal trend in both studies, with peak water-use in summer, due to longer day lengths and frequent rains, while water-use decreased in winter, due to a reduction in solar radiation and soil water deficits. A strategy of eucalyptus trees to avoid drought conditions is stomatal closure, this maintains leaf water potential above a critical threshold (Lange *et al.*, 1971; Schulze *et al.*, 1986; Tyree *et al.*, 1988). The large eucalyptus in the Vasi Pan area and eucalyptus trees in Kwambonambi, showed a similar rapid recovery in transpiration rates after a rainfall event, preceded by a period of drought. This indicated that the water-use of the eucalyptus trees in both studies, was generally affected by extended periods of soil water deficits. From these results, one can infer that the roots of the large eucalyptus trees in the Vasi Pan area were not in contact with the groundwater table.

The small eucalyptus trees were planted on the edge of Vasi Pan North, where the groundwater level was shallow. The decrease in water-use of the small eucalyptus trees over the seasons was not due to soil water deficits, but due to the seasonal decrease in solar radiation. Their winter water-use was ~3.5 $L.day^{-1}$ higher than the other trees monitored in the study. Dye (1996) conducted a study on 3- and 9-year-old *E. grandis* trees to determine the relationship between water-use and soil water availably. Plastic sheeting was placed on the ground to prevent soil water recharge. The trees showed no decline in water-use in response to increased soil water deficits. Dye (1996) attributed this to the ability of 3-year-old eucalyptus trees to abstract water from depths of 8 m, while 9-year-old eucalyptus trees can obtain water from deeper, as live roots have been found at up to 28 m below the surface (Dye, 1996). The lack of response to decreased water availability by the small eucalyptus was because their roots were in contact with the water table during dry periods and could maintain transpiration rates by accessing water stored in the soil water profile.

Apart from the small eucalyptus trees planted on the edge of Vasi Pan North, the results showed that the water-use of the other trees monitored were limited by water availability, indicating that their roots were not in contact with the groundwater table. Water levels of the nearby Lake Sibhya have dropped by almost 4 m from 2001 to 2010, this is in response to the area receiving below average rainfall over the period of 2001 to 2011 (Smithers *et al*., 2017). Lake Sibhya water levels can be used as a proxy interpreting groundwater levels in the area, therefore, one can infer that groundwater levels have dropped in recent years. The lowering of groundwater table in recent years may account for the trees, particularly the deep-rooted large eucalyptus trees, not abstracting water from the groundwater table during prolonged dry periods.

The average summer and winter water-use of the indigenous and pines trees were similar in this study. This contrasts with the previous studies which found that daily water-use was significantly greater for the pine trees than the indigenous spp. (Gush and Dye, 2009; Gush *et al.*, 2011). Results from a study by Gush *et al.*

(2011) in Karkloof, KZN midlands showed that in peak summer *P. patula* trees used more water per day (50-100 $L.day^{-1}$) than indigenous *Podocarpus henkelii* trees (10-20 $L.day^{-1}$). In this study, the eucalyptus trees used more water per day than the indigenous and pine trees. Numerous studies throughout South Africa monitoring various pine, eucalyptus and indigenous tree species have shown that the water-use of indigenous trees is lower than the water-use of pine and eucalyptus trees (Olbrich *et al.*, 1996; Dye *et al.*,2001; Gush *et al.*, 2011; Gush *et al.*, 2015). In this study, the water-use of the indigenous trees was low, as was the water-use of the pine trees.

6.5 Cosmic Ray Rover (CRR)

6.5.1 Hygrophilous grassland

The grassland survey took six hours to conduct. Figure 6.23 shows the survey maps of the hydro-sense soil water measurements (a) and the corrected neutron counts (b). The inverse relationship between soil water and neutron intensity can be seen, as the areas of higher soil water, subsequently have the lowest neutron intensities. The cosmic ray rover soil water map (Figure 6.23 c) correlates well with the hydro-sense soil water map with regards to the soil water patterns and the cosmic ray rover mapped high soil water areas very well. The cosmic ray rover and hydro-sense maps, when compared to the landcover image (Figure 6.23 d), show that the areas of high soil water correspond to the areas of the thicket vegetation. There is a discrepancy in the scale of soil water estimates between the hydro-sense, which ranges from 1.4 to 29.1 and the cosmic ray rover estimates, which ranges from 1.3 to 17.3.

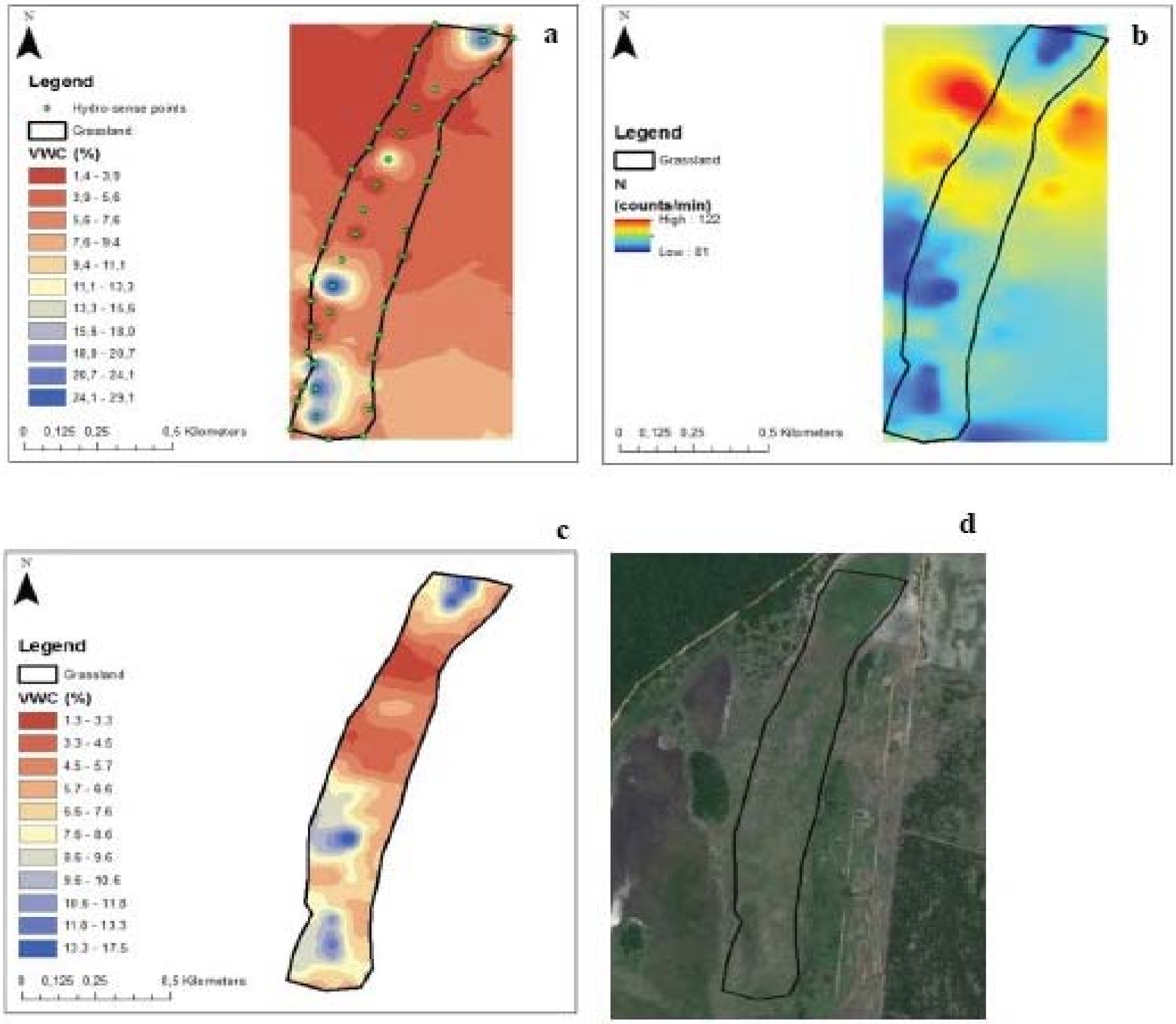


Figure 6.23 Maps of the Hydro-sense measurements (a), corrected neutron counts (b), cosmic ray rover estimates (c) and landcover (d)

6.5.2 *Commercial Eucalyptus*

The eucalyptus site survey took two hours to conduct. The hydro-sense soil water map (Figure 6.24 a) shows that the soil water is generally low throughout the area, with high soil water measurements towards the north-west of the site. The corrected neutron counts map (Figure 6.24 b) shows a decrease in neutron intensity, as you move from north to south of the site. The inverse relationship between soil water and neutron intensity is represented in this site. The cosmic ray rover soil water estimates map (Figure 6.24 c), correlates well with the hydro-sense soil water map, as the general soil pattern is captured. The landcover image (Figure 6.24 d), shows that the greener areas of the site (thicket), which is the north-western area of the site has higher values of soil water. These higher soil water areas are adequately captured by the cosmic ray rover map.

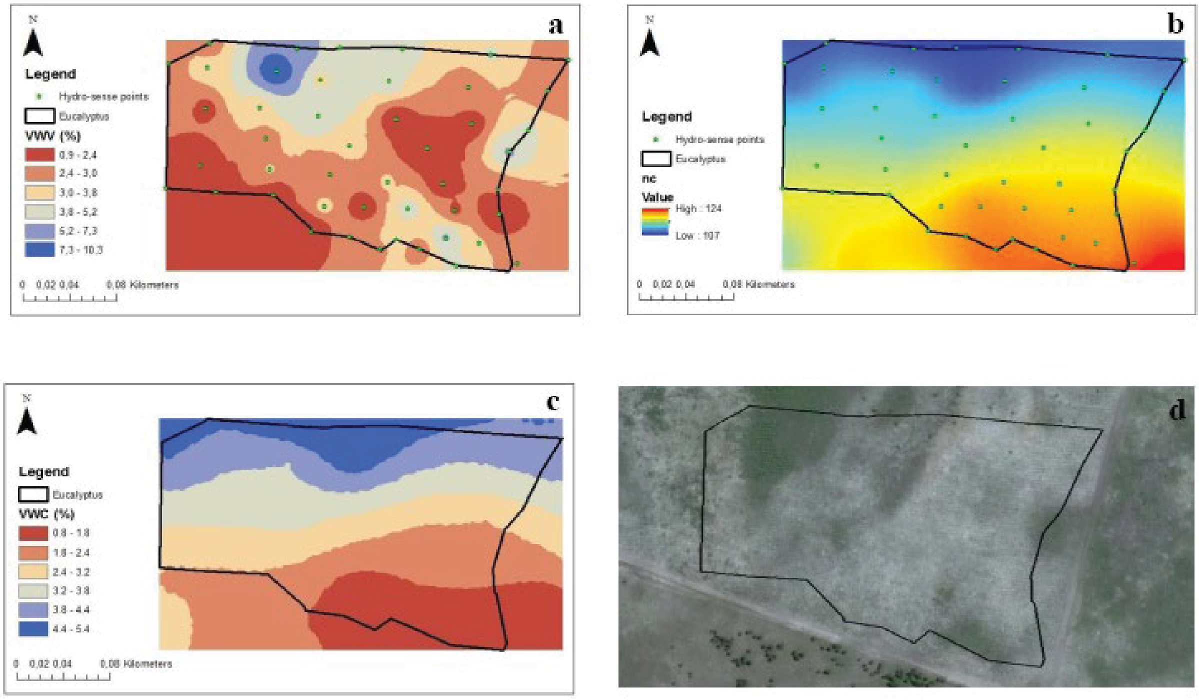


Figure 6.24 Maps of the Hydro-sense measurements (a), corrected neutron counts (b), cosmic ray rover estimates (c) and landcover (d)

6.5.3 Commercial Pine

The pine site survey took three hours to conduct. The hydro-sense soil water map (Figure 6.25 a), shows that the soil water is lower in the south-western side of the site and increases towards the north-eastern side of the survey site. The corrected neutron count map (Figure 6.25 b), agrees with the inverse relationship between soil water and neutron intensity as there is a decrease in neutron intensity in the north-eastern side of the site, which correlates to the higher soil water area of the site. The cosmic ray rover soil water estimates map (Figure 6.25 c), correlates well with the hydro-sense soil water map, as the general soil water patterns are similar, as both maps show an increase in soil water from the south-west to the north-east of the survey site. The landcover image (Figure 6.25 d), when compared with the hydro-sense and cosmic ray rover soil water maps, show that the area of high soil water corresponds to the area of thicket vegetation in the catchment. There is a slight difference in soil water ranges between hydro-sense and the cosmic ray rover.

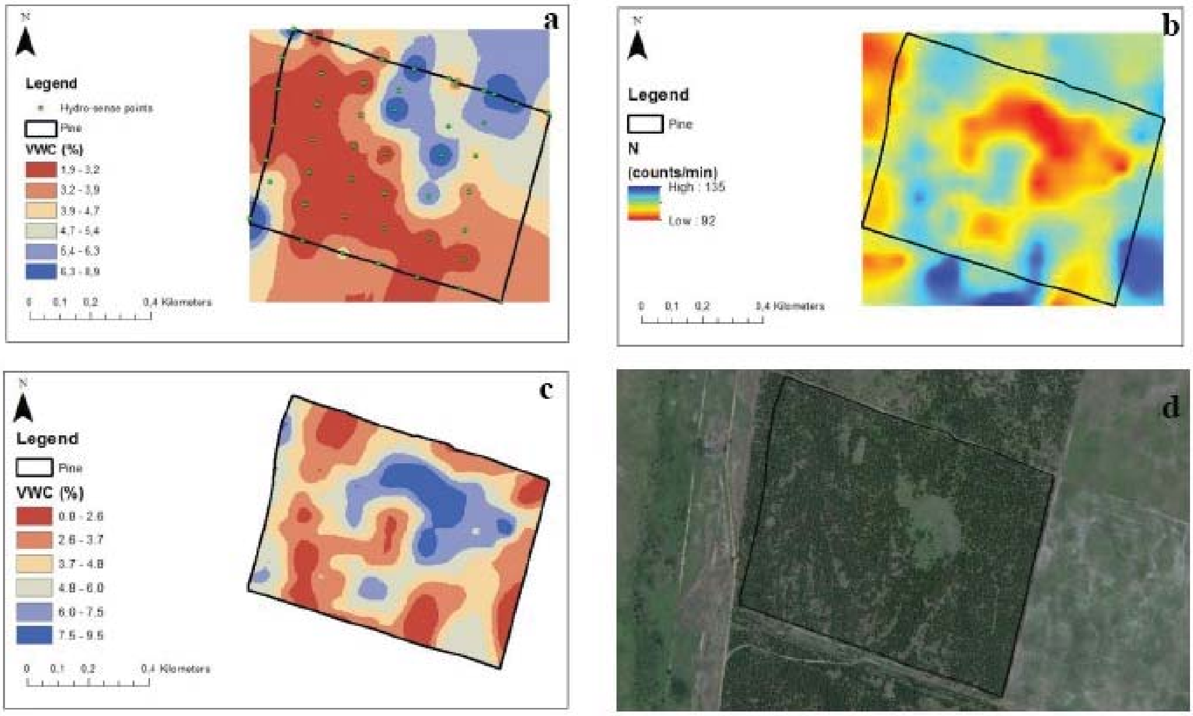


Figure 6.25 Maps of the Hydro-sense measurements (a), corrected neutron counts (b), cosmic ray rover estimates (c) and landcover (d)

6.6 Soil Water Assessment Tool (*SWAT*)

The findings from the surface water modelling component have been separated into a model calibration section detailing the improvements and/or potential shortcomings of the model, and the findings from the scenario testing discussed in Section 5.4.1.3.

6.6.1 Initial model simulation and calibration

An initial simulation was undertaken to test the suitability of the model for this site and to identify areas where improvements or further investigations are required. The annual water balance (Figure 6.26) showed that a high proportion of water percolates to the shallow aquifer with approximately half of that reaching the deep confined aquifer. A large amount of the water balance was partitioned to total evaporation, indicating that a large amount of water was being used by the vegetation. The streamflow component (surface runoff, lateral flow and return flow) totalled 117 mm. The impact on the groundwater component on streamflow in this area was significant. Additionally, it was unlikely that runoff would contribute such a high amount to total streamflow. The sub-surface components were more likely to contribute to this component. This showed that calibration was required for the streamflow component and the linkage between the surface water and groundwater components would be key in improving this simulation.

