Pyrohydrology in African Savannas

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by

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EXECUTIVE SUMMARY

BACKGROUND AND RATIONALE

Soils are vital in supporting healthy and functioning ecosystems. Besides providing a medium for plant growth, soils play a major role in ecosystem functioning through nutrient cycling and water filtration through the system, thus when soils are degraded important ecosystem services are affected. Degraded soils may not be able to store and filter water as efficiently thereby affecting water quantity and quality. This in turn has a detrimental effect on catchment hydrological processes. Soils play a major role in landscape hydrology by providing a medium for water distribution and storage. The complex relationship between soil and water has been described as interactive; meaning that the physical, chemical and biological properties of soil influence the manner in which water is transported and stored within the landscape which impacts the ecosystem.

As with many other biomes around the world, the structure and production of African savannas are controlled by the spatio-temporal availability of water. These savannas are considered complex and dynamic systems which are co-dominated by grasses and trees. Fire, along with fluctuations in water availability, nutrients and herbivory is regarded as one of the primary drivers responsible for controlling these heterogeneous savanna systems. Although savanna vegetation has been described as resilient and relatively well-adapted to fire, it is believed that frequently-recurring fires can prompt long-term soil degradation, changing the soil hydrology and ultimately reducing ecosystem productivity. The frequency of savanna fires are highly variable and influenced by factors such as preceding annual rainfall and pressure from herbivores. Both of these factors directly impact the fuel load that is required to support veld-burning.

In other landscapes around the world, it was found that fires affect soil hydrological properties and processes. In African savannas where fire is a key driver controlling ecosystem functioning, and more specifically in Kruger National Park where fire is used as a management tool, there is a lack in current understanding regarding the impacts of long-term fire management on soil hydrology. During the early 1950s, a long-term fire experiment was initiated in Kruger National Park using Experimental Burn Plots. These burn plots offered a unique opportunity to determine the effects of long-term fire treatments on soil hydrology on contrasting geologies in African savannas.

STUDY OBJECTIVES

Since fire plays a major role in savanna system dynamics and functioning. The long-term Experimental Burn Plots in Kruger National Park were used in order to investigate the effects of varying long-term fire treatments (annual vs. no burn vs. variable fire regime, in some cases) on soil hydraulic properties and water balances on granitic and basaltic geologies. The following were the objectives for the study:

Objective 1
Understand the effects of long-term fire treatments on soil hydraulic properties on two different geologies in Kruger National Park.

Objective 2
Investigate the effects of long-term fire treatments on surface runoff and sediment yield in Kruger National Park.

Objective 3
Determine the effect of long-term fire treatments exposure on soil water balances in contrasting geological soils in Kruger National Park.

METHODOLOGY

This study was conducted during May 2012-December 2013 on different soil types stemming from the two dominant geologies in Kruger National Park, i.e. granites and basalts. The granitic Experimental Burn Plots are dominated by Clovelly and deep red sands and receive a mean annual precipitation of ± 700 mm. The soils on the basaltic EBPs are characterized by Shortlands and Swartland soil types and receive a mean annual precipitation of ± 500 mm.

The effect of varying fire regimes on various hydrological parameters were investigated on various burn plots between the granites and basalts. A breakdown of these tests are summarised in Table 1. The varying fire regimes investigated include the frequently-burned annual plot, no burn plot (> 50 years fire exclusion) and the natural area surrounding the burn plots with a fire return period of roughly 4.5 years.

Table 1 A breakdown of the different tests applied on the various Experimental Burn Plot strings

Geology	Section	Experimental Burn Plots	Hydrological Tests	Plots
Granites	Pretoriuskop	Numbi	Soil hydraulic properties, Runoff simulations, Soil water balance	Annual and No Burn plots
		Kambeni	Soil hydraulic properties, Runoff simulations, Soil water balance	Annual, No Burn and Variable Fire Regime
Basalts	Satara	N’wanetsi	Soil hydraulic properties, Soil water balance	Annual, No Burn and Variable Fire Regime
		Satara	Soil water balance	Annual and No Burn plots

Soil hydraulic properties were determined using a tension disc infiltrometer to measure the unsaturated hydraulic conductivity at the soil surface and a guelph permeameter to measure saturated hydraulic conductivity between 2 and 7 cm of the soil surface. Soil compaction was determined using a drop-cone penetrometer while soil organic matter (total carbon) was measured using an analytic Leco TruMac Series machine. The water retention capacity was inferred by measuring soil water potential with a WP4-t dewpoint potentiameter. Furthermore, vegetation characteristics such as grass biomass and basal cover were measured using a disc-pasture meter and nearest-distance-to-tuft method, respectively.

Rainfall simulations were used in order to measure the effect of different fire regimes on surface runoff and sediment yields. Rainfall was simulated at two different intensities, which were applied 24 hours apart, on the annual and no burn plots on the granitic Experimental Burn Plots. The subsequent surface runoff was measured and sediment collected for analysis using a spectrophotometer and the actual measurement (weight) of sediment. The soil water balances on the different burn plots were measured by using remote-sensing analyses to determine evapotranspiration rates and applying the HYDRUS 3D model to simulate water balances for the different fire regimes in question.

RESULTS AND DISCUSSION

This study revealed that it is rather the time following a fire, and not necessarily frequency, which resulted in decreased soil infiltration, with slowest infiltration rates immediately after the fire. Findings suggested that fire primarily affected infiltration rates at the soil surface and that these fire effects would dissipate within approximately two years — suggesting the soil's ability to recover; at least in terms of their hydrological function. Soil compaction, which is recognized for impeding soil infiltration, was attributed to soil processes such as raindrop impact and splash but deeper compaction was linked to high herbivore concentrations trampling the soil.

In addition, long-term fire management effects on soil organic matter content and soil water retention was investigated. Besides promoting soil fertility, soil organic matter is considered hydrophilic and aids in soil water retention. Although alluding to greater organic matter on the fire-suppressed plot on the granitic Experimental Burn Plots, there were no statistically-significant differences found across the varying fire frequencies. However on the basaltic Experimental Burn Plots, organic matter content varied between the various fire frequencies. Unlike the granitic plots where it is believed that fire intensities are not substantial enough to transfer heat deep into the soil and consume organic matter, it is thought that the huge contrast in above-ground biomass between the basaltic burn plots is in fact responsible for the contrast in organic matter contents. Consequently, soil water retention was found to be greatest on the fire-suppressed no burn plots. The ability of the soil to retain moisture, especially at low water contents, is crucial in a post-fire environment in order to facilitate re-establishment of vegetation.

A reduction in vegetation cover is believed to be responsible for the increased runoff rates observed on the annual burn plots in the granitic region of Pretoriuskop. Reduced vegetation or surface cover will result in less rainfall interception and thus exposing the soil surface to direct raindrops known to compact soil surfaces and inhibit infiltration. More runoff was generated from the annual plots compared to the no burn plots at the 200 mm/h rainfall intensity 24 hours after the 157 mm/h intensity was applied. The effect of fire on the amount of runoff generated as well as the rate of runoff increases as rainfall intensity increases. Surprisingly, less sediment was yielded off the annual burn plot. It is believed that this phenomenon is due to compacted soil which required more energy (higher rainfall intensities over longer periods) to dislodge and redistribute more sediment.

Fire regimes influence the various soil properties which in turn impacts the soil water balance on the burn plots. On the granites, it was found that due to the reduction in vegetation on the annually-burned plots there were lower evapotranspiration rates measured. Stemming from a reduction in evapotranspiration, more water was subsequently available in the soil medium to percolate and potentially recharge groundwater. However, there were conflicting trends measured on the basaltic Experimental Burn Plots. One Experimental Burn Plot string (N'wanetsi) had a similar trend like the granitic burn plots whereby evapotranspiration rates were lower on the annual plots due to lower vegetation, while the Experimental Burn Plot string (Satara) observed higher evapotranspiration on the annual burn plot. This increased evapotranspiration was attributed to more vegetation growth on the annual plot since it was burned by a prescribed fire roughly 3 months prior which would have stimulated vegetation recovery. Additionally, the fire would have rendered a greater extent of bare soil vulnerable to evaporation than on the denser no burn plot.

The key hydrological mechanisms and their interactions which were highlighted during this study are summarised in Figures 1 and 2 below. These mechanisms were almost identical between the dominant granitic and basaltic geologies.

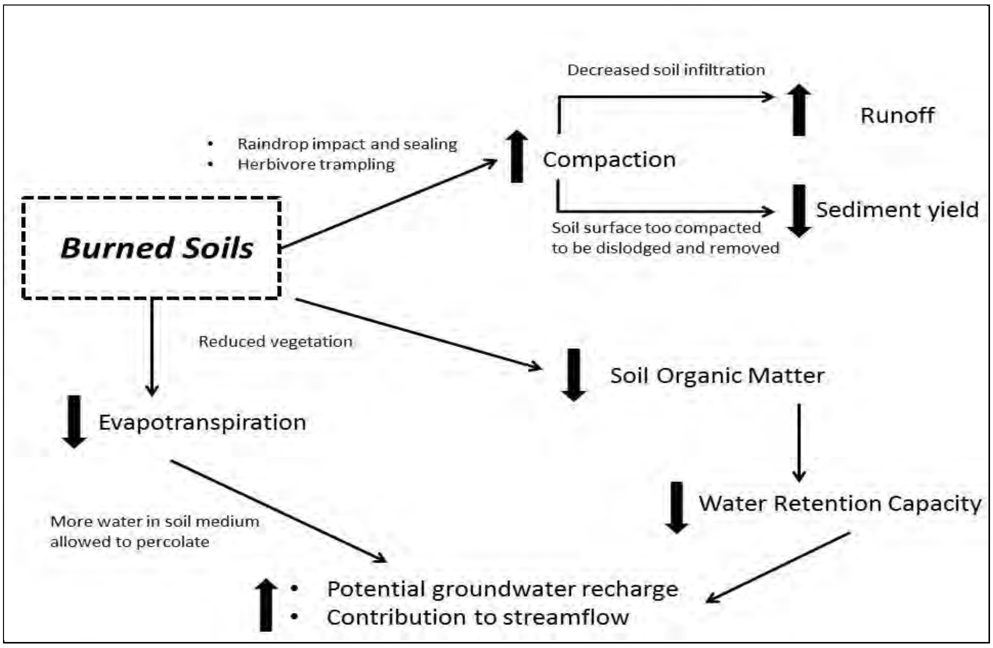

Figure 1 The mechanisms observed on the annually-burned soils on granitic and basaltic Experimental Burn Plots

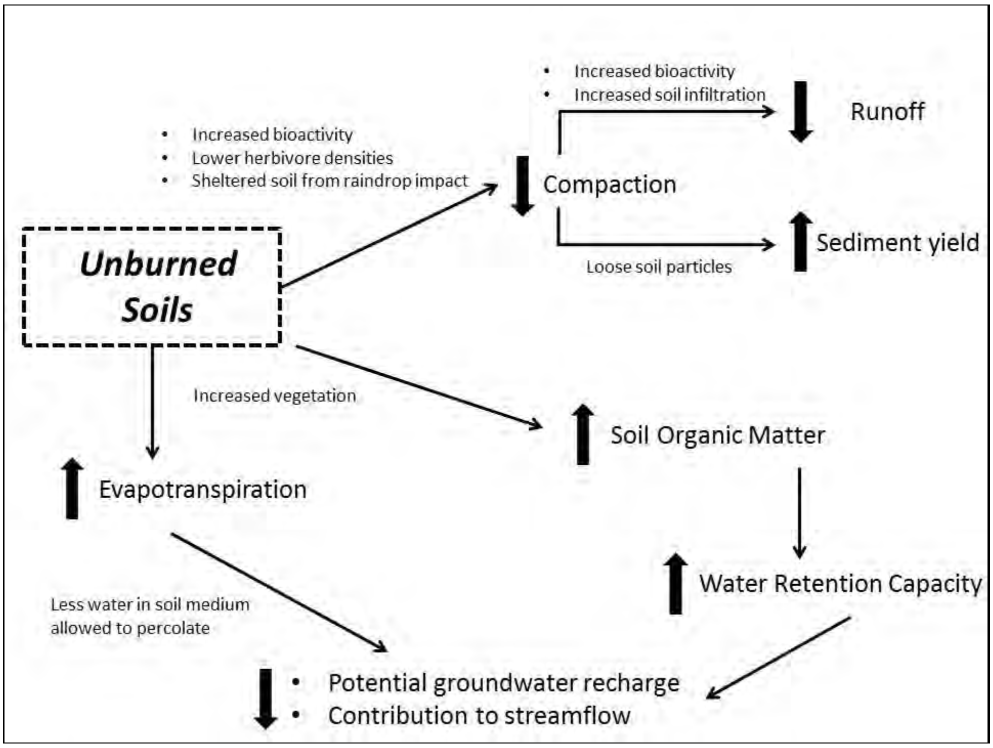

Figure 2 The mechanisms observed on the unburned soils on the granitic and basaltic Experimental Burn Plots

CONCLUSIONS

Fire effects are complex owing to many interrelated factors which all play a role in influencing each other. Fire impacts on soil hydraulic processes ultimately influence soil water balances. These impacts may have cascading effects on large-scale catchment processes.

The effect of fire frequencies on soil hydraulic properties is negligible considering that it is actually the time following a fire which plays a significant role on soil hydrology in a savanna ecosystem. The reduction in hydraulic conductivity were primarily observed at the soil surface suggesting that savanna fires may lack the high intensities required and/or due to its rapid burning behaviour, does not have sufficient contact time to transfer heat beyond the soil surface. Furthermore data suggested that after two years following the fire, soil infiltration rates improved suggesting that soils are capable of recovery relatively soon.

Even though soils were compacted by both fire (indirectly) and herbivores (directly), this did not impact soil hydraulic properties significantly. It is believed that decreased infiltration rates observed were likely due to hydrophobicity. In this case, the influence of soil compaction by fires and herbivores on soil hydrology is considered negligible. However, compacted soils affected sediment yield by maintaining its structure, due to the extra cohesion between soil particles, and preventing sediment redistribution. With the water-holding capacities of the soil influenced by above-ground biomass and organic matter, the effect of fire frequencies on the ability of the soils to retain moisture at low water contents is critical to understand; seeing as it is one of the most important properties in a post-fire environment.

Vegetation cover and soil properties were found to influence the onset of runoff generation. After performing rainfall simulations in order to compare the effect of historical fire regimes (annual vs. no burning) on the runoff and sediment yield generated, it was discovered that long term fire management unequivocally affects the amount of runoff generated from the savannas of the Kruger National Park. It is likely that long-term fire management practice, i.e. fire frequency, will affect the rate of evapotranspiration losses from savannas in the Kruger National Park. Additionally, these fire regimes affect soil properties and soil water balances which ultimately control the distribution of water through the landscape. The impact of fire on soil water balances was found to be significant in both the granitic Pretoriuskop area, characterised by sandy soils and higher rainfall, as well as the basaltic Satara area, characterised by clayey soils and lower rainfall. Since fire impacts the availability of water within a catchment, it is critical that a suitable fire management regime applied in order to ensure that water distribution in the catchment is not adversely affected.

Besides the need for research in African savannas which focuses on the impact of fire on soil hydrology, it is a vital aspect for management in Kruger National Park to take cognisance of seeing as fire applied as a management tool to control and manipulate vegetation structure and composition. This study provides valuable insight not only into the relationship between water and fire but also how other factors such as soil, vegetation and herbivores all interact within a water-controlled savanna landscape.

RECOMMENDATIONS FOR FUTURE RESEARCH

In light of climate change and problems associated with bush encroachment, it is critical for scientists and managers to understand how fires impact soils and their hydrology, especially in a fire-manipulated landscape such as Kruger National Park. Considering that park management policies are designed for large-scale areas, these results would need to be extrapolated and confirmed at a catchment scale. The findings gathered in this study provide the initial platform from which further large-scale studies may be initiated to compliment, support and improve these results.

Once our understanding has been enriched as to the effects of both fire frequency and fire intensity, it would be ideal to up-scale this type of study to larger areas. Stoof *et al.* (2011) recognized the scarcity in pyro-hydrology research at catchment scales and attempted to investigate this fire-water relationship by burning an entire catchment. Their study highlights the need for catchment-scale fire experiments considering that the fire effects observed at plot scale may be diluted by the heterogeneity and variation inherent in larger areas such as catchments. Thus, by increasing the scale of this study, results will be more applicable to management policies since these policies are designed for implementation at a large scale.

Since fire is implemented as a management tool, management in Kruger National Park could benefit from this study by integrating its fire policy with its water in the landscape policy. In order to ensure that catchment hydrological properties are not adversely affected by unsuitable burning regimes which may result in increased water repellency, decreased infiltration rates and decreased water retention capacities, it is advised that management actively ensures that the veld does not burn as often as every two years. Soil properties require a minimum of two years to return to pre-fire conditions on both the granitic and basaltic regions of the park. Since management utilises a Strategic Adaptive Management approach with clear objectives which undergoes regular reviews, policies should be modified in order to take these findings into account when making fire management decisions. A co-operative relationship between science and management is necessary to ensure a steady transfer of knowledge between the two sectors to facilitate adaptive management.

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ANOVA	-	Analysis of Variance
BoAr	-	Bonheim - Arcadia
BoSw	-	Bonheim - Swartland
dCl	-	Deep Clovelly
DPM	-	Disc Pasture Meter
dRs	-	Deep Red Sands
EBPs	-	Experimental Burn Plots
Es	-	Estcourt
ET	-	Evapotranspiration
HSD	-	Honest Significant Difference
ILWRM	-	Integrated Land and Water Resources Management
KNP	-	Kruger National Park
K_{sat}	-	Saturated Hydraulic Conductivity
K_{unsat}	-	Unsaturated Hydraulic Conductivity
mdShSw	-	Moderately Deep Shortlands - Swartland
PCA	-	Principle Components Analysis
PVC	-	Polyvinyl Chloride
SAM	-	Strategic Adaptive Management
sCl	-	Shallow Clovelly
VFR	-	Variable Fire Regime

1. INTRODUCTION

Soil is a natural resource which forms an essential component of the earth's biosphere and is vital in supporting healthy and functioning ecosystems. Besides providing a medium for plant growth, soils play a major role in ecosystem functioning by cycling nutrients and filtering water through the system (Erickson and White, 2008). When soils are degraded, important ecosystem services are affected. Degraded soils may not be able to store and filter water as efficiently thereby affecting water quantity and quality. This in turn has a detrimental effect on catchment hydrological processes. Hydrologically, soil partitions water. Rain water is partitioned into overland flow and infiltrated water. Infiltrated water is then partitioned into water available to vegetation for root uptake and drained water. While the ecosystem services of overland flow is focussed on stream flow, the infiltrated water impacts the vitality of vegetation and the broader ecosystem. Van Tol *et al.* (2010) describe the complex relationship between soil and water as *interactive* meaning that the physical, chemical and biological properties of soil influence the manner in which water is transported and stored within the landscape which impacts the ecosystem.

As with many other biomes around the world, the structure and production of African savannas are controlled by the spatio-temporal availability of water. These savannas are considered complex and dynamic systems which are co-dominated by grasses and trees (Scholes and Archer, 1997; Sankaran *et al.*, 2004). Fire, along with fluctuations in water availability, nutrients and herbivory is regarded as one of the primary drivers responsible for controlling these heterogeneous savanna systems (Walker and Noy-Meir, 1982; Van Wilgen *et al.*, 2000; Kraaij and Govender, 2010). Savanna fires can be ignited either by anthropogenic activities, whether accidentally or purposefully, or naturally through lightning (Archibald *et al*., 2009). Ignition by lightning is less common and these fires do not often burn through extensive areas of natural woodland (Walter, 1971). Although savanna vegetation is resilient and relatively well-adapted to fire (Furley *et al.*, 2008), it is believed that frequently-recurring fires can prompt long-term soil degradation, changing the soil hydrology and ultimately reducing ecosystem productivity (Cerda *et al.*, 1995). The frequency of savanna fires are highly variable and influenced by factors such as preceding annual rainfall and pressure from herbivores (Trollope, 1993; Van Wilgen *et al*., 2004). Both of these factors directly impact the fuel load that is required to support veld-burning.

In the Kruger National Park (KNP), fire is used as a critical management tool to help control the vegetation structure in these dynamic savannas (Smit *et al.*, 2010). The Experimental Burn Plots (EBP) is a long-term fire experiment, initiated in the early 1950s, with the aim of assessing the impacts of fire on ecosystem dynamics and functioning (Biggs *et al*., 2003). Numerous studies have focused on fire impacts on various vegetation characteristics (e.g. Gertenbach and Potgieter, 1979; Enslin *et al.*, 2000; Higgins *et al.*, 2007; Smit *et al*., 2010), soil nutrients (Webber, 1979; Mills and Fey, 2003) and small mammals (e.g. Kern, 1981). A lack of information on the impacts of long-term fire on soil hydrology in African savannas creates a critical gap in the current understanding of savanna ecosystem dynamics. The EBPs offered a unique opportunity to determine the effects of long-term fire treatments on soil hydraulic properties. Since fire is implemented as a management tool, KNP management could benefit from this study by improving fire policies and making integrated decisions with respect to the role of both fire and water in the landscape. The added value of this study is that it will provide further understanding of the role of fire in catchment hydrological properties, important for integrated land and water resources management (ILWRM).

Since fire plays a major role in savanna system dynamics and functioning. The long-term EBPs in KNP were used in order to investigate the effects of varying long-term fire treatments (annual vs. no burn vs. variable fire regime (VFR), in some cases) on soil hydraulic properties and water balances on granitic and basaltic geologies. The following were the objectives for the study:

Objective 1: Understand the effects of long-term fire treatments on soil hydraulic properties on two different geologies in Kruger National Park.
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1.1 Literature Review

As mentioned above, it has been established that there is a critical need for fire and hydrology linked research in African savannas. Since the majority of the work relating to fire effects on soil properties has been conducted in other landscapes around the world, most of the literature presented below stems from these studies abroad. Literature has been reviewed in order to generate an understanding regarding the topic, to formulate hypothesises and to review the methodological approaches used in other studies.

Fires can be both constructive and destructive to soils, depending on perspective as well as scale (Erickson and White, 2008). One of the key advantages of fire is an increase in soil fertility (Erickson and White, 2008) whilst potential disadvantages include water repellency (Scott, 1993; Ice *et al.*, 2004), loss in nutrients (DeBano and Conrad, 1978), decreased soil water retention (Stoof *et al.*, 2010) or decreased infiltration rates (Martin and Moody, 2001). Fire-induced changes to vegetation and soil properties result in changes to the hydrological cycle of a specific location or at a local scale, which in turn alters the movement of water and sediment through watersheds at a larger scale (Swanson, 1981). Fires stimulate critical changes in the soil and the microclimate associated with the soil surface (Mallik *et al.*, 1984) which in turn influences the hydrological cycle and chemistry of the soil (Thonicke *et al.*, 2001). According to Certini (2005), and Doerr and Cerda (2005), soil properties can endure short-term, long-term or permanent fire-induced changes; of course, this depends on factors such as the type of soil property, intensity and frequency of fires as well as the post-fire climatic conditions.

1.1.1 The effect of fire on soil hydraulic properties

(i) Water repellency

Water-repellent (hydrophobic) layers reduce soil infiltration and percolation. Fires may prompt or facilitate hydrophobicity by heating the hydrophobic organic compounds found at the soil surface (Doerr *et al*., 2009). Some of those organic compounds include hydrocarbons (DeBano, 2000) as well as fulvic and humic acids (Giovannini and Lucchesi, 1984; cited by DeBano, 2000). According to Ice *et al.* (2004), when volatized organic compounds condense on cooler soil particles, negatively-charged layers repel water. The extent of the water-repellent layer depends on the steepness of the temperature gradient near the soil surface, soil moisture as well as the physical properties of the soil (DeBano, 1990). After fires, water repellency is more likely to occur in coarse-textured than fine-textured soils and in areas of high burn severity (Erickson and White, 2008). Furthermore, less intense fires that burn over moist soils tend to produce less water repellency than intense fires over dry soils (Ice *et al*., 2004). Occasionally, strong surface water repellent layers may not exist, but it is possible that water repellent layers may be present below the soil surface (Lewis *et al*., 2006). As water content increases within the soil, soil from both burned and unburned areas may become less hydrophobic or may even lose its hydrophobic characteristic completely (Doerr *et al*., 2009).

It is worth noting that not all water repellent layers are fire-induced but are naturally-occurring due to the soil texture and presence of hydrophobic organic matter. Some studies have attempted using fire to destroy water repellent layers in the soil. DeBano and Krammes (1966) suggest that the naturally-occurring non-wettability of the top few centimetres of the soil surface may be destroyed by fire temperatures high and deep enough to which non-wettability is destroyed. This depends on the intensity and duration of the fire. Furthermore, they believe that the temperatures of the fire are sometimes not intense enough to destroy the non-wettability but instead to intensify it. It is critical to note that this conclusion was based on laboratory experiments and may not be applicable to fire burning in the savanna landscape.

(ii) Infiltration

With regards to the hydrological cycle, soil infiltration rate is vital in partitioning rainfall into surface runoff and subsurface flows (Cerda and Robichaud, 2009). Infiltration refers to the downward movement of water through the soil surface into the soil medium (Schaetzl and Anderson, 2005). After fires have burned and denuded an area of vegetation, the result may be changes to a number of soil hydrological properties (Scott, 1993; Erickson and White, 2008). Bare soil becomes exposed to natural elements such as direct solar radiation and heat, wind and rainfall. Once fire has removed vegetation cover the soil surface is exposed to raindrop impact and splash which results in the sealing and compaction of surfaces thus reducing infiltration (DeBano, 2000; Ice *et al.*, 2004). In a post-fire environment where soil infiltration rates are low, trees may be hydrologically disadvantaged since water might not be able to penetrate deep enough to reach their roots. Ultimately, this could temporarily interfere with the co-dominance of tree and grasses in savanna systems.

According to Mallik *et al.* (1984), infiltration through burned soil surfaces could be inhibited by the blockage of larger pores by ash particles. Infiltration is characterised by either short- or long-term scale responses. The short-time scale response depends on the relation between sorptivity (ability of soil to absorb moisture) and soil moisture which provides an indication of the infiltrability and capillary forces (which allow for the upward movement of water) acting on the soil (Moody *et al.*, 2009). On the other hand, the long-time scale response depends on the relation between hydraulic conductivity and soil moisture, which provides an indication of the gravitational forces acting on the soil (Moody *et al.*, 2009).

Vegetation cover and soil properties have assorted effects on soil infiltration rates. Soil infiltration is a function of soil porosity and structure, which is facilitated by biological activities (Cerda and Robichaud, 2009). Bioactivities by burrowing worms and insects and the penetration by roots are known to facilitate infiltration by increasing the soil porosity and preferential pathways (Cerda and Robichaud, 2009). In addition to increasing soil infiltration, vegetation cover protects the soil surface from processes such as raindrop impact and splash (DeBano, 2000; Cerda and Robichaud, 2009). Vegetation leads to a soil litter layer which promotes bioactivity, soil aggregation, water storage, and macro- and micro-pore development (Cerda and Robichaud, 2009).

(iii) Runoff

Often, there is an increase in rill, sheet and mass movement erosion following an intense fire (Swanson, 1981). In cases where the intensity of rainfall is greater than the soil's ability to allow the infiltration of water, Hortonian overland flow will occur and could lead to erosion. According to Sidle *et al.* (2007), the process of Hortonian overland flow occurs in the following sequence of events: (1) a thin layer of water develops on the soil surface and initiates surface runoff (2) surface runoff collects in and fills surface depressions (3) as the surface depressions fills up, they spill over and lead to overland flow (4) this overland flow collects into micro-channels which may result in the formation of rills and gullies (5) these micro-channels direct the flow into streams. Hosseini *et al.* (2014) suggest that the generation of runoff in a post-fire environment is strongly dependent on past fire regimes.

Rainfall simulations are commonly used to measure runoff and sediment yield from small runoff plots representative of an area of interest. For example several rainfall simulations have been performed on areas with contrasting land use or characteristics. The rainfall simulation itself may be defined as the application of artificial rainfall at a set intensity to generate such runoff and sediment loss (Podwojewski *et al.*, 2011). Podwojewski *et al.* (2011) recently performed rainfall simulations in the KwaZulu-Natal province of South Africa in the upper part of the Potshini SSI experimental catchment in the 'midlands', downstream of the Drakensberg Mountains. The experimentation was undertaken to compare the effect of vegetation cover on soil infiltration, runoff and sediment yield at various rainfall intensities, within a degraded rangeland. This technique could also prove useful in other applications such as experimental fires in order to determine the impact of fire on soil infiltration, runoff and sediment yield.

(iv) Organic matter

According to Thonicke *et al.* (2001), fire is important in savanna systems because it speeds up the nutrient cycle through the rapid mobilization of nutrients. Even though some nutrients are volatized and lost, the majority of them are made more readily available to the system (DeBano, 1990). Through the burning of organic matter in the soil, important nutrients are released which aids in the regeneration of plants (Nardoto and Bustamante, 2003). Organic matter plays a vital role in the physical, chemical and biological properties and processes of the soil and thereby contributes to overall soil productivity (DeBano, 1990). Snyman (2002) suggests that a significant decrease in soil organic matter will not only initiate a reduction in soil fertility and production, but could also lead to the destruction of soil structure which would inevitably bring about increased runoff and soil erosion.

According to DeBano (1990), organic matter plays a critical role in the formation and maintenance of well-aggregated soils since it acts as a cementing agent between soil aggregates. Aggregates stem from the organization of soil mineral and organic particles (Mataix-Solera *et al.,* 2011) and improve soil structure which creates macro pore space, improves soil aeration and increases hydraulic conductivity (DeBano, 1990). Aggregated soils are found to have higher infiltration rates than non-aggregated soil with less organic matter (DeBano, 1990). Aggregate stability can be used as an indicator of the state of soil structure and physical stability since it refers to the soils ability to maintain its structure when exposed to external forces (Mataix-Solera *et al.,* 2011). These external forces may include raindrop impact, moisture or heat from fire. Fire affects soil structure when organic matter, the cementing agent, on or near the soil surface is combusted (DeBano, 1990). This break down in soil structure could lead to increased runoff and soil erosion (Snyman, 2003).

By altering the fire regime in these fire-driven ecosystems such as savannas, there could be either an overall loss or gain in nutrients in the system (Thonicke *et al.*, 2001). Mills and Fey (2003) suggest that it is the first couple of centimetres, also known as the pedoderm, of intact topsoil that houses the majority of nutrients, humus and salts in comparison to the subsequent strata. Therefore, this layer is important in a post-fire environment because it stores critical nutrients required by plants to facilitate regeneration.

