An assessment of water use by *Acacia longifolia* trees occurring within the hillslopes and riparian zone of the Heuningnes Catchment, Western Cape

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ABBREVIATIONS

ABI	Agulhas Biodiversity Initiative
CSIR	Council for Scientific and Industrial Research, South Africa
CWSI	Crop Water Stress Index
DWS	Department of Water and Sanitation
EC	Electrical conductivity
ET	Evapotranspiration
ETo	Reference evapotranspiration
HPV	Heat Pulse Velocity
IAP	Invasive alien plants
MAR	Mean annual runoff
PAW	Plant available water
PM	Penman - Monteith
Q_f	Overland flow
Q_s	Lateral flow
SAI	Sapwood area index
SMAX	Maximum soil water content
SMIN	Minimum soil water content
SWB	Soil water balance
SWC	Soil water content
SWD	Soil water deficit
VPD	Vapour pressure deficit
VWC	Volumetric water content
WfW	Working for Water

ABSTRACT

An assessment of water use by Acacia longifolia trees occurring within the hillslopes and riparian zone of the Heuningnes River Catchment, Western Cape

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The increasing expansion of *Acacia longifolia* trees along the riparian zones in South Africa demands an urgent intervention as the species is listed in the National Environmental Management: Biodiversity Act (2004). This list includes species that are prohibited from growing, or being imported into South Africa. The detrimental effects of alien vegetation have been observed on the hydrology of the ecosystems invaded. However, the actual water use by *Acacia longifolia* has never been quantified. Therefore, there is inadequate knowledge of the actual rates and the differences in water use rates by *A. longifolia* occurring in the riparian zones and hillslopes. This study addresses this gap in knowledge by quantifying the diurnal and seasonal transpiration dynamics of hillslope and riparian *A. longifolia*. The variations of climate and soil water content on the hillslope and riparian zones were also examined in this study. The study was conducted on the Spanjaardskloof hills and along the Nuwejaars River (Moddervlei) in the Heuningnes Catchment, Cape Agulhas.

Water use by *A. longifolia* was quantified using the heat pulse velocity (HPV) of the heat ratio technique. Soil water variation at various depths was monitored, using soil water probes inserted at 0.1 to 0.9 m depths. Site microclimate was monitored using weather stations. The measured peak transpiration rate on the hillslopes was 1.4 mm/day and 3.5 mm/day at the riparian site during the dry season. In winter, ETo was the main driver of water use at both sites. Although riparian trees occur at close proximity to the river channel, their rate of water use was limited by increasing soil water deficit in summer. This was rather unexpected as soil water content had no influence to transpiration rates by hillslope invasions. Results suggested that transpiration by riparian invasions highly depended on water stored in the shallow soil layers, whereas hillslope invasions could possibly be using groundwater. At stand level, riparian trees transpired 146% more water than the hillslope invasions.

Overall, at the catchment scale, IAP's were using 20.5 Mm^3. The total amount of water use can reach 49 Mm^3 depending on prevailing soil water content. The results from this study agreed with other studies in literature that clearing of *A. longifolia* should be prioritised in the riparian areas as this is likely to lead to incremental water use of 17 Mm^3.

KEYWORDS

Evapotranspiration

Heat pulse velocity

Invasive plants

Sap flows

Soil water dynamics

Transpiration

DECLARATION

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I **Yonela Princess Mkunyana**, student number **3137866** declare that the thesis titled ***"Assessment of water use by Acacia longifolia trees occurring within the hillslopes and riparian zone of the Heuningnes Catchment, Western Cape"*** is my own work and that all the sources I have quoted have been indicated and acknowledged by means of complete references.

Signed this day ………… of ………..2018

Signature:

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CHAPTER 1: GENERAL INTRODUCTION

1.1 Introduction

The hydrological cycle describes the continuous movement and storage of water in different phases (Ward and Robinson, 2000; Brutsaert, 2005). The movement of water in the form of stream flow, groundwater flow and evaporation ensures the continuous transfer of water between land, ocean and the atmosphere, followed by its return as precipitation to the earth's surface (Ward and Robinson, 2000). Only a portion of precipitation reaches the ground with the remainder being intercepted by vegetation and evaporates back into the atmosphere. The portion that reaches the ground will infiltrate into the soil. The infiltrated water may flow rapidly through the near-surface soil layers and exit as springs (Brutsaert, 2005). Once the infiltration capacity of the soil in the area is reached, water will flow over the surface as runoff into streams or it may percolate into groundwater as recharge (Ward and Robinson, 2000; Brutsaert, 2005).

Evaporation and transpiration from plants (collectively known as evapotranspiration) can return about 60% of precipitation back to the atmosphere. This contribution however can be much greater in arid and semi-arid regions. Evapotranspiration (ET) is considered as the second largest flux of the hydrological cycle (Ward and Robinson, 2000; Mu *et al.,* 2011; Le Maitre, 2015). Evapotranspiration varies spatially, between uplands and low lying areas in a given catchment (Ward and Robinson, 2000). This variation is mainly controlled and accords with the variation of other physical environmental factors such as soil water, vegetation type, and climate variability.

The disturbance of the hydrological cycle processes is also caused by the transformation of catchments that result from the introduction of alien vegetation (Rogers, 2012). Invasive alien plants (IAPs) are plants that survive and rapidly expand outside their native distributional range (Van den Berg, 2010). Initially, these plants are introduced into the ecosystem due to human activity, either deliberately as commercial or ornamental garden plants, or accidentally (Enright, 2000; Mampholo, 2006). Accidental introductions occur when species are dispersed by seed pollution or by human transport, such as airplanes and ships into new geographical regions (Enright, 2000; Van den Berg, 2010). Through seed distribution by wind or birds and the lack of adequate control, invasive plants have consequently spread into natural ecosystems, hence being recognised as “invasive” (Enright, 2000). Their impacts include habitat loss, ecosystem changes, and disruption of hydrological processes.

1.2 The distribution of invasive alien plants

The diversity, abundance, and impacts of alien plants on natural systems are currently a global ecological and economic problem, especially in semi-arid countries (Tickner *et al.*, 2001; Richardson *et al.*, 2007; van Wilgen *et al.*, 2012). The taxonomic biases, geographical patterns, modes of dispersal, reasons for introductions and key issues regarding invasions of alien woody plants around the world were discussed by Richardson *et al.* (2011). The study listed regions with the largest number of woody invasive species. Australia was the leading country with 183 woody plants, followed by Southern Africa with 170, North America 163, Pacific Islands 147, and 107 in New Zealand. In Europe, there are 5 789 alien plant species, 43 of these are in riparian forests (Herbarium *et al.*, 2008). In the USA, *Tamarix* species (*T. chinensis, T. gallica, and T. ramosissim)* commonly known as saltcedar are problematic alien invaders in southern California and other areas of the southwestern United States (Hamada *et al.*, 2007). Since the introduction of these woody species to the western United States during the 19th Century, saltcedar has dominated riparian, wetland, xeric, and halophytic plant associations; and the perennial river systems in the western U.S. and northwest Mexico (Nagler *et al.*, 2005).

Invasive alien plants have been reported to threaten biological diversity by eroding gene pools and thus resulting in extinction of endemic species, especially in freshwater ecosystems (Bonanno and Bonanno, 2016). The invasions also affect vegetation dynamics by altering colonisation ability (Holmes *et al.*, 2008) because the thick and tall stands of invasive alien plants cause the indigenous understory plantations to die as a result of shading by high canopies of the alien plants. In hydrology, their impacts include reductions of stream flows (Prinsloo and Scott, 1999), lowering of groundwater levels (Dzikiti *et al.*, 2013; Fourie *et al.*, 2002; Scott *et al.*, 2008). They disturb the soil particles and expand into grazing lands (Ndhlovu, 2011), which may consequently change soil productivity.

Pines and Acacias are among the common species in many parts of the world, particularly in South Africa, and they have become invasive. Acacia is native to Australia and has been widely distributed for over a century in many parts of the world (Richardson *et al.*, 2011).

It is only recent that their detrimental impacts are recognised in semi-arid regions. The vulnerability of semi-arid countries to invasions is mostly in the riparian zones. This is aggravated by the instabilities of the riparian zones, such as the occurrence of floods, which aid in the transportation and distribution of invasive seeds. About 70% of invasive plants in South Africa originate from Australia and South America (Richardson and Kluge, 2008). Alien species from Australia reproduce quite rapidly in South Africa, due to similar climatic conditions. The rapid reproduction leads to environmental problems, such as reduction of stream flows or lowering of groundwater table in areas in which they occur (Enright 2000; Le Maitre *et al.*,2002; Chamier *et al.*,2012; Dzikiti *et al.*,2013; and Meijninger and Jarmain,2014)..

Many Australian Acacia species, including *A. cyclops*, *A. dealbata*, *A. decurrens*, *A. longifolia*, *A. mearnsii*, *A. melanoxylon*, *A. pycnantha* and *A. saligna* were introduced to South Africa in the middle of the 19th century (Richardson and Kluge, 2008). The *A. longifolia*, commonly known as long-leaved wattle is native to the southeastern coast of Australia. It is an evergreen shrub that can grow 2-8 meters high (Morais et al., 2015). It was primarily introduced in South Africa as ornamental and for sand dune stabilization and has spread along coastal areas, where it competes with and replaces the indigenous species. The bright yellow and cylindrical flowers are usually seen from August to October in South Africa (Figure 1.1). The species is highly problematic in most of the wetter parts of the Western Cape, Eastern Cape, Kwa-Zulu Natal and scattered parts of Mpumalanga Province (Henderson, 2001). The increasing expansion of *A. longifolia* trees on the hillslopes and riparian zones demand an urgent intervention as the species is listed in category 1a in the National Environmental Management: Biodiversity Act (NEMBA, 2004). This category consists of invasive species that cannot be owned, imported, grown, or sold into South Africa. In areas where they grow, property owners and government officials are required to control and/ or monitor their spread.

Figure 1.1: A typical flowering Acacia longifolia and the Trichilogaster acaciaelongifoliae (gall wasp) (Field pictures)

1.3 Strategies adopted to control or manage the spread of IAPs

To prevent the spread of invasive alien plants, South Africa established a clearing strategy through organizations, such as the Working for Water (WfW), local municipalities and property owners to be implemented in areas where benefits, such as increased surface runoff and groundwater recharge will be maximised (Meijninger and Jarmain, 2014). The objective of clearing is to enhance and prioritise the removal of alien species occurring in water sensitive areas with the intention to save water and creating employment in the process (Van Wilgen *et al.*, 2001; Richardson and Kluge, 2008).

A variety of management techniques have been used to manage *A. longifolia*. These include the biological and physical controls. The common biological control agents used are the gall wasp, *Trichilogaster acaciaelongifoliae* (Figure 1.1), and the seed-feeding weevil, *Melanterius ventralis* (Dennill & Donnelly, 1991). These insects both control *A. longifolia* at seed level. The *T. acaciaelongifoliae* affects floral and vegetative buds, causing gall formation that terminates the development of buds, while *M. ventralis* preys on seeds that are unaffected by *T. acaciaelongifoliae* (Dennill & Donnelly, 1991).

The physical management techniques used on *A. longifolia* include felling the alien trees (Figure 1.2) and applying herbicide on the stumps thereafter. This prevents the plants from re-sprouting (Richardson and Kluge, 2008). The Agulhas Biodiversity Initiative (ABI) clearing projects under the Nuwejaars Wetland Special Management Area and the Spanjaardskloof residence organization were formed in collaboration with the government, land-owners (farmers), and non-governmental organizations with the aim to clear invasive alien plants in the Heuningnes catchment.

Figure 1.2: Clearing of Acacia trees in a farmland situated on the Spanjaardskloof hills in 2016

Forsyth *et al.* (2009) highlighted that the Heuningnes Catchment falls within the top five of the main primary catchments that are invaded within the Western Cape Province. The study identified the highest priority for managing invasive alien plants within the Western Cape and compared them with the current budget allocations. The highest priority catchments were those that occur in mountainous areas and yield large volumes of water for domestic, industrial and agricultural water supply in the province. The quaternary catchments G50 B&C in the Overberg District were considered as high priority catchments and received a large budget, probably because they are situated within a national park (Figure 1.3 and 1.4).

The Nuwejaars River crosses through quaternary catchments G50 B&C, where invasive alien trees were found to be a problem.

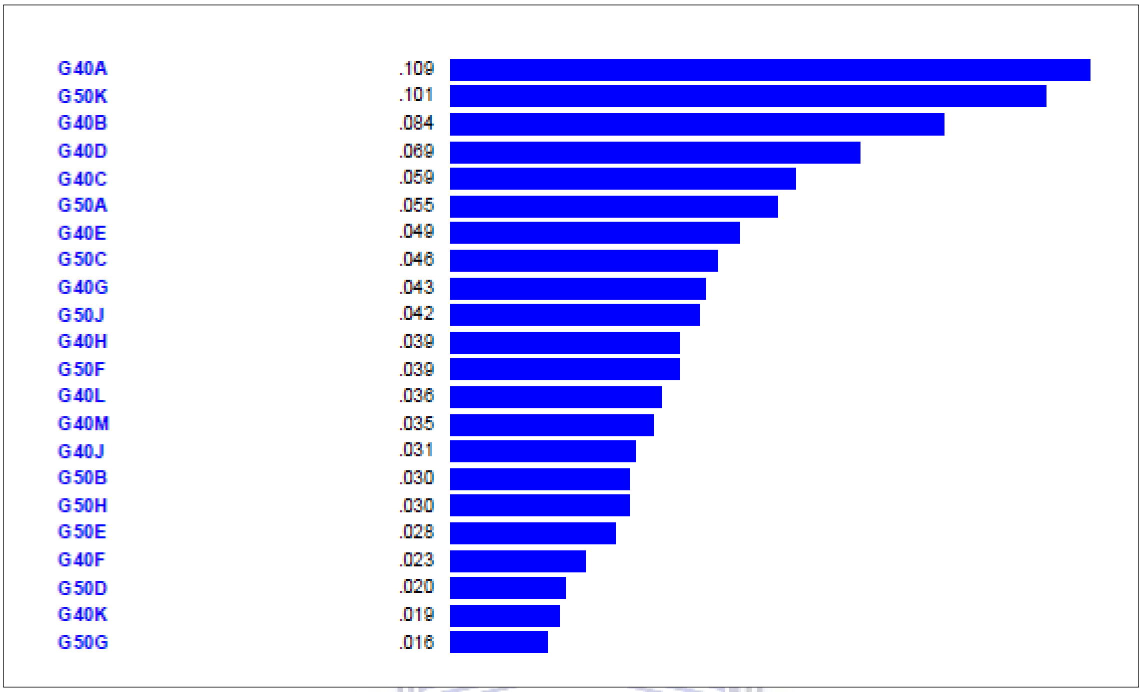

Figure 1.3: The importance and ranking of the 22 quaternary catchments in primary catchment G2 (Overberg) adopted from Forsyth et al. (2009).

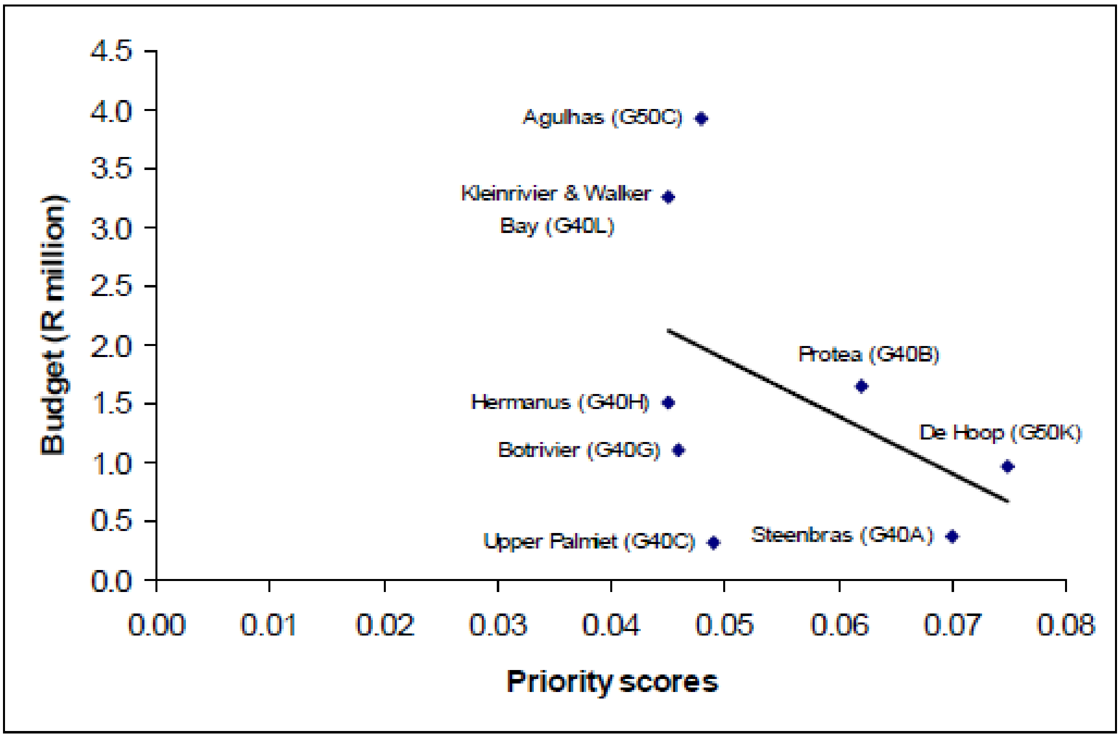

Figure 1.4: The 2009/10 budget for IAP clearing projects in the Overberg District (Source: Forsyth et al., 2009).

1.4. Effects of alien invasions on catchment processes

Changes in hillslope hydrological regime affect the downstream water availability and the overall water balance of the catchment (Mul, 2009). Quantifying runoff components and identifying the dominant hydrological processes is critical for sustainable water resources management (Gebrekristos, 2015). It is also understood that the transformation of many catchments is caused by the presence of invasive alien species (Le Maitre *et al.,* 2002; van Wilgen *et al.,* 2004). Therefore, it is crucial to understand how invasions affect hydrological processes of landscape units that they mostly dominate, namely the hillslopes and wetlands.

Soil water controls the interactions between the land surface and the atmosphere and thus influences catchment processes, such as runoff generation, evapotranspiration, and drainage to groundwater and streams (Western *et al.,* 2002). Soil water affects the rainfall-runoff response of catchments and a variety of processes related to plant growth, soil processes, and the water balance of the area (Western *et al.,* 2002; Bittelli, 2011). The presence of invasive alien plants can also affect soil water evaporation by forming dense canopies which minimizes the amount of solar radiation reaching the surface, therefore, lowering the rate of soil water evaporation under the canopies.

Alien vegetation with dense canopies also intercept precipitation and increase infiltration through stem flow and their root networks. According to Horton (1933), some of the precipitation that reaches the soil surface infiltrates and percolate into groundwater. The portion that cannot infiltrate on the hillslope flows down the slope as overland flow and into the streams (Selby, 1993). Consequently, the rapid or slow responses on hillslopes affect the magnitude of storm flow peaks (Lorentz *et al.,* 2004). Some of the infiltrated water on the hillslope is lost through lateral flow. The lateral flow then redistributes soil water often leading to soil saturation and generation of saturation excess runoff from uplands to low-lying areas (Western *et al.,* 2002). Thus, the riparian zones tend to be moist and nutrient rich. Thus, causing them to be extremely important in sustaining ecosystem services by providing buffer zones that filter sediments, stabilizing banks, water storage, moderating stream water temperature through evapotranspiration and shading, and enhancing aquifer recharge (Richardson *et al.,* 2007; Freitag, 2014).

Riparian vegetation changes the riparian hydrology by delaying the rate of infiltration of surface water into the hyporheic zone through interception, trapping of fine sediments during high flows and high water consumptions, especially the deep-rooted alien vegetation (Tabacchi *et al.,* 2000; Dzikiti *et al.,* 2013). The invasion of riparian zones changes the composition of the indigenous communities and the way the catchments respond to natural disturbances which further results in invasion, bank instability (Rowntree, 1991), and the reduction in river water quality due to their ability to fix nitrogen (Le Maitre *et al.,* 1995; Fourie, 2012).

The expansion of invasions in a catchment alters both the hillslope and riparian hydrological processes. Therefore, the invasion of alien plants in catchments plays a major role in shaping the terrestrial water balance (Enright, 2000; Rascher *et al.,* 2011). However, there are few direct methods to investigate the impact of vegetation change on the hydrological cycle, due to complex interactions between the vegetation functioning (for example, ecological strategy, water use efficiency, phenology) and the abiotic characteristics of ecosystems (i.e. precipitation regime, groundwater depth) (Rascher *et al.,* 2011). The invasion of hillslopes by alien vegetation does not only affect habitats along the hillslope, but also the adjacent low lying areas, such as downstream water availability (Mark and Dickinson, 2008). Thus investigating how plant invasions affect the catchment hydrological processes is essential for developing appropriate management policies.

1.5 Research Problem

About thirty-one (31) Australian *Acacia* species are in the top 200 environmental weeds invading natural or near-natural habitats (Henderson, 1998) and they are major invaders in many parts of the world including South Africa (Kotze *et al.,* 2010; Le Maitre *et al.,* 2011; van Wilgen *et al.,* 2011). These Acacia species have various ecological and socio-economic impacts and the magnitudes of the impacts are increasing (Le Maitre *et al.,* 2011). Le Maitre *et al.* (2000) estimated that approximately 643 000 hectares of land in South Africa are invaded by the Australian Acacia species. The most recent estimates by Kotze *et al.*(2010) suggests that the invasions have declined to 554 000 hectares, due to the biological control of *A. cyclops* and *A.saligna*, as well as to the intensive harvesting of fuel wood (Fourie, 2012).

In South Africa, the Australian Acacias mostly invade the riparian zones, the wetter catchments of the coastal mountain ranges and the coastal lowlands of the Western Cape Province (Brown *et al.,* 2004; Fourie, 2012). Thus, the increasing invasions of this species have been a major concern for many catchments in the Province. The Heuningnes Catchment in the Cape Agulhas is among the heavily infested regions in the Western Cape Province. The area is identified as a biodiversity hotspot. This is due to the presence of fynbos vegetation in the catchment, which consequently attracts various bird species. However, invasive alien plants threaten the exceptional biodiversity (Nowell, 2011). *Eucalyptus*, *Pinus* and *Acacia* (*Acacialongifolia, A. cyclops*and *A. saligna*) are the dominant genera in this catchment (Visser, 2001; Nowell, 2011). They account for 93% of the alien plants that have heavily infested the mountains and riparian zones of the Heuningnes catchment, thus adversely affecting the available water resources. However, there are no previous studies that have investigated the significant differences in water use rates by Australian Acacia invasions on hillslopes and riparian zones in the Western Cape (Fourie, 2012).

1.6 Research Questions

- What are the seasonal and annual water use patterns by *Acacia longifolia* invasions, and how these rates are influenced by location in the landscape?
- Are there significant differences in climate and soil variability on the hillslope and riparian zones?

1.7 Hypothesis

The hypothesis of this study is that *Acacia longifolia* trees invading riparian zones have access to readily available water and therefore consume more water than those growing on the hillslopes which are likely to have low water tables.

1.8 Aim and objectives

The current study aims to compare the temporal variability of water use by riparian and hillslope *Acacia longifolia* trees in the Heuningnes Catchment of the Western Cape Province. This study will contribute towards improving knowledge on the water use and hydrological impacts of *Acacia longifolia* species whose water use characteristics are still unknown. This information will contribute towards improved decision-making by programmes, such as the Working for Water to help them focus their management (clearing) on priority species and areas.

