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A comparative assessment of the quantity and sources of water used by alien invasive *Prosopis spp* and indigenous *Acacia karroo* in the Northern Cape Province

A thesis submitted in fulfilment of the requirements for the degree of Magister Scientiae in Environmental and Water Science

By

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Abstract

A comparative assessment of the quantity and sources of water used by alien invasive Prosopis spp and indigenous Acacia karroo in the Northern Cape Province

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MSc Environmental and Water Science Thesis, Department of Earth Science, University of the Western Cape

Invasive alien plants (IAPs) are often reported to use more water than indigenous plants. In addition, IAPs have an ability to adapt to harsh environmental conditions and they tend to spread at rapid rates, thereby threatening the country's water resources, agricultural land, and biodiversity. Much of South Africa is expected to get drier in future due to climate change and the new climatic conditions are also predicted to accelerate the rate at which alien plants will spread. Approximately 10 million hectares are currently estimated to have been invaded by alien plants in South Africa, with an estimated average annual rate of spread of more than 5%. The first objective of this study was to compare the water use by deep rooted tree species which include invasive alien *Prosopis (sp)* trees and the co-occurring indigenous *A. karroo.* These trees are growing in a flood plain of a groundwater dependent catchment in the Northern Cape Province. Both species are dependent on groundwater and thus compete with local communities for this resource. The second objective was to determine the sources of water that the trees were using in order to understand the impacts of each species on groundwater resources. Transpiration was measured using the heat ratio method of the heat pulse velocity sap flow technique while the volumetric soil water content was monitored at several depths down the soil profile using automated capacitance soil water content probes. Weather data was collected using an automatic weather station. Stable isotopes of oxygen and hydrogen from plant, soil and groundwater samples were analysed to determine the sources of water used by the trees. Average tree density was approximately 613 stems per hectare for *Prosopis* compared to about 100 stems per hectare for *A. karroo.* Comparative measurements of water use shows that the annual stand level transpiration from *Prosopis* invasions was approximately 353 mm/year while that from *A. karroo* was only about 137 mm/year. Differences in stand transpiration were a result of the higher plant density for *Prosopis* than *A. karroo*. There were no significant differences in the transpiration rates of the two species for trees with a similar transpiring leaf area. Application of a two compartment linear mixing model for the oxygen isotope ratio during the peak transpiration period in summer showed that *Prosopis* derived 23% of its water from the unsaturated zone and 77% from the saturated

zone. *A. karroo* on the other hand derived 53% of its water from the unsaturated zone and 47% from the saturated zone. Diurnal fluctuations in groundwater levels were strongly related to the transpiration dynamics of both species. This supports the observation that these deep rooted trees have substantial impacts on groundwater at the study site. Root sap flow patterns of *Prosopis* showed evidence of hydraulic redistribution wherein the groundwater abstracted by the tap roots was deposited in the shallow soil layers by lateral roots. However, the root sap flow patterns of *A. karroo* growing adjacent to the *Prosopis* did not show this phenomenon.

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Declaration

I declare that *A comparative assessment of the quantity and sources of water used by alien invasive Prosopis spp and indigenous Acacia karroo in the Northern Cape Province* is my own work, that it has not been submitted for any degree or examination in any other University, and that all the sources I have used or quoted have been indicated and acknowledged by complete references.

Full name.................................... Date.................................

Signed..

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CHAPTER 1: Introduction

Invasive alien plants (IAPs) often have higher transpiration rates than indigenous plants (Cavaleri and Sack, 2010). This is because most IAPs adapt to harsh conditions, spread at rapid rates and often develop large canopy sizes (Calder and Dye, 2001). Much of South Africa is expected to become drier in future due to global warming (Midgley *et al*., 2003). It is thought that the warm conditions will accelerate the rate of invasion by alien plants (Richardson and Van Wilgen, 2004) thereby worsening the negative impacts on the environment. Approximately 10 million hectares have been invaded by alien plants in South Africa with an estimated annual rate of spread of more than 5% (Le Maitre *et al*., 2000). The spreading of deep rooted invasive alien plants like *Prosopis spp* at high rates of approximately 15% in upland areas and up to 30% per year in riparian areas in the arid and semi-arid parts of South Africa (Van den Berg, 2010) is a major cause for concern. For this reason *Prosopis* invasions were used as the case study in this research and Table 1.1 summarises the major invading species in the country.

Table 1.1 Top 10 invading species in South Africa categorized by condensed invaded area. Habitat = the main habitats invaded by the species, I = landscape, r = riparian, R (a) = alluvial plain (Le Maitre *et al*., 2000).

Species	Habitat	Condensed invaded area	Total invaded area	Density
		(ha)	(ha)	%
Acacia cyclops	L	339 153	1 855 792	18.28
Prosopis spp.	R(a)	173 149	1 809 229	9.57
Acacia mearnsii	r,l	131 341	2 477 278	5.3
Acacia saligna	l,r	108 004	1 852 155	5.83
Solanum mauritianum	r,l	89 374	1 760 978	5.08
Pinus spp.	L	76 994	2 953 529	2.61
Opuntia spp.	L	75 356	1 816 714	4.15
Melia azedarach	r,l	72 625	3 039 002	2.39
Lantana camara	R	69 211	2 235 395	3.1
Hakea spp.	L	64 089	723 449	8.86

Note: The condensed area is the total area adjusted to bring the cover to the equivalent of 100%. Density is the estimated mean cover over the total invaded area (Le Maitre *et al*., 2000).

The total area invaded by alien plants in South Africa is over 8 percent of the country's total area (Van Wilgen *et al*., 2001) and *Prosopis* is the second largest invasive species after *A. Cyclops* accounting for 9% of the total invasions (Table 1.1). These invasions are mostly concentrated in wetter regions of the country or along river courses. Alien plants have invaded the major biomes in South Africa (Le Maitre *et al*., 2000). The most invaded are; 1) the fynbos biome where *Pinus*, *Acacia*, and *Hakea* species are prevalent; 2) the forest biome where *A. Cyclops*, *A. mearnsii* and *A. Saligna*, dominate, and; 3) the grassland savannah biome invaded by mostly *Acacia spp., Melia azedarach* and *Jacaranda mimosifolia* (Richardson *et al*., 1997; Cowling *et al*., 1999; Le Maitre *et al*., 2000; Van Wilgen *et al*., 2001). The *Nama karoo* (semi-desert shrub land of summer rainfall) is probably the fourth most invaded biome where *Prosopis* species have invaded at least 18 000 km^2 of the flood plains of seasonal and ephemeral water courses (Le Maitre *et al*., 2000). According to Richardson *et al*. (1997), the *succulent karoo* (semi-desert shrub land with winter rainfall) is also heavily invaded by *Prosopis* spp.

Over time six *Prosopis* species have been introduced into South Africa to provide fodder for livestock, fuel, and shade. Dominant species include *Prosopis chilensis, P. glandulosa (var torreyana) and P. velutina* (Poyton, 1988; Zachariades *et al*., 2011), among others. The latter two species have hybrids that are aggressive invaders which form dense, impenetrable thickets (Poynton, 1998). Before the year 2000, *Prosopis* species had invaded more than 2 million hectares of land in South Africa. The principal species in terms of condensed area are *Acacia cyclops*, which is found in the Western and Eastern Cape, and *Prosopis* species which are found mainly in the Northern Cape, the North West, the Free State and parts of the Limpopo Province.

A large amount of funding is given annually by the government, local municipalities and private sector in support of the Working for Water Program, which is responsible for managing alien plants in South Africa (Dye *et al*., 2001; Van Wilgen *et al*., 2012). Several studies have shown that removing alien trees enhances stream flow (Prinsloo and Scott, 1999; Clulow *et al*., 2011) and the rate of groundwater recharge as the dense stands of alien plants will be replaced by indigenous plants which are believed not to use as much water (Calder and Dye, 2001).

However, some recent studies have shown that some species of indigenous vegetation do use large amounts of water (Dye *et al*., 2001; Dzikiti *et al*., 2014). Therefore a sound

understanding of how IAPs affect water resources requires detailed information on the water use characteristics of the indigenous vegetation that would normally replace the invasions once they have been cleared.

Few studies have quantified the incremental water use by invasions in South Africa above that used by the indigenous vegetation. In one of these, Dye *et al.* (2001) compared the water use of wattle thickets (*A. mearnsii*) relative to indigenous plant communities on riparian sites in the Western Cape and Kwa-Zulu Natal Provinces. They concluded that the removal of riparian wattle and its replacement by indigenous herbaceous plants may result in significant reductions in annual evapotranspiration which could likely lead to stream flow enhancement. They then emphasized that water use by IAPs remains largely unknown in South Africa especially in the very dry parts of the country where invaders like *Prosopis* are widespread. This adds further uncertainty about the benefits of removing IAPs and more research is therefore needed.

In densely vegetated areas a substantial proportion of rainfall is intercepted by plant canopies. The rest passes through the canopy to reach the ground, and some drips down the stem as stem flow (David *et al*., 2006). Net rainfall received infiltrates into the soil and then depending on the type of soil this water will percolate down into deeper soil layers. Some of this water can eventually recharge groundwater. Plants use either soil water or groundwater depending on how far their roots reach. Plants with longer roots have access to groundwater while plants with shorter roots depend mainly on the water available in the soil (Chen and Hu, 2004).

This study specifically compares water use by deep rooted invasive alien plants like *Prosopis* and deep rooted indigenous vegetation that would normally replace the *Prosopis* once it has been cleared in the dry parts of the country. Communities in the Northern Cape Province, which is the driest province in South Africa, rely heavily on groundwater and yet *Prosopis* invasions cover extensive parts of the Province. Van den Berg (2010) estimated that about 1.5 million hectares are invaded by *Prosopis* in this Province. In order to estimate potential groundwater savings that can be achieved by clearing *Prosopis*, information on the incremental water use by *Prosopis* over and above that used by the co-occurring indigenous vegetation such as the various *Acacias* (e.g. *A. karroo, A. arioloba*, among others) is needed.

1.1. Research problem

Invasive alien plants have been reported to have higher transpiration rates compared to indigenous plants (Cavaleri and Sack, 2010). Deep rooted plants like *Prosopis* have been reported to deplete groundwater resources (Fourie *et al*., 2002; Dzikiti *et al*., 2013a), affect biodiversity (Dean *et al*., 2002), occupy grazing land (Ndhlovu, 2011) and exacerbate the problem of wild fires. To accurately quantify the impacts of *Prosopis* invasions on groundwater there is a need to compare the water use of this species with that of co-occuring indigenous species.

1.2. Research questions

➢ How much water do *Prosopis* invasions use compared to the indigenous tree species that also rely on groundwater?
➢ To what extent do the species rely on different water sources?
➢ Is there any relationship between the water transpired by the plants and the changes in groundwater levels?

1.3. Aims and objectives
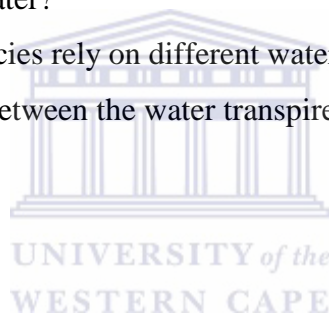
The main aim of this study is to compare the relative water use (transpiration) rates by *Prosopis* invasions and *A. karroo* trees growing in a semi-arid catchment.

Specific objectives are to:

➢ Establish whether the water use rates differ between an alien invasive tree species (*Prosopis*) and an indigenous tree species (*A. karroo*).
➢ Quantify the subsurface component of water used by an alien invasive and an indigenous tree species.
➢ Determine whether water use by selected alien invasive and indigenous tree species affect groundwater levels.

1.4. Research Hypothesis

Hypothesis 1: *Prosopis* invasions use more water than indigenous *A. karroo* trees.

Hypothesis 2: *Prosopis* trees will transpire more groundwater while the indigenous *A. karroo* trees will transpire more soil water.

Hypothesis 3: The amount of water transpired by *Prosopis* trees will show a strong correlation with the changes in groundwater levels, but the correlation between the water transpired by *A. karroo* trees and the changes in groundwater levels will not be as strong.

1.5. Thesis outline

Chapter 1 presents an introduction to the project as well as the motivation for the study, aims, objectives and an outline of the thesis. A review of relevant local and international literature and the most relevant topics and issues addressed in this thesis will be thoroughly investigated and discussed in **Chapter 2**. **Chapter 3** is the materials and methods section and this will present the experimental set-up and a detailed description of the study area. Results and discussions will be presented in **Chapter 4**. Conclusions and deductions that were made from the results and recommendations for further research will be presented in **Chapter 5**.

1.6. Chapter summary

The research being conducted is important because there is lack of information on the water use of alien plants compared to indigenous plants in South Africa. The knowledge surrounding the issue is inadequate particularly for deep rooted species which are the main plant types in the driest parts of the country. The solutions being presented currently are considered ineffective as they rely heavily on studies conducted elsewhere (mainly in the USA for *Prosopis*) where the growing conditions are different from those in South Africa. Alien plants have invaded over 10 million hectares of land in South Africa (Van Wilgen *et al*., 2001) which is over 8 percent of the country's total area. Much of South Africa is expected to get drier in future due to global warming as a result of climate change (Midgley *et al*., 2003) and yet the new climatic conditions are predicted to accelerate the rate at which alien plants are spreading (Richardson and Van Wilgen, 2004). Detailed information on the hydrological impacts of invasive alien plants is therefore critical to ensure future water security for the country.

CHAPTER 2: Literature Review

2.1. Introduction

This chapter presents the outcomes of the review of relevant literature. Information on what is known/unknown about the problem is presented. The theories surrounding water use by plants, water transport through plants and water uptake by roots was examined. The information that other researchers have published about similar problems was summarised. The methods that other researchers have used to address similar problems were reviewed.

2.2. Invasive alien plants in South Africa

Invasive alien plants (IAPs) are plants that have successfully spread outside their indigenous range and adapted to their new locations (Williamson, 1996; Richardson *et al*., 2000). More than 200 species of alien plants have been reported to be causing serious problems in natural and semi-natural ecosystems of South Africa (Chamier *et al*., 2012; NEMBA, 2014). These species cover approximately 10 million hectares of land, which is 8% of the country's surface area (Le Maitre *et al*., 1999; Van Wilgen *et al*., 2001). Current estimates are that IAPs use about 7% of the country's runoff (Le Maitre *et al*., 2000; Chamier *et al*., 2012). When IAPs invade an ecosystem, they increase biomass thereby increasing fire intensity (Van Wilgen *et al*., 2001). They also increase evapotranspiration thus reducing available water, threaten the survival of indigenous species, and occupy vital agricultural land (Chamier *et al*., 2012). *Prosopis* in particular is well known to have significantly reduced the available grazing land in the Northern and Western Cape Provinces (Ndhlovu, 2011).

When indigenous vegetation is replaced by thick stands of invasive alien plants, the water balance of the ecosystem is affected often leading to reductions in stream flow and declining groundwater levels (Calder and Dye, 2001; Fourie *et al*., 2002). The Northern Cape Province is the driest province in the country. It has an area of 12 214 307 ha and 13.9% of the area is invaded by alien plants, mainly *Prosopis* (Table 2.1). Invasive alien species have been reported to change ecological compositions at global and local spatial scales for many decades (Bennett and Kruger, 2013). In order to manage the spread and impacts of the invasions, the South African government initiated a multimillion Rand programme named Working for Water in 1995, thus acknowledging the severity of problems with IAPs. This programme is responsible for the removal of alien plants in water sensitive areas with the intention to save water and creating employment in the process. Local municipalities, private

organizations and individual farmers also invest substantial resources to deal with the problem of IAPs. However, key decisions by these entities e.g. prioritising clearing operations usually require support from research into the eco-hydrological impacts of IAPs to ensure optimal use of often limited resources.

Table 2.1 Areas invaded by alien plants in the different provinces both as hectare and as a percentage of the area of the province (Le Maitre *et al*., 2000).

Province	Area (ha)	Total area invaded		Condensed invaded area	
		(ha)	(%)	(ha)	(%)
Eastern Cape	16 739 817	671 958	4.01	151 258	0.9
Free State	12 993 575	166 129	1.28	24 190	0.19
Gauteng	1 651 903	22 254	1.35	13 031	0.79
KwaZulu-Natal	9 459 590	922 012	9.75	250 862	2.65
Lesotho	3 056 978	2 457	0.08	502	0.02
Mpumalanga	7 957 056	1 277 814	16.06	185 149	2.33
Northern Cape	36 198 060	1 178 373	3.26	166 097	0.46
Northern Province	12 214 307	1 702 816	13.94	263 017	2.15
North West	11 601 008	405 160	3.49	56 232	0.48
Western Cape	12 931 413	3 727 392	28.82	626 100	4.84
RSA+Lesotho	124 803 707	10 076 365	8.07	1 736 438	1.39

Note: The condensed area is the total area adjusted to bring the cover to the equivalent of 100% (Le Maitre *et al*., 2000).

2.3. Legislations and plant water use in South Africa

The National Water Act (Act 36 of 1998) defines the ecological reserve and stream flow reduction activities and emphasizes that the interrelationships between vegetation and all water sources must be understood. This will ensure that environmental managers make informed decisions and policies can be put in place to ensure that the limited resources are used in a sustainable manner (Van Wilgen *et al*., 1997). The Constitution of South Africa (Act 108 0f 1996) has an environmental clause (clause number 24) that emphasizes that all natural resources must be used in a sustainable manner, so that future generations can benefit from these resources. The Biodiversity Act of 2004 provides for the management and conservation of South Africa's biodiversity within the framework of the National

Environmental Management: Biodiversity Act of 1998. The act promotes the protection of species and ecosystems and encourages a sustainable use of indigenous biological resources.

According to the National Environmental Management: Biodiversity Act (NEMBA) of 2014, *Prosopis* is a category 1b invader in the Eastern Cape, Free State, Northwest and the Western Cape Provinces. It is a Category 3 invader in the Northern Cape. Category 1b invasive species are species that must be controlled according to sections 75(1), (2) and (3) of NEMBA. In addition, if an invasive species management program has been developed, a person must control the species in accordance with such a program. Also the person whose property is occupied by this species must allow authorised officials to enter into the property and to monitor, assist with or implement the control of the species or they must facilitate compliance with the invasive Species Management Program. Category 3 invasive species are treated in the same way as Category 1b invasions if they occur in riparian areas.

2.4. Hydrological impacts of invasive alien plants

The invasion of natural ecosystems by alien plants is a serious environmental problem that threatens the sustainable use of ecosystems (Van Wilgen *et al*., 2001; Van Wilgen *et al*., 2012). The most damaging invasive alien species transform ecosystems by using excessive amounts of resources like water and light (Richardson and Wilgen, 2004). Invasive alien plants can dominate ecosystems and threaten the delivery of ecosystem goods and services (Van Wilgen *et al*., 1998; Levine *et al*., 2003; Wise *et al*., 2012). These species are able to survive, reproduce and spread at high rates across the landscape (Van Wilgen *et al*., 2001). Some invasive alien plants are nitrogen fixing thereby promoting or suppressing fires. Invaders are most likely to have substantial effects on ecosystems by rapidly changing the water balance and biomass composition of landscapes thereby exacerbating, for example, problems with wild fires (Richardson and Van Wilgen, 2004). According to Van Wilgen *et al.* (2001) ten million hectares of South Africa had been invaded by 180 alien plant species in 2001 whose impacts are still not understood.

Invasive alien plants impact both fresh water and terrestrial water ecosystems negatively (Richardson and Van Wilgen, 2004; Chamier *et al*., 2012). When IAPs occupy an ecosystem, they compete with the indigenous vegetation that occurs in that ecosystem for resources such as water, light and nutrients. Because these plants tend to have greater heights, bigger canopies, high plant densities, and root depth they often out compete the indigenous plants

that they find in an ecosystem (Calder and Dye, 2001). Le Maitre *et al*. (2000) estimated that the invasions that had occupied South Africa by 2000 were responsible for a reduction of 33 000 Mm^3 in surface water each year. Van Wilgen *et al.* (2008) on the other hand concluded that had there not been any alien plant control activities, the reduction in available water resources would have been 8 times more than it was in 2008. A reduction in available water resources impacts negatively on the economy of the country as key sectors of the country's economy are heavily dependent on reliable water supplies e.g. irrigated agriculture, industry and domestic uses. The cost of alien plants to the economy of South Africa was estimated to be R 6.5 billion (0.3% of the country's GDP of R2 000 billion) in 2012 (Chamier *et al*., 2012). Invasive alien plants reduce the rate of recharge of aquifers (Colvin *et al*., 2002) thereby impacting negatively on the yield of aquifers. This is a major problem for groundwater dependent ecosystems and settlements.

Table 2.2 Impact of the water use by invading alien plants on mean annual runoff in each of South Africa's provinces and in Lesotho (Le Maitre *et al*., 2000).

Province	Mean annual runoff (Mm³/year)	Condensed invaded area (ha)	Incremental water use (Mm³)	Water use (% of MAR)	Water use in rainfall equivalents (mm)
Eastern Cape	9 998.76	151 258	558.19	5.58	369
Free State	3 546.10	24 190	86.19	2.43	356
Gauteng	551.97	13 031	53.93	9.77	414
KwaZulu-Natal	12 517.61	250 862	575.74	4.6	230
Lesotho	4 647.19	502	1.88	0.04	374
Mpumalanga	6 303.01	185 149	446.29	7.08	241
Northern Cape	910.94	166 097	150.86	16.56	91
Northern Province	3 383.63	263 017	297.7	8.8	113
North West	1 081.57	56 232	95.4	8.82	170
Western Cape	6 555.18	626 100	1 036.82	15.82	166
South Africa	49 495.96	1 736 438	3 303.00	6.67	190

The water use by alien invaders in the Northern Cape Province where *Prosopis* is dominant is estimated at 150.86 Mm^3 per year or 16.6% of the mean annual runoff (Table 2.2). The invaders in this driest province pose the greatest threat compared to any other province in South Africa. Invasions in the Western Cape Province have the second largest impact (15.82%). This is mainly because large areas of catchments are mountainous and heavily invaded by *pines*, and most river systems are densely invaded by *wattles* (Le Maitre *et al.*, 2000) that are known to use significant amounts of water.

The impacts of *Prosopis* on groundwater are mainly harmful due to their ability to form dense stands. Different approaches are currently being implemented to control the spread and densification of *Prosopis* invasions. These include combinations of manual, chemical and biological control methods. This collection of approaches is aimed at maximising the benefits while minimising the negative impacts of *Prosopis* (Wise *et al.*, 2012).

Groundwater use by *Propsopis* trees has a major impact on water supply for groundwater dependent communities (Le Maitre *et al.*, 1999) and there is a need to reduce this impact (Van Wilgen, 2012). *Prosopis* trees develop extensive root systems that influence water tables at depths of up to 15 m and, under certain circumstances greater than 50 m (Maeght *et al.*, 2013). In floodplains (where groundwater is potentially accessible) *Prosopis* trees form thickest stands and use the water in the reach of their roots. Transpiration is limited by obtainable soil water content, but the trees can sustain high transpiration rates despite high moisture stress levels (Le Maitre *et al.*, 1999). When estimating water use by invasive *Prosopis* trees, it is necessary to differentiate between upland and floodplain landscapes because of the differences in accessibility of water in these situations. Alluvial floodplains are characterised by periodic floods and groundwater inflow from the adjacent upland areas. In such situations the annual evaporation rate, can exceed the annual rainfall (Le Maitre *et al.*, 1999; Scott *et al.*, 2006; Scott *et al.*, 2008).

Wise *et al.* (2012) used Van den Berg's (2010) estimates of the extent of invasion map for the Northern Cape Province and divided the area into upland and floodplain landscapes to estimate water use by *Prosopis*. Their results showed that the mean incremental water use was 33.2 m³ per hectare over a year for uplands and 212.3 m³ per hectare over a year for floodplains. The proportion of the water lost due to *Prosopis* was assumed to be ~17% of the

total water use, which is the amount of the total recharge registered for use in the Northern Cape region (DWAF 2005).

Invasive alien plants are known to use large quantities of water when compared to indigenous plants. Therefore quantifying the amount of water that these species use will provide information necessary for taking measures to minimise the negative impacts that this may have on the country's water resources.

Yasuda *et al.* (2014) conducted an investigation of the diurnal fluctuation of groundwater levels caused by the invasive alien *Prosopis.* They collected data on the plant water uptake and groundwater level changes in an arid area in Sudan. The sap flow of *Prosopis* showed a single peak after rainfall and a double peak under dry conditions. Their results showed that the changes in groundwater level closely followed plant water uptake. The groundwater levels declined during the day when transpiration was high and recovered during the night when the rate of transpiration had decreased.

Hultine *et al.* (2006) investigated the hydraulic constraints on water uptake by *Prosopis velutina* at one site with sandy-loam soil and at another site with loamy-clay soil in eastern Arizona, USA. Before conducting the study they predicted that trees on sandy-loam soil had less negative xylem and soil water potential than trees on loamy-clay soil. The results showed that minimum pre-dawn leaf xylem water potentials measured in summer were significantly lower at the sandy-loam site (-3.5 +/- 0.1 MPa) than at the loamy-clay site (-2.9 +/- 0.1 MPa). Minimum midday xylem water potentials were also lower at the sandy-loam site (-4.5 +/- 0.1 MPa) compared to the loamy-clay site (-4.0 +/- 0.1 MPa).

2.5. *Water transport through plants*

Plants need water to maintain turgor pressure which helps them to stay upright and is accomplished when the plasma membrane pushes against the cell wall (Jones, 2004). The overall movement of water through plants is driven by a water potential gradient which comprises the sum of osmotic potential and hydrostatic pressure gradients (Tang and Boyer, 2008). Water potential is defined as a measure of free energy that is available to do work to move water from one part of the plant to the other (Jones, 1992; Hodson and Acuff, 2006; Tang and Boyer, 2008; Chavarria and Dos Santos, 2012). Measurements of the plant water

potential at predawn is a useful measure of soil water status and this is useful for calculating the total water potential gradient that determines plant water use (Tang and Boyer, 2008).