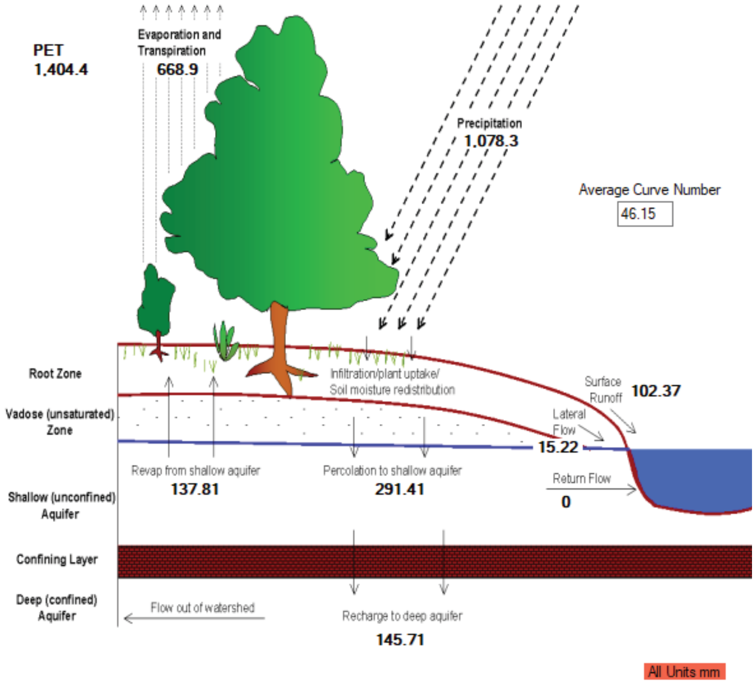


Figure 6.26 SWAT annual water balance for the Vasi Pan system

Through the calibration process, an improvement of the simulation was gained. The pre-calibration coefficient of determination was 0.49. The post-calibration coefficient of determination was 0.69 which was a significant improvement. The pre-calibration flows over-simulating peak events with low flows being over-simulated by approximately 0.3 $m^3.s^{-1}$ throughout the observation period (Table 6.10).

The calibrated flow had a lower mean flow than that of the observed data. Through the 379 day period, the sum of squares was 75.3 and the correlation coefficient (Pearsons r) was 0.83. These findings indicated that the calibrated model is suitable for this site although numerous groundwater inputs had to be changed to obtain this relationship.

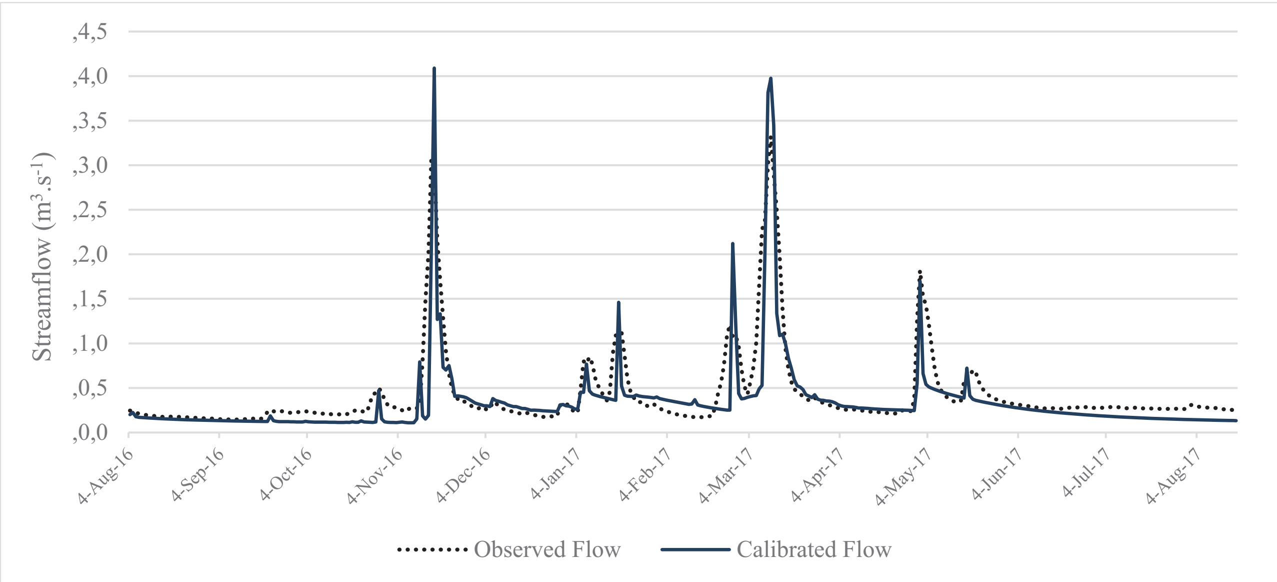


Figure 6.27 Observed streamflow (military bridge) against calibrated simulated flow

Table 6.10 Statistics between observed streamflow and calibrated simulated flow

Conservation Statistics	
Mean Observed	0.42
Mean Simulated	0.34
% Difference Between Mean	19.114
T Statistic for Comparing Means	2.417
Standard Deviation Observed	0.467
Standard Deviation Simulated	0.446
Coefficient of Variation Observed	111.324
Coefficient of Variation Simulated	131.433
Correlation Coefficient - Pearsons r	0.832
Regression Coefficient (Slope)	0.795
Regression Intercept	0.006
Number of Data Points	379
Total Sum of Squares (SST)	75.286
Sum of Squares Due to Regression (SSR)	52.143
Residual Sum of Squares (SSE)	23.143
Coefficient of Determination (R Squared)	0.693

6.6.2 Scenario testing

Generating spatial output data is a key component of SWAT as it allows for data to be quickly and easily relayed to interested parties and various decision makers. There was some difficulty in reducing the time series to a manageable level for graphical and spatial display. Annual data of specific output parameters were spatially output. Seasonal changes could also be displayed (e.g. monthly maps). Furthermore, percentage change between scenarios could be calculated and displayed. This allowed for the identification of sensitive areas or areas where management will have the largest benefit.

Representing total evaporation for each individual hydrological response unit (HRU), although data demanding, provides an indication of which areas with their associated climate, land use, soils, aspect and management are the highest water- users. The land-use was the largest determinant of streamflow reduction. Figures 6.28, 6.29 and 6.30 show the spatial distribution of total evaporation (ET) between the three scenarios. The results showed that ET can be highly variable within land-use types and between various land-use types. This was largely due to changes in soil, depth to water table and management. This was evident where plantations in the lower lying areas (near or within wetlands) had the highest ET.

Groundwater recharge was also highly variable throughout the catchment. Areas of low recharge corresponded to higher areas and vegetation with a high biomass and deep rooting depths outside of wetlands. The recharge in the low-lying wet areas was naturally high, suggesting that if the trees were not growing in these areas, it would be even higher. At a catchment scale, groundwater recharge increased by 13 % under scenario 2 and by 23 % under scenario 3.

The spatial distribution of ET at Vasi Pan (Figures 6.28, 6.29, 6.30 and Table 6.11) showed that the commercial forestry areas were the dominant water-users in the catchment. This area had a shallow water table, which allowed for the rapid growing and deep-rooted introduced species to readily uptake water. The annual summary showed that *E. grandis* had a high ET (799 mm) with the indigenous forest (582 mm) and the grassland (519 mm) using significantly less water. Furthermore, the contribution to groundwater and streamflow was significantly higher for grassland areas (297 mm). At a catchment scale, ET decreased by 2.7 % under scenario 2 and decreased by a further 6 % under scenario 3. At this site, having no typical surface water components, the groundwater fluctuations and interactions with the surface components should be investigated further. Although the groundwater routines in SWAT are not comprehensive, the interactions with the shallow and deep aquifers could be undertaken if coupled with a suitable groundwater model.

Table 6.11 Annual hydrological output summary per land use class at Vasi Pan

Research Catchment	Area (km^2)	Curve Number	Total Evaporation (mm)	Sediment Yield ($T.ha^{-1}$)	Groundwater Contribution (mm).
Grassland	301.77	49.00	519.96	1.30	297.72
Cultivated Lands (irrigated)	8.58	67.00	757.20	4.23	131.30
Eucalyptus grandis	73.85	36.00	799.09	1.71	134.79
Pinus elliotti	80.12	39.00	749.09	1.32	155.81
Indigenous Forest	0.21	49.00	582.44	0.49	245.72
Cashews (irrigated)	9.75	45.00	755.05	0.22	46.15