Specific objectives are:

- To determine if there are any significant differences in transpiration rate between *A. longifolia* on hillslopes and riparian zones
- To determine the influence of soil water content and atmospheric evaporative demand in transpiration rates differences between the hillslope and riparian site

1.9 Rationale

The Western Cape Province suffers from the largest invasion of alien plant and the areas affected call for urgent control measures (Enright, 2000). This is because the infested mountain catchments are considered to be the main sources of the country's water supply (Nel *et al.*, 2013). The Acacias are major invaders and they threaten the fynbos shrublands in the Province. With South Africa being semi-arid, it is essential to manage or minimise the impacts of invasive alien plants on our water resources. Numerous studies have shown that invasive alien plants reduce surface runoff and groundwater recharge (Le Maitre *et al.*, 2002; Chamier *et al.*, 2012; Meijninger and Jarmain, 2014). A recent study by Dzikiti *et al.* (2016) showed that each hectare of land invaded by the invasive *Eucalyptus camaldulensis* along the Berg River used an additional ~ 2 million litres of water per year above that used by the indigenous vegetation growing along the same stretch of river. Therefore, there is a need for detailed studies to understand how specific invasive influence the water resources, in order to make informed decisions on how to manage the invasions.

In South Africa, detailed water use data on the Australian Acacias exists only for *Acacia mearnsii* (black wattle) (Clulow *et al.*, 2011; Dye *et al.*, 2004). Little is known about the water use patterns by other Acacia species. It is important to investigate and compare the diurnal and seasonal water use patterns of other species, such as *Acacia longifolia* to understand how the water use is influenced by environmental factors and to quantify the impacts on water resources. Thus, results from this study are essential not only for understanding the hydrological impacts of Acacias growing on riparian and non-riparian zones, but also for facilitating decision-making in governmental programmes, such as the

Working for Water or any other projects that prioritise the clearing of invasive alien plants. As South Africa is a semi-arid country with limited resource, it is therefore critical to quantify water use spatially and temporally to inform decision-makers on the sustainable use and management of the resource (Ramoelo *et al.*, 2014).

1.10 Research outline

Chapter 1 introduces the impacts of invasive alien plants on the hydrological cycle / processes. This section also elaborates on the rationale, aim and objectives of the study. A summary of discussions, theories and debates regarding the impacts of invasive alien plants on water resources are included in *Chapter 2*. *Chapter 3* describes the characteristics of the catchment in which the study was conducted on, and the sites that were selected to conduct the study. Climate and soil water variations are described in *Chapter 4*. The diurnal and seasonal transpiration dynamics are discussed in *Chapter 5*. Lastly, the general conclusions and recommendations of the study are described in *Chapter 6*.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

This chapter reviews the discussions and studies that were done to assess the impacts of invasive alien plants on water resources. The theories and principle of the different approaches that have been used to quantify water use by trees will be examined. Thereafter, the knowledge gap that will be addressed by this study will be established from what is not known about this topic.

2.2 The extent of invasions in South Africa

The extent of transformation and degradation of ecosystems, due to alien invasions is a global and economic problem (Versfeld *et al.*, 1998; Fourie, 2012). The spread of invasion is considered as the second largest threat to indigenous species and water yield in South Africa (Fourie, 2012). In South Africa, about 10 million hectares of land is estimated to be invaded by alien plants (Le Maitre *et al.*, 2000). Recent surveys by Kotze *et al.* (2010) and van den Berg (2010) showed that the extent of invasion increased from 1736 million hectares estimated in 1996 to approximately 1813 million hectares in 2008. These plants consume 6.7 % and 15.8 % of the Mean Annual Runoff (MAR) at the national level and in the Western Cape Province respectively (Enright, 2000; Le Maitre *et al.*, 2000; 2012; Shackleton *et al.*, 2015). Such water use is an environmental problem in a country like South Africa where average precipitation is approximately 500 mm per year, which is below the world average of 860 mm per year (Fourie, 2012). Consequently, legislation that prohibits the plantation of alien vegetation was enacted to protect the riparian areas where the greatest impacts are on the river flows (Dye and Versfeld, 2007). Despite these efforts, the thick and dense self-established invasive alien stands are still occupying river systems and they are expanding their range in South Africa (Figure 2.1) (Le Maitre *et al.*, 2002; Dzikiti *et al.*, 2016). Although the management or monitoring of alien trees has focused on the riparian zones, but, the mountain catchments in the Western Cape have a very significant role in the water supply and conservation of indigenous vegetation (Scott *et al.*, 1998). They cover about 10% of the land surface area and yet yield over 50% of water (Hosking *et al.*, 2002). Therefore, they have high conservation value and provide valuable ecosystem services such as water supply (Paulchard *et al.* 2009, Nel *et al.* 2013). It is therefore important to understand the implications of invasive alien trees occurring both on the hillslopes and riparian zones as Le Maitre *et al.* (2000) estimated that over 3000 million m^3 (~ 7%) of surface runoff is lost annually to invasive alien plants.

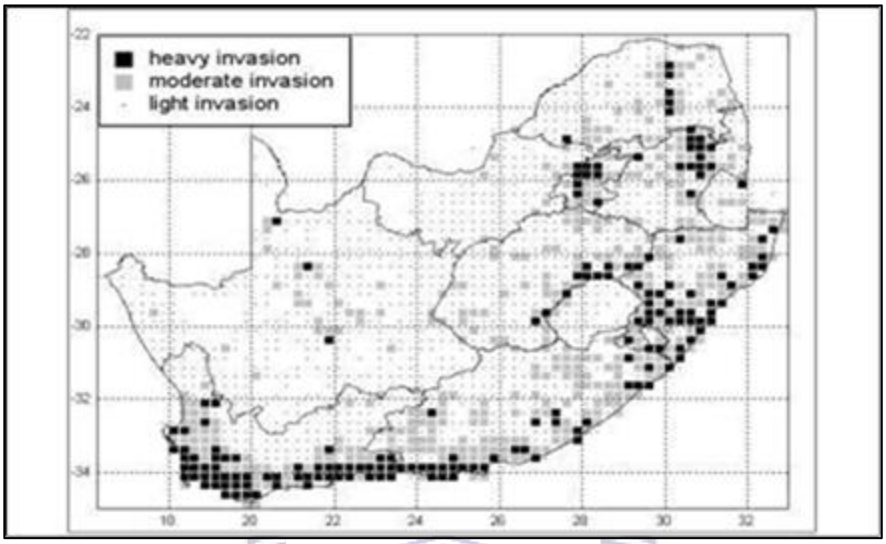

Figure 2.1: Distribution and abundance invasive alien plants in the Southern African region (Source: Henderson, 2007)

The riparian zones in South Africa are vulnerable to invasions by alien species (Le Maitre *et al.*, 2000; 2002, Richardson *et al.*, 2007; Fourie. 2012). The South African Plant Invaders Atlas (SAPIA) illustrates that the Western Cape Province is the most invaded region of the country where a large number of invasive species are found along the eastern seaboard and into the eastern interior (*Figure 2.1*) (Richardson and van Wilgen, 2004). The riparian vegetation in the winter rainfall region of South Africa is mainly impacted by Australian Acacias (e.g. *A. mearnsii, A. longifolia, A. saligna*) and Eucalypts (e.g. *Eucalyptus camuldulensis*) species, due to reliable availability of water in the riparian zones (Reinecke *et al.,* 2007). To improve knowledge about the above-mentioned impacts, there are several studies done in South Africa that quantified the water use by invasive alien plants (Dzikiti *et al*., 2013; 2016; Everson *et al.,* 2014; Scott – Shaw *et al.,* 2017).

2.2.1 Assessing water use by invasive alien plants

A paired catchment study was conducted by Scott (1999) in the Western Cape Province of South Africa to investigate the response of stream flows following the clearing of riparian invasions on three catchments. The results showed that clearing the riparian alien vegetation resulted in an increase in stream flows from 55 to 110 mm/year compared to an increase of 27 to 35 mm/year that was observed when 10% of the non-riparian plantations were cleared. The water salvaged was attributed to the ability of riparian vegetation to have access to multiple sources of water, which include the recent rainfall, soil water, stream water and groundwater. These results validated that riparian vegetation use more water than vegetation growing in other parts of a catchment and that clearing of vegetation in the riparian zone of the catchment will result in greater gains in water yield than would result from clearing similar vegetation elsewhere in the catchment. Nowell (2011) also confirmed these results on a study that illustrated the benefits of clearing invasive alien plants on the water resources of the Agulhas Plain. Furthermore, Doody *et al.* (2011) added that the possibility of water salvage when the alien vegetation is cleared and replaced by native species is determined by the rate of water use that the replacing species has relative to the water use by the cleared species. These studies highlighted the importance of understanding the water use patterns of the rehabilitating species after clearing has been done.

In contrast to these studies, the current study seeks to examine the rate of water used by *Acacia longilolia* that grow under different conditions, mainly controlled by water availability. An example of such study is one that was done by Dzikiti *et al.* (2013) to quantify the water use by invasive alien plants, namely *Pinus pinaster* and *P. halipensis.* The study compared the water use by *Pinus* species growing on riparian and non-riparian sites in the Western Cape. These species are not a high priority since the previous literature has highlighted that the Australian Acacias are problematic species that has intensively invaded the riparian zones in the Western Cape (Reinecke *et al.*, 2007). Tree water-use was estimated using the Heat Pulse Velocity (HPV) of the heat ratio technique which is a reliable method for directly quantifying water use by woody plants (Dye *et al.*, 1996). The results from the study by Dzikiti *et al.* (2013) highlighted that there were differences in the morphology of the same species but growing under different conditions. The riparian species have bigger and larger stems compared to those that grow on the non-riparian site. The annual transpiration rate from the riparian Pines was 36% more than those occurring in non-riparian settings. These results justified the high priority given to clearing invasive trees in riparian zones.

2.3 Common methods used to quantify the rates of water-use by IAPs

Water use rates by alien plants have been studied using different techniques, such as stable isotope ratios in xylem sap to determine the fractional use of different water sources (Ehleringer & Dawson, 1992; Dzikiti *et al.*, 2013). Water budget methods, such as lysimetry and the water balance of a basin. The water vapour transfer methods, such as the Bowen ratio and eddy covariance, as well as large scale evaporation methods using scintillometers (Tian *et al.*, 2013) have been used to estimate water use by plants. Local scale methods, such as the FAO56 method that is based on the Penman-Monteith equation (Allen *et al.*, 1998), or sap flow measurements (Bastiaanssen *et al.*, 2001) have also been used to estimate water use by plants. The strengths and weaknesses of these methods are described below.

2.3.1 Empirical models

The empirical methods that were developed to estimate crop reference ET use weather variables and adjusting this by an appropriate crop coefficient (Kc) (Subedi & Chavez, 2015). This includes the Blaney-Cridle Method, Thornthwaite Method, Hargreaves equation, Priestley Taylor Method, and the Penman – Monteith equation (Subedi & Chavez, 2015). From these methods the Penman - Monteith equation is considered to be a robust method to estimate crop ET (Allen *et al.*, 1998; Subedi & Chavez, 2015). However, the method has some limitations. There is a problem to estimate appropriate surface resistance which is very important for estimating the rate at which water is lost through the stomata (Subedi & Chavez, 2015). The exclusion of surface temperature while deriving the PM equation can induce errors especially in areas where surface temperature and air temperature are significantly different (Subedi & Chavez, 2015). However, among other models, the Penman Monteith (PM) equation was found to be more consistent over a wide range of climatic conditions. The robustness of the PM method has been demonstrated as the method does not require local calibrations, provided there are complete input data. The PM equation also does not have any wind function. Rather, it has aerodynamic and surface resistance terms.

2.3.2 Surface energy balance models

Over the last few decades, the introduction of satellite remote sensing has led to a substantial amount of work in resolving whether such systems can provide spatially explicit information relating to surface fluxes (Liou *et al.,* 2014). Satellite remote sensing techniques have become attractive for the retrieval of these parameters because of their ability to provide repetitive and synoptic views in a spatially contiguous manner without any disturbance and site accessibility issues in the area to be surveyed (Liou *et al.,* 2014). Consequently, remote sensing has been used to observe and monitor the spatial variation of hydro-meteorological variables and fluxes over large areas (Schmugge *et al.*, 2002). This has led to the innovation of advanced technologies that estimate ET (Nouri *et al.*, 2013) and be applied at large scales (Revollo, 2010). Courault *et al.* (2005) classified these satellite-based methods into Empirical Direct Methods, Residual Methods of Energy Budget, Deterministic Methods and Vegetation Index Methods. Remote sensing methods generate surface parameters on a pixel scale and are suitable for spatial modelling of ET (Revollo, 2010).

SEBAL and SEBS are examples of models that estimate ET from the combination of empirical relationships and physical components (Courault *et al.*, 2003; Revollo, 2010). They generate a series of atmospheric variables from remote sensing data and assume semi-empirical relations to estimate emissivity and surface roughness. To estimate the sensible heat flux, an area has to be divided into the wet and dry land (Courault *et al.,* 2003). Remote sensing models have been commonly used for estimating ET at large scales with the advantage of broad spatial coverage with high temporal, spatial, and spectral resolution. Nonetheless, there are some parameters that have been reported to be difficult to estimate, such as the stomatal resistance and temperature which can lead to model errors. Not much has been done to show the performances of these models at different spatial scales and the related errors. Dzikiti *et al.* (in review) added that irrespective of the advances in remote sensing models, there are still gaps that exist with regards to the accuracy of the models, particularly in arid and semi-arid environments. Jarmain (2010) attributed the limitations of remote sensing models to the limited availability of high - spatial and temporal resolution thermal infrared imagery needed on the energy balance approach, the scattering and the absorption of radiation by clouds. Furthermore, the temporal and spatial scales of earth observation data are not sufficiently high for use in the estimation of spatially distributed ET for on-farm irrigation management purposes (Gibson, 2013).

The MODerate Resolution Imaging Spectroradiometer (MODIS) MOD16 algorithm was developed by Mu *et al.* (2007a, 2011) to provide the global estimates of ET (Ramoelo *et al.*, 2014). MOD16 is a remotely sensed ET model that is based on the Penman–Monteith approach (Cleugh *et al.*, 2007) with some modifications that account for parameters that are not readily available from space (Mu *et al.*, 2011; Wang *et al.*, 2012). The algorithm accounts for both surface energy partitioning and environmental constraints on ET. The algorithm also includes canopy transpiration, canopy evaporation, and soil evaporation (Wang *et al.*, 2012). Terrestrial ET includes evaporation from wet and moist soil, evaporation from rain water intercepted by the canopy before it reaches the ground, the transferred water vapour from ice and snow and the transpiration through stomata on plant leaves and stems (Mu *et al.*, 2011).

The limitations of the MOD16 ET comes with the coarse spatial resolution of 1 km^2 (Ramoelo *et al.*, 2014) which cannot be easily compared to point or field measurements. The inconsistency of the spatial resolution of the input data sets, especially for regions with strong climatic gradients can introduce errors (Region *et al.*, 2013). Even though this product has been calibrated and validated in many countries in the North and South America, Europe, Asia, and Australia. There are still inaccuracies such as over- or underestimation which are not known in South African ecosystems (Ramoelo *et al.*, 2014).

2.3.3 Experimental Methods

Lysimeters

Lysimeters are used for estimating ET from the differences between the amount of precipitation received at an area and the amount lost through the soil (Seyfriend *et al.*, 2001). There are two main types of lysimeters; the drainage and the weighing types. Using drainage lysimeter, evaporation is obtained as the difference between the added and drained water quantity. In weighted lysimeters, changes in the total weight of the soil sample are measured (Johnson and Odin, 1978); where ET is estimated:

$$ET = P - \frac{V_l + V_r + \Delta V_s}{A} \quad (2.1)$$

P is the precipitation, Vl is the volume drainage loss m^3, Vr is volume of surface runoff m^3, ΔVs is the change in the volume of soil water in the lysimeters and A is the area of the lysimeters m^2 (Seyfriend *et al.*, 2001).

The limitation of using lysimeters is that ET estimates are made for a single point and may not be applicable to large areas (Johnson & Odin, 1978). Lysimeters are also difficult and expensive to construct and maintain.

Eddy Covariance

The eddy covariance is a method of estimating turbulent fluxes and ET. This technique provides continuous measurements of long-term fluxes above a canopy at a high temporal resolution (Shi *et al.*, 2008). Simultaneous measurements of sensible heat flux and other trace gas fluxes, such as carbon dioxide, are feasible (Petropoulos *et al.*, 2013). In this method, sensible and latent heat fluxes are measured directly. Eddies are turbulent airflows caused by wind, the roughness of the Earth's surface, and convective heat flow at the boundary between the Earth's surface and the atmosphere (Shi *et al.*, 2008).

The advantage of using eddy covariance is that soil surface heterogeneity issues are eliminated by placing the sensors above the crop canopy, and ET can be measured from various type of vegetation. The technique allows for direct, continuous and tower-based ecosystem-scale estimation of surface – atmosphere scalar fluxes by simultaneous sampling of atmospheric fluctuations of wind and scalars (Sievers *et al.*, 2015). The weakness of this method is that the measurements are sometimes difficult to interpret when the atmospheric turbulent is weak, which occurs at night (Shi *et al.*, 2008). The system does not provide spatial trends (or distribution) at the regional scale especially in regions with changing climatic conditions (Liou *et al.*, 2014)

Scintillometer

Sensible heat flux (H) is an important energy dissipation component in surface energy balances and evapotranspiration (ET). A scintillometer is a method to estimate H over a relatively large area by directing a light beam between a transmitter, and a receiver. The receiver records and analyses fluctuations in the turbulent intensity of the air refractive index caused by changes in temperature and humidity, due to heat and moisture eddies (Moorhead *et al.*, 2017). The benefit of a scintillometer over other flux measurement instruments is the ability to determine spatially averaged sensible and latent heat fluxes over heterogeneous terrain at scales up to 10 km. In addition, scintillometry does not require corrections (such as frequency response corrections for eddy covariance). The disadvantage is that a scintillometer cannot determine the direction of sensible heat flux (H), so the temperature difference from additional temperature sensors or other methods must be used to determine the flux direction (Moorhead *et al.,* 2017).

Sap flow methods

Sap flow methods are divided into three categories, those which use a pulse of heat and include the heat ratio (HR), compensation heat pulse (CHP), calibrated average gradient and sap flow methods. The methods that continuously apply heat include the thermal dissipation (TD) or Granier method and Heat Field Deformation (HFD). The continuous application of heat makes them expensive. Therefore, three techniques (HR, CHP and TD) have been used successfully in stems, braches, and sometimes in the roots of woody plants (Sam, 2016). The sap flow methods are used to directly measure plant or tree transpiration. All sap flow methods are based on the same physical principle (Tatarinov *et al.,* 2005), where the conductive xylem tissue is heated and heat dissipation is assessed by measuring temperature at two locations on the stem (Tatarinov *et al.,* 2005). The heat pulse technique measures the linear velocity of ascending sap or water from the time when the applied heat pulse reaches the temperature probes (Huber and Schmidt, 1937).

Huber and Schmidt (1937) developed a direct method of quantifying ET of an individual stand. Initially, the sap flow measurements were based on the compensation heat pulse velocity (CHPV) technique. The disadvantage of the method was the inability to measure low rates of sap flow in woody plants and this limitation could affect the measurement of transpiration during the winter season, at night, or on short growing plants (Burgess *et al.*, 2001). The heat ratio version of the HPV technique was then introduced as an improvement of the previous technique (Burgess *et al.*, 2001).

The heat pulse velocity (HPV) method

This method is underlain by theory of thermal conductance and convection (Sam, 2016; Forster, 2017). Sap flow is measured by determining the velocity of the heat pulse moving along the stem (Smith, 1996). HPV methods, which were developed by Huber and Schmidt (1937), were the first sap flow techniques to utilize heat as a tracer of sap movement. A theoretical framework for HPV methods was further developed by Marshall (1958), and numerical corrections to account for departures from idealized heat transport theory were developed several decades later by Swanson and Whitfield (1981).

The advantages of the HPV are that no reference temperature is required, so the influence of the ambient temperature gradients or that from wood heterogeneity is minimized. HPV systems are also easy to automate, the data is easily interpreted, they do not alter the microclimate of the plant and they can estimate transpiration over extended periods (Sam, 2016). The system can detect low and reverse flows that are critical for determining and quantifying processes like hydraulic redistribution, and requires low power. The data is produced as signals, and is suitable for further processing or storage in data loggers (Sam, 2016). Sap flows can be measured in plant stems with minimal or no disruption to the sap stream (Ntshidi, 2015).

The disadvantages of the HPV heat ratio method is related to the underestimation of sap flow which occurs as a result of wounding caused by the insertion of sensors into the sapwood (Sam, 2016). There is an assumption made in HPV theory that the stem is infinitely homogenous, which means that there is no delay in heat exchange between the water in the conducting tissue and the matrix of the xylem. This assumption applies to species such as apples, with small uniform vessels. However, in some species with large vessels, sap flow does not adhere to the original definition of a homogenous and porous material (Sam, 2016).

Forster (2017) highlighted that sources of errors in sap flow measurements includes errors in converting heat velocity into sap velocity, misalignment, scaling of point measurements to whole plant transpiration, wound corrections, thermal diffusity, and the determination of moisture fraction. Sap flow errors are assumed to be 5 – 15% for individual plants. At plot scale, the magnitudes of errors are determined by the number of samples measured and the variability in these samples (Shuttleworth, 2008). These errors are incorporated in the processing of HPV signals i.e. the misalignment error is reduced by establishing the zero flux flow of the measured tree. These values assist in correcting the diurnal signals. Swanson and Whitfield (1981) developed a method to account for the correction of wounding. Errors resulting from sapwood variability are minimised by inserting HPV probes at different depths. The HPV sap flow method has been successfully used in several studies (Dye, Soko and Poulter, 1996; Burgess *et al.*, 2001).

Summary

The impacts of invasive alien plants on biodiversity, water resources, and the functioning of the ecosystem as a whole are well documented. Studies have shown that accurate estimation of ET is critical for water resources management. The several methods for estimating ET have therefore been developed. These include empirical, surface energy based models, and experimental field methods. The introduction of remote sensing models has played a major role in measuring the spatial and temporal variations of ET on larger scales. However, many of these models still require modifications when applied to certain areas. Among the experimental methods, HPV sap flow technique is recognised as the most efficient method to measure direct transpiration, due to its ability to detect low and reverse sap flow velocities using simple instrumentation. The processing of HPV data was found to eliminate most of the errors that could be encountered.

Intensive research has been done on the comparison of water use by invasive alien plants and the indigenous vegetation. Results from these studies led to the general assumption that IAP's use more water than the indigenous vegetation. These studies also highlighted the importance of prioritising the eradication of alien plants along the riparian zones. However, there is inadequate knowledge about the actual volumes that the IAP's transpire especially in arid to semi-arid areas. Therefore this study will contribute to this knowledge

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CHAPTER 3: DESCRIPTION OF THE STUDY AREA

3.1 Introduction

The aim of this study was to compare the temporal variability of water use by riparian and hillslope *Acacia longifolia* trees in the Heuningnes catchment of the Western Cape Province. To achieve this, sap flow rates and the microclimate of the selected sites were monitored from June 2016 – June 2017. The results from this study will contribute towards improving knowledge on the water use, the hydrological impacts of *Acacia longifolia* species and the benefits of clearing these species in areas in which they invade. This chapter will provide a description of the catchment and the selection criteria of the study sites.