Water moves from the soil to the root because of the soil-root water potential gradient. Then it moves from root to the leaf down a root-leaf water potential gradient (Hodson and Acuff, 2006; Chavarria and Dos Santos, 2012). Water in the leaf interstices evaporates into the atmosphere via stomata on the leaves driven by a leaf-air water potential gradient and the available energy for evaporation. The movement of water from soil to root is largely due to the total water potential gradient and osmotic potential gradient, where the solute concentration in the root is higher than the solute concentration in the soil, while the movement from the root to the leaf is largely due to the tension cohesion mechanism (Domec, 2001). The rate of water uptake from the soil to satisfy the transpiration demand can be considered to be directly proportional to the difference in water potential between the soil and the plant canopy. It is also directly proportional to the root density and to the root-soil hydraulic conductance (Cook & O'Grady, 2006; Sperry and Love, 2015).

During transpiration, water is pulled up from the soil into roots and through xylem conduits in plants (Hodson & Acuff, 2006). Xylem pressure is negative because the water in the xylem is under tension. With limited soil water, the tension in the xylem increases and this can cause air bubbles to enter the xylem vessels (a process called cavitation) thereby increasing the hydraulic resistance and the leaf water potential becomes more negative (Tang and Boyer, 2008).

2.6. Root systems and water uptake

Root systems are often composed of a complex network of individual roots that differ in age, length and functions. Roots initially take the form of thin non-woody fine roots as they grow from their tips. Fine roots are the most absorptive portion of a root system, and have the ability to absorb water and nutrients (McCully, 1999). Fine roots can be enclosed by root hairs that considerably increase the absorptive surface area and in the process improve contact between roots and the soil. Some plants improve water uptake by creating co-operative relations with mycorrhizal fungi, which increases the total absorptive surface area of the root system (Wilson and Jackson, 2006). Roots of woody species have the ability to grow extensively in lateral directions and "scavenge" for water and nutrients in large volumes of the soil. Deep root systems that extend towards the saturated zone make it possible for

plants to access water from permanent water sources at substantial depths (Schenk and Jackson, 2002).

Some plants allow for the movement of water from the tap root into the dry parts of the lateral roots at night. This hydraulic redistribution process is called hydraulic lift (Fig. 2.1a) (Richards and Caldwell, 1987; Dawson, 1993; Caldwell *et al.*, 1998). This night-time transfer of soil water through roots occurs when reduced transpiration allows xylem water potential to surpass water potential in dry soils thereby creating a lateral water potential gradient away from the tree stems. Some studies have reported a reverse process in which water is channelled from the wet soil surface (by lateral roots) to deeper soil layers via the tap root (Fig. 2.1b). This process often occurs under conditions of flooding or very wet top soil and it is called hydraulic descent or downward siphoning (Hultine *et al.*, 2003a).
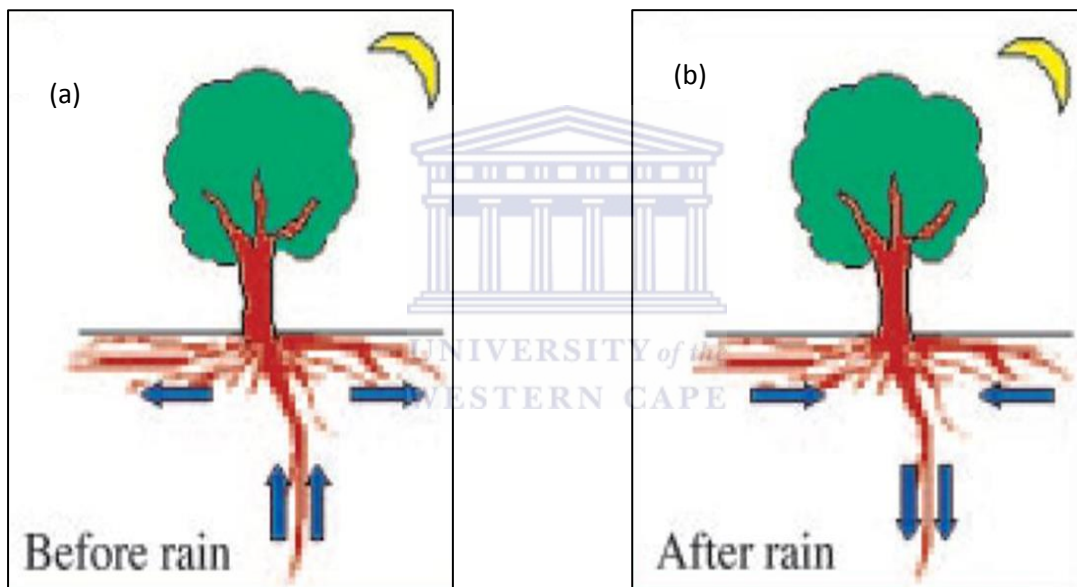
Fig 2.1. Illustrations of the processes of (a) hydraulic lift, and (b) hydraulic descent or downward siphoning in deep rooted trees as influenced by rain. Blue arrows depict the direction of water transport.

Burgess and Adams (1998) used a modification of the heat pulse velocity method to measure sap flow in roots of two different plant species. Their aim was to demonstrate redistribution of soil water from deeper in the profile to dry surface horizons by the root system (i.e. hydraulic lift). However they were not the first ones to observe this phenomenon. It had been previously reported by (Richards and Caldwell, 1987; Dawson, 1993; Horton and Stephen, 1998) in various deep rooted tree species. Even though the phenomenon had been previously reported, they further demonstrated that after the soils were rewetted, water was transported by roots from the surface to deeper soil horizons (i.e. hydraulic descent) (Hultine *et al.*,

2003b). They then suggested that "hydraulic redistribution" of water in tree roots is significant in maintaining root viability, facilitating root growth in dry soils and modifying resource availability.

2.6.1. Significance of hydraulic redistribution

Hydraulic redistribution improves transpiration and plant growth during dry periods by storing water in the dry rhizosphere. This stored water can be accessed by lateral roots during the day (Hultine *et al.*, 2006). This phenomenon may also be beneficial by promoting growth of shallower-rooted species which may take up some of the redistributed water (Dawson, 1993). In regions where droughts occur frequently, hydraulic descent (Hultine *et al.*, 2003a), promotes plant water conservation by channelling the water deeper into the soil column when it is plentiful in near surface soil layers. The water near the soil surface is exposed to evaporation, it is therefore a sensible act to store it underground (Ryel *et al.*, 2004). Hydraulic redistribution plays a role in soil water recharge and storage (Burgess *et al.*, 2001; Ryel *et al.*, 2003) and to increase long-term transpiration by plants (Ryel *et al.*, 2002). The moist upper soil layers also enhance nutrient cycling and eventual uptake by the plants (Dawson, 1993). This in turn promotes survival of seedlings that do not have access to groundwater, and enables microbe-mediated nutrient transformations in the soil, which are more rapid at higher soil water contents (Dawson, 1993). McCulley *et al.* (2004) hypothesized that hydraulic redistribution improves a deep rooted plant's nutrient status by increasing the mobility of deep nutrients, and maintains favourable water status for fungi in the near-surface rhizosphere (Querejeta *et al.*, 2007).

2.7. Prosopis invasions in South Africa

The genus *Prosopis* consists of trees and shrub species that are indigenous to arid and semi-arid regions of North America, South America, Northern Africa and Eastern Asia (Zachariades *et al.*, 2011). *Prosopis* species were introduced in South Africa to provide fodder and shade for livestock. But some have become invasive impacting groundwater and occupying grazing land (Ndhlovu, 2011; Wise *et al.*, 2012). *Prosopis* species occur as large thorny shrubs or trees that can grow up to 10 metres tall (Zachariades *et al.*, 2011). Many *Prosopis* species are phreatophytic and are thus able to utilise both near-surface soil moisture and groundwater at great depths. In regions of extreme aridity where there is little rainfall, *Prosopis* relies predominantly on its deep tap root for survival. The tap roots can extend to great depth (>52 m) where they tap into groundwater (Nilsen *et al.*, 1983). In wetter sites,

where there is frequent wetting of surface soil horizons, *Prosopis* relies on shallow lateral roots and utilize the deep tap roots during drought (Jacoby *et al*., 1982, Ansley *et al*., 1993). In these situations, *Prosopis* is then a facultative phreatophyte switching between soil and groundwater sources.

The ability to overcome water stress endowed by its rooting system has enhanced the competitive success of *Prosopis* in South Africa's semi-arid environments to the detriment of indigenous vegetation (Roberts, 2006). *Prosopis* competes for light, soil moisture and nutrients with indigenous vegetation (Meyer and Bovey, 1986). Such competitive interactions are especially evident in arid to semi-arid areas where competition between woody plants and grass is critical (Jacoby *et al*., 1982). Clearing of *Prosopis* increases the amount and duration of supply of soil moisture (Tiedemann and Klemmedson, 1973). This is because *Prosopis* trees use two to three times more water than natural herbaceous vegetation as noted by Tiedemann and Klemmedson (1973) in studies in the USA. This effect may be felt both beneath the trees and in the open as *Prosopis* roots extend downwards and laterally (Tiedemann and Klemmedson, 1973). Another study by Jacoby *et al*. (1982) observed that soil moisture depletion occurs rapidly near *Prosopis* tree bases both with depth and distance from the tree.
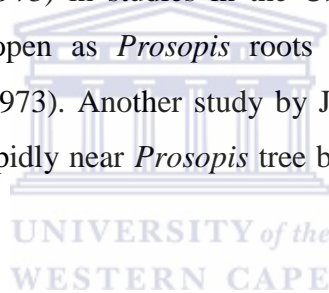
Because of the lack of information on water use by deep rooted invasions in the dry parts of South Africa, *Prosopis* was chosen as the case study for this project as its root system typically extends from 20-30 m under local conditions capable of reaching the groundwater table in most landscapes. Dense impenetrable thickets of *Prosopis* are common in the Northern Cape, Western Cape, Free State and North West provinces of South Africa. Van den Berg (2010) estimated that up to 1.5 million hectares of land had been invaded by *Prosopis* in the Northern Cape Province alone, and an estimated 5 million hectare had been invaded by this species in the whole of South Africa (Versfeld *et al*., 1998) (see Table 1.1).

Prosopis does not invade steadily but rather in episodic bursts (Ndhlovu, 2011).The spread of *Prosopis* is usually associated with years of above-average rainfall, which enhances the chances of rapid plant growth. Seedling recruitment requires this excess rainfall (Poynton, 1988; Wise *et al*., 2012). A rapid spread of *Prosopis* trees reported by Van den Berg (2010) between 2002 and 2007 coincided with above-average rainfall that was recorded during the same period (Wise *et al*., 2012).

Fourie *et al.* (2002) quantified the effects of *Prosopis (sp.)* on groundwater levels in Rugseer River at Kenhardt in the Northern Cape, South Africa. The study (the first of its kind on *Prosopis* in South Africa) aimed at quantifying the actual volumes of water used by *Prosopis.* They collected data on groundwater levels and groundwater quality from eight boreholes at their study site. They also collected rainfall data to examine the effect of surface runoff on groundwater levels. Their results showed that water levels declined during summer (October to March) due to evapotranspiration. They measured declines of between 0.97 m and 1.57 m and found that water levels rose immediately after surface runoff. Fifty percent of the study area was cleared and the effect of post clearing was measured. The water levels followed a declining trend in the summer months but the decline on average was 45% less than it was before clearing. They concluded that a volume of 50 m^3 per month per hectare could be saved by clearing *Prosopis.*

2.8. Method of quantifying plant water use

One way of determining the amount of water that a plant uses is to understand the process of transpiration, because the amount of water required by a plant is equivalent to the amount that the plant loses through transpiration (Schuch & Burger, 1997). The overall amount of transpiration for a crop over an entire growing season is about the same as the seasonal water requirements of plants. More than 99.9% of the water used by plants is drawn through the roots and transpired through the leaves. Only a small amount (about 0.1%) of the water taken up by plants is used to produce plant tissue.

The water that falls on a vegetated surface (gross rainfall) may either reach the ground surface (net rainfall) or be intercepted by the canopy cover and evaporated back to the atmosphere (Cui and Jia, 2014). This process is known as interception and it is dependent on the canopy (storage capacity and roughness) and rainfall (intensity and distribution). The interception of water by trees is mainly high in forests, and this is because of their high aerodynamic roughness (David *et al.*, 2006). Interception can be calculated as the difference between the water that reaches the ground surface (net rainfall) and the water that is intercepted by tree canopy (gross rainfall) (Cui and Jia, 2014).

The most important factors needed to estimate evapotranspiration are the local weather conditions, consisting of solar radiation, temperature, relative humidity and wind speed. In

instances where the soil is able to supply enough water to satisfy the evaporation demand, the evaporation from the soil is determined only by the meteorological conditions. Other important factors include the type of vegetation, deciduousness of the vegetation, vegetation height and roughness, groundcover and crop rooting. Where the evaporating surface is a soil surface, the degree of shading by the vegetation canopy and the amount of water available at the evaporating surface are other factors affecting the process of evapotranspiration.

2.8.1. Estimates of water use based on climate data

The United Nations Food and Agriculture Organization (FAO) adopted the Penman-Monteith method as a global standard for estimating reference evapotranspiration from meteorological data (Allen *et al*., 1998). By definition, reference evapotranspiration (ET_0) is evapotranspiration from a short grass cover that is healthy, not short of water and fully covers the ground (Allen *et al*., 1998). The reference evapotranspiration estimation method uses readily available climate data which can be obtained from a local weather station. The modified Penman-Monteith equation uses standard climatological records of solar radiation, air temperature, humidity and wind speed. To ensure the reliability of computations, the weather measurements are made at 2 m above the reference surface and ET_0 is calculated as:

$$ETo = \frac{0.408\Delta(Rn-G)+\gamma\frac{900}{T+273}u_2(es-ea)}{\Delta+\gamma(1+0.34u_2}\quad\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{ (2.1)}$$

where:

Rn – net radiation at the surface [MJ m^{-2} day^{-1}],

G – soil heat flux [MJ m^{-2} day^{-1}],

T – air temperature at 2 m height [ºC],

$u2$ – wind speed at 2 m height [m s^{-1}],

es – saturation vapour pressure of the air [kPa],

ea – actual vapour pressure of the air [kPa],

es-ea – vapour pressure deficit of the air [kPa],

Δ – slope of the saturation vapour pressure-temperature curve [kPa ºC^{-1}],

γ – psychrometric constant [kPa ºC^{-1}].

The Penman-Monteith model uses a theoretical short green grass reference surface that is vigorously growing and is sufficiently watered with an assumed height of 0.12 m, with a

surface resistance of 70 s/m and an albedo of 0.23 (Allen *et al*., 1998). This approach is commonly considered as the most reliable, in a wide range of climates and locations, because it is based on physical principles and considers the main climatic factors, which affect evapotranspiration.

However, evapotranspiration from natural surfaces differs from that from a reference crop. A correction factor, called the crop coefficient (Kc) is applied to ET_0 to give estimates of actual evapotranspiration under conditions of no water stress (ET) such that:

$$ET = K_c x ET_0 \text{... (2.2)}$$

where:

ET – evapotranspiration

K_c – crop coefficient

ET_0 – reference evapotranspiration
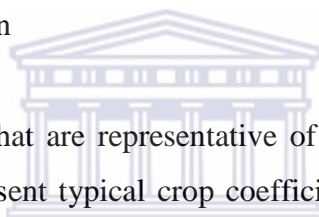
To use this method, Kc values that are representative of the different vegetation types are required. Irmak *et al*. (2013) present typical crop coefficients for riparian vegetation in the USA, but local values are required for vegetation growing under local conditions in South Africa. In situations where the vegetation suffers from water stress e.g. in upland areas, the Kc value must be adjusted for stress e.g. using soil water content information as detailed in Allen *et al*. (1998).

2.8.2. Sap flow methods

Direct transpiration by plants can be measured using sap flow methods. The heat pulse velocity sap flow method is a typical example of a technique that is widely used on woody plant species. This method was discovered by Huber (1932). He came up with the idea of using heat as a tracer of the movement of sap. Huber discovered that when heat was applied for a few seconds (one to two seconds) it was still detectable as a pulse at the intersections of a thermocouple sensor some 30 cm below the heater. He then assumed that the time for the detection of heat at the sensor was the same as the time taken for the sap to move this distance.

Huber later tested his work again, but this time at slower sap speeds. He then recognized the importance of differentiating between the effect of convection by the moving sap and the

transport of heat by thermal conduction. Huber and Schmidt (1937) thus developed an early version of the 'compensation' heat-pulse velocity method in order to separate the two effects. In the 'compensation' heat-pulse velocity method they put one sensor below and the other sensor on top of the heater. The time it took to warm the upstream sensor compared to the time taken to warm the downstream one, was used to 'compensate' for the effects of thermal conduction. They assumed that the speed of the sap was identical with that of the heat pulse.

However the velocity of a heat pulse moving through the xylem of a stem is not the same as the sap velocity. Sap velocity can be measured by sensibly characterising the shape of such a pulse. To get to the actual litres of water transpired by a plant one must first get the sap velocity by correcting for the moisture fraction of the wood, wood density and wounding widths as a result of sensor implantation. The sap velocity is then multiplied by the size of the conducting sap wood area (Burgess *et al*., 2001).

One advantage of the heat pulse velocity technique is that it can be used to measure sap flow in plant stems with insignificant disruption to the sap stream (Swanson and Whitfield, 1981; Cohen *et al*., 1981; Green and Clothier, 1988). The measurements of the heat pulse velocity method are reliable; they have been tested by many authors (Dye *et al*., 1996; Burgess *et al*., 2001; Fernandez *et al*., 2001; Green *et al*., 2003; Romero *et al*., 2012; Mahohoma *et al*., 2013). This method uses technology that is affordable, but provides a good time resolution of sap flow (Dye *et al*., 1996; Burgess *et al*., 2001; Green *et al*., 2003). Sap flow techniques are compatible to automatic data collection and storage. Concurrent measurements on various trees are possible, allowing the estimation of transpiration from whole stands of trees although only a few representative trees are sampled in practice for practical and cost reasons. The heat ratio method of the heat pulse velocity sap flow technique (Burgess *et al*., 2001) has the added advantage of being capable of detecting reverse sap flows and low flows which is critical for quantifying processes like hydraulic redistribution. The one disadvantage of the heat pulse velocity methods is that they cannot be used on non-woody species.

In South Africa for example, the water use by alien and indigenous plants has been quantified in experimental catchments such as the Jonkershoek in the Western Cape Province, and Gilboa situated in Kwazulu-Natal midlands. Dye *et al.* (2001) compared the water use of wattle thickets and indigenous plant communities at riparian sites in the Western Cape and Kwazulu Natal Provinces. For their experiment they used the Bowen ratio energy balance

(BREB) technique to obtain a 12-month record of 20 min evapotranspiration rates from a fynbos riparian plant community in the Jonkershoek valley, and a grassland riparian community on the property Gilboa. In the Western Cape region, mainly in Wellington and Groot Drakenstein areas, established stands of *A. mearnsii* were selected to provide comparative transpiration data. The compensation heat pulse velocity (HPV) technique was used to record the flow of sap at hourly intervals in six sampled trees representing the range of stem sizes at both wattle sites. Total diurnal sap flow in all sampled trees with sufficient soil water availability was strongly correlated to the size of the trees and an index defined as the product of mean daily vapour pressure deficit (VPD) of the air and the number of daylight hours. To predict the water use of wattle thickets these relationships were used, using VPD and day-length data recorded at both sites. Published estimates of canopy rainfall interception were added to the sap flow (transpiration) component to yield a combined annual ET to compare to the BREB ET data. Table 2.3 summarises the annual evapotranspiration at each site.

Table 2.3 A summary of annual evapotranspiration differences among the study sites (Dye *et al*., 2001).

Locality	Vegetation	Annual evapotranspiration estimate (mm/year)			
		Transpiration	Rainfall interception	ET	Difference relative to baseline
Jonkershoek	*A.mearnsii*	1318	185	1503	171
	Fynbos			1332	
Gilboa	*A. mearnsii*	1077	183	1260	424
	Grassland			836	

From the results in Table 2.3 they concluded that the removal of riparian wattle and its replacement by indigenous herbaceous plants may indeed result in significant reductions in annual ET, and could very likely lead to stream flow enhancement. This would impact positively on the availability of water in catchments, and improve the lives of the people who use the water. However, their study has clearly shown that annual ET varies significantly in different riparian plant communities, and that the structural and physiological characteristics of both the pre-clearing and post-clearing vegetation must be considered in order to predict the net change in ET. Their conclusion supports an earlier view by Versfeld *et al*., (1998) which specified that there is a requirement for an improved methodology of general applicability to enhance the accuracy of water use predictions for a wide range of alien and

indigenous plant communities. Such predictions are important to prioritise clearing operations in areas invaded by alien trees.

2.9. Determining plant water sources

Trees use multiple sources of water and not all the transpired water comes from groundwater. At the same time, different sources of water used by plants e.g. rainwater, soil water, stream water or groundwater have unique isotopic signatures and stable isotopes remain unchanged once taken up by plants. This allows the sources of the water transpired by the plants to be determined by matching the isotope signatures of the xylem water with that of the water sources (Schachtschneider and February, 2010). Studying hydrogen and oxygen stable isotope ratios of water within plants can provide information on the water sources that the plants have used (Ehleringer and Dawson, 1992) as water is not isotopically fractionated when taken up by the plant (Thorburn and Walker, 1994). During water transport between the roots and shoots, the isotopic composition of xylem water remains unaltered until it reaches tissues undergoing water loss, where evaporative enrichment in the heavier isotope of hydrogen and oxygen takes place.

The method to determine the stable isotope ratio of a plant's water source using the plant's transpired water has been used as an alternative to standard xylem extraction methods (Schachtschneider and February, 2010). Differences in the use of summer rain by arid land species and limited use of stream water by mature riparian trees are two examples of how stable isotope studies have improved the understanding of plant water relations and plant water sources (Ehleringer, 2006). Analysing the sap flowing on the xylem can provide both short term and long term data on plant water use patterns (Ehleringer *et al*., 2000).

The primary sites of evaporation enrichment are plant leaves. However the magnitude of the enrichment is dependent on humidity gradients, transpiration rate and the isotopic composition of atmospheric water (Schachtschneider and February, 2010). If the hydrogen or oxygen isotopic composition of water within the xylem sap is analysed before any exposure to evaporative processes, this isotopic composition is a combined measure of overall water uptake reflecting the various zones and depths from which the plant is currently extracting soil water (Schachtschneider and February, 2010). The stable isotopic analyses of source and xylem sap water provide a powerful tool for improving the understanding of the extent of active rooting zones and water uptake processes. An understanding such as this can provide

awareness about the role that water plays in influencing ecological and physiological processes.

There are often large inclines in isotopic composition of water within plant communities. Analysing stable isotopes in water along such gradients makes it easy to conclude which water source is currently exploited by plants (Ehleringer *et al*., 2000). In order for the analysis to be a success a small quantity of water is needed, this makes it efficiently non-destructive.

During a rainfall event, the precipitation that falls is enriched in the heavier isotopes of both hydrogen and oxygen when compared to snow. This is predominantly because of the differences in the vapour pressures of heavier and lighter water (Ehleringer *et al*., 2006). This leads to marked differences between the isotopic composition of precipitation falling in summer and winter and across latitudinal and elevational gradients.

2.10. Chapter summary

This chapter has summarized the extent of the problems of invasive alien plants in South Africa. Previous studies have suggested that invasive alien plants use more water than indigenous species. However, there is inadequate knowledge about the exact volumes of water used compared to indigenous plants especially deep rooted species in catchments in the driest parts of South Africa.

CHAPTER 3: Materials and Methods

3.1. Introduction

This chapter presents the data collection methods used in the study. The selection criteria for the study site are also outlined. A description of the location of the study site, microclimate and vegetation characteristics is also given. The approach to the study included detailed measurements and analysis of transpiration rates, the dynamics of soil water content and weather elements. Transpiration was measured using the heat pulse velocity sap flow method, while the volumetric soil water content was monitored at several depths down the soil profile using automated capacitance soil water content sensors. Weather data was collected using an automatic weather station. Oxygen and hydrogen stable isotopes of plant, soil and groundwater samples were analysed to determine the source of water transpired by the trees.

3.2. Site requirements

To address the objectives of this study as set out in Chapter 1, a suitable study site was needed. The selection criteria of the study site involved finding:

(a) A site where there are dense *Prosopis* invasions and co-occurring indigenous plants that have deep root systems.

(b) A site with boreholes where the water levels could be monitored.

(c) A site where there is adequate security for equipment.

(d) A site that is close to a groundwater dependent community.