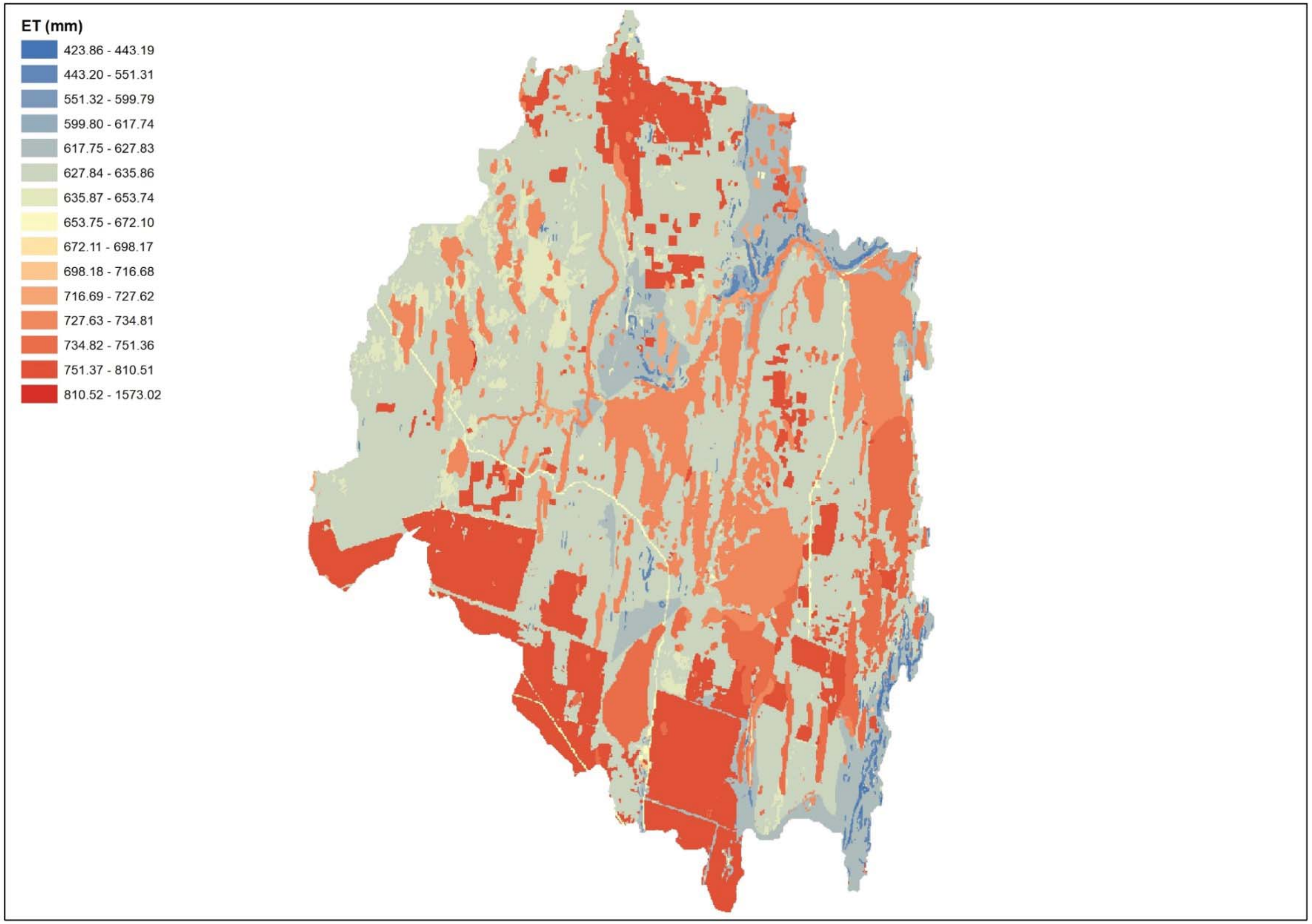


Figure 6.28 SWAT modelled annual average total evaporation for scenario 1

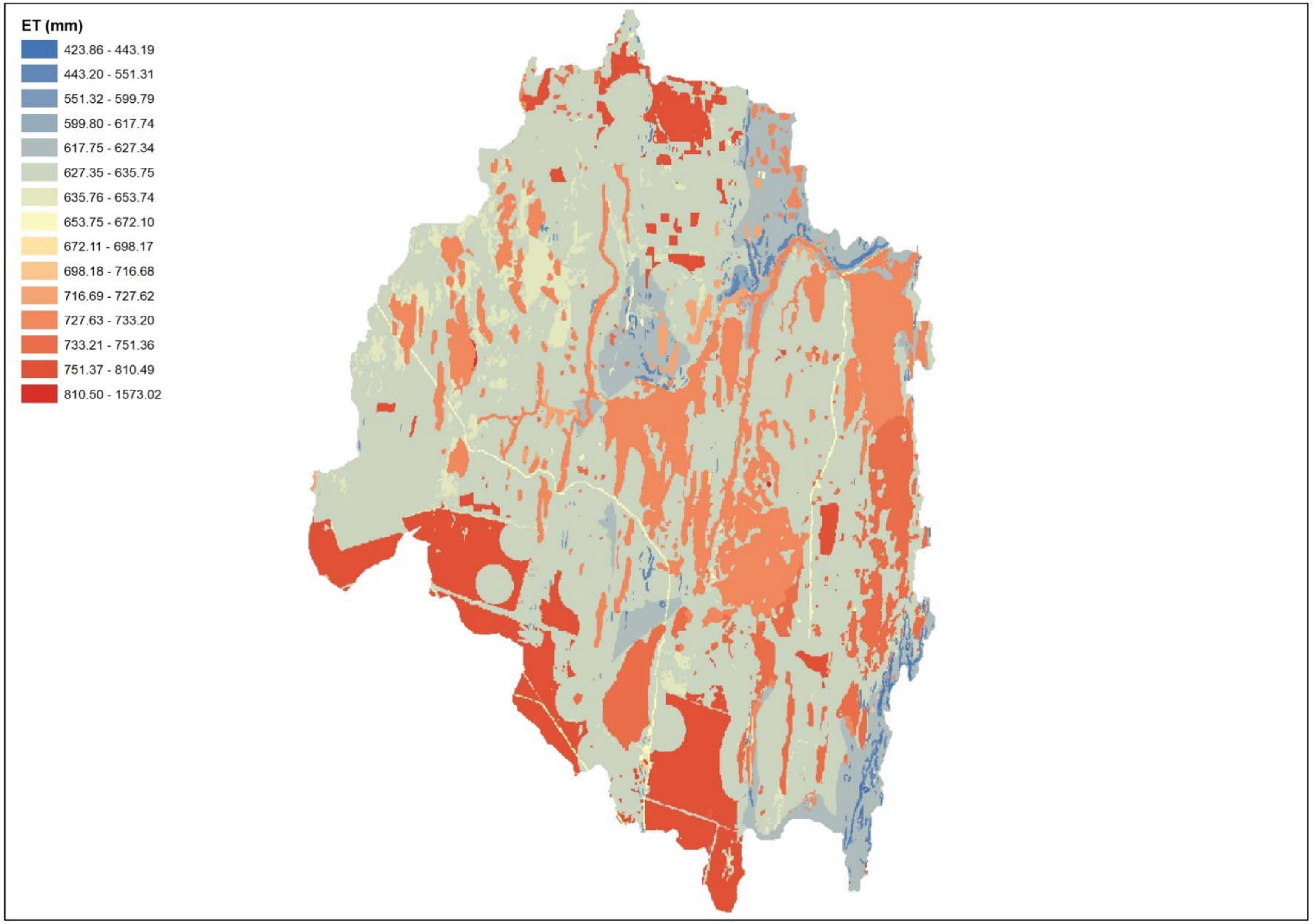


Figure 6.29 SWAT modelled annual average total evaporation for scenario 2

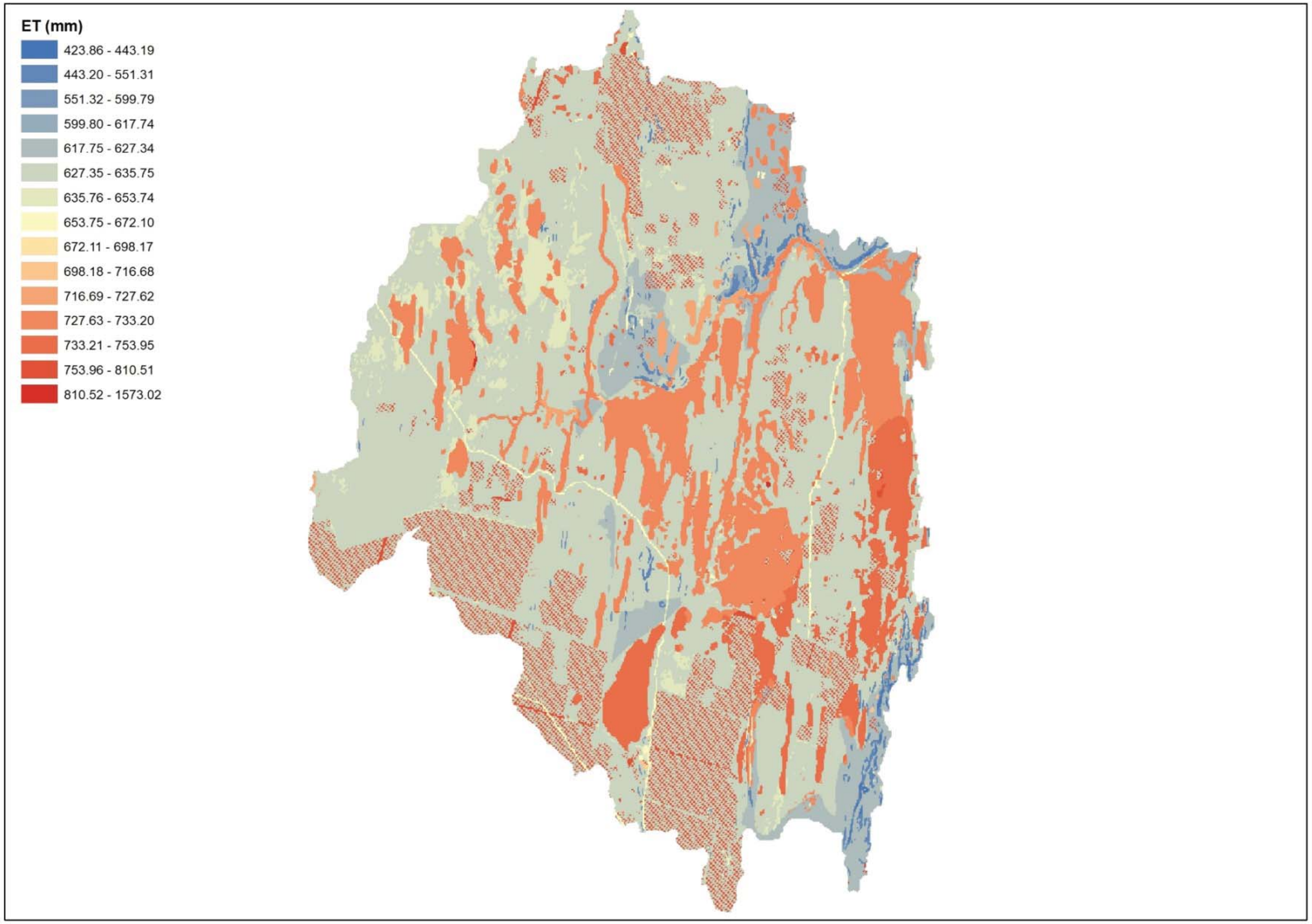


Figure 6.30 SWAT modelled annual average total evaporation for scenario 3

The exported outputs were linked to each HRU for each scenario. The water yield (total amount of water leaving the HRU and contributing to the main channel; is equal to surface runoff + lateral flow + groundwater contribution to streamflow – transmission losses and abstraction losses) remaining after total evaporation was output and exported to a high resolution raster. The raster calculator (yield difference / baseline scenario * 100) was then used to determine the potential gain due to the proposed scenarios and areas of high potential hydrological gain (Figure 6.31). The results showed that the plantation areas to the east have the greatest potential for increasing the contributions to catchment flows if it were to be transformed to an agroforestry system after wetland buffers had been returned towards their natural state.

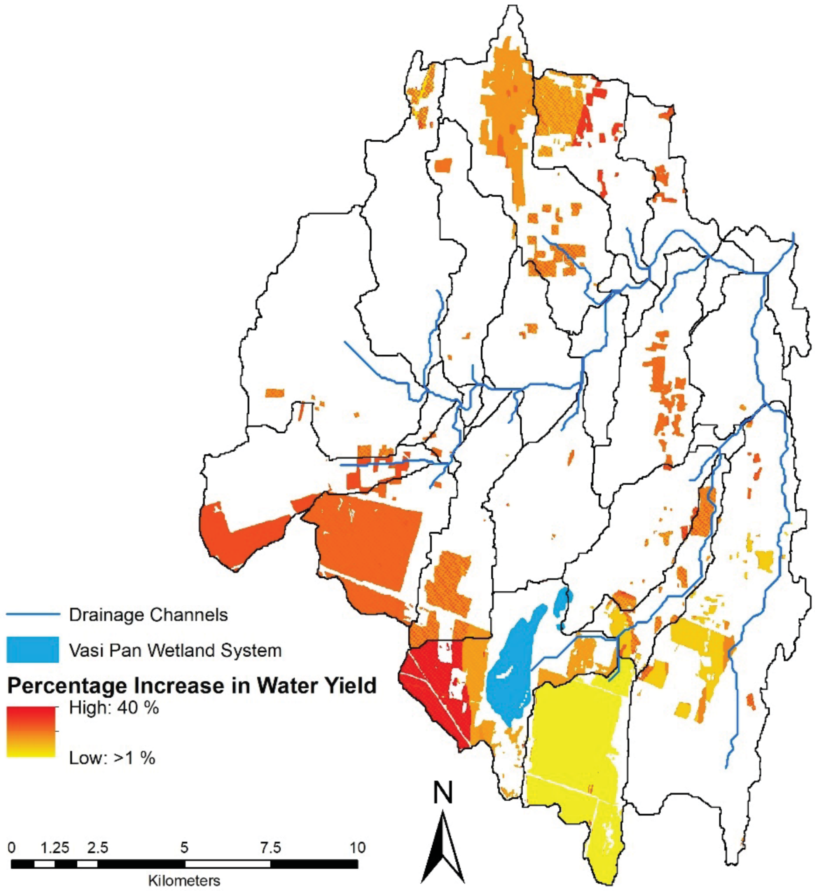


Figure 6.31 Percentage increase in water yield between scenario 1 and scenario 2 & 3

6.6.3 Discussion

The use of the SWAT model throughout the world is extensive and well documented. However, there is a general lack of studies where sufficient results of uncertainty and sensitivity analyses as well as model validations are presented. This is especially true for studies focusing on evaporation outputs and calibration. The use of the Sequential Uncertainty Fitting (SUFI-2) algorithm within the SWAT-CUP programme in this study has allowed for the auto-calibration of the SWAT model. The availability of detailed observed streamflow and total evaporation (ET) datasets has allowed for an assessment of the objective function for a multi-variable calibration. This is important in extending the application of the model to areas with limited observations. The distributed calibration approach using spatially explicit HRUs lends itself to the use of spatial observations such as scintillometry, eddy covariance and remote sensing.

This study provided substantial insights into the spatial distribution of total evaporation (ET) throughout the Vasi Pan area. This information could be particularly useful for land management decisions, such as riparian/wetland clearing programmes, as areas of high water-use can be easily identified and prioritized for rehabilitation. Additionally, a quantification of the hydrological gain can be obtained for user defined scenarios. The use of default SWAT plant growth values in South Africa was problematic as the natural vegetation differs substantially to that of the natural vegetation growing in the United States. In order to meet the study objectives, a new set of SWAT input plant growth parameters for introduced and indigenous forests was provided.

In areas such as Vasi Pan, components of the groundwater routines can be interrogated, especially if the SWAT-MODFLOW user interface is adopted. This would potentially address short-comings of the current groundwater routines. As vegetation dynamics differ in South Africa, an approach to automatically initiate annual growing cycles using changes in soil moisture should be investigated. This approach may be more suitable for South African vegetation and would negate the need to define management operations to initiate growth at a fixed date.

6.7 MODFLOW

The model code selected for evaluating the interaction between the surface-water and groundwater resources is the industry standard MODFLOW from the USGS.

Modflow: a 3D modular groundwater model developed by the US Geological Survey (USGS) that is freely available from their website and is continually being updated and can be adapted to most situation involving a strong groundwater-surface water (SW-GW) interaction. The groundwater storage and flow are linked to surface water resources using a selection of modular functions that can be activated to suit the important/ dominate processes for specific studies.

6.7.1 Regional Model Predictions

The Regional model average water table profile established using the external drainage boundaries for the simulation period from 2010 to 2017 is shown in Figure 6.32. The Vasi Pan focus area lies on a groundwater ridge between the Malangeni drainage system to the north and the Lake Sibaya groundwater catchment in the south. Due to its position along the transient groundwater ridge, Vasi Pan

- has no identifiable recharge catchment;
- will experience relatively large changes in water table elevation under varying climatic conditions due to its position on the ridge; and
- will have upstream and downstream impact from water-use across the region that will influence the position and magnitude of the ridge.

Since the Vasi Pan has no discernible groundwater catchment area it was necessary to evaluate the model performance on a well-defined catchment with the necessary calibration targets. Consequently, the Regional Model with its calibrated hydraulic aquifers was used to extract a catchment (local) model that incorporated the entire recharge zone discharging though the Malangeni River gauging station using a technique called Telescopic Mesh Refinement (USGS). The selected catchment (local model domain) is shown in relation to the regional model in Figure 6.34. The specific catchments used in the MODFLOW and SWAT simulation are shown in Figure 6.33.

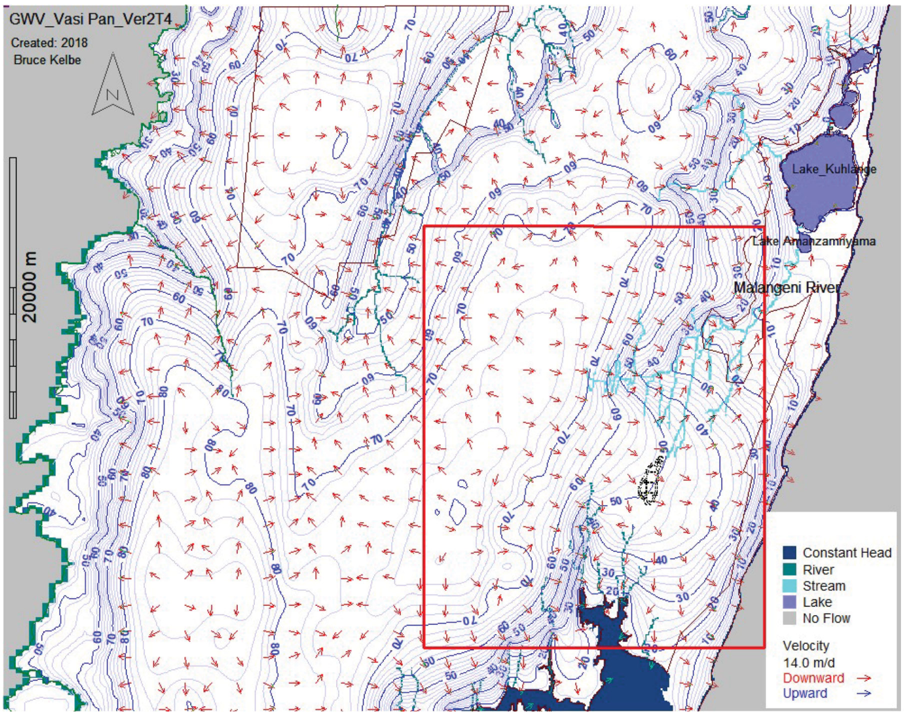


Figure 6.32 The simulated water table elevation contours (mMSL) for the Regional Model. The red arrows indicate the flow direction that is perpendicular to the head contours.

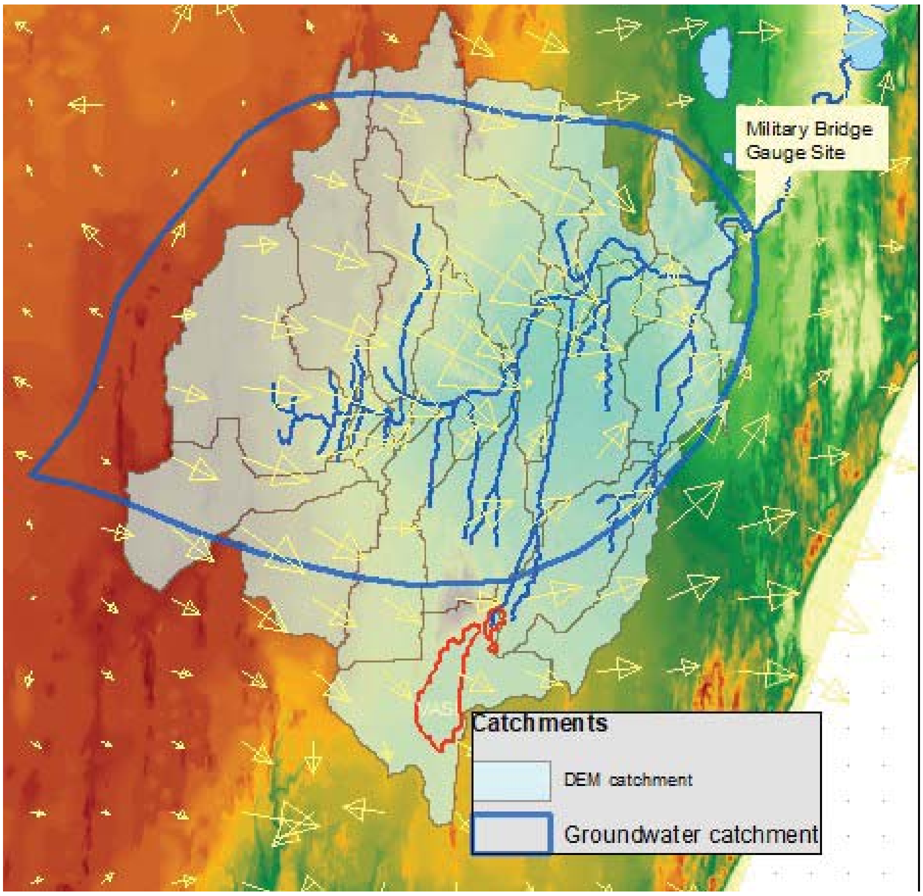


Figure 6.33 Surface and groundwater catchments for the Malangeni flow monitoring site at the Old Military Bridge

6.7.2 Vasi local model validation

The local model extracted from the regional model assumed that the hydraulic properties were stationary and adopted without further calibration. It was further assumed that the adjustment factor for the rainfall and evaporation would also applicable for the local transient model. Consequently the rainfall and evaporation rates were discretised into break point series representing average rates over specific events (dry, wet, extreme) and these values were adjusted accordingly.

The model simulations for the period were compared to the corresponding target values for validation purposes and slight adjustment made to improve the predictions. Figure 6.34 shows the comparison between the calculated flow rates and the model predictions. While attempts to use simulation intervals that represented the rainfall events, there is an underestimation of the flow during the two large storm events and a slight over prediction in the general base flow. However, the cumulative discharge over the same period shows good agreement. The difference between the measured and predicted storm runoff could be attributed to the reliability of the rainfall applied to the catchment area.