(v) Soil water retention

Water is held in soil pore spaces by capillarity, thus smaller pore-sizes result in greater soil water retention (Úbeda and Outeiro, 2009). Soil water retention increases with an increase in clay and organic content since these substances are hydrophilic (Schaetzl and Anderson, 2005). Clays and organic matter are hydrophilic due to the strong attraction between bipolar water molecules and the charged sites on clays and organic matter (Schaetzl and Anderson, 2005). According to Stoof *et al.* (2010), fires are known to change soil properties which in turn influence soil water retention. Water is held in the soil in two forms, i.e. adsorption and absorption (Schaetzl and Anderson, 2005). Due to chemical or physical bonds, water is adsorbed to the surface of soil particles whereas absorbed water is taken up into the solid soil particle (Schaetzl and Anderson, 2005). The loss of soil organic matter and subsequent reduction in structure during a fire results in a decreased soil water retention capacity (Úbeda and Outeiro, 2009). Since soil water retention infers the ability of a soil to store water, it is obvious why it plays a major role in the restoration of plants in a post-fire environment (Stoof *et al.*, 2010).

1.1.2 Pyro-hydrology studies in South Africa

There is a scarcity in existing literature where local studies determined the effects of fire on soil properties. A study conducted in a semi-arid grassland, investigated the impact of fire on various soil characteristics such as soil water content, compaction, soil temperature and so forth (Snyman, 2002). Snyman (2002) found that due to the fire reducing vegetation cover, there was an increase in soil temperature and compaction but a decrease in organic matter content. This in turn resulted in a decrease in soil water content. A study conducted by Scott (1993) in the fynbos catchments of South Africa investigated the effects of fire on soil infiltration rates. He concluded that fires negatively impacted soils by decreasing soil infiltration. Similar studies conducted locally in African savannas found that fire resulted in crusted and compacted soil surfaces which reduced infiltration (Mills and Fey 2003; Mills and Fey, 2004). The study by Mills and Fey (2004) which concluded that fires would lead to crusted soil surfaces that inhibited soil infiltration was conducted in a laboratory experiment. Furthermore, the Mills and Fey (2004) study was only conducted on soils derived from one geological substrate only, i.e. the granites in KNP. The research presented in this report addressed the need to conduct in-situ measurements where soils are not disturbed or manipulated in order to confirm these findings. In addition, this study was conducted on the two dominant geologies in KNP, i.e. granites and basalts. Besides soil infiltration and soil compaction, this study investigated the effects of three different fire regimes on soil water retention as well as how herbivores influence soil compaction.

1.1.3 Methods applied in similar studies

There are a number of different techniques and methods which can be used to test a number of soil properties with regards to fire effects. Double-ring infiltrometers and cylinder infiltrometers are the most widely used techniques for quantifying soil infiltration rates (Cerda and Robichaud, 2009). Although ring infiltrometers are simple and robust instruments which provide accurate measurements of field-saturated hydraulic conductivity, they are difficult to insert and use in stony, porous soils and may result in soil disturbance during insertion (Reynolds, 1993a). Additionally, these instruments require relatively flat surfaces and soils that are not too sandy which will result in the prevention of ring infiltrometers from ponding and cylinder infiltrometers to leak due to poor contact between the instrument and soil surface (Cerda and Robichaud, 2009). Infiltration rates can also be measured using rainfall simulations and runoff plots, although these are very time-consuming and require bulky equipment (Podwojewski *et al*., 2011).

Other instruments such as well permeameters (Elrick and Reynolds, 1992; Adhanom *et al*., 2012) and tension disc infiltrometers (Ankeny *et al*., 1991; Riddell *et al*., 2012) can also be applied to test in situ hydraulic conductivities. The constant-head well permeameter is inserted into an uncased well and maintains a constant depth (head) of water, measuring the flow of water out of the well into unsaturated soil. Initially, the flow rate will decline rapidly before reaching a steady state— which is the desired measurement (Reynolds, 1993b). The well permeameter takes hydrostatic pressure, gravity and capillarity into account when calculating hydraulic conductivities which is generally variable in natural soils (Elrick and Reynolds, 1992). There are many advantages to using well permeameters and tension disc infiltrometers. They are considered as simple, robust instruments which are easy to transport allowing for relatively rapid spatio/temporal replication (Reynolds, 1993b). These versatile instruments generally require low volumes of water and can be applied to a range of soil textures (Reynolds, 1993b) which are critical for remote fieldwork in KNP.

Since infiltration may be inhibited by soil compaction, it is useful to measure the degree of soil compaction. Cone penetrometers are simple instruments which may be used to measure soil compaction (Vaz *et al*., 2001; Herrick and Jones, 2002; Riddell *et al*., 2012). They are cost-effective devices which enable multiple replications over extensive areas and easy interpretation of data.

Soil organic matter content may be analysed using a number of methods such as the loss on ignition method (Stoof *et al*., 2010; Velasco *et al*., 2014), near infrared reflectance (NIR) spectrometry (Yong *et al*., 2005) or the Walkley-Black method involving chemical digestion and titration processes (Hartnett *et al*., 2004; Mills and Fey, 2004). All of these methods are specialised and time-consuming. LECO carbon analysers are instruments which may be used to determine percentage total carbon in soil samples (Wang and Anderson, 1998; Bell *et al*., 2003). This method, on the other hand, is not as time-consuming and more efficient as it requires a smaller sub-sample of soil.

A common technique of determining soil water retention involves using pressurizing plates to subject saturated soil sample to different tensions in a laboratory and then plotting water retention curves (Van Genuchten *et al.*, 1991; Wesseling *et al*., 2009; Stoof *et al*., 2010). Lorentz *et al.* (2003) applied a similar approach using the Cell Outflow Method to determine soil water retention at varying pressures. However, the main disadvantages are that these methods are sensitive and time-consuming.

1.1.4 Statistical analyses in similar studies

Statistical analyses are important means of interpreting complex datasets and understanding trends. This section describes how similar studies used different types of statistical analyses in order to aid in the correct interpretation of data.

Previous studies that were conducted on the EBPs utilised various statistical analyses. Many of these studies (Enslin *et al*., 2000; Shackleton and Scholes, 2000; Higgins *et al*., 2007) used analysis of variance (ANOVA) to analyse various variables in order to determine the differences in variation across the different burn plots. For example, Higgins *et al.* (2007) used ANOVA to analyse three response variables i.e. change in tree density, change in small tree dominance and change in biomass. Two of these variables were Box-Cox transformed in order to normalise data which is a pre-requisite for the ANOVA test. They used two ANOVA models to analyse the three response variables whereby the first model allowed the comparison of the effects of fire exclusion to the effects of burning at various seasons and frequencies. The second model excluded fire exclusion plots and only focused on the fire return intervals. Snyman (2003) investigated the short-term response of soil properties following a rangeland fire and applied a two-way ANOVA for soil water content and soil properties. All other data based on basal cover, soil compaction and soil temperature were tested using a one-way ANOVA.

Enslin *et al.* (2000) carried out a combination of statistical analyses when they investigated the long-term effects of fire frequency and season on woody vegetation dynamics. All their data were analysed using ANOVA. Parameters such as tree density, basal area and tree height in relation to distance from permanent water were tested using linear regressions. Furthermore, T-tests were used to compare mean densities over two years and principle components analysis (PCA) was used to ordinate species community data.

1.1.5 Soil water balances

Environmental modelling explores the behaviour of processes and their inter-linkages to better understand these processes and ultimately test hypotheses. Wainwright and Mulligan (2004) reveal that models are a simplification of reality and incorporate the components or processes that are important. A soil water balance (mass balance) can be calculated using the generalised water balance equation (Lu Zhang *et al*., 2002):

$$\Delta \text{ Storage} = \text{Precipitation} - \text{Evapotranspiration} - \text{Runoff} - \text{Free Drainage}$$

Ogorzalek (2008) states that only a few documented studies on water balance simulations have compared numerical models such as HYDRUS, LEACHM and UNSAT-H model predictions with actual field measurements. Additionally many of the studies have utilized estimated input parameters, such as soil hydraulic properties and vegetation characteristics, or have alternatively obtained these input parameters through calibration exercises. Therefore resulting in inaccurate water-balance predictions and supplying a poor understanding of hydrological processes. Ogorzalek (2008) suggests that model predictions of water balance simulations should be based on independently measured input data, parameters that are measured directly as they are in the study site, and compared to field measurements, to assess and improve the accuracy with which models predict water balance simulations.

The objective of the study undertaken by Ogorzalek (2008) was to evaluate the accuracy of three commonly used hydrological models to predict the water balance of a capillary barrier cover soil profile (a layered soil e.g. gravel underlain with silt) in a sub-humid climate (Western Montana, USA), comparing the results to field measurements obtained from a lysimeter. The input parameters used in the models were derived from real physical data obtained in the study area and analysed in the laboratory, in an attempt to accurately assess the ability of the models to predict water balance simulations. It was found that all the models (HYRUS, LEACHM and UNSAT-H) predicted seasonal variations in water balance quantities well. The HYDRUS as well as the LEACHM model, however, predicted water balance quantities with the greatest accuracy compared to the field data, only slightly over or under predicting parameters such as runoff, evapotranspiration, soil water storage and percolation (Ogorzalek, 2008). Scanlon *et al.* (2002, 2005) also suggest that models such as HYDRUS that implement Richards' equation predict water balances most accurately. Yu and Zheng (2010) reviewed the HYDRUS model and software and also found that the model predicts soil water flow in the unsaturated zone well.

The HYDRUS[1] (Šimůnek *et al.*, 2011) model is a 3D soil water movement, heat and solute transport model. The model solves Richards' equation using linear finite elements pattern, for simulation of water movement in the soil (Honar *et al*., 2011). For example, research conducted by Zhao *et al.* (2004) to determine the suitability of alfalfa grass in the remediation of degraded land in the semi-arid Chinese Loess Plateau employed the water balance equation to determine the effect of the alfalfa on soil moisture content (or the change is soil water storage). The investigation was undertaken to identify if implementation of the alfalfa vegetation was ecologically viable, i.e. assessing if the alfalfa grass would deplete the soil moisture storage. Comparing its ecological effects to the economic effects, i.e. related to its ability to remediate the land and prevent soil erosion for example. At the same time, however, Zhao *et al.* (2004) analysed the suitability of combining measured parameters with model-generated parameters as input into the water balance equation to estimate the temporal variations in soil water content, i.e. accounting for the inputs and outputs. Their results showed that the calculated variations in soil water content were in good correlation with those measured in situ, suggesting that the approach may be adopted to estimate soil water content in catchments without in situ measurements.

1.1.6 Remote sensing data used for the soil water balance

A key output from the soil water balance is of course evapotranspiration (ET). Remote sensing technology can be used in several ways to estimate ET including; empirical methods, deterministic methods, vegetation index methods and finally Residual methods (Courault *et al.,* 2005). The method selected for this study is the Surface Energy Balance Algorithm for Land (SEBAL) model which uses surface energy equations combined with remote sensing images to directly estimate ET (Bastiaanssen *et al.,* 1998). The SEBAL model computes ET from remote sensing images and weather data using the surface energy balance as depicted in

[1] For information on the HYDRUS model refer to http://www.pc-progress.com

Figure 1.1 and expressed mathematically in Equation 1.1 (Waters *et al*., 2002). The satellite can only capture an instantaneous image of the area of interest (AOI) as it passes over. Additionally when satellite images are not available or interference from cloud cover prevents the use of satellite imagery to calculate ET, i.e. evapotranspiration measurements using remote sensing require cloud free conditions, daily ET is estimated by linearly interpolating the reference ET fraction over periods between two consecutive images and multiplying this value by the cumulative 24 hour reference ET for that day (Li *et al*., 2008; Tasumi *et al*., 2005; cited by Yang *et al*., 2012).

Generally, however, the SEBAL model calculates an ET flux for immediate images. The ET flux is determined for each pixel of the satellite image as a "residual" of the surface energy budget equation (Waters *et al*., 2002):

$$\lambda ET = R_n - G - H \tag{1.1}$$

where

λET = latent heat flux (W/m^2),
R_n = net radiation flux at the surface (W/m^2),
G = soil heat flux (W/m^2), and
H = sensible heat flux to the air (W/m^2).

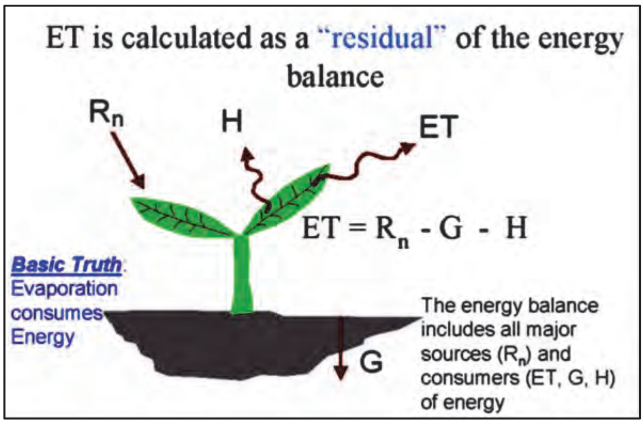

Figure 1.1 The surface energy balance (after Waters *et al*., 2002)

The remote sensing satellites have sensors that receive spectral bands (or wavelengths of electromagnetic energy) emitted from objects on the earth's surface. Healthy vegetation reflects very strongly in the near-infrared part of the electromagnetic spectrum. The amount of infrared reflected by vegetation is used in an equation to calculate the normalised difference vegetation index (NDVI). In simple terms the SEBAL model then estimates an actual ET amount using various parameters and calculations based on the amount of reflectance, at different wavelengths or electromagnetic bands, from the vegetation in each pixel, or area of interest (Waters *et al*., 2002).

Yang *et al*. (2012) state that the greatest advantage of the SEBAL model is its ability to avoid the difficulty of estimating true values for aerodynamic temperature (T_{Aero}) and air temperature at a reference height (T_a), by assuming that the temperature difference (dT) between T_{Aero} and T_a is linearly related to land surface temperatures (T_s). Using this assumption and various calculations involving wind speed, air density, specific heat capacity and aerodynamic resistance to heat transport the sensible heat flux (H) is calculated (refer to Yang *et al*. (2012). Once the sensible heat (H), a more complex parameter, has been determined the remaining two parameters required to calculate the residual latent heat flux (λET) from the surface energy balance equation (Equation 1.1) are the net radiation flux (R_n) and the soil heat flux (G), which are more simply derived (Waters *et al*., 2002).

Remote sensing technology has been used extensively in recent years due to its ability to map the spatial and temporal structure of evapotranspiration (Waters *et al*., 2002). Bastiaanssen *et al*. (1998a) have shown that remote sensing and the SEBAL model in particular have accurately predicted evapotranspiration in several countries, when comparing the values to field data. While Bastiaanssen *et al.* (2005); Li *et al*. (2008) and Wang *et al*. (1998) cited in Yang *et al*. (2012) agree, showing that SEBAL has been successfully tested in many regions.

Yang *et al.* (2013) state that the SEBAL model is generally preferred to other methods when estimating surface-energy fluxes from remote sensing data because; it uses minimal ground-based data; the near-surface air temperature is not mandatory, as required in many other bulk transfer models and each region/pixel in the remotely sensed image of interest is automatically self-calibrated through (1) the identification of dry and wet pixels and (2) the determination of the near-surface air temperature difference. The METRIC (Mapping Evapotranspiration at High Resolution with Internalised Calibration) model uses similar principles to SEBAL; however, it differs from SEBAL in its determination of reference evaporation, obtained from ground based measurements (Bastiaanssen *et al.,* 1998). The advantage of SEBAL as mentioned above is that it requires minimal ground based data. The SEBS (Surface Energy Balance System) model is data intensive and requires detailed data about the surface conditions, i.e. fraction of basal cover, leaf area index of the vegetation, height of the vegetation and surface reflectance and temperature, climatic conditions and radiation data. The model predicts evaporation poorly if there are uncertainties in data such as vegetation roughness, height and atmospheric stability conditions (Su, 2002). A study by Marx *et al.* (2008) investigated the uncertainty surrounding satellite-derived sensible heat fluxes as a result of input data, coefficients for determining leaf area index as well as the differences in surface temperature estimation methods. It was calculated that the total relative uncertainty in sensible heat flux averaged at 17.5% in a savanna in West Africa (Marx *et al*., 2008). Furthermore, the uncertainty in instantaneous ET was much less than the uncertainty in sensible heat flux. A different study by Timmermans *et al.* (2007) suggested that errors in surface temperature and/or surface-air temperature differences would have the greatest impact on sensible heat flux estimates. They also suggested that the pixel selection for representative wet and dry moisture end-member conditions could affect the heat flux estimates.

1.1.7 Conclusion

Various studies from different locations around the world deduced that fire can play a major role in soil hydrological properties and processes. Depending on factors such as soil physical properties, fire intensity, fire severity, vegetation biomass and soil moisture amongst others, fire can impact soil hydraulic properties such as infiltration, water repellency, water retention capacities and ultimately, soil water balances both positively and negatively. Fire impacts on these hydraulic properties can lead to major influences on the generation processes of overland flow, runoff amounts and erosion yields. Therefore, the role of fire in the local hydrological cycle can be quite significant.

There were contradictory findings in the literature regarding the effects of fire on soil properties. These contradictions were based on differences in factors such as soil texture, soil type, fire intensity, vegetation cover and above-ground fuel loads. The spatial and temporal variations in post-fire effects were also identified as confounding challenges in these types of studies. These variations in post-fire effects were due to variations in soil and fire intensity caused by differences in pre-fire vegetation cover, fuel load and soil moisture contents (Cerda and Robichaud, 2009).

Considering that most fire and hydrology-linked studies was based on single fires, it would be important to investigate the effects of more than 50 years of continual prescribed fires on soil hydraulic properties. Robichaud and Cerda (2009) also acknowledged the need for continued research investigating the effects of long-term treatments on soil properties. In water-controlled ecosystems such as African savannas, examining the link between fire and soil hydraulic properties is critical in understanding the vital role of water in these savannas.

1.2 Study Hypotheses

Based on the literature review, the following hypotheses were articulated for this study:

- The annual burn plot will have the slowest K_{unsat} and K_{sat} due to changes in the soil structure caused by the frequent fires.
- The soil on the annual burn plot will be the most compacted due to frequent fire altering the chemistry of the soil and denuding an area thus exposing it to processes such as raindrop impact and splash.
- Soil organic matter will be greatest on the no burn plot due to many (> 50) years of fire exclusion.
- Soil water potential will be greatest on the no burn plot since fire exclusion would have allowed for an increase in the organic matter content which is hydrophilic and thus also increases soil water retention.
- Due to the suppression of fire, the no burn plot will have the highest grass biomass and percentage basal cover. This in turn will lead to more evapotranspiration from the unburned plots.
- More runoff and sediment yield will be generated on the annually-burned plots.

2. STUDY SITE

2.1 Kruger National Park (KNP)

2.1.1 History and location

Even though Sabi Game Reserve was proclaimed in 1898, formal conservation of game only began in 1902 when James Stevenson-Hamilton was appointed as warden (Mabunda *et al*., 2003). The Shingwitsi Game Reserve was proclaimed in 1903 and the Sabi Game Reserve expanded by including the area between the Sabie and Olifants rivers under its protection (Mabunda *et al*., 2003). After the National Parks Act was passed in 1926, the Sabi and Shingwitsi game reserves were merged to form the KNP (Carruthers, 1995; cited by Mabunda *et al*., 2003).

KNP, roughly 1 950 000 ha, is situated on the Lowveld in the north-eastern most part of South Africa, bordering Zimbabwe in the north and Mozambique in the east (refer to Figure 2.1). It lies between latitude 22° 25’ to 25° 32’ East and longitude 30° 50’ to 32° 02’ South with a north-south distance of roughly 320 km and a mean east-west distance of approximately 65 km (Joubert, 1986).

2.1.2 Climate

The climate in the Lowveld is correlated with the sub-continent’s regional climate and is influenced by the anticyclonic systems which travel from west to east over southern Africa (Venter and Gertenbach, 1986). The summer season extends from around November to February while the winter season falls between June and August. Summers are wet and characterised by hot temperatures, with an average daily maximum of 34°C and minimum of 21°C (Kennedy and Potgieter, 2003). Winters are dry with mild June and July temperatures averaging at a maximum and minimum of 27°C and 10°C, respectively (Kennedy and Potgieter, 2003). On average, rainfall in KNP increases from north and south, and from east to west. The central and southern parts of the park are located within the lowveld bushveld zone which experiences an annual rainfall of 500-700 mm (Venter *et al*., 2003). Potential evaporation ranges from 1400 mm in the East to 1700 mm in the West (Heritage *et al*., 2001a). The north falls in the northern arid bushveld zone where annual rainfall ranges between 300 and 500 mm (Venter *et al*., 2003). The potential evaporation for this northern arid bushveld zone of the park varies from 1400 mm (in the east) to 1900 mm (in the west) (Heritage *et al*., 2001b). Heritage *et al*. (2001a) suggest that during summer months, evaporation rates are 60% higher than during winter. The beginning of the rainy season is exemplified by thunderstorms with extreme lightning events. The fact that KNP’s climate is divided into distinct dry winter and wet summer periods produces the ideal conditions for fire (Kennedy and Potgieter, 2003). The summer rains provide the moisture required for sustained growth during the dry season and when the next summer cycle arrives, there is ample grass biomass, and hence fuel load available for late winter/ early summer fires.

2.1.3 Geology

KNP is underlain by a variety of igneous, sedimentary and metamorphic geological formations. The geology changes from west to east due to the lithological strikes in a primarily north-south direction (Venter *et al*., 2003). Geologically, the park is divided roughly into the granites (coarse-grained igneous rock) on the west and basalts (fine-grained igneous rock) on the east, as illustrated in Figure 2.1. A narrow north-south stretch of sedimentary rocks separate the granitic and basaltic regions while a rhyolite band runs parallel on the eastern boundary of the park (Venter *et al*., 2003). There is an assortment of geological parent material in the park which is evident from the Lebombo Mountains on the eastern boundary with Mozambique, the sandstone hills northeast of Punda Maria and the granitic rocky terrain in the southwest of the park between Pretoriuskop and Malelane (Mabunda *et al*., 2003)

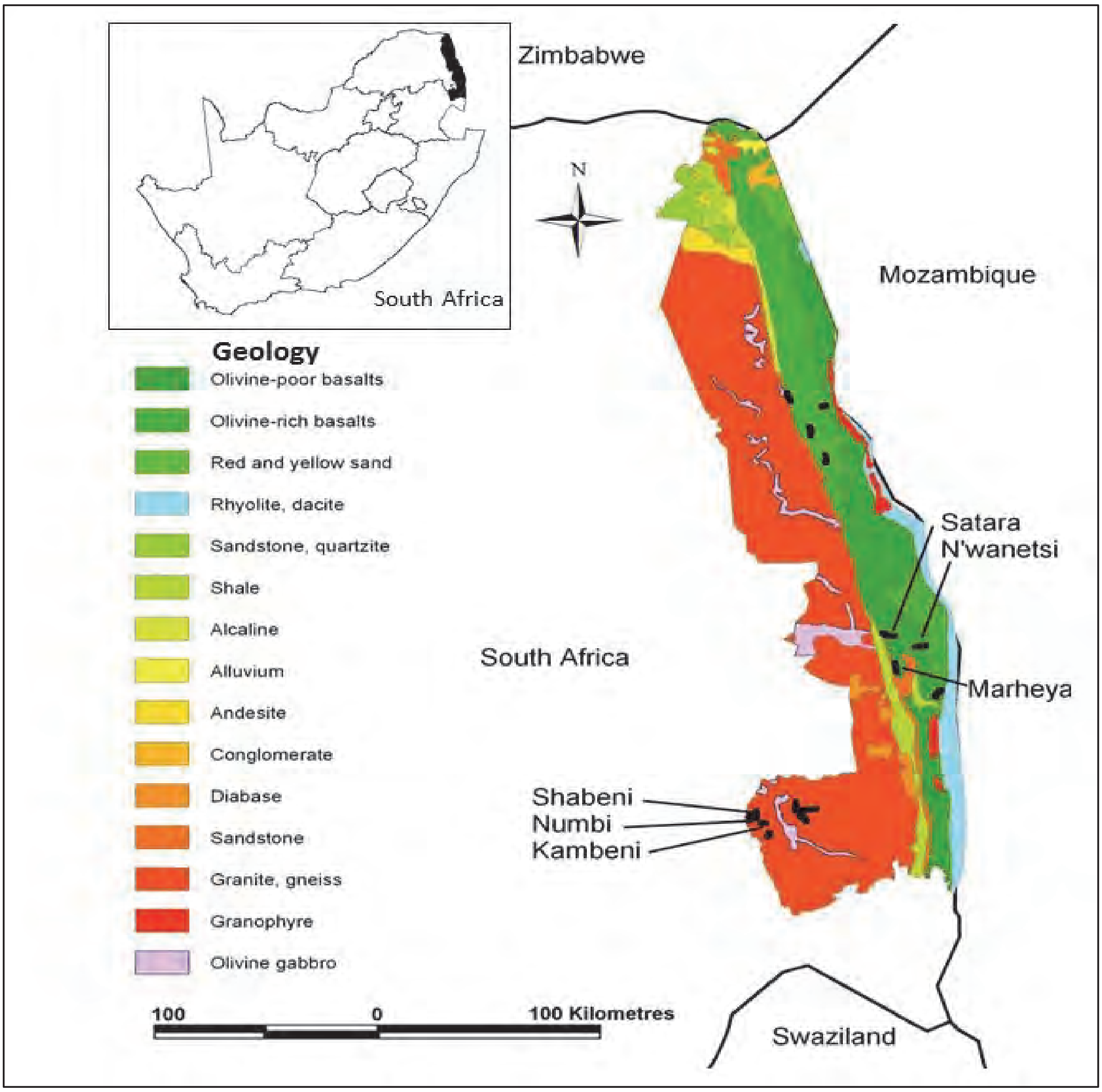

Figure 2.1 A detailed geological map illustrating the location of KNP in the relation to South Africa as well as the EBPs in the park (after Riddell *et al*., 2012)

2.1.4 Soils

The soils in the southern granitic area of the park are characterised by coarse-grained sands and loamy sands. Venter (1986) confirms that soils in this Pretoriuskop region of KNP generally follow the typical catenal sequence from crest to valley bottom as sandy, hydromorphic, duplex and alluvial soils. Crests are described as large and dominated by red apedal sands (Harmse and Van Wyk, 1972; cited by Venter 1986). Crests and upper midslopes are characterised by Huttons, Bainsvlei, Clovelly and Avalon soil forms (Venter, 1990). The hillslope has narrow footslopes distinguished by duplex soils from the Kroonstad and Estcourt soil forms along drainage lines (Venter, 1990). Venter (1990) recognized that due to extended periods of saturation, the lower midslopes often have varying hydromorphic soils. In the central basaltic regions of KNP, the nutrient-rich soils are characterised by fine-grained material such as clays. These basaltic plains which are olivine-poor lavas are dominated by moderately deep to shallow, red and brown, structured and para-duplex soils belonging to the Shortlands and Swartland soil forms (Venter, 1990).

Soil can be defined as a naturally-occurring body of unconsolidated material which supports functional ecosystems. This vital resource delivers very specific services to the ecosystem which varies between soil types. Since the factors which influence soil formation, i.e. parent material, topography, biology, climate and time (Park *et al*., 2001), the soil types typically show strong relationships with the geology, topography and climate. The relationship with time is associated with topographical position and the correlation with biology is rather an indication of the ecosystem services delivered to the ecotope. Venter and Gertenbach (1986) suggest that several plant species can be used as indicator species of specific soil conditions due to the strong correlation between vegetation and soil types (inherited from the geological parent material) in the park. Soil properties such as depth, texture and structure control the fate of rainfall and influences soil water content. These soil properties along with soil nutrients are evidently reflected in the biotic components of the ecosystem (Venter, 1986). The abiotic template of KNP forms an integral and vital role in the ecology of the area (Venter, 1986).

2.1.5 Vegetation

The vegetation of KNP includes nearly 1 968 different plant species in a range of structural features varying from dense forest through to open plains with low shrubs (Venter and Gertenbach, 1986; Mabunda *et al*., 2003). In the south-western section of the park, characterised by undulating terrain and catenas, the vegetation consists of relatively dense woodland species. Typically, tree species such as *Combretum apiculatum* (red bushwillow) and *Terminalia sericea* (silver cluster-leaf) dominate the sandy soils on crests and midslopes while grasses such as *Pogonarthria squarrosa* (herringbone grass) and *Digitaria eriantha* (common finger grass) sparsely cover the crests (Venter and Gertenbach, 1986; Venter, 1990). The footslopes are dominated by tree species such as *Acacia nigrescens* (knob thorn), *Dichrostachys cinerea* (sickle bush) and *Euclea divinorum* (magic guarri) and grass species such as *Themeda trianda* (red grass) and *Panicum maximum* (white buffalo grass) (Venter and Gertenbach, 1986). In the higher rainfall region of Pretoriuskop, where annual rainfall is above 700 mm, the vegetation is primarily mesic with dominant tree species such as *Terminalia sericea* and *Dichrostachys cinerea,* and tall grasses such as *Hyperthelia dissoluta* (yellow thatching grass) (Venter and Gertenbach, 1986). The Satara area in the central region of KNP comprises primarily of fine-leaved tree savanna and is dominated by tree species such as *A. nigrescens*, *D. cinerea* and *Sclerocarya birrea caffra* (marula) (Venter *et al*., 2003). The basaltic, nutrient-rich soil in the Satara area offers suitable grazing to game by favouring palatable grasses (Venter, 1990). Along footslopes, grass cover is thicker, more palatable and thus more vulnerable to overgrazing by herbivores (Gertenbach, 1983; Venter and Gertenbach, 1986).

Herbivory is considered a key driver in savannas by facilitating heterogeneity in this dynamic system. Herbivore densities fluctuate due to fluctuations in rainfall (Mills *et al*., 1995; cited in Van Wilgen *et al*., 2003). Increased herbivore concentrations increase the grazing pressure on vegetation and have cascading effects on fire intensities due to the reduction in fuel loads. Unlike other fire-prone regions around the world, African savannas are unique due to the presence of both meso- and mega-herbivores such as elephant, rhinoceros, buffalo and hippopotamus (Van Wilgen *et al*., 2003).