3.2.1. Description of the study site

A site that closely met this selection criteria was identified in the Northern Cape Province of South Africa (Fig. 3.1a). The study was conducted at Brandkop farm (S31.23254°; E019.20284°; 390.5 m asl) (Fig. 3.2). This farm is situated on the Bokkeveld plateau about 22 km to the northwest of the town of Nieuwoudtville. Brandkop farm is located on the floodplain of the Doorn River upstream of its confluence with the Hantam River (Fig. 3.2). The floodplain is broad and flat with numerous braided channels and has been significantly modified by cultivated lands and irrigation furrows which link both the Doorn and Hantam Rivers. The monitored site is approximately 3 hectares; the mean annual rainfall in the vicinity of the study site is about 150 mm/year with a coefficient of variation of about 32% and a mean annual potential evapotranspiration of more than 2600 mm/year (Mucina and Rutherford, 2006). The rainfall is strongly seasonal with the peak occurring in June and July and very little or no rainfall from December to February. The mean annual temperature is 15-

17°C with maximum temperatures in summer being greater than 40°C in January-February and minimum temperatures in June-July of <1°C with occasional frosts, especially after snowfalls on the escarpment to the west and Hantam mountains to the east.
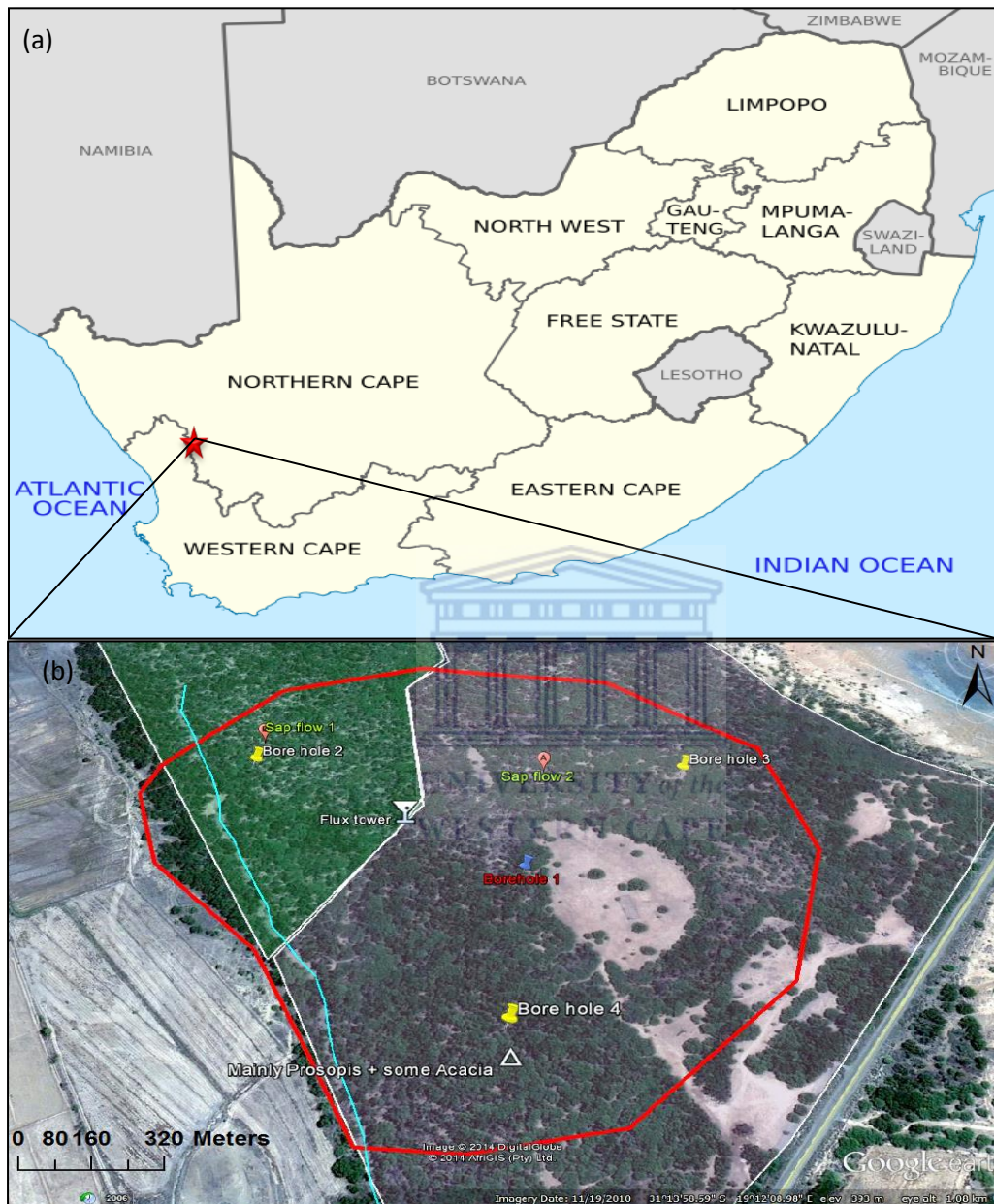
Fig. 3.1 (a) A map of South Africa showing the location of Nieuwoudtville (denoted by the red star) in the Northern Cape Province; (b) A Google Earth image of the study site at Brandkop farm showing the location of the equipment installed and the river that runs through the farm.

The vegetation is dominated by stands of *Acacia karroo (A. karroo)* which are steadily being replaced by *Prosopis* species which were introduced to the farm in the mid-20th century. Parts of the riparian vegetation are dominated by *Prosopis* but along the main channel of the Doorn

River, there are still stands of nearly pure *A. karroo* (Fig. 3.1b). *Prosopis* invasions extend onto the drier parts of the floodplain and the adjacent dryland areas. Much of the invasion is on lands previously flood irrigated for growing wheat when there was sufficient rainfall in the catchment.

The geology of the Olifants-Doorn Water Management Area is dominated by metamorphic rocks. These metamorphic rocks belong to the Nama Group in the north and sedimentary rocks of the Cape Supergroup in the southern and south-western parts. The rocks of the pre-Cape Van Rhynsdorp Group, and the sedimentary rocks of the lower karoo Supergroup are dominant in the northern and north-eastern parts. The intrusive karoo dolerites are also dominant is some parts of the area. The *Prosopis* invasions at Brandkop farm occur in an area underlain by quaternary sediments, which in turn is underlain by shales and siltstones of the Van Rhynsdorp Group (Fig. 3.2).

Fig. 3.2 The town of Nieuwoudtville, the location of Brandkop farm, the boreholes, rivers, catchments and geology of the study site (CGS, 1997).

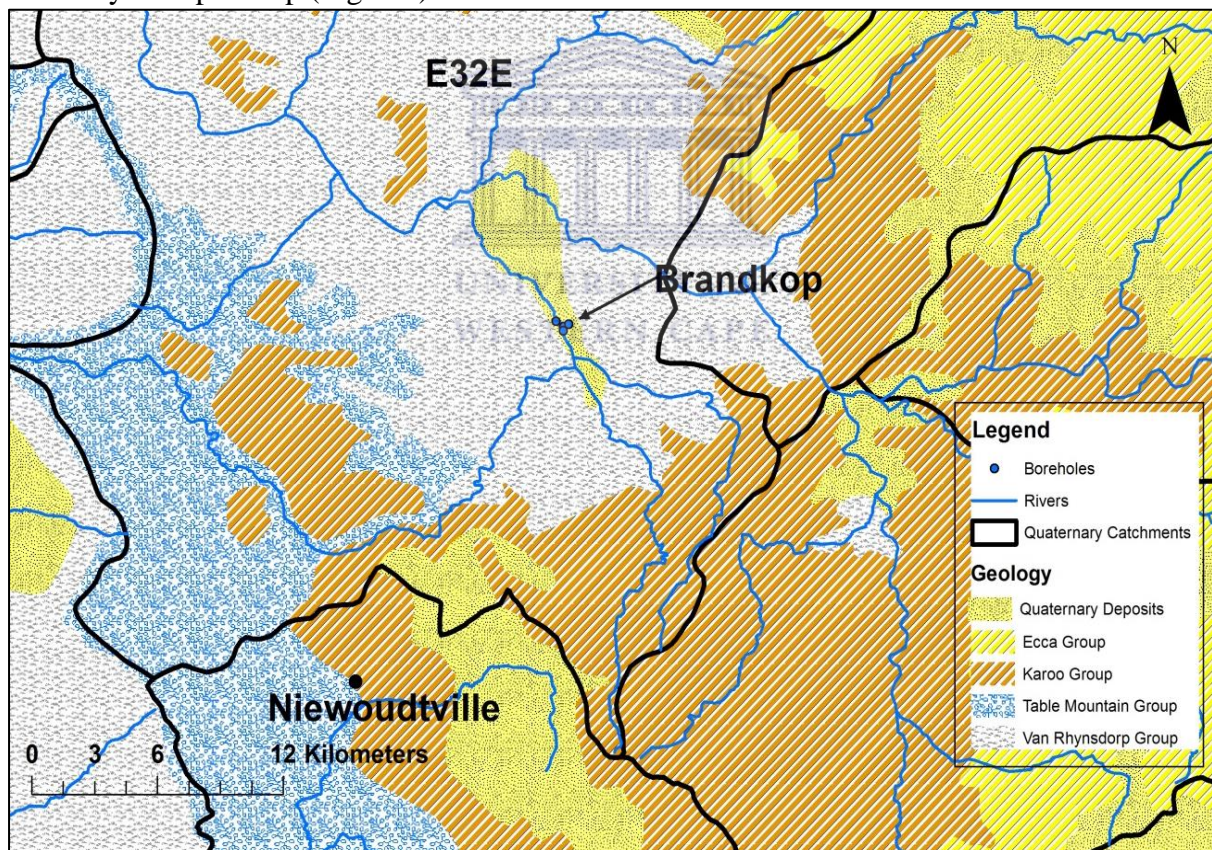The dominant dryland vegetation is a succulent karoo shrubland known as Hantam karoo, dominated by a mixture of succulent-leaved and non-succulent leaved shrubs (Mucina and

25

Rutherford, 2006). The natural floodplain vegetation is called Namaqualand Riviere and is a complex mixture of shrublands and tussock gramioids (grass-like plants) with patches dominated by *Acacia karroo* and *Tamarix usneoides*. The soils are typically fine, clayey and saline, with the salinity varying from low to quite high depending on the degree of leaching.

A. karroo is an important riparian tree species which provides nesting sites for bird and a habitat for a range of other fauna. It is a weedy, pioneer species and can form dense stands which open out through self-thinning as it ages. *A. karroo* has a lifespan of about 30-40 years (Barnes *et al*., 1996). Stands dominated by *Prosopis* become very dense, suppressing or displacing other species and unsuitable for many animal species (Steenkamp and Chown, 1996; Dean *et al*., 2002). The *A. karroo* and *Prosopis* trees in the study site range in height from about 2 m to 10 m tall with many young plants mainly of the *Prosopis* species on the forest floor. Grasses mainly *Stipagrostis* spp also sprout in open spaces between the trees after substantial rains. *Prosopis* water use is believed to be higher than that of the indigenous species, including *A. karroo* (Wise *et a*l., 2012). This is the hypothesis tested in this study.

A. karroo (Fig. 3.3a) is one of the fastest-growing *acacia*s, and produces high-density wood (800-890 kg/m³).This tree grows up to 12 m high and is indigenous to South Africa. It has paired thorns, usually up to 100 mm long and occasionally as long as 250 mm (Table 3.1). These thorns protect the plant from predators. *A. karroo* trees grow in many different soil, climatic and altitude conditions. The limiting factors to their growth include intense cold and lack of moisture (Barnes *et al*., 1996). *Acacia* trees have waxy leaves that reduce water loss and a long tap root system allowing them to reach groundwater. *A. karroo* grows on deep, blackish nutrient-rich clay soils, and not on sand, and because of this association it is regarded as an indicator of good agricultural soils and rangeland (Schenk and Jackson, 2002). In the early days of colonisation in South Africa, *A. karroo* was used for fuel, fodder and shade, and for the construction of wagon wheels, poles and rural implements (Schenk and Jackson, 2002).

Prosopis (Fig. 3.3b) grows in arid to semi-arid environments including deserts, open woodlands, grasslands, shrublands and floodplains. Being frost tolerant, it thrives under very low (-12 °C) and high (40 °C) temperatures, and survives in areas with very low precipitation (Barnes *et al*., 1996). *Prosopis* is mostly found in sandy and even poor saline or alkaline

soils, and has deep rooted species (up to 30 m or more), that often reach water tables. This allows them to grow and fruit even in the driest of years (Van den Berg, 2010).

Table 3.1 Typical characteristics of *A. karroo* and *Prosopis (spp)* trees (Stuart-Hill and Tainton, 1989), (Barnes *et al.*, 1996), (Ndhlovu, 2011).

A. karroo	*Prosopis* (spp)
Stem 0.5 m or taller	Branches from surface with zig-zag stem
Thorns can reach 250 mm	Thorns can reach 75 mm
Average height of 12 m	Average height of 6 m
Bark becomes rougher with age	Smooth bark
Usually single stemmed	Usually multi stemmed
Fern-like leaves, paired (3-10 pairs of each point along the stem)	Fern-like leaves, paired (1-3 pairs, often with gap between leaves)
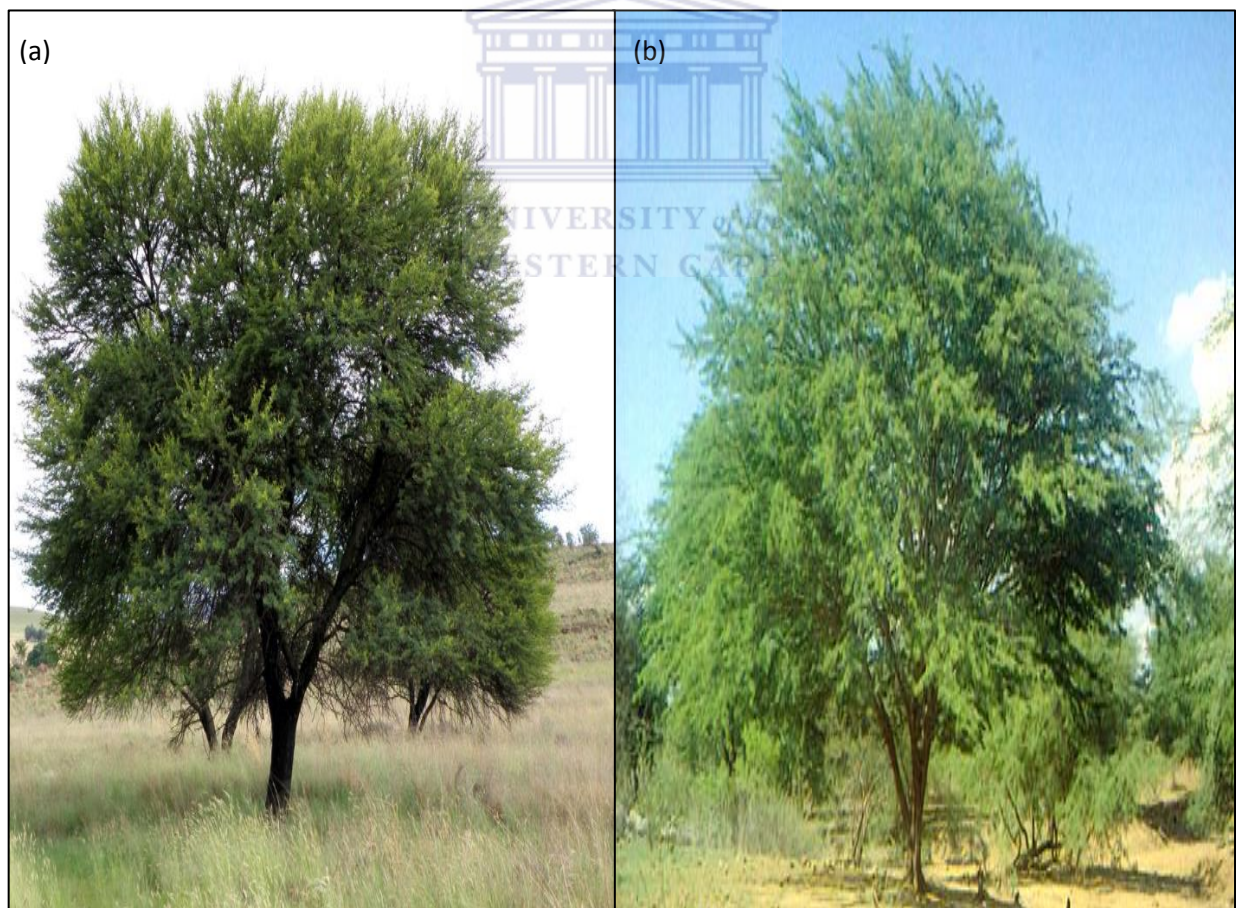
Fig. 3.3 (a) *A. karroo* tree and; (b) *Prosopis* tree.

3.3. Monitoring meteorological elements

The microclimate at the study site was monitored using an automatic weather station (Fig. 3.4) which was installed in the farmer's yard about 1.5 km from the study site. The equipment comprised a pyranometer (Model SP 212 Epogee Instruments, Inc., Logan UT, USA) for measuring the solar irradiance. This was installed on a horizontal levelling fixture mounted on a north facing cross bar to avoid self-shading by the equipment. Air temperature and relative humidity were measured using a temperature and humidity probe (Model CS500, Vaisala, Finland) installed at a height of about 1.6 m above the ground. A wind sentry (Model 03001, R.M. Young; Campbell Scientific, Inc., Logan UT, USA) was used to measure the wind speed and direction at 2.0 meters height, while rainfall was monitored using a tipping bucket rain gauge (Model TE525-L; Campbell Scientific, Inc., Logan UT, USA) mounted at 1.2 m above the ground (Fig.3.4). All the sensors were connected to a data logger (Model CR1000 Campbell Scientific, Inc., Logan UT, USA) programmed with a scan interval of 10 seconds and recorded measurements at hourly and daily intervals, respectively.

Fig. 3.4. An automatic weather station monitoring the microclimate of the study area.

The modified Penman-Monteith equation (Equation 2.1) that uses standard climatological records of solar radiation, air temperature, humidity and 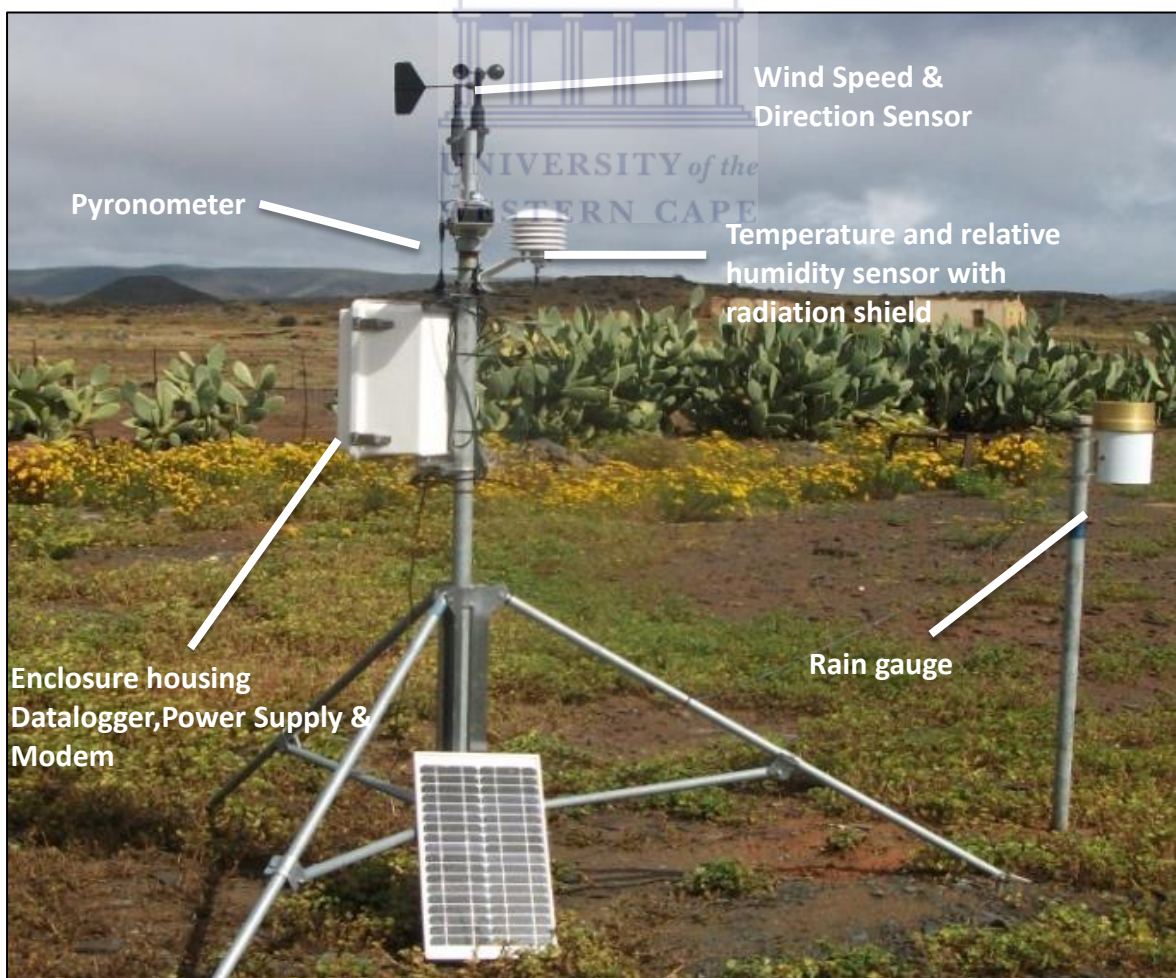wind speed was used to calculate the reference evapotranspiration from the weather elements collected by the weather station (Fig. 3.4). The Penman-Monteith model uses a hypothetical green grass reference surface that is actively growing and is adequately watered with an assumed height of 0.12m, with a surface resistance of 70 s m^{-1} and an albedo of 0.23 (Allen *et al.*, 1998) which closely resembles evapotranspiration from an extensive surface of green grass cover of uniform height, completely shading the ground and with no water shortage. The study site closely met these reference conditions.

3.4. Monitoring the soil water status

Knowing the water content in the soil can assist in finding out how much water is available in the soil for plants to use (Bilskie, 2005) and in the determination of the water balance of the study site. Soil water content was measured at three different depths down the soil profile (0.25 m, 0.5 m, 1.0 m) using three capacitance probes (Model CS616: Campbell Sci. Inc., UT., USA) (Fig. 3.5) next to the sap flow instrumented *Prosopis* and *A. karroo* trees (section 3.5). Most of the lateral roots were concentrated in the top 0 − 0.6 m depth (Fig. 3.5) with a prominent thick tap root extending vertically into the deeper soil layers.

Fig. 3.5 Soil profile pit showing soil sensors monitoring the volumetric soil water content at different depths down the soil profile.

3.5. Monitoring plant water uptake

To quantify the amount of water used by the plants, the heat ratio method of the heat pulse velocity (HPV) sap flow technique was used on both *Prosopis* and the co-occurring indigenous *A. karroo* trees. Standard procedures for HPV sap flow equipment installations were adopted from Burgess *et al.* (2001) and Davis *et al.* (2012).

The selection criteria for the instrumented trees involved first conducting a stem diameter survey on twenty five trees of each species. Stem diameters were measured at approximately 15 cm for *Prosopis* and about 50 cm for the *A. karroo* above the ground just before the main branches. Surveying the stem sizes at breast height was not possible because of the low branching nature of both species. The stem diameters were then categorized into three size classes namely the small (0 – 10 cm), medium (11 – 20 cm) and large (> 21 cm). Trees whose stem diameters were close to the median stem sizes in each diameter class were selected and instrumented taking into account practical limitations such as the heater and thermocouple cable lengths. The sap flow sensors were installed on the branches of two trees of each species (Fig. 3.6) so that the whole tree sap flows were calculated as the sum of the branch sap flows. To establish the mechanisms by which the trees take up water, a pair of sap flow sensors was installed on the tap root and another pair on the lateral roots of one tree per species (Fig. 3.6). The HPV sensors were installed at depths ranging from 8-20 mm from the bark for *Prosopis* which had a thinner sap wood area, and from 10-50 cm on *A. karroo* which had a thicker sap wood area. Data was collected at hourly intervals for one year from 2 August 2013 to 2 August 2014.
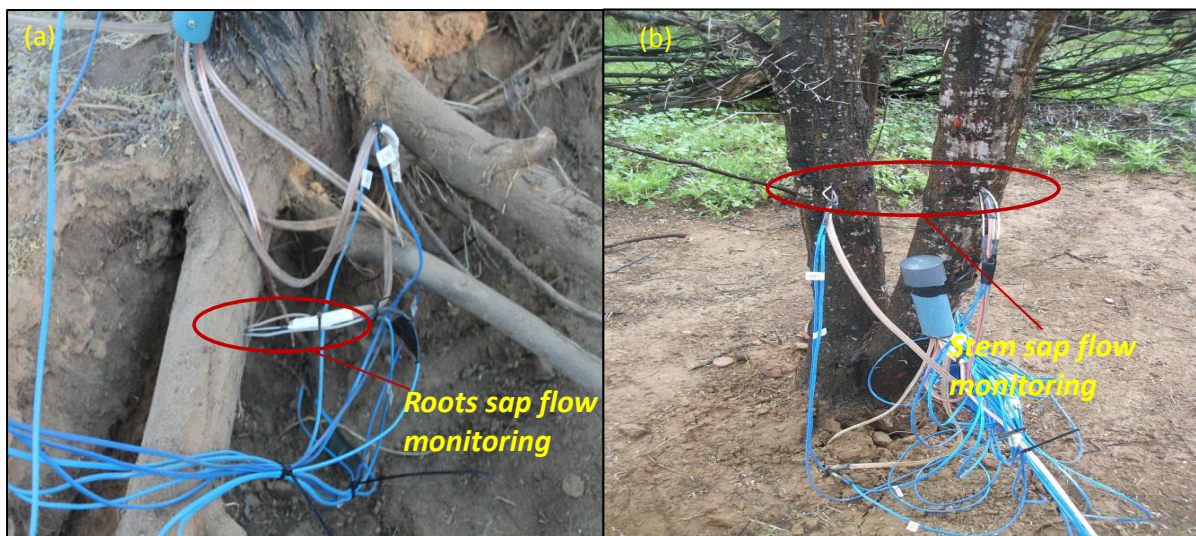

Fig. 3.6 (a) Sap flow sensors installed in roots measuring the root sap flow (b) Sap flow sensors installed on the stem measuring the stem sap flow.

Installation of the sap flow sensors on roots was achieved by carefully excavating the soil around half of the main stem taking care to minimize damage to the roots (Fig. 3.6a). Once the sensors were installed, the soil was put back into the pit and compacted, taking care not to damage the sensors (Fig. 3.6b).

The lateral roots of *Prosopis* trees tended to run parallel to the soil surface at approximately 90^0 angle from the stem and they were located closer to the surface (Fig. 3.7a). Those of *A. karroo* on the other hand were at an angle much steeper than 90^0 to the stem and running downwards into the soil (Fig. 3.7 b).

Fig. 3.7 *Difference between the lateral roots of (a) Prosopis and (b) A.karroo tree.*

The two HPV systems that were installed each comprised a CR1000 data logger, a multiplexer (Model AM16/32B; Campbell Scientific, Inc., Logan UT, USA), a custom made relay control module, a 70 Ah battery, 12 heater probes and 24 copper-constantan thermocouples. All this equipment was stored in two strong metal boxes placed at different locations in the invaded area for security reasons.