3.2 The Heuningnes Catchment

The Heuningnes Catchment covers an area of 1 401 km^2 and is located in the southernmost region of South Africa, in the Cape Agulhas Municipality (Hoekstra and Waller, 2014). The Heuningnes River which feed an estuary has two major tributaries, the Kars River which rises in the Bredasdorpberge and runs for 75 km to its confluence with the Heuningnes River, and the Nuwejaars River that rises from the Bredasdorpberge, Koueberge and Soetangsberg and runs for some 55 km to the Soetendalsvlei (Heydorn & Grindley, 1984). The flat area of the catchment has several wetlands such as pans, lakes, and floodplains. A floodplain wetland which is about 22 km long and a width of up to 1.5 km occurs along the Nuwejaars River between Elim and Soetendals vlei which is one of the major lakes in this catchment (~20 km^2) followed by Voelvlei (~5 km^2) (Hoekstra & Waller, 2014) (Figure 3.1).

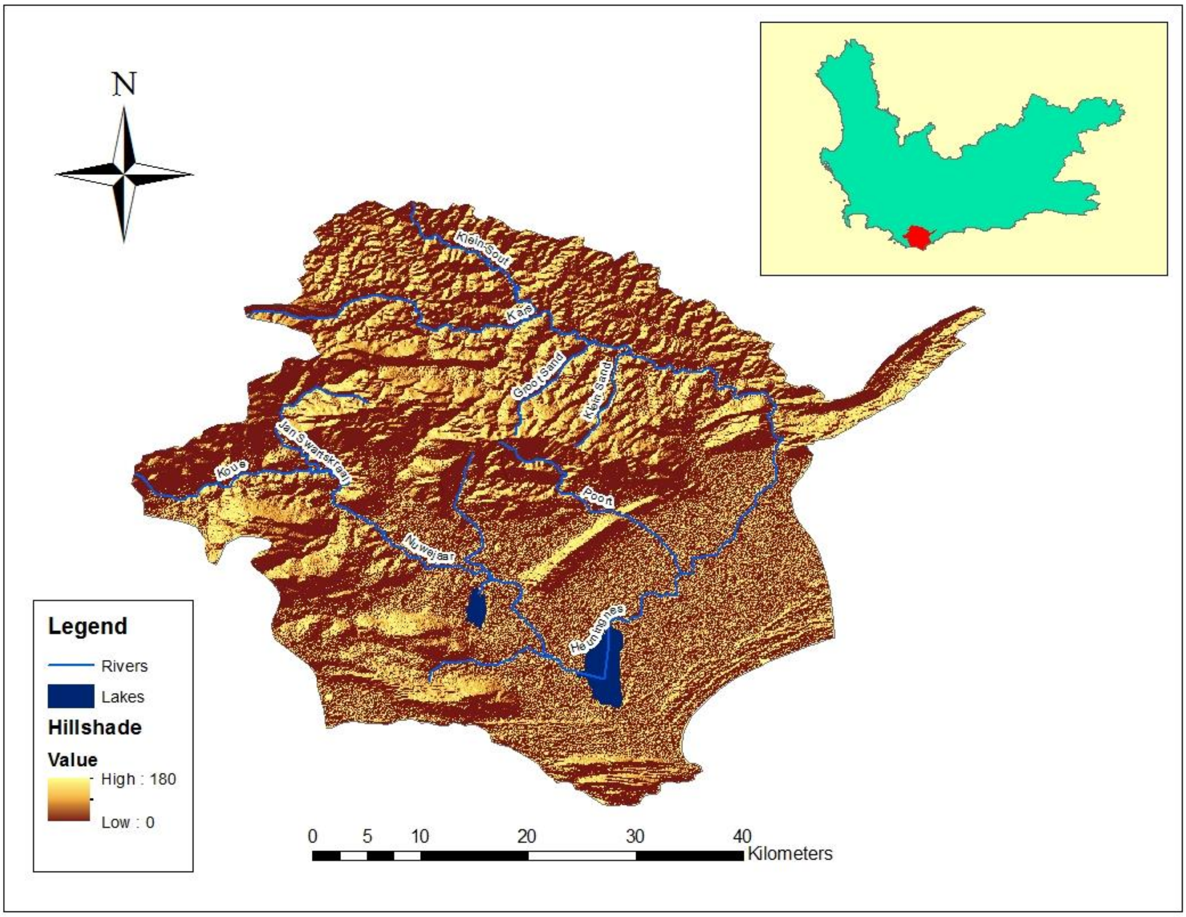

Figure 3.1: The Heuningnes Catchment in the Western Cape Province of South Africa

Geology

The geology of the area is rather very variable. The Heuningnes Catchment is underlain by the Bredasdorp Beds which comprise calcified dune sand (Figure 3.2). The geology of the upper catchment of Kars River is dominated by Table Mountain Group sandstones, quartzite and shale of the Bredasdorpberge in the southern parts, and Bokkeveld shale occur in the undulating northern parts. The geology of the upper catchment of the Nuwejaars River is dominated by Malmesbury and the Peninsula Group (Figure 3.2). The low lying areas of the catchment where the major lakes occur is underlain by Bredasdorp beds (Figure 3.2).

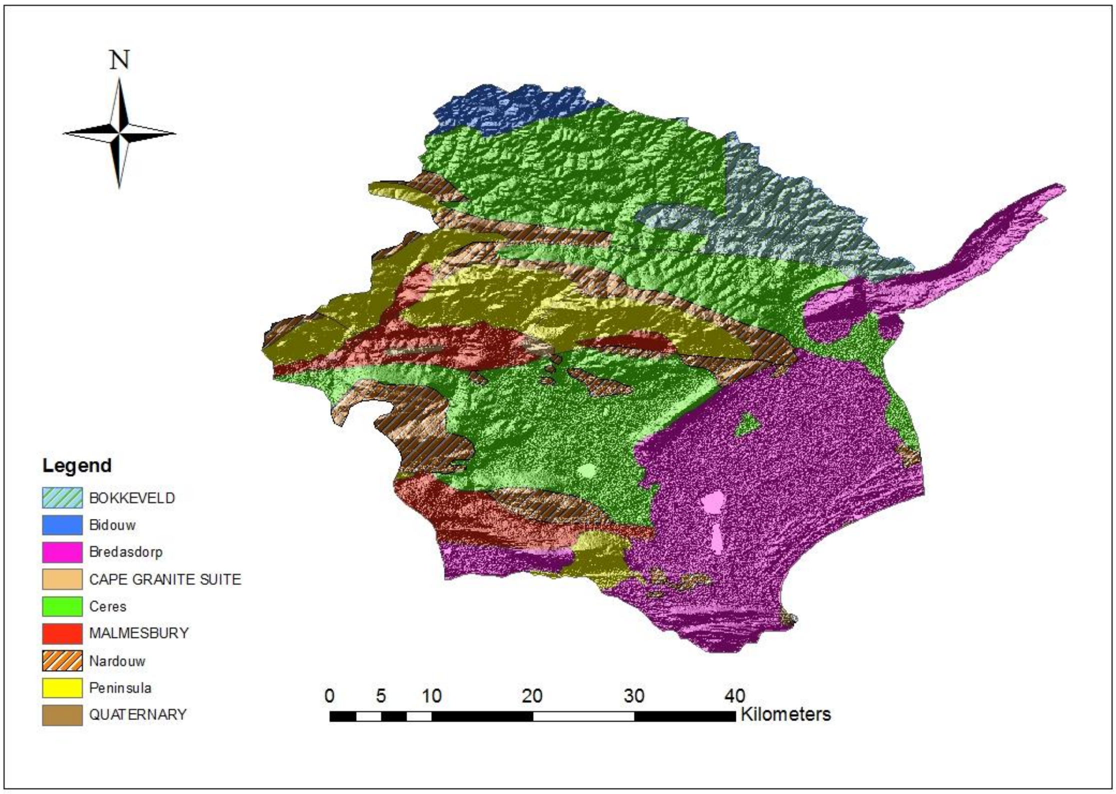

Figure 3.2: Geology of the Heuningnes Catchment

Land cover and land use

About 41% of the catchment is under agriculture and most of this consists of commercial dryland crop production, and some commercial forestry (Figure3.3) (Herdien *et al.,* 2010). The cultivated lands occur mostly on the mountainous and south-east coastal parts of the catchment (Figure 3.3). Major lakes and pans are found on the low lying part of the Nuwejaars Catchment. Thick / dense bushes occur on the mountainous part and stretch along rivers down to the wetland areas. The occurrence of these bushes is associated with the establishment of alien trees / bushes that are slowly replacing the fynbos shrublands. Moreover, these bushes reduce the productivity of the land and disrupt the ecosystem by occurring very close to the rivers systems. Bare surfaces are found close on top of the mountains. This is caused by the clearing activity that is taking place as part of the rehabilitation strategies in the catchment. The cleared land on the mountains is being used for grazing and agricultural purposes.

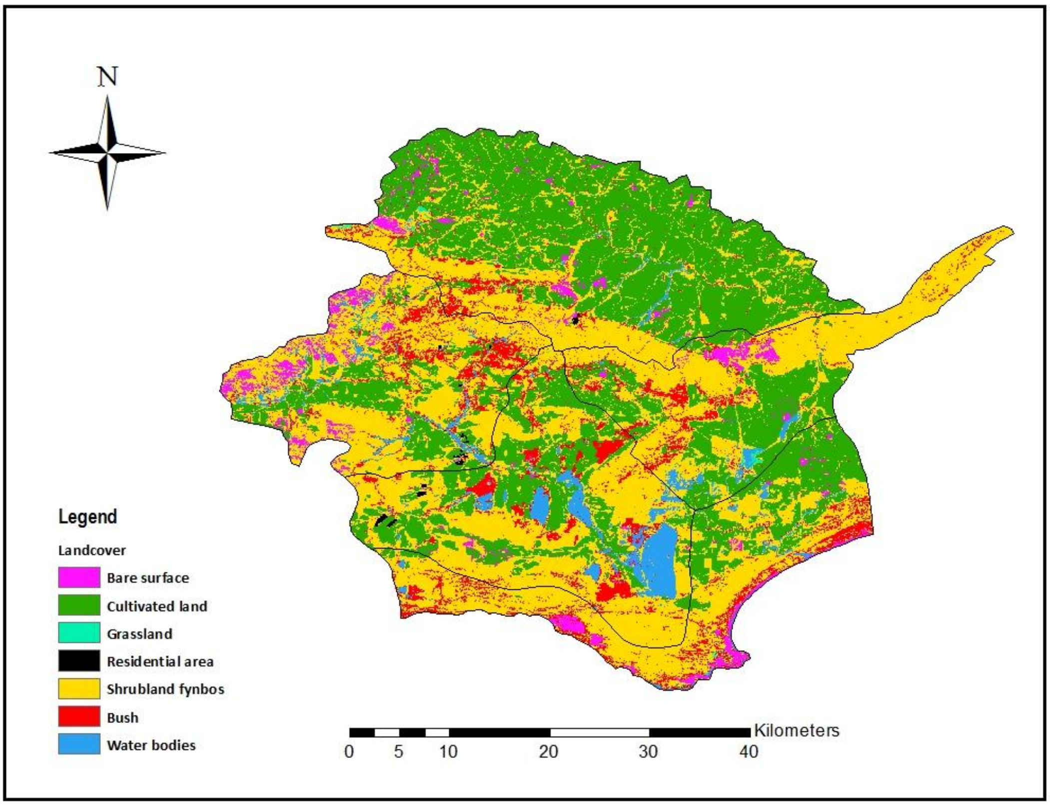

Figure 3.3: Land cover and land uses in the Heuningnes Catchment

Climate

The catchment lies within a Mediterranean climatic region, receiving most of the rainfall during the winter season from mid-May to late August. The mean annual rainfall over most of the catchment is between 400-600 mm/year, with a mean annual precipitation of 650 mm/year on the hills that form the northern watershed (Herdien *et al.*, 2005; Kraaij *et al.*, 2009). Maximum temperatures occur in January and the minimum temperatures occur in July and August (Hanekom, Russell and Randall, 2009; Herdien *et al.*, 2010; Hoekstra and Waller, 2014).

Vegetation

There are more than 1 750 plant species that are present in the catchment (Kraaij *et al.,* 2008; Nowell, 2011). These plant species are grouped into Mountain Fynbos, Proteoid Fynbos, Restioid Fynbos and Asteraceous Fynbos (ODM, 2004; Fourie *et al.*, 2013). Mountain Fynbos occurs on shallow, sandy, acidic soils, most of which are derived from sandstones of the Table Mountain Group and are highly infertile. The Mountain Fynbos is found extensively in moist areas on the steep south-facing slopes of the mountains and also occurs in small patches on seaward-facing coastal slopes (Figure 3.4). The Limestone Fynbos is rich in species and most of the vegetation is relatively intact (ODM, 2004).

The Restiod Fynbos is dominated by tall reeds and is confined to low lying areas (Figure 3.4). This vegetation type is closely associated with vleis and may be flooded during the winter season. It is mostly found along the coast and the east of Soetendalsvlei. The Asteraceous Fynbos is distinguished into two types, namely Elim and Dune Fynbos. The Elim Fynbos is characterized by the absence or sparse cover of a tall Proteoid shrub layer. It occurs on dry, gravely soils, usually overlying Bokkeveld Shales or sand stones of the Table Mountain Group and occurs on low lying areas. The Dune Fynbos on the other hand occurs on coastal sands that are subject to severe winds (ODM, 2004).

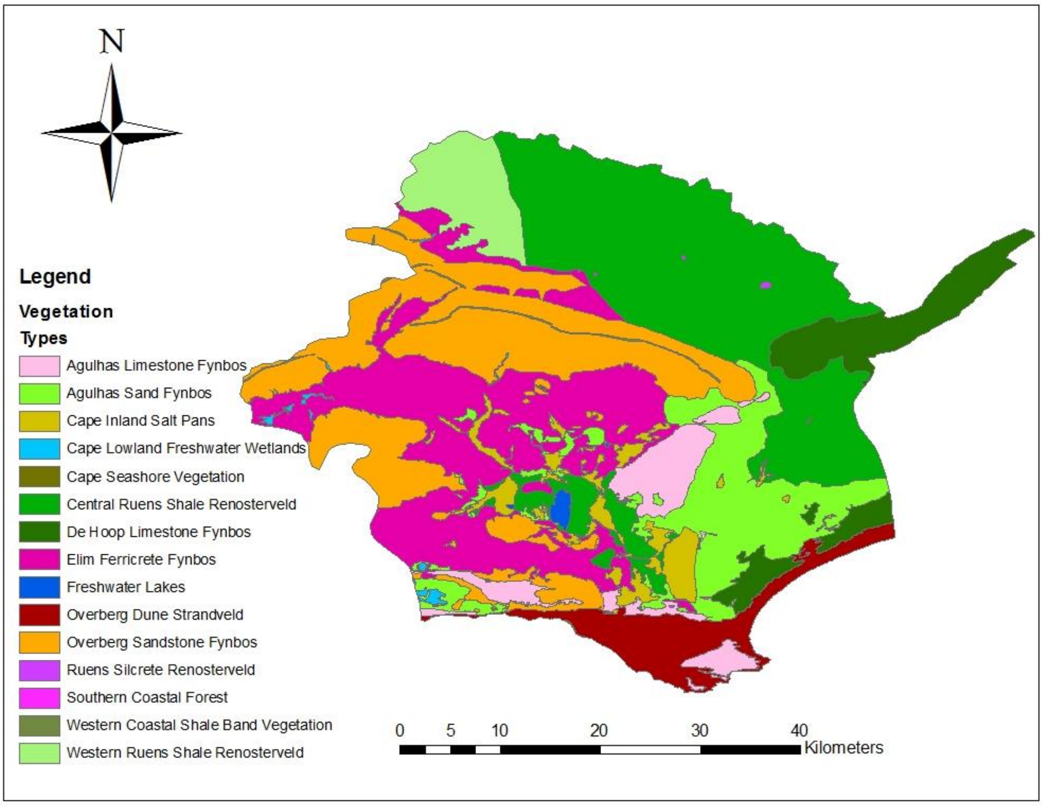

Figure 3.4: Vegetation types found in the Heuningnes Catchment

The presence of dense bushes formed by invasive trees constrains and / or compromises the production of ecosystem goods and services provided by Fynbos vegetation (Fourie *et al.,* 2013) by slowly replacing the indigenous species. The dominant invasive species in the catchment are *Eucalyptus*, *Pinus*, and *Acacia* (Herdien *et al.,* 2005; Nowell, 2011).

Invasive alien plants

The eucalypts and pines have been planted as wind-breaks, plantations, as well as around homesteads. The seeds are predominantly spreading across the landscape in the direction of the wind. Hence, low densities of young pines are found on mountainous areas. Conversely, the Eucalypts drop their seed below parent trees, thus forming clustered stands. Acacia species inhabit the deep sandy coastal areas where they form closed stands with large seed banks (van Wilgen *et al.,* 1998; Holmes *et al.,* 2000; Nowell, 2011). Acacia species were the dominant IAP species that accounted for 71% of the invaded areas in the year 2000. The distribution of IAP’s is higher on the mountainous part of the catchment (Figure 3.5).

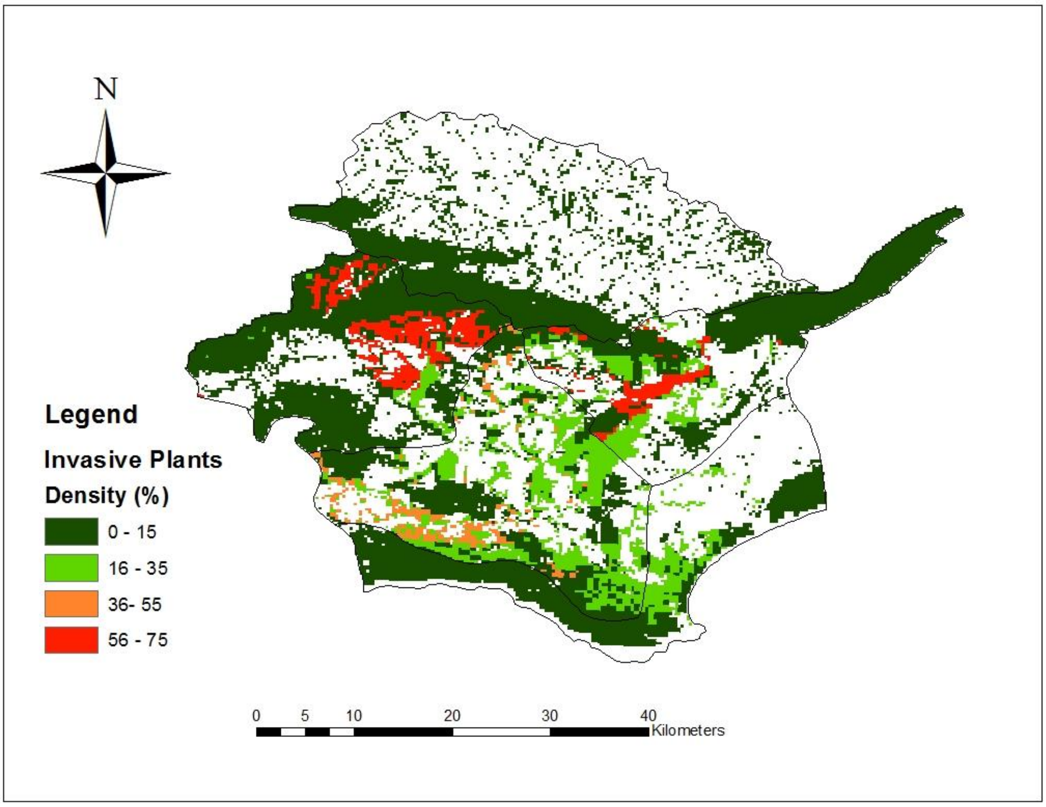

Figure 3.5: The distribution and density of alien vegetation in the Heuningnes catchment

3.3 Study sites

Selecting sites to install the HPV systems involved several reconnaissance visits and assessment of sites in the catchment. This resulted in two sites, one situated on the hillslope and another on a riparian zone along the Nuwejaars River being selected. The selection criteria of these sites included finding sites that are:

(i) Invaded by actively growing *Acacia longifolia* trees;

(ii) Safe for the equipment – to avoid vandalism

(iii) Accessible – required permission from the relevant landowners to install and regularly visit the sites at-least twice a month.

The hillslope site was selected on the southern hillslope of the Bredasdorp hills in Spanjaardskloof. The riparian site was located 20 m from the Nuwejaars River in the Zoetendals farm. The site was located within the floodplain wetland known as the Moddervlei (Figure 3.6). Both sites were located within private properties and permission to access the sites every two weeks was granted by the land-owners.

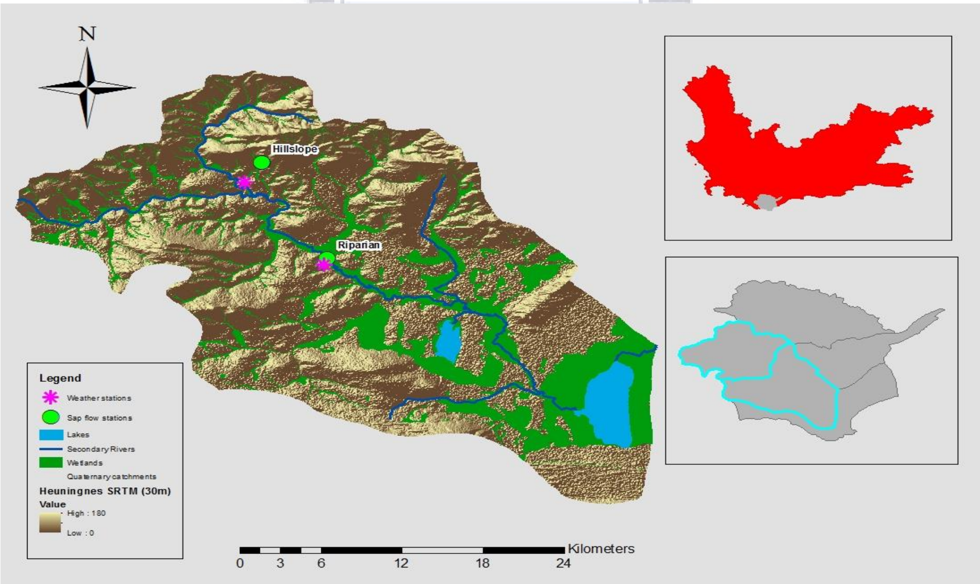

Figure 3.6: The location of study sites within the Heuningnes Catchment.

Location and Topography

The study sites were located in quaternary catchment G50B of the Heuningnes Catchment. Site A is the hillslope which is 1.7 km below the top of the hill with an altitude of 430 m. This site is at 125 m with a slope of 8%. Baboons which can damage monitoring equipment occur in this area. Therefore, the site was selected at an altitude that the landowner indicated was beyond the range of baboons. The riparian site is located in Moddervlei along the floodplain of the Nuwejaars River. The elevation of the area is 25 m (Figure 3.7).