2.2 Experimental Burn Plots (EBPs)

The EBPs in KNP form a large, long-term fire-management experiment. The history and development of this experiment is described in further detail in the following subsection. Furthermore, the experimental design and layout is explained as well as the soil and geomorphic template of the burn plots. Selection of particular EBPs where the study is focused are presented and justified.

2.2.1 EBPs history and design

Earlier ideas considered fires to be harmful to the environment and that it would lead to land degradation and ultimately, soil erosion. Thus, KNP management avoided fires by actively supressing and preventing them. Except, after 1957 when it was discovered that fire is an important driver in savanna systems, fires were implemented at a fixed return period (Van Wilgen *et al*., 2000; 2003). KNP management and scientists acknowledged that an understanding of the features of natural fires be developed (Van Wilgen *et al*., 2000). This research experiment was developed in the early 1950s and replicated in four major vegetation landscapes of the KNP (Biggs *et al.*, 2003; Higgins *et al.*, 2007). The experimental design was a randomised block arrangement with four replications of 12 to 14 fire treatments of different combinations of seasons and frequencies of fire in each landscape (Trollope *et al.*, 1998; Biggs *et al.*, 2003). As described by Gertenbach (1983), the four major vegetation landscapes that were selected for these EBPs include the Lowveld Sour Bushveld of Pretoriuskop (sandy granitic soils); the Mixed *Combretum spp. / Terminalia sericea* Woodland west of Skukuza (sandy granitic soils); the *Sclerocarya birrea caffra/ Acacia* *nigrescens* Savanna around Satara (clay basaltic soils); and the *Colophospermum mopane* Shrubveld on Basalt north of Letaba (clay basaltic soils) (see Table 2.1). Figure 2.1 illustrates the distribution of the EBPs in the park and highlights the Pretoriuskop and Satara burn plots that were used for this study. There are a total of 208 burn plots with an average size of roughly 7 ha (370 m x 180 m) each (Trollope *et al.*, 1998). Figure 2.2 illustrates the difference in vegetation density and structure across the two extreme fire treatments, i.e. annual burn and no burn (control) plots.

Table 2.1 The four vegetation types where the EBPs were configured for the fire experiment in the early 1950s (after Van Wilgen *et al.*, 2007; Venter and Govender, 2012†)

Vegetation/ veld type	**Region**	**Common tree species**	**Geology**	**Dominant soil types †**	**Mean annual rainfall (mm)**
Sourveld	Pretoriuskop	*Terminalia sericea, Dichrostachys cinerea*	Granite	Clovelly, Hutton, Estcourt, deep red sands	705
Combretum	Skukuza	*Combretum collinum, Combretum zeyheri*	Granite	Clovelly, Hutton, Estcourt, Glenrosa	572
Knobthorn-Marula	Satara	*Acacia nigrescens, Sclerocarya birrea caffra*	Basalt	Shortlands, Swartland, Bonheim, Mispah	507
Mopane	North of Letaba	*Colophospermum mopane*	Basalt	Maya-milkwood, Bonheim, Arcadia	451

Table 2.2 Description of the treatments (frequency and season) each veld type receives

Sourveld	**Combretum**	**Knobthorn-Marula**	**Mopane**
Oct B2	Oct B2	Oct B2	Oct B2
Oct B3	Oct B3	Oct B3	Oct B3
Dec B2	Dec B2	Oct B4	Oct B4
Dec B3	Dec B3	Oct B6	Oct B6
Feb B2	Feb B2	Dec B2	Dec B2
Feb B3	Feb B3	Dec B3	Dec B3
Apr B2	Apr B2	Feb B2	Feb B2
Apr B3	Apr B3	Feb B3	Feb B3
Aug B1	Aug B1	Apr B2	Apr B2
Aug B2	Aug B2	Apr B3	Apr B3
Aug B3	Aug B3	Aug B1	Aug B1
C	C	Aug B2	Aug B2
		Aug B3	Aug B3
		C	C

Frequency:		**Season:**	
B1-	Annual burn	Oct-	Spring
B2-	Biennial burn	Dec-	Early summer
B3-	Triennial burn	Feb-	Late summer
B4-	Quadrennial burn	Apr-	Autumn
B6-	Sexennial burn	Aug-	Mid-winter
C-	No burn/ Control		

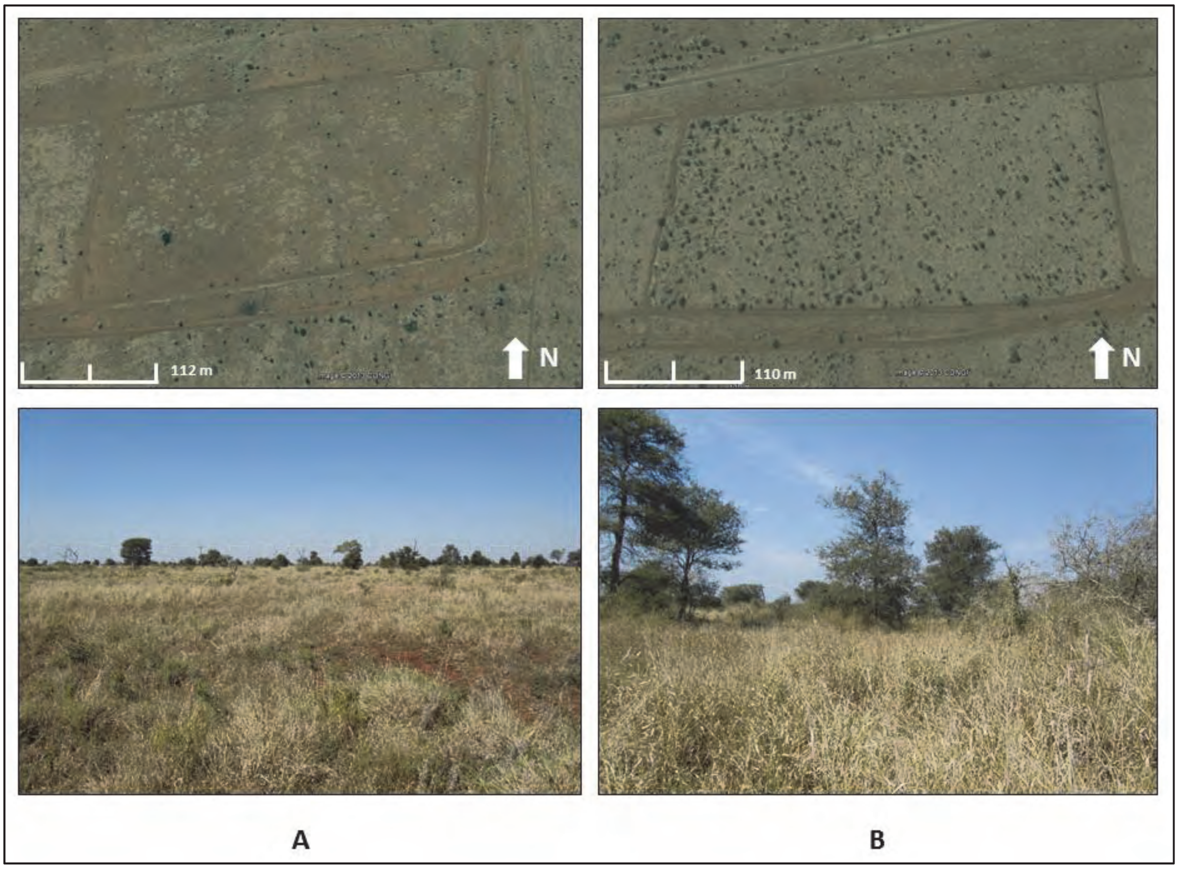

Figure 2.2 Illustrations of how the two extreme burn plots, i.e. annual burn (A) and no burn (B) vary with regards to vegetation density and structure (basaltic N'wanetsi EBPs). Pictures above provide an aerial view whereas the bottom photographs were taken on the plots

2.2.2 EBP soils

Since these EBPs are spread across large areas, soil variation and heterogeneity within the plots and the effects thereof is questioned. The EBPs, especially on the granites, were replicated on the crests (Biggs *et al*., 2003) in an attempt to reduce the uncertainty regarding soil variation. Venter and Govender (2012) conducted a study in which EBP soils were assessed for similarity between plots, strings and the surrounding environment. A combination of both aerial photography and field surveys were used in order to map the burn plots based on the soil and corresponding vegetation patterns on each plot. They developed a scoring system for identifying similarity or representativeness. This scoring system was based on the geomorphic and soil characteristics on each burn plot in relation to the surrounding environment. The following is based on their study:

Scoring for how representative each plot and string is to its surroundings:

1- Not representative at all
2- Slightly representative
3- Moderately representative
4- Well representative
5- Totally representative

Pretoriuskop (sandy granitic soils):		*Satara (clayey basaltic soils):*	
Numbi -	5	Marheya -	4
Kambeni -	5	Satara -	5
Shabeni -	5	N'wanetsi -	5
Fayi -	4	Lindanda -	3

2.3 EBP Sites

EBP strings were chosen on soils belonging to the two dominant geologies in KNP, i.e. granites and basalts. Besides a geological gradient, EBP strings were selected in order to account for the variable rainfall gradient across the park. The effects of varying fire treatments were compared across the annual burn plot, no burn (control) plot and, unless otherwise stated, outside of the EBP string exposed to a variable fire regime (VFR).

2.3.1 Granites (Pretoriuskop)

Pretoriuskop is underlain by a granitic geology with gabbro, shale and doleritic intrusions in a few areas. It is situated in the South-western part of the KNP characterised by sandy granitic soils. The dominant vegetation found in Pretoriuskop is the Lowveld sour bushveld, with *Terminalia sericea* and *Dichrostachys cinerea* tree species, which receive a mean annual precipitation (MAP) of 705 mm (van Wilgen *et al*., 2007). The following EBP strings were selected for this study:

i. Numbi EBPs

Numbi was selected based on the similarity in soils across the string and because the annual and no burn plots were located adjacent to each other (Figure 2.4). This site was used to determine the impact of varying fire treatments on soil hydraulic properties (section 4.1) and water balances (section 4.3) across the annual and no burn plots.

Figure 2.3 The similarity in soil types across the Numbi burn plots (KrMiWa- Kroonstad-Glenrosa-Wasbank, dCl- deep Clovelly, dRs- deep Red Sand, rGa- red Gabbro), (after Venter and Govender, 2012)

ii. Kambeni EBPs

Kambeni was selected as one of the focus sites due to the similarity in soils, as illustrated in Figure 2.4 (Venter and Govender, 2012). This site was used to investigate the impact of fire on soil hydraulic properties (section 4.1), runoff process (section 4.2) as well as soil water balances (section 4.3).

Figure 2.4 The variation in soil types across the Kambeni burn plots (Es- Estcourt, dCl- deep Clovelly, dRs- deep Red Sand, sCl- shallow Clovelly), (after Venter and Govender, 2012)

2.3.2 Basalts (Satara)

Satara is situated centrally in the KNP and lies above the Sabie River Basaltic geological formation. The MAP is approximately 507 mm, i.e. lower than that of Pretoriuskop, and the soil formation is characterised by a clayey basaltic soil. The vegetation is predominantly knobthorn/marula veld dominated by *Acacia nigrescens* and *Sclerocarya birrea* tree species (van Wilgen *et al.*, 2007).

i. N'wanetsi EBPs

N'wanetsi (Figure 2.5) was selected as a key site on the basalts due to the similarity in soils (Venter and Govender, 2012). This site was used to investigate the impact of fire on soil hydraulic properties (Section 4.1) as well as soil water balances (Section 4.3).

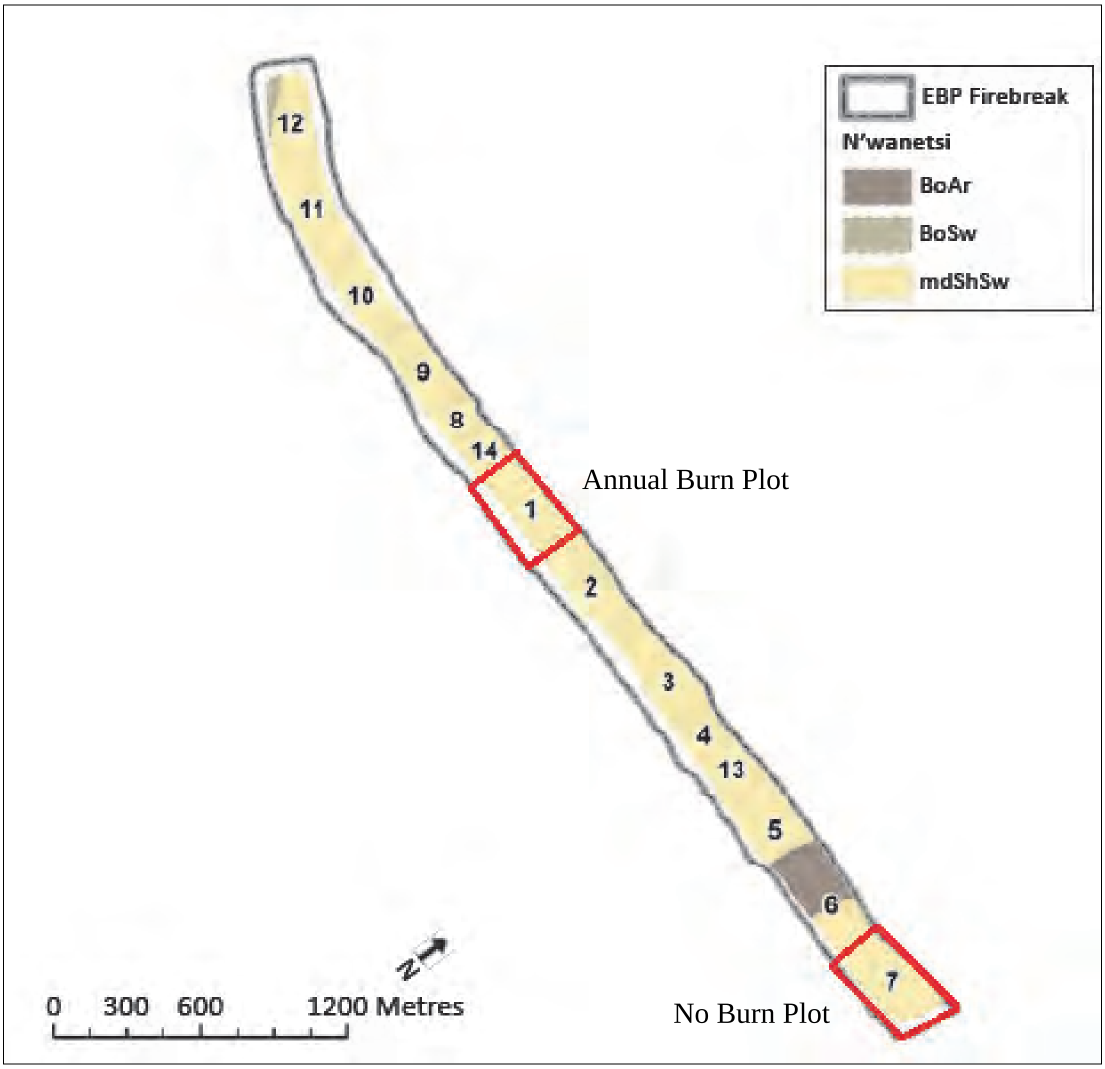

Figure 2.5 The variation in soil types across the N'wanetsi burn plots (BoAr- Bonheim Arcadia, BoSw- Bonheim Swartland, mdShSw-moderately deep Shortlands Swartland), (after Venter and Govender, 2012)

ii. Satara EBPs

Satara was chosen due to the similarity in soils across the string (Figure 2.6). This site was used to determine the impact of varying fire treatments on soil water balances (section 4.3) across the annual and no burn plots.

Figure 2.6 Satara burn plots and the similarity in soil types (DO- Depressions and pans, RO- Rocky outcrop, mdShSw-moderately deep Shortlands Swartland), (after Venter and Govender, 2012)

3. METHODOLOGY

In order to address the objectives of determining the effect of long-term fire treatments on soil hydraulic properties and water balances in savanna systems, the following chapter details the methodology applied during this study. The overall period for data collection extended from June 2012 to December 2013 (a summary provided in Table 3.1).

Table 3.1 A breakdown of the different tests applied on the various EBP strings

Geology	Section	EBP	Plots	Last Burned	Hydrological Tests
Granites	Pretoriuskop	Numbi	Annual Burn	≥ 9 months	Soil hydraulic properties, Soil water balance, Runoff simulations
			No Burn	N/A	
		Kambeni	Annual Burn	≥ 21 months	Soil hydraulic properties, Soil water balance, Runoff simulations
			No Burn	N/A	
			VFR	≥ 3 months	
Basalts	Satara	N'wanetsi	Annual Burn	≥7 years	Soil hydraulic properties, Soil water balance
			No Burn	N/A	
			VFR	≥ 18 months	
		Satara	Annual Burn	≥ 3 months	Soil water balance
			No Burn	N/A	

Data collection was focused on the annual burn plot (burned once a year every August), no burn plot (fire exclusion for more than 50 years) as well as on a plot outside of the EBP string that receives a VFR, so as to account for the effect of a more "natural" fire frequency (roughly 4.5 years) on soil properties. The VFR plot is subjected to fire started by man (rangers who implement prescribed fires and other indiscriminate sources such as tourists, poachers and people walking through the park). Prescribed fires are lit when the area has not burned within a couple of years and fuel load is too high, thereby posing a fire risk. These VFR plots were selected adjacent to the annual burn plots in order to ensure similar landscape positions and representative soils.

3.1 Soil Hydraulic Properties

A number of soil hydraulic properties were measured across the varying fire frequencies on the granitic Kambeni EBPs, and on the basaltic N'wanetsi EBPs. The methodologies applied in order to measure these various properties are discussed below.

3.1.1 Unsaturated hydraulic conductivity (K_{unsat})

Unsaturated hydraulic conductivity (K_{unsat}) was measured in order to establish whether the different fire treatments had any effect on the infiltration rate at the soil surface. K_{unsat} was measured at the soil surface using an instrument known as a tension disc infiltrometer (Figure 3.1). Infiltration was measured under two tensions, i.e. 5 mm and 30 mm. Water maintained under tension (suction) infiltrates into the soil and the steady-state infiltration rates are read manually. These infiltration rates are then used to calculate the hydraulic conductivity of unsaturated soil by plotting the steady-state infiltration rates and using the slope of the graph to determine the volumetric hydraulic conductivity. This volume is then converted into a one-dimensional flux based on the method of Ankeny *et al*. (1991) described in the equation:

$$A = \frac{Q_{t\,0.5} - Q_{t\,3}}{Q_{t\,0.5} + Q_{t\,3}} \times \frac{2}{t\,3 - t\,0.5} \tag{3.1}$$

where

A	=	parameter required in the follow-up equation (3.2) [cm^{-1}],
Q	=	steady state infiltration rate [$cm^3.min^{-1}$],
$t\,0.5$	=	tension of 0.5 [cm], and
$t\,3$	=	tension of 3 [cm].

Hence, the final hydraulic conductivity is calculated as:

$$K = \frac{AQ_{t\,3}}{(A\pi r^2) + 4r} \tag{3.2}$$

where

K	=	hydraulic conductivity [$cm.min^{-1}$], and
r	=	infiltration radius [cm].

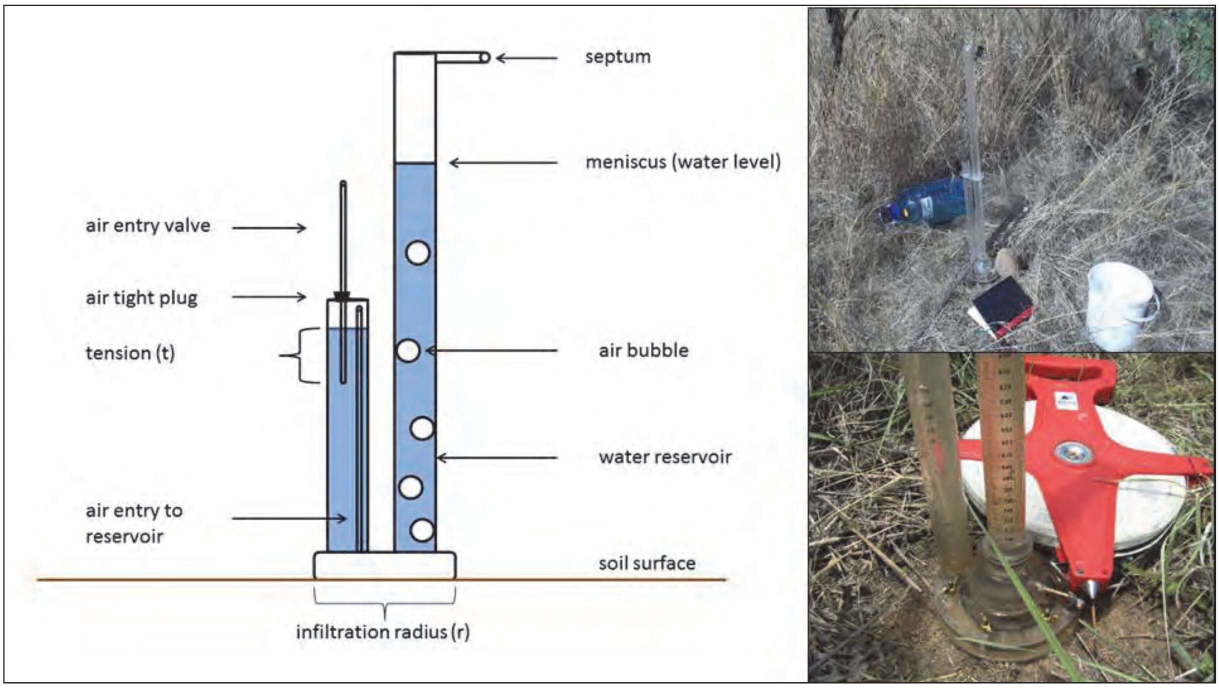

Figure 3.1 The various components of a tension disc infiltrometer and how it is used in the field

3.1.2 Saturated hydraulic conductivity (K_{sat})

Aimed at determining the effect of various fire treatments on hydraulic conductivity within the soil matrix, saturated hydraulic conductivity (K_{sat}) was determined using a Guelph permeameter (Figure 3.2). This instrument was applied in two small holes which were augered at depths of 2-3 cm and 5-7 cm. These sampling depths were selected because literature suggested that fire effects are only prominent within the first few centimetres (pedoderm) of the soil surface (DeBano and Krammes, 1966; Certini, 2005; Mataix-Solera *et al.*, 2011). The Guelph permeameter operates by allowing water to flow from the permeameter into the augered hole and to enter the soil. Eventually, the outflow from the permeameter reaches a steady-state once a saturated ‘bulb’ is formed in the soil (refer to Figure 3.3) (Eijkelkamp Agrisearch Equipment, 2008). Field saturated conductivity (K_{fs}) is measured using the rate of constant outflow, the diameter of the augered hole and the height of the water in the well, explained in the following equations:

$$C^1 = \left(\frac{\frac{h}{r}}{2.074 + 0.093\ \frac{h}{r}} \right)^{0.754} \tag{3.3}$$

where

C^1 = parameter required in the follow-up equation (3.5),
h = height of water in augered hole [cm],
r = radius of augered hole [cm],

Hence, K_{sat} is calculated as:

$$K_{fs} = \frac{C^1 Q}{2\pi h^2 + \pi r^2 C^1 + 2\pi \frac{h}{\alpha}}$$

(3.4)

where

K_{fs} = one dimensional field saturated hydraulic conductivity [cm.s^{-1}],

Q = three dimensional infiltration rate [cm^3.s^{-1}], and

α = soil texture, based on Elrick *et al.* (1989).

Based on suggestions by Elrick *et al.* (1989) (refer to Table 9.1 in Appendix A), different alpha (α) values were used for the granites (Kambeni) and basalts (N'wanetsi) due to differences in soil textures. The granitic EBPs (Numbi and Kambeni) required an α value of 0.12 (most structured soils with medium and fine sands) and the basaltic N'wanetsi EBPs required an α value of 0.04 (unstructured, fine textured soils).

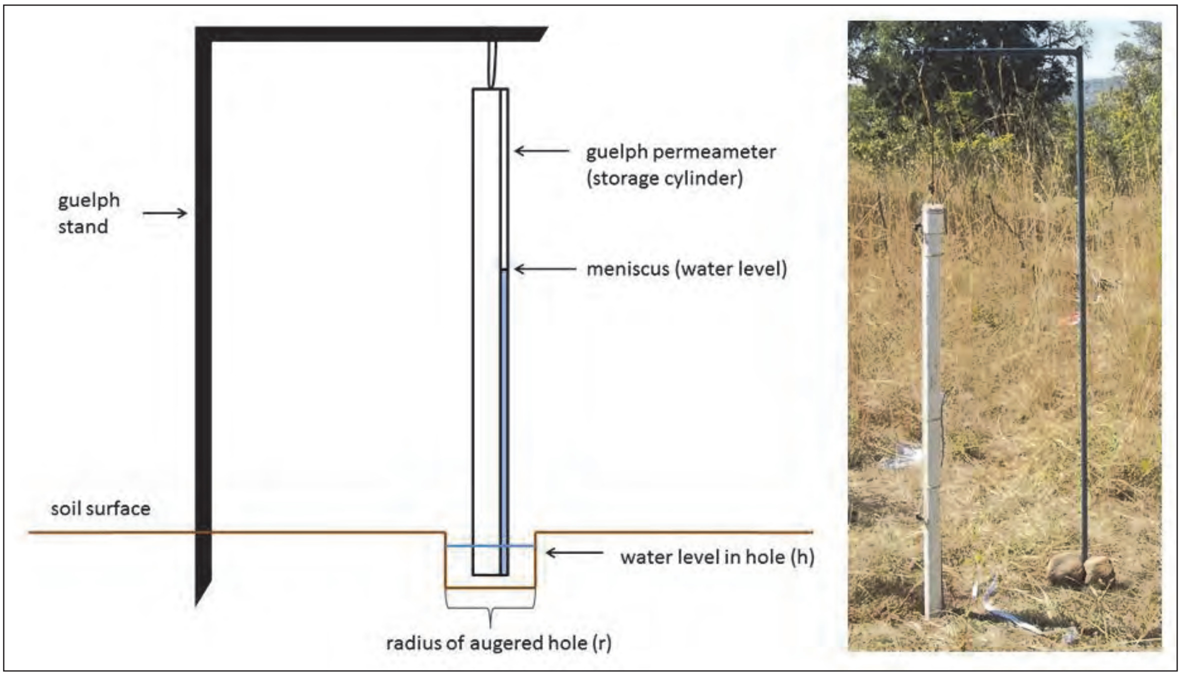

Figure 3.2 An illustration of a Guelph permeameter setup in the field

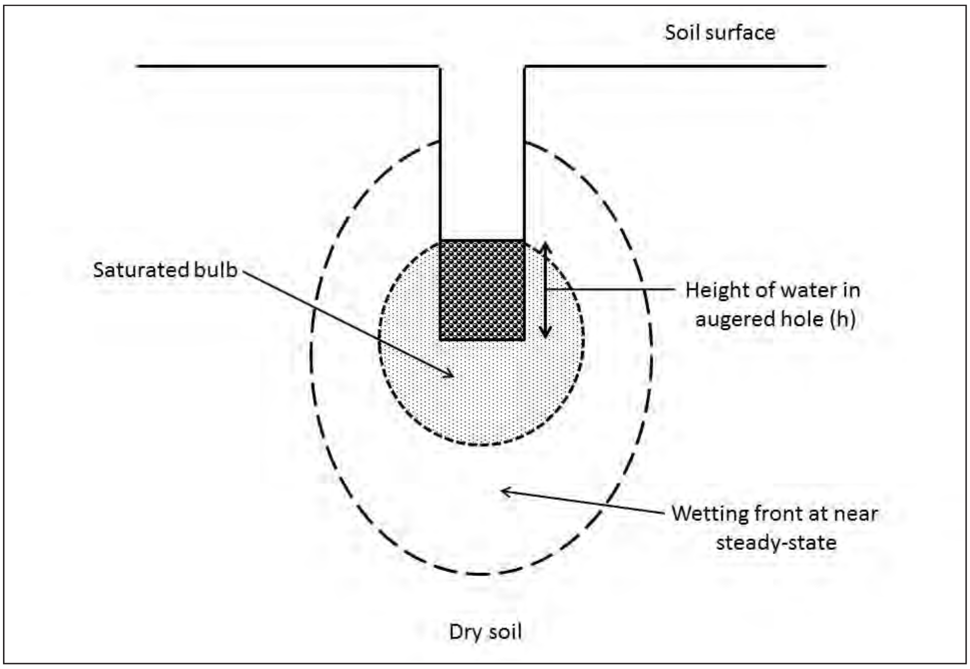

Figure 3.3 An illustration of the saturated bulb which forms at steady-state (after Rodgers & Mulqueen, 2006)

3.1.3 Soil compaction

Soil compaction was determined by means of a drop cone penetrometer (Figure 3.4). A 2 kg weight is dropped from a known height and the resulting energy used to penetrate the soil surface is measured using the equation:

$$E = mgh \tag{3.5}$$

where

E = energy [j],
m = mass of penetrometer weight [kg],
g = gravitational constant [$m.s^{-1}$], and
h = height at which weight is dropped [m].

Soil compaction was measured within a 3 m radius around the point at which the hydraulic tests were performed. A total of ten random measurements were taken and after each strike (release of weight from known height), the depth at which the penetrometer penetrated the soil was measured. At each point, a total of ten strikes were conducted resulting in a total cumulative energy of 307 joules. Therefore, a total of 10 strikes were measured at each of the 10 random points along each of the 15 transect points across the plot. The resistance of the soil to penetration (compaction) is a function of the soil water content, soil type and bulk density. At each EBP site, soil compaction was measured across the different fire treatments at a similar time of year (within the same month) in order to ensure similar water contents. As mentioned before, soils were classed in advance to ensure representativeness and comparability between burn plots (see Venter and Govender, 2012).