To estimate the sapwood depth of the instrumented trees, allometric relationships were developed between the bark to bark cross sectional areas and related to the sapwood areas of the stems, branches and roots of the trees. This was necessary given that the measurements

are still ongoing and the instrumented trees will only be felled at the end of the study. To develop the allometric relations, nine *Prosopis* and four *A. karroo* trees in the size classes representative of the instrumented trees were cut down. The stems were then cut at approximately 15 cm above the ground. The tap roots were partially excavated and also excised about 15 cm below the base of the stem (Fig. 3.8a) where the tap root sap flow sensors are installed. Sap flow sensors on the branches were located approximately 75 cm from the branching point on the main stem, and the branches of the cut trees were also removed at this location (Fig. 3.8b).
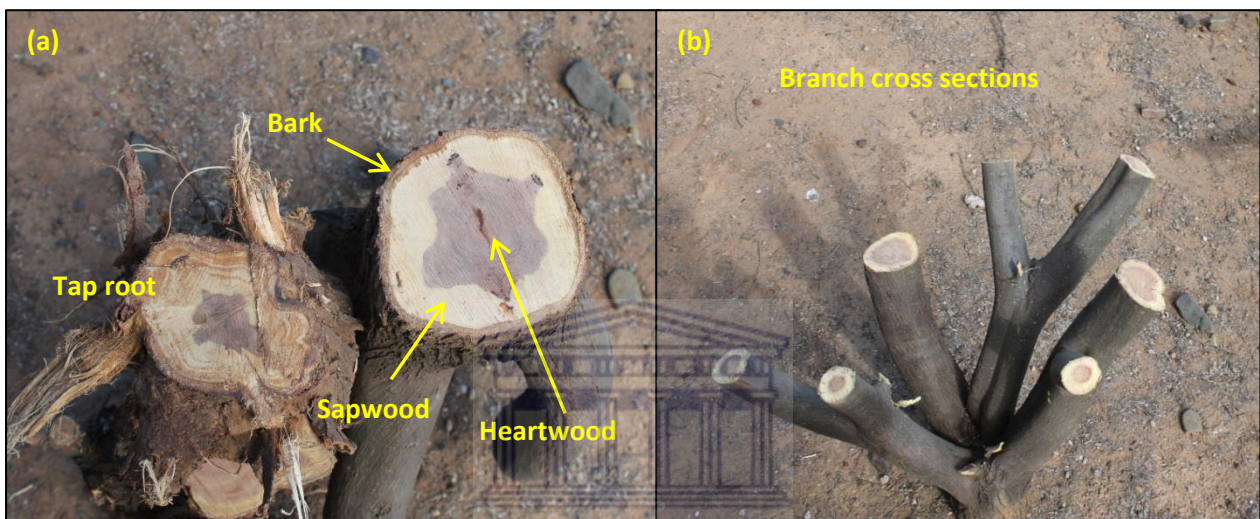
Fig. 3.8 (a) Typical cross sectional areas of the tap root and stems, and (b) the branch of felled *Prosopis* trees.

Similar samples were prepared for *A. karroo*. The heartwood-sapwood boundary was clearly visually distinguishable for *Prosopis* (Fig. 3.8) but not for A. karroo. Methylene blue dye was injected into the stem of *A. karroo* to determine the fraction of the conducting sap wood area. The leaf area index of the plants was measured using the leaf area meter (Model LAI-2000 Plant Canopy Analyzer, Li-Cor, Lincoln, USA) as described by Jonckheere (2003). Leaf area index (*LAI*) is the total one-sided area of leaf tissue per unit ground surface area (Breda, 2003).

3.6 Allometric relations of A. karroo and Prosopis (sp)

The sapwood area and the bark-to-bark cross sectional area of both the stem and branches of *Prosopis* at the study site are related by quadratic functions (Fig. 3.9a and b). A similar relationship was derived by Dzikiti *et al.* (2013b) for the stem section of *Prosopis* in a study conducted near the town of Kenhardt in the Northern Cape.
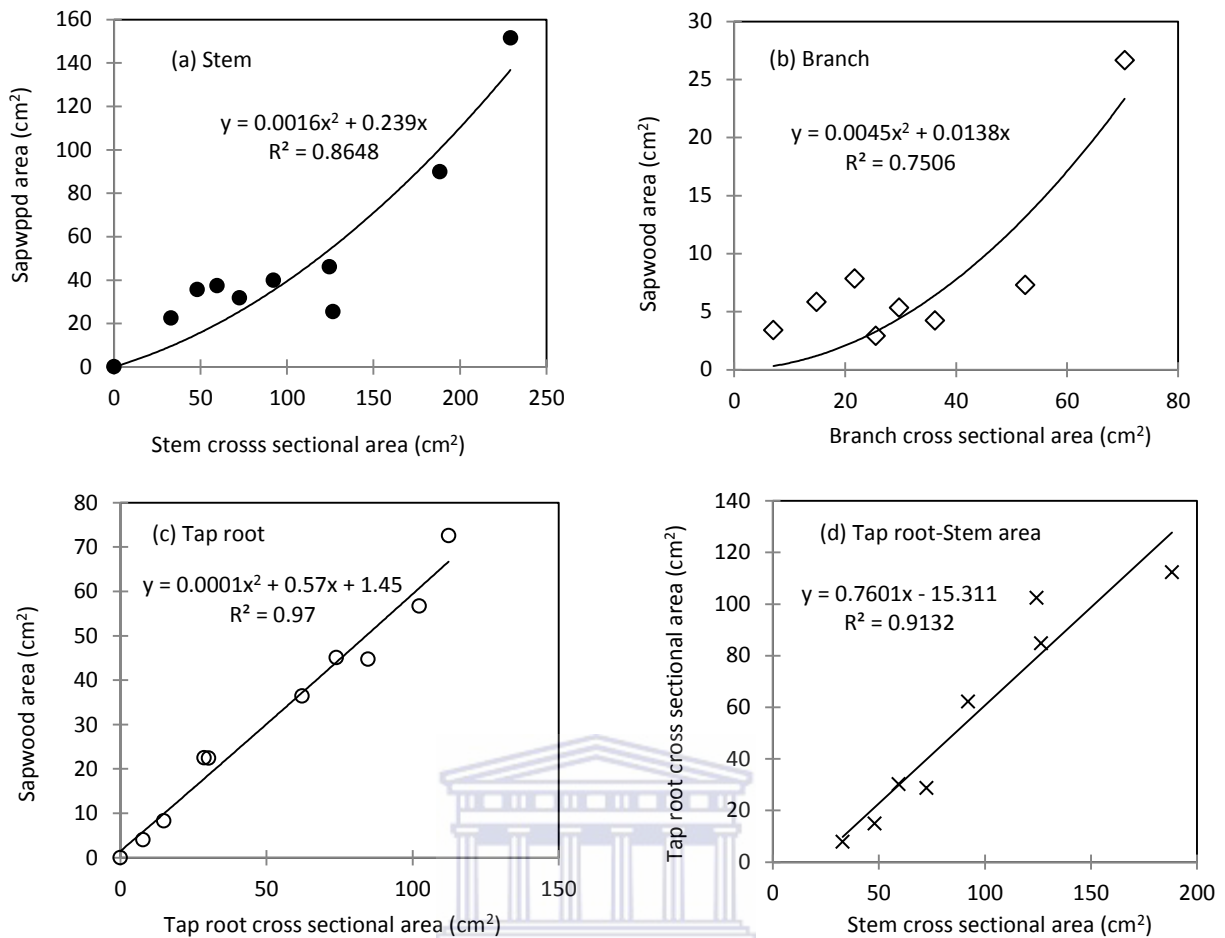
Fig. 3.9. Allometric relationships between the size of the conducting sap wood area and (a) stem cross sectional area, (b) branch cross sectional area and (c) tap root cross sectional area for *Prosopis*. Graph (d) shows the taproot to stem cross sectional area relationship.

The fraction of sapwood as a proportion of the total area for the stem, branch and taproot of a *Prosopis* tree are presented in Fig. 3.10. The sapwood to heartwood ratio of *Prosopis* is largest in the roots and smallest in the branches. The sapwood area accounted for a maximum of 40% of the branch cross sectional area, 65% of the stem cross sectional area, and up to 80% for the tap root cross sectional area. This pattern implies that the hydraulic conductance is highest in the roots followed by the stems and lastly the branches. This suggests that for *Prosopis*, the roots are therefore efficient in facilitating water transport compared to the above ground organs (stems and branches).

However, the sapwood – tap root cross sectional area relationship for *Prosopis* (Fig. 3.9c) on the other hand is quite linear with a high coefficient of determination ($R^2=0.97$). Similarly the tap root cross sectional area at 15 cm below the ground is also linearly related to the stem cross sectional area 15 cm above the ground (Fig. 3.9d).

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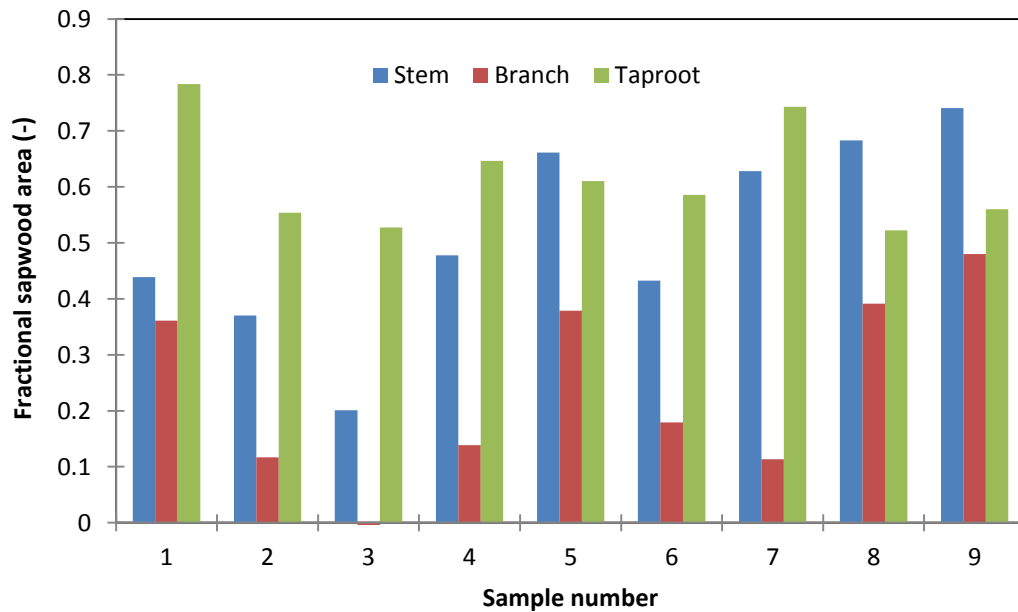
Fig. 3.10. Sapwood as a fraction of the stem area for the tap root, stem and branches of *Prosopis* trees.

The allometric relations for *A. karroo* showed strongly linear relationships between the sapwood and the stem cross sectional area (Fig. 3.11a) and the tap root cross sectional area (Fig. 3.11b). Nine *Prosopis* and Four *A. karroo* trees were cut for this experiment. The fewer number of *A. karoo* trees that were cut was due to environmental considerations.
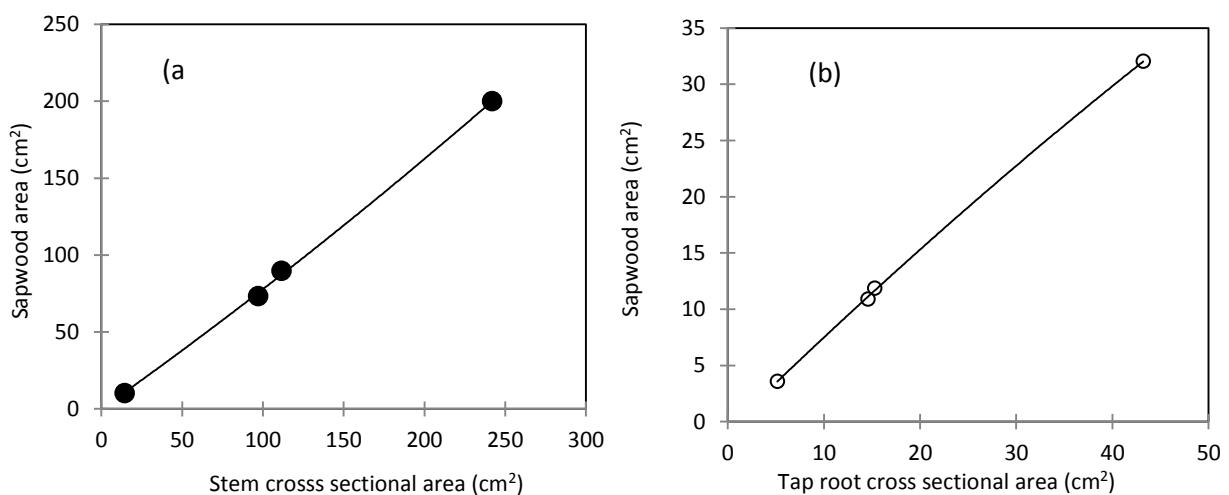
Fig. 3.11 Allometric relations for *A. karroo* where (a) shows the sapwood area- stem cross sectional area relationship, and (b) sap wood area – tap root cross sectional area relationship.

Average tree density, determined from tree counts in four 20 m x 20 m quadrants located in different parts of the forest was 613 trees per hectare for *Prosopis* and 100 trees per hectare for *A. karroo* (Table 3.2).

Table 3.2 Estimation of tree densities at the study site.

|	Trees per 400m^2			Tree density		Trees per hectare	
Quadrant (20 m x 20 m)	Number of *Prosopis* trees	Number of *A. karroo* trees	Total number of trees	*Prosopis* tree density (trees/m^2)	*A. karroo* tree density (trees/m^2)	Number of *Prosopis* trees per hectare	Number of *A. karroo* trees per hectare
1st	17	3	20	0.0425	0.0075	425	75
2nd	16	0	16	0.0400	0.0000	400	0
3rd	44	2	46	0.1100	0.0050	1100	50
4th	21	11	32	0.0525	0.0275	525	275
Average number of trees per hectare						613	100

Actual water use by the invasions and the indigenous trees was calculated from the HPV data using the approach described by Burgess *et al.* (2001). First the raw heat pulse velocity data was corrected for wounding according to the method by Swanson and Whitfield (1981). Then the wood density and the moisture fraction were also taken into account to derive the sap flux density (Burgess *et al.*, 2001). The product of the mean sap flux density and the estimated size of the conducting sap wood area (from allometric equations) was calculated to derive the sap flow in litres per hour for each species. To scale up the transpiration by each species to the stand level (in mm/d), a stand level equaling one hectare, a weighted sum of the daily total sap flow (in m^3) by trees in the different stem size classes per hectare was used. The weighting functions were the proportion of trees of a given stem size as a fraction of the total number of trees of that species per hectare using the tree density information in Table 3.2.

3.7. *Determining the sources of water used by the trees*

To determine the extent to which the plant species depend on either soil or groundwater; soil, groundwater, rainwater samples and non-photosynthesizing twigs from both *Prosopis* and *A. karroo* trees were collected. The winter data provided baseline information on plant water sources outside the active water uptake periods. Two rainwater and one groundwater samples were collected for oxygen and hydrogen isotope analysis. Rainwater samples were collected using a container with a silicon oil layer at the top to minimize evaporation. Groundwater

samples were obtained from a borehole after pumping for at least 30 minutes. The water from the borehole was purged in order to remove the stagnant water. Rainwater and groundwater samples were stored in glass vials, sealed and refrigerated.

Hand augured soil samples were collected at depths of 0 – 50, 50 – 100 and 100 – 160 cm. To minimise evaporation, the soil samples were stored in two individually secured air tight polythene bags per sample and frozen. Six twig samples were collected from trees adjacent to the instrumented trees; 6 *Prosopis* and 6 *A. karroo* twigs for measurements of the plants' xylem water isotopic signature. The twig samples were collected before sunrise when the tissues were still fully hydrated. The samples were placed into borosilicate tubes (Kimax − Kimble, New Jersey, USA) and frozen for later insertion into a cryogenic vacuum extraction line to separate the water for isotope analysis (Sharp *et al.*, 2001). All extracted tree xylem, soil, rain and groundwater samples were processed at the University of Cape Town Archaeology laboratory.

A ten gram sample of the soil was transferred into borosilicate tubes in order to extract the water for oxygen and hydrogen isotope analysis (Sharp *et al.*, 2001). A variation of the zinc closed tube reduction method was used to determine ^{2}H/H ratios (Coleman *et al.*, 1982), while ^{18}O/^{16}O were obtained using the CO_2 method of Socki *et al.* (1992). Isotopic ratios of both ^{2}H/H in H_2 and ^{18}O/^{16}O in CO_2 were determined using a Thermo Delta Plus XP Mass Spectrometer (Hamburg, Germany). Internal standards were run to calibrate results in accordance to the Standard Mean Ocean Water (V-SMOW) and to correct for reference gas drift. The deviation from V-SMOW is denoted by the term δ and results are expressed as parts per mil (‰) through the equation:

$$\delta xxE = [\ (R_{sample}/R_{standard}) - 1] \times 1000 \ldots \ldots (3.1)$$

where δxxE is the respective element (^{2}H, ^{18}O), xx is the mass of the heavier isotope in the abundance ratio, and R_{sample} and $R_{standard}$ are the ratios of the heavy to light isotope of sample and standard, respectively (Dawson *et al.*, 2002). The analytical uncertainty is approximately 2 ‰ for δ^{2}H and 0.2 ‰ for δ^{18}O.

3.8. Chapter summary

A suitable study site was identified at Brandkop farm near Nieuwoudtville town in the Northern Cape Province. Transpiration and root water uptake patterns were measured for *Prosopis* and *A. karroo* trees. Transpiration was measured using the heat pulse velocity sap flow method while the volumetric soil water content was monitored at several depths down the soil profile using automated CS616 soil water content sensors. Weather data was collected using an automatic weather station. Oxygen and Hydrogen stable isotopes of plant, soil and groundwater samples were analysed to determine the source of water used by the trees.

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CHAPTER 4: Results and Discussion

4.1. Introduction

This chapter presents the results obtained in this study. The first set of information presented is on the microclimate of the study site. The second set of results are in support of the first objective which is to establish whether the water use differs between an alien invasive tree species (*Prosopis*) and an indigenous tree species (*A. karroo*). The third set of results address the second objective, which is to identify the sources of the water used by these two tree species. The last set of results shows the impacts of the water use on groundwater levels.

4.2. Site microclimate

The prevailing climate at the study site is known as a local steppe climate which is classified according to Köppen and Geiger as BSk which is characterized by hot and dry (often exceptionally hot) summers (Mucina and Rutherford, 2006). In this study daily total irradiance varied from less than 8.0 MJ/m^2/d in winter (July 2014) to a peak of more than 33.0 MJ/m^2/d during summer (late December 2013) as shown in Fig. 4.1a. More than 50% of the days were cloudless. The annual average temperature (August 2013 - August 2014) at Brandkop was 18.7 °C. A maximum air temperature of 43.9 °C was recorded in January 2014 while the minimum temperature was -4.8 °C in July 2014 (Fig. 4.1b). Maximum air temperature exceeded 40 °C during five months of the year (November - April) (Table 4.1). Day time relative humidity tended to be low on most days with values as low as 5% being common. Consequently, the vapour pressure deficit of the air was very high with peak values exceeding 8.0 kPa during warm dry days (Fig. 4.1c).

The study area is located at the boundary of the summer and winter rainfall regions of South Africa. For this reason the area received small amounts of rainfall throughout the year (Fig. 4.1d) but with more than 70% of the rain falling in winter. Daily total reference evapotranspiration (ET$_0$) was very high in summer reaching close to 10 mm/d during some days in the December - January period (Fig. 4.1d). The atmospheric evaporative demand was therefore exceptionally high at this site.
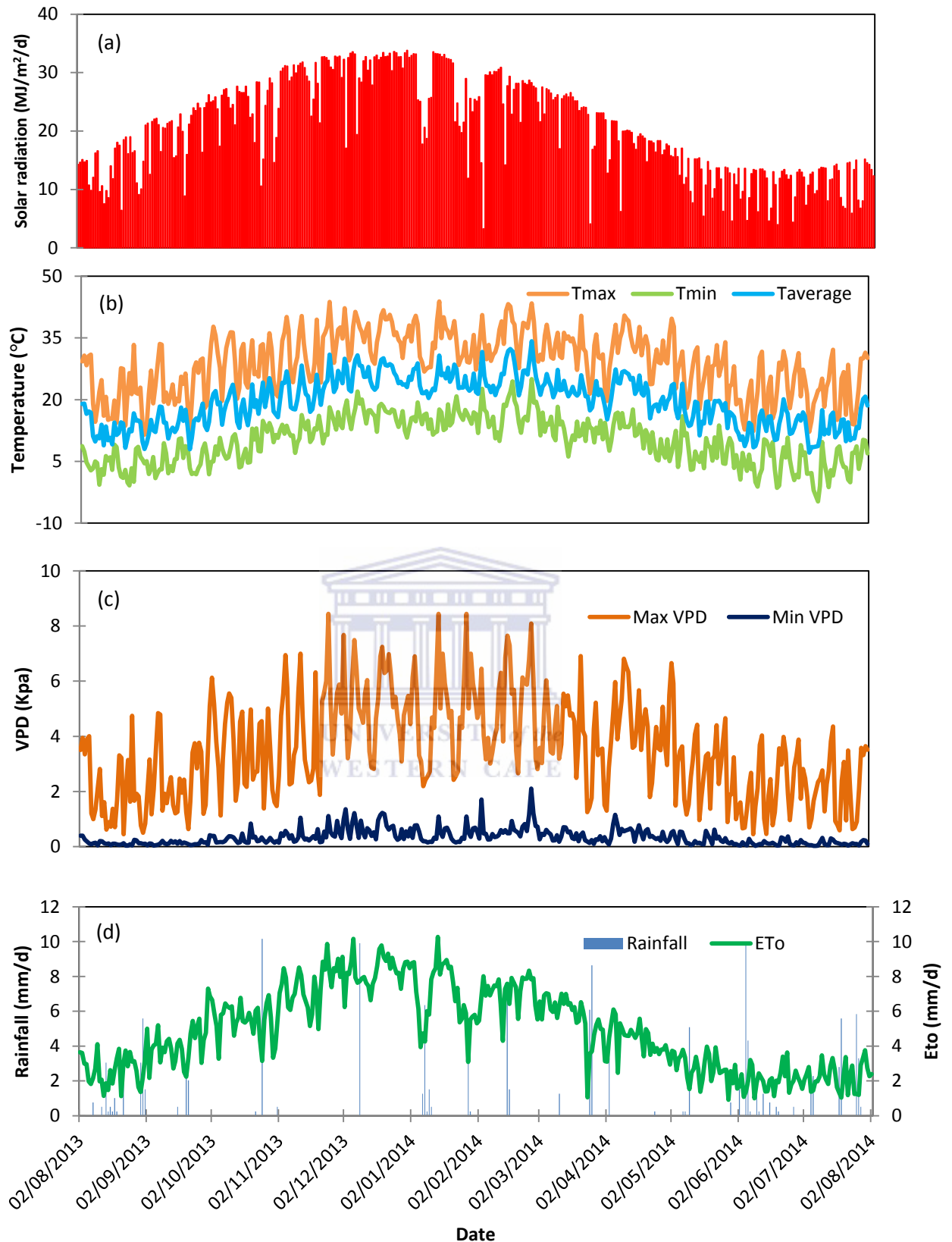
Fig. 4.1 Daily variation of (a) solar radiation; (b) maximum, minimum and the average air temperature; (c) vapour pressure deficit of the air; (d) rainfall and reference evapotranspiration at Brandkop farm.

The annual ET_0 from 2 August 2013 to 2 August 2014 of 1 791 mm was more than ten times higher than the rainfall (136.9 mm) received during the corresponding period (Table 4.1). The highest daily rainfall received at the study site was 10 mm recorded in October 2013. The long-term mean annual rainfall in the vicinity of the study site is about 150 mm with a coefficient of variation of about 32%. In the current study, more than 50% of the total annual rainfall was received in three months in winter (June - August) with July 2014 being the wettest month which received 21.8 mm of rain. The driest month was November 2013 which received only 0.5 mm rainfall. The atmospheric evaporative demand, depicted by ET_0, varied from 61.5 mm in June to a peak of 258.3 mm in December.
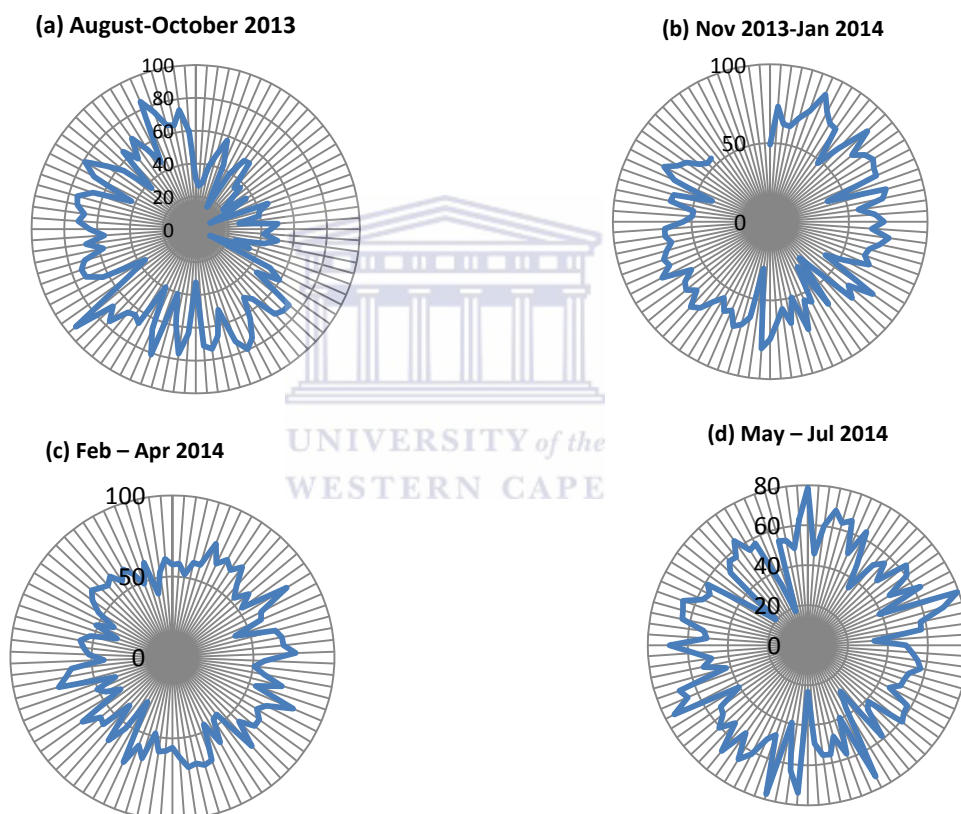
Fig. 4.2 Prevailing wind direction for the period August 2013 to July 2014 recorded by the automatic weather station at Brandkop farm.