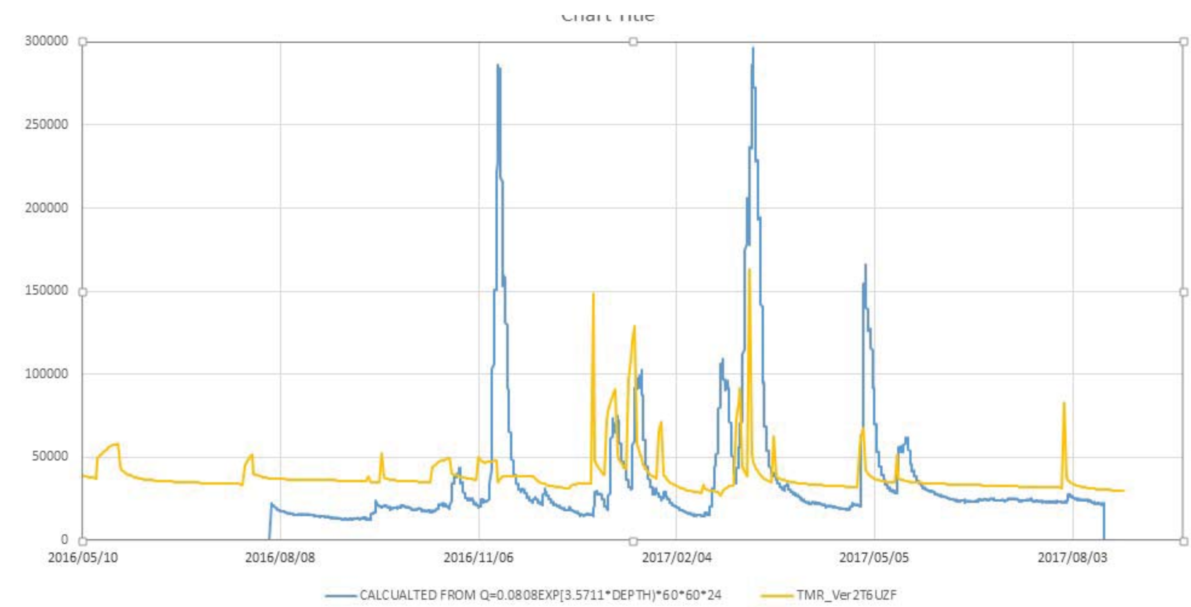


Figure 6.34 The simulated and measured transient flow rates at the Malangeni monitoring site beneath the old Military Bridge

The correlation between the simulated and weighted observed heads at all the targets within the Vasi model domain are shown in Figure 6.35 and indicate that the model predictions are generally within ±2-3 m of the observations over the entire model domain. Figure 6.35 also shows the sites with the greatest residual error. These are generally located amongst other monitoring sites with small residual errors and indicate the problems of the observation database described in the study area section.

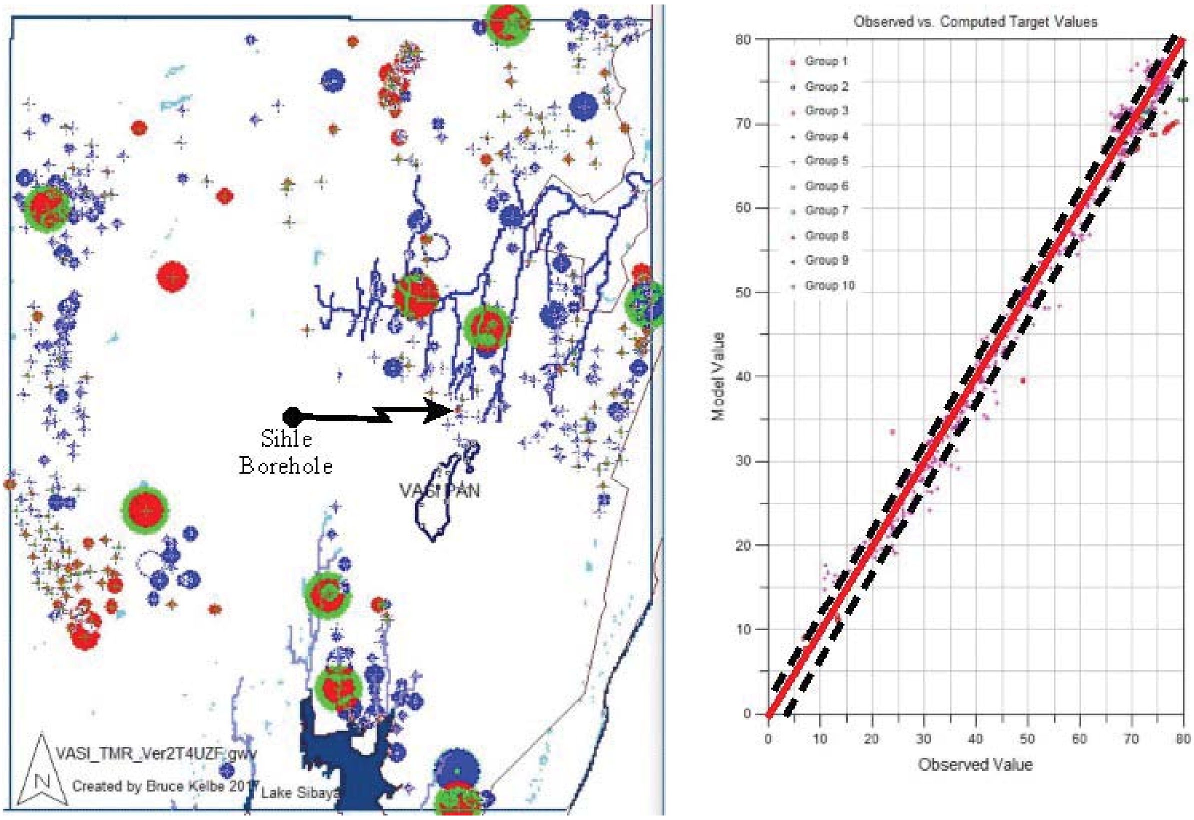


Figure 6.35 (Left) The map showing the relative magnitude of the residual error (blue=positive, red=negative residuals). The large dots with green backgrounds have residual errors >5 m. The scatter plots (Right) shows the 1:1 relationship (red line) within the 2 m error band (dashed lines).

A borehole in the immediate vicinity of Vasi Pan has been monitored by SAEON since 20 July, 2016. The model simulated elevation series and measured heads plotted in Figure 6.38 show the same general trends for this production borehole although the model has greater variability that may need further calibration of the storage coefficients.

These revised calibrations of the recharge and hydraulic properties for the Vasi Model are considered adequate to evaluate the model predictions for the purposes of this study.

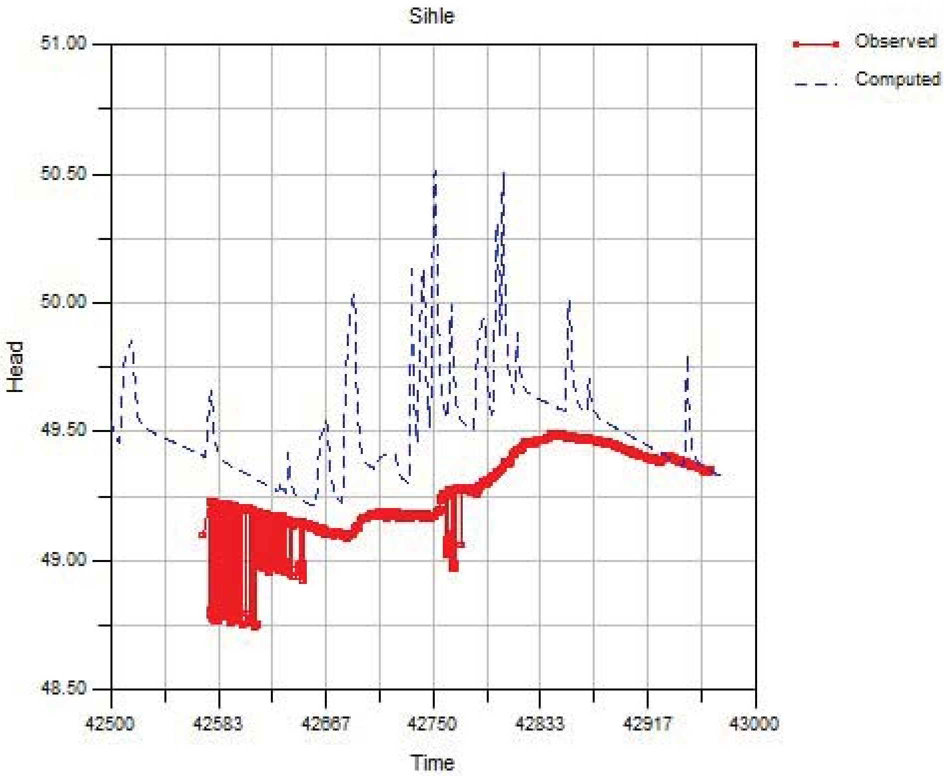


Figure 6.36 The simulated and observed heads variation for the Sihle Borehole near Vasi Pan. The large drawdown and recovery in measured head during the early monitoring period was due to short periods of abstraction.

6.7.3 *Model Predictions for the Study Area (Vasi Pan)*

The main purpose of the model was to evaluate its potential to predict the downstream impacts of land use changes on the receiving water resources, mainly the groundwater storage. The principle land use types are exotic plantations, mainly Pine and Eucalyptus species, and areas of indigenous grasslands and indigenous forest.

The distribution of the exotic plantations was supplied by DWS from a recent (2016) survey and were parametrised according to the species. The natural vegetation was taken from a map supplied by ARC for 2015 and parametrised by species groups. ARC also supplied the summer and winter LAI for each species (except the commercial forests and woodlots) that was used to drive the initial estimate of effective rainfall (infiltration to UZF).

The model has been used to simulate the temporal rates of recharge and evaporation from the unsaturated and saturated zones. Of importance is the rate of evapotranspiration for the different species under different hydrological condition, particularly the varying depth to the water table. It is perceived that in the areas with a very deep-water table, there is likely to be a much greater difference between species rates of evapotranspiration than in shallow aquifers due to the difference in the rooting characteristics. Consequently, is it important for the model to prove a reliable estimate of the depth of the unsaturated zone.

6.7.4 Water table fluctuations and depth to the water table

One of the main factors that distinguish plantations with high water consumption from other species is their ability to mine water at greater depths is primarily due to their deep rooting characteristics. In water stressed environments such as Vasi Pan, this can cause severe impacts on the local water resources. The impact will be increased when the plantations can lower the water table below the rooting depth of the natural vegetation (Brites and Vermulen, 2013).

The simulated water table elevation profile and the derived topographic surface elevation (DEM) both have similar levels of uncertainty (±2 m) that must be considered in the assessment of the impact studies. While attempts have been described to reduce the uncertainty in the SRTM data within tall vegetation, these errors have not been completely eliminated and need to be considered in the impact studies.

The elevation of the water table can vary by 1-2 m along groundwater ridges over the simulation period. The simulated depth from the topographical surface to the water table in the area around the research sites near Vasi Pan area during Aug 2016 is plotted in Figure 6.37. The model indicates that there are periods when sections of Vasi Pan have the water table very close to the surface while the deep-water table (>10 m) around the Lattice mast is due to the high topography in this area. Consequently, similar vegetation species will have varying rates of evaporation from the groundwater depending on their location within the catchment. Any vegetation with a potential rooting depth of >10 m is unlikely to harvest the groundwater in the white zones in Figure 6.37. Conversely, all types of vegetation should be able to mine the groundwater in the dark blue zones under average geohydrological conditions.

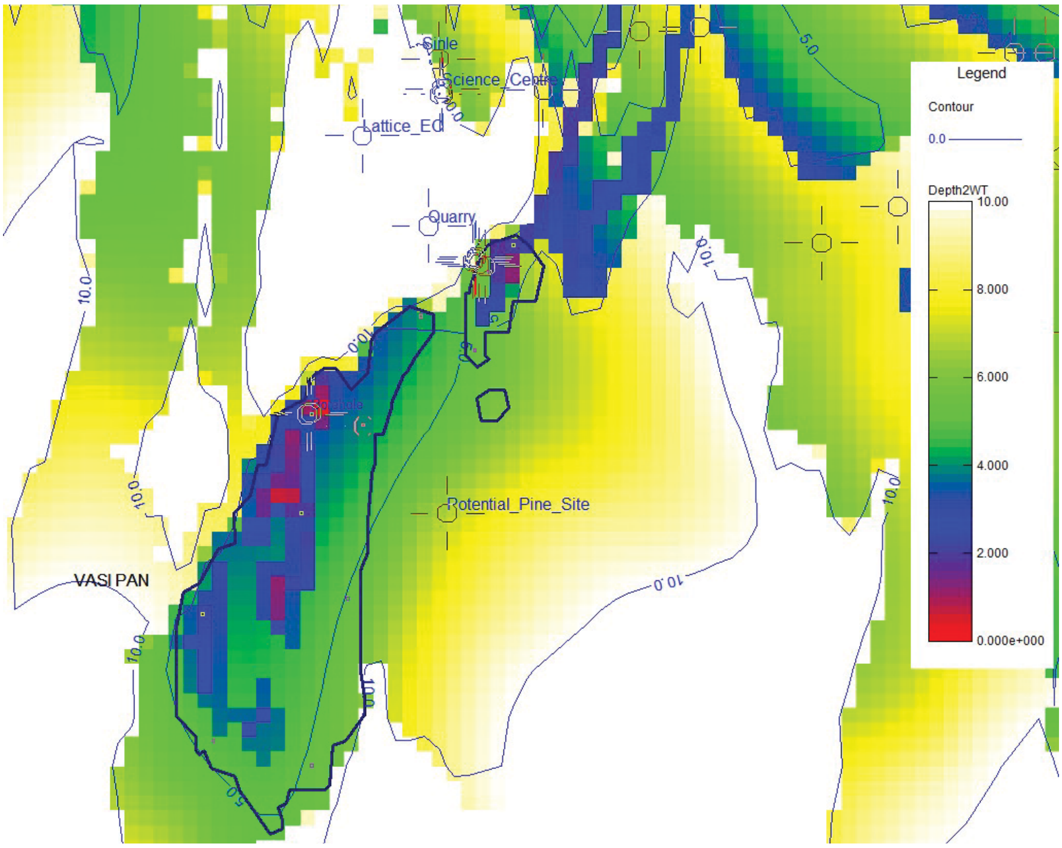


Figure 6.37 Map showing contours of the depth to the water table below the topographical surface (mBGS) in the focus area around Vasi Pan.

The depth to the water table (*i.e.* the unsaturated zone) is a direct function of the topography but it also varies spatially and temporarily in response to the recharge and evapotranspiration process linked to various landuse types. It is also an important criterion for soil water accessibility to deep rooting vegetation species. Figure 6.38 shows the simulated evaporation from the groundwater and illustrates the variable abstraction rate by the different vegetation species when the depth to the water table varies due to topographical features. For example, to the east of Vasi Pan, the plantations show a similar abstraction gradient to the depth of the water table shown in Figure 6.38.

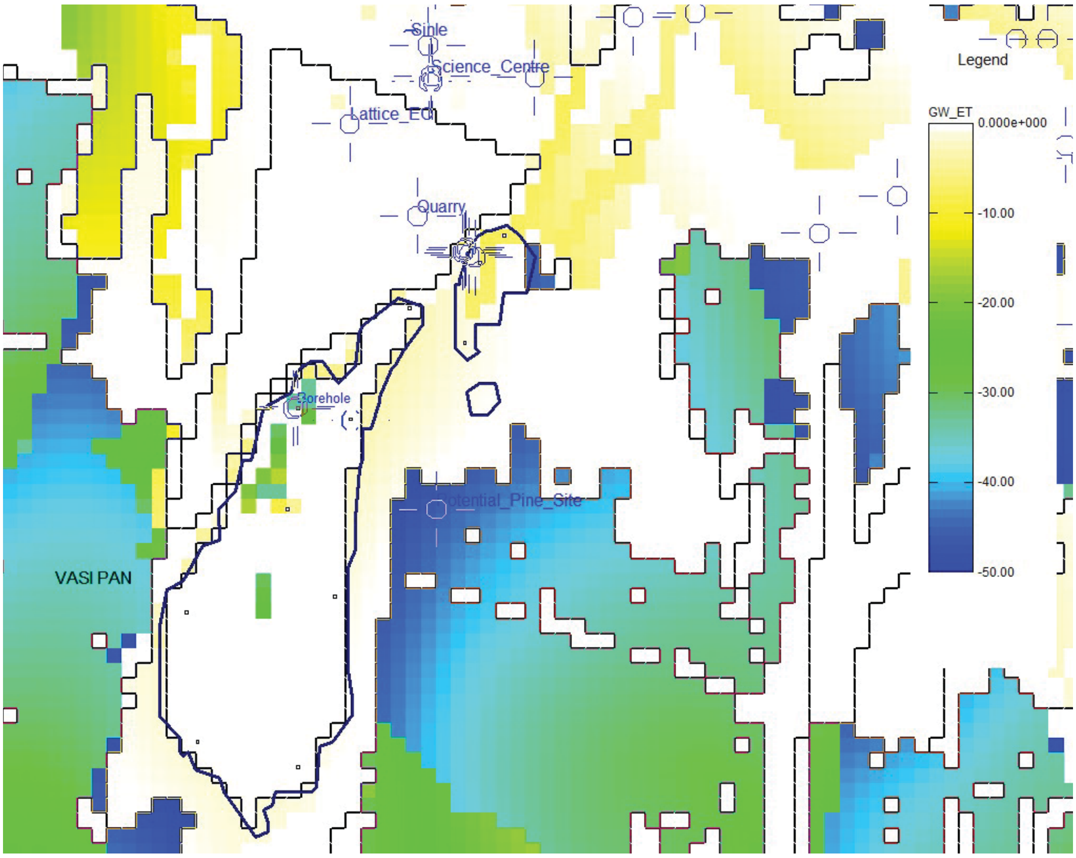


Figure 6.38 The simulated rate of evapotranspiration (10^{-1}mm/day) from the saturated zone for each 100x100 m cell. The black lines are the different land use zones. The scale shows the groundwater evaporation in units of m^3/day from an area of 100x100 m^2.