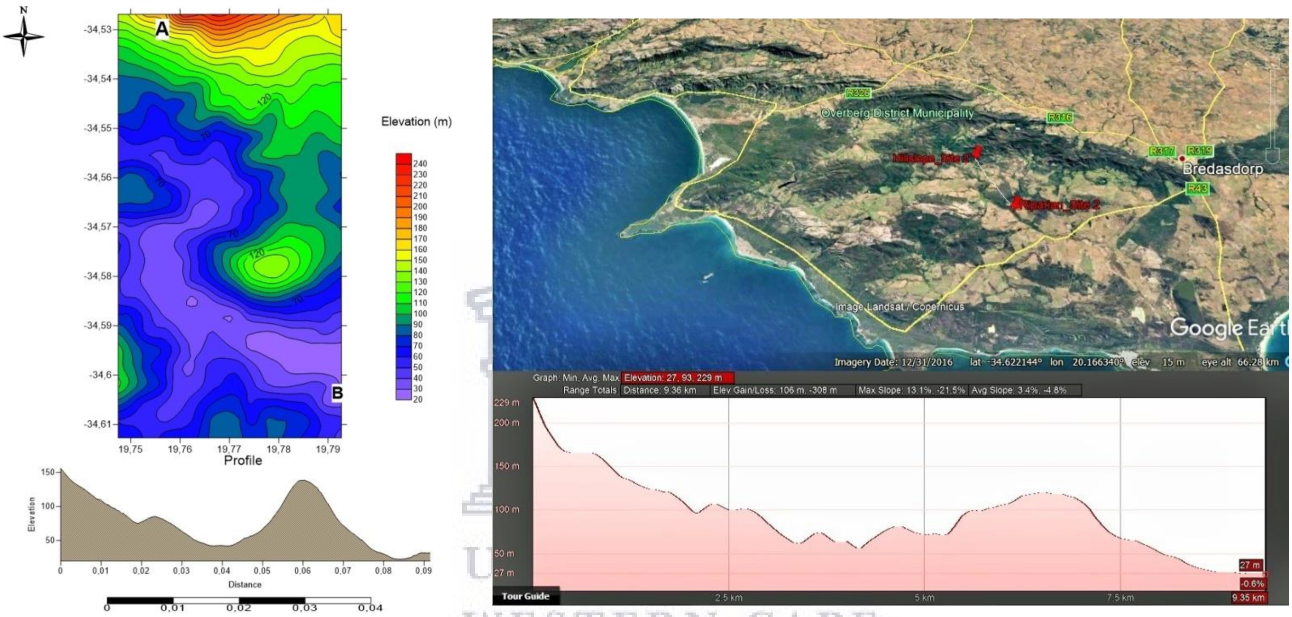

Figure 3.7: The topography of the study area showing selected sites (produced from Surfer 11 and 2016 Google earth imagery.

Climate

The ambient climate of the study sites varied with elevation. Maximum solar irradiance ranged between 32 – 35 MJ/m^2/day between November 2016 and January 2017 on the hillslopes. The maximum temperatures were 33 – 39 °C during the same period. The lowest temperatures of 1°C were measured in June 2016 and June 2017 (Figure 3.8). Seasonal variation of wind speed was also observed on the hillslopes, the highest wind speed of 4.7 m/s occurred in February 2017 and the lowest (0.1 – 0.8 m/s) was measured in June 2016 and June 2017. On the duration of the study, two major rainfall events occurred, in June 2016 (36.4 mm/day) and June 2017 (44.6 mm/day). The total rainfall of 496 mm/year on the hillslope was exceeded by reference evapotranspiration (ETo) of 1 449 mm/year.

The high wind speeds has become the distinctive feature of the riparian site. This feature is attributed to the high exposure of the area compared to the other site and the funnelling of winds through the river valley. The highest wind speed of 14 m/s occurred in June 2017 and the lowest (1.6 m/s) was measured in June 2016. The highest measured rainfall at the riparian site was 72 mm/day on the 26th July 2016, with the highest ETo rates of 11 mm/day in January 2017. The total rainfall of 461mm/year was exceed by ETo rates of 1 509 mm/year that was measured during the period of the study.

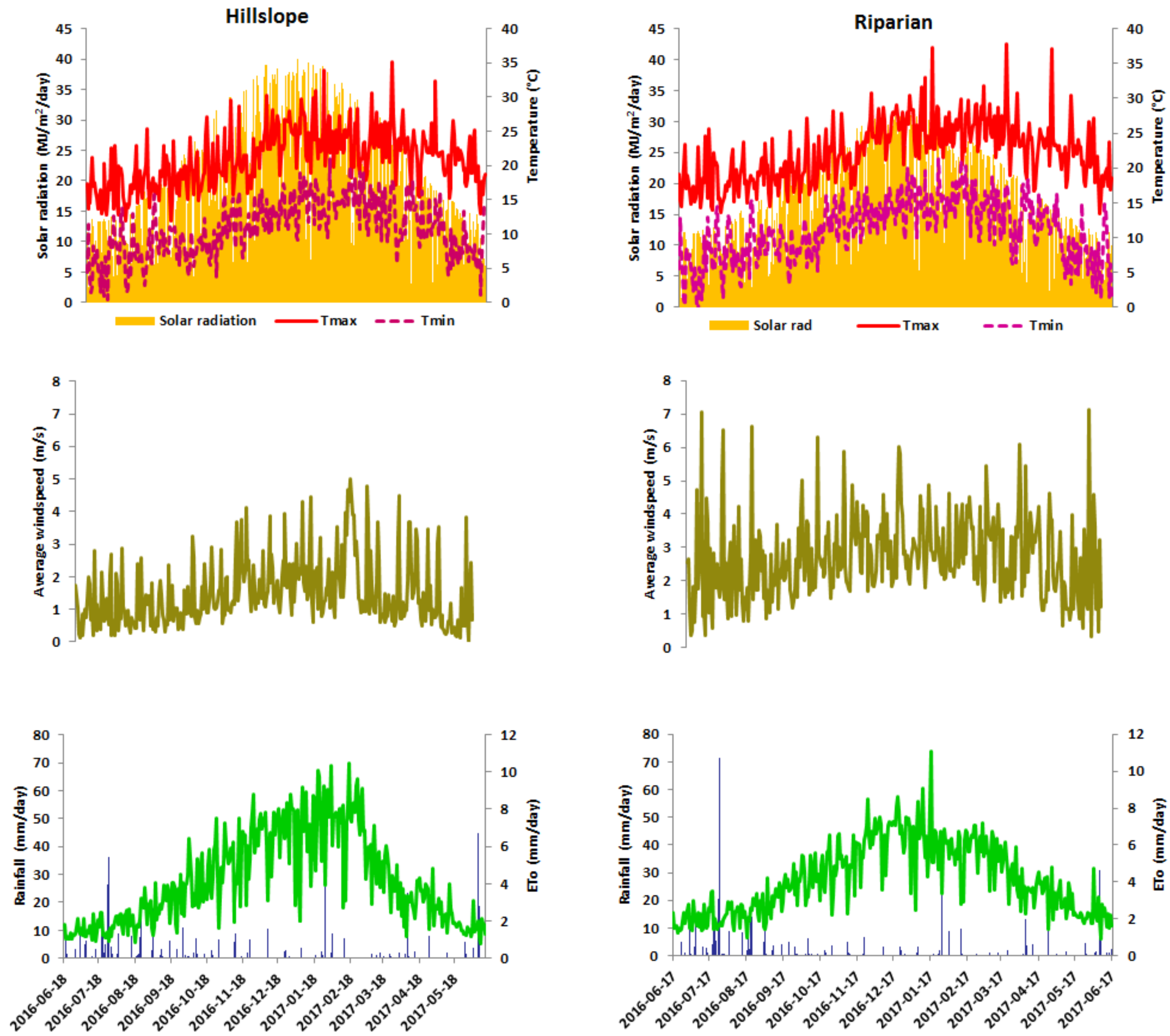

Figure 3.8: The ambient climate of the selected sites

CHAPTER 4: UNDERSTANDING CLIMATE AND SOIL WATER VARIABILITY ON THE HILLSLOPES AND RIPARIAN ZONES

4.1 Introduction

For many years, weather-based methods, soil water measurements, and surface energy balance techniques have been used to estimate ET from vegetated surfaces (Allen *et al.,* 1998; Yuan *et al.,* 2010; Mu *et al.,* 2011; Bastiaanssen *et al.,* 2012; Dzikiti *et al.,* 2013; 2016). Hence, a great number of models currently exist to estimate ET at local and regional scales. However, the majority of these models require input data of soil properties, vegetation and climate, which limits their application to areas that cannot be accessed remotely (Nouri, 2013). Penman – Monteith is a method for estimating ET that has been globally accepted. ET and soil water availability are both important drivers for understanding the water use patterns by plants. Therefore, the first section of this chapter examines temporal variations of weather characteristics on hillslope and the riparian sites selected for this study in the Heuningnes Catchment. The second section of this chapter examines how soil water at the study sites responded to rainfall, and varied seasonally.

The variation of soil water from the hillslope to low lying areas may be influenced by differences in soil composition. The parent material on hillslope soil is sandstone, whereas the riparian soils are composed of minerals originating from shale and sandy shale which are frequently waterlogged (Mikkelsen and Vesho, 2000). The riparian soils are expected to have high levels of soil water compared to the hillslope soils, due to ponding and the capillary movement of groundwater into the rooting zone of the riparian vegetation (Mikkelsen and Vesho, 2000). Monitoring soil water content assists in determining the available water to plants, and how plants respond to seasonal variations of soil water, including water stress. Monitoring of soil water has traditionally been a tedious and time consuming exercise. Soil water balance has therefore been used alternatively for determining temporal variations in soil water. Soil water balance modeling also simplifies the complex processes by conceptualizing the processes taking place. The knowledge of soil water is necessary for assessing the partitioning of rainfall and energy fluxes between land and the atmosphere (Seneviratne *et al.,* 2010). Effective crop management including irrigation also requires accurate information about soil water. This chapter therefore addresses the second objective of the study, which is to establish the differences and or similarities in weather characteristics (described by ETo) as well as soil water variations in the selected sites.

4.2 Materials and methods

This study required monitoring of microclimate on the hillslope and riparian zones of the Heuningnes Catchment in the Western Cape. The approach of the study was to select two study sites with different topography, as explained in Chapter 3. The climate on the hillslope was monitored using a HOBO U30 weather station located on the Spanjaardskloof hills (34° 32' 24.64"S, 019° 44' 25.66"E) with an elevation of 85 meters above sea level (Figure 4.1a). This station is part of an on-going catchment monitoring project. A Campbell GRWS100 weather station was established at the riparian site (34° 36' 18.4"S, 019° 47' 45.9"E) in June 2016 (Figure 4.1b). One year of data was collected from June 2016 – June 2017 from both stations.

4.2.1 Monitoring meteorological factors

The weather station on the hillslope measured the solar radiation, ambient temperature, relative humidity; wind speed and direction at 2 meters height. Rainfall was measured using a tipping bucket rain gauge. All the sensors were connected to a data logger that was programmed to store data at 15 minutes intervals. A solar panel was used to charge the 4-Volts rechargeable sealed lead-acid battery that powered the station. Data was downloaded using a cable.

The weather station at the riparian site was established on the 17th of June 2016 at Moddervlei. The station measured solar radiation, air temperature, relative humidity, wind speed and direction. Rainfall was collected using a tipping bucket rain gauge mounted at 1.2 m above the ground. A solar panel was used to charge the 7AH battery that supplied the system with energy. All the sensors were connected to a data logger recording at 15 minutes interval. Data from this station could be acquired in two ways, either by directly downloading using SC9A connection cable or remotely, using an enabled modem. In this study, data was downloaded remotely.

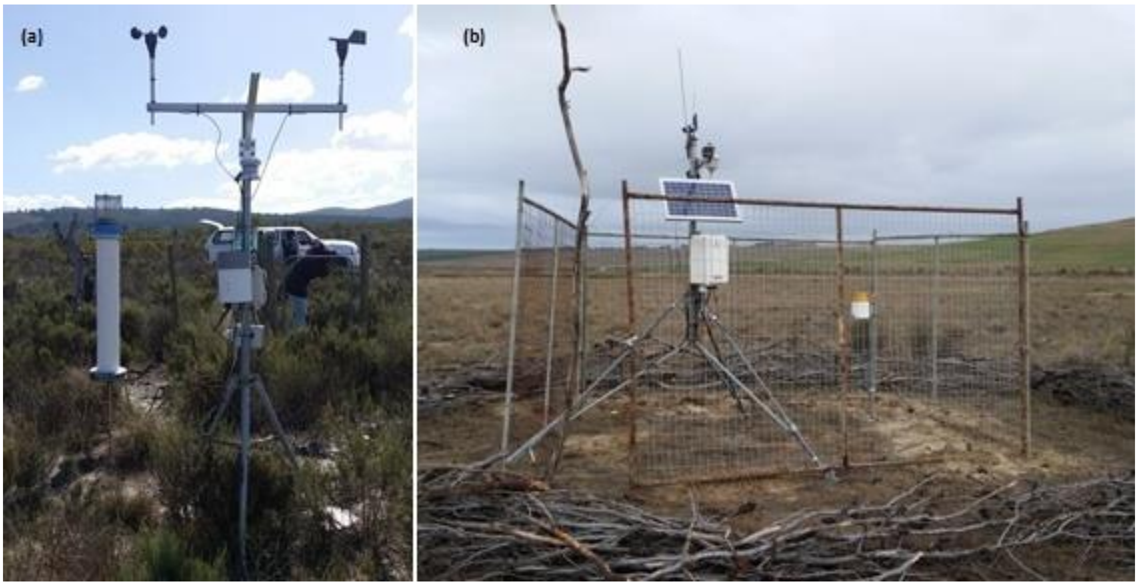

Figure 4.1: Automatic weather stations established at the sites. (a) A Hobo station located ~1.8 km from the hillslope sap flow monitoring site and (b) A Campbell station located 80 m Nuwejaars River, Moddervlei.

4.2.2 Classification of soils

Soil textures

The settling method which is based on Stokes' law settling velocity of soil particles was used to determine the distribution of particle sizes. Disturbed soil samples were acquired from augering at different depths (0 - 10 cm, 11 - 30 cm, 31 - 60 cm, and 61 - 90 cm) on each site. The soil aggregates of the samples were grinded and sieved to remove the large organic fragments that were greater than 2 mm. About 40 g of soil samples from each depth were sieved. The sieved samples were then transferred to eight different beakers (600 ml) and labelled for each depth and study site. Distilled water was then added to dampen the samples. 20 ml of hydrogen peroxide (H_2O_2) was added to the samples and heated over a hot plate. The beakers were removed from the hot plate and 8 ml of HCL (hydrochloric acid) was added to each beaker. One hundred mililitres of distilled water was then added into the mixtures and the contents in the 600 ml beakers were poured into the funnel containg a filter paper. Once all the liquids filtered through, the filter papers were then placed into clean 600 ml beakers and dried in the oven at 105 ^{o}C for 24 hours.

The dried samples were then grinded with a pestle to disperse the samples. One hundred (100) ml of the dispersing agent sodium hexametaphosphate was added to the grinded samples, and the mixtures were transferred to 1000 ml cylinders which were labelled for different depths and sites. Three aliquots were taken at different settling times on each cylinder, the settling times were depended on the temperature of the sample in the cylinder. The aliquots were then dried for 24 hours and then weighed. The results were then plotted on the USDA Soil Texture Triangle to describe the soil textures at different depths.

Bulk densities

The core method (Grossman and Reinsch, 2002) was used to determine the bulk densities of the soils. The undisturbed soil samples were taken at 0-10 cm, 11-30 cm, 31-60 cm, and 61-90 cm depths at each site (which are the same depths at which probes for monitoring soil water content were installed) using an augur that contained soil rings with a volume of 100 cm^3 (Figure 4.2). The samples were weighted in the laboratory. Thereafter, the samples were placed in the drying oven for 24 hrs to obtain the oven-dry samples. The bulk density of the soil at varying depths was then determined for each site using:

$$\text{Bulk density (BD)} = \frac{Mass\ of\ oven\text{-}dry\ soil\ (g)}{Volume\ of\ the\ soil\ (cm^3)} \tag{4.1}$$

Figure 4.2: Auguring soil samples at different depths.

4.2.3 Monitoring soil water content

Close to the sap flow monitoring systems, soil water contents were monitored at various depths. This was done to determine the amount of water available in the soil for plants to use and to monitor the influence of soil water variations to plant water use.

A 1 metre deep pit was dug very close to the sap flow system (Figure 4.3). The variation of soil water at different depths and the responses of the soil to rainfall were monitored by installing Five (5) Decagon EM50 5TE soil moisture sensors horizontally at depths of 0.1 m, 0.3 m, 0.5 m, 0.7 m, and 0.9 m. The sensors measured temperature (°C), EC (mS/cm), and volumetric water content (m^3/m^3) simultaneously. The cables were labelled for easy of identification (Figure 4.3) and thereafter, were connected to a data logger that was stored in a safe box. After the installation, sensors were scanned to check if they worked. Thereafter, the excavated pit was backfilled carefully taking into consideration the sensitivity of the sensors and cables. Backfilling was done with the disturbed soil material that was stacked up next to the pit during excavation. This was carefully done to ensure that the bulk density of the area to which sensors were installed would resemble the natural state of the soil at the site and to minimize or prevent preferential flow.

Figure 4.3: Pit excavated to a depth of one meter, used to horizontally install soil water probes at 0.2 m intervals

4.2.4 Soil water balance

Given that probes for continuous monitoring of soil water are often not available in many studies and for soil water management practices. This study explored the feasibility of using a soil water balance model for monitoring soil water content. A conceptual soil water balance model was developed to simulate soil water content at various depths. For this purpose, a simple bucket model using readily available data on rainfall and ET was used. All processes were simulated at the daily time interval (t) to illustrate the daily soil water variations. Using soil classification from the previous section, the soil profile was divided into different layers (Figure 4.4).

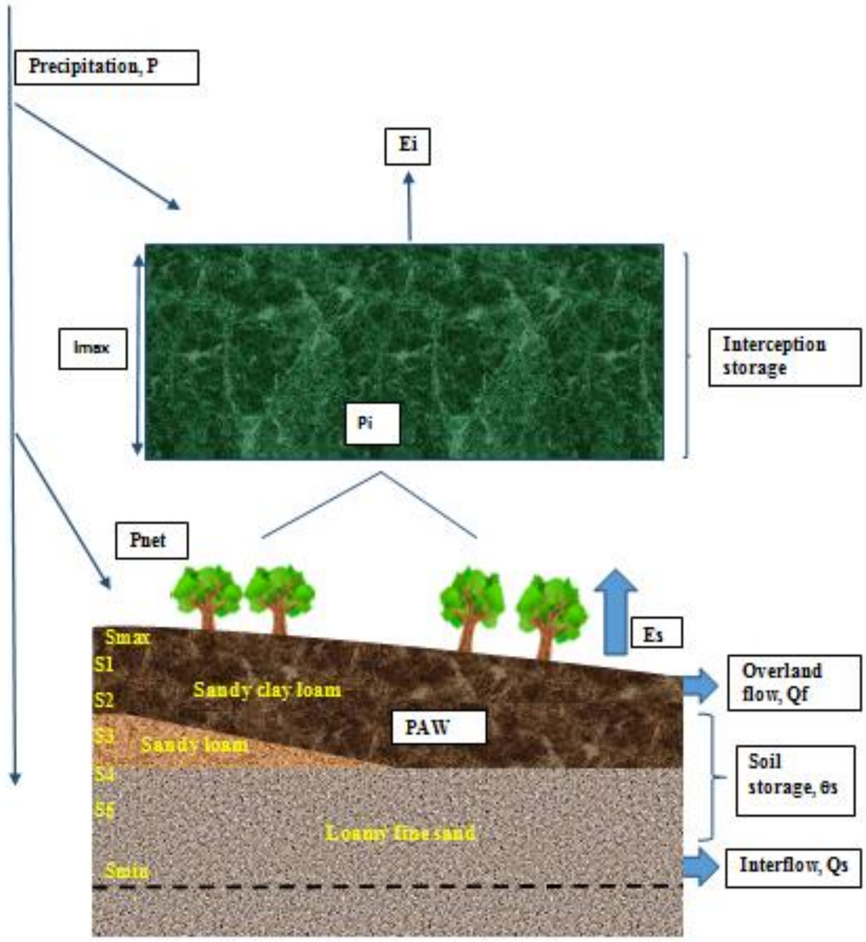

Figure 4.4: Conceptual model of the soil water balance processes

Precipitation, P_t

When rainfall received on a particular day [$P(t)$] is less than the maximum interception storage (*Imax*) of the canopy, then all the rainfall contributes to the interception loss [$P_i(t)$]. Therefore, the amount of rainfall reaching the ground [$P_{net}\ (t)$] becomes zero.

$P_{net}(t)$ occurs when $P(t)$ is greater than the maximum interception storage (*Imax*);and contributes to soil water storage (ϑ_s):

$$P_{net}(t) = max\,[P(t) - Imax;\ 0] \tag{4.2}$$

Surface evaporation, E_s

Surface evaporation in this model refers to evaporation of soil water. The rate at which water is lost from the soil layers depends on the solar radiation reaching the ground. The high rates of surface evaporation reduces soil water content (ϑ). When the soil water content (ϑ) is less than the field capacity of the soil (*Smax*), E_s *(t)* is then limited by ϑ *(t):* For $0 \leq \theta_1(t) \leq Smax$;

$$E_s(t) = E_p(t) * [\frac{\theta_1(t)}{Smax}] \qquad (4.3)$$

Where, E_p (t) is reference evapotranspiration, E_s is the actual rate of evaporation from the soils with soil water content (ϑ_1 (t)), and S_{max} is the maximum soil water content.

Also, the rate of evaporation is limited by water available in the soil. In semi-arid to arid areas, rainfall is usually exceeded by the evaporative demand. Thus, for evaporation to take place, the amount for water in the soil has to be above the wilting point (W_p). The wilting point is defined as the minimum soil water that the plants require not to wilt. Therefore:

$$E_S(t) = 0 \; if \; \vartheta_1(t) < Wp \qquad (4.4)$$

Where, $Wp(t) = \max[\vartheta(t) - Smin; 0]$ (4.5)

S_{min} is the minimum soil water storage

Therefore, soil water content after surface evaporation is given as:

$$\vartheta(t) = \vartheta(t-1) - E_s(t) \qquad (4.6)$$

Available water for plants, PAW

Soil water is also the source of water for plants. However, for plants to be able to extract the available water, soil water content has to be above the wilting point (W_p) but not greater than *Smax*, as plants may be waterlogged. Therefore the available water for plants (*PAW*):

$$\mathrm{PAW} = \frac{\vartheta(t) - Wp(t)}{Smax - Wp(t)} \qquad (4.7)$$

Lateral flow, Q_s

When ϑ *(t)* is greater than minimum soil water content, *Smin*, water can also be lost through lateral flow. The relationship is explained by a power curve:

$$Q_s \; = \; a \, [\vartheta(t) - Smin]^b \tag{4.8}$$

Overland flow, Q_f

When the field capacity of the soil (*Smax*) is reached, the soils can no longer absorb water, therefore, rainfall [*P (t)*] will contribute to the generation of overland flow (Q_f):

$$Q_f \; (t) \; = \max[\vartheta \; (t) - Smax; 0] \tag{4.9}$$

When the excess rainfall has drained out of the soil layers, the amount of soil water content (θ_2) left will be equal to the field capacity of the soil (*Smax*):

$$\theta_2(t) \; = \; Smax \tag{4.10}$$

Soil water storage, θ_s

The simulated or estimated soil water content (ϑ_s) is then calculated as:

$$\theta_s(t) \; = \; \theta_1 \; (t) \; + \; [P_{net} \; (t) - E_s \; (t)] - [Q_s + \; Q_f] \tag{4.11}$$

4.2.5 HYDRUS 1D

The performance of the above conceptual model was compared with the commonly used HYDRUS 1D model. HYDRUS model (PC-Progress) was used simulate the variation of soil water content during the study period (Radcliffe and Simunel, 2010). HYDRUS was run using the input rainfall and ETo data acquired from the weather stations established at the study sites. The model numerically solves Richard's equation for saturated water flow. The modelling procedure that was followed was based on the description of transient water flow in soils by Radcliffe and Simunel (2010).