Mean wind speed varied slightly between months with November being the windiest month at 2.3 m/s compared to 1.4 m/s in July (Table 4.1). Maximum wind speeds varied widely from month to month with September 2014 recording the highest value of 4.5 m/s. Prevailing winds during the period August - October were south to south westerly changing to south easterly during the early summer months from November to January (Figs 4.2a and b). Wind

direction was highly variable from February to July with no clear prevailing wind direction (Figs 4.2c and d).

Table 4.1 Summary of monthly climatic conditions at Brandkop farm, Northern Cape.

Year	Month	Mean daily solar radiation (MJ/m^2)	Tmax (°C)	Tmin (°C)	Rainfall (mm)	ET$_o$ (mm)	Average wind speed (m/s)	Maximum wind speed (m/s)
2013	Aug	13.4	33.3	-0.9	18	81.3	1.7	3.0
	Sept	20.1	33.6	0.9	6.4	121.9	1.7	3.7
	Oct	24.2	37.8	3.5	10.4	170.8	2.0	3.7
	Nov	29.6	43.7	7.0	0.5	221.5	2.3	3.7
	Dec	31.2	42.2	10.8	9.9	258.2	2.5	3.4
2014	Jan	27.2	43.9	11.5	13.7	215.3	1.9	2.9
	Feb	26.1	43.4	9.9	8.9	198.5	2.0	3.4
	Mar	23.5	40.4	6.2	16.0	176.9	1.9	3.1
	Apr	18.0	40.5	5.2	3.6	130.4	1.6	3.8
	May	12.4	39.7	2.9	6.4	85.9	1.4	3.6
	Jun	10.7	31.8	-1.5	21.3	61.5	1.5	4.1
	Jul	11.5	32.2	-4.8	21.8	68.9	1.4	3.4
Annual totals					136.9	1791.1		

The long-term average annual rainfall of the study site reported by Mucina and Rutherford (2006) was 150 mm. During the one year selected for this study (02/08/2013 to 01/08/2014) the rain gauge at the study site recorded slightly lower rainfall i.e. 136.9 mm. It appears 2013/14 was a slightly drier year than normal. Mucina and Rutherford (2006) reported a long term potential evapotranspiration of 2600 mm. However, in this study annual reference evapotranspiration of 1 791 mm was recorded (Table 4.1). There is a correlation between the climatic variables and the transpiration from each species (see Appendix A).

4.3. Comparison of transpiration by Prosopis (sp) and A. karroo

Transpiration by both species peaked in summer when the leaf area index and atmospheric evaporative demand were highest (Fig. 4.3). The mean leaf area index of the trees ranged from zero in early to mid-September when both species had shed their leaves (Fig. 4.3a) to a peak of 1.2 for *A. karroo* and 1.4 for *Prosopis* in January when the tree leaves had grown back (Fig. 4.3b). Some *Prosopis* trees maintained their leaves well into August while *A. karroo* shed all leaves much earlier in the winter.
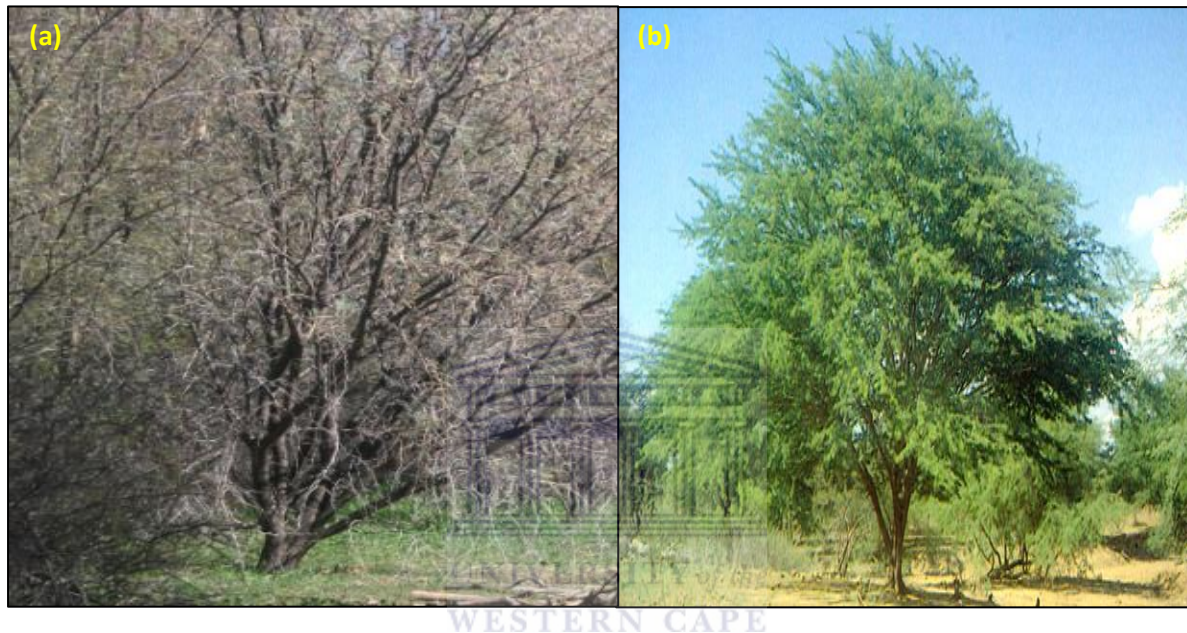

Fig. 4.3 Seasonal changes in tree characteristics (a) tree with fewer leaves in winter and (b) tree with green leaves in summer.

Typical seasonal trends in the daily transpiration rates by a *Prosopis* tree (LAI ~ 1.4) and an *A. karroo* tree (LAI ~ 1.2) are shown in Fig. 4.4. Transpiration by *A. karroo* ranged from 3 litres per day in late winter – early spring to as much as 57 litres per day in summer. For *Prosopis* on the other hand, the daily transpiration rates varied from about 4 litres per day to a peak of about 41 litres per day. Overall it is apparent that *A. karroo* transpired more water than *Prosopis* for most of the season despite *Prosopis* having a slightly higher leaf area index. This observation is rather unexpected as most published literature suggest that invasive alien plants generally have higher transpiration rates than indigenous vegetation (Cavaleri and Sack, 2010; Le Maitre *et al*., 2000; Calder and Dye, 2001). The most likely reason for this trend at this particular site could be that *A. karroo* had a much higher sapwood-heartwood ratio (Fig. 4.5a) than *Prosopis* (Fig. 4.5b). Reasons for this are unclear although it is likely that the conversion of more sapwood to heartwood by *Prosopis* could be an adaptation

strategy to survive the dry conditions. The relatively larger sapwood area of *A. karroo* promotes higher transpiration rates while the smaller water transport pathways in *Prosopis* limit the volume of water that can be transpired even when water is not limiting. The total amount of water used by the *A. karroo* tree was 9845 litres for the period starting from 2 August 2013 – 2 August 2014 while the total amount used by the *Prosopis* tree was 6918 litres, for the same period of time.
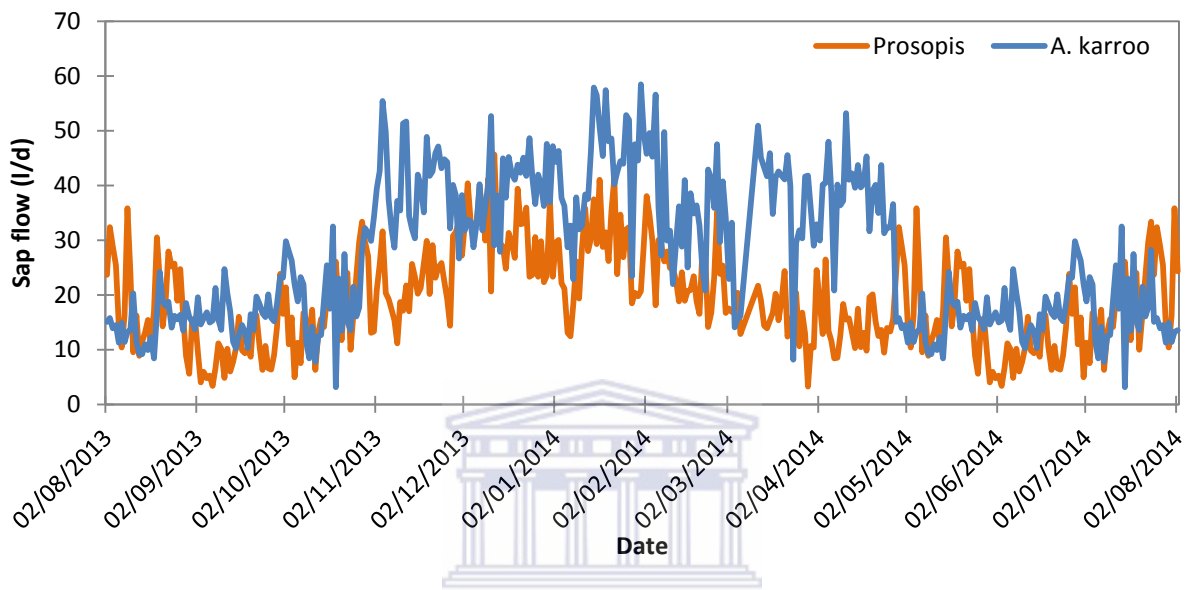

Fig. 4.4 A comparison of the water used by *a Prosopis* and an *A. karroo* tree of more or less the same size showing *A. karroo* to be using more water than *Prosopis* from 02/08/2013 to 02/08/2014.
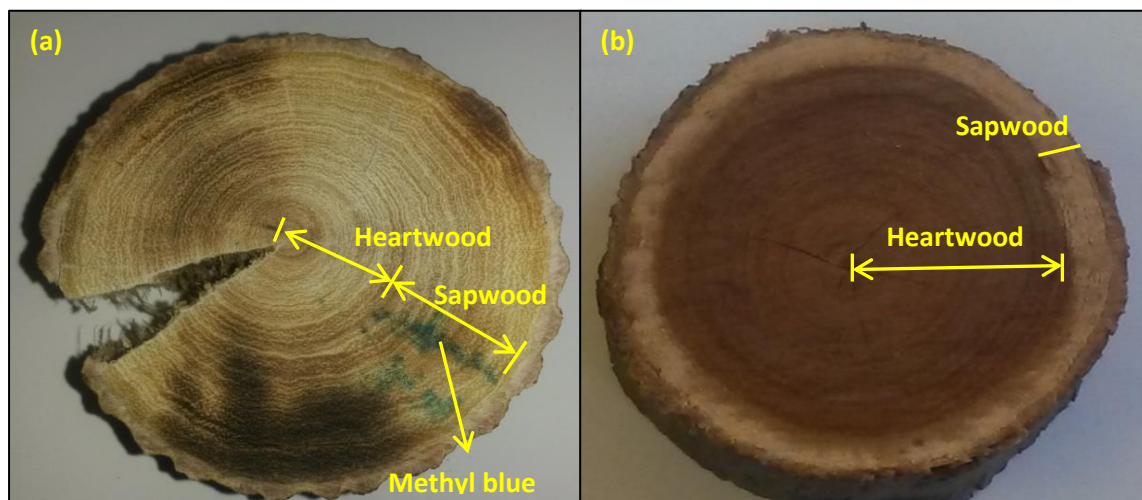

Fig. 4.5 A comparison of the size of the sapwood conducting area in; (a) an *A. karroo* stem and (b) *Prosopis* stem of similar size. The blue radial line in (a) shows the extent of the sapwood of *A. karroo* marked by the methyl blue dye injected into an intact stem. This is clearly much larger than the sapwood area of *Prosopis* depicted by the lighter portion in (b).

The annual (August 2013 to August 2014) total transpiration rate for the one hectare with *A. karroo* and *Prosopis* (sp) was 490 mm. Of this amount, transpiration by *Prosopis* amounted to ~353 mm per annum (or 72% of the total) while *A. karroo* transpiration was ~137 mm per annum accounting for only 28% of the total stand transpiration (Fig. 4.6c). The larger stand level transpiration by *Prosopis* (Fig. 4.6b), was because of its higher plant density (613 stems per hectare) compared to about 100 trees per hectare for *A. karroo*.

It appears from this study that the larger rates of water use by the *Prosopis* invasions was a result of the higher plant density than higher transpiration rates by individual trees. In a review by Cavaleri and Sack (2010), they noted that in general IAPs had higher stomatal conductance than the indigenous species although leaf level measurements were not taken in this study. They further concluded that IAPs and indigenous vegetation were likely to have higher sap flow/transpiration rates in some ecosystems.

Prosopis transpiration at this site, where the groundwater level fluctuated between 4.0 and 8.5 m below the ground, was higher than that at another invaded site near the town of Kenhardt in the Northern Cape where annual transpiration was less than 100 mm and the groundwater level was much deeper varying between 10 and 12 m (Fourie *et al.*, 2002; Dzikiti *et al.*, 2013b). Trees at the Kenhardt site were also smaller than the ones studied in this study.

Transpiration by both *Prosopis* and *A. karroo* was linearly related to the atmospheric evaporative demand (Fig. 4.7) at the stand level. *Prosopis* transpiration on average translated to 19% of ET_0 while that of *A. karroo* was only 7 % of ET_0 (Table 4.3). These are equivalent to basal crop coefficients of 0.19 for *Prosopis* and 0.07 for *A. karroo* based on the method of Allen *et al.* (1998). Monthly total transpiration by *Prosopis* peaked at 54 mm in December and January while that of *A. karroo* was less than 20 mm per month (Fig. 4.8).

Although the water use rates by individual trees was higher in *A. karroo* than in *Prosopis*, stand level transpiration from *Prosopis* was more than 3 times that from *A. karroo*. More details on the day to day, and month to month, water uses per individual trees are shown in Appendix B.
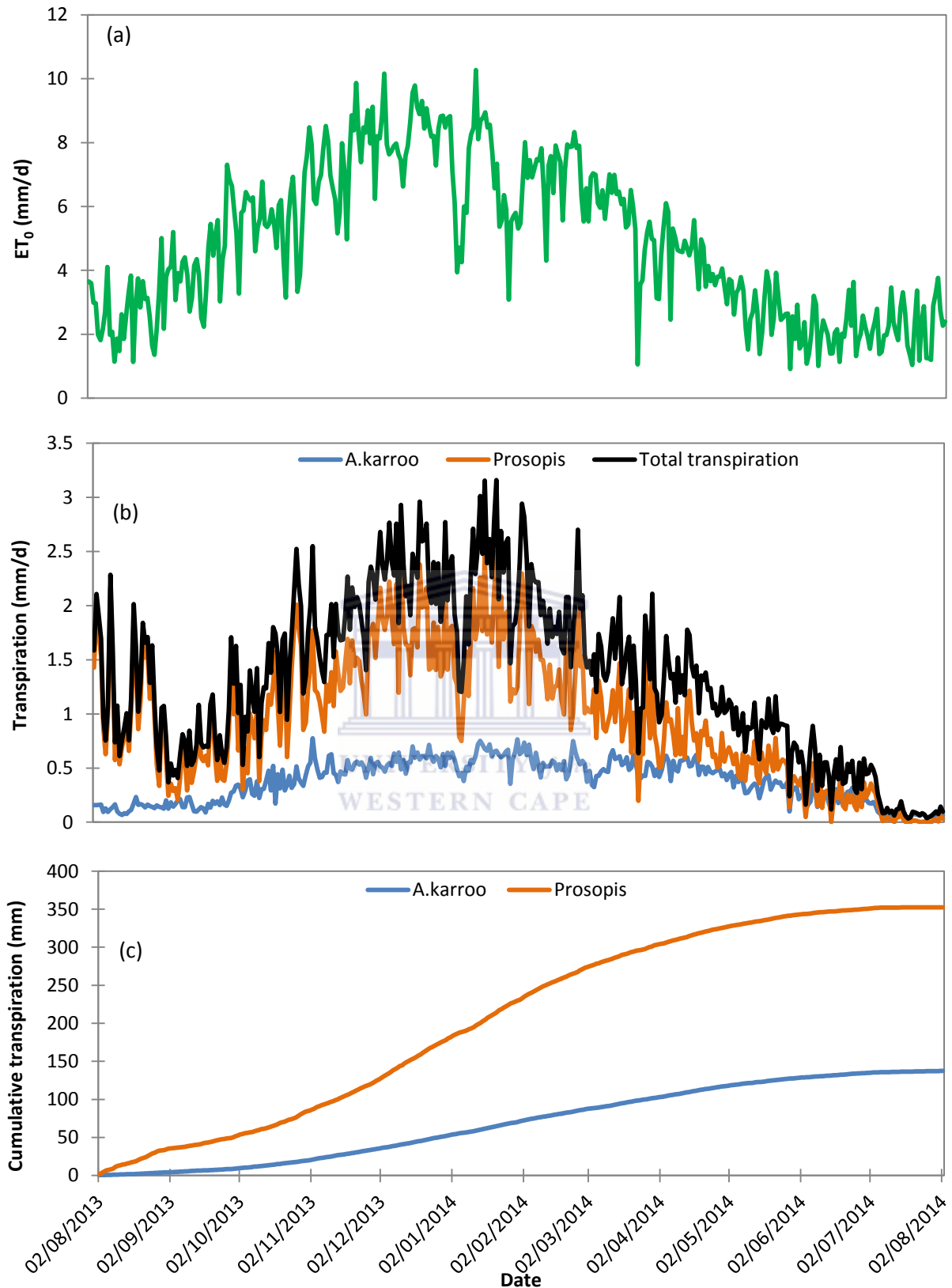
Fig. 4.6 Seasonal variations in (a) the reference evapotranspiration, (b) transpiration of indigenous *A. karroo*, *Prosopis* invasions and total transpiration and; (c) the cumulative transpiration of *A. karroo* and *Prosopis*, over the study period.

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Scott *et al.* (2000) compared the water use of two dominant vegetation communities in a semi-arid riparian ecosystem. Their data collection included measurements of surface energy balance and water fluxes for an annual cycle over two dominant types of vegetation in the riparian floodplain of the San Pedro river in Southern Arizona. The vegetation communities on their site consisted of a perennial floodplain grassland, and the tree grouping was composed largely of *Prosopis velutina*. They compared their measurements with estimates from previous studies. Additionally they took measurements of soil water content and water table levels and used them to infer the dominant sources of the evaporated water. The results they obtained indicated that the grassland relied primarily on recent precipitation, while *Prosopis* obtained water from deeper in the soil profile.

When Cavaleri and Sack (2010) compared the water use of an indigenous and invasive plants of the same growth form at multiple scales (leaf, plant and ecosystem), they found that at leaf scale invasive species have a greater stomatal conductance than native species. However at plant scale indigenous plants and invasive alien plants equally had high sap flow rates. At ecosystem scale, invasive dominated ecosystems were most likely to have higher sap flow rates per unit ground area than indigenous dominated ecosystems.
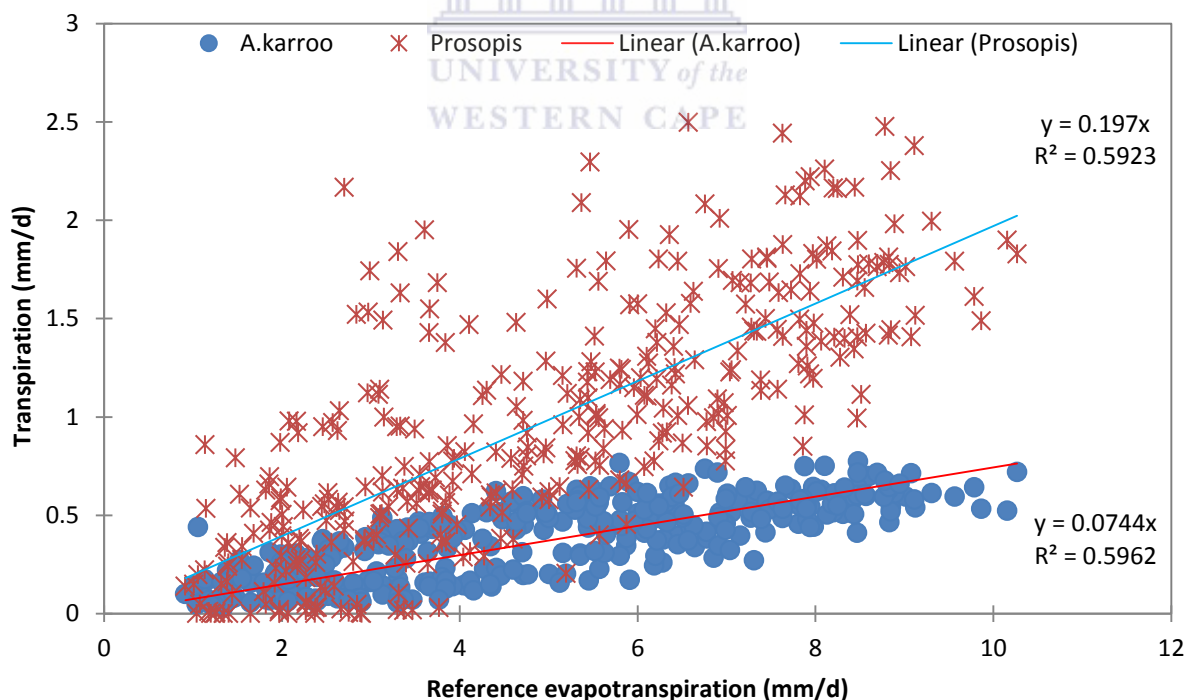

Fig. 4.7 Effect of the atmospheric evaporative demand, depicted by ET_0 on stand level transpiration by the indigenous *A. karroo* and *Prosopis* invasions at Brandkop farm, Northern Cape.

From August 2013 to July 2014 the total transpiration from *Prosopis* stands was higher than the total transpiration from *A. karroo* stands (Fig. 4.8). Maximum transpiration from the *Prosopis* stands reached 54 mm in December 2013 while that *A. karroo* reached 17 mm. The lowest monthly transpiration recorded from *Prosopis* was 1.6 mm recorded in July 2014, and 2.3 mm for *A. karroo* also recorded in July 2014 (Fig. 4.8). July 2014 is the only month where the monthly total transpiration from *A. karroo* trees is more than the transpiration from *Prosopis* trees.
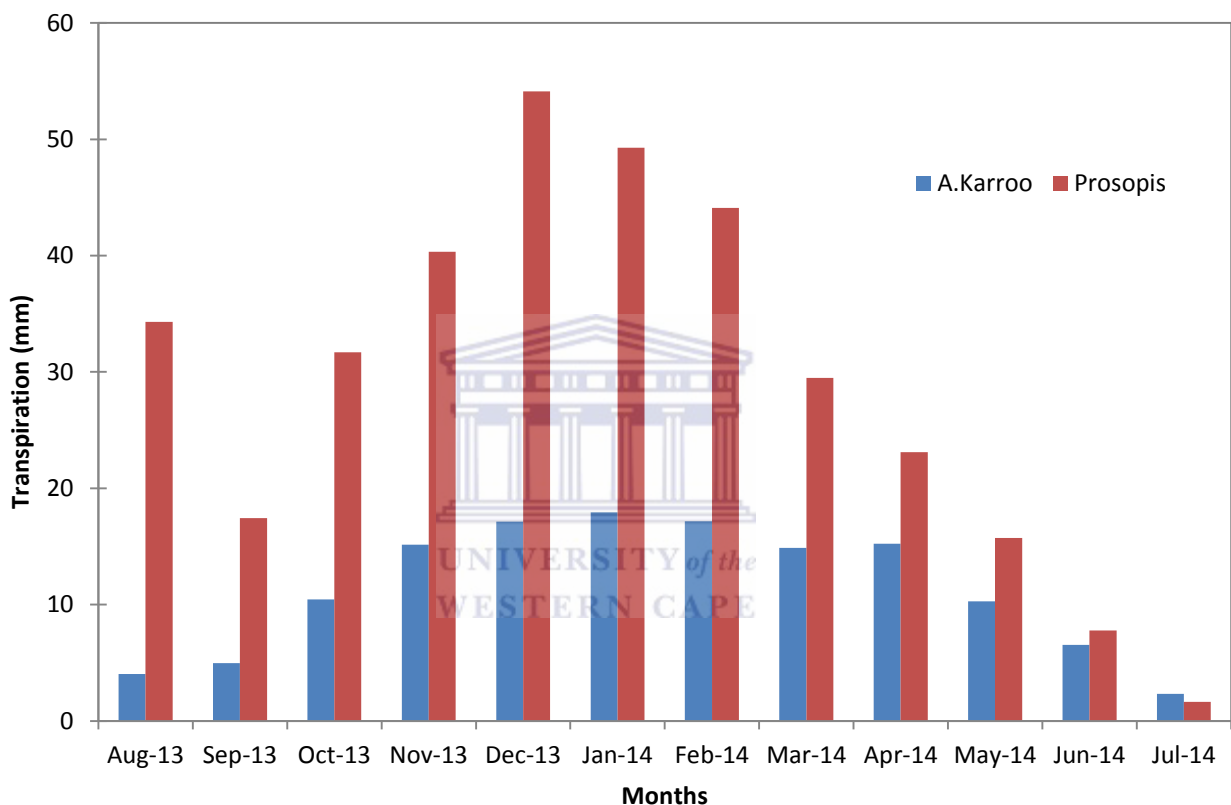

Fig.4.8 *Monthly total transpiration by the indigenous A. karroo and Prosopis invasions for a period of one year.*

4.4. Comparison of the root water uptake patterns of Prosopis (sp) and co-occurring A. karroo.

The water uptake patterns by *Prosopis* invasions were substantially different from those of *A. karroo* even though the measured species were growing next to each other. *Prosopis* root water uptake showed evidence of hydraulic redistribution (Fig. 4.9a) with a significant proportion of water taken up by the tap root and then channelled to the shallow soil layers via the lateral roots. Positive flows in Fig. 4.9 depict water transport towards the stem (or

canopy) while negative flows depict water transport away from the stem. However, no redistribution was apparent with the indigenous *A. karroo* (Fig. 4.9b).
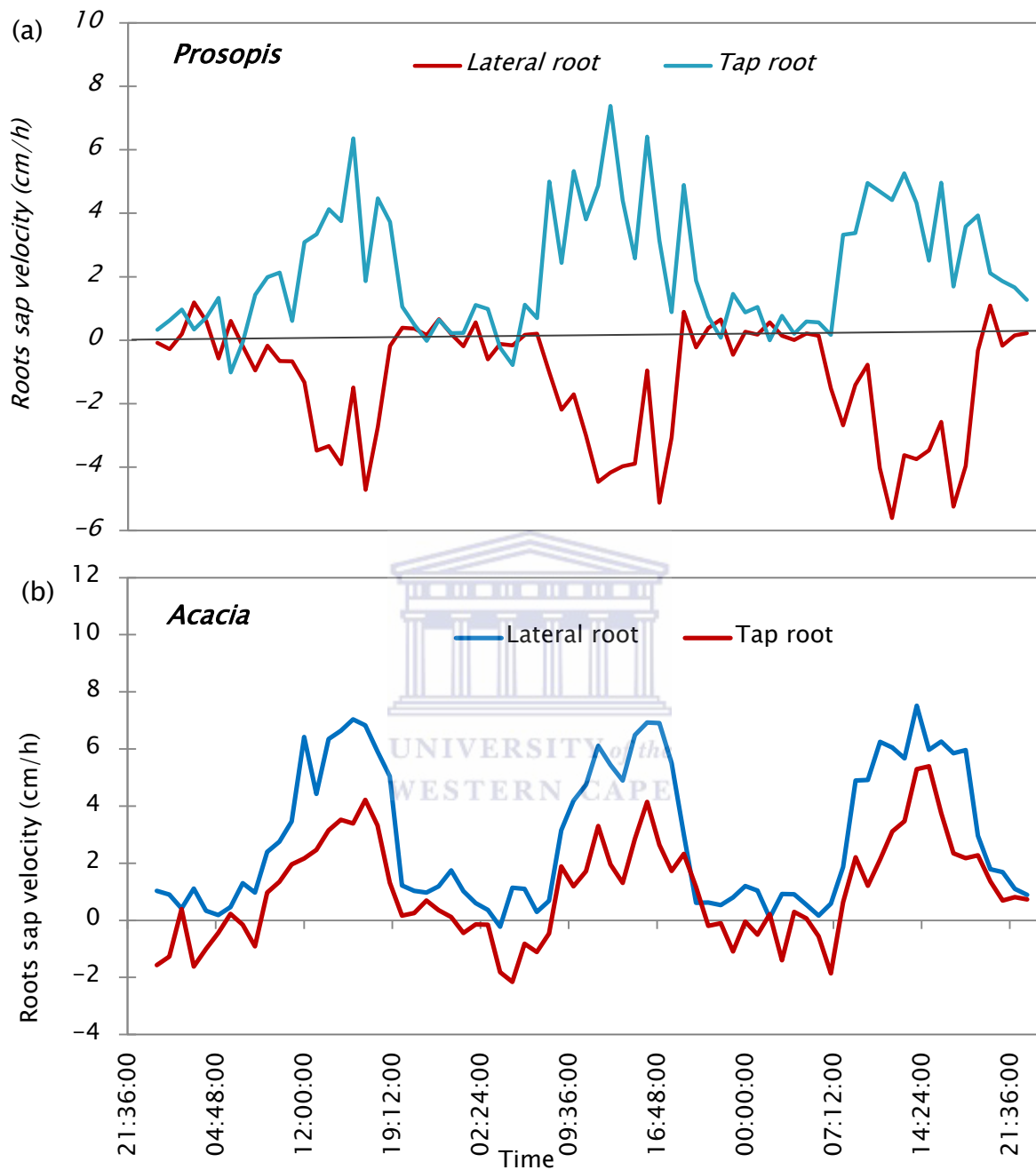
Fig. 4.9 Water transport through the (a) *Prosopis* lateral and tap roots, (b) *A. karroo* lateral and tap roots.