6.7.5 Model Application

The main aim of the overall project was to investigate various alternatives to monocultures in the water stress environment near Vasi Pan, with particular reference to plantations. The groundwater model was developed, calibrated and evaluated as a suitable tool for evaluating cropping options in the groundwater dominated environment. This section evaluates the simulated influence on the water resources of the region of several different land use options.

The groundwater model was calibrated and evaluated for existing land use conditions with extensive areas under exotic plantations. Since these plantations are considered SFRAs and licensed accordingly, the alternative options are based on scenarios relative to the existing conditions. The following sections describe the relative changes on specific features of the downstream water resources in comparison to the existing conditions.

6.7.5.1 Scenario 1: Removal of all the exotic plantations

The plantations were replaced in the model by the grassland parameters based on the vegetation type provided by the ARC in 2006 (Grundling *et al.,* 2012) and shown in Figure 6.39. Also shown in Figure 6.39 are the outline of the plantations for 2016 provided by DWS that were replaced by the vegetation shown.

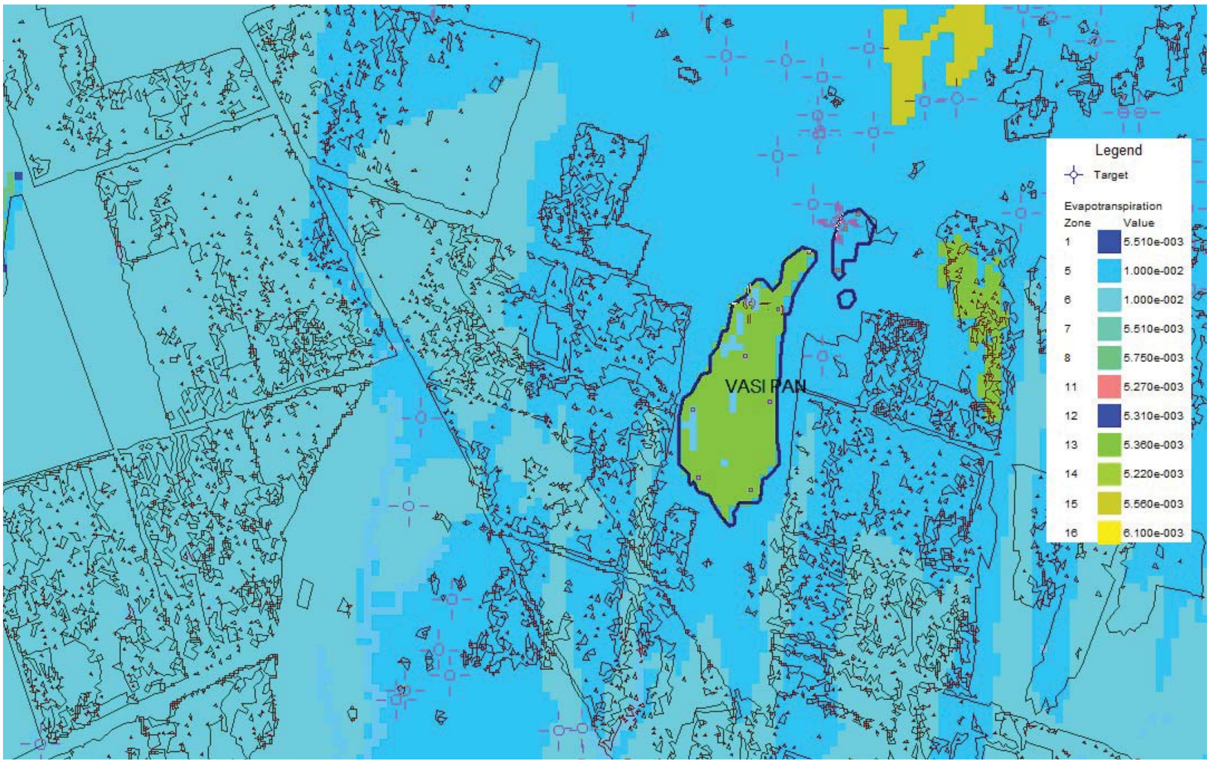


Figure 6.39 Map of the land use types used in the model to represent the Natural Conditions. The black lines show the outline of the plantations that were replaced by the natural vegetation species shown by the coloured zones. The scale shows all vegetation types, many of which ae not shown in this section of the map.

Under the natural conditions, the water table near Vasi Pan representing the groundwater levels in a borehole in the region of concern has been used to evaluate the impact of land use change. The water table is predicted to have risen by over 2 m from existing conditions as discussed in the next sections.

6.7.5.2 Scenario 2: Percentage reduction of area under plantations

One of the options considered for investigation was alternate vegetation types with the plantation. To estimate the impact of reducing the area under plantations by replacing total area under a single species was strip cropping. In this scenario, the plantations were divided into bands of exotic tress and other land use types. Figure 6.40 shows the landuse configuration using 100 m strips alternating between exotic trees and Maputaland Wooded Grassland (Zone 6). This was repeated using 300 m strips of exotic trees and Subtropical Dune thicket (Zone 7).

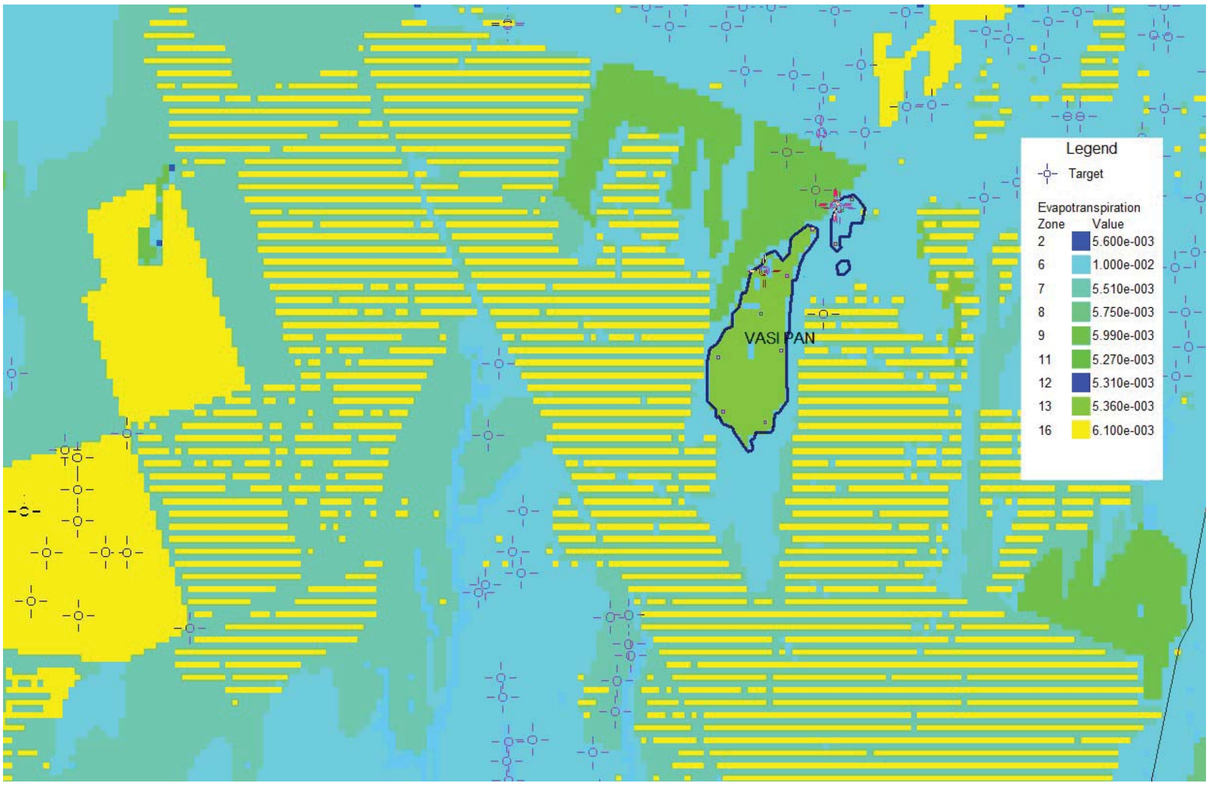


Figure 6.40 Map of the land use types used in the model to represent the Natural Conditions overlain by the plantation band of 100 m width. The 300 m bands in the other scenario ran from north-south

6.7.5.3 Aquifer Drawdown

The different land use scenarios described above showed a significant change in the water table elevation around Vasi Pan for the simulation period from 2010-2017. This is illustrated by the simulated rise in water level at the Sihle Borehole just to the north of Vasi Pan (Figure 6.41). The 100 m and 300 m plantation bands are approximately equivalent to a reduction in the plantation’s area (assuming the same tree density) of 50% but the impact on the groundwater levels is significantly different. The reason for this simulated difference has not been fully investigated but is probably due to the difference in the alternate land use applied in the strip between the plantations. There may also be other issues that the model is not designed to simulate such as the edge effects on the canopy structure (LAI).

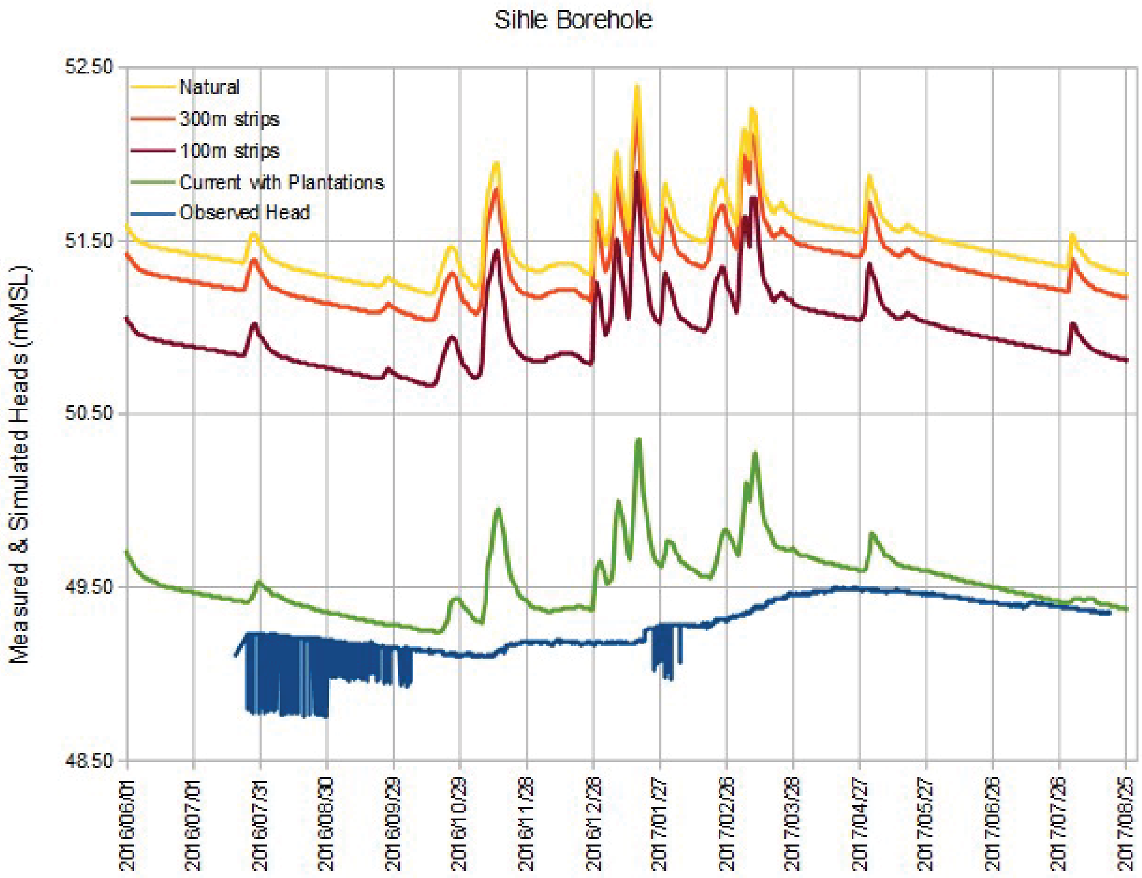


Figure 6.41 The observed water level in the Sihle Borehole (dark blue) with the corresponding series for the different land use scenarios.

The Sihle monitoring borehole lies to the north of Vasi Pan and the Manzengwenya Plantations. Consequently, it is unlikely to experience the greatest impact of the plantations. A regional assessment of the impact was conducted by plotting the cumulative difference between the simulated water table profiles for the current land use (exotic plantations) and natural vegetation models. The cumulative impact of the change in land use over the full simulation period is shown in Figure 6.42 by the shaded DEM. Also shown in Figure 6.42 are the current plantations used in the assessment. The model indicates a cumulative drawdown in the main sections of the Manzengwenya Plantations that can exceed 15 m over the full simulation period.

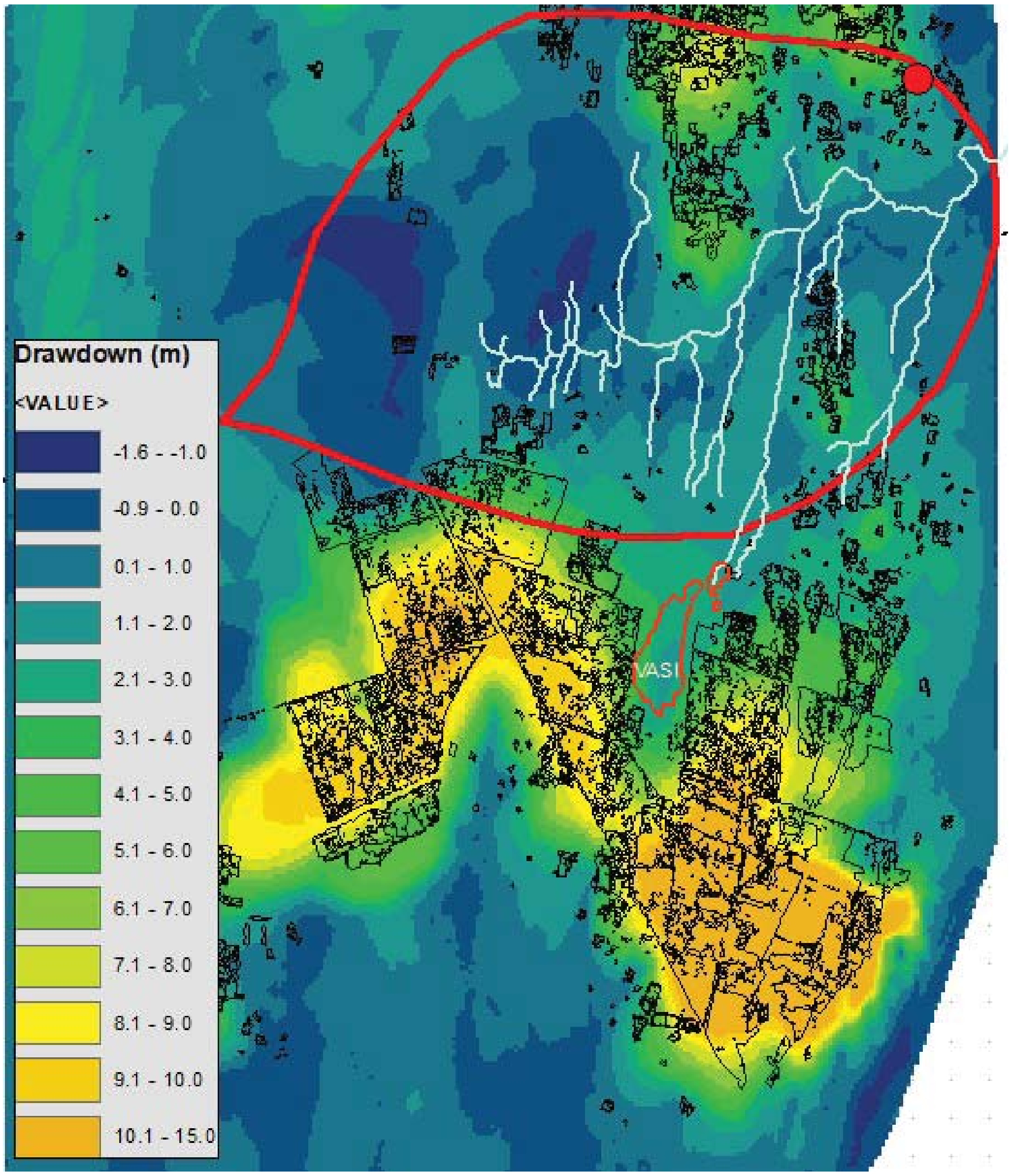


Figure 6.42 The simulated drawdown (m) in the Manzengwenya region for the current groundwater relative to the natural vegetation.