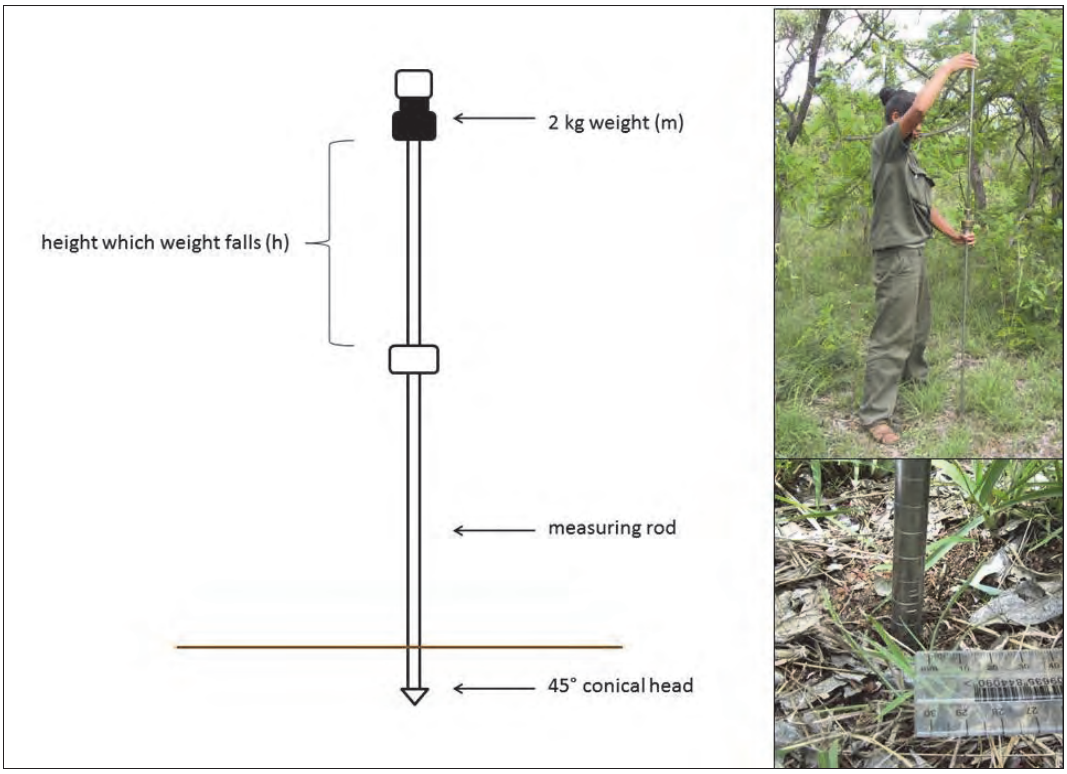

Figure 3.4 The different components of a penetrometer and how it is applied during measurement

Whilst it is acknowledged that herbivores are an important and integral part of the savanna system, it was recognized that herbivory would act as a confounding factor whereby the influence of “fire” versus the influence of “fire and herbivory” would have been difficult to distinguish. Therefore the herbivore exclosures erected on the N’wanetsi EBPs (basalts) in 2005 (Knapp *et al.*, 2006) were used in order to exclude the impact of herbivores and identify the influence of fire *only*, on soil compaction.

The herbivore exclosures were constructed with dimensions of 2 m in height and 7 m in diameter with a diamond-shaped mesh (5 cm diameter). These exclosures were constructed in order to exclude all animals ranging from small herbivores such as steenbok to large herbivores such as buffalo and elephant. The herbivore exclosures used were constructed on the annual and no burn plots, only. The distinction between soil surface compaction and deeper subsurface compaction is illustrated through the use of these herbivore exclosures. Soil compaction was determined by measuring penetration resistance of the soil both inside and outside the exclosures on the annual burn plot. In addition, compaction was determined by comparing soil resistance to penetration within the exclosures across the annual and no burn plot; thereby determining the effect of annual fires vs. fire suppression without the additional impact of herbivores. When differences were identified within the top few centimetres (pedoderm) of the soil, it was regarded as surface compaction (sealing). When differences in penetrometer depth were measured in the deeper layers of the soil (> 3 cm), the subsurface soil would be regarded as compacted.

3.1.4 Soil organic matter and water potential

Besides playing a major role in soil fertility, soil organic matter influences the way in which water is transported and stored within the soil matrix. Since fire consumes biomass and organic matter, soil samples were collected various sample points across the different burn plots to determine the effect of contrasting fire frequencies on soil organic matter. A total of 45 soil samples (collected across the three contrasting fire regimes at Kambeni and N'wanetsi) were oven-dried at 105°C for 24 hours and ground, and then sieved using a 2 mm soil sieve. The percentage of total carbon in these soil samples were analysed by Cedara College of Agriculture using a LECO machine (TruMac Series) (refer to Figure 3.5).

Figure 3.5 The Leco TruMac Series used to measure percentage total carbon to infer soil organic matter content (LECO Corporation www.leco.com)

Understanding how water is retained in the soil is critical since it aids post-fire re-establishment of vegetation. Initially, soil water retention capacities were supposed to be measured using the controlled outflow cell method (Lorentz *et al.*, 2003) but due to time constraints and other logistical impediments, water potential of the soils were measured using a WP4-t dewpoint potentiameter. The WP4-t measures the combined effect of matric and osmotic potential of the soil sample. These potentials are dependent on the amount of dissolved material in the soil and provide an indication of the adsorptive forces binding water molecules to the soil. The dewpoint potentiameter uses a chilled-mirror technique in order to determine water potential. A soil sample is inserted into the sample chamber and the water potential of the sample is equilibrated with the air within the chamber. The chamber is equipped with a mirror which is monitored for condensation. A thermoelectric cooler controls the temperature of the mirror and photoelectric cell then measures the exact point at which condensation occurs on the mirror surface (WP-4 Dewpoint Potentiameter: Operator’s Manual V5, Decagon Devices, Inc. 1998-2007).

On the granitic Kambeni and basaltic N’wanetsi plots, undisturbed soil samples were collected using stainless steel or PVC rings of known volume (i.e. d = 4 cm and h = 5 cm) at depths of between 0 to 5 cm. The soil samples were then taken to a soil laboratory and oven-dried at 70°C for 48 hours (Wilson *et al*., 2009). The top-most layer of soil was removed and transferred to a special WP4-t plastic cup used for water potential determination. Measured amounts of deionised water (between 0.1-0.2 g) were added in daily increments in order to calculate the gravimetric water contents at which the water potential (matric and osmotic potentials) was measured using the WP4-t (refer to Figure 3.6). These readings would continue until the soil sample was fully saturated (≥ 0 MPa). Unfortunately, the soil structure may have been compromised due to difficulty collecting a small enough, undisturbed subsample to use for water potential measurements. Therefore, it is acknowledged that these results might only have at best a semi-quantitative interpretation. However the instrument manufacturer, Decagon Devices, assessed the effect of sample disturbance on soil water potential (Decagon Devices, 2011). The study recognized that soil disturbance and changes in bulk density primarily affects the sizes of the large pores, therefore soil disturbance may influence the water content-water potential relationship of the large pore range only. However, these disturbances will have a negligible effect on the water potential of samples in the tightly absorbed and adsorbed ranges; these are the exact ranges in which this study is interested in. These findings coincided with previous studies by Box and Taylor (1962), and Campbell and Gardner (1971).

Figure 3.6 Photograph of a WP4-t dewpoint potentiameter used to measure water potential

3.1.5 Vegetation characteristics

Since this study acknowledges the impact of the immediate surrounding environment on the soil hydrology, certain vegetation characteristics were investigated within a 3 m radius around where the K_{unsat} and K_{sat} measurements were collected. These characteristics were quantified because vegetation influences soil organic matter content, which in turn influences the water-holding capacity of the soil.

Grass biomass was measured by means of a disc-pasture meter (DPM) which has been calibrated for use within the KNP (Trollope and Potgieter, 1986; Zambatis *et al*., 2006). Random biomass readings were repeated ten times within the 3 m radius. Grass biomass was calculated using the equations formulated for use within KNP by Zambatis *et al*. (2006).

If the average DPM height ≤ 26 cm then Equation 3.6 is used and if average height ≥ 26 cm then Equation 3.7 is used.

$$kg.ha^{-1} = \left[31.7176\left(0.3218^{1/x}\right)x^{0.2834}\right]^2 \tag{3.6}$$

$$kg.ha^{-1} = [17.3543\ (0.9893^{x})\ x^{0.5413}]^2 \tag{3.7}$$

where

x = mean DPM height [cm]

At the point where the hydraulic tests were performed, the basal cover was measured as prescribed by Trollope *et al.* (2004). This measurement serves as an indication of the area of bare soil exposed. Ten nearest-distance-to-tuft measurements were collected randomly around the hydraulic test sampling points as well. A formula developed by Hardy and Tainton (1993) was used to calculate basal cover (%) using the nearest-distance-to-tuft measurements:

$$Basal\ Cover\ (\%) = 19.8 + 0.39(\bar{D}) - 11.87(\log_e \bar{D}) + 0.64\left(\bar{d}\right) + 2.93(\log_e \bar{d}) \tag{3.8}$$

where

$\bar{D}$= mean distance from a point to nearest grass tuft [cm], and

$\bar{d}$= mean tuft diameter [cm].

3.2 Runoff and Sediment Yield Analyses

Rainfall simulations are commonly used to measure runoff and sediment yield from small runoff plots representative of an area of interest. The rainfall simulation itself may be defined as the application of artificial rainfall at a set intensity to generate such runoff and sediment loss (Podwojewski *et al.*, 2011). Podwojewski *et al.* (2011) recently performed rainfall simulations in the KwaZulu-Natal province of South Africa in the upper part of the Potshini SSI experimental catchment in the ‘midlands’, downstream of the Drakensberg Mountains. The experimentation was undertaken to compare the effect of vegetation cover on soil infiltration, runoff and sediment yield at various rainfall intensities, within a degraded rangeland. Thus, this technique was applied on the EBPs in order to determine the effect of different fire regimes on runoff and sediment yield. Due to time and logistical constraints, these rainfall simulations were applied to the annual burn and no burn plots on the granitic Numbi and Kambeni EBP strings only.

3.2.1 Runoff calculation

A steel frame was required to support sensitive equipment such as the actual rainfall simulator which consists of a small metal box with a spray nozzle at the end of a motorised arm (Figure 3.2). The rainfall simulator is controlled by computer software, i.e. CAPRAIN 1700, which enables the user to set the desired rainfall intensity. The intensity is based on three inputs; i.e. the angle of the motorised arm, the velocity of the motorised arm and the run time (Figure 3.2).

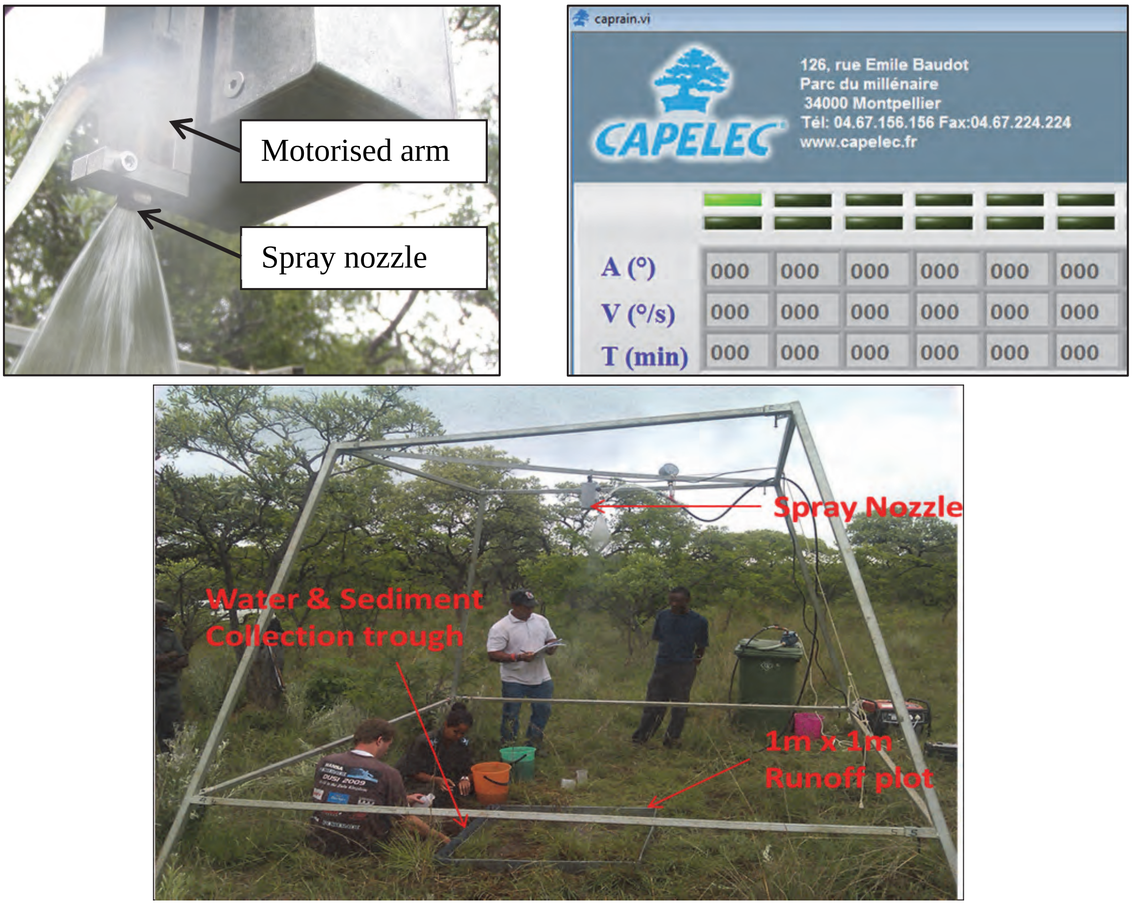

Figure 3.7 Rainfall simulator (top-left); CAPRAIN 1700 Computer program (top-right); field set-up (bottom)

Two rainfall intensities were selected for the analyses; i.e. an initial intensity of 157 mm/h followed by 200 mm/h rainfall intensity 24 hours later. The latter intensity accounted for runoff comparisons at a different antecedent soil moisture contents than the initial intensity. Due to difficulties encountered as a result of the extensive experimental setup, complete sample replication was declared unfeasible. Thus, only six replicates were performed on the Numbi annual and no burn plots, while five replicates were performed on the Kambeni annual and no burn plots. Additionally, time constraints necessitated that each simulation was run for approximately 10 minutes at these extreme rainfall intensities. Such intense rainfall intensities are not unrealistic and have been recorded before in this semi-arid region of the Lowveld (e.g. Riddell, 2011). A calibration frame (1 x 1 m) was required in order to calculate the rainfall intensity based on the height of the simulator, the angle and velocity selected, and the time (Figure 3.8). The intensity was simply calculated by recording the volume of runoff discharged from the calibration frame over a specified time. The area of the frame was then used to convert the volume discharged per unit time to a rainfall intensity in mm/h. Thereafter, a runoff plot (1 x 1 m) was used to measure the volume of runoff generated from the set rainfall intensity at different points within the different EBPs (Figure 3.8). The volume of infiltration and/or interception was calculated by subtracting the measured runoff volume per unit time by the volume of total rainfall for the same time period. These volumes were then converted in order to calculate the rate of runoff (mm/h).

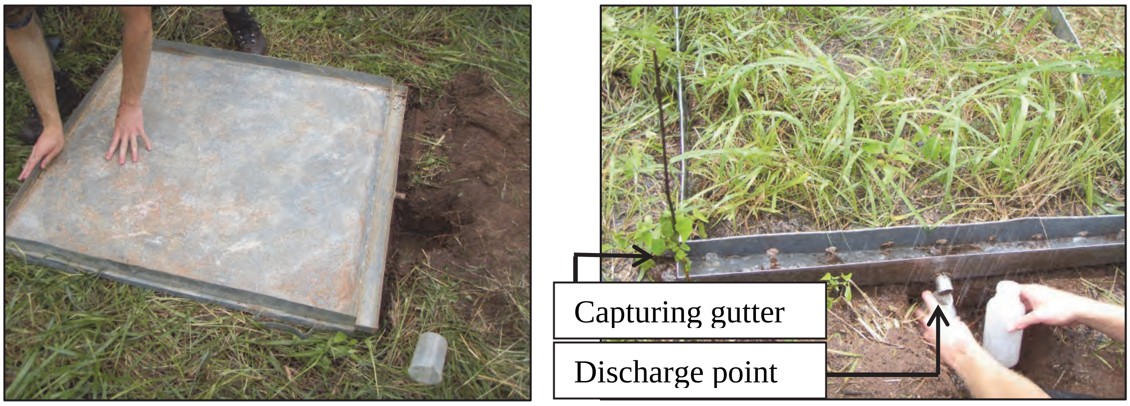

Figure 3.8   Calibration frame (left) and runoff plot (right)

3.2.2 Sediment yield

In order to determine the sediment yield per rainfall intensity on each plot, all the runoff water and sediments were collected in 10 L buckets and a 250 ml subsample taken. The samples were then taken to the laboratory and analysed for both turbidity and Total Suspended Solids (TSS). “Turbidity in water is caused by suspended and colloidal matter which can be either organic or inorganic in origin and is a measure of the optical clarity of a sample. More precisely turbidity is an expression of the optical property that causes light to be scattered and absorbed rather than transmitted with no change in direction or flux level through the sample” (Clesceri *et al.*, 1998). Turbidity was analysed using a technique developed by Goodner (2009), where an equation is used to convert the absorbance of light at a wavelength of 750 nm to Nephelometric Turbidity Units (NTU). The equation developed by Goodner (2009) is as follows:

$$\mathrm{NTU} = 0.191 + 926.1942 * \mathrm{A}_{750};\ 0.95\ \mathrm{Pred.Int} \tag{3.9}$$

where

A_{750}= the absorbance at a wavelength of 750 nm [NTU]

The 0.95 Pred.Int indicates that 95% of the time, the real NTU value will fall within a close range of the calculated NTU value. Thus, this method provides a good estimate of the NTU. The absorbance of each sample was measured with a spectrophotometer set at a wavelength of 750 nm (Figure 3.9). The absorbance measurements were then converted to NTU's using Equation 3.9.

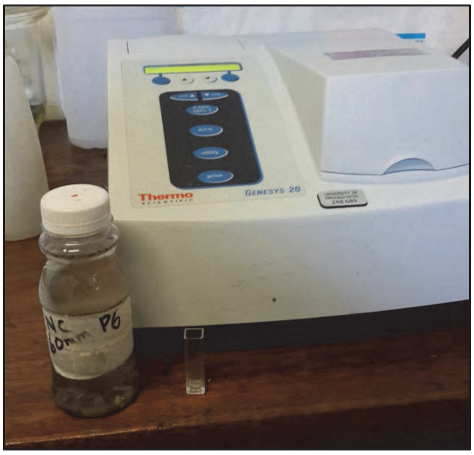

Figure 3.9 Spectrophotometer and sample bottle

In order to compliment the turbidity data, samples were also analysed for TSS; this was done gravimetrically using a similar technique implemented by Clesceri *et al.* (1998). The samples were filtered through filter paper and the mass of the sediments captured were recorded with a fine scale (Figure 3.10). After filtration the sediments and filter paper were left to air-dry for 24 hours. The mass of the filter paper prior to filtration was subtracted from the mass of the filter paper and sediments in order to calculate the mass of sediments within each sample. Since the sample volume was 250 ml, the TSS in each sample was calculated by dividing the mass of the sediments by the volume of the sample, expressed in units of mg/l.

Figure 3.10 Filtration of samples (left) and weighing of the filtered samples (right)

3.3 Soil Water Balance

The HYDRUS 3D soil water movement, heat and solute transport model was used to develop soil water balances for the granitic Numbi and Kambeni EBP strings of Pretoriuskop and the basaltic Satara and N'wanetsi EBP strings of Satara. Simultaneously the model was used to compare instantaneous evapotranspiration rates. The fire regimes that were analysed included the annual burn, no burn (control) and VFR plots. All of the three aforementioned fire regimes were modelled for the N'wanetsi and Kambeni EBPs, however, for the Numbi and Satara EBPs the VFR plots were not modelled as specific soils information was not available, i.e. saturated and unsaturated hydraulic conductivities. The modelling period for the granites (Pretoriuskop) and the basalts (Satara) was limited to the growing season which had sufficient input data. For example the time period that was modelled for the granitic EBPs was the 4th of October 2012 until the 01st of May 2013, due to the availability of SEBAL data covering this period. Conversely the modelling period for the basaltic EBPs ran from the 15th of November 2012 until the 01st of May 2013, since data from the automatic weather station was only available for this period.

To perform mass balance calculations the inputs and outputs of the hydrological cycle were required as inputs into the model on an hourly time-step, as well as site specific soil characteristics. The major driving parameters that were required included rainfall and evapotranspiration.

- Rainfall data was obtained from the University of Cape Town (UCT) Tree-Grass Programme meteorological stations situated in Pretoriuskop and Satara, i.e. the sites of the granitic and basaltic EBPs respectively.
- Hourly actual evapotranspiration (aET) was estimated by extracting weekly aET from SEBAL remote-sensing images and then disaggregating that to hourly values using trends provided by calculation hourly potential evapotranspiration (pET).
- Hourly pET was calculated using the Penman-Monteith equation (Allen *et al*., 1998) which required hourly meteorological inputs such as relative humidity, air

temperature, wind speed and solar irradiance which were recorded at the respective UCT meteorological stations.

- Weekly aET was obtained in the form of raster images captured from the SEBAL remote-sensing satellite (Figure 3.11), provided by eLeaf to the Inkomati Catchment Management Agency. The raster images provided weekly aET measurements as a function of infra-red reflectance from the vegetation, calculated by the SEBAL model. Since the rasters covered the entire area of the southern KNP (within the Inkomati river basin) and had a pixel size of 30 x 30 m. In order to obtain the weekly aET totals, the rasters were combined and converted to shape files in ArcGIS 9 thus joining the shape file grid-codes with the raster values. The intersect function in ArcGIS 9 was then used to intersect the aET values for each of the EBPs. The aET values within each EBP were averaged and these values represented the weekly .
- Hourly aET was then calculated using the following equation:

$$\text{Hourly aET} = \frac{\text{Hourly pET}}{\text{Weekly pET Total}} \times \text{Weekly aET Total} \tag{3.10}$$

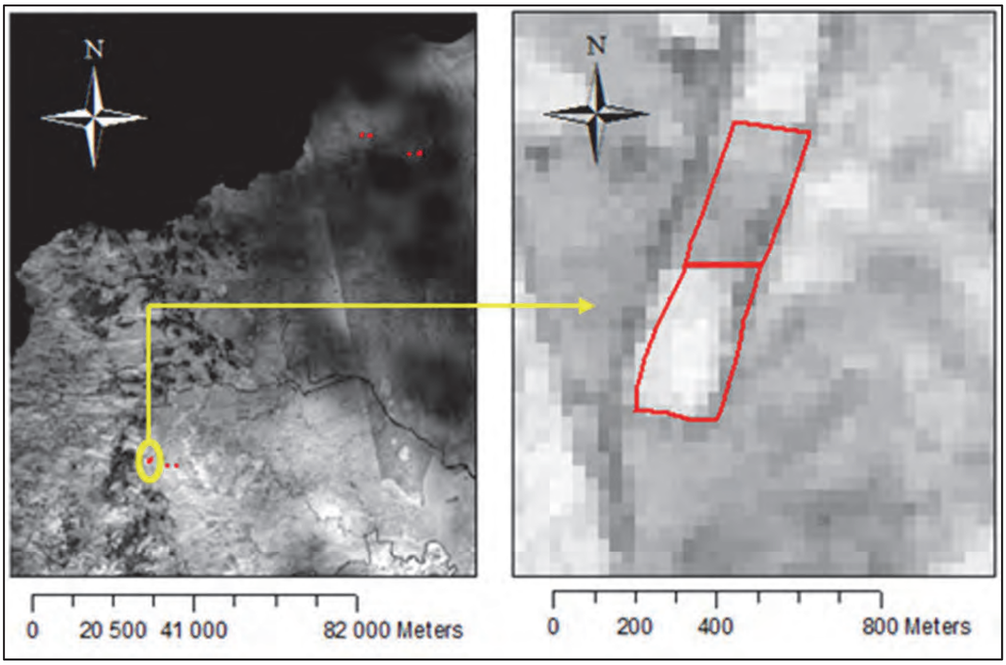

Figure 3.11 SEBAL aET raster image for the southern KNP (left), focusing on the 30 x 30 m pixel resolution for the Numbi EBPs (right)

In certain cases, the SEBAL weekly aET data displayed errors which could be attributed to cloud cover. This resulted in very low or zero values. These errors were corrected using percentage differences to fill-in the missing data (refer to Appendix: B).

Hourly aET measurements were partitioned into evaporation and transpiration, to satisfy the atmospheric boundary condition and the root water uptake parameter, respectively, within the HYDRUS model. The fraction of total evaporation, or evapotranspiration, made up of transpiration was estimated using the maximum transpiration from the crop coefficients equation (Equation 3.11) obtained from the ACRU (Agricultural Catchments Research Unit) model (Schulze, 1989):

$$F_t = \frac{0.95(K_d - 0.2)}{0.8}\text{; When } K_d > 0.2 \tag{3.11}$$

where

F_t = fraction of transpiration, and

K_d= daily crop coefficient.

Canopy cover is described by K_d (1 representing full canopy cover and anything less than 0.2 representing no canopy cover). The equation is derived from the assumption that at full canopy cover, evapotranspiration comprises of 95% transpiration from the vegetation and 5% evaporation from the soil (Childs and Hanks, 1975 cited in Schulze, 1989). For simplicity it was assumed that the vegetation cover was generally fairly high (K_d = 0.8). This resulted in the fraction of transpiration (F_t) being 71.25% and subsequently the fraction of soil evaporation being 28.75%. This partitioning was applied consistently throughout all the model runs. Justification of the selected ET partitioning is explained in Appendix: C.

The soil hydraulic properties (K_{unsat} and K_{sat}) measured at Numbi, Kambeni and N'wanetsi were required as model inputs. Since K_{unsat} and K_{sat} values were not measured at Satara EBPs, soil information stemming from the N'wanetsi plots were used to substitute hydraulic values for Satara EBPs. It was noted that the dominant soil type (moderately deep Shortland-Swartland) between the N'wanetsi and Satara EBPs was identical (Venter and Govender, 2012). These soil characteristics, along with textural analyses, were used as inputs into the RETC (version 6.02) soil water retention program in order to develop soil water characteristic curves for each of the EBPs. These curves were required for HYDRUS model to calculate water flow (Richard's equation) within each soil medium.

HYDRUS was used in order to model water flow as well as root water uptake. In HYDRUS, the EBPs were modelled using a simple 3D geometry. Some of the subsequent steps in the HYDRUS model included:

- setting the modelling time information and boundary conditions; the time units were set to hourly measurements. A time-variable boundary condition was selected, i.e. to input the hourly rainfall, evaporation and transpiration measurements as observed or estimated for each EBP.
- stipulation of the output information, selecting daily print times. Additionally, the EBP domains were modelled as one homogeneous sub-region.
- defining the iteration criteria. In this case left to the default values as suggested in the HYDRUS user manual (Šejna *et al*., 2012).

- selecting the soil hydraulic model used to develop soil water characteristic curves. The *van Genuchten-Mualem model with no hysteresis* (no change in the soil water retention curve upon drying and wetting cycles) was selected.
- inputting water flow parameters such as the soil texture, Θ_s (saturated water content), Θ_r (residual water content), α, n, (soil specific parameters related to pore size distribution and porosity – determined from the soil water characteristic curves using the van Genuchten-Mualem equation), K_s (saturated hydraulic conductivity) and I (a constant. The soil texture was determined in the laboratory using the hydrometer method. Not all of the EBPs had textural data available, however, a review of the homogeneity of the EBP soils by Venter and Govender (2012) reveals that the EBPs are highly homogeneous. Therefore the soil texture in the unanalysed plots was extrapolated from the plots that had been analysed. The soils information was input into HYDRUS and fixed to represent the actual soil characteristics as obtained in the field (reality); values were not altered in an attempt to improve model performance.
- defining the tensors of anisotropy (lateral water movement), were left to the default values as recommended.

Hourly rainfall data was adjusted slightly in certain cases due to limitations of the model to accommodate rainfall events under considerably dry conditions, i.e. rainfall events succeeding a long drying period, were discretised over approximately five hours starting with small values that progressively became larger. The model requires slow wetting initially after a dry cycle and can accommodate more moisture (rainfall) as the matric potential and concurrent soil moisture increases. Since the model has difficulty simulating an input and an output simultaneously, evaporation and transpiration were set to zero where rainfall occurred. To improve model performance and fluency, 0.2 mm of rainfall was applied incrementally to the time-variable boundary condition of each EBP for the first five hours. The hCritA value (absolute value of the minimum allowed pressure head at the soil surface, applied to the atmospheric boundary) (Šejna *et al*., 2012) was set to –15000 mm. This value was used because excessive drying beyond this matric potential, especially for the sandy soils (granites), severely influences the ability of the model to transmit water through the soil. In other words, as the matric potential (tension) decreases (becomes more negative) the hydraulic conductivity decreases. Therefore the model has great difficulty in distributing any rainfall (water) through the soil at very low potentials, i.e. when the soil is dry. Similarly, the initial conditions which were assumed to be relatively dry since the modelling periods began at the end of the dry season, were also set to -15000 mm.

Furthermore, linked to the hCritA value are the root water uptake parameters. The root water uptake model used was the Feddes model, with no solute stress. Since the hCritA value was set to -15000 mm, the P3 (pressure head value below which root water uptake ceases) root water uptake parameter mathematically needed to be lower than this value. Therefore a value of -10000 mm was selected and the P2H and P2L (limiting pressure head values below which roots can no longer extract water at the maximum defined rate) values needed to be adjusted accordingly.

Finally, the culminating steps included:

- specification of the finite element mesh. The X and Y directions of the domain were discretised into 31 sections and the Z direction of the domain was discretised into 20 sections; relatively high compared to the X and Y directions as this is the direction in which most changes occur.
- specification of the boundary conditions. An atmospheric boundary condition was applied to the surface (i.e. where the time-variable boundary conditions were implemented), no flux on the sides and free drainage at the base of each domain.

The outputs from the HYDRUS model were then used to analyse instantaneous evapotranspiration rates, cumulative evapotranspiration totals and ultimately calculate a water balance (mass balance) for each EBP, using the generalised water balance equation (Lu Zhang *et al*., 2002):

$$\Delta S = P - ET - R - FD \tag{3.12}$$

where

ΔS = change in water storage,
P = precipitation,
ET = evapotranspiration,
R = surface runoff, and
FD = free drainage or groundwater recharge.