Variably saturated flow

The movement of water in the soil depends on the pore sizes and antecedent water. Therefore, water movement is a function of soil properties and volumetric water content. The Richards equation for saturated conditions:

$$\frac{\partial \vartheta}{\partial t} = \frac{\partial}{\partial z}\left(k(\vartheta)\frac{\partial h}{\partial z} + 1\right) - S\ (z,t) \qquad (4.12)$$

ϑ is volumetric water content (mm), t is the time (T), h is the pressure head (mm) and z is the gravitational head, S is the sink term accounting for root water uptake (mm/day)

Modelling period

The modelling time was from June 2016 to June 2017. The model was run in a daily time step (to compare with the daily outputs of the soil water balance).

Modelling domain

The domain of the simulation was a rectangular soil column. The depth of the domain was limited to the depth of the soil moisture probes (which was 1 meter). The node density was set to be higher at the surface and lower with increasing depth. This was done to increase the infiltration rates of high rainfall events. Initially, when the nodes were using the default density, the model crashed during high rainfall events. The top boundary condition was set as an atmospheric boundary condition and the lower boundary condition was free drainage.

Material distribution

Using the results from soil particle analyses, the hillslope domain had three different materials representing the various soil types, and two types on the riparian domain. The default soil hydraulic properties were acquired using the Van Genuchten (1980) and Resetta pedotransfer soil hydraulic function for unsaturated flow. The function provided soil type properties such as unsaturated hydraulic conductivity, field capacity, and wilting point of each soil type.

Initial conditions

The initial conditions that were selected were that of the minimum soil water content at which the model would run, which was 0.05 mm for both sites.

Time dependent variable boundary conditions

Precipitation

The input rainfall data used in the model was from the weather stations at the study sites. The rainfall was measured in millimetres per day.

Reference evapotranspiration

The FAO-56- Penman Monteith was used to calculate reference evapotranspiration. This was done using climate data from the weather stations.

Observation points

Observation nodes were set at depths to which the soil moisture probes were installed i.e 0.1 m to 0.9 m.

4.3 Analysis

Statistical methods were used to determine the differences in climate and soil water variations at the study sites. T-test analysis was used to establish significant differences in weather characteristics of the study sites:

$$t = \frac{\bar{x}_1 + \bar{x}_2}{s_p\sqrt{\frac{1}{n_1}+\frac{1}{n_2}}},\ s_p = \sqrt{\frac{n_1 {s_1}^2 + n_2 {s_2}^2}{n_1 + n_2 - 2}} \qquad (4.13)$$

Where $\bar{x_1}$ and $\bar{x_2}$ represents the first and the second sample mean respectively, n is the number of samples, s is the sample standard deviation and Sp represents the pool standard deviation.

The simulated soil water variations were validated using the root mean squared error (*RMSE*) (4.14) and *Pbias*. (4.15), which are statistics used to measure the accuracy of a simulation to the observation. These illustrate the deviation of the soil water balance model from the observed soil water variations.

$$RMSE = \sqrt{\frac{\sum(\theta_{ob} - \theta_{sim})^2}{N}} \tag{4.14}$$

$$Pbias = \frac{\sum(\theta_{ob} - \theta_{sim}) * (100)}{\sum \theta_{ob}} \tag{4.15}$$

Where θ_{ob} *is* the observed water content, θ_{sim} is the simulated water content and N is number of measurements.

The Nash – Sutchliffe model efficiency coefficient (E) is a statistic used to evaluate how the simulated values resemble the observed values:

$$E = 1 - \frac{\Sigma(\theta_{ob} - \theta_{sim})^2}{\Sigma(\theta_{ob} - \overline{\theta_{ob}})^2} \tag{4.16}$$

Where θ_{ob} the observed soil water is content, θ_{sim} is the simulated water content, and $\overline{\theta_{ob}}$ represents the mean of the observed values

To test the differences in means of the simulated and observed soil water contents, an analysis of variance (ANOVA) was used. Once the differences were observed, the Least Significant Difference post – hoc test was used to indicate the outputs with the least differences to the observed soil water contents.

4.4 Results

Results presented in this chapter illustrate the diurnal and seasonal variation of meteorological factors of the study sites for the period June 2016 to June 2017.

4.4.1 Microclimate of the study sites

On the hillslope, solar radiation ranged between 5.9 – 17.5 MJ/m^2/day with average temperatures of 7.0 – 14.3ºC during the wet season. These cold conditions were further described by low vapor pressure deficit (VPD) of 0.4 - 0.6 KPa. Total rainfall of 496 mm/year was measured during the period of the study. Sixty percent of that rainfall occurred in 2016. The summer season (December 2016 – February 2017) had a peak solar radiation of 36 MJ/ m^2/day and temperatures ranging between 18 – 29 ºC. As expected, the Vapor Pressure Deficit (VPD) increased to 2.83 KPa. The aridity of the hillslopes was signified by total reference evapotranspiration of 1 449 mm/year that exceeded rainfall (Figure 4.5).

At the riparian site, solar radiation reached 31 MJ/m^2/day and average temperatures of 27 ºC during the dry season (September – December 2016). These warm conditions were accompanied by the maximum VPD of 2.86 KPa. Total rainfall of 461 mm/year was measured during the study period. Sixty-five percent of the rainfall occurred in 2016. The wet season also had solar radiation ranging between 12 – 15 MJ/m^2/day with low temperatures of 7 ºC. The dry conditions of the area were also indicated by ETo rates of 1 509 mm/year (Figure 4.5).

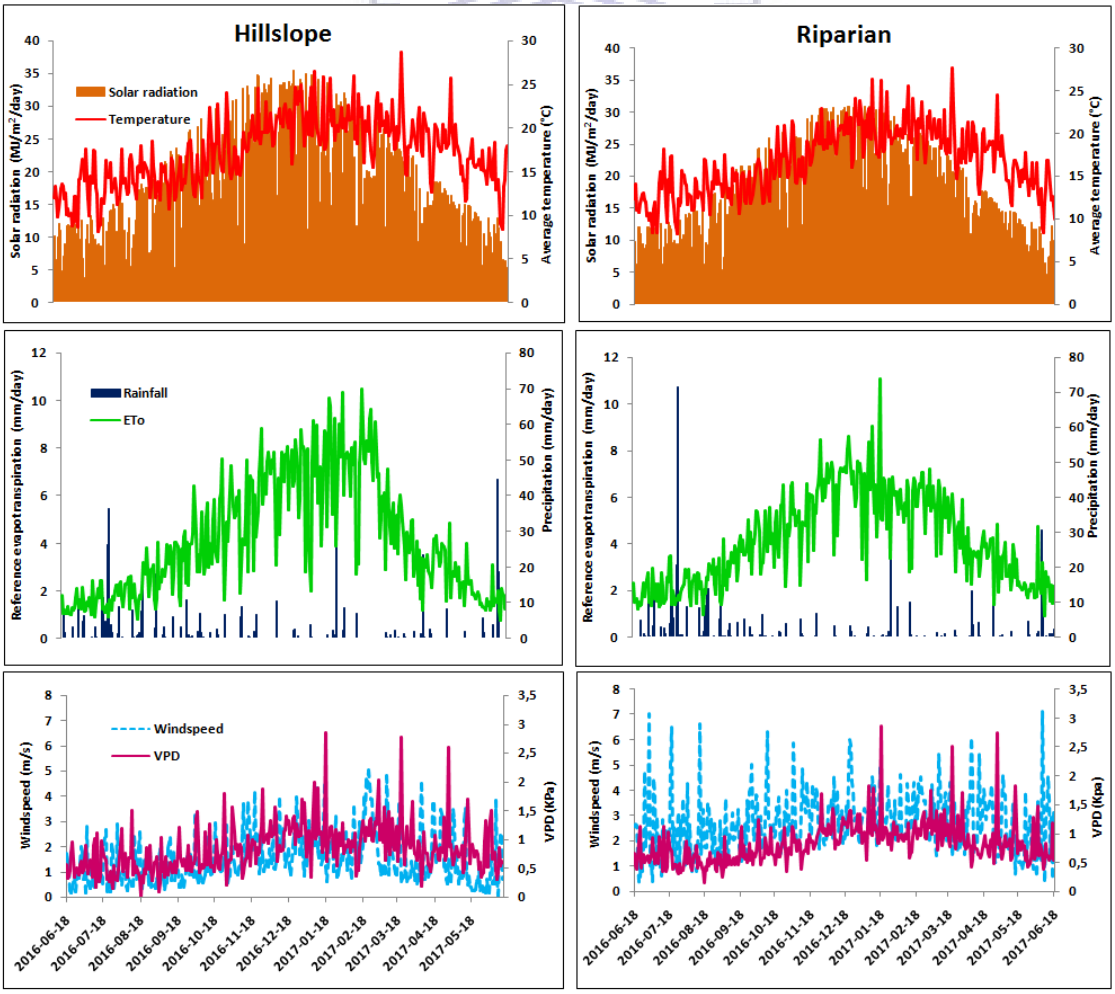

Figure 4.5: Weather characteristics of the study sites

It is apparent that wind speed was the only weather parameter that differed between the two sites ($P < 0.05$) (Table 4.1). Based on these results and field visit observations, the riparian site was windier than on the hillslopes. The wind speed was due to winds being funneled through the river valley. These results also show that the rainfall and ETo rates were not significantly different between the two sites as it was previously assumed that the hillslope received more rainfall and the riparian site will have higher ETo rates.

Table 4.1: Establishing the significance of differences in weather variables between the two sites

Variables	P_{value}
Solar radiation	0.22
Average temperature	0.09
Rainfall	0.77
Reference evapotranspiration	0.90
Wind speed	0.00
Vapor pressure deficit	0.46

4.4.2 Description of soils

A medium textured sandy clay loam layer was found on the surface on both sites. The layer was found between depths of 0 – 30 cm on the hillslope and 0 – 60 cm in the riparian zones (Table 4.2). On the hillslope, the thin sandy clay loam was underlain by a sandy loam layer at 31 - 60 cm depths. This layer was only observed on the hillslopes (Table 4.2). Sandy loam soils allow drainage as they consist of more than 50% sand content. The soil layer at 61 – 90 cm depths at both sites was coarse grained loamy fine sand (Table 4.2). Loamy sand soils consists of more than 70% sand content and less than 15% clay, which characterises high drainage rate in the profile.

Table 4.2 Soil textures at various depths on the hillslope and riparian study site

Depths (cm)	Hillslope	Riparian
0 - 30	Sandy clay loam	Sandy clay loam
31 - 60	Sandy loam	Sandy clay loam
61 - 90	Loamy fine sand	Loamy fine sand

The bulk densities of the soil increased with depth at both sites (Figure 4.6). The soil layer between 0 – 10 cm on the hillslope surfaces had a bulk density of 1.2 g/cm^3 and 0.85 g/cm^3 at 11 - 30 cm. The riparian soil at 0 – 10 cm depth had a bulk density of 0.3 g/cm^3 and the underlying layer at 11 – 30 cm had a bulk density of 0.86 g/cm^3. Loamy fine sand layer was observed between 60 – 90 cm depths both on the hillslope and the riparian site. However, the hillslope site had 1.63 g/cm^3 and 1.18 g/ cm^3 bulk density was measured at the riparian site.

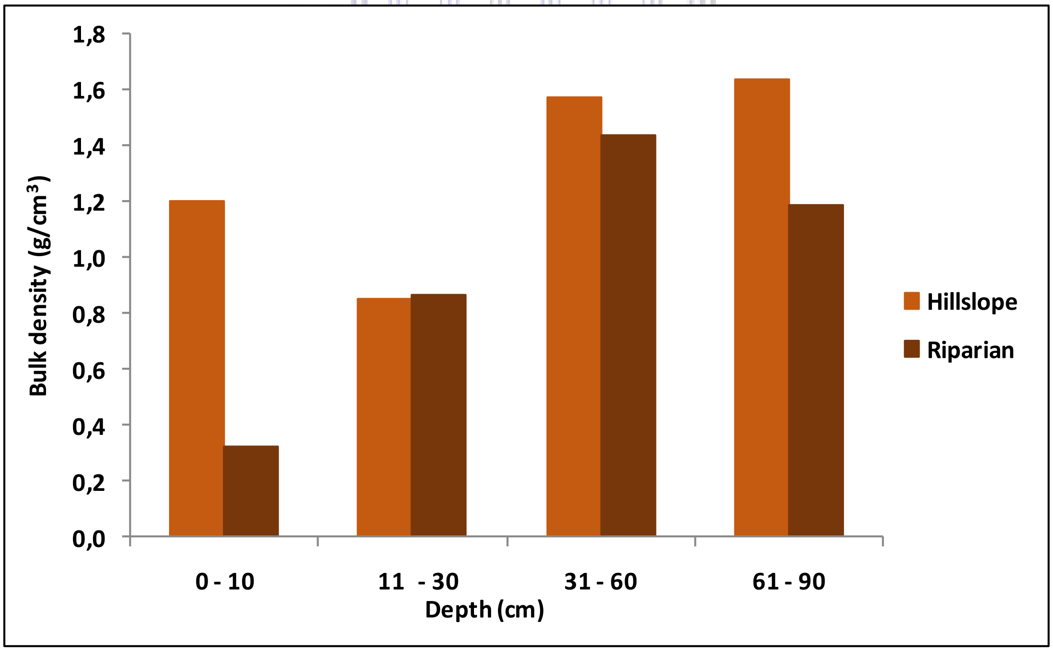

Figure 4.6: The bulk densities of soils at various depths at the study sites

The higher bulk density on the hillslope indicates the high compaction rates, root growth restriction and the poor movement of air and water in the soil. These conditions may cause low infiltration and runoff to occur frequently on the hillslope than on the riparian site.

4.4.3 Response of soil water content to rainfall events

The response of soils to rainfall was monitored at different depths from June 2016 – June 2017 (Figure 4.7). Seasonal trends were observed in soil water contents at both sites. The soils had higher water content during winter. As expected, low water content occurred during summer (Figure 4.7). The wet winter season in June 2016 resulted in the higher soil water contents of 0.25 and 0.55 and m^3/m^3 on the hillslope and riparian sites, respectively. During summer (December 2016), the soil moisture content at both sites ranged between 0.03 – 0.09 m^3/m^3. The summer rainfalls received on the hillslope caused the soils not to dry out completely. This is shown by 0.16 m^3/m^3 soil water contents in January 2016. Whereas, a consistent decline in soil water contents was observed from December 2016 in the riparian site (Figure 4.7).

At Moddervlei, the shallow soil layers at 10 – 30 cm remained relatively dry for most of the time during the study period (Figure 4.7). The opposite was observed on the hillslope, where high soil water contents were measured in shallow soil layers (Figure 4.7). The soil layer at 30 cm on the hillslope had low soil water content than at other depths. This coincided with the occurrence of the sandy loam soil profile which was only present on the hillslope (Table 4.2).

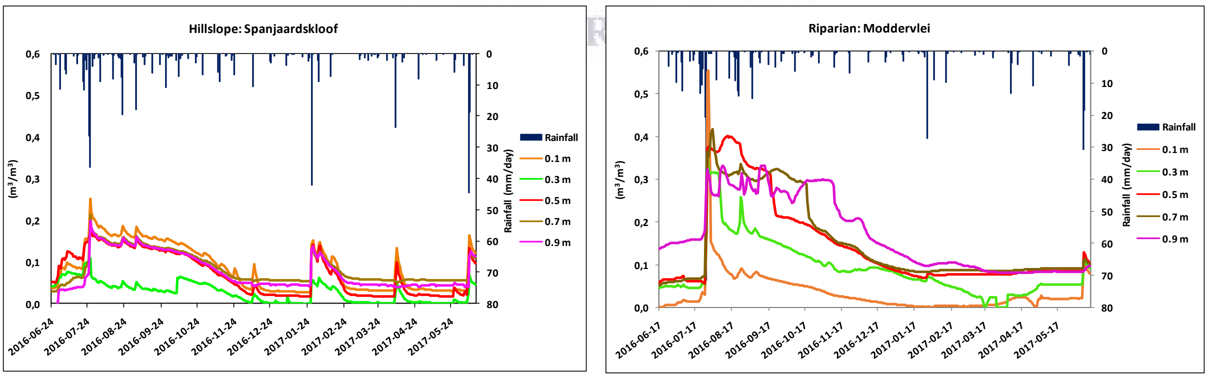

Figure 4.7: The simulated variations of soil water contents at 0.1 to 0.9 meters depth on the hillslope and riparian site.

The response of soils to rainfall was observed during the high rainfall event that took place in July 2016. The first major rainfall event in the catchment during the period of the study started at around 11:00 am on the 25th July 2016. The highest intensity at both sites was recorded at 01:00 am on the 26th July 2016, 10 and 21 mm/hr on the hillslope and riparian site respectively (Figure 4.8).

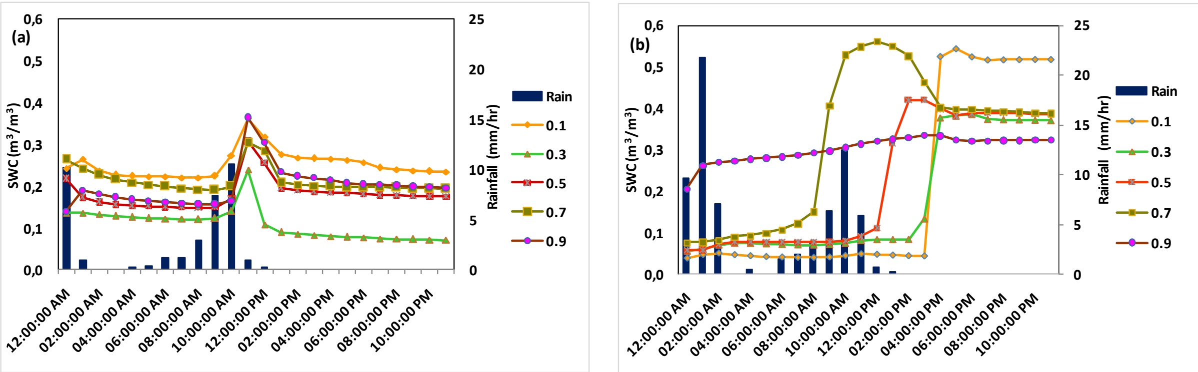

Figure 4.8: Soil water responses at 0.1 to 0.9 meters depths on the rainfall event that occurred on 26th July 2016 at (a) hillslope and (b) riparian site.

The shallow soil layer (10 cm) on the hillslope was the first to respond and maintained high moisture content throughout the day (Figure 4.8a). The maximum soil water content occurred towards the end of the rainfall event on the hills (11:00 AM). A decline in soil water content was observed at different depths an hour (at 13:00 PM) after the rain had stopped (12:00 PM). This is also shown by soil water content at 90 cm depth declining from 0.3 m^3/m^3 (12:00 PM) to 0.2 m^3/m^3 (13:00 PM).

At the riparian site, the soil profile at 90 cm responded first to the rainfall. The water content in the soil layer increased from 0.2 m^3/m^3 at 12:00 AM to 0.3 m^3/m^3 after an hour (01:00 AM). Thereafter, there was not much variation for most of the day at this depth (Fig 4.8b). Unexpectedly, a sharp increase in water content was also recorded at 70 cm depth, at 8:00 AM the water content was 0.15 m^3/m^3 and a peak of 0.5 m^3/m^3 was recorded four hours later (12:00PM). The increasing water content in this soil layer coincided with the declining water contents on the hillslope around mid-day. The rainfall stopped at 13:00 PM at the riparian site and a delayed response was observed in the shallow soil at 10 and 30 cm depths, where maximum soil water contents of 0.5 and 0.3 m^3/m^3 occurred around 04:00 PM. These results suggest that the response of soils on the hills to this rain event was from the shallow soil to the deep soil at 90 cm and / or below. As the rain stopped, soil water contents immediately declined. Unusual soil responses were observed at the riparian site where immediate response was observed from soil layers at 70 and 90 cm depths. A delayed response in the shallow soil profiles was observed three hours after the rain had stopped. This suggests preferential downward movement of water through macro-pores such as animal burrows.

4.4.4. Simulated responses of soil water content

Model parameters were estimated using the trial-and-error method (Table 4.3). Using these parameters, the soil water balance (SWB) model simulated the soil water variations (Figure 4.9).

Table 4.3: Estimated model parameters used for the soil water balance

Model Parameters	Hillslope	Riparian
Smax (mm)	72	151
Smin (mm)	12	20
Imax (mm)	1.5	2.5
a	0.02	0.05
b	0.86	0.48

The results from the trial and error agreed with the soil analyses results which suggested that the hillslope soils had low soil capacity than those on the riparian site. This was observed from the time taken for soils to drain water after the rainfall event on the 26th July (Figure 4.8). Thus, Smax and Smin values on the hillslope were less than those estimated for the riparian site. The estimated Imax values also agreed with the differences in canopy covers of the two sites.

Table 4.4: Evaluation of the soil water balance simulations

Indices	Hillslope	Riparian
RMSE (mm)	7.2	12.8
Nash coefficient (E)	0.9	0.9
Pbias (%)	3.6	10.9
R^2	0.9	0.9

The good performance of the model was also shown by the strong relationship (R^2 = 0.87 and 0.94) between the simulated and observed soil water variations on the hillslope and riparian site, respectively. The low values of RMSE (7.24 and 12.77 mm, on the hillslope and riparian, respectively) indicate the agreement between the simulated and observed soil water storages. Even though the results indicated a satisfactory performance of the water balance model, but soil moisture was overestimated, especially at the riparian site (Table 4.4).

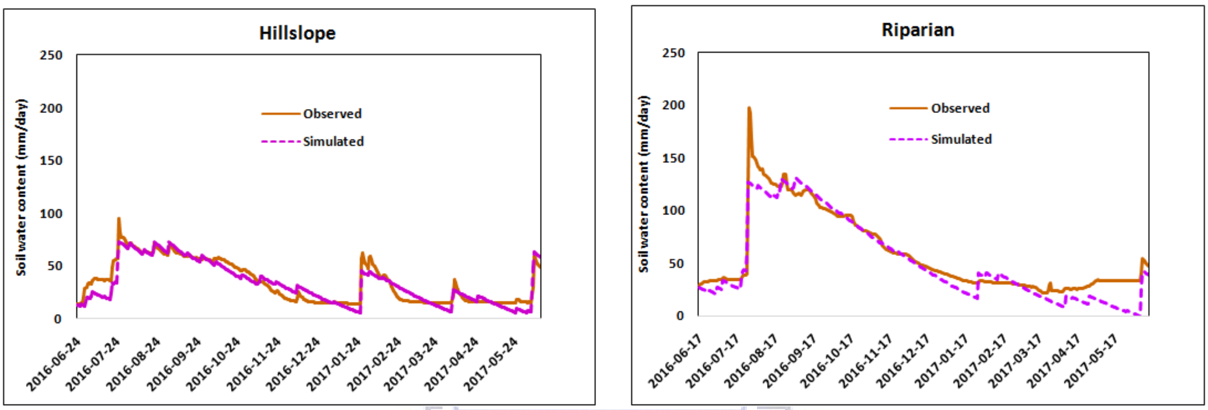

Figure 4.9: Simulated soil water dynamics on the hillslope and riparian site

4.4.5 Simulated responses of soil water content using HYDRUS 1D

Similarly to the soil water balance (SWB) model, HYDRUS 1D was used to simulate soil water variation during the period of the study (Figure 4.10). The model inputs were precipitation and evapotranspiration (ET) from the weather data. There was a poor agreement between HYDRUS 1D simulations and the observed soil water variations (Table 4.5).