Previous studies have reported the phenomenon of hydraulic redistribution on *Prosopis* (Mooney *et al*., 1980; Dzikiti *et al*., 2013b) but mainly as a nocturnal process. Hydraulic redistribution is thought to be driven by root and soil water potential gradients (Dawson, 1993). In this study however, the redistribution appears to be happening during the day time

presumably because of the very strong water potential gradient between the roots and the sandy soils in the very dry environment given that the *Prosopis* lateral roots were very close to the surface. Detailed studies by Dawson (1993) on sugar maple (*Acer saccharum*) revealed that hydraulic redistribution: 1) provided 3-60% of the water requirements of the shallow rooted neighbours and that, 2) this water influenced the stomatal conductance, water balance and growth of the neighbours. Therefore hydraulic redistribution has potential impacts on the population dynamics of the invasions. For example, a young *Prosopis* seedling growing next to larger trees could have a higher chance of survival under arid conditions because of the abstracted groundwater that is redistributed to the shallow soil layers.

The soil water content at the 0.25 m depth was mainly influenced by the presence of rainfall (Fig. 4.10). The groundwater level was at approximately 7 to 8 m below the ground surface. However, the soil moisture readings for probes inserted at 0.50 and 1.00 m depth seem to be independent of the rainfall events reaching peaks during the summer months when plant water uptake is highest.
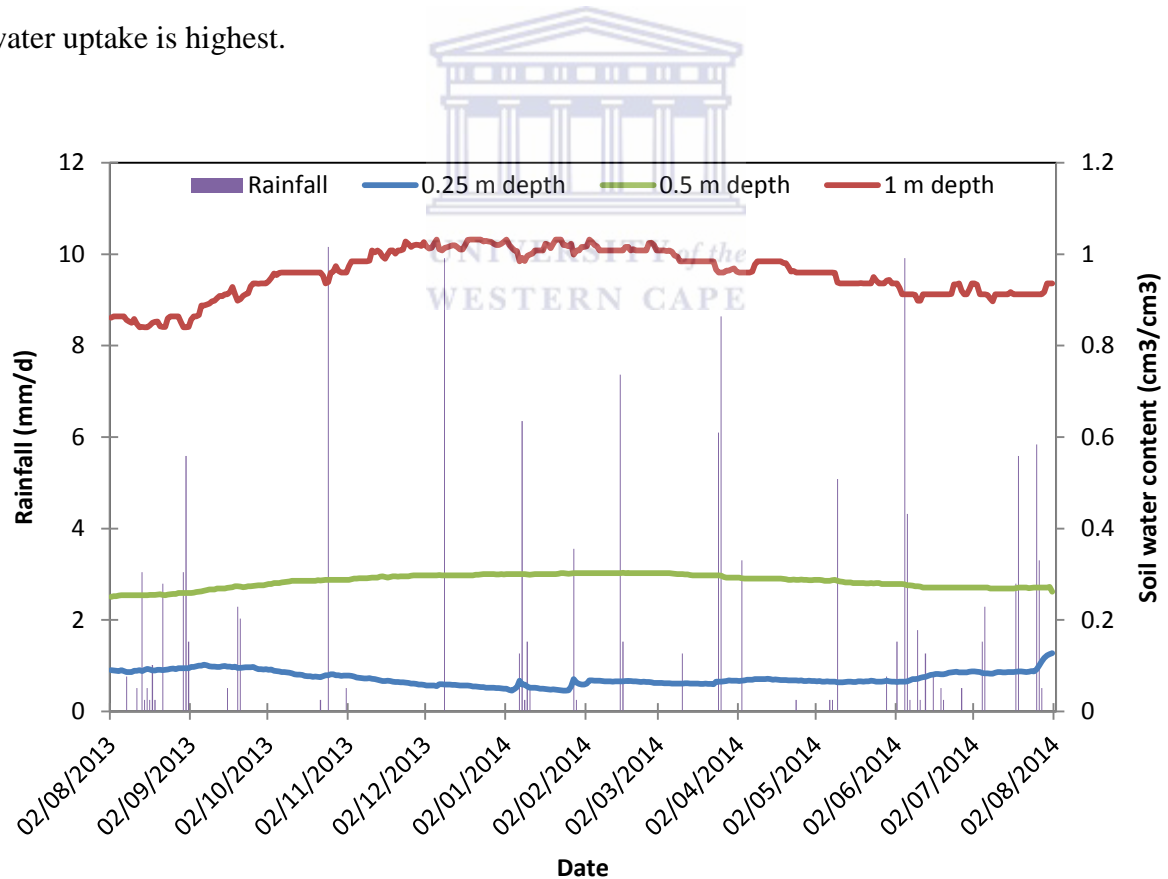

Fig. 4.10 The variation of soil water content at various depths under *Prosopis*, and daily rainfall recorded from 02/08/2013 to 02/08/2014.

The probe installed at the depth of 1.0 m initially had a soil moisture content of 0.87 cm³/cm³ in August 2013. The moisture content for this probe increased in October 2013 reaching 1.03 cm³/cm³ in January 2014 despite little rain falling during this period. The readings for this probe then dropped again towards winter (May to August 2014) reaching 0.91 cm³/cm³ in August 2014 cm³/cm³. Soil water content at 0.5 m increased during the summer season (Fig. 4.10) when plant water uptake was highest which was unexpected. Some other water source (possibly hydraulic redistribution) was likely responsible for the increase in soil water content given that the water table was at least 6 m below the ground during the dry summer months and capillary rise was unlikely to be a factor. The probe at 0.25 m was highly influenced by the presence of rainfall as it is much closer to the surface.

4.5. Plant water sources

The initial stable isotope results analysed during the first month of the experiment (August 2013) for the source waters showed that rainwater and groundwater samples had different isotope signatures (rain -12‰ $\delta^{18}O$ and -73‰ $\delta^{2}H$; groundwater - 3‰ $\delta^{18}O$ and -10‰ $\delta^{2}H$). This improved confidence that stable $\delta^{2}H$ and $\delta^{18}O$ isotopes was indeed a useful method to be applied throughout the study. The data in Fig. 4.11 was plotted against the global meteoric water line because, according to Craig (1961), meteoric waters follow a rayleigh distillation process that results in a linear relationship between $\delta^{2}H$ and $\delta^{18}O$ for water samples worldwide (Gat, 1996). This relationship is termed the global meteoric water line (GMWL) (Craig, 1961).

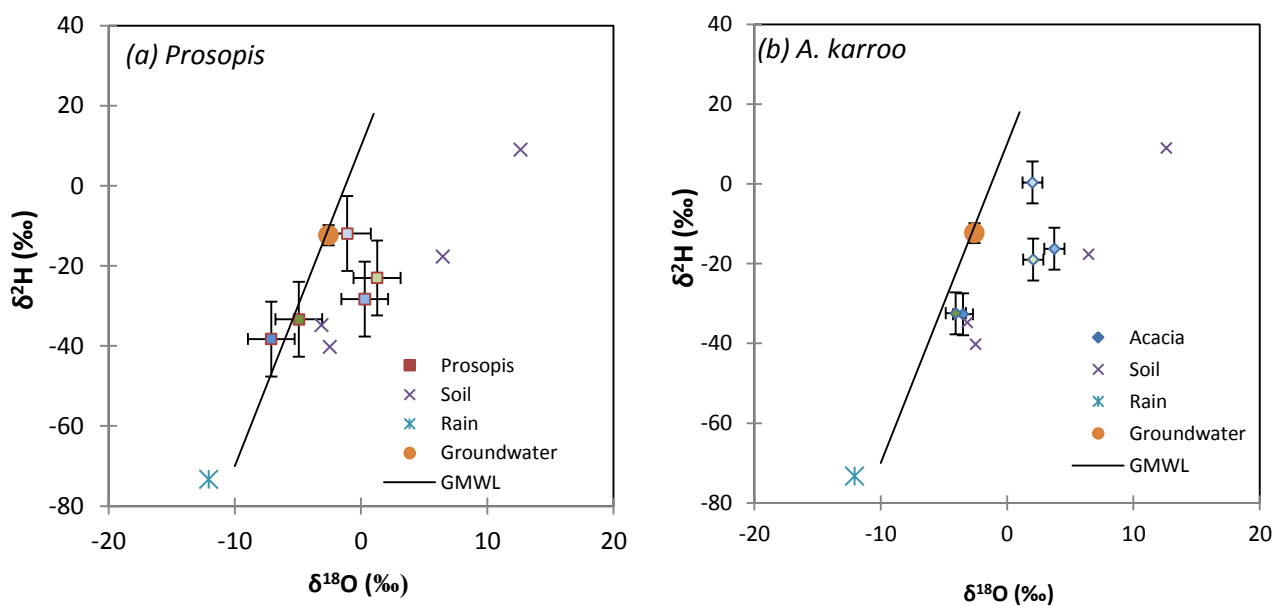**Fig. 4.11** Average $\delta^{18}O$ versus $\delta^{2}H$ values from (a) *Prosopis* and (b) *A karroo* over five sampling dates from October 2013 to November 2014.

Sampling for the data in Fig. 4.11 was done in spring (October 2013), summer (February 2014), autumn (April 2014) and again in October – November 2014. The groundwater signature is presented as a single average because this did not vary much between seasons. Both the rainwater and groundwater stable isotope values fall along the Global Meteoric Water Line (GMWL). Soil water showed a degree of evaporative enrichment, typical of arid areas, by plotting below the GMWL (Gat, 1996; Schachtschneider and February, 2010). The October 2013 and November 2014 samples, had δ^2H isotope values similar to rainwater, suggesting that the top 50 cm of soil are infiltrated by rainwater, but are also subject to evaporation. However, soil samples collected in the summer showed very high levels of enrichment because of the excessive evaporation typical of this time of year. The *Prosopis* isotope samples plot close to groundwater and deeper soil water for the autumn and summer (Fig. 4.11a) suggesting that the trees were using both sources of water during this time. However, *A. karroo* shows values similar to *Prosopis* and groundwater, as well as samples with more enriched $\delta^{18}O$ isotope values. Thus according to Fig. 4.11 shallow soil layers reflect some rainwater infiltration, while deeper soil layers correspond more to groundwater.
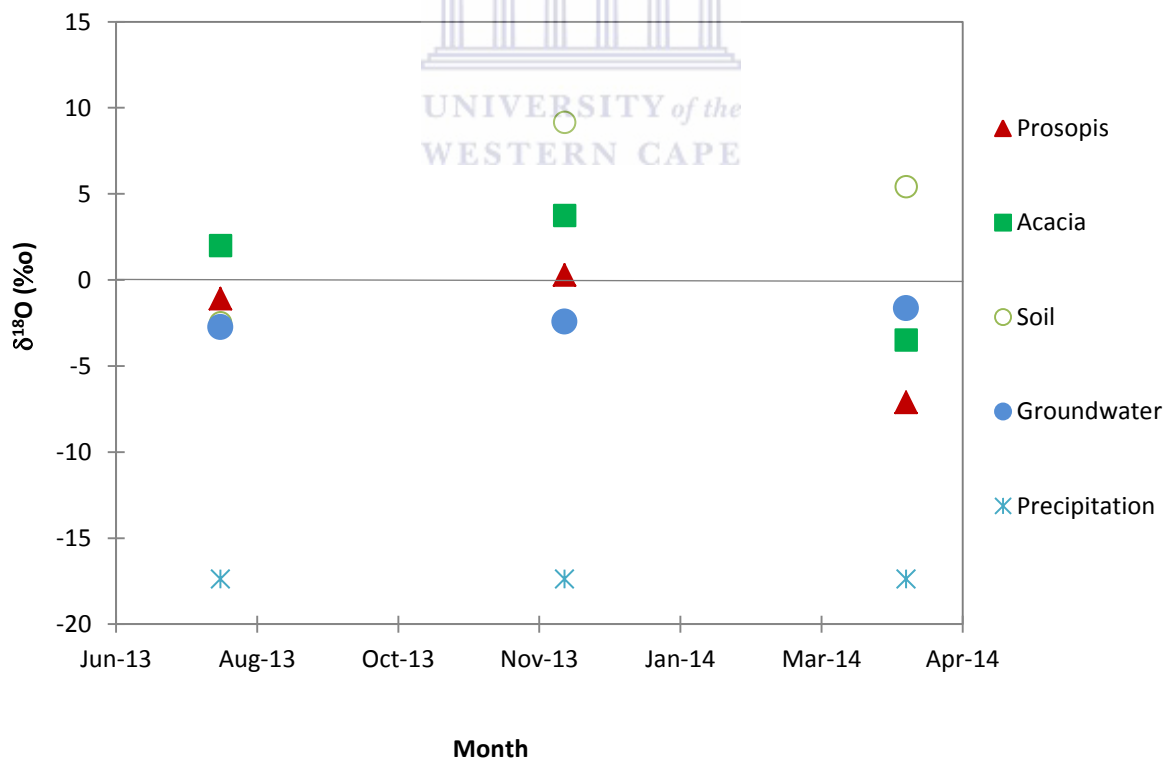

Fig. 4.12 Mean $\delta^{18}O$ values for *Prosopis* and A. *karroo*, groundwater, soil water and precipitation collected during the winter, summer and autumn seasons.

The δ^{18}O of *Prosopis* ranged from a mean of -7.1‰ in autumn to -1.09‰ in late winter while that of *A. karroo* varied from -3.5 to 3.8‰ during the same period. The δ^{18}O for groundwater remained fairly stable from late winter (August 2013) to autumn (April 2014) suggesting there was little direct influence of rainfall on groundwater during this period. The isotopic signature of both plant species resembled that of groundwater and soil water in winter implying that the species rely on both water sources during this time of year, particularly in early to mid-winter before the trees shed their leaves. *Prosopis* maintained its leaves until late winter in August. In summer both *A. karroo* and *Prosopis* plotted between the soil and groundwater sources (Fig. 12), although *Prosopis* appeared to be more strongly dependent on groundwater than soil water. Moreover, the soil δ^{18}O was substantially enriched in summer and autumn presumably due to the high levels of evaporation during those periods. There was increased dependence on rainfall by both *A. karroo* and *Prosopis* during the autumn 2014 period, possibly due to the fact that; 1) the groundwater level was at its lowest point in the 2014 year at this time, and 2) substantial rain fell during March 2014.

Given that the vegetation at the site effectively had access to only two sources of water (i.e. groundwater and soil water), a two compartment linear mixing equation proposed by Snyder and Williams (2000) was applied to derive the proportion of plant xylem water derived from the two sources using the following equation:

$$ f = \frac{\left(\delta^{18}O_x - \delta^{18}O_{gw}\right)}{\left(\delta^{18}O_{so} - \delta^{18}O_{gw}\right)} \quad \ldots\ldots\ldots (4.1) $$

where:

$\delta O^{18}x = \delta O^{18}$ of tree xylem

$\delta O^{18}so = \delta O^{18}$ of soil

$\delta O^{18}gw = \delta O^{18}$ of groundwater

f = fraction of transpired H_2O from soil

Table 4.2 Fraction of *Prosopis* and *A. karroo* xylem water derived from soil and groundwater sources, respectively, based on the approach by Snyder and Williams (2000).

Month	Sample	$\delta O^{18}x$	$\delta O^{18}so$	$\delta O^{18}gw$	f (soil wáter)	Groundwater fraction
(Aug' 13)	*Prosopis*	-1.09	-2.48	-2.75	-	-
	A.karroo	2.01	-2.48	-2.75	-	-
Summer (Dec' 13)	*Prosopis*	0.29	9.17	-2.42	0.23	0.77
	A.karroo	3.74	9.17	-2.42	0.53	0.47
Autumn (Apr 2014)	*Prosopis*	-7.12	5.42	-1.64	-	-
	A.karroo	-3.49	5.42	-1.64	-	-

The partitioning of the xylem water between the soil and groundwater sources for the winter and autumn seasons were not realistic, likely because of the lack of contrast in the isotope signature of the plant xylem water and the groundwater. Thus the calculations were done using the partitioning of the xylem water between the soil and groundwater sources for the summer period only.

Based on this analysis *Prosopis* derived about 23% of its water from the shallow soil layers and 77% from groundwater in summer. *A. karroo* on the other hand derived 53% of its water from the shallow soil layers and 47% from the saturated zone in summer. The low proportion of water from the unsaturated zone for *Prosopis* could be a result of the fact that the lateral roots of this species form a dense mat close to the soil surface (see Fig. 3.7) which is much drier compared to deeper soil layers. The lateral roots of *A. karroo* on the other hand are inclined at a steeper angle from the surface thereby accessing water from the less exposed parts of the soil.

If it is assumed that the proportion of water derived from soil and groundwater sources remains the same throughout the year, then *Prosopis* abstracted 272 mm from groundwater and only 81 mm from the unsaturated zone (Table 4.3). This translates to 2 720 m^3 (or 2.72 ML) groundwater abstraction per hectare per year.

Table 4.3 Amount of transpiration derived from the soil and groundwater sources by *Prosopis* and *A. karroo*, respectively.

Species/stand	Variable	Amount (mm/year)	Period
Prosopis	Total transpiration	353	Aug 2013 - Aug 2014
Prosopis	Transpiration from soil	81	Aug 2013 - Aug 2014
Prosopis	Transpiration from GW	272	Aug 2013 -Aug 2014
A. karoo	Total transpiration	137	Aug 2013 - Aug 2014
A. karoo	Transpiration from soil	73	Aug 2013 - Aug 2014
A. karoo	Transpiration from GW	64	Aug 2013 - Aug 2014
Stand level	Total transpiration	490	Aug 2013 - Aug 2014
Stand level	Transpiration from soil	154	Aug 2013 - Aug 2014
Stand level	Transpiration from GW	336	Aug 2013 - Aug 2014
	Reference evapotranspiration (ET$_0$)	1 791.1	Aug 2013 – Aug 2014

For *A. karroo* on the other hand, 73 mm of the annual transpiration came from soil water and 64 mm from groundwater. Thus it appears that the indigenous vegetation used only 640 m^3 (or 0.64 ML) of groundwater per hectare per year which is at least four times less than that used by the IAPs. Incremental groundwater consumption by *Prosopis* is therefore a

significant proportion of that required by the indigenous vegetation of a similar growth form. The total contribution of groundwater to stand level transpiration was 336 mm/annum compared with about 154 mm/annum from the unsaturated zone.

4.6. Vegetation-groundwater interactions

The groundwater level fluctuated between 8.4 mbgl (meters below ground level) at the beginning of monitoring on 2 August to 3.85 mbgl on 1 September 2013 (Fig. 4.13). The pronounced rise in the groundwater level observed in late August 2013 was a result of flooding that occurred at the site (Fig. 4.14). The flooding was a result of the Doorn River overflowing its banks after heavy rains upstream in the Niewoudtville area. The study site itself received very little rainfall during this time (< 3 mm). As expected the logged groundwater level exhibits signs of a seasonal oscillation (Fig. 4.13).
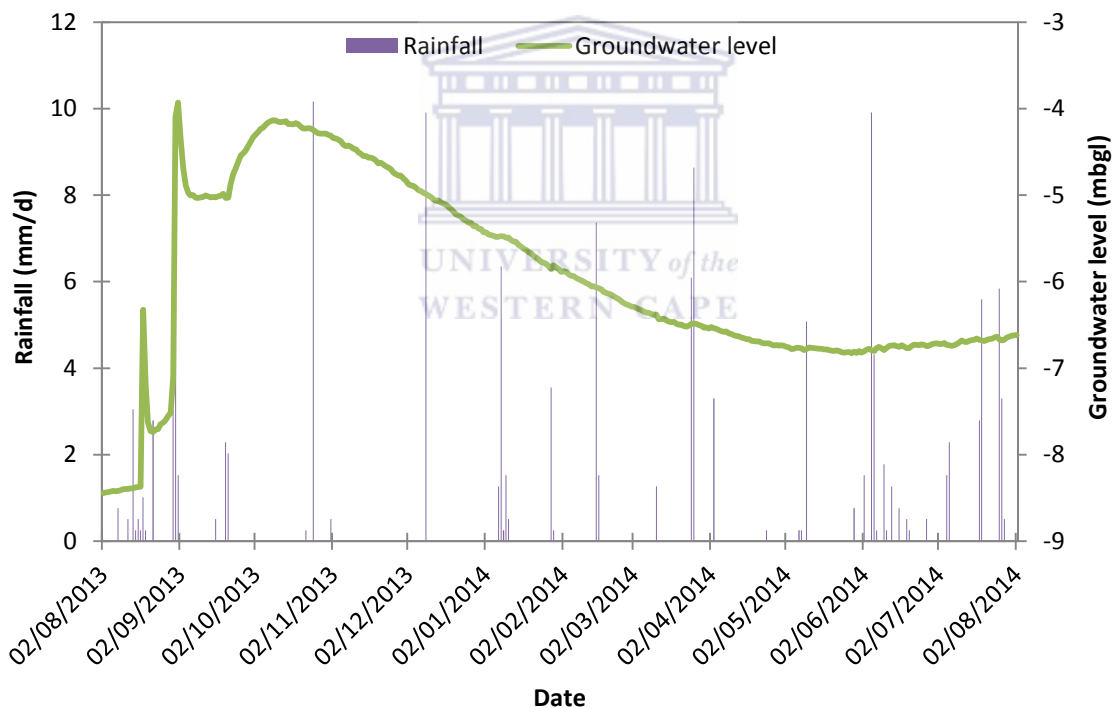

Fig. 4.13 Changes in groundwater levels measured from a borehole located in a *Prosopis* invaded area at Brandkop farm.