Storage or the change in storage is generally controlled by the major inputs and outputs of the system, i.e. the rainfall, evaporation and transpiration. Additionally, the soil physical properties such as texture determine the soil hydraulic conductivity and therefore influence storage. The soil type or texture also affects the water-holding capacity of the soil and relative ease with which plants absorb water from the soil. Subsequently the specific soil characteristics (i.e. K_s, texture, n and α values) as inputs into the HYDRUS model for each of the EBPs will also greatly influence the mass balance information, not only the rainfall and evapotranspiration.

4. RESULTS

4.1 Soil Hydraulic Properties

4.1.1 Granites

The Kambeni EBPs are situated in the higher rainfall, granitic area of Pretoriuskop (refer to Figure 2.1). These soils are dominated by the Clovelly soil type and deep red sands (Figure 2.3). Data was concentrated not only on the annual burn and no burn plots but outside and adjacent to the EBPs too (refer to Figures 3.1 and 3.2). The area outside of the EBPs is referred to as the VFR plot where the landscape is not manipulated by the EBP experiment. It has a more variable fire return period of roughly 4.5 years. Approximately three months before data collection, the VFR area surrounding the burn plots was burned by a hot fire. A full summary of all the statistical analyses is provided in Appendix E: Tables 9.4 (Numbi) and 9.5 (Kambeni). The confidence interval used to determine significance is 95%, except where otherwise stated.

(i) Numbi EBPs

Unsaturated hydraulic conductivity (K_{unsat})

Under both pressure heads i.e. 5 mm and 30 mm, there is no significant difference (U = 143, P = 0.191 and U= 125, P = 0.254, respectively) in K_{unsat} between the annual and no burn plots (Figure 4.1). This finding challenges results by previous studies by DeBano (2000) and Ice *et al.* (2004) which found that once a fire has removed vegetation cover, the soil surface is exposed to raindrop impact and splash which results in the sealing and compaction of surfaces thus reducing infiltration. When compared to Riddell *et al.* (2012), their study discovered slight differences in unsaturated hydraulic conductivities but stated that it was unclear and required greater replication. We propose two likely reasons for our finding. Firstly, it is likely that reduced infiltration rates are most pronounced immediately after a fire and the effect of the fire dissipates over time. Therefore, fire frequency may not be the primary factor influencing infiltration rates but rather the length of time following a fire (refer to Table 3.1). Secondly, a study conducted by Snyman (2003) in a semi-arid rangeland in South Africa found similar results when no significant differences were found between burned and unburned plots. Snyman (2003) suggested that the higher soil compaction and lower soil litter retarded infiltration rates regardless of the fact that the burned plot had lower soil water content.

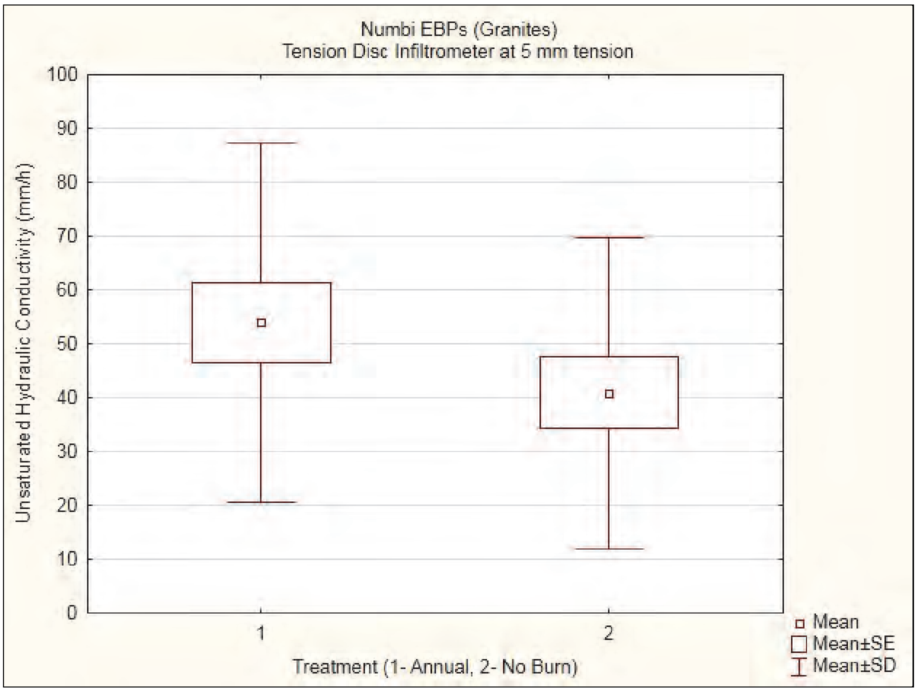

Figure 4.1 The average K_{unsat} (mm/h) at 5 mm tension across the different fire treatments on Numbi EBPs

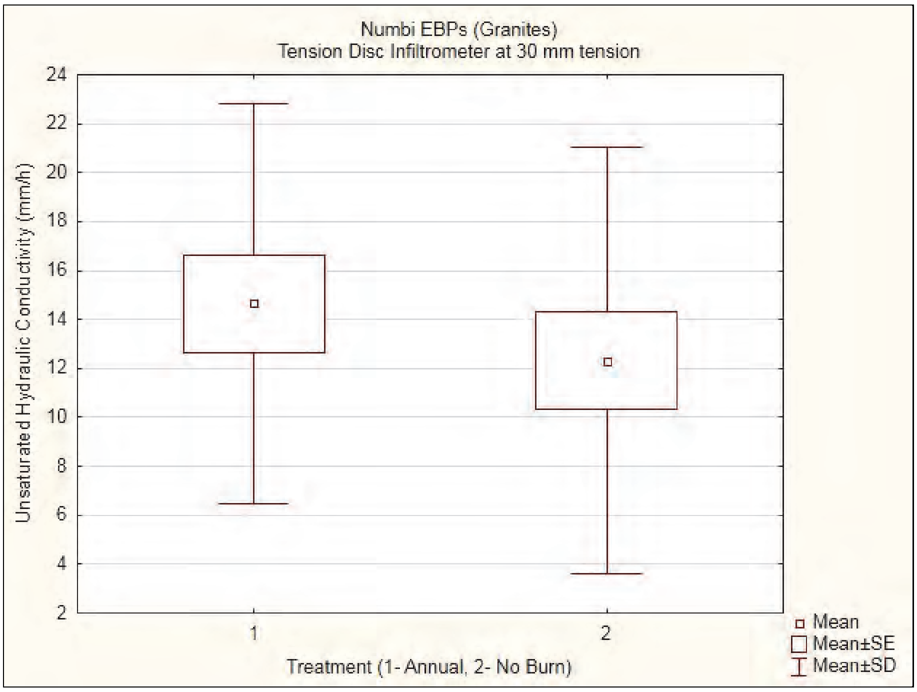

Figure 4.2 The average K_{unsat} (mm/h) at 30 mm tension across the different fire treatments on Numbi EBPs

Saturated hydraulic conductivity (K_{sat})

At Numbi EBP, there was a higher K_{sat} on the no burn plot than the annual plot (Figures 4.3 and 4.4). However, this result was only statistically significant ($U = 61$, $P = 0.000$) at 2-3 cm beneath the soil surface while there was no significant difference at 5-7 cm below the surface

(U = 124, P= 0.068). However it was calculated that at a confidence interval of 90%, there was a significant difference in K_{sat} at 5-7 cm as well. Hence, it is believed that fire may penetrate as deep as 7 cm below the soil surface. It is this top layer which houses majority of the organic matter and bioactivity, particularly on the no burn plot where faster K_{sat} was measured.

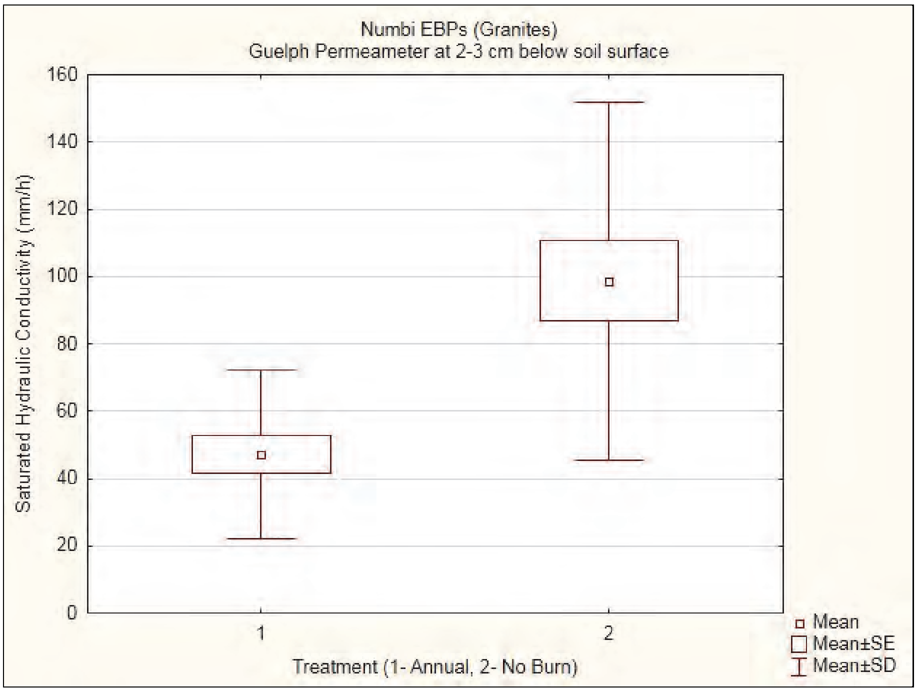

Figure 4.3 Box-whisker plots describing K_{sat} measured at the Numbi EBPs at a soil depth of 2-3 cm

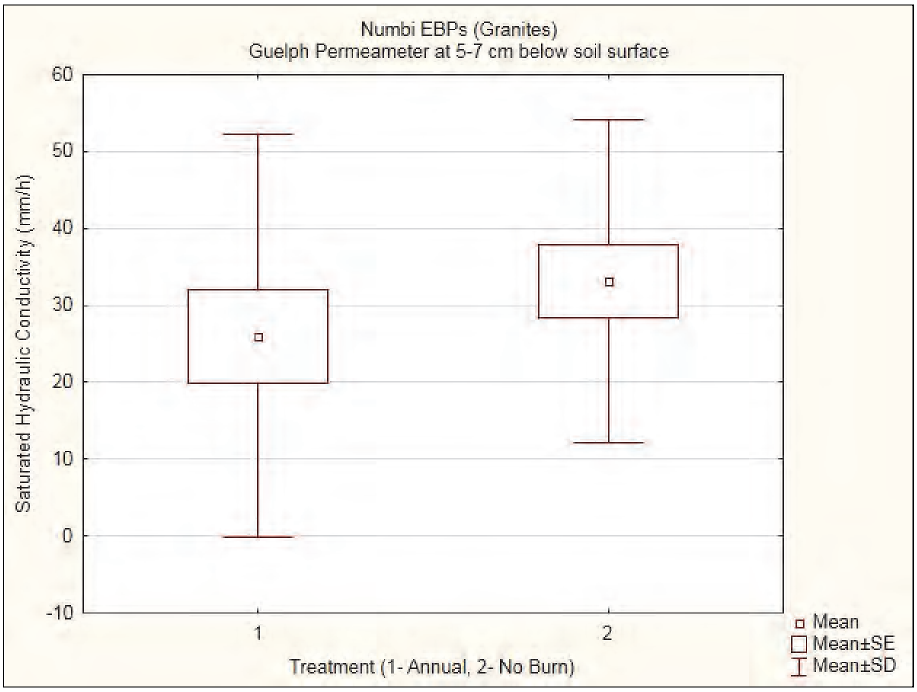

Figure 4.4 Box-whisker plots describing K_{sat} measured at the Numbi EBPs at a soil depth of 2-3 cm

Soil compaction

The penetrometer data in Figure 4.5 revealed that the annual burn plot is more compacted than the no burn plot. This compaction test analysed the first three penetrometer strikes to account for the pedoderm (< 4 cm) to identify shallow surface compaction, and the final tenth strike to account for deeper layers of the A-horizon to distinguish whether the subsurface soil is also compacted (± 10 cm). The Mann-Whitney U test determined the differences in the mean penetration depth of the initial three strikes and the final strike. All strikes were found to be significantly different between the fire treatments, i.e. 1st strike P-value = 0.000, 2nd strike P-value = 0.000, 3rd strike P-value = 0.000 and the 10th strike P-value = 0.000. Besides bare soil being vulnerable to soil processes such as raindrop impact and splash which result in soil compaction (DeBano, 2000), these plots are exposed to wildlife which aggregates on the annual plot due to the improvement in grazing quality. It is likely that trampling due to the increase in wildlife on the annual plot may have contributed to higher soil compaction than the no burn plot.

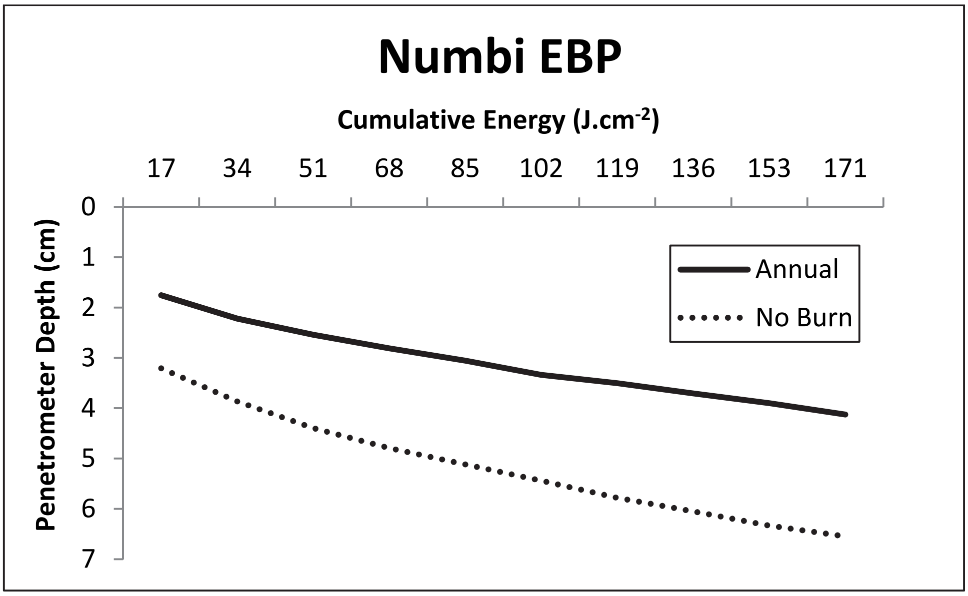

Figure 4.5 Soil compaction measured on the Numbi EBPs

(ii) Kambeni EBPs

Unsaturated hydraulic conductivity (K_{unsat})

K_{unsat} data across the fire treatment extremes (annual vs. no burn) and under the variable fire frequency were measured using 5 mm and 30 mm tensions on Kambeni EBPs (Figures 4.6 and 4.7). Under both tensions on the no burn (fire exclusion) plot, the average K_{unsat} was found to be higher than that of the annual burn plot while the VFR plot had the lowest K_{unsat}.

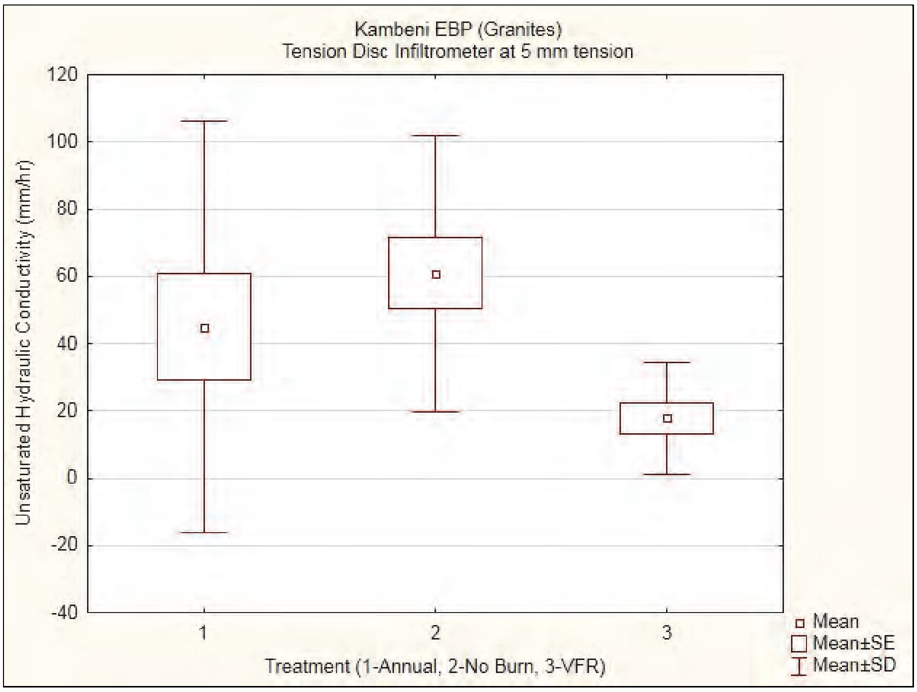

Figure 4.6 Box-whisker plots illustrating the average K_{unsat} (mm/h) at 5 mm tension across the three different fire treatments on Kambeni EBPs

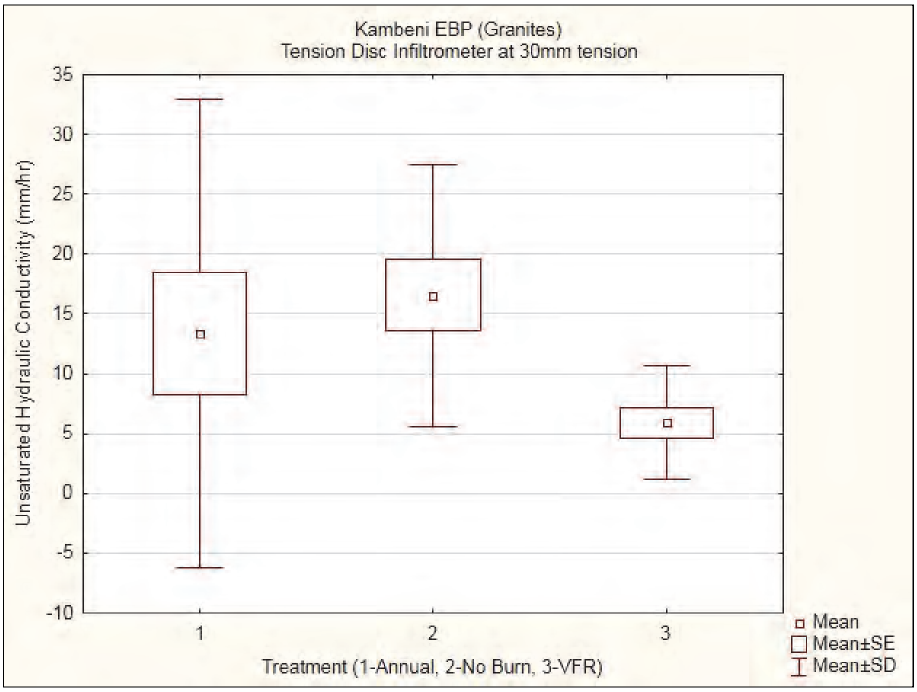

Figure 4.7 Box-whisker plots illustrating the mean K_{unsat} (mm/h) at 30 mm tension across the three fire treatments

Under both tensions, statistical analyses found these results to be significantly different. A non-parametric Kruskal-Wallis test under a tension of 5 mm resulted in a significance level of P = 0.005 (H = 10.830) while under 30 mm tension P = 0.01 (H = 9.183). A post-hoc pairwise multiple comparisons test was performed in order to identify across which fire frequencies these significant differences were. For 5 mm tension, the multiple comparisons test found that the significance actually lies between the VFR and no burn plots ($P = 0.003$). A similar trend was observed under 30 mm tension where a significant difference in K_{unsat} was found between the VFR and no burn plot ($P = 0.007$). It was hypothesised that the plot with the most frequent fires, i.e. annual burn plot, would result in the slowest infiltration rates. However, these results do not confirm this as the VFR plot with a mean fire return period of 4.5 years has significantly slower infiltration rates. This is most probably due to the VFR plot burning roughly three months before the site was sampled (refer to Table 3.1). The amount of time after a fire is likely to play a significant role in how soils respond to hydrological processes such as infiltration, in the short term. Therefore, it is speculated that it is not necessarily fire frequencies affecting soil infiltration rates but rather the time following a fire.

Interestingly in Figures 4.6 and 4.7, the variation (i.e. standard deviation) observed in the data is greatest on the annual burn plot which may be explained in the way or patterns in which fire burns in savanna systems. Generally on the annual fire treatment, fires are cooler and tend to burn more heterogeneously resulting in a patchy fire mosaic. This is due to less biomass available to burn and reduced fuel continuity after only one season's growth (Govender *et al*., 2006). The least amount of variation in the data is observed on the VFR plot which was exposed to a high intensity fire just three months prior to sampling and it is believed to have resulted in soil being burned in a more homogenous manner. In addition, the increased variation on the annual burn plot may be due to preferential pathways through the soil in certain areas where dense root networks may have died-off during the fire.

Saturated hydraulic conductivity (K_{sat})

Across the three different fire regimes at Kambeni, K_{sat} were measured at two different soil depths i.e. 2-3 cm and 5-7 cm, Figures 4.8 and 4.9 respectively. At both soil depths, results indicated that the slowest K_{sat} was on the VFR plot, similarly observed in the K_{unsat} measurements. However, the Kruskal-Wallis test revealed that there was no significant difference between EBPs in K_{sat} at both depths. The Kruskal-Wallis test for data collected at 2-3 cm depth indicated a significance level of $P = 0.47$ ($H = 1.512$) while at a depth of 5-7 cm, $P = 0.633$ ($H = 0.914$). Even at a confidence interval of 50%, results at both soil depths are still not significantly different.

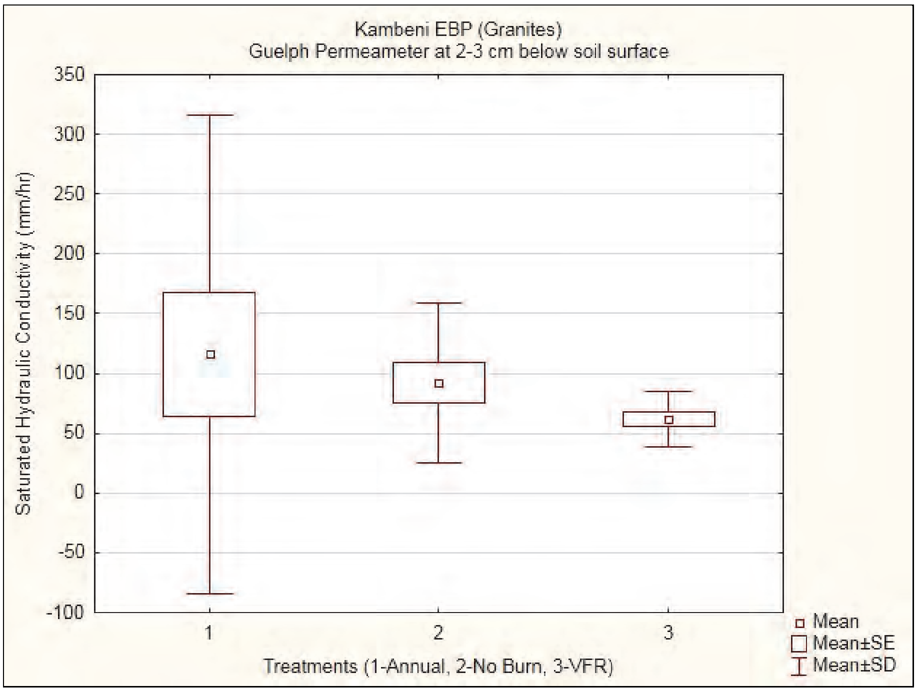

Figure 4.8 K_{sat} (mm/h) at 2-3 cm below soil surface across contrasting fire treatments on Kambeni EBP

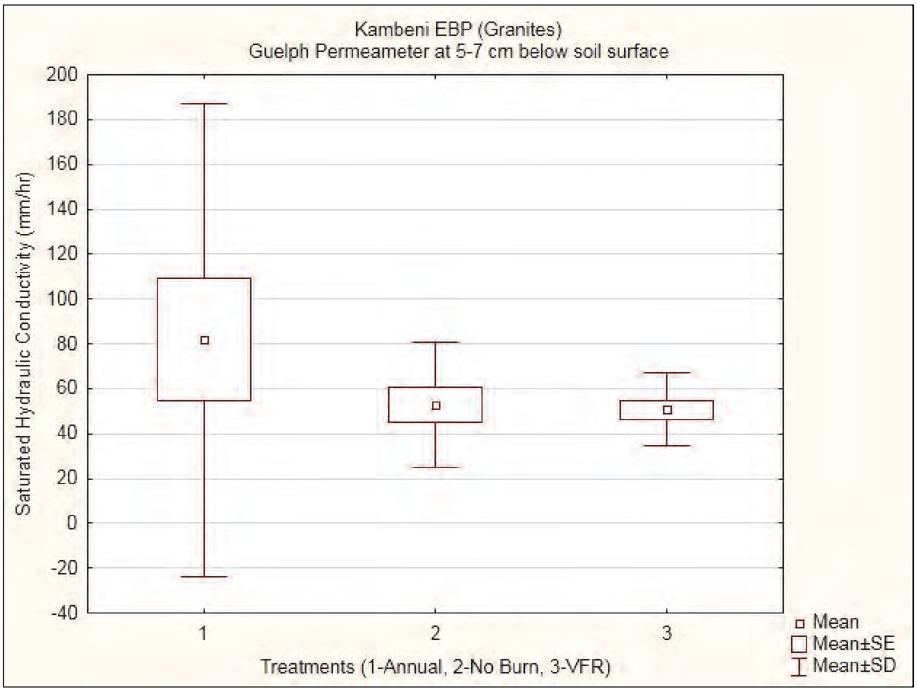

Figure 4.9 Mean K_{sat} (mm/h) at 5-7 cm below soil surface across the various fire treatments on Kambeni EBP

Based on the hydraulic conductivity data collected at the soil surface and at the two shallow depths below the soil surface, it appears as though it is only the unsaturated conductivities at the soil surface which is significantly affected by fire. This is likely since fires in savanna systems travel so rapidly across the soil, that there is not enough time to allow substantial transfer of heat between the fire and soil. However, this may only be applicable for situations where there is low aboveground fuel and where fires are less intense.

Soil compaction

The data illustrated in Figure 4.10 suggests that the first few centimetres of soil on the annual burn plot, is more compacted than the VFR and no burn plots. These tests analysed the first three penetrometer strikes to account for the pedoderm (< 4 cm) to identify shallow surface compaction, and the final tenth strike to account for deeper layers of the A-horizon to distinguish whether the subsurface soil is also compacted (± 10 cm). The Kruskal-Wallis test determined the differences in the mean penetration depth of the initial three strikes, which are roughly at a depth of 2-6 cm and the final strike at a depth of ± 10 cm. All strikes were found to be significantly different between the fire treatments, i.e. 1st strike P-value = 0.000, 2nd strike P-value = 0.000, 3rd strike P-value = 0.000 and the 10th strike P-value = 0.000.

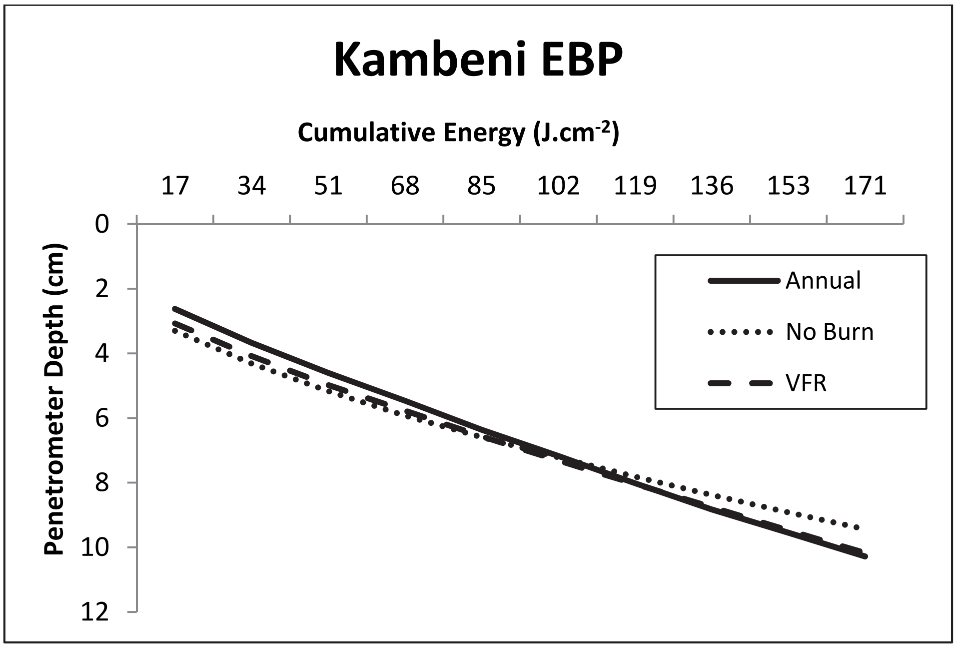

Figure 4.10 Average soil compaction measured using a drop-cone penetrometer on Kambeni EBP

Since significant differences were found, data were further analysed in order to identify where those differences lay by using a post-hoc multiple comparisons test. Based on the initial three strikes, the post-hoc analysis indicated that the shallow soil surface layer is more compacted on the annual burn plot than compared to the other fire frequencies. This finding coincides with studies by Snyman (2002, 2003) which were conducted in semi-arid grasslands in South Africa, whereby it was also found that fire resulted in compacted soils. Fire burns and removes vegetation, reduces cover and increases soil surface exposure to natural elements such as direct rain, wind and heat. The bare soil is then vulnerable to mechanical processes such as raindrop impact and splash which result in soil compaction (DeBano, 2000). However, it is difficult to conclude whether these differences in soil compaction are due to different fire regimes or due to varying herbivore densities across the plots. After a fire, the annual burn plot has a higher density of herbivores due to the improvement in grazing quality as well as the added advantage of better visibility for herbivores spotting predators (Owen-Smith, 1982).