Table 4.5: Evaluation of HYDRUS 1D simulations

Indices	Hillslope	Riparian
RMSE (mm)	102.2	71.8
Nash co-efficient (E)	-69.1	-2.8
Pbias (%)	-74.4	-50.6
R^2	0.4	0.3

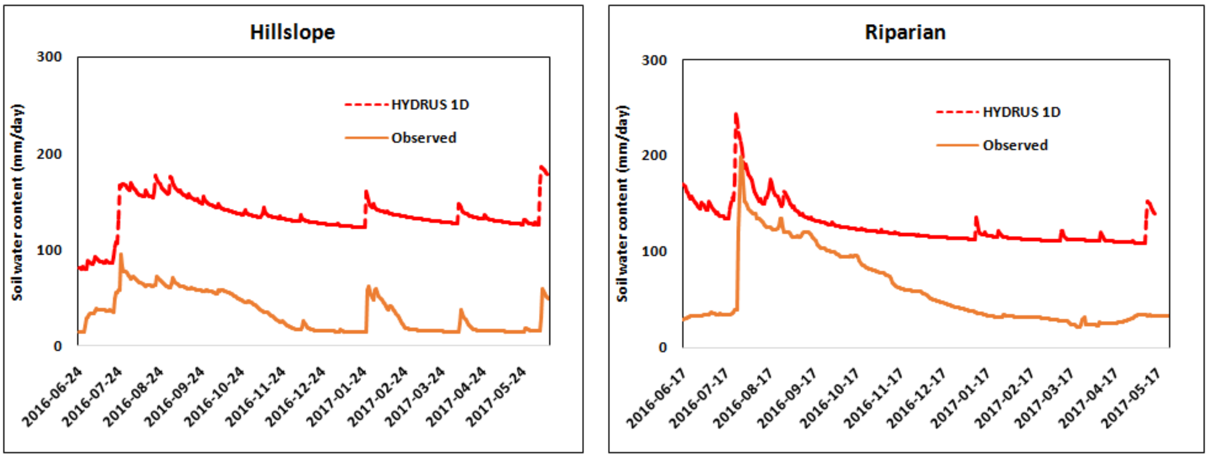

Figure 4.10: HYDRUS 1D simulation of soil water contents

Despite the seasonal simulation of the changes in soil water contents, the overestimation of the simulated soil water variations resulted to the poor performance of the model relative to the observed soil water variations.

4.4.6 Validation of model simulations

Both model simulations (SWB and HYDRUS 1D) were tested against the observed soil water contents to determine the better performing model. There were significant differences between the simulations and the observed values ($P < 0.05$) (Table 4.6).

Table 4.6: Determining the significant differences between the model simulations and observed values using the ANOVA test.

Site	P_{value}
Hillslope	0.00
Riparian	0.00

A post-hoc test was done to determine the model with the least difference (to the observed soil water contents) (Table 4.7).

Table 4.7: Post hoc test between the simulated and observed values

	Hillslope		Riparian	
	LSD	ABS Diff.	LSD	ABS Diff.
Observed vs SWB model	2.9	1.2	5.0	6.4
Observed vs Hydrus 1D	2.9	100.5	5.1	69.8

The soil water balance simulations closely represented the soil water variations than HYDRUS 1D at both site. The soil water balance also performed better on the hillslopes than on the riparian site.

4.5 Discussion

The Cape Agulhas is situated in the Mediterranean climate region that is characterized by dry summers and wet winter seasons. The highest rainfall event that was recorded during the period of the study occurred in July 2016 and the lowest in December 2016. The year 2017 was relatively dry with the highest measured daily rainfall on the hillslope and riparian site being 62 and 56 mm/day, respectively. The aridity of the area is evident from ETo rates that exceeded total rainfall measured by three to four times on the hillslope and riparian site, respectively, during the period of the study. The highest ETo rates were measured in December 2016. These results were in agreement with the results from a study by Ndara (2017), where MOD16 ET detected high ET rates in the southern part of the Heuningnes Catchment (range from 81-160 mm/month). These rates were associated with the occurrences of wetlands in the area. Moreover, Jovanovic *et al.* (2015) and Ndara (2017) observed that the years with high rainfall have high ET rates. These observations were witnessed again between the years 2016 and 2017. In this study, the ETo rates were then used to describe the evaporative demand of the study sites. There were no significant differences in weather characteristics between the two sites, except wind speed. Therefore, the windy conditions at the riparian site explain the higher ETo rates than on the hilllopes. These findings agreed with findings by Allen *et al.* (1998), where solar radiation, wind speed and VPD were found to be major drivers of evapotranspiration.

Soil classification revealed that there was a sandy loam layer on the hillslope which was not present in the riparian site. The sandy clay loam layer was thicker at the riparian site than on the hillslope. These differences accounted for the differences in responses of soils to rainfall events. As a result of thinner soil profiles with higher bulk densities on the hillslopes, the soils did not retain water during and after a rain event which caused runoff in the area and thus resulting to soil water content declining at a faster rate than in the riparian site where the soil profiles were thicker and had low bulk densities which are associated with fast water movement.

At the riparian site, the response to rainfall was observed from the bottom to shallow profiles. This observation was unusual and different from what was observed on the hillslope. Justifications around this occurrence were on preferential flow that may result from macro-pore flow caused by the burrowing of animals and decayed roots. Also, the digging and back-filling that was done when the soil moisture probes were installed could also have influenced this observation. Radcliffe and Simunek (2010) and Huang *et al.* (2012) explained that sometimes the irregular wetting of the soil profile is caused by the sloping of a soil layer that overlies a horizontal profile, causing funnel flow. This could be possible because the sandy loam profile at 30 cm on the hillslope (see Figure 4. 4) overlaid a loamy fine sand profile which is also present in the riparian site. Therefore, sloping of the sandy loam layer could have occurred between the hillslopes and the riparian zone. Thus, water was funneled from the sandy loam on the hillslope into the loamy fine sand profile in the riparian zone. Hence, the delayed response was observed at the riparian site.

The soil water balance model developed in this study was found to be a better method to simulate soil water responses to rainfall if soil moisture probes could not be used. This is because the soil water balance accounts all other physical processes, such as interception, evaporation from the soil, overland flow, interflow etc. some of these processes could not be specified on HYDRUS, hence the poor performance was observed.

Summary

The microclimate results show that average temperatures range between 27 °C – 29 °C in summer and low temperatures of 7 °C occur in winter at both sites. Total rainfall measured during the period of the study was 496 and 461 on the hillslope and riparian sites, respectively. Wind speed was the only weather parameter that differed significantly between the two sites ($P < 0.05$). The high wind speed in the riparian site was accounted for the high total ETo rates of 1 509 mm than 1 449 mm on the hillslopes.

Particle size analyses results suggested that the two sites had similar soil types, except the sandy loam layer that was found at 30 cm depth on the hillslope. The presence of the sandy loam layer caused the sandy clay loam layer on the hillslope to be thinner than that of the riparian site. The differences in soil layer thicknesses may affect soil water storage. Thus, the response of the soils to rainfall events differed. Soil water content increased with rainfall and a decline was observed an hour after the rainfall had stopped on the hillslopes. Whereas, a delayed response was observed in the riparian site, soil water contents of the shallow soil profiles did not respond immediately to rainfall. Peak soil water contents occurred at mid-day (an hour before the rainfall stopped). The high bulk density of the hillslope soils which is associated with high compaction and therefore less water retention, explained the immediate decline of soil water content after the rainfall stopped on the hillslope. At the riparian site, preferential flow which may occur as a result of animal burrow and the possible sloping of the sandy loam layer on the hillslope were accounted for the deep-to-shallow soil response that was observed at the site. As direct soil water monitoring is time consuming and expensive, indirect methods of soil water measurement are considered very important nowadays. In this study, soil water balance realistically simulated the seasonal responses of soil to rainfall than HYDRUS 1D. This approach can be used in areas where continuous monitoring using soil water probes cannot be made.

CHAPTER 5: TRANSPIRATION DYNAMICS OF HILLSLOPE AND RIPARIAN *A. longifolia* INVASIONS

5.1 Introduction

Transpiration is defined as the vaporization of water contained in plant tissues through their stomata and into the atmosphere (Allen *et al.*, 1998). This process requires the availability of solar energy, vapor pressure gradient, and wind. Therefore, solar radiation, air temperature, wind, and atmospheric evaporative demand influence the rate at which plants take up water (Allen *et al.,* 1998; D' Odorico and Porporato, 2006). Transpiration rates differ for each species and these are driven by the availability of soil water and meteorological factors mentioned above. This chapter addresses the main objective of this study, which is to quantify and compare water use rates by hillslope and riparian *A. longifolia.* The Heat Pulse Velocity (HPV) method was used to quantify the rates of water use by hillslope and riparian *A. longifolia* trees. The method provides accurate estimates of diurnal and seasonal rates of water use and it has been extensively used in South Africa and elsewhere (Everson *et al.,* 2014; Dzikiti *et al.,* 2016). The description of selected sites and the installation of sap flow system will also be included.

5.2 Methodology

5.2.1 Plant species identification

Plant specimens were collected at the sites and dried using a plant-presser to identify the species. Thereafter, an identification key from the South African Plant Invaders Atlas (African and Invaders, 2008) was used to identify whether the trees are invasive, naturalised or casual aliens in South Africa. The results confirmed that the trees at the proposed sites resembled the morphologies of the invasive *Acacia longifolia.*

5.2.2 Tree selection

Both sites had infestations of *Acacia longifolia.* However, the riparian site had thick-dense stands of *Acacia longifolia* along the stretches of the Nuwejaars River. Mixed community of

Acacia species was observed on the hillslope. The instrumentation of selected trees (as observed in Figure 5.1) will be elaborated in the next section.

One HPV system was installed on the Spaanjaardskloof hills in the Heuningnes Catchment (34° 31’ 45.7’’ S, 19° 45’ 9.2’’ E). The second system was located at about 20 meters away from the Nuwejaars River in Moddervlei, also in the Heuingnes catchment (34° 36’ 15.8’’ S, 19° 47’ 46.7’’ E). The distance between the two sites is 8 km. Each system monitored three (3) trees simultaneously from June 2016 until June 2017. The selection of trees for instrumentation required a stem survey at both sites to identify the representative trees. The selection criteria for trees to be monitored were:

(i) Actively growing and had relatively straight trunks with no knots as water flow patterns are distorted around knots

(ii) Trees showing no visible evidence of fungal infestation.

(iii) Different stem sizes at breast height, and;

(iv) Growing close to each other (2-5 meters) to account for the HPV cable length

Trees measured during the stem survey were then categorized into three size classes of the circumferences. These were the small (0–10 cm), medium (11–20 cm) and large (> 20 cm). Trees selected at the riparian site had circumferences between 18 and 58 cm. The largest instrumented tree on the hillslope had a circumference of 40 cm.

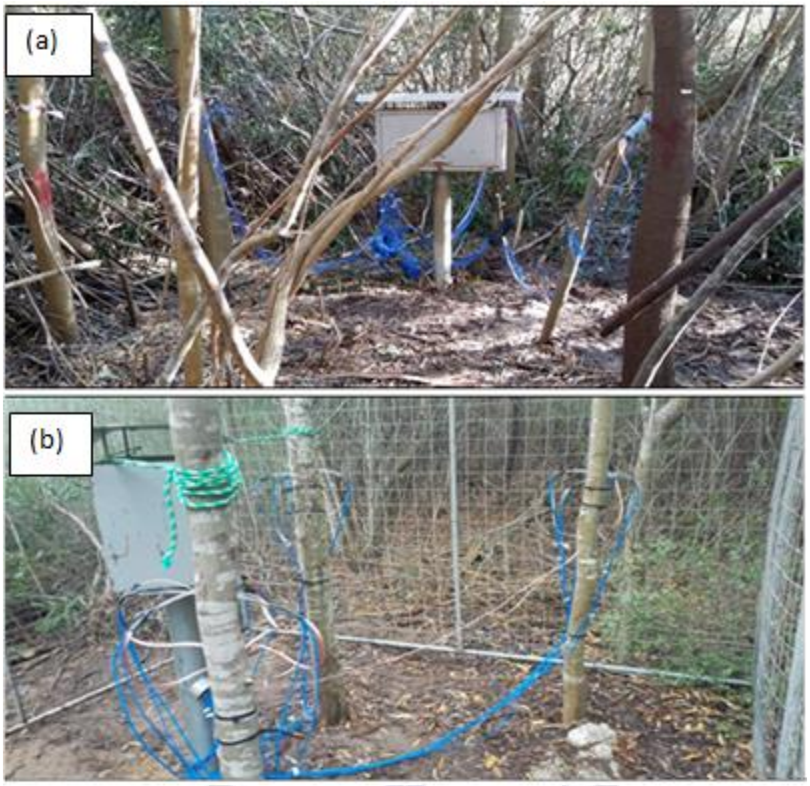

Figure: 5.1: Sap flow monitoring system installed on three adjacent A. longifolia trees on (a) riparian and (b) hillslope sites to measure rates of water-use.

5.2.3 Instrumentation of selected trees

The techniques used to install the HPV system were adopted from Burgess *et al.* (2001). After suitable sites were identified; the morphology of the trees had to be established to ascertain the mechanisms by which the selected trees transpired water, particularly the locations and/or thickness of the sapwood depth (conductive xylem). This was done so as to determine the depths to which probes must be inserted in the selected trees. A methylene blue dye was injected through a 1.8 mm diameter drilled hole on the stem, and was left for a few hours to allow the movement of water with the injected dye simultaneously (Figure 5.2). A core a sample just above the part where the dye had been injected was extracted. The cored sample was used to determine the sapwood area, heartwood, and bark thickness. Based on this information, the depths to which the thermocouples were to be inserted was determined. This ensured that probes were not inserted into the non-conductive heartwood.

Figure: 5.2: Methylene blue dye injected on to a stem to determine the thickness of the sapwood depth.

A drilling template consisting of three holes was tied around the stem of the selected trees at breast h 0eight as illustrated in Figure 5.2. The central hole (~1.8 mm) was used for the heater while the other two 2 mm holes located 5 mm below and above the central hole were used to insert the thermocouples. Four (4) sets of probes were installed on each tree. Twenty-four copper-constantan thermocouple probes were used at each site. The T-type thermocouples were marked to indicate the depths to which they would be inserted. The depths to which thermocouples were inserted on the hillslope ranged between 10 – 50 mm, and 12 - 40 mm at the riparian site. This was done so as to account for radial variation of the sap velocity. Each heater probe released a pulse of heat lasting about 0.5 seconds at hourly intervals throughout the study period. The sapwood temperature was measured before injecting a heat pulse and then one and half minutes after the initiation of the heat pulse. The thermocouple cables were connected to a multiplexer (AM16/32) that allowed multiple measurements to take place (Figure 5.3). The multiplexer and heater cables were connected to a relay control module which functions as a switch that turned on the heaters after every hour. A CR 1000 data logger stored all the data collected.

The study sites were in a remote area. Therefore, the system was powered by a 105AH battery that was charged and changed every two weeks. A safe box was used to store all the equipment as shown in Figure 5.3. The safe box was used to protect the equipment from rain, theft, and vandalism. When equipment installations were completed, fencing was done to keep away primates, cattle, pigs, and other animals that could damage the wiring on and around the system. As highlighted in Chapter 2, this method provides the water use dynamics of an individual tree. Therefore, characterization of the stand properties was done to upscale the acquired results. This will be explained in the next section.

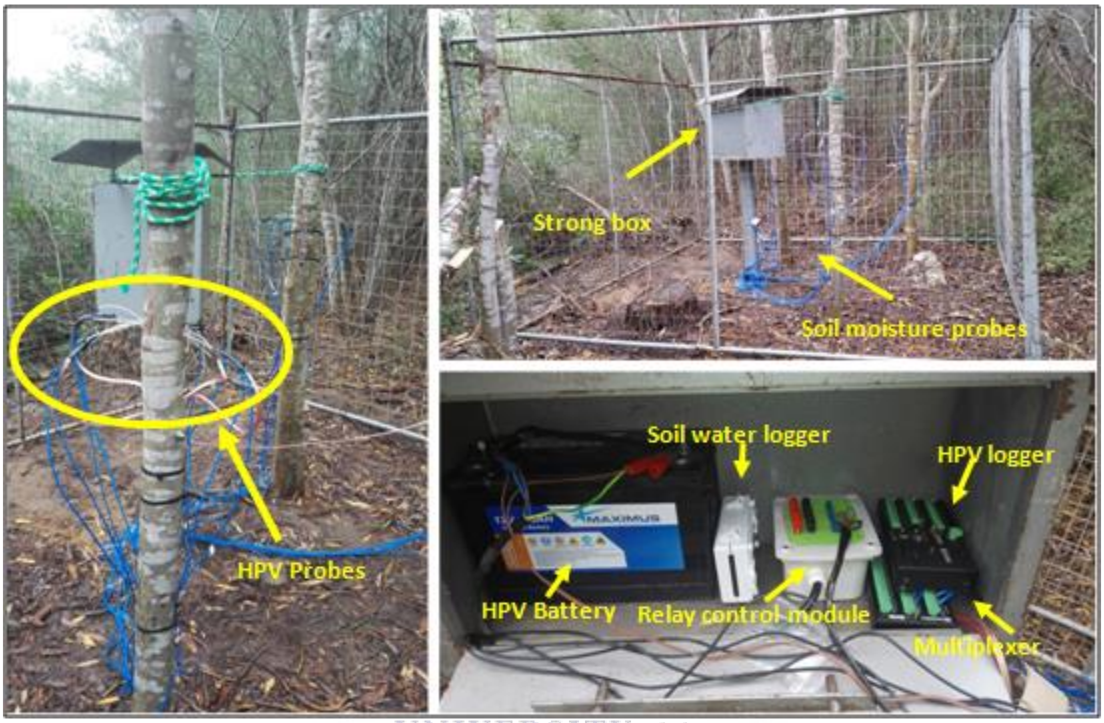

Figure 5.3: A complete HPV system installed on three adjacent trees on the hillslope and a metal enclosure that housed the HPV data logger, multiplexer, relay control module, battery, and a soil moisture logger.

5.2.4 Quality control of HPV sap flow data

The downloaded HPV data were regularly checked for quality. Data of poor quality were flagged with NAN's (not-a-number), which were then removed and interpolated using data collected before and after the missing data. In cases where there were successive missing data was observed, patching was done. The patching process involved determining other functional probe sets containing data for the missing period. In cases where there was more than one functional probe, the probe with the highest correlation with the faulty probe was used. A linear regression equation was used to patch the faulty probe data using a functional probe set or with climate data. Unrealistically high or low values in the data were checked and if the responses were not evident in other probes, they were assumed to be faulty and the data was patched.

Diurnal sap signals are expected to be low in the early morning, peak in the afternoon, and then decline as the sun set. Thus, the velocities in the morning and at night are often assumed to be zero, as trees close their stomata. However, due to other causes such as the misalignment of probes, the lowest values in the diurnal trends do no always stabilise around zero. Therefore, it is important to determine the true zero of each probe. This was done by felling the instrumented trees and continued monitoring for 24 hours. The HPV signals at night and in the early morning were subsequently adjusted to match the zero flow conditions imposed by excising the trees. Alternatively, for deciduous trees, the true zeroes may be determined during the leafless seasons (Everson *et al.,* 2014)

5.2.5 Characterising stand properties of each site

The results obtained from the HPV sap flow system were used to determine the water use rates of the selected trees from both the hillslope and riparian sites in litres per hour / day. The stem size distribution, tree density, sapwood area index (m^2 of sapwood per m^2 of ground area), wounding widths, wood moisture fraction, and the wood densities of the instrumented trees were needed to derive the transpiration rates of individual trees and to scale up the water use to stand level.

(i) Tree density

Tree density (defined as the number of trees per unit area) was determined by creating 100 m^2 quadrants at each site. The trees had a very high density at both sites. Due to this, it was challenging to estimate tree density by means of counting. Consequently, four (100 m^2) quadrants were established at each site. The total number of trees in each quadrant was counted. The number of trees per hectare (x) was estimated from the number of trees estimated from the quadrants.

(ii) Stem size distribution

The stem size distribution was determined to facilitate the scaling up of water use from single trees to stand level at each site. This was done by measuring the circumferences of forty (40) randomly selected trees at breast height for both sites. Results were used to create stem size classes for each site.

(iii) Sapwood area index

The Sapwood Area Index (SAI) represents the relationship between stem sizes and sapwood areas. Six trees with various stem sizes were felled. These included three of the instrumented trees. The circumference, bark thicknesses, heartwood, and sapwood areas were measured from the stem cross sectional areas of the cut trees. These were used to derive stem cross-sectional area vs. sapwood area relationships (allometric relations). The SAI of trees in a particular stem size class was calculated as the ratio of the total sapwood area to one hectare of ground area (i.e. 1 ha = 10 000 m^2). Total sapwood area was calculated as the product of the mean sapwood area of trees in a given stem size class (calculated from the allometric relation graph) and the number of trees of that size class in a hectare.

(iv) Determining the size of the wounding widths

The size of the wounding width indicates the extent of damage that resulted from drilling and sensor implantation into the trees. The wounding widths were determined at the end of the experiment when all thermocouples and heaters were disconnected. Wood samples were collected from the stems which were drilled and cut out to identify and measure the widths of the area that showed signs of disturbance that could have resulted from drilling. Discoloration on and around the drilled holes indicated the extent of the wound.

(v) Moisture fraction and wood density

The moisture fraction of the trees was determined at the end of the monitoring period, by cutting a section of the stem (a disk of ~ 6 cm thickness) from the instrumented trees. The samples were placed in zip-lock bags to prevent or minimize the loss of moisture which may affect the mass of the fresh sample. The samples were then taken to the laboratory and weighed. The weight of the fresh wood (in grams), was denoted as *Mw*. The samples were oven-dried at 70°C and were weighed until the weight was constant. The weight of the dry sample was denoted as *Md*. The moisture fraction of each sample (*ΔM*) was then given as:

$$\Delta M = \frac{Mw - Md}{Md} \qquad (5.1)$$

Wood density of the samples was determined as the ratio of the dry mass to the volume of the wood. The volume of the wood was determined by placing the oven-dry sample into a beaker or measuring cylinder with water of a known volume. The volume of the wood was calculated as the change in volume of the water when the sample was submerged in the beaker.

5.3 Data Analysis

The statistical methods that have been used to address the research questions are t-test analysis, correlation coefficient (r), and the root mean square error. These statistical methods have been used in previous studies (Yoder *et al.,* 2005; Kim *et al.,* 2012; Chai and Draxler, 2014; Ramoelo *et al.,* 2014 etc.). The t-test analysis is crucial for identifying the significance of the differences in water use rates between the hillslope and riparian site.