The total rainfall recorded for the month of August 2013 is 18 mm. At the beginning of the monitoring the measured groundwater level was 8.4 mbgl. After a short period of rainfall (from the 13th – 18th August), the water level rose to 5.9 mbgl, and dropped again in the absence of rainfall (from 21st 28th August). When Fourie *et al*. (2002) quantified the effects of

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Prosopis on groundwater levels in Rugseer River, Kenhardt, Northern Cape, South Africa. They reported that water levels declined during summer (October to March) due to evapotranspiration. They measured declines of between 0.97 m and 1.57 m and also stated that water levels rose immediately after surface runoff.
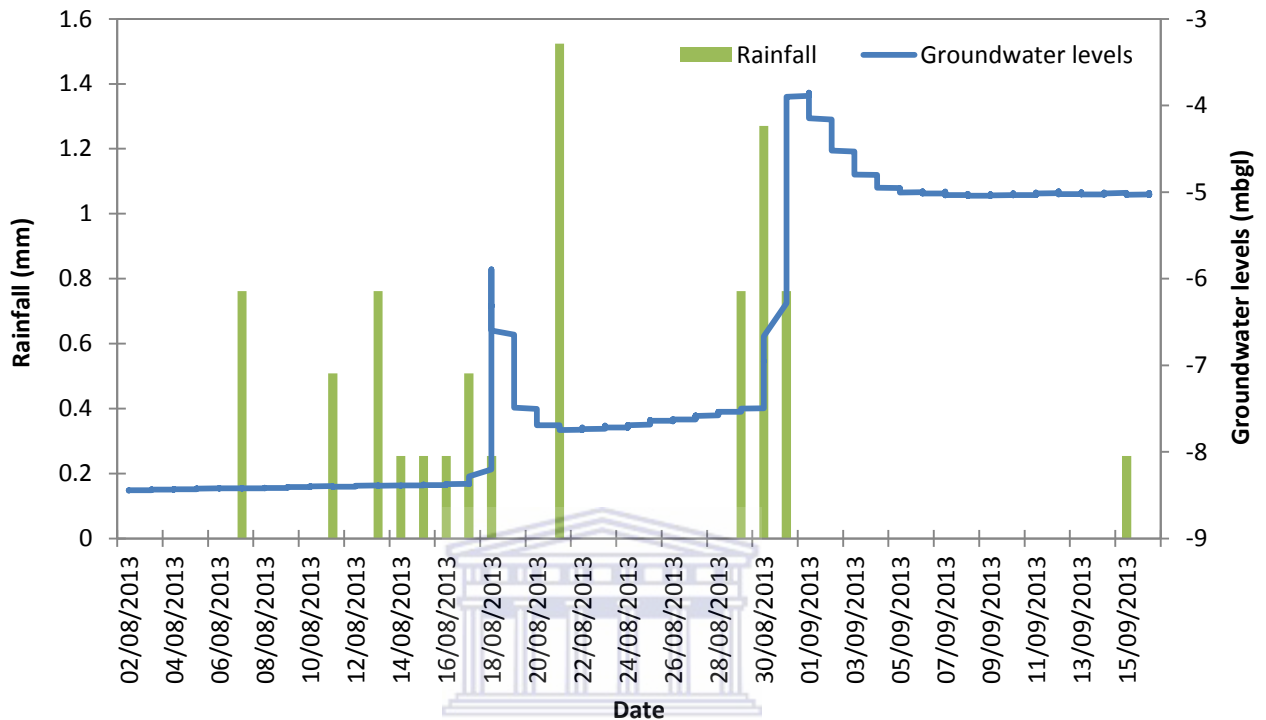

Fig. 4.14 Relationship between rainfall occurrence and groundwater level changes in the August-September 2013 period.

Diurnal changes in groundwater levels showed direct evidence of abstraction by the trees. It is apparent from (Fig. 4.15) that groundwater level dropped sharply at the onset of plant water uptake (transpiration) in the morning. The water level dropped throughout the day and stopped when transpiration was zero in the evening. The water level rose during the night when plant water uptake was minimal and also due to lateral inflows. A lower peak was reached before transpiration commenced the following day (Fig. 4.15). There is a correlation between water uptake by each species and groundwater, as as further explained in Appendix C.

When Yasuda *et al*. (2014) investigated the diurnal fluctuation of groundwater levels caused by the invasive alien *Prosopis,* they discovered that the changes in groundwater level closely followed plant water uptake. In their case, the groundwater levels also started to decline a few

hours before sunrise and recovered around noon, and then continued to decline until a few hours after sunset, before recovering again during the night.
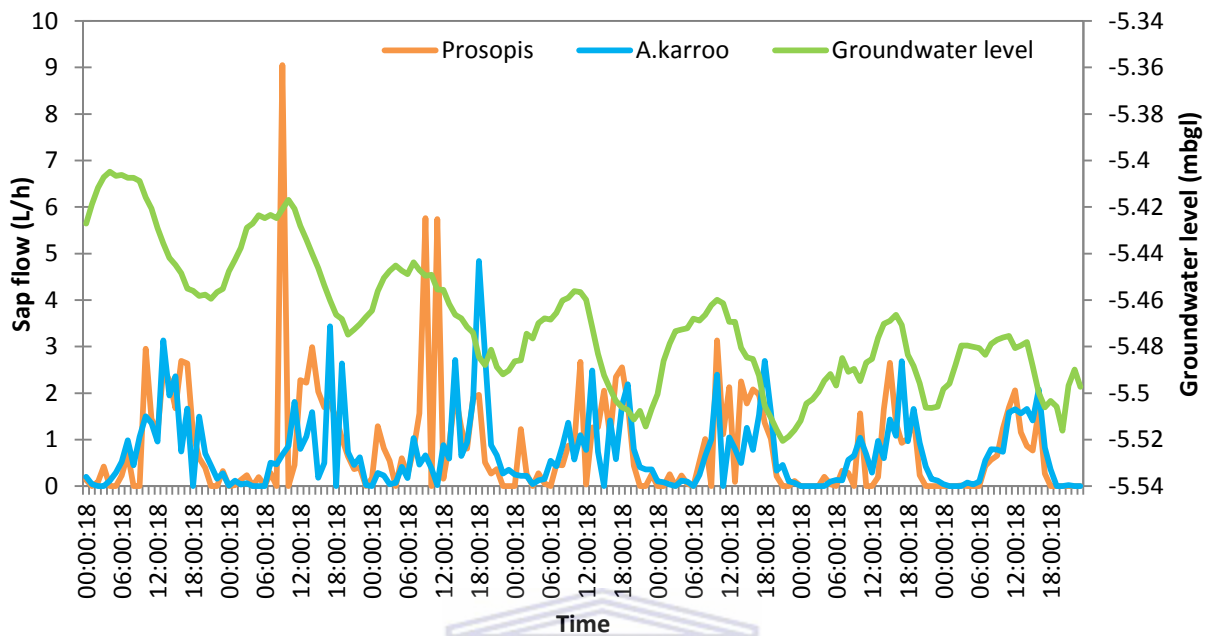

Fig. 4.15 Direct impact of (a) *A. karroo* and (b) *Prosopis* sap flow on groundwater levels for the period 1 – 7 January 2014.

Fig. 4.15 shows a dropping groundwater level with an increasing transpiration for a period of 7 days in summer. Fig. 4.16 shows a similar situation over a longer period (from January 2014 – August 2014). However the impacts of transpiration on groundwater levels are clearer when plotted over a shorter period of time. Snyder and William (2003) discovered that at a site with limited groundwater availability, *Prosopis* derived a greater percentage of water from the shallow soil in summer than did trees at a site with greater availability of groundwater. Fourie *et al.* (2002) mentioned that a volume of 50 m^3 per month per hectare could be saved by clearing 1 hectare of *Prosopis*.

Dzikiti *et al.* (2013b) collected data on tree water uptake, evapotranspiration and water table depth over different seasons in the Northern Cape Province of South Africa. They quantified the effects of tree clearing on groundwater by comparing data from a *Prosopis* invaded and an adjacent cleared area. Using the heat pulse velocity method they found that transpiration rates were less than 1.0 mm/d throughout the year and the trees showed structural and physiological adaptations to the combined low rainfall and low water holding capacity of the soils by developing very narrow sapwood areas and by closing their stomata. The trees

abstracted groundwater as evidenced by the decline in borehole water levels in the *Prosopis* stand before the rainy season. Groundwater savings of up to 70 m^3/month could be achieved for each hectare of *Prosopis* cleared. They concluded that clearing of invasive *Prosopis* would conserve groundwater in the arid parts of South Africa.
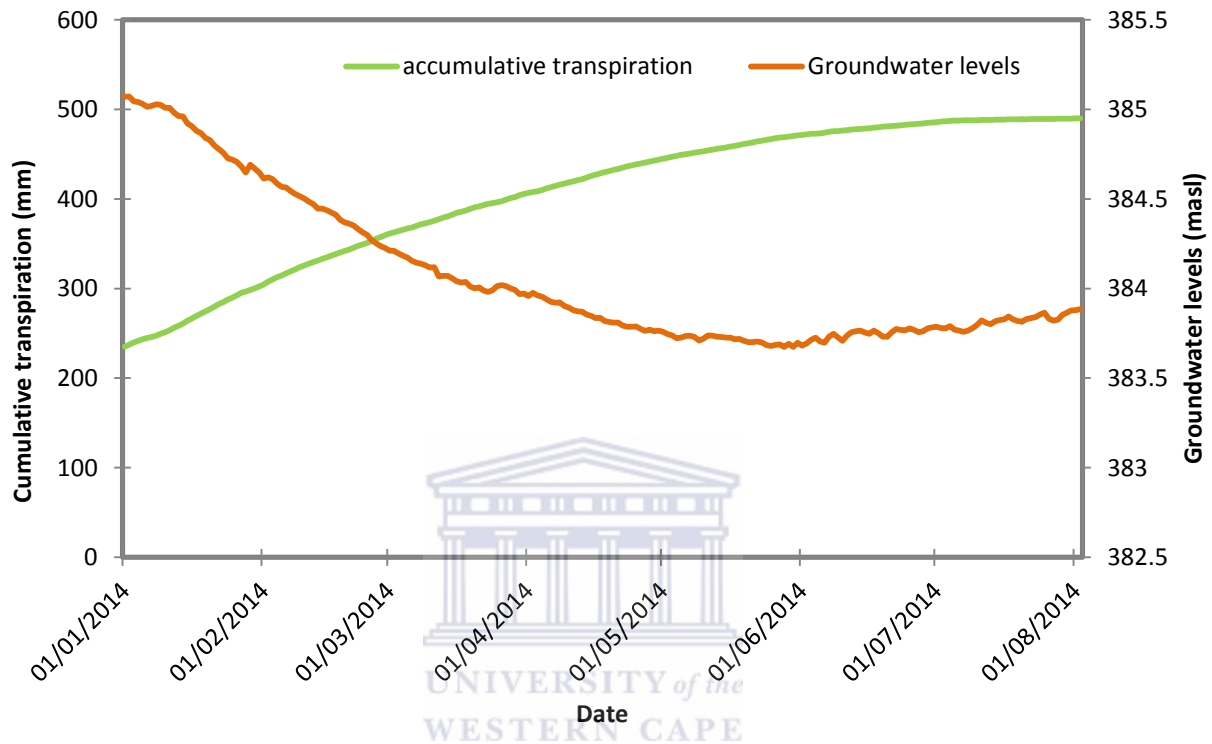

Fig. 4.16 An increasing transpiration followed by a drop in groundwater levels recorded at the study site from January 2014 to August 2014.

Doody *et al.* (2011) investigated the potential for "water salvage" by removal of non-indigenous woody vegetation from dryland river systems. Using two case studies in the USA and Australia they illustrated the factors that contribute to water salvage feasibility for a given ecological setting. After reviewing both the American and Australian case studies, they concluded that water salvage feasibility is highly dependent on the ecohydrological setting in which non-indigenous trees occur.

4.7. Chapter summary

The microclimate results obtained showed that the temperatures can rise up to 40°C in summer and can drop to less than -1°C in winter at the study site. The recorded amount of

rainfall was   136.9 mm for the period starting from 02/08/2013 to 01/08/2014, and a total reference evapotranspiration of 1791.1 mm was recorded for the same period of time. For *Prosopis* and *A. karroo* trees with a similar LAI, *A. karroo* appeared to use more water *Prosopis* mainly because of its larger conducting sapwood that promotes quicker water transport. At the stand scale, *Prosopis* typically transpired more than 3 mm of water per day in warm summer weather while *A. karroo* transpired less than 1 mm during the same period. Based on the analysis of isotope signatures, *Prosopis* transpired ~ 77% groundwater and 23% soil water, while the *A. karroo* transpired ~ 53% groundwater and 47% soil water. A close correlation between the cumulative drop in groundwater levels was found with the accumulative transpiration.

CHAPTER 5: Conclusions and Recommendations

This study shows that there were some differences in the transpiration rates of individual *Prosopis* and *A. karroo* trees of similar canopy size. Peak transpiration of a *Prosopis* with a leaf area index of 1.4 was 41 litres of water per day compared with 54 litres of water per day by *A. karroo* with a leaf area index of ~ 1.2. The relatively lower transpiration rates by *Prosopis* were a result of a lower sapwood to heartwood ratio in this species compared with *A. karroo*. It appears there is a larger resistance to water transport in *Prosopis* stems at this site due to a larger heartwood (see Fig. 3.8) compared to *A. karroo*. This observation is consistent with the observation by Cavaleri and Sack (2010) who noted that indigenous vegetation are equally likely to use as much water as invasive alien plants in some cases.

However, considering the water use at the entire monitored site (approximately 3 hectares), *Prosopis* used more than 3 times more water than the co-occurring *A. karroo*. The reason for this is because of the high plant density that *Prosopis* invasions form compared with the indigenous species. At this study site there was approximately six times more *Prosopis* than *A. karroo* and this substantially raised the stand level water use of the invasives. As expected both *Prosopis* and *A. karroo* consumed groundwater. The isotopes studies showed that *Prosopis* derived up to 77% of their water from the saturated soil zone during the peak transpiration period in summer while *A. karroo* derived about 53% of its water from the groundwater. This translated to approximately 2.72 megalitres for *Prosopis* and 0.64 megalitres for *A. karroo* of groundwater per hectare per year.

While most of the groundwater taken up by *A. karroo* is lost via transpiration, *Prosopis* on the other hand losses some of the water to transpiration but it also redistributes significant amounts to shallow soil layers via its extensive lateral root network. This redistributed water may be available to the tree during periods of prolonged dry periods. But other studies have reported that the redistributed water is vital for supporting adjacent younger trees with no access to groundwater and to enhance nutrient cycling under the relatively wet soil conditions (Dawson 1993). All these factors enhance the chances of survival of the saplings of invasive alien plants and likely contribute towards the population dynamics of the species. It is not clear why hydraulic redistribution was not observed in the indigenous *A. karroo*. A possible reason is the fact that the lateral roots of *A. karroo* were inclined at a steeper angle into the soil (Fig. 3.7b) than those of *Prosopis* (Fig. 3.7a) which run very close to the surface. As a

result the water potential gradient was likely to be steeper between *Prosopis* stem and lateral roots than between *A. karroo* stems and the roots.

Based on the water use observations, it is therefore likely that the widely reported adverse impacts of *Prosopis* invasions on groundwater arise as a result of the ability of this species to form very high plant densities rather than high individual tree transpiration rates compared with the indigenous vegetation. Given limitations in the resources to clear alien vegetation in order to salvage groundwater, informed prioritization of clearing activities is very important. Dense and impenetrable thickets of *Prosopis* invasions are often found in riparian areas along river courses and in flood plains. The results of this study therefore support the idea that areas with dense invasions should receive a high priority for alien plant clearing programs as the chances of saving water is higher in these areas than in areas with sparse populations of *Prosopis* invasions. In addition, potential water savings as a result of clearing *Prosopis* are likely to be small in areas where there are large numbers of indigenous vegetation that use groundwater like *A. karroo* because the incremental water use by *Prosopis* will also be small.

The hypothesis that *Prosopis* trees use more water than *A. karroo* trees is not supported by the results obtained during this study. Rather it shows that the density of the trees rather than high transpiration rates by individual invasions play a bigger role in depleting water resources. Hypothesis 2 assumed that *Prosopis* trees will transpire more groundwater than *A. karroo* trees. Indeed the results show that *Prosopis* trees derived approximately 77% of their water from groundwater and 23% from the soil, while *A. karroo* trees derived approximately 53% from groundwater and 47% from the soil. The water transpired by *Prosopis* trees show a strong correlation with the changes in groundwater levels, similarly with the water transpired by *A. karroo* trees (Appendix C).

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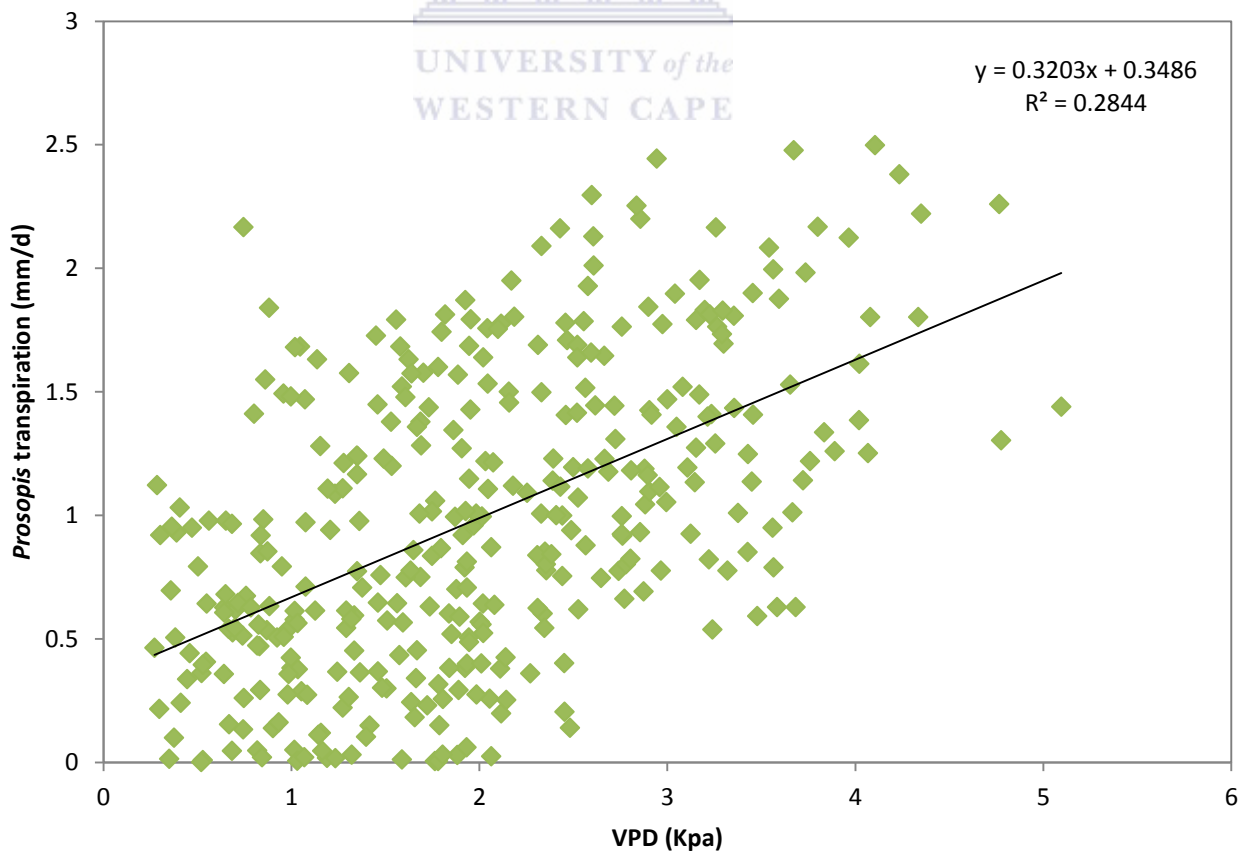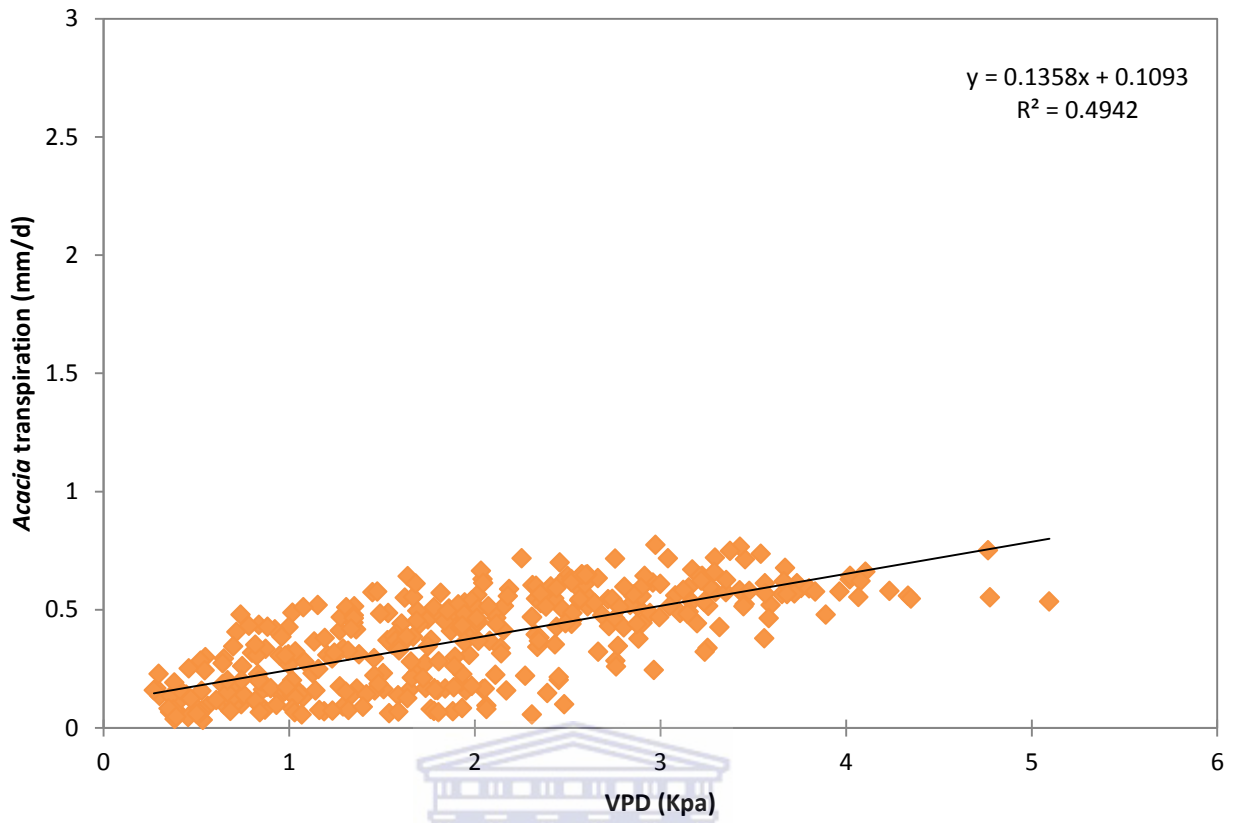
Appendices