Based on the deeper tenth strike, post-hoc analysis indicated that compaction is significantly more on the no burn plot than the burned plots. This result is the inverse of the soil surface compaction, i.e. the no burn plot was not as compacted as the burned plots. It is believed that the deeper soil layer on the no burn plot is not necessarily more compacted but rather, more structured. The deeper structured soil may be due to higher organic matter (compared to the burned plots) acting as a cementing agent binding soil aggregates (DeBano, 1990). Snyman (2002) noted that decreased soil organic matter content leads to poorly-structured soils.

Soil organic matter and water potential

Soil organic matter not only drives soil fertility but also affects how water moves through the soil matrix due to its hydrophilic properties. The organic matter, i.e. total carbon, was measured in soil samples collected across the various fire frequencies. As hypothesized, the soils on the annual burn plot had the lowest total carbon (Table 4.1). However, the results of the Kruskal-Wallis test suggested that these differences in organic matter across the different fire frequencies were not statistically significant ($H(2) = 1.260$, $P = 0.533$). It was found that only at a confidence interval of 15%, is there a significant difference between total carbon between the different fire regimes.
It is plausible that fires on these burn plots in the Pretoriuskop region of the park do not significantly alter the soil organic content because these fires are fast-moving surface fires and do not have the time required to penetrate deep into the soil. Certini (2005) established that at sites with high biomass, intense but fast-moving fires do not allow for deep heat penetration into the soil. Fast-moving fires are typical phenomena in the African savannas of KNP, thus not allowing enough contact time with the soil surface to facilitate the transfer of heat into the soil.

Table 4.1 The percentage of total carbon (organic matter) measured in the soils sampled across the different fire frequencies at Kambeni EBPs

	Annual	No Burn	VFR
Average Total Carbon (%)	1.023	1.365	1.262
Standard Deviation	0.194	0.707	0.652

The water potentials measured from the soil surfaces collected across the three contrasting fire frequencies provide a semi-quantitative interpretation of how fire may influence the water retention (or water-holding) capacities of the soils as it consumes hydrophilic organic matter. At similar water contents, the no burn plot has the lowest water potential (Figure 4.11). This is particularly true for water contents ranging 3-12 %. Statistically, it was found that mean water potentials at low water contents did not differ significantly between different fire frequencies (H (2) = 0.902; P= 0.637). Using statistical analyses to test the significance of the results is believed to be too sensitive since these water potential ranges are marginal.

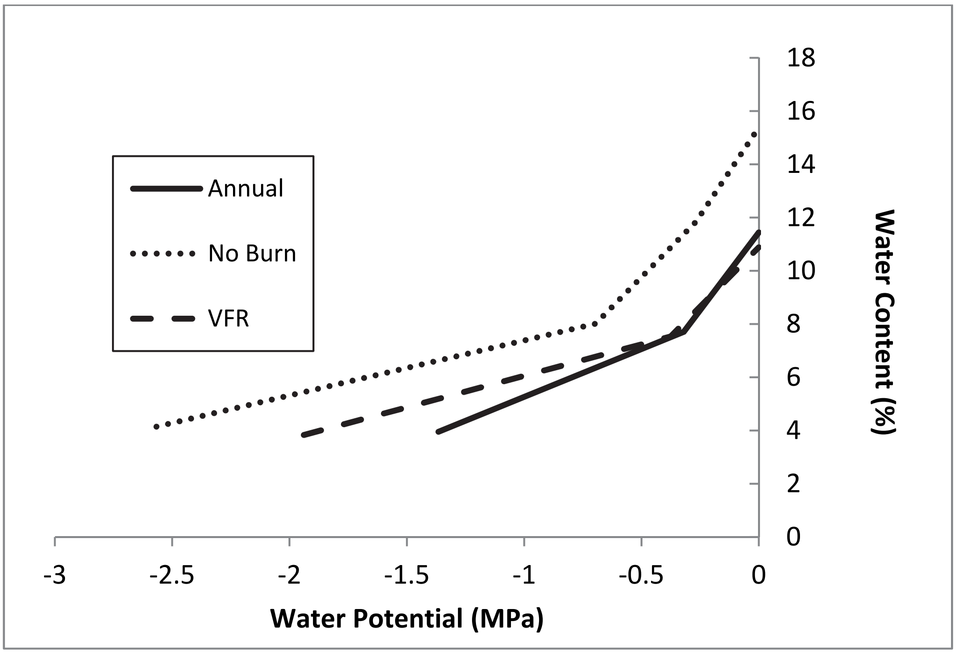

Figure 4.11 A graph providing a qualitative illustration of the water potentials across the different burn plots on Kambeni EBP

Although not statistically significant, these results suggest that on the no burn plot, water is held more tightly in the soil matrix and is less able to move freely. It is likely that this linked to higher biomass (Table 4.2) and bioactivity on this plot due to decades of fire exclusion. Laboratory observations found that some of the samples collected from the soil surface of the VFR were hydrophobic. This would explain and contribute to the slowest infiltration rates measured on this VFR plot which burned roughly three months prior to sampling.

Vegetation characteristics

Grass biomass was compared across the three fire regimes on Kambeni EBP using a DPM (Table 4.2). As expected, the fire-suppressed no burn plot had the highest biomass (2199 $kg.ha^{-1}$). A Kruskal-Wallis test found biomass to be significantly different across all the plots H (2) = 157.162, P = 0.000) (Figure 4.7). Thereafter, a post-hoc pairwise multiple comparisons test identified that the grass biomass differed between all three fire frequencies. It is likely that the greater grass biomass observed on the no burn plot is linked to the low water potential of the soil measured on the no burn plot due to the presence of hydrophilic organic matter which accumulated after > 50 years of fire suppression. Interestingly, the VFR plot which had burned more recently than the annual burn plot had a higher fuel load than the annual plot.

Table 4.2 The grass biomass measured across the varying fire frequencies at Kambeni EBPs

	Annual	No Burn	VFR
Grass Biomass (kg.ha^{-1})	984	2199	1193

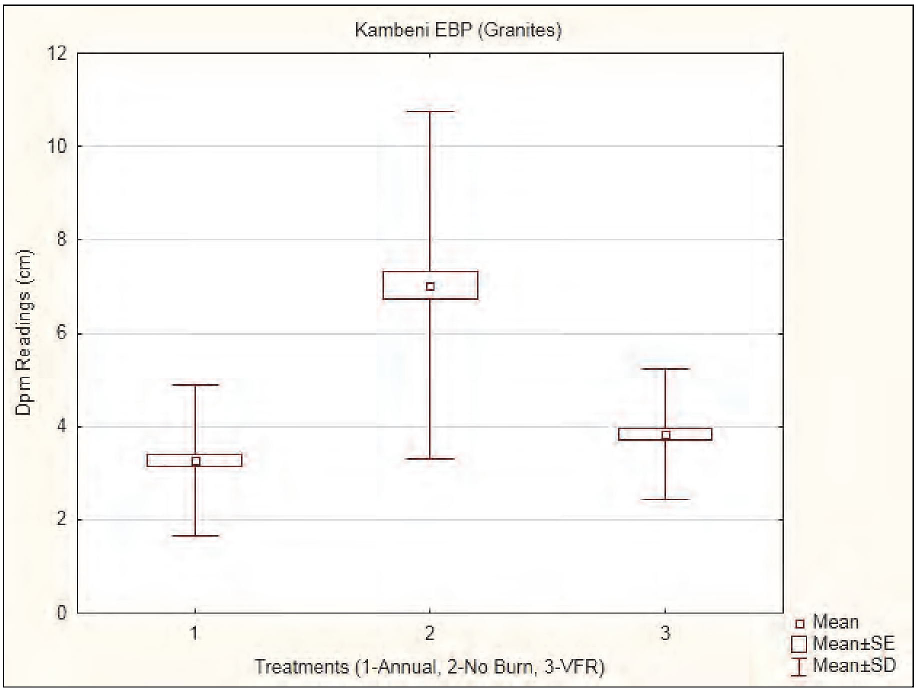

Figure 4.12 A boxplot illustrating the different means in DPM readings across the different plots

Unlike initially predicted, the no burn plot had the lowest percentage basal cover (Figure 4.13). Lower basal cover calculated for the no burn plot on Kambeni implies that the area of bare soil exposed is greatest on this plot, which is untrue. Based on field observation, this pattern would be the opposite of what was calculated, i.e. there is a higher percentage basal cover on the no burn plot. Since the fate of raindrops are influenced by vegetation, an increased amount of bare soil results in a larger area for raindrops to land and infiltrate whilst also, providing a larger evaporative surface area whereby water can be lost to the atmosphere.

Two possible reasons for this confusing finding are provided. Firstly, this is due to the fact that fire exclusion for > 50 years has disturbed the co-existence between trees and grasses, favouring trees rather than grasses on these plots. Some studies conducted in African savannas found that grasses benefit from fires because trees are greatly impacted and grasses can recover and re-establish more quickly due to less competition with trees and simpler life-history strategies (Higgins *et al.*, 2000; Smit *et al.*, 2010). Thus, since fire has been suppressed for many decades, it is possible that grasses may not be able to compete with trees for resources. The second possible explanation is that the formula provided by Hardy and Tainton (1993) (Equation 3.8) to calculate basal cover may not be applicable to this particular environment. Hardy and Tainton (1993) developed their formula based on a study conducted in the grasslands of South Africa whereas the Kambeni EBPs are a fire-manipulated area situated in a lower rainfall region dominated by woody vegetation such as *Dichrostachys cinerea* and *Terminalia sericea*. Thus, the proportions of trees and grasses would differ between the two biomes.

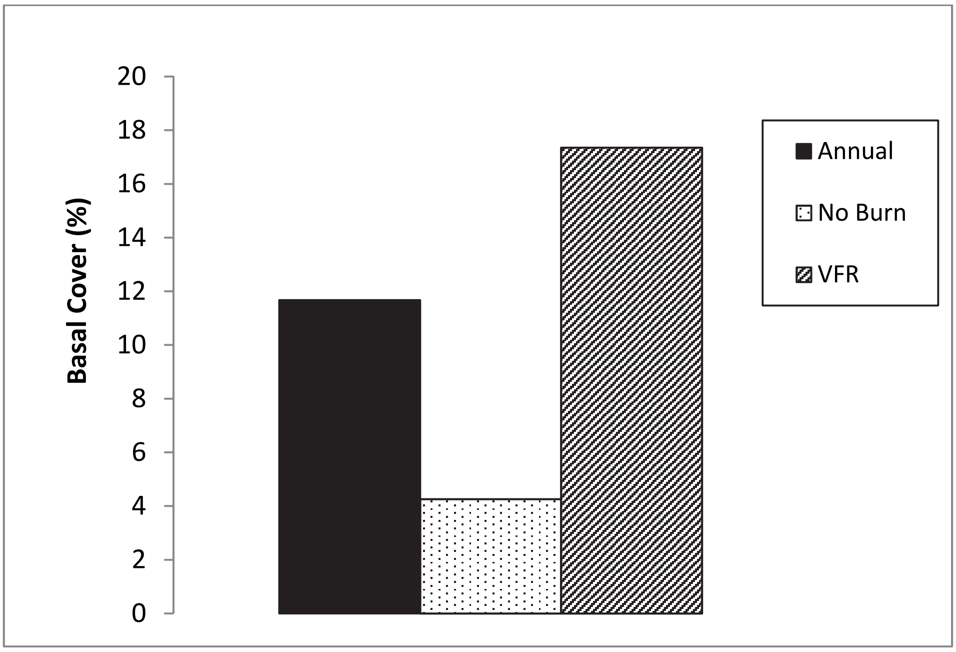

Figure 4.13 Bar graph illustrating the difference in basal cover across the different fire regimes on Kambeni EBPs

4.1.2 Basalts

The N'wanetsi EBPs are situated on the basalts in the central region of KNP, near Satara (refer to Figure 2.1). The dominant soil types on these burn plots are Shortlands and Swartland (refer to Figure 2.4). Data was collected on N'wanetsi towards the end of the wet season in May 2013. Similar to the Kambeni EBPs (granites), the study included an area outside of the EBP string that accounted for the effect of a more "variable" fire frequency (VFR) on soil properties. Therefore, data collections were concentrated on the annual burn and no burn plots as well as outside of the experimental burn plots (refer to Table 3.1). For all statistical analyses, the confidence interval is set at 95% (except where otherwise stated).

(i) N'wanetsi EBPs

Unsaturated hydraulic conductivity (K_{unsat})

Under both tensions, i.e. 5 mm (Figure 4.14) and 30 mm (Figure 4.15), the graphs suggest a similar K_{unsat} across the three fire treatments. Furthermore, a non-parametric Kruskal-Wallis test suggests that there is no significant difference in K_{unsat}, under 5 mm suction, across the three fire regimes ($H(2) = 1.463$, $P = 0.481$). Similarly under 30 mm suction, there is no significant difference in K_{unsat} across the different fire regimes ($H(2) = 2.468$, $P = 0.291$).

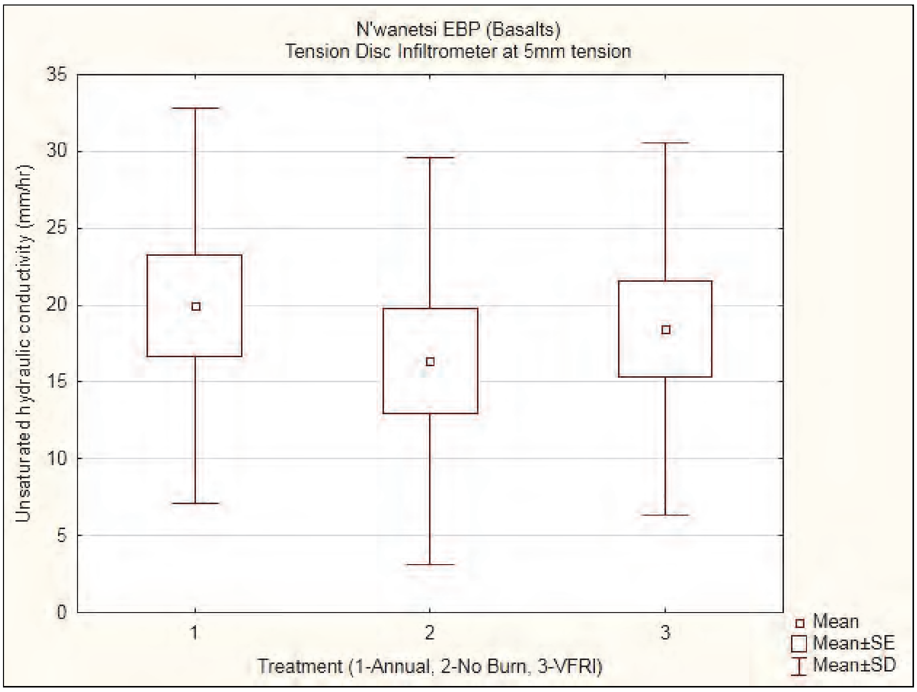

Figure 4.14 Box-whisker plots illustrating the K_{unsat} (mm/h) measured under different fire treatments at N'wanetsi burn plots under a tension of 5 mm

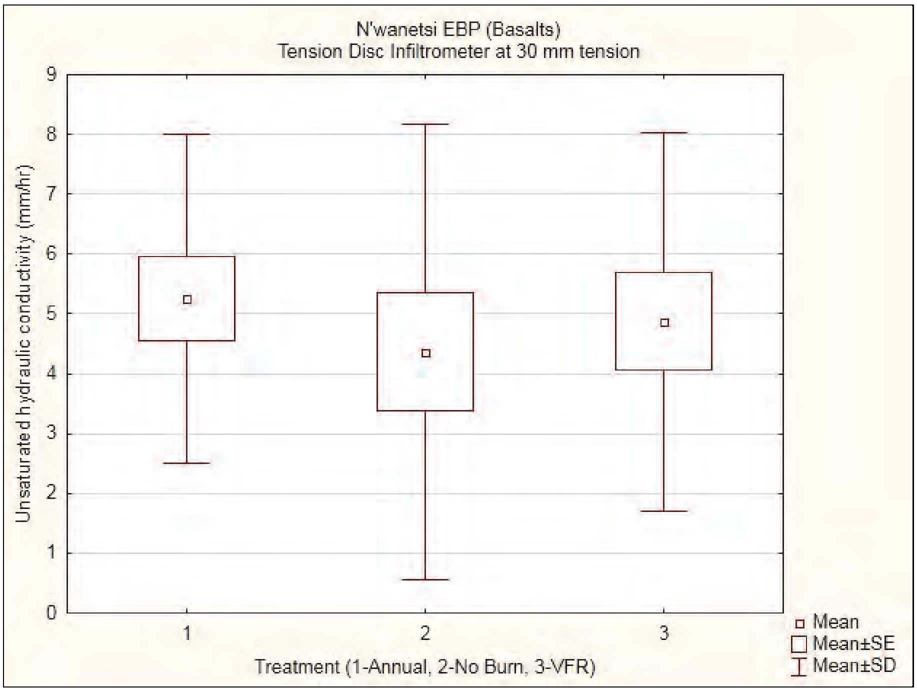

Figure 4.15 Box-whisker plots illustrating the mean K_{unsat} (mm/h) measured on the basaltic N'wanetsi burn plots under a suction head of 30 mm

Results indicated that there was no significant difference in K_{unsat} across the three different fire regimes. For the last few years (± 7), this annual plot has not been fully burned due to insufficient fuel loads to support the prescribed fires. However, when the plot did burn, it only burned in a very patchy manner. The low biomass measurements as well as the low basal cover, measured on the annual burn plot, would lead to such fire behaviour.

Even though the VFR plot outside the EBPs burned more recently than the annual burn plot, both had burned more than 1.5 years before this study (refer to Table 3.1). Based on the theory suggested previously that fire effects are most pronounced immediately after a fire and that these effects dissipate over time, it seems logical why all three plots had similar infiltration rates.

<u>Saturated hydraulic conductivity</u> (K_{sat})

At a depth of 2-3 cm below the soil surface, a Kruskal-Wallis test found that there was no significant difference in K_{sat} across the different fire treatments (H (2) = 5.791, P = 0.055) (refer to Figure 4.16). Furthermore, there was also no significant difference in K_{sat} 5-7 cm below the soil surface (H (2) = 4.431, P = 0.109) (refer to Figure 4.17). The variability in the data is however quite distinct and interesting. The variability is greater on the VFR plot than on the other two plots, especially the annual plot. It is speculated that this variance is due to the homogenous vegetation cover on the annual and no burn plots. In addition to the heterogeneous vegetation cover on the VFR plot, the fires which burn across this area will naturally induce variability. Alternatively, the fire which burned across the VFR area could have resulted in the decay of root networks which lead to preferential pathways.

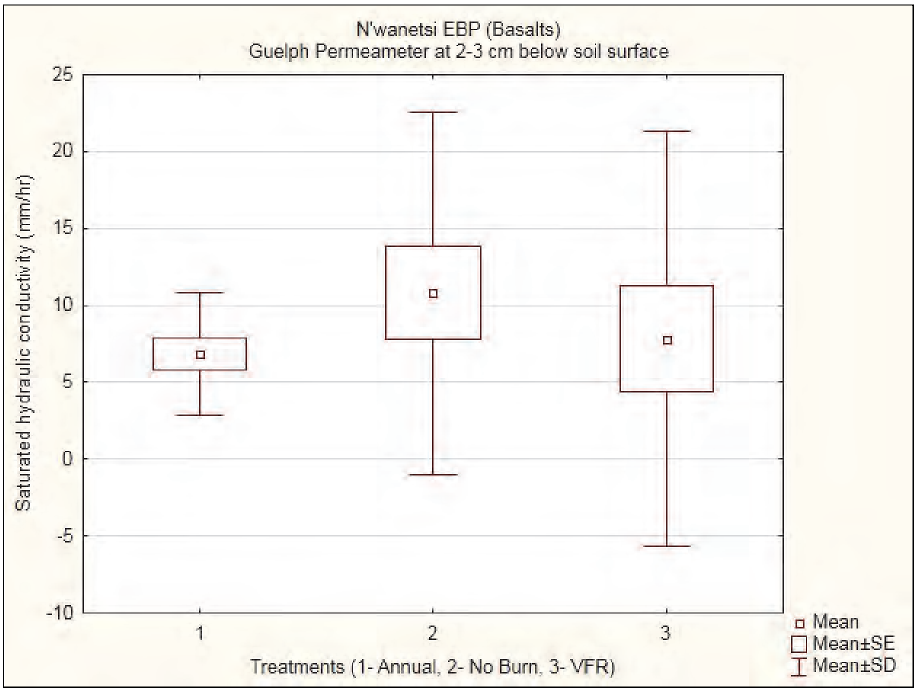

Figure 4.16 Box-whisker plots describing K_{sat} (mm/h) at a depth of 2-3 cm below soil surface across various fire treatments on N’wanetsi EBP

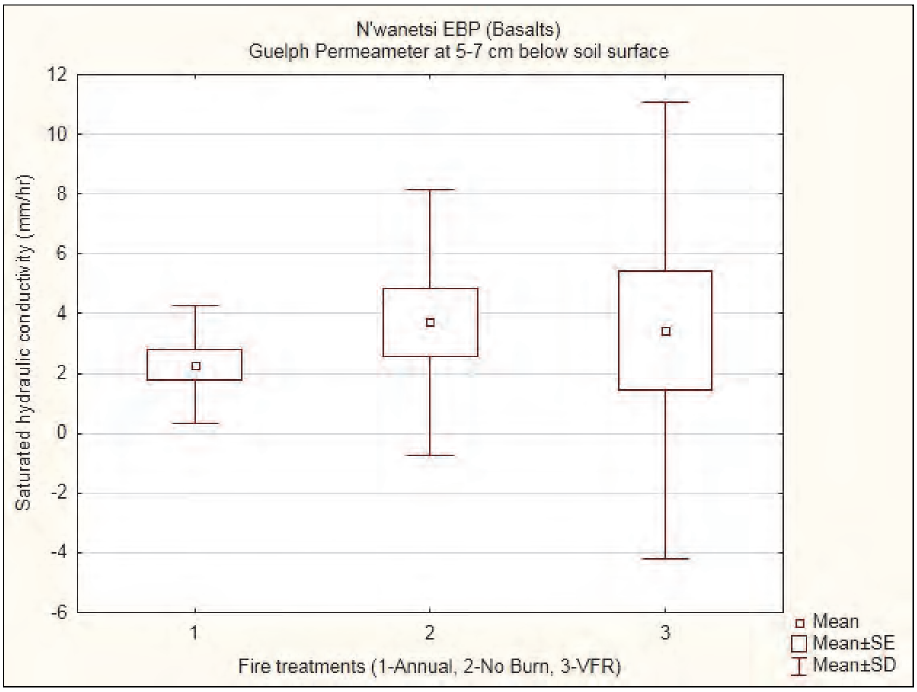

Figure 4.17 Box-whisker plots describing the K_{sat} (mm/h) measured at N'wanetsi at a depth of 5-7 cm below the soil surface

Soil compaction

Results indicate that the annual burn plot is the most compacted (Figure 4.18). The mean penetrometer depth for the initial three strikes were compared across the different burn plots to account for the pedoderm (< 3 cm) and to identify shallow surface compaction while the final tenth strike was analysed to account for deeper layers of the A-horizon and to distinguish whether the subsurface soil was also compacted (± 5 cm). The Kruskal-Wallis tests revealed that the mean penetrometer depths for all three initial strikes as well as the tenth (final) strike were significantly different across the varying fire frequencies and no burn plot. Post-hoc multiple comparisons tests where used to identify where these differences lied. The multiple comparisons tests established that the difference was significant between the annual and the no burn plots as well as between the annual and VFR plots.

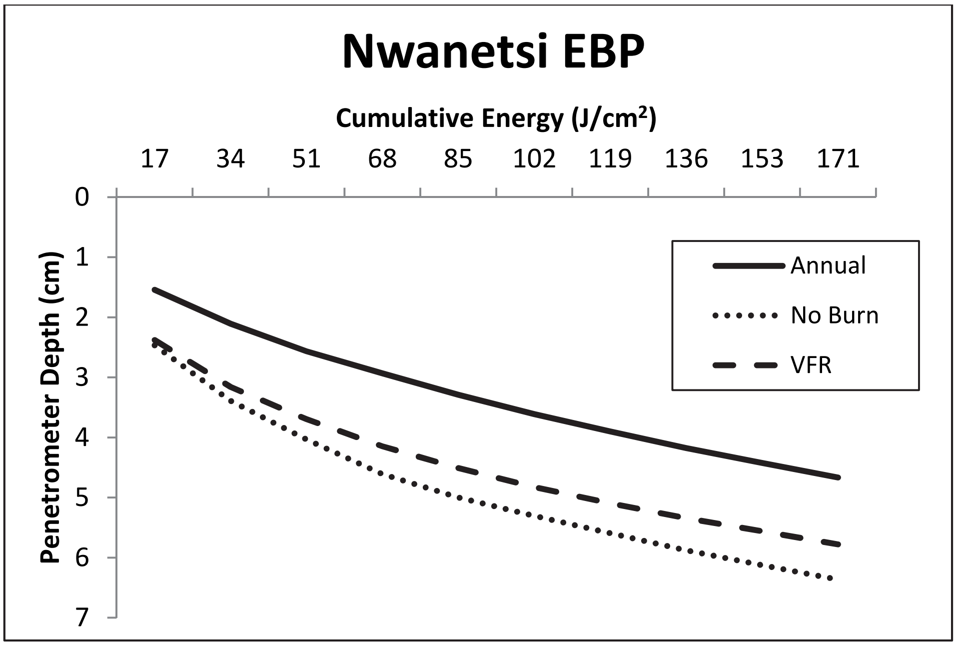

Figure 4.18 Penetrometer measurements collected on the N'wanetsi EBP indicating the compaction of the soil across the different fire treatments

The findings illustrated in Figure 4.18 suggest that the soil on the annual burn plot is more compacted than the VFR and no burn plots. This coincides with the results obtained on the granites (Kambeni EBPs) as well as previous studies by Riddell *et al.* (2012) and by Snyman (2002, 2003) which were also conducted in semi-arid landscapes in South Africa. It is understood that a greater area of soil surfaces is exposed to the elements once a fire burns and denudes an area of vegetation cover. Thus, the bare soil surfaces become susceptible to compaction due to soil processes such as raindrop impact and splash (DeBano, 2000).

Literature (e.g. Cerda *et al.*, 1995; DeBano, 2000; Ice *et al.,* 2004; Mills and Fey, 2003; Snyman, 2003) suggested that fire would lead to a more compacted soil surface. However, it was later discovered that for the last seven years the annual burn plot did not burn as frequently as it should have due to low biomass which could not support the fires. This discovery creates concern regarding the absence of fire yet the exposure to a high density of herbivores on the annual burn plot. Herbivores often congregate on the plots after the prescribed fire in August due to improved grazing quality and better visibility against predators (Owen-Smith, 1982). In addition, this plot is in close proximity to a watering hole and would provide further motivation for animals to congregate on this plot. The herbivore exclosures erected on the annual and no burn plots were used to determine the effect of herbivores on soil compaction.

The penetrometer data collected inside and outside the herbivore exclosures on N'wanetsi EBPs did not have a normal distribution thus a non-parametric, Mann-Whitney U test was used in order to test for any significant differences in mean penetrometer depths. The results from penetrometer readings collected both outside and inside herbivore exclosures on the annual and no burn plots revealed that soil is more compacted outside the herbivore exclosures (U = 137.5, P = 0.000 and U = 149, P = 0.000, respectively) (refer to Figure 4.19). Similar results were found for the deeper tenth strike. These results imply that the effect of herbivore trampling on subsurface compaction has a greater impact than the effect of fire considering that subsurface compaction was even found on the no burn plot. The effects were observed to a minimum soil depth of 4.5 cm.

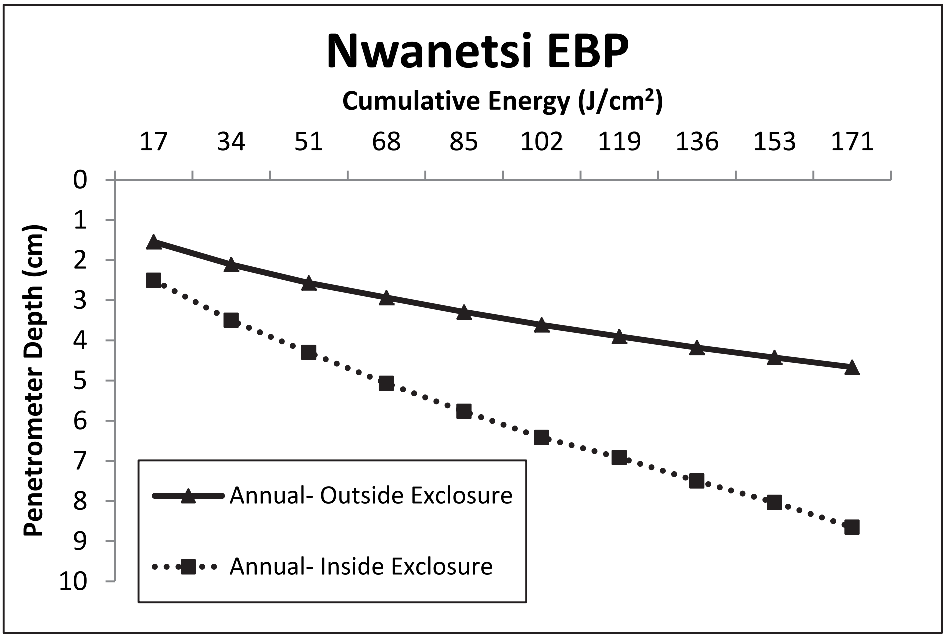

Figure 4.19 Penetrometer measurements collected on the N'wanetsi annual burn plot indicating the compaction of the soil outside and inside herbivore exclosures

In order to determine, solely, what the effect of fire on soil compaction is, penetrometer readings collected in the herbivore exclosures across the annual and no burn fire treatments were compared. Since data was not normally distributed, a non-parametric Mann-Whitney U test was applied to test for significant differences in mean soil compaction across the different fire frequencies (without the influence of herbivores). Results indicated that even when herbivores are excluded from the system, fire still impacts soil surface compaction where the annual plot had a more compacted and sealed soil surface than the no burn plot (U = 28, P = 0.000). These marked differences were observed beyond the soil surface. Thus in the absence of herbivores, fires lead to disturbed soil surfaces which are sealed and compacted due to processes such as raindrop impact and splash resulting from reduced protection by vegetation cover (DeBano, 2000).