6.7.5.4 Stream Flow Reduction

The various scenarios described above all indicate various levels of stream flow reduction on the Malangeni River due to the different land use options. However, the magnitude of this impact is due primarily to the new wood-lots that have been recorded in the Malangeni Catchment (Figure 6.43).

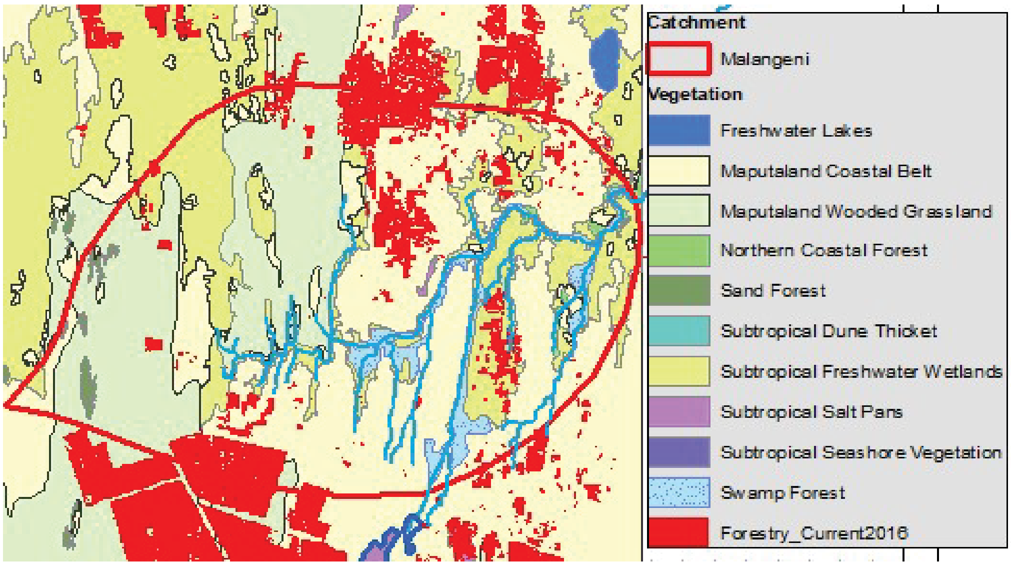


Figure 6.43 The catchment for the Malangeni Gauging Station use to evaluate stream flow reduction due to land use changes.

The stream flow at the Military Bridge gauge site under current landuse condition using the actual plantations and woodlots identified and mapped by DWS in 2016 were simulated for the period from 2010 to 2017. The area under plantations and woodlots is shown in Figure 6.43. The cumulative runoff for the current conditions is shown as the cumulative series in Figure 6.44 by the grey line. Similar cumulative plots for two of the scenarios described above (100 and 50% reduction in exotic plantations) are also shown in Figure 6.44

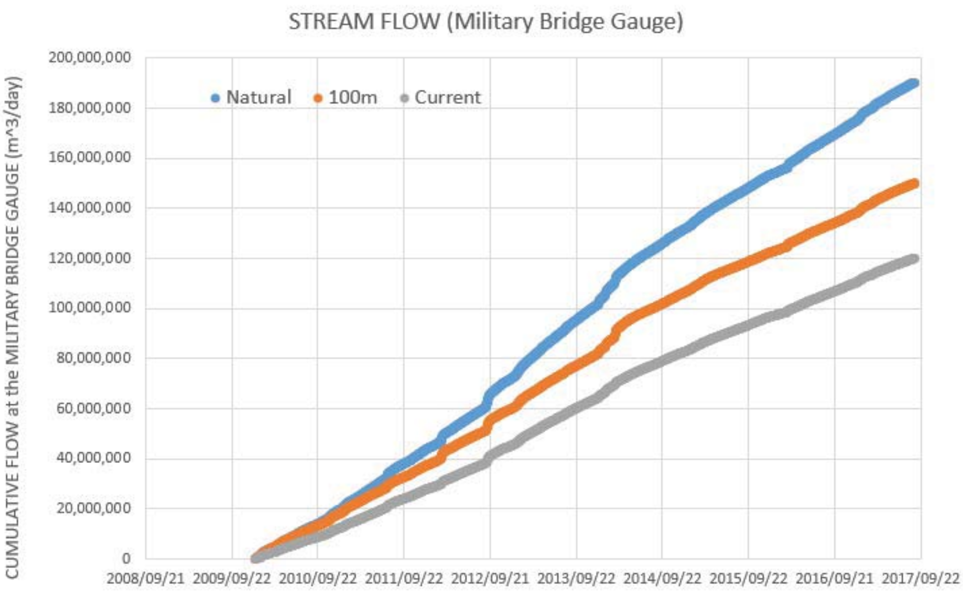


Figure 6.44 The cumulative simulated stream flow at the Military Bridge Gauge for the three different land use scenarios

7. POTENTIAL SILVOPASTURE SYSTEMS FOR THE MAPUTALAND COASTAL PLAIN

7.1 Native species silvopasture

Indigenous silvopasture tree products can be specifically grown for timber, pulp, fruit, nut products or fodder (Table 2.4). Natural systems have a greater diversity of tree species than planted systems, and therefore offer a greater variation of indigenous knowledge products. In this regard there are a number of useful indigenous trees species that could potentially be incorporated into semi-natural or natural silvopasture systems in Maputaland (*cf.* Table 6.1*)*. One of these species is a highly traded medicinal tree, *Warburgia salutaris*.

Warburgia salutaris has been the subject of much research into its traditional applications (Maroyi, 2013; Leonard and Viljoen, 2015), pharmacology (Kotina *et al*., 2014), sustainable use (Botha *et al*., 2004; Williams *et al*., 2007) , phylogeny (Muchugi *et al*., 2008) cultivation (Maroyi, 2012) and potential commercialization (van Wyk *et al*., 2003). The biological activity of the bark is used to treat stomach aches, fever and headaches (Leonard and Viljoen, 2015) making it one of South Africa's most popular medical plants. In 1998, the market for the bark was estimated to be up to 40 tons per year, with most of the supply being sourced from Mozambique, because wild populations in South Africa have largely been depleted (Mander, 1998). However, despite the demand for the bark and its international conservation importance, few or none commercial growing operations exist. The current preferred method for cultivation is with homesteads through tree planting projects (for example at Skukza in the Kruger National Park).

Sclerocarya birrea (marula) is another obvious candidate for silvopasture in Maputaland. Like *Warburgia salutaris*, an exhaustive amount of research has been published on this tree (see Shackleton *et al*., 2003 and Leakey *et al*., 2005). This species is culturally iconic in Maputaland. Its fruits are traditionally used to brew beer, make juices and jams, however the oils from the seed kernel appear to be the most valuable product (Vermaak *et al*., 2011). Seed oil contains fatty acids (such as oleic and linoleic acid) and anti-oxidants that are a commodity for the food and cosmetics industry (du Plessis, 2007; Vermaak *et al*., 2011). Improved planting material of grafted cuttings can produce about 6000 to 7000 fruits within 8-9 years (Mahlati, 2011). Trees grown around homesteads have been recorded produce upwards of 17,000 fruits per tree (Shackleton *et al*., 2003). The market value for one kilogram of marula kernals in 2012 was ± R25.00 (Lombard and Beckett, 2012). Marulas should be well suited to silvopasture systems. They grow naturally in disturbed areas at Manzengwenya, they are deciduous (and therefore do not utilise water resource in the dry season), are fire-tolerant and provide both cultural and commercial value through their fruit and seed products.

The use of indigenous tree species in semi-natural silvopastures are suited to environmentally sensitive areas and can be used as productive land-use bufferzones (Zabala, 2015). At Manzengwenya, indigenous trees in silvopasture systems would suite the hydrologically sensitive areas that have been proposed as buffer zones around degraded wetlands such as Vasi Pan (Taylor *et al*., 2006). Indigenous species based silvopasture systems provide many options for genus exchange initiatives which have been proposed at Manzengwenya, since they utilise less water and are grown in less dense planting arrangements than current plantation methods.

7.2 Plantation species silvopasture

Silvopasture systems grown for pulp or timber are commercially a viable land-use option (Cubbage *et al*., 2012). A common tree spacing method are so called double rows arrangements (1.6 m x 3.2 x16 m) which accounts for about 1, 010 stems ha^{-1}. This approach has been used for 30-year pine rotations (Figure 7.1). Livestock are grazed in tree lanes and were reported to be stocked at up to 4 LSU ha^{-1} after seven years (Nowack and Long, 2002). Fastwood pulp based silvopasture systems have also been attempted by adapting tree spacing to accommodate the light requirements for forage grass species (Oliveira *et al*., 2015). In a study conducted in Brazil (Oliveira *et al*., 2015), the production of various eucalyptus clones grown in double row spacings of (2x2 m x12 m; 3x3 m x12) and a single row spacing of (9x3 m) after 62 months ranged between 13.2 – 17.9 cm, 15.07 – 19.6 cm and 16.1 – 21.8 cm, respectively. Average tons per hectare of *Brachiaria brizantha* fodder after 50 months was 1.2,, 1.9 and 1.9 tons respectively across the three different treatments.

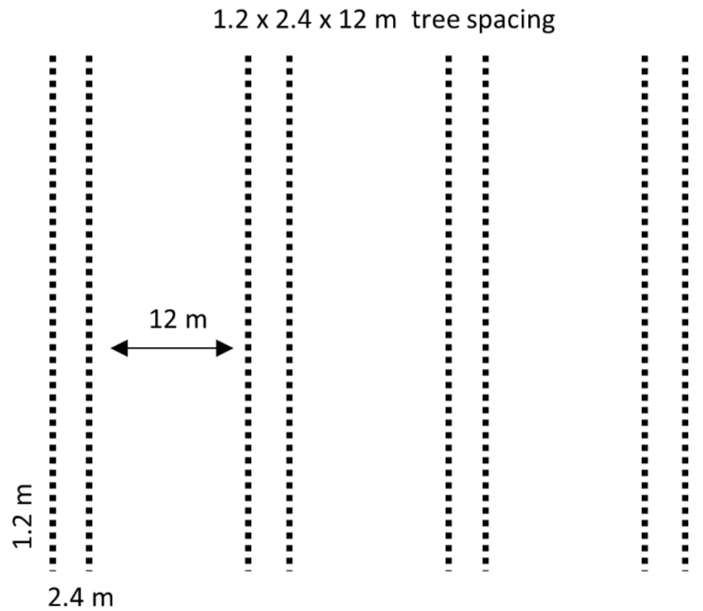


Figure 7.1 A double row silvopasture system of 1.2x2.4 m tree spacing with 12 m wide alleys between pairs of tree rows of Lewis *et al*., (1985) was found to satisfy both timber and forage requirements in the southern United States (Nowack and Long, 2002)

An alternative integrated method mentioned by Dr. Ronald Heath (pers. comm., 2018) would be to rotate livestock during intermediate years of stand development (i.e. during the second, third and fourth years of the cropping cycle). In this way, adequate light would increase forage production and trees would be large enough to sustain damage from livestock. Fernanda *et al*., (2015) noted that livestock were usually allowed into planting blocks when trees are about 12 months old or have a stem diameter of six centimetres. Based on an estimate of 1.5 tons ha^{-1} y^{-1} of grass production, this method would add an estimated 9 tons ha^{-1} of forage over a 14- year pulp rotation.

7.3 Livestock and fodder

Livestock management in silvopasture is not well quantified in the literature. Animal rotations tend to depend on forage availability which is often influenced by the chronology of the tree component (Hamilton, 2008), rainfall and soil variables. Information on how LSUs relate to different silvopasture systems is scarce and difficult to compare. However, stocking densities of between 0.29 – 0.34 LSU ha^{-1} (cattle) and 0.5 – 1.0 LSU ha^{-1} (goats) have been reported in Loblolly pine (*Pinus taeda*) silvopastures in the southern United States (Grado *et al*., 2001; Kumi *et al*., 2015). These figures are comparable with those based on the veld condition assessments conducted within the grasslands surrounding Manzengwenya (Table 6.7) and with the long-term grazing guidelines set out by DAFF (Figure 7.1). Forage grasses in silvopasture systems can be planted pastures (Oliveira *et al*., 2015) or combinations of natural species (Le Houerou, 1987). Many indigenous South African grasses such as *Brachiaria brizantha, B. humidicola* and *Panicum maximum* are suitable silvopasture species. *Brachiaria brizantha* is highly productive and produced between 1.9 – 2.6 tons ha^{-1} of dry matter yield in eucalyptus stands grown at 550 trees ha^{-1} in the central Brazilian savanna region, which had a MAP of ±1600 mm (Oliveira *et al*., 2015).

During sampling, the mean forage mass for the different grasslands ranged from 3100 kg ha^{-1} to 9400 kg ha^{-1} (Figure 7.2). The veld condition and grazing capacity results of the natural grassland types are detailed in section 6.1 and presented in Table 6.6 and Table 6.7. Veld condition scores suggested that secondary grassland was in moderate condition (59%), suggesting that after disturbances such as many years of plantation forestry, there was sufficiently available palatable grass species and grass biomass to provide forage for livestock. Lawn grass and tufted grass species that were sampled in secondary grassland which would likely be suitable for silvopasture systems were: *Digitaria diversinervis, Panicum maximum, Brachiaria brizantha, Brachiaria arrecta Cynodon dactylon Digitaria eriantha*.

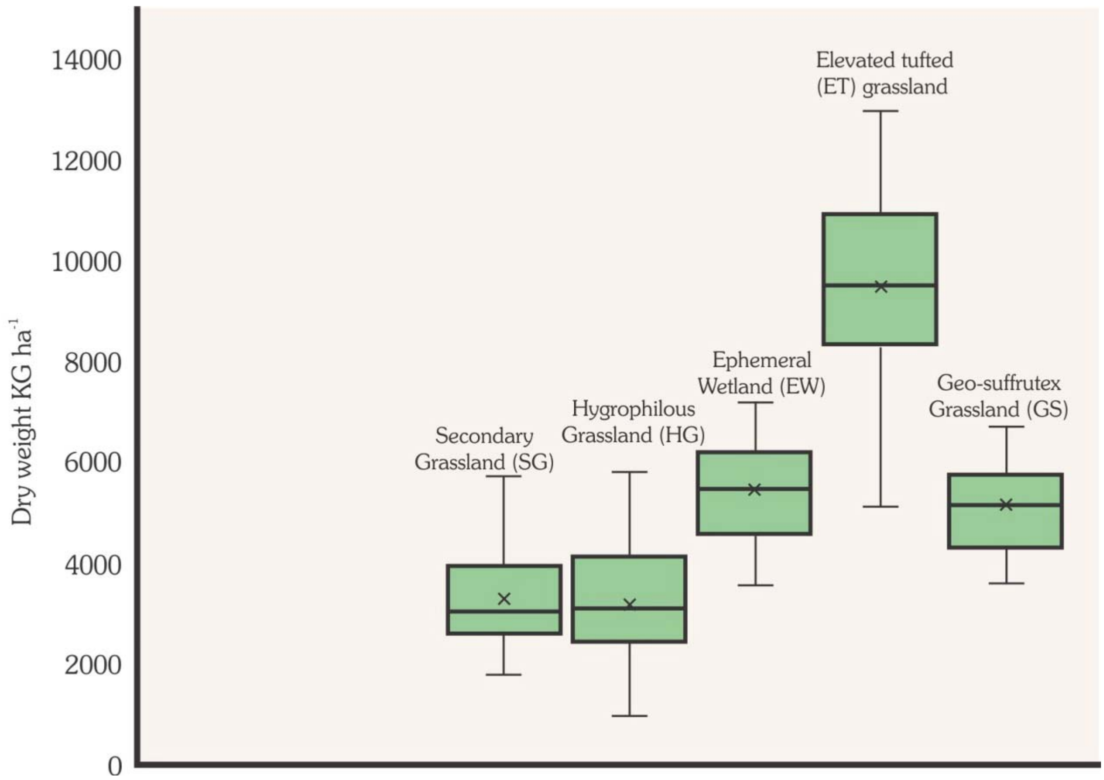


Figure 7.2 Box plot showing the median dry weight (as recorded during summer 2016/17), 1st and 3rd quartile, and minimum and maximum values in kg ha^{-1} for each grassland type.