Appendix A: Relationships between microclimate variables and species transpiration
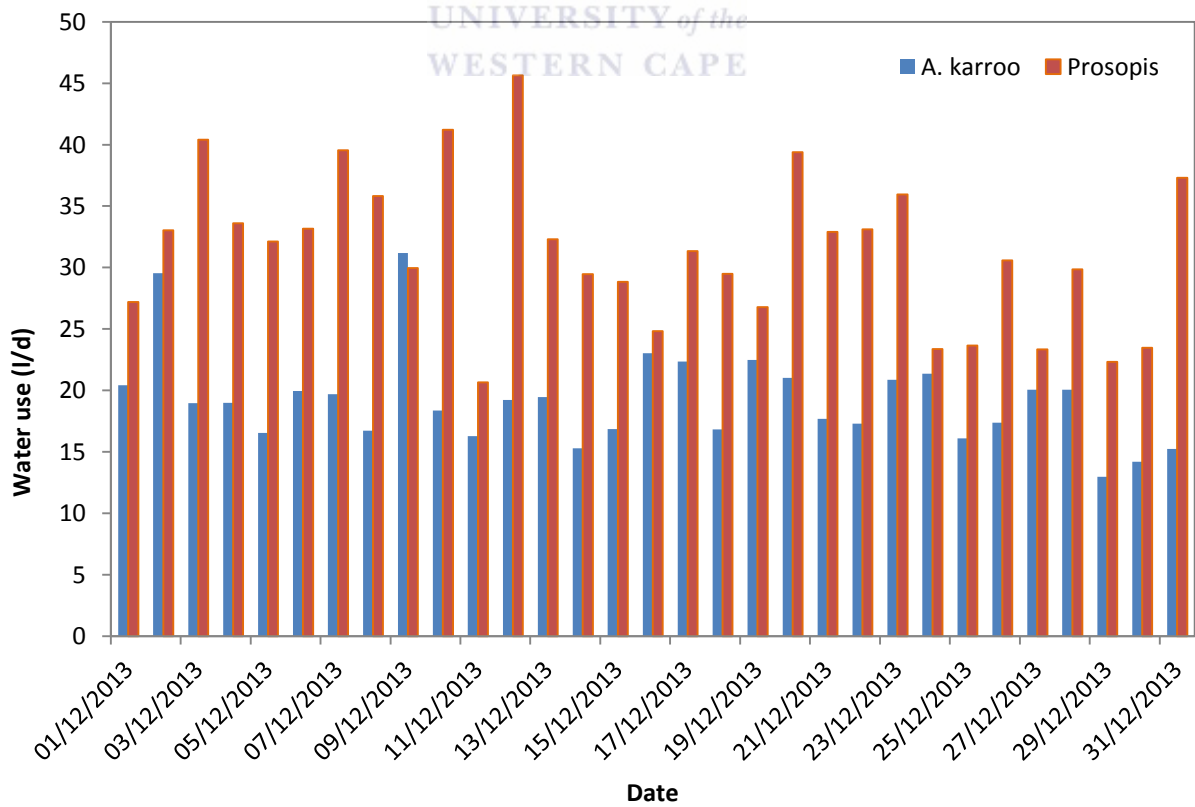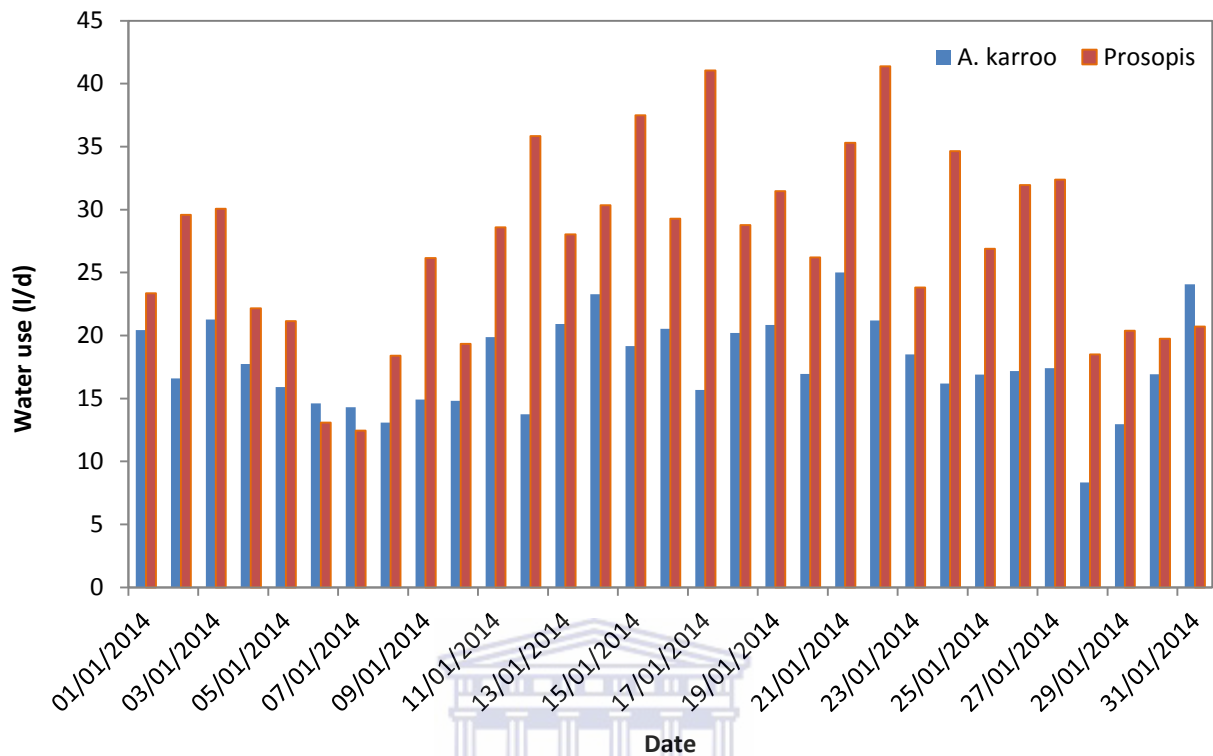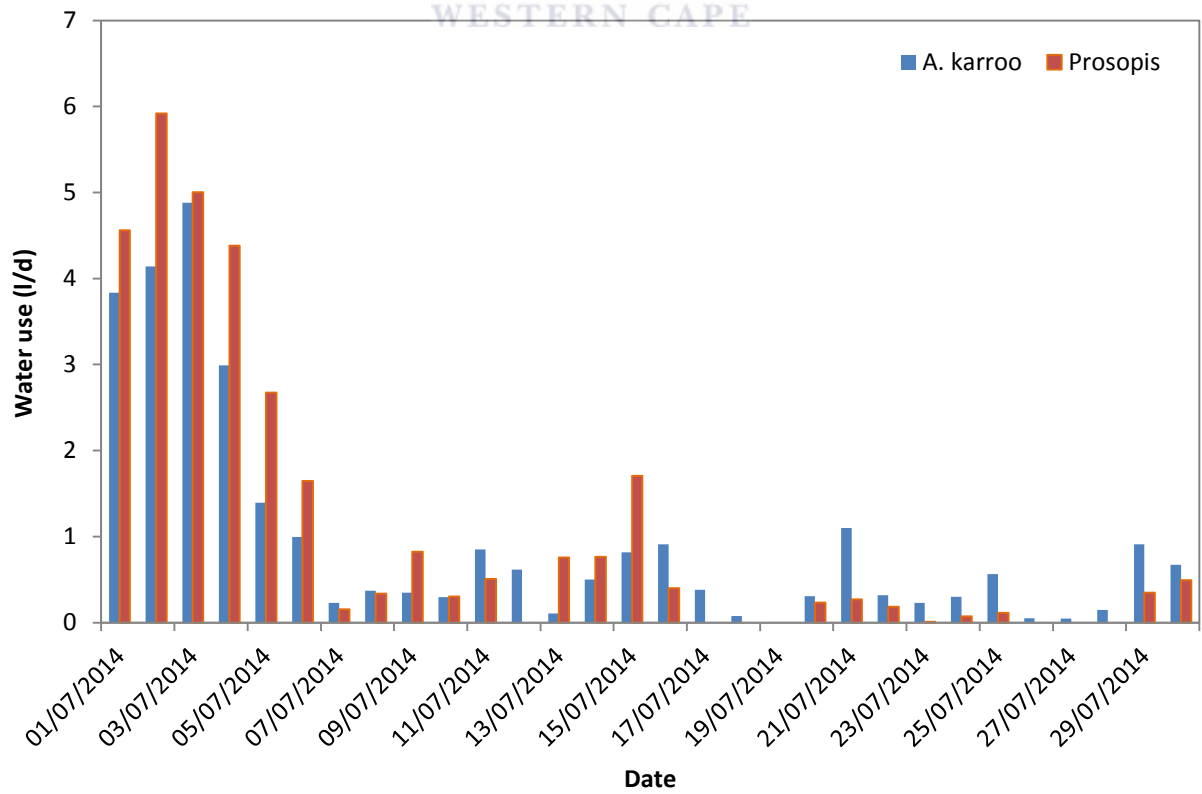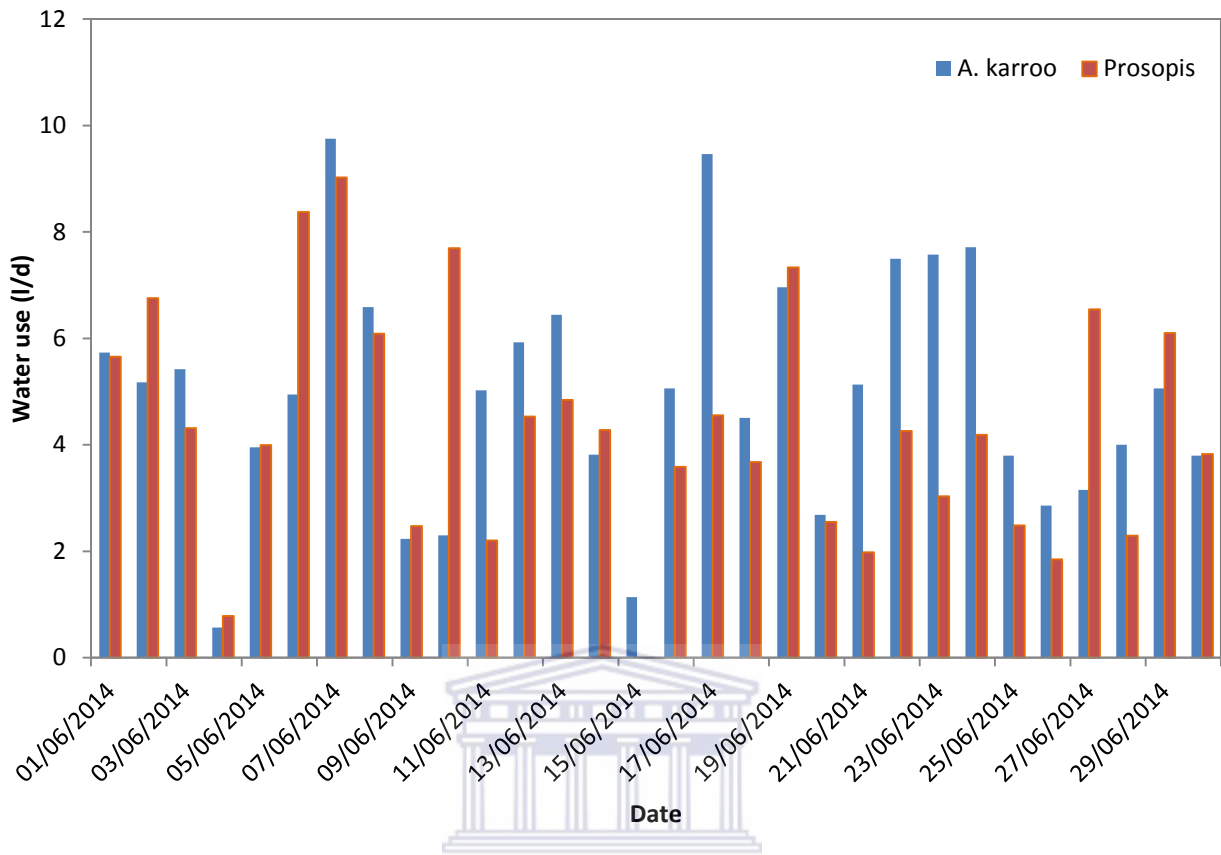

y = 0.0744x
R² = 0.5962

y = 0.1975x
R² = 0.5752
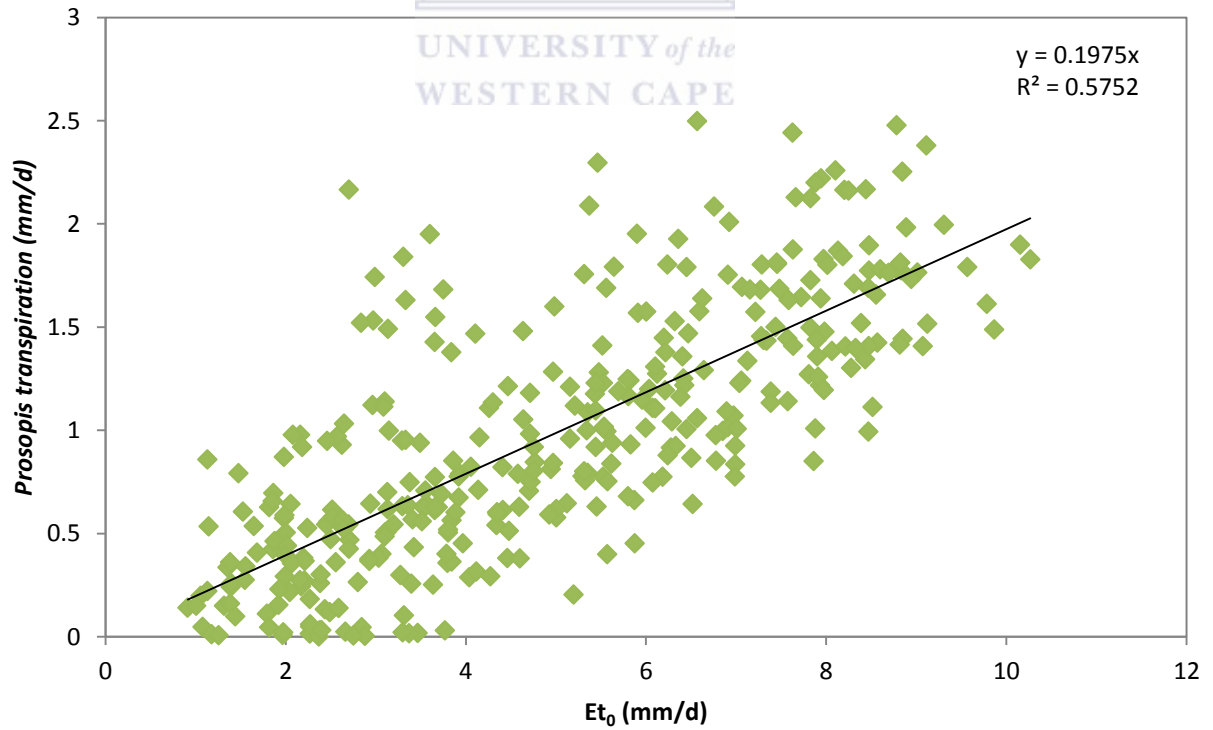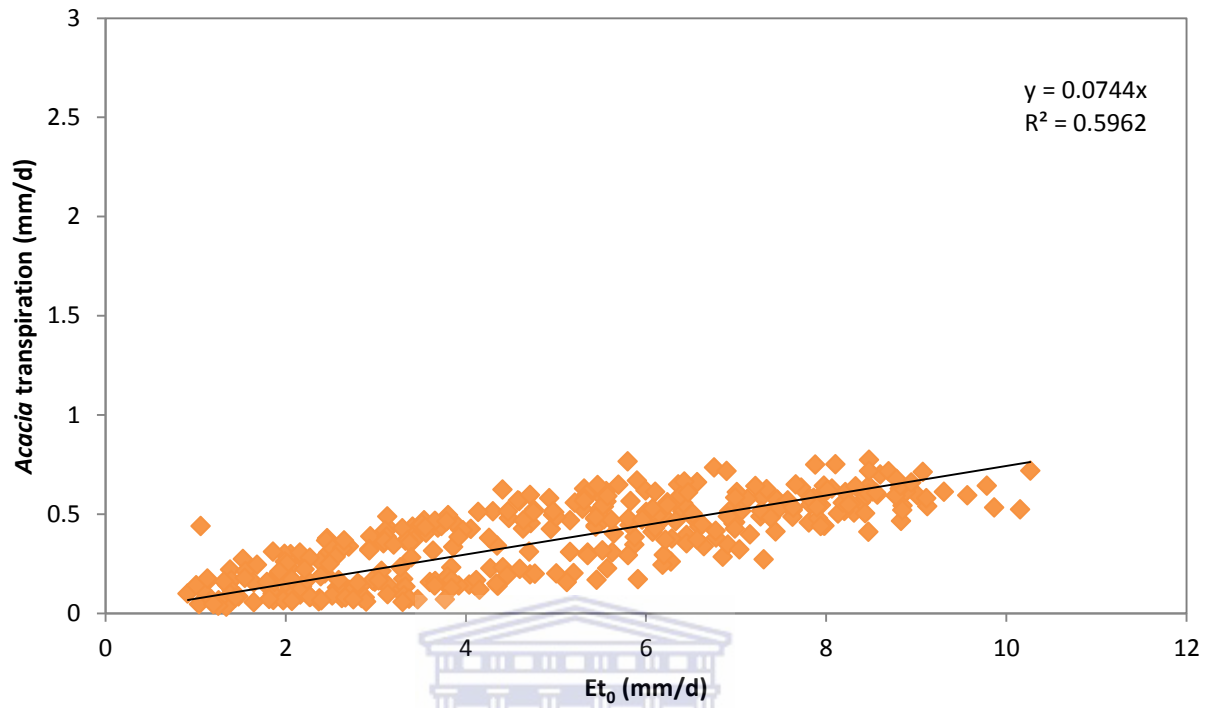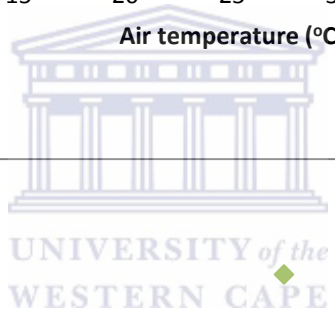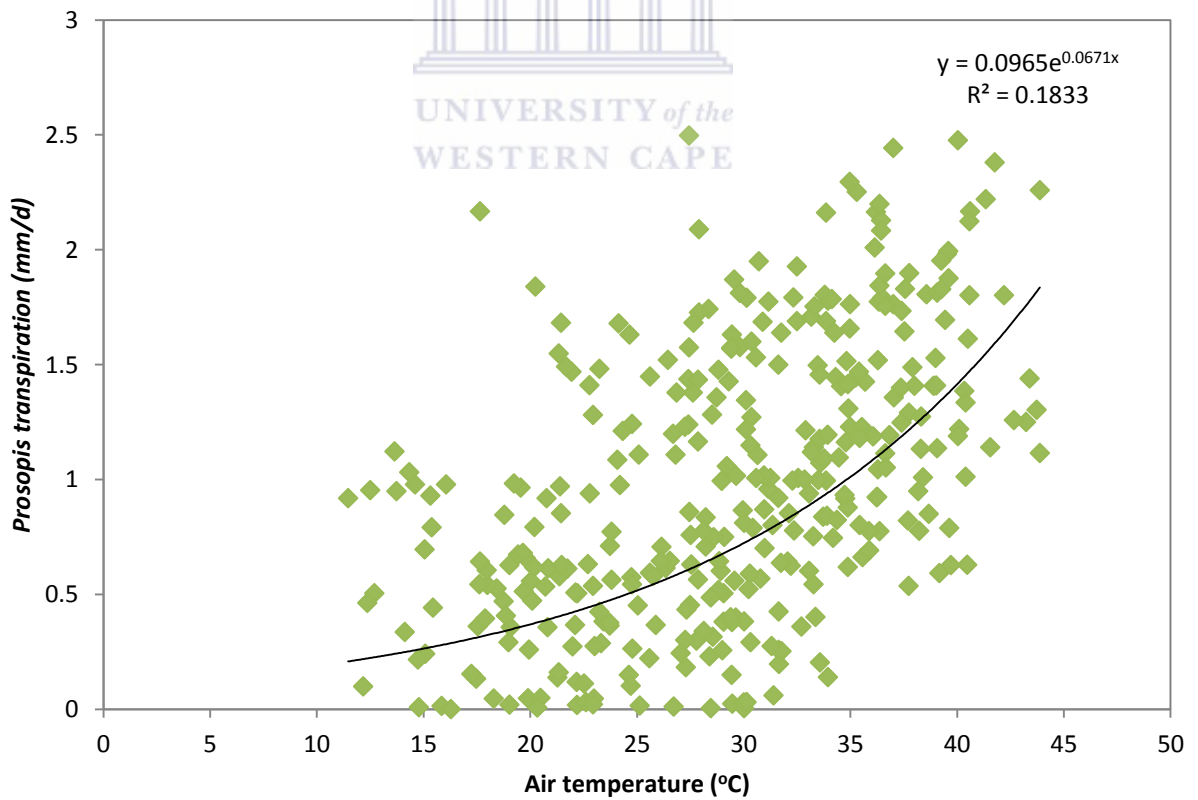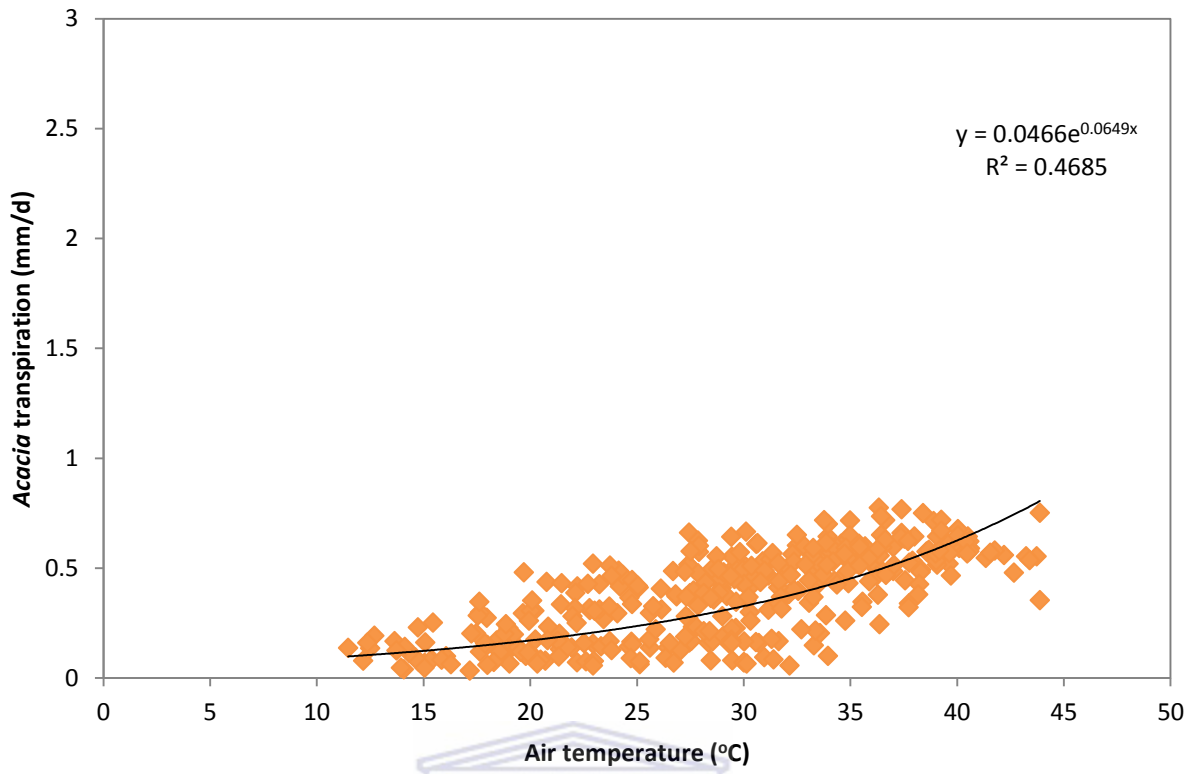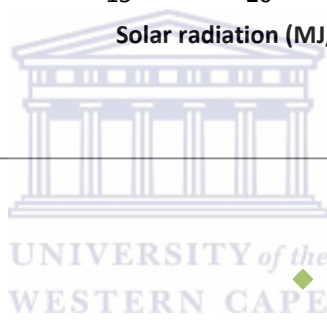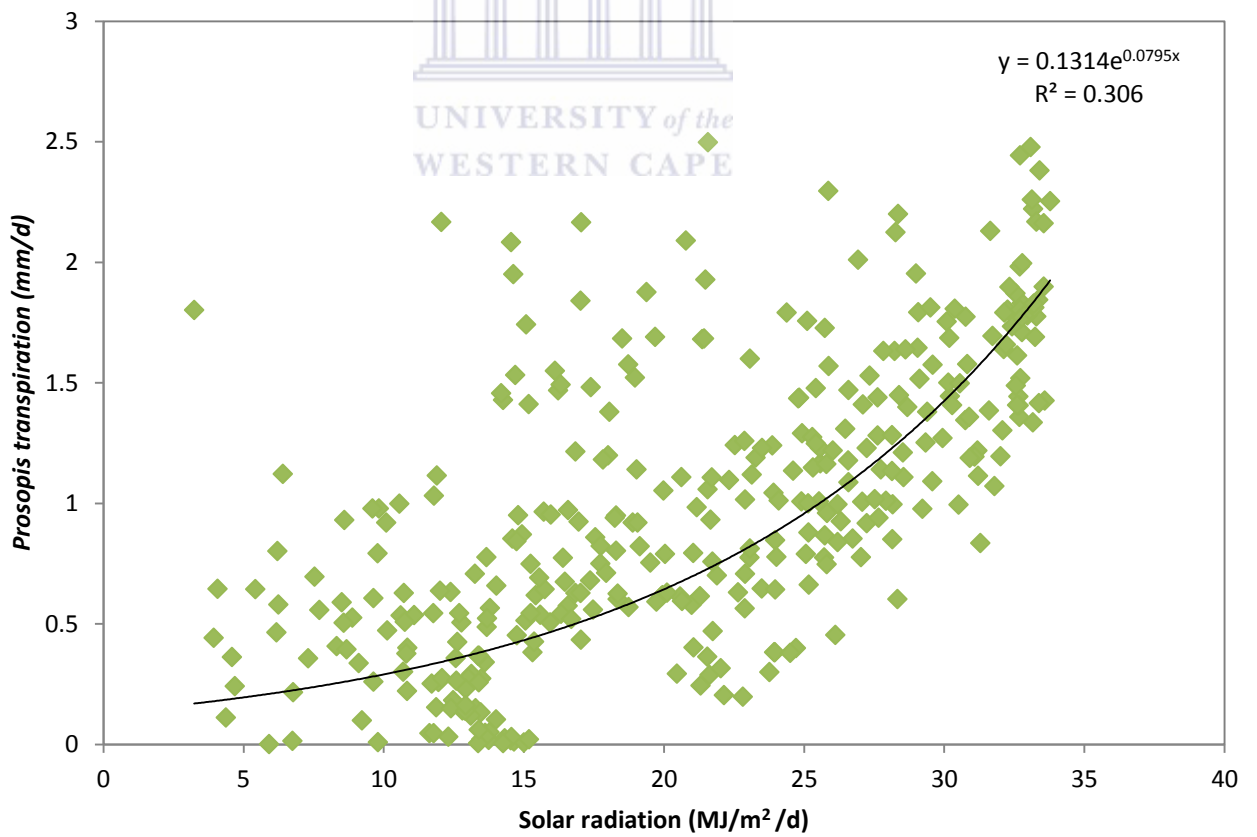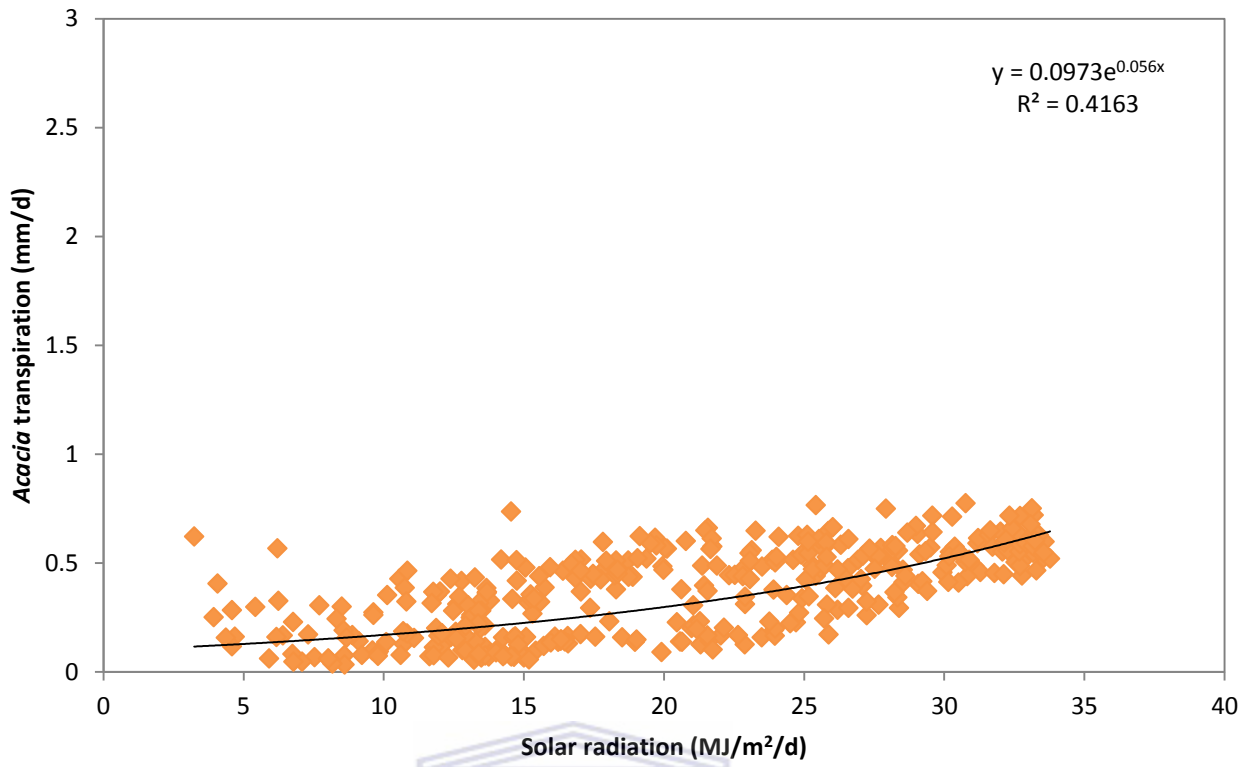
Appendix B: Water use by *A. karroo* and *Prosopis* (per tree)

Appendix C: Vegetation-groundwater interactions