Soil organic matter and water potential

Results presented in Table 4.3 indicate that the soils on the annual burn plot had the lowest total carbon. The Kruskal-Wallis results suggested that these differences in organic matter across the different fire frequencies were statistically significant (H (2) = 29.337, P = 0.000). As a result of decades of fire exclusion, the above-ground biomass is greatest on the no burn plot and likely contributing to the increased soil organic matter measured on this fire-suppressed plot.

Table 4.3 The percentage of total carbon (organic matter) measured in the soils sampled across the different fire frequencies at N'wanetsi EBPs

	Annual	No Burn	VFR
Average Total Carbon (%)	2.105	3.561	2.24
Standard Deviation	0.407	0.455	0.342

At similar water contents, the no burn plot has the lowest water potential (Figure 4.20). This is particularly true for water contents ranging 2-10 %. The Kruskal-Wallis found that soil water potentials did not differ significantly between different fire frequencies (H (2) = 1.800; P= 0.407). These results coincide with the granite EBPs (Kambeni) results which also suggested that on the no burn plot, water is held tightly in the soil matrix and is less able to move freely. It is speculated that due to many years of fire suppression on the no burn plot, there is a greater concentration of biomass and consequently more organic matter on this plot in relation to the other plots exposed to fires. Soil organic matter is known to be hydrophilic due to the strong attraction between water molecules and the charged polar sites on organic matter (Schaetzl and Anderson, 2005).

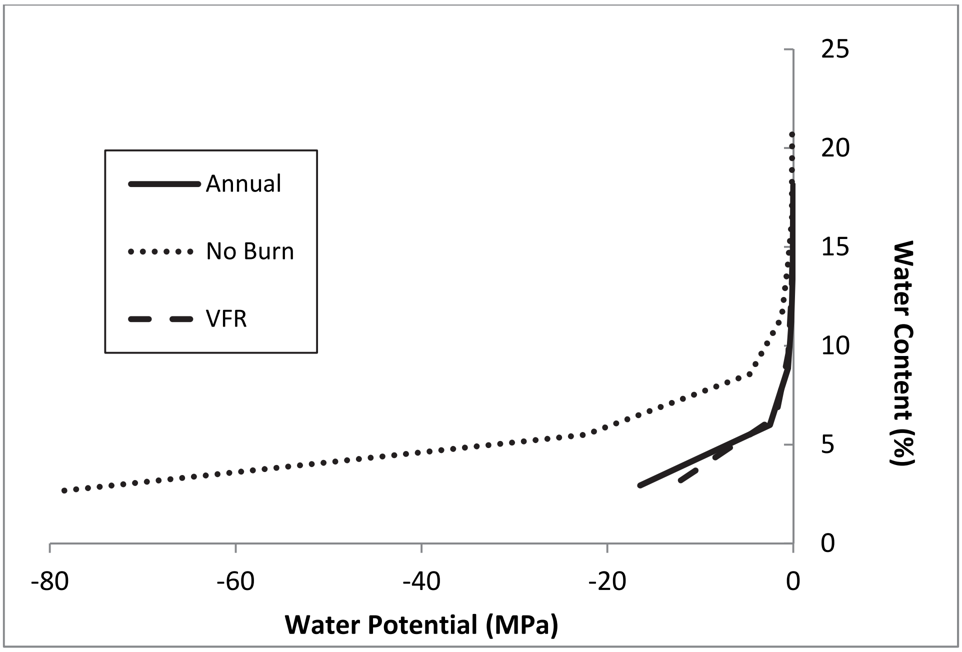

Figure 4.20 A graph providing a qualitative illustration of the water potentials across the different burn plots on the basaltic N'wanetsi EBPs

<u>Vegetation characteristics</u>

Results from a Kruskal-Wallis test indicated that the fire-suppressed no burn plot had a significantly higher grass biomass than the other two fire treatments (H (2) = 176.041, P = 0.000) (Table 4.4). The post-hoc pairwise multiple comparisons test revealed that all the plots were significantly different to one another. It is interesting to note that the lowest biomass was measured on the annual plot which had the unsuccessful fires which were prescribed for the past seven years.

Table 4.4 The grass biomass measured across the different fire frequencies at N'wanetsi EBPs

	Annual	No Burn	VFR
Grass Biomass ($kg.ha^{-1}$)	1734	4119	2990

As expected, basal cover is lower on the annual plot than the no burn plot (Figure 4.21). However, basal cover is lowest on the VFR plot which may be due to the VFR plot burning more frequently than the annual plot since the annual plot has been unable to support a prescribed fire for roughly the last 7 years (since 2006). It is interesting that in basaltic regions of KNP, the formula (Equation 3.8) provided by Hardy and Tainton (1993) is applicable unlike on the EBPs in the granites. Since Hardy and Tainton (1993) conducted their study in a South African grassland, it is likely that their formula would be suitable to the *Sclerocarya birrea caffra/ Acacia nigrescens* Savanna in Satara due to the lower proportion of trees in the landscape whereas the granites are classified as the Lowveld Sour Bushveld which had more woody vegetation than the Satara section (Smit *et al*., 2010).

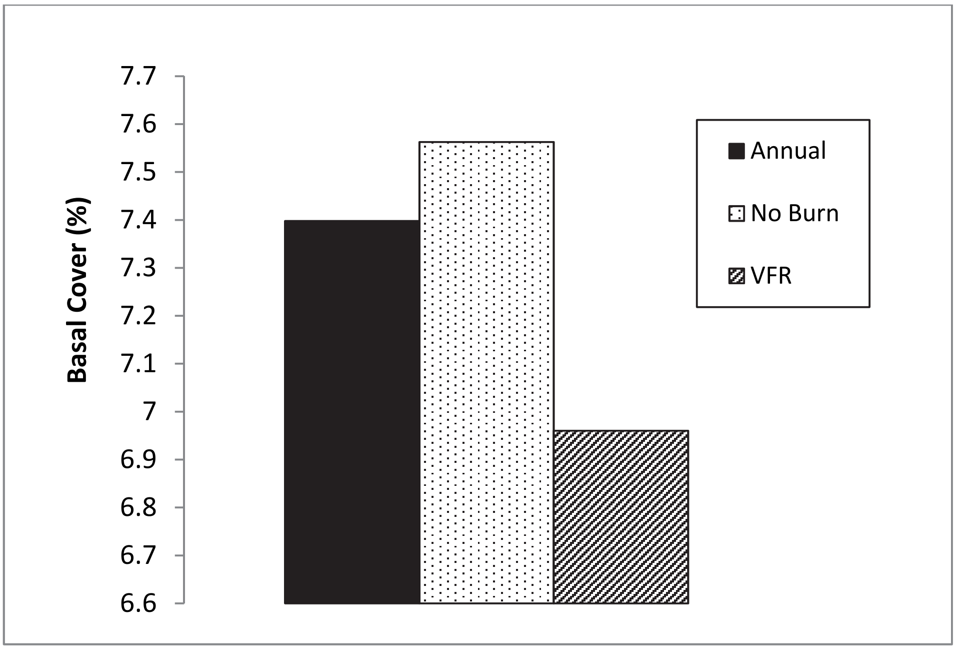

Figure 4.21 The difference in basal cover across the different fire regimes on the N'wanetsi EBPS

4.2 Runoff and Sediment Yield Analyses

This experiment compared the amount of runoff and sediment yield generated from two different rainfall intensities on the burn plots on the granitic Numbi and Kambeni EBP strings of Pretoriuskop (refer to Table 3.1). Based on the impacts that fire has on the landscape, it was hypothesised that more runoff and subsequently more sediment yield would be generated from the annually burned plots compared to the fire-suppressed (no burn) plots.

4.2.1 Runoff

The runoff data was found to be best expressed as an average of all the data points collected from each EBP on the two strings, therefore allowing clear comparisons to be made. The following acronyms will be used in the figures below:

NA_R- Numbi annual runoff,
NNB_R- Numbi no burn runoff,
KA_R- Kambeni annual runoff, and
KNB_R- Kambeni no burn runoff.

As hypothesised, the trends displayed in Figure 4.22 suggest that more runoff is generated on the annual plots (NA_R and KA_R) than the no burn plots (NNB_R and KNB_R). Even though the cumulative runoff scale is very small, in reality the differences in cumulative runoff between all four plots are quite substantial given that these amounts will yield significant volumes of water through an entire catchment (on a larger scale). Thus, fire management seems to have quite an impact on the amount of runoff generated when a rainfall intensity of 157 mm/h is applied for 10 minutes.

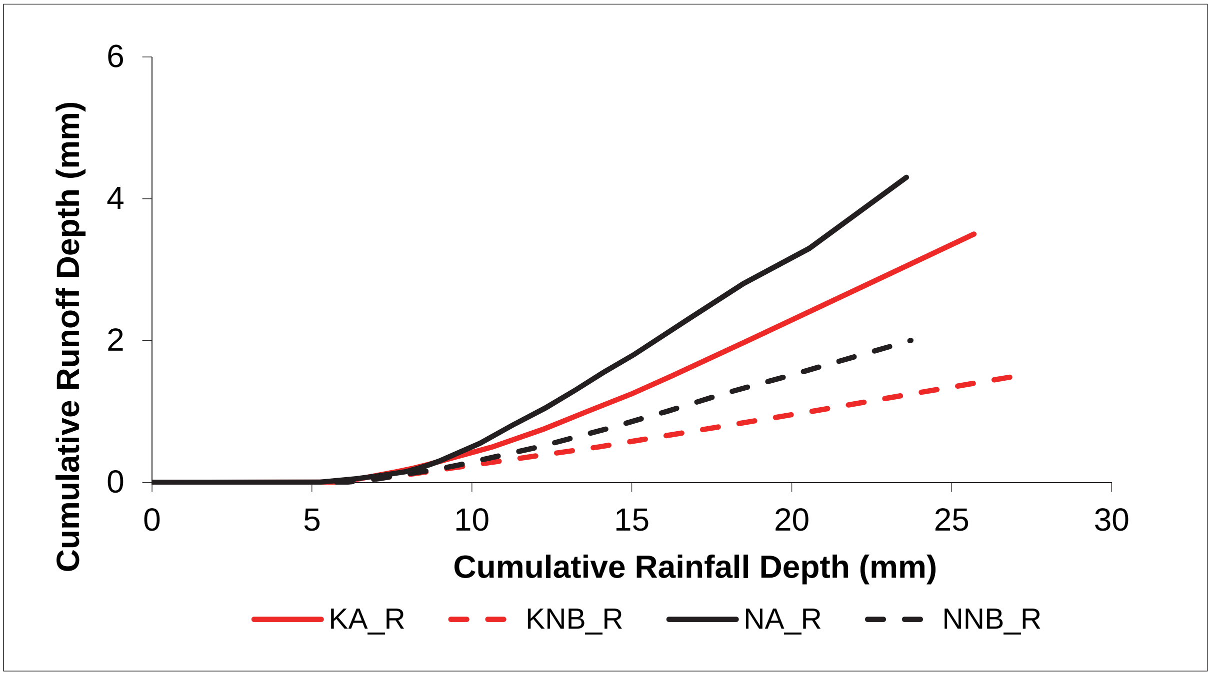

Figure 4.22 Average rainfall-runoff relationship for the Numbi and Kambeni annual and no burn plots at a rainfall intensity of 157 mm/h

Compared to the 157 mm/h rainfall intensity observed previously, there is a greater difference in the cumulative runoff depth between the annual and no burn plots at a rainfall intensity of 200 mm/h (Figure 4.23). Under the 200 mm/h rainfall intensity, the cumulative runoff depth for the Numbi and Kambeni annual plots are similar whilst there is a clear difference between the Numbi and Kambeni no burn plots. This distinction may be attributed to the runaway fire which burned across the Numbi no burn plot in September 2012. While the 157 mm/h rainfall simulation acknowledges that annually burned plots generates more runoff than the no burn plots, when rainfall intensity was increased to 200 mm/h the fire effects on runoff generation is greater. The amount of runoff generated during the subsequently higher intensity rainfall simulation was greater than the initial 157 mm/h.

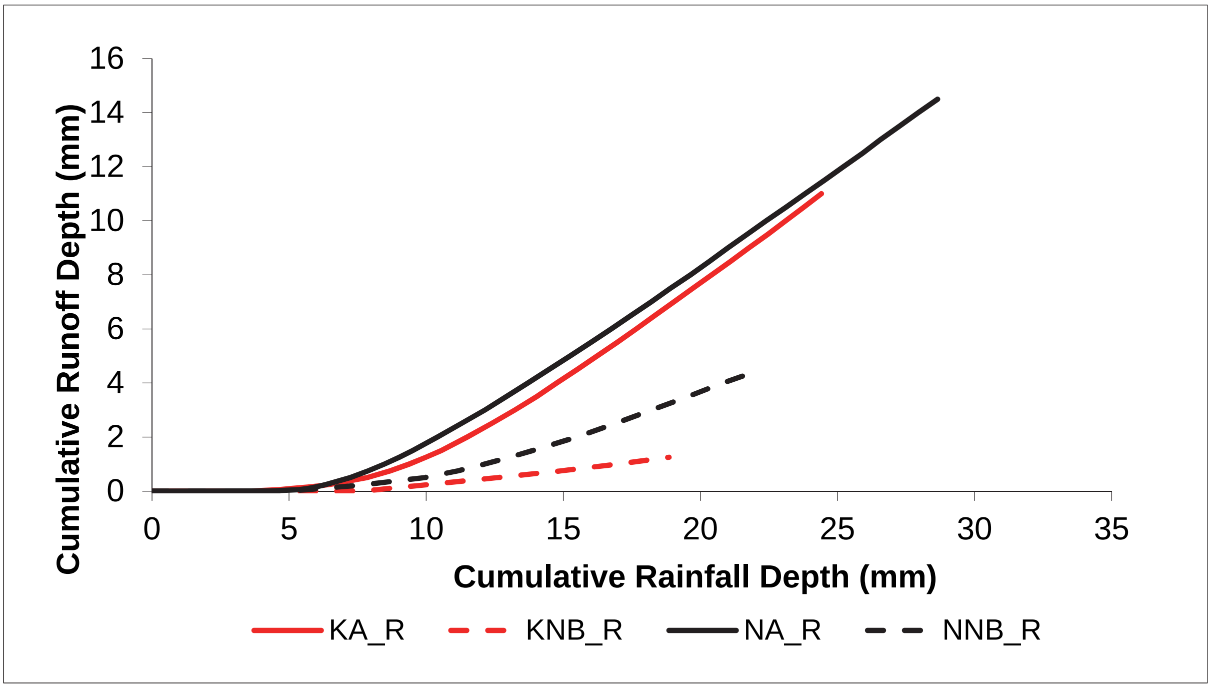

Figure 4.23 Average rainfall/runoff relationship for the Kambeni and Numbi annual and no burn plots at a rainfall intensity of 200 mm/h

In both Figures 4.23 and 4.24, the annual plots generated greater runoff rates than the no burn plots. As expected, higher runoff rates are experienced under the higher 200 mm/h rainfall intensity. The annual burn plots compared between the Numbi and Kambeni strings have similar runoff rates yet the no burn plots are very distinct. This highlights the effect that the recent runaway fire at the Numbi no burn plot has had on the soil and resulting in different runoff rates. It is interesting to note that it is only under the higher, subsequent rainfall intensity (200 mm/h) that these trends emerge. It is believed that under the initial lower intensity (157 mm/h) the plots are confounded with differences in soil moisture but when the higher rainfall intensity (200 mm/h) is applied 24 hours later, soil moisture has equilibrated thus allowing for such discrete trends to be detected.

Under a rainfall intensity of 157 mm/h (Figure 4.24), the onset of runoff for all four plots occurred roughly simultaneously (±130 sec) although slight faster on the annual plots. Similarly with an intensity of 200 mm/h (Figure 4.25), the onset of runoff is slightly faster on the annual burn plots. This is likely due to less vegetation intercepting rainfall as well as less vegetation allowing water to infiltrate through preferential pathways.

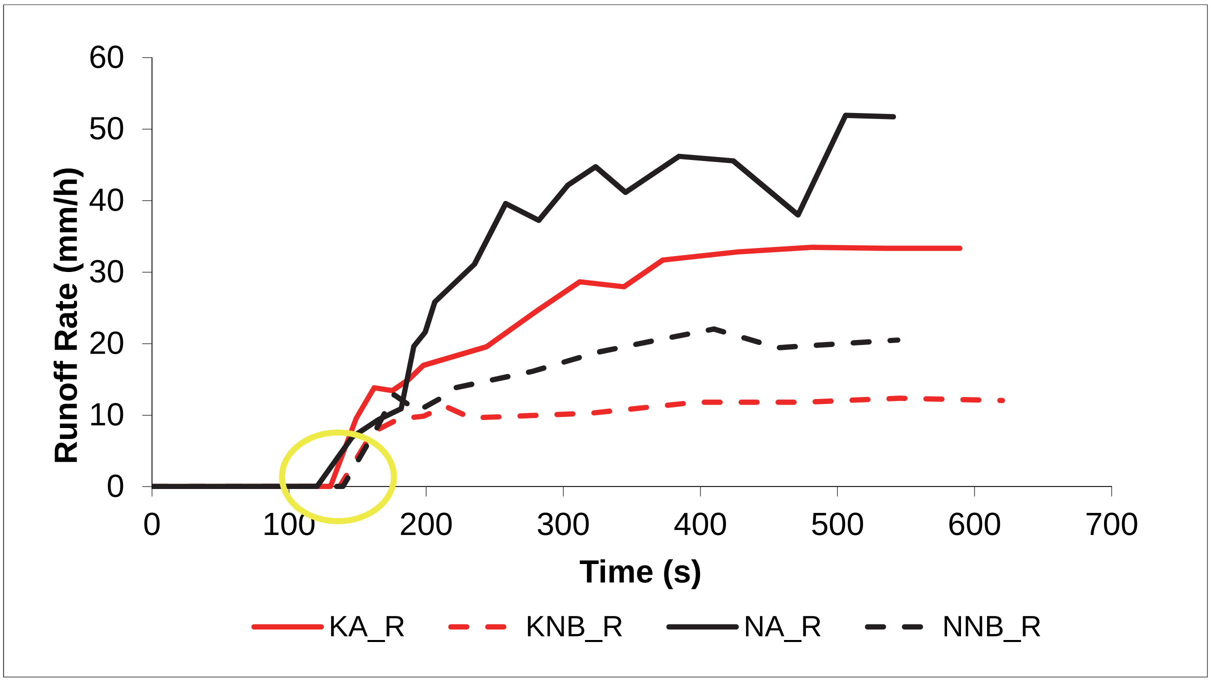

Figure 4.24 Average runoff rate versus time for the Kambeni and Numbi annual and no burn plots at a rainfall intensity of 157 mm/h

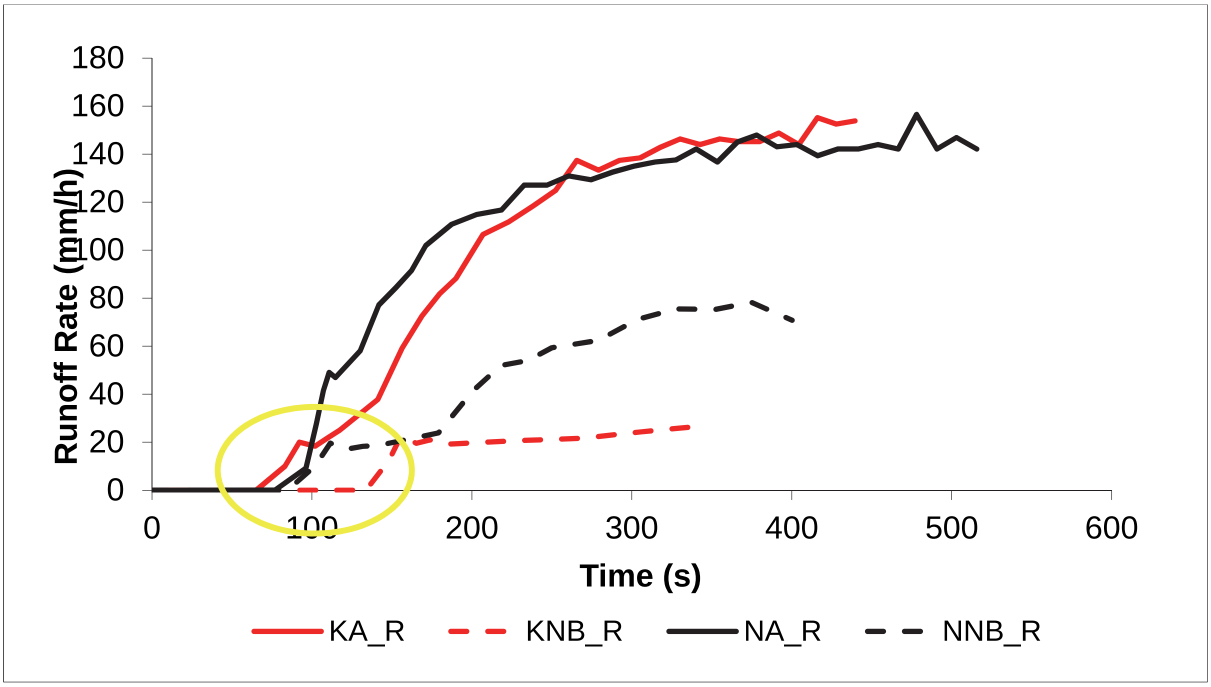

Figure 4.25 Average runoff rate versus time for the Kambeni and Numbi annual and no burn plots at a rainfall intensity of 200 mm/h

4.2.2 Sediment yield

Unlike initially hypothesized, the fire-suppressed no burn plots generally yielded more sediments than the annual plots (Figure 4.26). This is particularly surprising since it was identified that more runoff was generated from the annual plots under both rainfall intensities. It is thought that more sediment would be yielded off the no burn plot due to the compacted soil on the annual plot cementing soil particles and making it difficult to dislodge. The following acronyms were used in the figure below:

NA- Numbi annual at 200 mm/h;
NNB- Numbi no burn at 200 mm/h;
KA- Kambeni annual at 200 mm/h; and
KNB- Kambeni no burn at 200 mm/h.

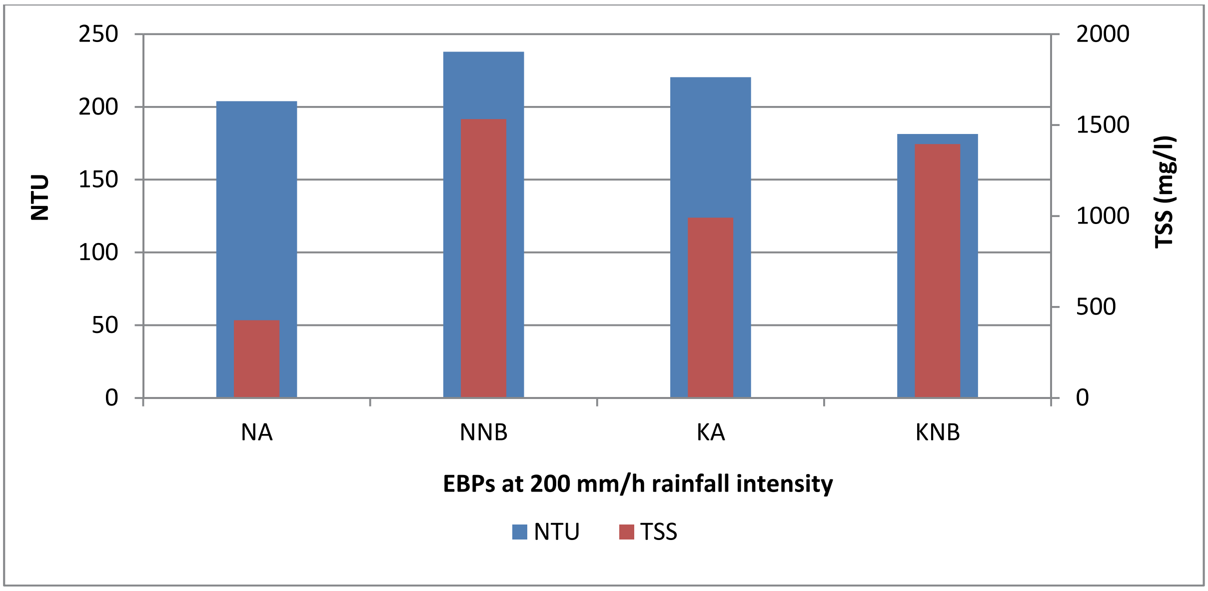

Figure 4.26 Sediment yield measured using both Nephelometric Turbidity Units (NTU's) and Total Suspended Solids (TSS)

4.3 Soil Water Balance

4.3.1 Granites

(i) SEBAL Cumulative Actual Evapotranspiration (aET) Analysis

Analysis of the SEBAL data was performed as this directly influences the mass balance comparisons between the varying historical fire regimes. Varying fire regimes are expected to render different vegetation densities and compositions, hence contrasting evapotranspiration totals (Bijker *et al.*, 2001 and Oliveira *et al.*, 2005). Initial analysis of the granitic EBPs revealed that at the beginning of the modelling period, low weekly totals for aET were obtained from the SEBAL data. These raster images displayed dark black areas within the image as extremely low evapotranspiration amounts, both in and around the granitic EBPs of

Pretoriuskop (including the basaltic EBPs in Satara) (Appendix B: Figure 9.1). Further investigation revealed that a runaway fire occurred during this period, October 2012, and burned several hectares surrounding many of the EBPs. This likely resulted in the low pixel values obtained at the beginning of the Pretoriuskop modelling period. The granitic EBPs affected by the runaway fire included both the annual and no burn plots at Numbi and the VFR plot at Kambeni.

The granitic Numbi (Figure 4.27) and Kambeni (Figure 4.28) EBPs of Pretoriuskop initially had very similar cumulative aET amounts. In particular, the VFR plot on Kambeni displayed a slightly higher cumulative aET value compared to the annual and no burn plots. The Numbi EBPs suggested more obvious differences in cumulative aET, whereby the no burn plot more aET than the annual EBP.

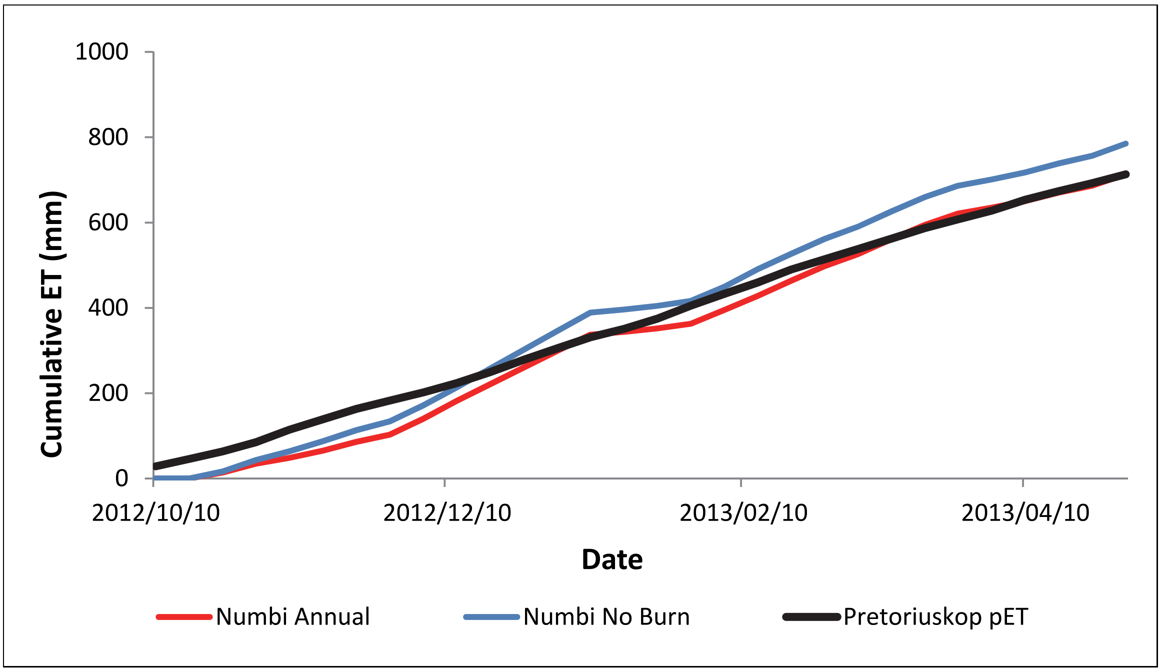

Figure 4.27 Cumulative weekly aET for the Numbi EBPs of Pretoriuskop (granites) and the pET for the region

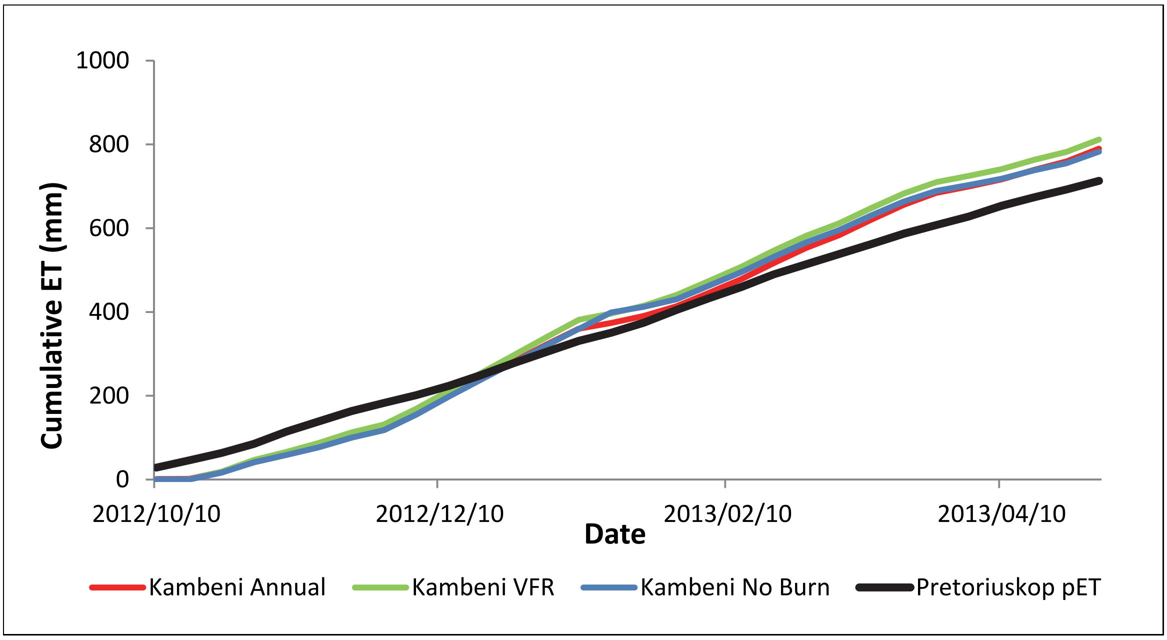

Figure 4.28 Cumulative weekly aET for the Kambeni EBPs (granites) and the pET expected for the Pretoriuskop region

(ii) HYDRUS Analyses

The instantaneous ET rate (mm/h) was obtained from the v_Mean output file, where the HYDRUS model calculates all the fluxes into and out of the domain at each iteration time step.