8. DISCUSSION AND CONCLUSION

The aim of this study was to understand and quantify the water-use of different agricultural and ecological land-use components of the Maputaland Coastal Plain, which could potentially be developed into an integrated, multiple-use agroforestry system(s), as an alternative to commercial plantation forestry in water stressed catchments. The Maputaland coastal plain is under significant threats at both a social and environmental level. The research on the plant water-use of the species selected for this study will help land owners and government to optimally manage this area. Furthermore, this information supports modelling simulations that are used to extrapolate data to larger areas that cannot be monitored in detail. This information also allows for the refinements of model inputs and model calibrations.

8.1 Ecology and Agroforestry

The aim of the ecological investigations for the project was to better understand the response of natural forest and grassland mosaics to land-use change from plantation agriculture, and through this process, identify species and methods which would be suited to be incorporated into agroforestry systems. The study found that woody species (mostly forest pioneers) had benefited through changes in fire patterns and disturbance regimes brought about through plantation forestry. A similar composition of plant species was observed growing within the sub-canopy of plantation stands (on both forest edges and within central plantation areas), whereas within slightly fire-exposed secondary grassland (which was in clear-felled plantation areas) species composition tended to reflect savanna conditions. The differences in the compositional variation between these vegetation types reflected the relative influence of the environmental conditions between shaded understory and exposed clear-felled land. This provided an ecological screening mechanism for identifying which indigenous species would be suited to integration with different agroforestry systems, as it highlighted which species were fast growing and easily available, but also which species preferred slightly fire-exposed grassland conditions over shaded forest conditions.

A review of plant use (cultural, environmental and economic) of the woody species which were part of the forest and woodland expansion processes was conducted. This component of the study found up to 193 uses for the 29 woody plant species that occurred in secondary vegetation. The results demonstrated the diversity of plant products and environmental services that were potentially available through forest expansion. The composition of secondary vegetation was such that commercially related species were generally not common and therefore at current abundances the products derived from these species would likely not be economically viable. However, the occurrence of five woodland species with cited commercial development potential namely, *Sclerocarya birrea*, *Trichilia emetica*, *Vangueria infausta*, *Hyphaene coriaceae*, *Annona senagalensis* and *Strychnos spinosa,* pointed towards the use or development of these species in cultivated silvopasture systems.

Of the grasslands which were sampled, the drier, elevated grassland on dune crests had similar gazing potential to lying hygrophilous grasslands. However, this did not account for the greater moisture regime of the hygrophilous and wetland depression grasslands, which are likely to continue to be productive throughout the dry season because of the greater plant available moisture and soil organic carbon. The grasslands sampled within the community at KwaZibi and Mvelabusha had relatively high grazing potential if compared with inland areas in Maputaland (*cf.* Figure 6.4). In areas with a mean annual precipitation of about 1000 mm, the grazing capacity was estimated to be between 0.3-0.4 LSU ha^{-1}. Grass productivity of lower lying hygrophilous areas was not calculated.

The grass species in the secondary grassland (within old lands at Manzengwenya) differed compositionally from the grassland sampled in the community grasslands. The obvious difference was that almost no *Themeda triandra,* an indicator of good veld condition, was observed in the secondary grassland areas which were overgrazed, whereas, it was relatively abundant throughout the community grassland areas. *Themeda triandra* is also a nutritious and fast-growing species suited to hygrophilous and dune ridge grasslands (Figure 8.1). Its absence at Manzengwenya was presumed to be through past disturbance from plantation forestry.

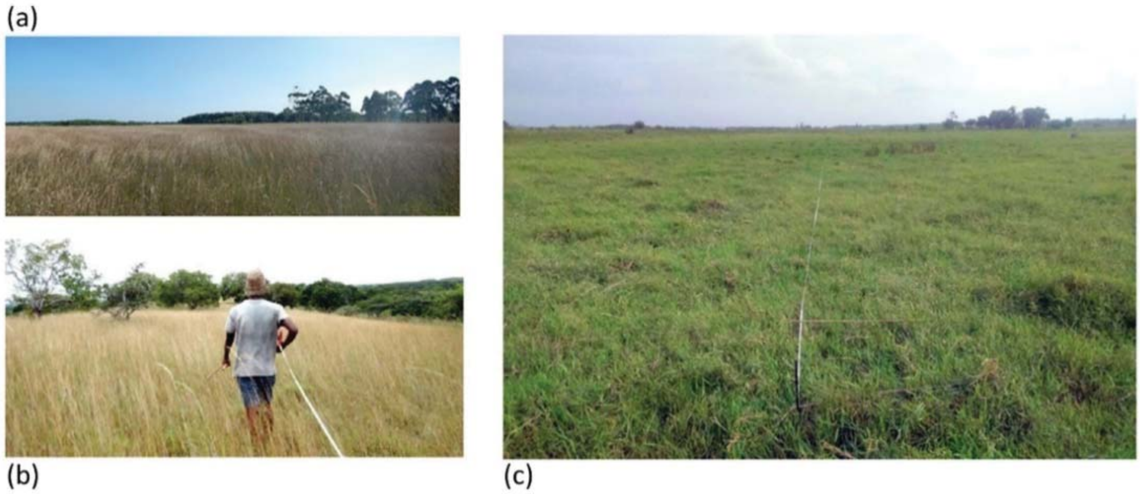


Figure 8.1 Common grassland types within community managed areas at Manzengwenya. (a)*Themeda triandra* dominated areas of low-lying hygrophilous grassland (b) Dune-ridge grasslands with a species composition dominated by thatching grass (*Hyperthelia dissoluta*) but also *Themeda triandra*. (c) Lawn grass communities in hygrophilous grassland comprising mostly of *Acroceras macrum*, *Ischaemum fasciculatum* and *Digitaria diversinervis*.

8.2 Individual Tree Water-use

The average daily water-use, for all the tree species monitored, was higher in summer than in winter (Table 6.9). In summer, the average daily water-used was highest for the small eucalyptus (19.24 L.day^{-1}) and lowest for indigenous trees (10.02 L.day^{-1}). The large and small eucalyptus trees used substantially more water per day (~ 8 L.day^{-1}) than the pine and indigenous trees. In winter, the average daily water-used was highest for the small eucalyptus trees (7.95 L.day^{-1}), and lowest for the invasive pine trees (4.67 L.day^{-1}).

It was concluded from the long-term HPV results, that tree water-use was affected by climatic variables and soil water retention properties. The VPD in the area was low throughout the year, due to the proximity of the site to the coast. This affected transpiration rates as there was little atmospheric demand to drive transpiration. The sandy soils present at the sites had low water retention properties and therefore held little water in the soil water profile and drained quickly after rainfall events. During the wet summer months, when the water supply was not limited, the transpiration rates were driven by solar radiation, and on cloudy days, transpiration rates decreased for all species. In the dry winter months, the water-use of the large eucalyptus and pine trees was limited by water availability, indicating that trees close their stomata during extended dry periods to maintain a relatively constant leaf water potential to survive (Klien *et al*., 2011; Lagergren and Lindroth, 2002). The water-use of the indigenous trees was seasonal, as they are semi-deciduous and reduce their water-use with the onset of the dry season. The small eucalyptus site was energy-limited and transpiration rates decreased in response to a decrease in solar radiation. The small eucalyptus trees were planted on the edge of the Vasi Pan North wetland, where the groundwater is shallow. Therefore, it was concluded that the small eucalyptus trees were potentially accessing water from the groundwater table. To assist in verifying these results, soil water content probes need to be placed at the site to determine the interaction between tree water-use and soil water content and additional information from the installation of boreholes would be beneficial.

8.3 Landscape Total Evaporation

The ET_a measured in the indigenous forest site, using the EC system, indicated that the indigenous forest's water-use followed the same seasonal trend as found in the HPV data, with ET_a peaking in the wet summer and decreasing with the onset of the dry season. In conclusion, the water-use of the tree species that were monitored in this study was low in comparison to previous studies in South Africa. The daily water-use of the trees was limited by water availability, except for the small eucalyptus stand, which was energy-limited. From this study, it was clear that the placement of plantations, in relation to groundwater levels, is critical for forestry management in the area, as this can determine whether the trees will be energy- or water-limited. Further research is needed to determine whether the small eucalyptus trees are accessing water from deeper in the soil water profile during the dry season.

8.4 Soil Water

The use of the cosmic ray rover to map soil water is a promising technique, as the soil water maps produced by the cosmic ray rover correlate well with the soil water maps produced with the hydro-sense data. Overall, the spatial patterns were adequately captured, and the cosmic ray rover could identify changes in soil water over the landscape and effectively illustrate the soil water gradients over the three different land uses. The cosmic ray rover is a promising instrument, which could be beneficial for both scientists and engineers.

Although the cosmic ray rover correlated well with the hydro-sense, with regards to the spatial soil water patterns, there were discrepancies between the soil water ranges. This is due to the hydro-sense measuring at a point scale, whilst the cosmic ray rover was measuring at an area-average scale. Future surveys will aim at obtaining more hydro-sense sample points to reduce the mismatch in measurement scale.

The first survey is always the most challenging, as the cosmic ray rover must be calibrated at each site, which requires *in-situ* estimates of soil water (hydro-sense data). Due to the cosmic ray rover technique being new and innovative, there is currently no "correct" method in conducting the surveys, coupled with each site being different, the surveys need to be planned beforehand. Thus, each survey is useful in better understanding the technology and its capabilities. The results obtained from the surveys demonstrated that the rover system has the potential to provide a rapid screening technique to identify riparian zones and wetlands. The survey time and accuracy can also be significantly reduced by adding more detector tubes to the neutron counting system.

8.5 Surface Water Modelling

The SWAT model provided useful results for detailed time series data and spatially explicit data. Going forward, additional validations are required using updated long-term and high frequency evaporation data to determine if the results obtained are accurate enough for decision making. It is clear from the results that the SWAT model is a suitable model for the required purposes and can provide high resolution temporal and spatial data. The scenario testing provided an indication of what gains could be obtained from clearing wetland buffers and enforcing an agroforestry system. Up to a 40 % increase in water yield could be gained in certain areas in they were changed into an agroforestry system. Additionally, the spatial distribution of the gains was output to promote areas that should be prioritised for clearing. There is a great potential to expand the knowledge of the surrounding vegetation to improve the input to the model through additional measurements or remotely sensed products. There is further potential to calibrate the model using soil water data from the cosmic ray probe. The scenarios tested could be modified to meet any vegetation change or specific management approach should this be required.

8.6 Groundwater Modelling

The MODFLOW model incorporating the unsaturated processes controlling the recharge and evaporation features was compiled and calibrated for the existing land use conditions that included extensive regions of commercial and private plantations. The rainfall rate was adjusted (calibrated) to achieve an acceptable level of agreement between simulated and measured discharge rates at select sites under known groundwater storage levels. The Vasi Pan Model simulations were conducted over a transient period from 2010 to 2017. This was preceded by a steady state simulation representing the average conditions from 1900 to 2010 (110 years or 3700 days) that is a necessary initial starting condition for the model simulations. Consequently, the cumulative effects illustrated by the groundwater drawdown have occurred over this period. This is important in evaluating the impact scenarios described above. Additional model studies need to be done using the appropriate simulation periods. However, the stream flow simulation does not represent a cumulative impact so the relative increase in stream flow shown in Figure 6.40 are representative of the likely change that would have occurred over the past 7 years if the indicated scenarios were implemented.

The model simulations clearly show a downstream impact on the water resources due to the escalating expansion of deep-rooted vegetation with high transpiration rates. The model also indicated that the consolidation of these plantations (i.e. spatial density) is a contributing factor to the magnitude of the downstream impact. The study has indicated that the model is a reliable tool when properly developed, calibrated and evaluated for studying specific features of the surface-ground-water interaction related to land use changes involving vegetation. However, there are several issues that are of great concern in the application of this model in this study.

There is a serious lack of information on the rooting characteristics of the important species, particularly the exotic tree species that are having a significant impact on the water resources of the region. It is also extremely difficult to calibrate this parameter. Bate *et al.,* (2016) tried to calibrate the rooting depth by comparing two different catchments with different land use in a similar environment just south of the study area, but the results were inconclusive.

8.7 Silvopasture Opportunities for the Maputaland Coastal Plain

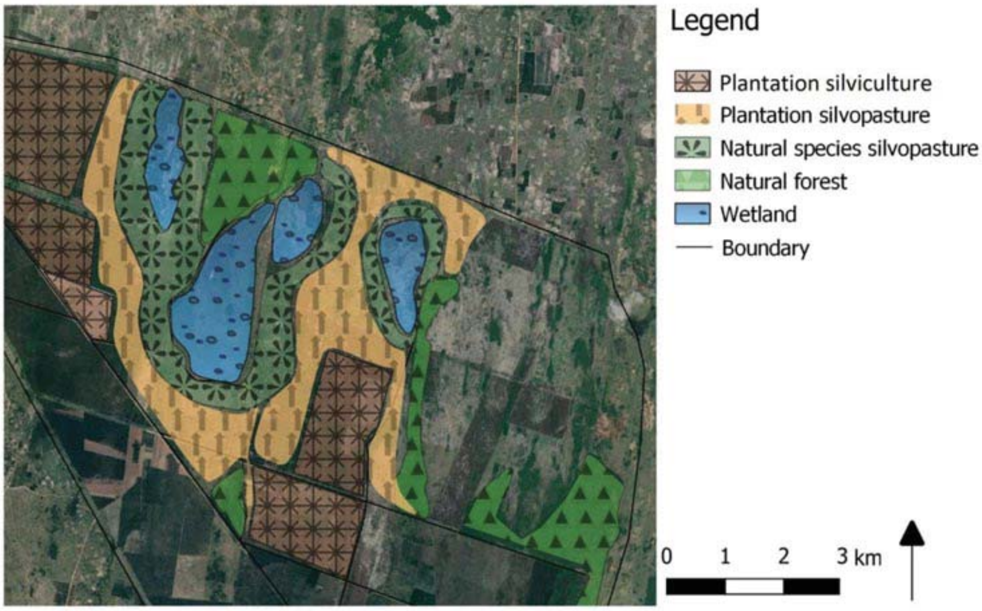
There are opportunities for silvopasture systems at Manzengwenya to function as an income generating buffer around important wetland areas such as Vasi Pan. This would suit former hygrophilous grasslands or dune ridges, using a natural-silvopasture approach with a known economic tree species (i.e. *Sclerocarya birrea*) and, indigenous grasses and livestock. The development of such an arrangement would consume less ground water resources when compared with eucalyptus plantations, while also diversify income and skill development through livestock management. Although research (i.e. Van Wyk, 2011; Vermaak *et al*., 2011) and the government intuitions i.e. (DAFF, 2013) cite South African indigenous tree products as having economic potential, information on cultivars and breeding stock is not readily accessible. This is a limiting caveat for the development of semi-natural silvopasture in South Africa. Alternatively, a eucalyptus or pine based silvopasture system would likely be more economically realistic in the short term, and also warrants testing. These systems should use less water than current plantation models and provide an economic return through timber, pulp or livestock products.

(a) (b)

Figure 8.2 (a) Marula (*Sclerocarya birrea*) stand that has regenerated after abandoned plantation activities. This is a good example of the type of natural species silvopasture systems that merit further research at Maznengwenya (b) An example of a pinus stand growing at a stand density between 400 and 600 stems ha^{-1}, with an estimated forage value of between two and three tons ha^{-1}.