5.3.1 Establishing the significance of differences in water use rates

The study hypothesises that the riparian trees use more water than trees growing on the hillslopes. Therefore, a t-test at 5% significance level was used to establish the significance of differences in volumetric water use rates by *A. longifolia* trees growing on the riparian and the non-riparian hillslope. The null hypothesis was that there is no difference between the water use rates. A t-test is used for testing the significance of differences between averages of two samples.

To test transpiration drivers for each site, a regression analysis was used. This is a statistical tool that is used to examine the relationship between two variables (dependent and independent variable).

5.4 Results

5.4.1 Characterization of stands

Tree density was approximately 1 800 and 2 500 on a 1 hectare stand on the hillslope and riparian site, respectively The distribution of stem sizes at the sites shows that 63% of the stem sizes on the hillslope belonged to the small class size (1 – 10 cm), whereas, large stem size dominated the riparian site (Figure 5.4).

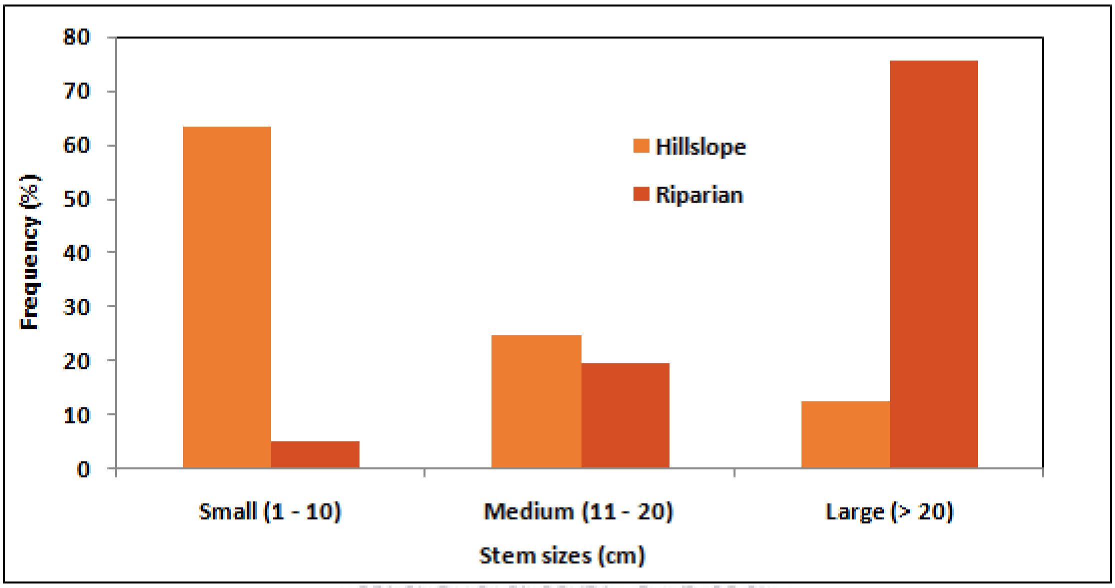

Figure 5.4: The stem size distribution determined from measurements of stem diameters at breast height of 40 trees on the hillslope and riparian site.

The results show that hillslope invasions had lower densities than trees at the riparian site. Similar findings were observed in a study by Dzikiti *et al.* (2013), where the riparian pine trees had larger stem diameters compared to non-riparian trees. These differences were attributed to the availability of water in the riparian zone, whereas those growing in the non-riparian site had experienced and adapted to water stress. The allometric relations show a very strong relationship between the stem cross-sectional area and sapwood area at the sites (Figure 5.5).

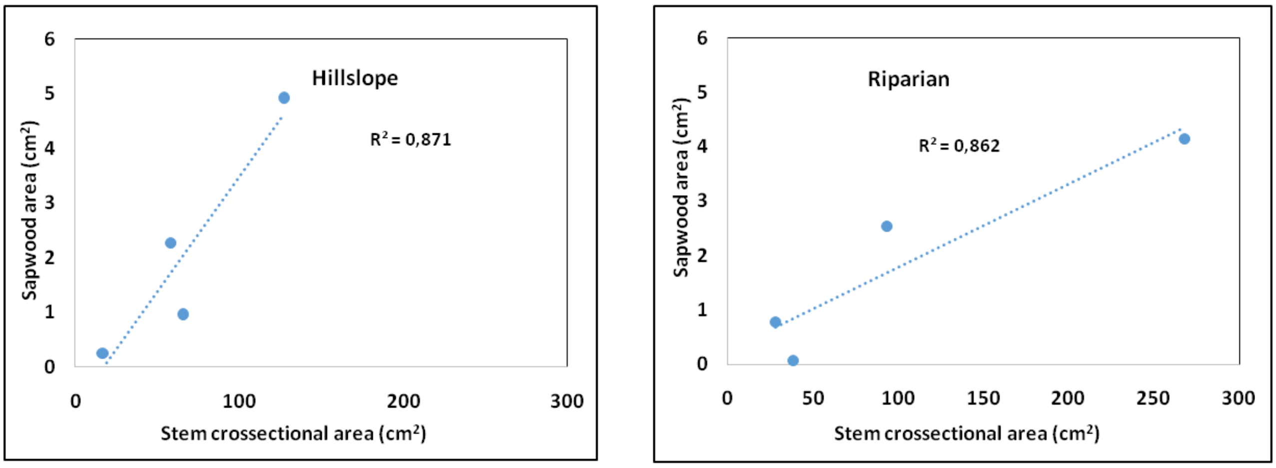

Figure 5.5: Allometric relationships between the sapwood areas and the stem cross-sectional area of A. longifolia on the hillslope and riparian site.

Allometric relations show that the sapwood area of the trees increased with stem diameter. Thus, trees with large stem diameters had large sapwood areas which are associated with increased water use rates. The small sample size was also accounted for the strong relationship. Therefore, the relationship is expected to change with increasing number of samples.

5.4.2 Transpiration dynamics

The evaporative demand at both sites was high in summer and low in winter as expected. On the hillslope, ETo was between 8 – 9 mm/day in December 2016 – February 2017 and 0.9 – 1.4 mm/day in winter. At the riparian site, ETo ranged between 8 – 11 mm/day in December 2016 – January 2017 and 0.9 – 2 mm/day in June to August for both 2016 and 2017 (Figure 5.6).

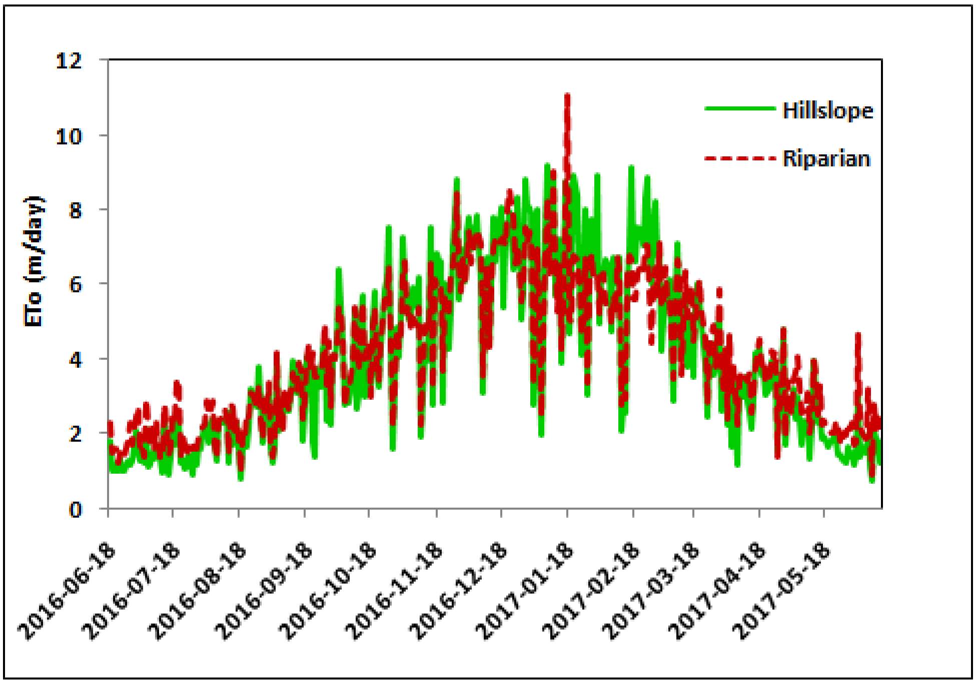

Figure 5.6: Seasonal trends of reference evapotranspiration on the hillslope and riparian site.

Total reference evapotranspiration measured during the study period June 2016 to June 2017 on the hillslope site was 1 449 mm/year and 1 509 mm/year at the riparian site (Table 5.1).

Table 5.1: Total monthly transpiration and reference evapotranspiration

Hillslope	Transpiration	ETo	Riparian	Transpiration	ETo
2016			**2016**		
Jun	3.3	17.2	Jun	3.8	23.1
Jul	10.1	47.6	Jul	26.8	62.6
Aug	25.4	69.3	Aug	66.8	75.1
Sep	28.5	90.1	Sep	71.1	99.0
Oct	35.9	133.0	Oct	88.6	135.8
Nov	30.1	167.5	Nov	75.0	165.6
Dec	26.0	213.1	Dec	65.3	209.9
2017			**2017**		
Jan	19.7	198.7	Jan	44.7	189.6
Feb	22.0	181.0	Feb	46.8	161.3
Mar	17.0	151.0	Mar	36.2	161.3
Apr	11.5	94.6	Apr	35.3	105.4
May	9.4	64.7	May	25.4	80.9
Jun	2.9	21.2	Jun	10.6	39.2
Total	**242**	**1449**	**Total**	**596**	**1509**

The riparian site had higher rates of evapotranspiration as a result of the high wind speeds (7.1 m/s) experienced at Moddervlei in comparison to 4.7 m/s measured on the hillslope. Although seasonal evapotranspiration rates were observed, there were no seasonal changes in the canopy cover at both sites as the trees were evergreen. Also, there was not much variation in canopy cover. This was indicated by the leaf area index (ratio of the leaf area per unit ground area) that ranged between 2.1 -.2.2 on the hillslope and 3.3 – 3.4 in the riparian site.

The variations in ETo rates coincided with transpiration rates. Transpiration measured on the hillslope varied from 0.4 mm/day in July 2016 to a peak rate of 1.4 mm/day during late October to early November 2016, and from 0.5 – 3.5 mm/day in same periods at the riparian site (Figure 5.7).

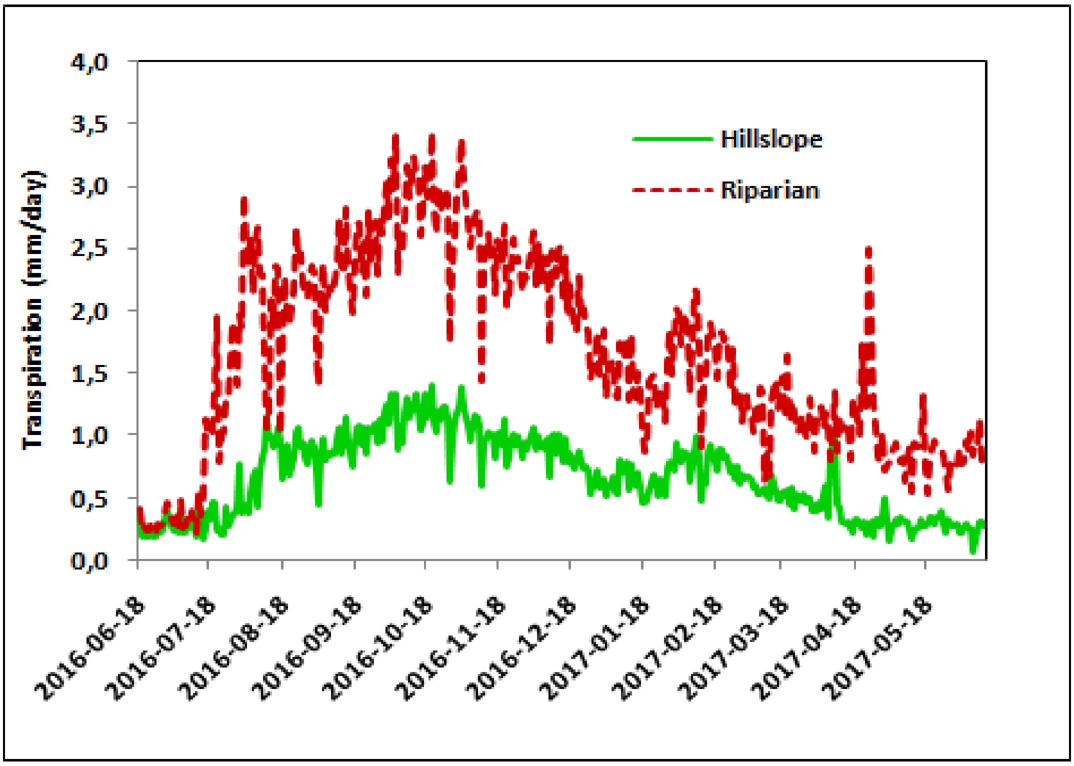

Figure 5.7: Seasonal trends in Acacia longifolia transpiration rates at the study site.

The two sites had similar seasonal variations in transpiration rates. Peak rates occurred in late October - early November 2016. Unexpectedly, a constant decline was observed in December 2016 – January 2017 at both sites. This was shown by transpiration rates of 0.4 and 0.9 mm/day in January 20th on the hillslope and riparian site, respectively. Total transpiration by *A. longifolia* during the period of the study on the hillslope was 242 mm/year and 596 mm/year at the riparian site (Table 5.1) which suggests that, at stand level, the riparian tree water use was two times more than that of the hillslope invasions. The differences in water use by hillslope and riparian invasions were statistically significant (P < 0.05) (Table 5.2).

Table 5.2: The Significance of the differencesin transpiration rates of the hillslope and riparian invasions

	Hillslope	***Riparian***
Mean	0.67	1.66
Variance	0.10	0.63
Observations	360	360
Hypothesized Mean Difference	0	
df	473	
t Stat	-21.88	
P(T<=t) two-tail	0	
t Critical two-tail	1.96	

The impact of seasonal variation in climate parameters and soil water content was also illustrated.

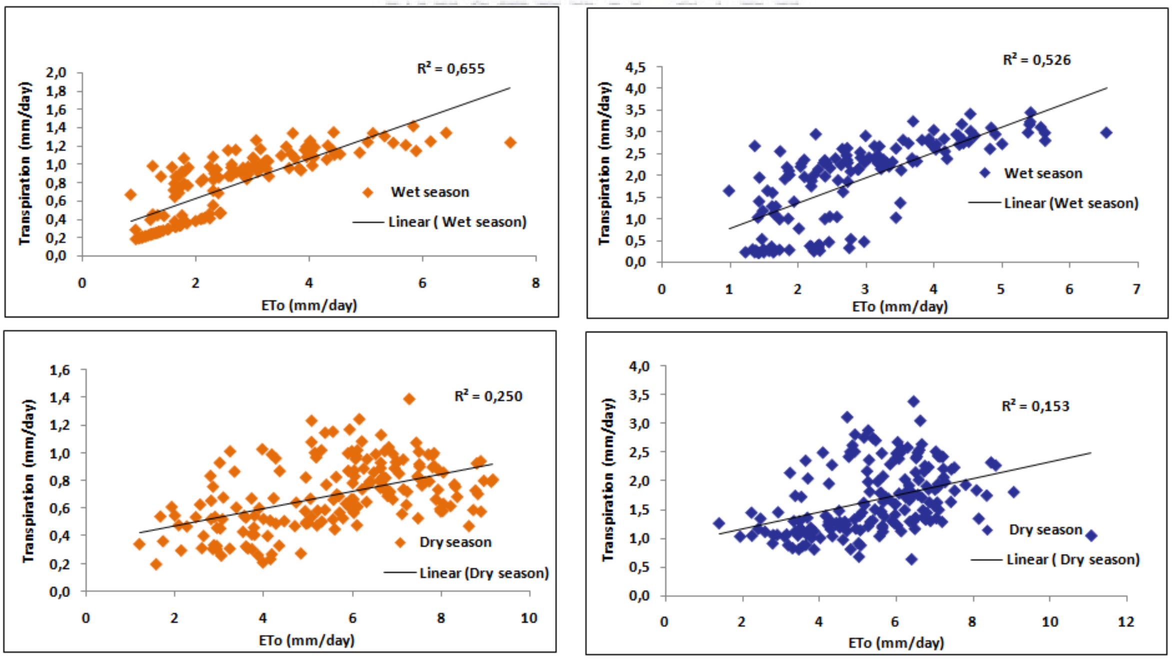

Figure 5.8: Transpiration rates with response ETo changes during the wet and dry season on the hillslope (brown) and riparian (blue) site.

During winter, when soil water content is not the limited, ETo was the main driver of water use (R^2 = 0.6 and 0.5). In a Mediterranean climate region, soil water tends to be depleted during the drying season, thus limiting the rates of water use by plants despite the increasing atmospheric demand. Hence the poor relationship (R^2 = 0.2 and 0.1) between transpiration and ETo was observed in summer. The impact of soil water availability on transpiration was also examined by determining the influence of soil water content and deficit on plant water use rates (Figure 5.9).

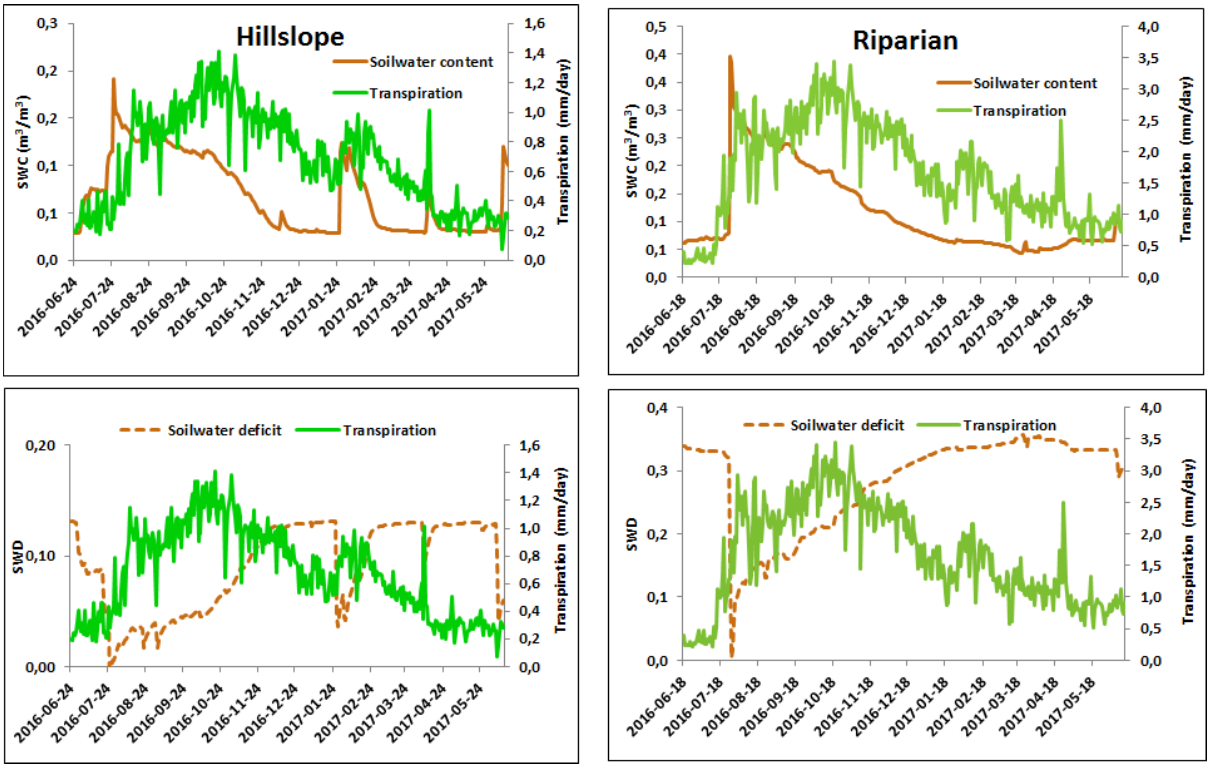

Figure 5.9: The influence of soil water content and deficit on transpiration rates.

During the dry season, soil water content at both sites was the main factor limiting transpiration. Hence there was a poor relationship between transpiration and ETo during the dry season (R^2 = 0.2 and 0.1 on the hillslope and riparian site) (Figure 5.8). This was further observed in November – October 2017, when there was a decline in rates of water use that coincided with the drying out of the soil (Figure 5.9). The increasing soil water deficit coincided with the period in which the peak transpiration rates were measured. This showed the reversed impact of transpiration on soil water, which consequently can imply that these trees were depended on soil water (Table 5.3). The relationship between soil water deficit and transpiration rates by riparian trees was $R^2 = 0.4$ and 0.7 and on the hillslope R^2 was 0.1 and 0.2 in summer and winter, respectively. These results show that transpiration rates by riparian trees were more influenced by soil water deficit than hillslope invasions (Figure 5.10).

Table 5.3: Total monthly transpiration and soil water availability

Hillslope	Transpiration	ETo	SWC	Rainfall	Riparian	Transpiration	SWC	ETo	Rainfall
2016					2016				
Jun	3.3	17.2	0.2	12.2	Jun	3.8	0.8	23.1	6.1
Jul	10.1	47.6	3.0	123.0	Jul	26.8	3.7	62.6	161.0
Aug	25.4	69.3	4.1	50.6	Aug	66.8	8.0	75.1	57.7
Sep	28.5	90.1	3.6	48.4	Sep	71.1	6.7	99.0	40.6
Oct	35.9	133.0	3.3	24.6	Oct	88.6	5.6	135.8	15.5
Nov	30.1	167.5	1.9	25.2	Nov	75.0	4.0	165.6	14.0
Dec	26.0	213.1	1.1	16.4	Dec	65.3	2.9	209.9	9.1
2017					2017				
Jan	19.7	198.7	1.3	51.4	Jan	44.7	2.1	189.6	35.1
Feb	22.0	181.0	2.1	18.4	Feb	46.8	1.8	161.3	20.3
Mar	17.0	151.0	1.0	10.6	Mar	36.2	1.6	161.3	4.8
Apr	11.5	94.6	1.1	38.0	Apr	35.3	1.6	105.4	32.8
May	9.4	64.7	1.0	10.0	May	25.4	2.1	80.9	7.9
Jun	2.9	21.2	0.9	67.2	Jun	10.6	1.1	39.2	56.4
Total	242	1449	25	496	Total	596	42	1509	461

Hillslope invasions transpired 51% of rainfall that was received during the study period. The total rainfall on the hillslope was ~ 7% more than the riparian site. However, soil water contents were higher at the riparian site, which resulted to transpiration rates being higher at the site. It was also evident that the variation in soil water deficit contributed to the seasonal variation of transpiration at the riparian site than on the hillslope (Figure 5.10).