Ecological but also economically active buffer-zones, that provide biodiversity refuges and mitigate biophysical stress (i.e. hydrological regulation) can take various forms (Kasolo and Temu, 2008; Zabala, 2015) In fire-dependent landscapes, the structural affinities of silvopasture (i.e. tree density per hectare) are more aligned with old-growth ecosystems (i.e. forest-grassland mosaics) than plantations are. Silvopasture is practiced and researched in fire-dependent ecosystems in the Brazillian Cerado, (Tonucci *et al*., 2011) and in the southern United States (Grado *et al*., 2001). A previous WRC project investigated *Jatropha curcas* for use in silvopasture (Everson *et al*., 2012), however, few other silvopasture studies have been conducted in South Africa. There is considerable overlap between silvopasture with grassland and natural resource management science. This information provided a basis for a theoretical framework based our findings related to plant water-use, grassland and forest dynamics. Figure 8.3 therefore provides a conceptualisationof a silvopasture framework that could be applied to hydrologically sensitive areas at Maznengwenya plantation or other similar areas on the Maputaland coastal plain.

The framework follows concentric contours of land-use, ranked by potential water-use and distance from nucleated wetland. Core wetland areas such as Vasi pan form the nucleation of the framework. No trees are planted in this central core area, but it would function as a productive pasture for livestock at an estimated stocking density of 0.8-1 LSU ha^{-1}. Natural silvopasture systems, would form a primary buffer around the wetland. This area could be planted at densities between 100 and 500 stems per ha^{-1} with an economically suitable species such as marula, stocked at between 0.3 – 0.4 LSU ha^{-1}, and conceivably produce two to three tons of forage ha^{-1} y^{-1}. Plantation based silvopasture would form a secondary land-use buffer around the nucleation wetland and natural silvopasture systems. This could be planted with eucalypts or pine cultivars at a density between 600 – 800 stems ha^{-1}, stocked between 0.2 – 0.3 LSU ha^{-1} and would produce an estimated two tons of dry weight forage ha^{-1}y^{-1}. Commercial plantations would be suited to areas furthest from the wetland nucleation area. Commercial plantations are usually planted at 1000 – 1200 trees ha^{-1}, they could be stocked rotationally between years two and five and thereafter years nine and twelve, following a method proposed Dr. R. Heath (see section 7.2). Existing natural forest areas would remain as conservation refuges, that conserve genetic diversity of natural forest species, function as a sustainable reservoir for medicinal and cultural products, and act as a seed source for nucleation or edge expansion processes, thereby gradually increasing diversity within natural and semi-natural silvopasture areas.



Land-use type	Tree component	Fodder component	Livestock component
Wetland nucleation	none	Indigenous lawn grasses, including *Acroceras macrum, Brachiaria brizantha*	0.8-1 LSU ha^{-1}
Natural silvopasture	*Sclerocarya birrea* or *Trichilia emetica* planted at a stem density of 100-500 trees ha^{-1}	Lawn and tufted grasses including: *Digitaria diversinervis, Digitaria eriantha, Brachiaria brizantha*	0.3 -0.4 LSU ha^{-1}
Plantation silvopasture	Eucalyptus or Pine hybrid species planted at 600 – 800 stems ha^{-1}	Lawn and tufted grasses including: *Digitaria diversinervis, Digitaria eriantha, Brachiaria brizantha*	0.2 -0.3 LSU ha^{-1}
Plantation silviculture	Eucalyptus or Pine hybrid species 1000 – 1200 stems ha^{-1}	Pioneer tufted grasses including *Dactyloctenium geminatum* or *Panicum maximum*	0.2 LSU ha^{-1}

Figure 8.3 Silvopasture conceptual framework for the landuse at Manzengwenya plantation. The nucleus of the framework are hydrologically sensitive wetlands, followed by concentrically less water demanding land-uses, such as natural species silvopasture, plantation species silvopasture. These silvopasture land-uses would act as a buffer from areas suited to plantation silviculture.

Summary of main findings

- The eucalyptus plantation trees used substantially more water per day (~ 8 L.day^{-1}) than the pine and indigenous trees. In summer, the average daily water-use was highest for the small eucalyptus trees (19.24 L.day^{-1}) and lowest for indigenous trees (10.02 L.day^{-1}). In winter, the average daily water-use was highest for the small eucalyptus trees (7.95 L.day^{-1}), and lowest for the invasive pine trees (4.67 L.day^{-1}). The large eucalyptus trees used the most water per month in March 2017 (735.11 L), while the indigenous trees used the least water per month in July 2016 (46.71 L).

- During the dry winter period of 2017, the commercial pine stands, which were a dominant land-use in the Vasi area, had a low average ETa (1.07 mm.day^{-1}) as rainfall and solar radiation were limiting. The ETa measurements indicated that the trees were conservative water-users in winter, despite the presence of a shallow groundwater table.

- The ecological study identified indigenous tree species that would be suited to integration with different agroforestry systems. *Strychnos spinosa, Sclerocarya birrea, Hyphaene coriaceae*, *Vangueria infausta*, *Annona sengalensis* and *Trichilia emetica* were considered to be disturbance resilient species that could be tested in silvopasture agroforestry systems that combine a moderate density of multi-functional trees with pasture for livestock production. Indigenous South African grasses that are suitable silvopasture species are *Brachiaria brizantha, B. humidicola* and *Panicum maximum.*

- One of the concerns of the DEA and DWS is that water levels of the nearby Lake Sibhya have dropped by almost 4 m from 2001 to 2010. One of the critical factors in determining the impact of trees on the ground water table is whether a species is water- or energy-limited, since a species that is water-limited will use less water in a drought. Apart from the small eucalyptus trees planted on the edge of Vasi Pan North, the results showed that the water-use of the other trees were limited by water availability, suggesting that their roots were not in permanent contact with the groundwater table. The lowering of the groundwater table in the recent drought years may account for the trees not abstracting water from the groundwater.

- Model simulations were used to investigate alternatives to monoculture plantations which are classified as SFRAs.

  Scenario 1: **Removal of all the exotic plantations**: The water table was predicted to rise by over 2 m from existing conditions.

  Scenario 2: **Reduction of area under plantations by strip cropping.** In this scenario the impact of reducing the area under plantations by replacing the total area with strip cropping was equivalent to a 50% reduction of water-use in the plantation area.

  Scenario 3: **Clearing wetland buffers and implementing an agroforestry system**. The SWAT model predicted an increase of up to 40 % water yield. Future research on the water-use of the potential agroforestry species and systems identified in this study is therefore recommended.

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10. APPENDICES

10.1 Capacity Building and Technology Transfer

The capacity building and technology transfer activities included the scientific training of students for postgraduate qualifications, scientific papers delivered at regional and overseas conferences and numerous informal study group sessions by local and international visitors to the trial sites.

The building of research capacity was achieved through the registration of students at the University of Stellenbosch and the University of KwaZulu-Natal. The following table indicates the students who have completed their qualifications as well as those who are in the process of completing them.

Table 10.1 Candidates for postgraduate qualification.

NAME	DEGREE	STATUS
Siphiwe Mfeka	Non degree	In Progress
Xolani Ngubane	Non degree	In Progress
Margaret Mugure	MSc – UP	In Progress
Tracy Pearton	MSc – UKZN	In Progress
Thigesh Vather	PhD – UKZN	In Progress
Allister Starke	PhD – UP	In Progress
Bruce Scott-Shaw	PhD/Post Doc – UKZN/UP	PhD Completed
Isibusiso Esihle Science Discovery Centre	N/A	In Progress

Progress report of Tracy Pearton (216075540)

Title: An assessment of indigenous and introduced tree water use and varying land uses around Vasi Pan, Maputaland, KwaZulu-Natal

I am currently registered for my second year of MSc Hydrology through the University of KwaZulu Natal (PMB). I presented my project proposal at SANCIAS conference in September 2016. My choice methods for monitoring water use in the Vasi Pan area were Sap flow measurements using the heat pulse velocity (HPV) system and the Eddy Covariance (EC) system. The HPV systems were successfully installed in the months of July and August 2016 at four sites. Each site monitored a particular species of importance to the area. The species onitored were: four indigenous trees species (*Shirakiopsis ellipticum, Albizia adiathifolia, Trema orientalis* and *Hymenocardia ulmoides*), four *Pinus ellitotti* trees, three *Eucalyptus grandis* trees aged one year and three *Eucalyptus grandis* trees aged four years. The data was regularly collected and analysed. There were two EC systems collecting data for this project. One is a permanent structure which is monitoring in an indigenous forest. This system has been collecting continuous data since November 2016 while the other system is a portable EC system which collected three week window periods of data. There were a number of additional ancillary measurements collected to assist with data interpretation such a leaf area index, growth measurements, volumetric water and automatic weather station data. The research for my MSc thesis was submitted in December 2017 for examination and was examined and awarded in April 2018.

Progress report of Allister Starke

Title: Integrating ecological and indigenous knowledge systems into land-use through agroforestry in Maputaland.

On the Maputaland coastal plain, agricultural land-use is dominated by Eucalypt plantations, which reduce groundwater availability. But are there agroforestry alternatives for communities to support their livelihoods? The PhDviewed from the perspective ecological and cultural land-use patterns as a basis for agroforestry system(s). This includes ecological systems management (e.g. natural forest and grassland utilisation), agriculture (e.g. indigenous tree cultivation) which may include combinations of trees and grasses such as silvo-pasture.

Study objectives:
Objective i) Understanding the ecology of forest expansion in Manzengwenya plantation?
Objective ii) Assess grazing potential across topographical landscape changes (i.e. dune slacks and depresses), and use this understanding to assist pastoral practice?
Objective iii) Analyse the resource potential of forest expansion in Manzengwenya and review its application for agroforestry systems.

Progress to date:
Objective i) Field work, data analysis and manuscript had been completed. This paper is ready for Journal submission to Forest Ecology and Management: *Forest expansion into abandoned plantations informs screening for native agroforestry species, Maputaland South Africa*

Objective ii) Field work is complete and initial has been provided in the annual report. Fibre analysis has analysis had been conducted but we await results from the Nitrogen analysis.
Objective iii) A review has been completed and a paper in is in the process of being drafted.This work complements the forest expansion paper detailed in the 1st objective by looking at the resource potential from this process.

I have presented at two workshops over the last year.

A. Starke (2017). Agroforestry opportunities in fire dependent biomes – a case study in Maputaland South Africa. In: The Role of Small holder Agroforestry in the Arid and Semi-arid regions in combating climate change. British Council, Researcher-links workshop, Pietermaritzburg, KZN. Kisumu, Kenya.

A. Starke (2018). Forest expansion and screening secondary vegetation for indigenous agroforestry species in Maputaland. In: Breeding and modelling underutilised crops for community resilience. British Council, Researcher-links workshop, Pietermaritzburg, KZN.

We have also been involved in a capacity building project at Isibusiso Esihle Discovery Centre (IESDC).

Progress report of Thigesh Vather

Title: The Applications of Cosmic Ray Technology

Cosmic ray technology is an innovative technique of obtaining area-averaged soil water estimates at an intermediate scale. The technology consists of the cosmic ray probe, which is a stationary instrument that is used for soil water monitoring and the cosmic ray rover, which is an instrument that is placed in a vehicle and driven around for soil water mapping. My PhD will look at the hydrological applications of both the cosmic ray probe and cosmic ray rover. This includes:

i. The validation of satellite-based soil water products (SMOS and Downscaled SMOS) using cosmic ray probe estimates.
ii. Using the cosmic ray probe to monitor changes in soil water in a catchment that that is undergoing a tree genus exchange.
iii. Iii) Testing and evaluating the cosmic ray rover's suitability to map soil water and its potential use to delineate wetlands and riparian zones.
iv. Other potential applications of the technology, such as its capability to isolate and measure different parameters of the hydrological cycle.

To date, I have attended the fifth international COSMOS workshop in Copenhagen, Denmark. Attending this conference early in my PhD has been beneficial in assisting to conceptualize cutting edge ideas within this research field for the project. I visited the University of Nebraska Lincoln, for a period of one month, where I was trained/mentored by Dr Trenton Franz, on cosmic ray technology. The main purpose of the trip was to obtain the necessary skills to carry out cosmic ray rover surveys. I have conducted two cosmic ray probe calibrations in Two-streams, as well as setting up a cosmic ray probe 18 meters above the soil surface. I have set-up and calibrated two cosmic ray probes in the Vazi area. I have conducted four cosmic ray rover surveys in Vasi, across two different landcovers (grassland, pine forest). I have completed writing two research paper for my PhD, the first paper is a review paper on cosmic ray technology and the second paper is a validation of SMOS Level three and Level four soil water with cosmic ray probe soil water estimates at two Catchment sites (Cathedral Peak and Two Streams). I am currently writing up the third PhD paper on the cosmic ray rover surveys. The hydrological applications of cosmic ray technology are continuously being explored.

Publication: Vather T, Everson C, Mengistu M, Franz T. Cosmic ray neutrons provide an innovative technique for estimating intermediate scale soil moisture. S Afr J Sci. 2018;114(7/8), Art. #2017-0422, 9 pages. http://dx.doi.org/10.17159/ sajs.2018/20170422.

Progress report of Bruce Scott-Shaw

Title: Groundwater and surface water interactions of introduced tree species at Vasi Pan, Maputaland coastal belt.

I am currently working on the tree water-use component involving the measurement of various tree species using the heat pulse velocity system and Dynamax collars. I am also involved in the measurement of total evaporation above various land uses using the eddy covariance system. However, the core focus of my work will be on modelling the groundwater and surface water interactions. The data recorded from the various vegetation types has been used to calibrate and validate the models used. Thus far the *ArcSWAT* model has been run for the area using detailed DEM, land-use, soils and climate data recorded at the site. A recent addition to this model is the linkage of the *MODFLOW* modular groundwater model to the *ArcSWAT* model. The linkages are as follows:

- Soil deep percolation (from SWAT HRUs to MODFLOW grid cells)
- Remaining potential evapotranspiration (from SWAT HRUs to MODFLOW grid cells)
- Sub-basin stream stage (from SWAT sub-basins to MODFLOW river cells)
- Groundwater discharge (from MODFLOW river cells to SWAT sub-basins)
- Water table elevation (from MODFLOW grid cells to SWAT HRUs)

Given the need for improved modelling in South Africa and the availability of detailed data at this site, efforts will be spent on developing this link to enhance the achievements of this model application already achieved thus far.
The SWAT modelling component of this project has formed a chapter of my PhD thesis which was started during WRC project K5\2580. The PhD thesis was submitted for examination in February 2018.

The following presentations were made by project team members and students at local and international conferences:

The capacity building and technology transfer activities included the scientific training of students for postgraduate qualifications, scientific papers delivered at regional and overseas conferences and numerous informal study group sessions by local and international visitors to the trial sites.

The following presentations were made by project team members or students:

- T. Vather, KT Chetty, CS Everson and M. mengistu (2016). Comparison between satellite-based and cosmic ray probe soil water estimates: a case study in the cathedral peak catchment. 18thSANCIAHS symposium, University of KwaZulu-Natal, Durban, September 2016.

- Kunz, R., M Mengistu, I Doige, C Everson and G jewitt. Assessing the hydrological impact of biofuel feedstock. 18th SANCIAHS symposium, University of KwaZulu-Natal, Durban, September 2016.

- Pearton, T., Everson CS and KT Chetty. Assessment of indigenous tree water-use in Vasi pan. KwaZulu-Natal. 18th SANCIAHS symposium, University of KwaZulu-Natal, Durban, September 2016.

- Scott-Shaw & Everson (2017). Modelling the Surface and Groundwater Interactions of Potential Agroforestry Systems for Use in Forestry Rehabilitation Programs in a Water Stressed Catchment of South Africa. SER 2017, Foz du Iguacu, Brazil.

- Everson & Scott-Shaw (2017). Rehabilitation of Alien Invaded Riparian Zones and Catchments Using Indigenous Trees: An Assessment of Indigenous Tree Water-Use. SER 2017, Foz du Iguacu, Brazil.

- Scott-Shaw & Everson (2017). Modelling the Surface and Groundwater Interactions of Potential Agroforestry Systems in a Water Stressed Catchment of South Africa. National Wetlands Indaba. Wild Coast Sun.

10.2 Data Storage and Knowledge Dissemination

All processed data have been stored at:

School of Life Sciences
University of KwaZulu-Natal
Carbis Road
Scottsville
Pietermaritzburg
3209
South Africa