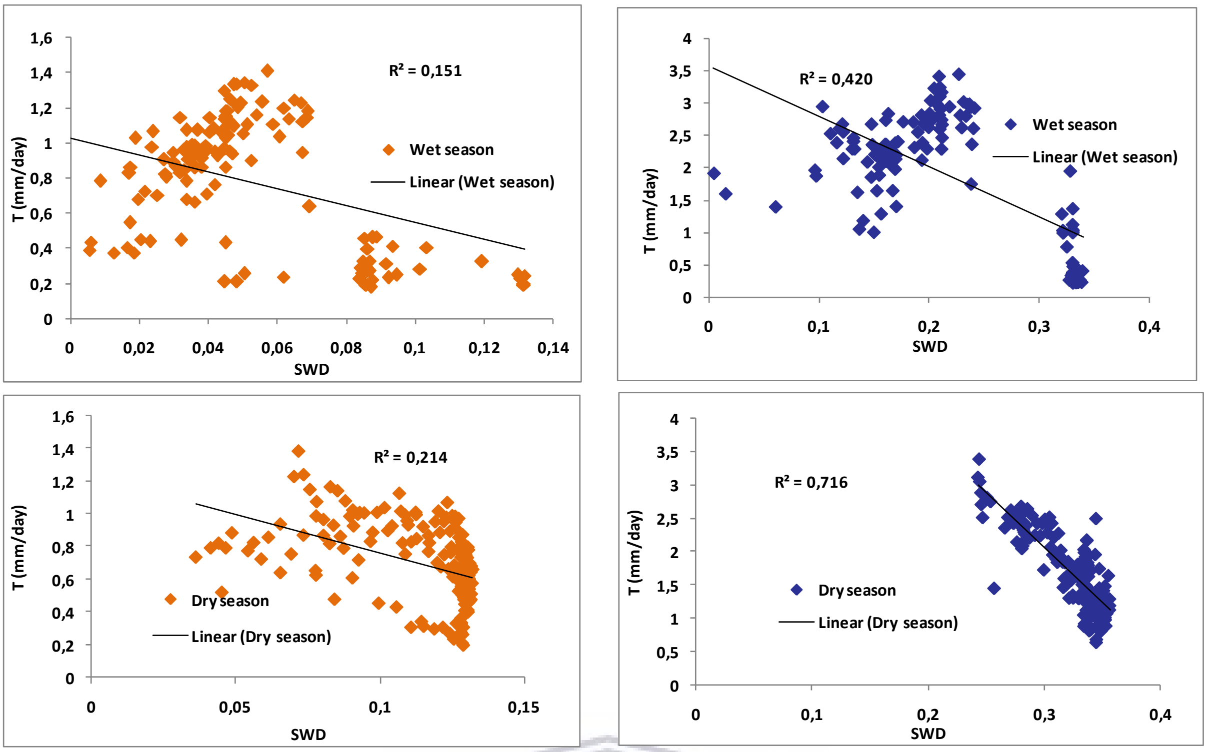

Figure 5.10: The seasonal influence of soil water deficit on transpiration rates on the hillslope (brown) and riparian (blue) site.

The inverse relationship between soil water deficit and transpiration show that the riparian trees responded much more strongly to changes in soil water than those growing on the hillslopes. This was rather unexpected since the riparian trees are known to tap into other water sources available at the riparian zones. Crop Water Stress Index (CWSI) was estimated to assess the influence of soil water stress to transpiration rates (Figure 5.11). This was important to determine whether the tress had gone under stress during the study period.

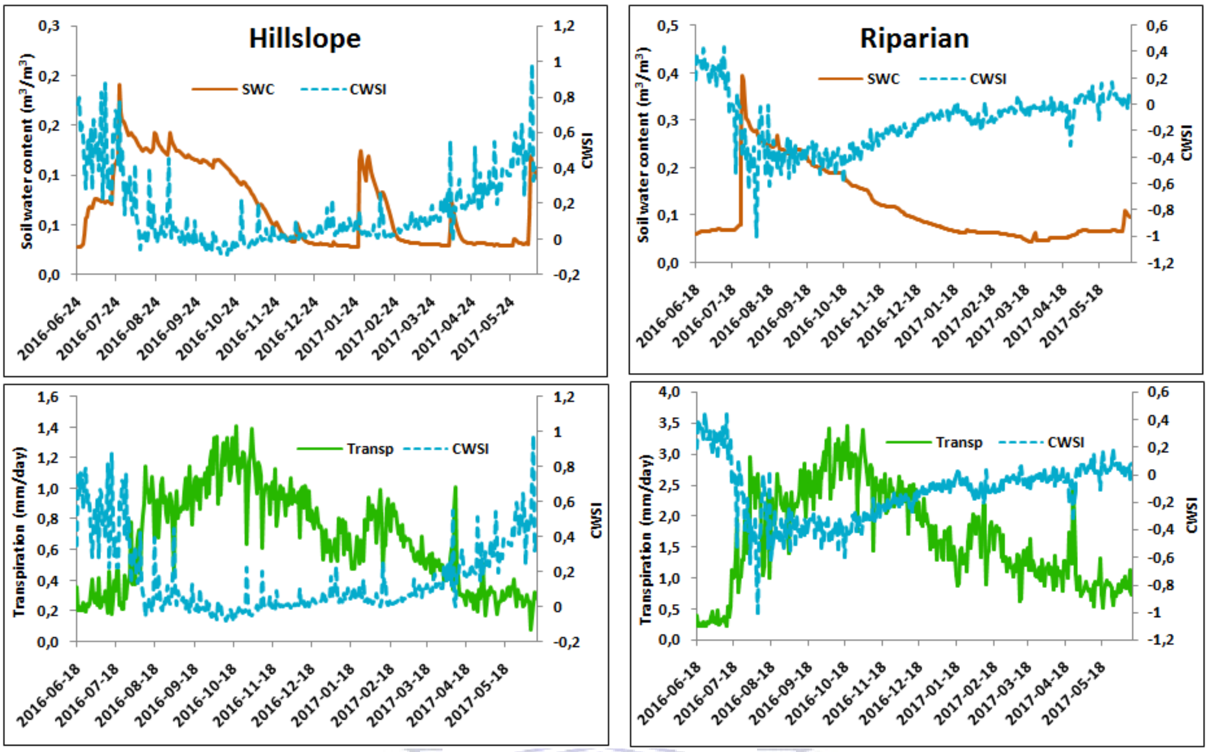

Figure 5.11: The influence of soil water availability and stress on transpiration

The availability of soil water during the winter season caused a reduction in plant water stress on hillslope and riparian invasions. This was expected as the previous results have already shown soil water availability to have a strong influence on transpiration rates in winter. During summer, the severity of plant water stress increased with the reduction in soil water availability at both sites. However, water stress was more severe on the hillslope despite rainfall events that were observed during the summer season (Figure 5.11).

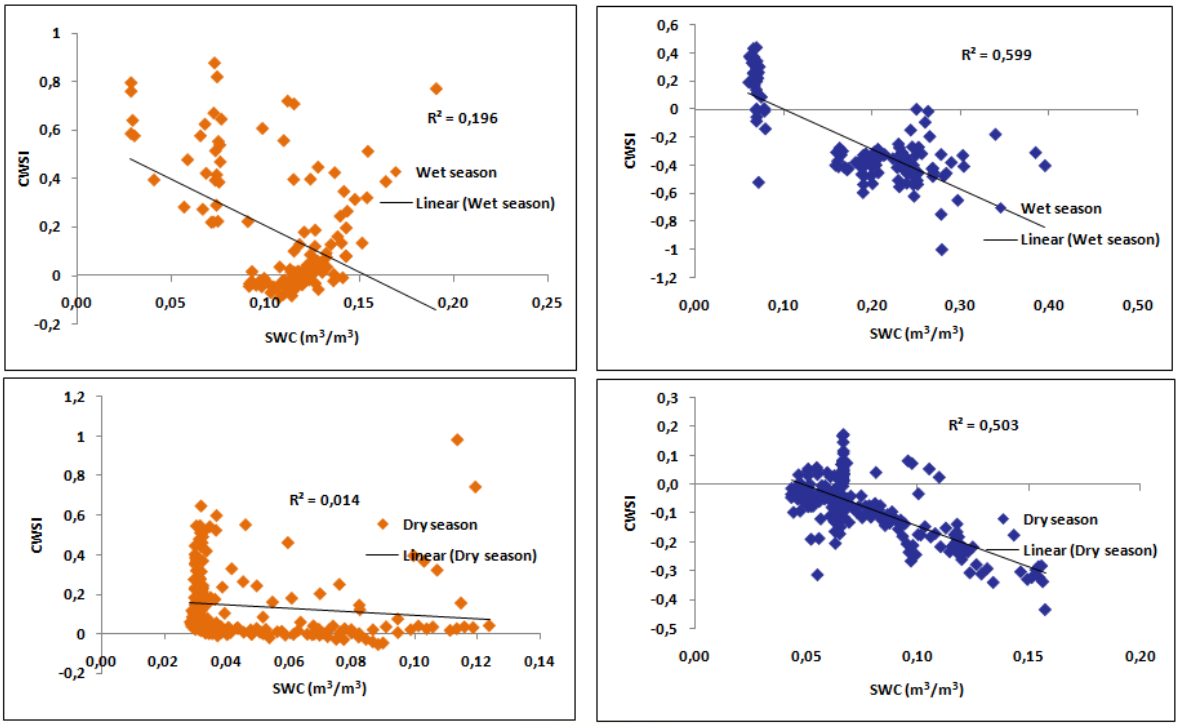

Figure: 5.12: The influence of soil water content on plant stress

Plant water stress that the hillslope trees experienced was not caused by seasonal variation in soil water content (R^2 = 0.1 and 0.0 in winter and summer). Whereas, at the riparian site, the variability of soil water content strongly influenced plant water stress (R^2 = 0.5 in winter and summer).

5.4.3 Transpiration dynamics under unstressed conditions

Rainfall data from the on-going monitoring in the catchment suggested that the total rainfall received at the catchment in 2017 was 50% of the total rainfall recorded in 2015, while 2016 had mean annual rainfall close to other previous years (Mazvimavi *et al.*, 2018). Therefore, total transpiration rates measured in 2016 and 2017 represents the water use rates under stressed conditions. Unstressed crop coefficient was estimated using data from August to September 2016, when soil water content was not limited and transpiration rates were increasing at both sites. It was then assumed that the unstressed coefficients remained the same from August 2016 to June 2017. Unstressed coefficient of the hillslope trees was estimated to be 0.39 and 0.90 for the riparian trees. These coefficients were used to estimate unstressed transpiration rates (Figure 5.13).

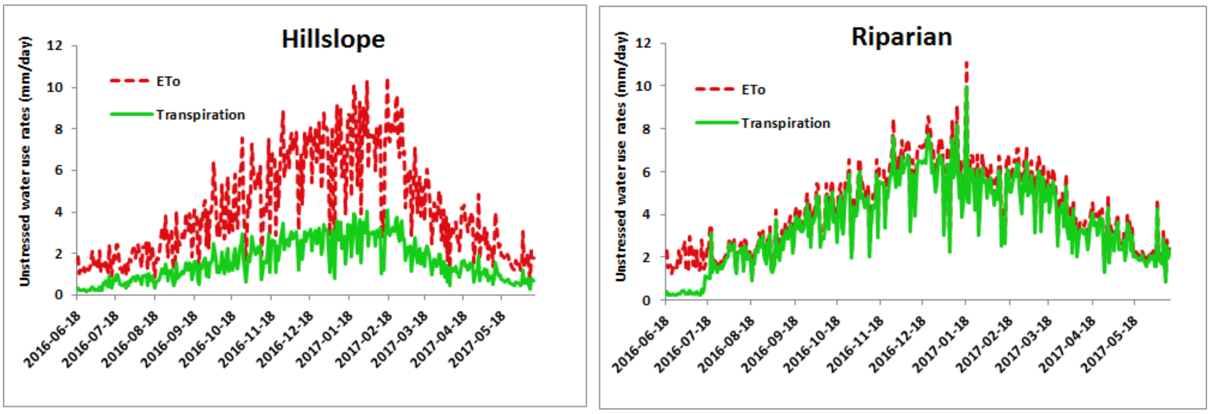

Figure 5.13: Unstressed water use rates by A.longifolia on the hillslope and riparian site

Unstressed transpiration from June 2016 to June 2017 on the hillslope was 579 mm/year and 1 348 mm/year for the riparian site. These results suggests that during years with rainfall above the average, *A. longifolia* invasions can use more than two times the estimated water use rates in this study.

5.4.4 The impacts of IAPs at a catchment scale

Kotze *et al.* (2010) highlighted that the area invaded by alien plants in the catchment is equivalent to 7 930 hectares at 100% density cover. Similar findings were observed through satellite imagery by Nowell (2011). The catchment scale estimates were based on the assumptions that other Acacia species transpire at similar rates to *A. longifolia* trees, the riparian zone make up 5% of the invaded area, as well as 95% being the hillslope with respective transpiration rates of 596 and 242 mm/year. Then, the total water use by IAP at a catchment scale was 20.5 Mm^3 from June 2016 to June 2017 which was a dry year. The estimated water use by these plants is in close range with the estimated annual runoff (18.8 Mm^3) of the catchment (Mazvimavi *et al.*, 2018). Using unstressed transpiration rates that may occur during years with rainfall above the average, total water use by IAPs can reach 49 Mm^3. Transpiration rates of the natural shrublands were not investigated in this study. However, assuming that the fynbos shrubs transpired at similar rates to grasses, which use 411 mm/year based on SAPWAT 4 estimates (van Heerden and Walker, 2016). Then, transpiration rates by IAP's were 30% more than that of the fynbos. The hydrological benefits of clearing IAPs was estimated as the difference in transpiration rates between unstressed *A. longifolia* trees (579 mm/year) and the fynbos shrubs. The incremental water use from clearing IAP and replacing by fynbos is 17 Mm^3.

5.5: Discussion

The hillslope and riparian *Acacia longifolia* invasions showed similar seasonal variations of transpiration rates. However, the total transpiration rates measured on the hillslope at stand level was 242 mm/year which was lower than the rates measured in the riparian site (596 mm/year). The 146% significant difference in water use rates was explained by high tree density dominated by larger stem sizes in the riparian site. The structural differences in riparian and hillslope invasions agreed with the findings of previous studies by Scott (999), Dye and Jarmain (2004), Clulow *et al.* (2011), and Dzikiti *et al.* (2013). Schachtschneider and Reinecke (2014) explained that plants growing under different conditions of water availability can adapt their physiology to maximize their chances of survival. Therefore, the availability of water in the riparian zones caused trees to have large stem diameters than those growing in non - riparian zones. Allometric relations showed that trees with large stem diameters had large sapwood areas which enable transportation of water (or sap).

The seasonal variations of transpiration rates were similar to those of the atmospheric evaporative demand which is indicated by the reference evapotranspiration of the sites monitored. The high evaporative demand at the riparian site (1 509 mm/year) was attributed to the higher wind speed that can be 7.1 m/s than the hillslope 4.7 m/s. Evapotranspiration is also increased by the taller, rougher canopies of invasive alien plants (Le Maitre 2004). The evaporative atmospheric demand was the major driver from winter to late spring when the trees accessed residual soil moisture from the rain at both sites (Figure 5.8). However, it was rather unexpected that the water use rate by riparian trees after the wet season was limited by soil water content. Riparian trees are known to be opportunistic water users (Le Maitre *et al.,* 2000). These findings therefore contradicted the previous literature (Scott, 1999; Doody *et al.,* 2011; and Nowell, 2011) which suggested that riparian trees tend to strongly depend on groundwater. Snyder and Williams (2000) however substantiated that not all woody species (as assumed) in the forest use groundwater. Results from this study were also in agreement with the findings from a study by Dzikiti *et al.* (2016), where riparian water use by riparian *Eucalyptus* declined with increasing soil water deficit in the upper soil horizons although the atmospheric evaporative demand was high. Which suggested that rain water stored in the shallow soil layers is an important source of water for the riparian eucalypts.

Le Maitre *et al.* (1999) stated that numerous species that grow in semi-arid to arid areas have shallow, spreading root systems that are used to scavenge water for plants. This behaviour was observed on both the hillslope and riparian *A. longfolia* invasions, as evident from the declining transpiration rates when soil water content also decreased. The relationship was stronger than expected at the riparian site which suggested that the riparian invasions were strongly dependent on soil water availability than hillslope invasions. The riparian trees had a very shallow root system (less than 60 cm) and a number of trees were uprooted by strong winds, due to poor anchorage. It is probable that the prevailing drought situation, evident from the ETo exceeding the rainfall received and observed by Mazvimavi *et al*. (2018), led to the substantial drying of the top soil where most roots were concentrated. Furthermore, this is supported by the inverse relationship between soil water content and plant water stress. Plant water stress increased with declining soil water content, which resulted to a reduction in transpiration rates. Under unstressed conditions, *A. longifoila* invasions have the ability to use double the total volumes of water that was measured in this study. Thus, in years with relatively high rainfall and when the water table is closer to the surface, *A. longifolia* transpiration rates can reach 579 and 1348 mm/year which are twice the totals that were estimated during the period of this study.

Preliminary results from the on-going groundwater monitoring in the catchment revealed the shallowness of the water table, which was 4.2 m and 1.6 m on the hillslope and riparian sites, respectively (Mazvimavi *et al.*, 2018). The water table at 1.6 m in the riparian zone may have caused the absence of the tap root which was observed on the inspected trees that had been uprooted by wind. The shallow water table caused trees to use substantial volumes of water. This was evident on transpiration rates by riparian trees that exceeded the rainfall received in the area. The fluctuation of groundwater table can also cause the riparian roots to be concentrated in shallow soil layers. These roots can be seen in moisture rich patches and respond opportunistically to precipitation (Le Maitre, 1999), therefore, reducing transpiration during periods when there is low rainfall.

The low water use rates by hillslope invasions (242 mm/year) compared to those at the riparian site was attributed to the low storage of soil water and the water table that was observed at 4.2 m which could have also caused the severity of plant water stress to be more on the hillslope trees than the riparian invasions. These conditions may have caused hillslope invasions to adopt characteristics that enabled them to withstand water stress. Thus, trees found on the hillslope had smaller stem diameters and sap wood areas as well as less dense vegetation cover. This behaviour was also observed in other species, which close their stomata (Eucalypts), shed off their leaves (Prosopis), or have a small surface-area-to-volume ratio and have a reflective colour to prevent water loss. Therefore, it is possible that invasions on the hillslope developed root systems that tap the water table. This was substantiated by low groundwater table and reduced spring discharge in areas where invasive trees were present on the hillslope (Mazvimavi *et al.,* 2018). It was also observed that water stress on hillslope invasions was not caused by soil water. The water table was expected to be lower in summer. Thus, explaining the severity of plant water stress on the hillslope despite the fluctuating soil water contents. However, the plant water sources were not investigated in this study.

The transpiration rates established in this study are similar to those determined in other studies for Acacia species in the Western Cape. Dye and Jarmain (2004) estimated 171 mm/year, and 585 mm/year was estimated by Scott-Shaw *et al.* (2017). Other riparian invasions such as Pines and Eucalyptus used ~ 980 mm/year and ~ 833 mm/year respectively as reported by Dzikiti *et al.,* (2013; 2016). The incremental water use of clearing IAP at catchment scale is 17 Mm^3. These results are in agreement with the results by Nowell (2011) which suggested that the potential water savings after clearing IAP's at the Agulhas Plain over the total area of 66 772 hectares was 36 Mm^3. Holmes *et al.* (2008) and Scott-Shaw *et al.* (2017) also highlighted that there would be a gain in groundwater recharge and/or stream flow if the alien trees are removed from the riparian zones. Le Maitre *et al.* (2000; 2015) agreed that the *Acacia* taxon has the most extensive invasion by area and likely the greatest impacts on water resources in South Africa although no studies had actually quantified the water use by this species. Based on the results, the hypothesis that riparian trees generally use more water than non-riparian species was accepted in this study. Therefore, clearing of *A. longifolia* should be prioritised in the riparian areas as this is likely to lead to potential water savings.

Summary

Transpiration varied seasonally with the atmospheric evaporative demand of the sites (depicted by ETo). The evergreen characteristic of *A. longifolia* was also observed at both sites. However, as expected, riparian invasions transpired 596 mm/year, which was two times more than the hillslope invasions (242 mm/year). These differences were attributed to the dense canopy formed by the riparian invasions which were dominated by trees with large stem sizes than those on the hillslope. This observation agreed with previous literature, where riparian invasions were found to have denser canopies than those growing on the non-riparian area. During winter, when soil water was not limited, the atmospheric evaporative demand was the main drive of tree water use at both sites. Soil water content was found to be the main factor influencing the riparian tree water use. This was rather unexpected as riparian trees are commonly known as “Phreatophytes” or plants that have access to multiple water sources. Also, transpiration by hillslope invasions showed a weak relationship with soil water deficit. Therefore, suggesting that when the water table is high during winter, soil water deficit did not influence transpiration by hillslope invasions. Furthermore, plant stress was more severe on hillslope invasions than the riparian trees. This occurred despite the more frequent rainfall events and fluctuating soil water contents on the hillslope than the riparian site. These findings therefore highlighted that during the dry period, soil water content is not the main driver of transpiration on the hillslope.

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

In this study, transpiration rates were monitored for one year, from June 2016 to June 2017. The first objective was to quantify and compare transpiration rates of *A. longifolia* growing on the hillslopes and riparian zones. This study found that riparian *A. longifolia* invasions transpired 596 mm/year, which was 146% more than the volume used by hillslope invasions (242 mm/year). During years with above average rainfall, transpiration rates can be 579 and 1 348 mm/year on the hillslope and riparian site. The high rates of transpiration by riparian invasions were attributed to dense canopy dominated by trees with large stem diameters than on the hillslope.

The second objective of the study was to investigate and assess the major drivers of water use at the two sites. Wind speed was the only weather parameter that differed significantly between the two site. High wind speed occurred frequently at the riparian site than on the hillslope, due to the funnelling of winds through the river valley. This resulted in total reference evapotranspiration being higher at the riparian site. In this study, reference evapotranspiration was used to describe the atmospheric evaporative demand of the study sites. Therefore, the transpiration rates at the riparian site were also explained by high atmospheric evaporative demand. This was evident from the correlation between ETo and transpiration rates during the wet and dry season showed that in winter, when soil water was available, ETo was the main driver of transpiration at both sites. During the dry period, however, soil water content was the main limiting factor of transpiration by riparian invasions. This finding contradicts the common belief that riparian trees always have ready access to water due to river water recharging the surrounding subsurface zone.

The unusual response of soil water content at the riparian site was explained by the occurrence of macropores. Hence, a delayed response in shallow soils was observed at the riparian site. Soil water content on the hillslope declined an hour after the rainfall event. The higher bulk density of the soils on the hills suggests high compaction on the soils, and therefore there is low water retention. Soil water balance a suitable alternative to monitor soil water variation in areas where soil water probes cannot be used. The shallow water table at the riparian site and the high storage of water in the soil caused the riparian trees to use substantial volumes of water than the hillslope invasions. Thus, the hypothesis that riparian trees use more water than invasions on non-riparian areas was accepted in this study. It was also concluded that clearing of *A. longifolia* should be prioritised in the riparian areas as this likely leads to water savings. At catchment scale, the incremental water use after clearing IAP's can be 17 Mm^3.

Recommendations

Results from this study resulted to interesting debates and assumptions since there is lack adequate knowledge about the water-vegetation-soil interactions of this catchment. There are no previous studies that have been conducted to investigate the interaction between vegetation and groundwater in this catchment. Recommendations from this study are:

I. Determining the sources of water used by invasive alien trees using isotope signatures.
II. The use of satellite imagery data to confirm or validate catchment scale benefits of clearing invasive alien trees, as the results from this study were species and site specific.
III. Comparative assessment of water use dynamics by a different species to evaluate if other invasive alien tree species have similar water use patterns.
IV. Improving understating of groundwater – surface water interaction using HYDRUS 2D to simulate the possible interflow/ seepage that this study assumes may be taking place on the hillslope.

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