Results suggest that the no burn plot at Numbi has a higher ET rate compared to the annual burn plot (Figure 4.29). For the Kambeni EBPs (Figure 4.30), the ET rate is generally very similar for the annual and VFR plots. The no burn EBP, however, displayed noticeably lower ET rates compared to both the VFR and annual EBPs. Interestingly, the ET is linked to rainfall whereby higher ET rates were observed after rainfall events on both EBP strings.

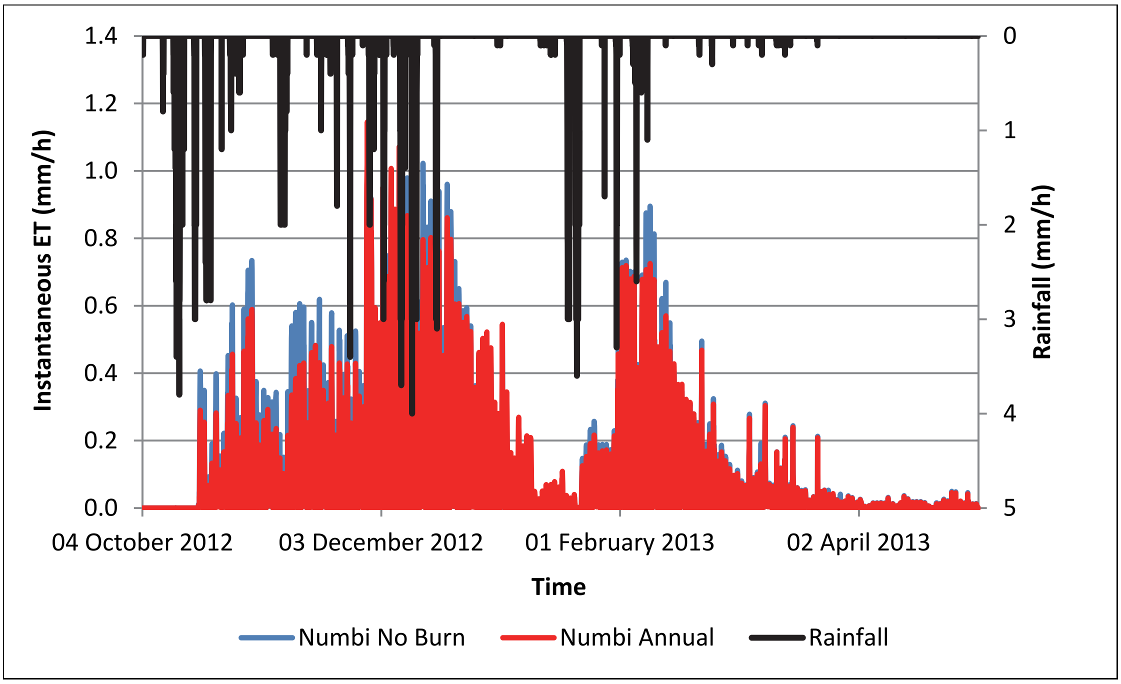

Figure 4.29 Numbi instantaneous evapotranspiration rate comparisons and the rainfall rate

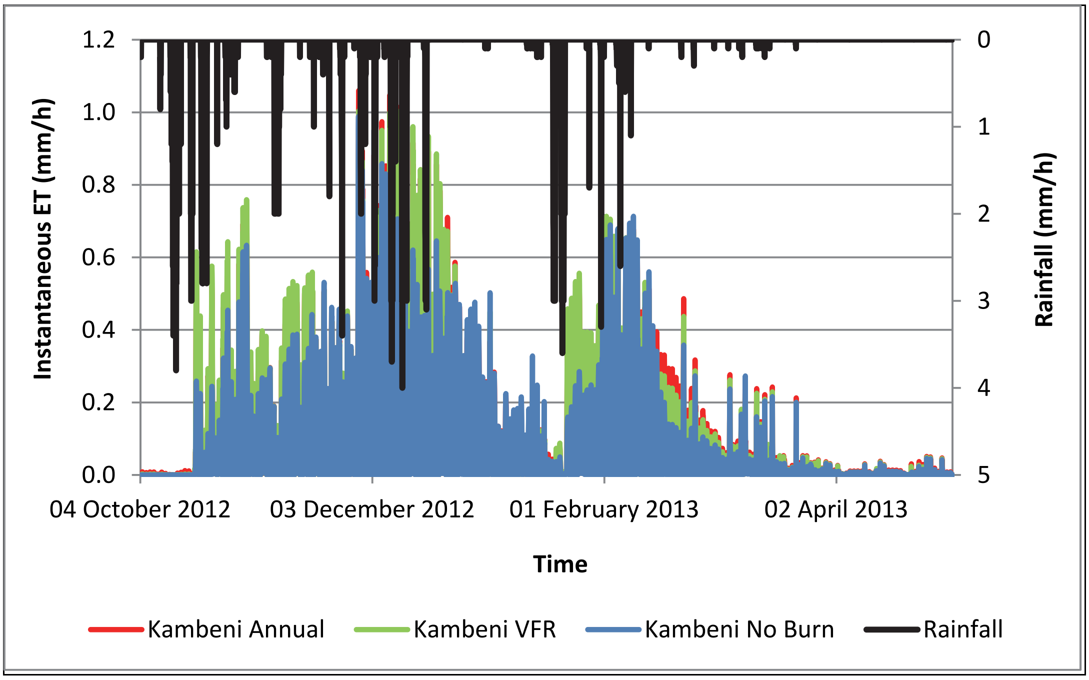

Figure 4.30 Kambeni Instantaneous evapotranspiration rate comparisons and the rainfall rate

Mass balance information was computed from the cumulative data calculated by the HYDRUS 3D model (Tables 4.5 and 4.6) for the granitic EBPs using Equation 3.12. In order to standardise the change in water storage to a flux in millimetres (mm), the volume of water was divided by the area of each domain (EBP area).

It is important to note that the depth of rainfall as a flux in mm is consistent for all the plots of the respective Pretoriuskop and Satara EBPs. However, because each EBP domain or area has different sizes, the volume of water (e.g. rainfall in mm^3) infiltrating into each domain is different, and thus resulting in differences in precipitation (P) under the mm^3 and m^3 columns of each EBP. Therefore for clarity and comparison, all values were converted to fluxes.

The annual burn plot on the Numbi string (Table 4.5) had a greater change in storage on a standard depth basis compared to the Numbi no burn plot. This increased change in storage on the annual plot may be attributed to a lower cumulative ET and subsequently increased drainage out of the soil domain.

Table 4.5 Numbi EBP mass balance information

	Numbi No Burn			Numbi Annual		
	mm^3	m^3	mm	mm^3	m^3	mm
FD	3570000000000	3570	46	5960000000000	5960	89
ET	31650000000000	31650	411	24840000000000	24840	370
P	34900000000000	34900	453	30300000000000	30300	453
R	0	0	0	10400000	0	0
ΔS	-320000000000	-320	-4	-500010400000	-500	-6

On a standard depth basis, the Kambeni no burn plot had the greatest change in storage (Table 4.6). This change in storage was so pronounced because the cumulative ET was considerably lower than the annual and VFR plots. Subsequently, the cumulative drainage out of the no burn plot was considerably higher than that of the annual and VFR plots, while the rainfall remained the same for all the plots (Table 4.6). Interestingly, the annual and VFR plots had higher ET than the no burn plots. This is believed to have been due to the accidental fire which burned the VFR plot and areas surrounding the annual plot where vegetation would be growing extensively in order to recover from this fire.

Table 4.6 Kambeni mass balance information

	Kambeni No Burn			Kambeni Annual			Kambeni VFR		
	mm^3	m^3	mm	mm^3	m^3	mm	mm^3	m^3	mm
FD	6960000000000	6960	135	3690000000000	3690	46	2540000000000	2540	47
ET	16970000000000	16970	330	33290000000000	33290	411	21930000000000	21930	407
P	23300000000000	23300	453	36700000000000	36700	453	24400000000000	24400	453
R	61900000	0	0	0	0	0	3150000	0	0
ΔS	-630061900000	-630	-12	-280000000000	-280	-4	-70003150000	-70	-1

4.3.2 Basalts

(i) SEBAL Cumulative Actual Evapotranspiration (aET) Analysis

Figure 4.31 and Figure 4.32 reveals clear differences in cumulative aET between the various burning regimes for N'wanetsi and Satara, respectively. The N'wanetsi no burn plot displayed higher cumulative aET compared to the VFR, and the VFR area in-turn displayed greater cumulative aET than the annual EBP. Unexpectedly, the annual EBP of Satara had a higher cumulative aET rate compared to the no burn plot.

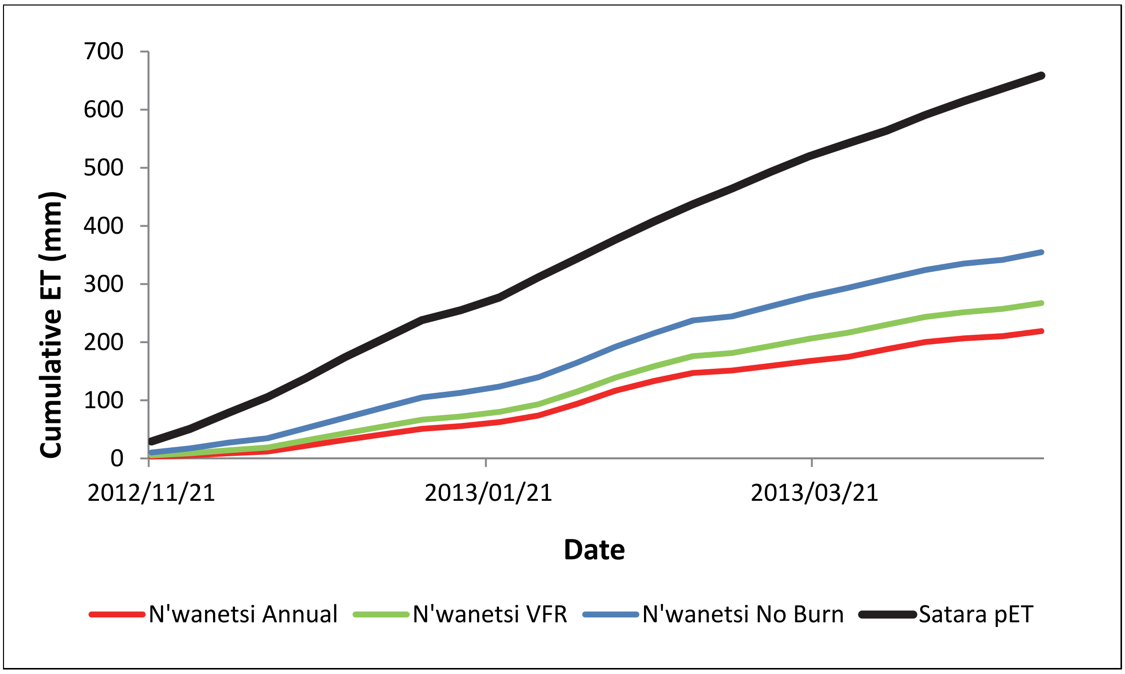

Figure 4.31 Cumulative weekly aET for the N'wanetsi EBPs of Satara (basalts) and the pET

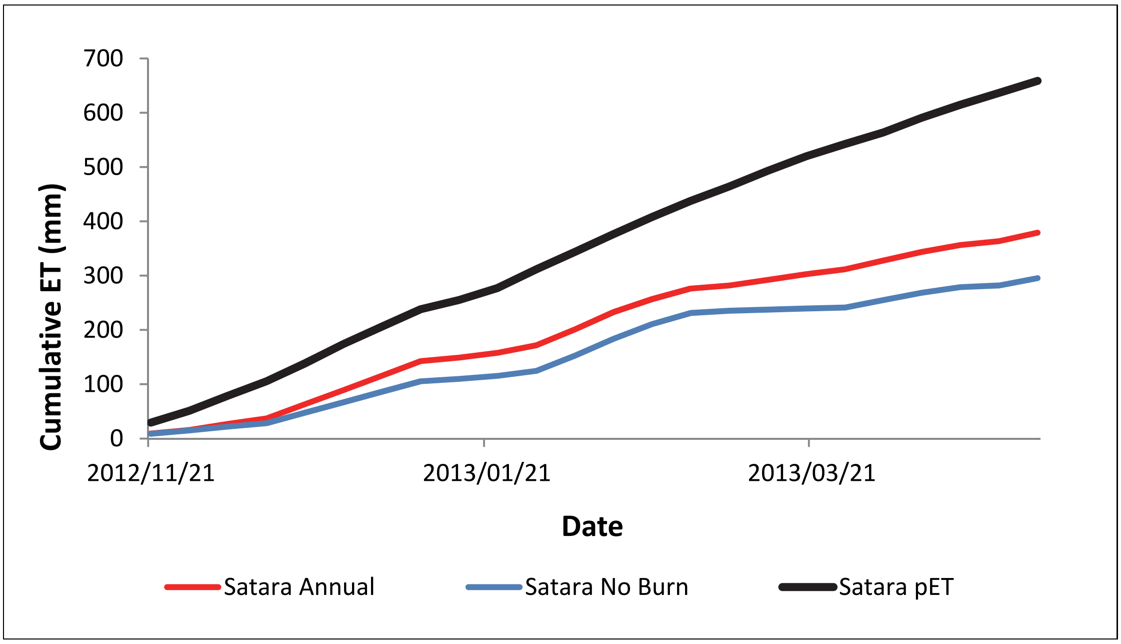

Figure 4.32 Cumulative weekly aET for the Satara EBPs of Satara (basalts) and the pET

(ii) HYDRUS Analyses

The instantaneous ET for the Satara EBPs was modelled on a daily time-step because the only data available that had a complete and correct rainfall record was daily rainfall data collected by the rangers in the Satara region of the KNP.

The N'wanetsi EBPs (Figure 4.33) displayed a clear and consistent ET pattern. The annual, no burn and VFR plots displayed a very similar trend throughout the modelling period. The no burn plot, however, predominantly displayed a consistently higher ET rate compared to the VFR and annual plots. The Satara EBPs (Figure 4.34) displayed similar ET patterns, with the annual EBP generally showing a greater ET rate compared to the no burn EBP. However, during the period around the 15th of March 2013, the ET pattern between the annual and no burn plot was not similar, i.e. the ET for the no burn plot was noticeably lower than that of the annual plot. After analysis of the SEBAL aET data, it was discovered that poor pixel values resulted in this obscure pattern, likely attributed to cloud-cover or an error in the SEBAL algorithm – keeping in mind that aET adapted from the SEBAL model was applied as a boundary condition in the HYDRUS model.

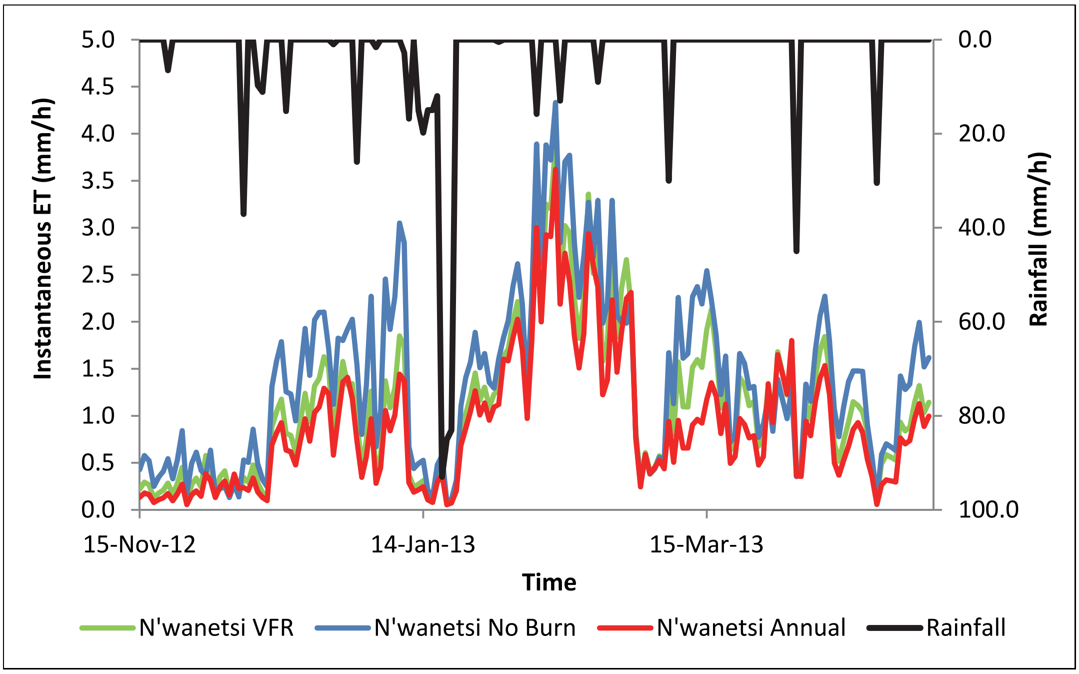

Figure 4.33 The instantaneous evapotranspiration and rainfall rates measured for the N'wanetsi EBPs

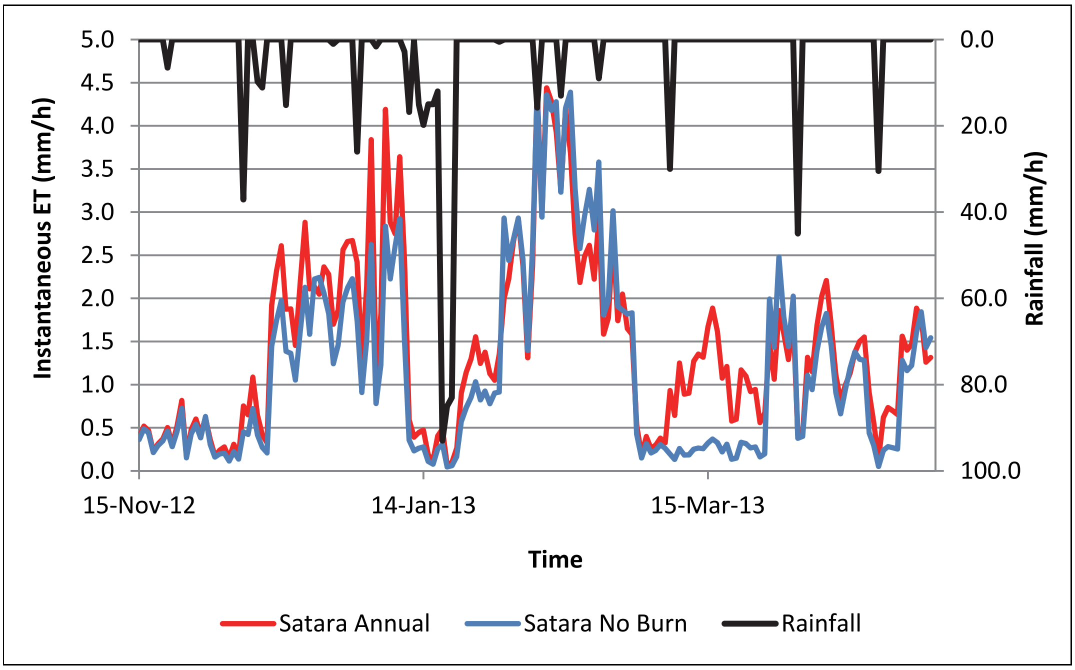

Figure 4.34 The instantaneous evapotranspiration and rainfall rates measured for the Satara EBP string

Similarly to the granitic EBPs, the mass balance information was computed from the cumulative data calculated by the HYDRUS 3D model for the basaltic strings using Equation 3.12. Soil properties substantially influence the change in water storage calculated in mass balance analyses.

The change in storage for the N'wanetsi no burn plot is lower than that of both the VFR and annual plot. This is attributed to major differences in the cumulative ET with slight difference in free drainage across each of the burn plots over the entire modelling period. The higher ET calculated on the no burn plot is due to increased vegetation after years of fire exclusion.

Table 4.7 N'wanetsi EBP mass balance information

	N'wanetsi No Burn			N'wanetsi Annual			N'wanetsi VFR		
	mm^3	m^3	mm	mm^3	m^3	mm	mm^3	m^3	mm
FD	24400000000000	24400	325	31600000000000	31600	379	27800000000000	27800	354
ET	17610000000000	17610	235	12680000000000	12680	152	14560000000000	14560	186
P	45700000000000	45700	609	50800000000000	50800	610	47800000000000	47800	609
R	85600000	0	0	44100000	0	0	26500000	0	0
ΔS	3689914400000	3690	49	6519955900000	6520	78	5439973500000	5440	69

Table 4.8 shows that the Satara EBPs displayed a converse trend to the N'wanetsi EBPs, with the annual plot showing a lower change in storage compared to the no burn plot. Surprisingly, the annual burn plot had the highest ET. It is believed that ET was greatest on the annual plot because it was the first rainy season (growing season) after the scheduled burn during August that year. Similarly which occurred on the granites (i.e. Kambeni EBPs), the period which

was modelled was the time when the vegetation on this burned plot would have been recovering and thus transpiring more than usual. This effect may have been coupled with the increase in bare soil (due to the fire) which would have rendered the soil exposed to increase heat and ultimately soil evaporation.

Table 4.8 Satara mass balance information

	Satara No Burn			Satara Annual		
	mm^3	m^3	mm	mm^3	m^3	mm
FD	38200000000000	38200	327	29300000000000	29300	316
ET	23730000000000	23730	203	22340000000000	22340	241
P	71100000000000	71100	610	56600000000000	56600	610
R	7900000	0	0	20500000	0	0
ΔS	9169992100000	9170	79	4959979500000	4960	53

5. DISCUSSION

Since fire is a critical driver in savanna ecosystem dynamics, it is vital that their influence on savanna hydrology is understood. Thus, the EBPs provided an ideal opportunity to investigate the effect of long-term fire frequencies on soil hydrology.

5.1 Soil Hydraulic Properties

A review of the literature suggested that fires affected soil by decreasing infiltration rates due to a change in the hydrological functioning of the soil (Martin and Moody, 2001; Thonicke *et al*., 2001). Therefore, it was initially hypothesized that high fire frequencies would result in decreased infiltration rates. However, results gathered on the granitic EBPs revealed that soil infiltration rates were actually slowest on the VFR plot at Kambeni which burned roughly three months prior. It is believed that this is attributed to the time following the fire and not the long-term fire regime. Fire effects appear most pronounced shortly after a fire and dissipates with time. Field observations showed that while soil surfaces are covered by ash, water infiltrates rapidly into the soil surface. Yet when these ash particles disappear, either blown away by wind or percolates through the soil profile, the charred soil surface beneath the ash layer is hydrophobic and inhibits infiltration. Similarly, DeBano *et al.* (2005) suggests that water will infiltrate through this wettable ash layer until the water-repellent, charred soil surface is reached where soil infiltration is constrained. Once water infiltrates beyond the ash layer (or the ash layer has disappeared), the ability of the soil to allow infiltration may not be sufficient and thus forces water to run across the hydrophobic soil leading to soil erosion. In an African savanna such as KNP where short, high-intensity rainfall events are typical, the ability of the soil to allow infiltration is critical to prevent substantial topsoil erosion. If rainfall intensity exceeds the rate of soil infiltration, runoff is inevitable. This in turn leads to increased amounts of water contributing to streamflow in nearby streams and rivers. Therefore, the effect of fire on soil hydrology could impact the hydrological processes and hydro-dynamics of entire catchments.

The findings stemming from the K_{unsat} data infers that soil infiltration rates eventually improve following a fire. The K_{unsat} rates measured on the annual burn plots was similar to the no burn plot where fire has been actively suppressed for decades. Therefore at Numbi (granites) where the annual plot last burned 9 months before, infiltration rates were not substantially slower than the unburned plot. Likewise for the other granitic EBP, Kambeni, where the annual plot last burned 1.5 years prior. These similar infiltration rates measured between the annual and no burn plots indicate that the effects of the fires 9 months and 1.5 years prior were no longer current. This theory held true for both the EBPs on granites and basalt soils. There was no significant difference in infiltration rates between the three fire regimes considering that the annual and VFR plots burned seven years and 1.5 years prior, respectively. Thus, it appears as though the soil has recovered here as well since infiltration rates are similar to the plot where fire has been suppressed for the past few decades. It is acknowledged that burned soils will recover or return to its natural equilibrium at different rates depending on factors such as pre-fire soil moisture content, fuel load, fire duration and fire intensity. It is suggested that soils recover due to surface runoff process which allow for the removal and redistribution of hydrophobic soil particles and ash. Jacobs *et al.* (2007) suggested that due to the low infiltration capacity, even minor rainfall events may trigger surface runoff which promotes the redistribution of sediment, organic material and nutrients. The mechanism for the recovery of burned soils in a post-fire environment is recommended for future research.

Except for the granitic Numbi string, there was generally no significant difference in K_{sat} between the different fire regimes at neither 2-3 cm nor 5-7 cm below the soil surface on either geology. Amongst others, studies by Certini (2005), DeBano *et al.* (2005) and Mataix-Solera *et al.* (2011) suggested that the effects of fire on soil properties is most pronounced in the pedoderm where the greatest change in temperature occurs but could be measured up to depths of 10 cm. Considering that these studies were conducted in Europe and North America, it is likely that these differences are due to differences in the types of fires experienced in African savannas. Typical savanna fires are less intense (Govender *et al.*, 2006) and rapid-moving compared to the intense fires which burn across pine forests in Europe and North America where the majority of these studies were conducted. Therefore, it is believed that the fires burning across these burn plots may not be intense enough to penetrate beyond the soil surface and/or that these fires burn too rapidly across the surface to allow enough contact time for heat transference. In addition, grasses which are the dominant fuel for savanna fires (constitutes 70-98 % of the total fuel) (Shea *et al.*, 1996), combusts rapidly due to their fine structure. This may contribute to the low heat transference in savanna fires.

The K_{unsat} and K_{sat} measured across the two geologies found that both these hydraulic properties were slowest on the basaltic EBPs. This would be expected considering the higher proportion of clays and finer particles in basaltic soil. The differences in variation in the K_{unsat} and K_{sat} data measured on Kambeni (granites) and K_{sat} data measured on N'wanetsi (basalts) were particularly intriguing. When compared to the other plots on Kambeni, there is not as much variation in the hydraulic conductivities measured on the recently burned VFR plot. This means that the hot fire which burned across the VFR area outside of the EBPs likely homogenized the soil properties across the plot. This is contrary to the typical behaviour of savanna fires which characteristically burn in a heterogeneous manner due to the inherent heterogeneity of the landscape (Trollope and Potgieter, 1985). These fires result in a patchy mosaic of varying degrees of fire intensities across the landscape. However, the homogeneity in the K_{sat} data measured on the annual burn plot on the N'wanetsi string is believed to be site-specific and attributed to the lack of mixed vegetation across the plot; hence no heterogeneous burning. Unlike the VFR and no burn plots where grass biomass was significantly greater, the lack of heterogeneity resulting from no patches of different vegetation types would lead to a more homogenized substrate. Grass tufts and their roots are known to create preferential pathways for water infiltration through the soil. Furthermore, these results coincides with Riddell *et al.* (2012) which found similar results and also proposed that these reduced variation in K_{sat} on the annual burn plot is due to the development of a more homogenized soil surface structure.

Since similar studies (e.g. Snyman, 2003; Mills and Fey, 2004; Riddell *et al.*, 2012) which were conducted in semi-arid areas in South Africa found that fire induced soil compaction, it was hypothesized that the soils on the annual burn plots would be the most compacted. This was shown on both geologies, where the soils were more compacted on the annual plot compared to the other fire and no fire treatments. Initially, it was difficult to determine whether these differences in soil compaction were due to the effect of fire on the soils or as a result of the high density of herbivores which concentrate on the annual plots in search of improved grazing quality and/or improved visibility against predators after a fire. The herbivore exclosures erected on the annual and no burn plots on N'wanetsi (basalts) provided the ideal opportunity to investigate the effect of herbivores on soil compaction. It was found that the effects of the herbivores were greater than the effects of fire on soil compaction. Herbivores usually concentrate around recently burned areas for improved grazing and generally avoid denser vegetation, preferring open areas for better visibility against predators (Owen-Smith, 1982). Russell *et al*. (2001) found similar results when cattle lead to compacted soil surfaces but did not reduce infiltration rates. Furthermore, an investigation into the effects of fire alone revealed that with the exclusion of herbivores, fire may still lead to shallow soil compaction and sealing due to fire burning vegetation, denuding an area and leaving it exposed to processes such as raindrop impact and splash (DeBano, 2000). The impact of raindrops and splash is assumed to be particularly significant on the N'wanetsi EBPs due to the high clay content present at these sites which may be affected by the dispersion of clay and blocking of pores at the soil surface; similar results were found by Mills and Fey (2004).

Unlike the initial hypothesis that the soil organic matter content would be significantly lower on the frequently-burned annual plot on both strings, this was found to be valid for the basalt N'wanetsi strings only. It is believed that the fire intensities on these burn plots are not sufficient enough to impact soil properties beyond the soil surface. Scholes and Walker (1993) proposed that under varying fire frequencies, the increase or decrease in soil organic matter is controlled by the intensity of the fire as well as the changes in primary production affected by the fire. With regards to the low organic matter content measured on the N'wanetsi annual burn plot, it is believed that the significantly reduced above-ground biomass is the agent leading to significantly less soil organic matter. The role of soil organic matter is twofold; it drives soil fertility as well as influence water movement and storage via the water-holding capacity of the soil, which will now be discussed next.

The hypothesis that soil water potential would be lowest on the no burn plot because the water-holding capacity of these soils would be high was found to be valid. The water-holding capacity of these soils on the fire-suppressed no burn plots on both geological EBP strings are likely linked to increased biomass and organic matter content as a consequence of decades of fire exclusion. The reduced water potential and subsequent water-holding ability of the soils on the annually-burned plots will result in water percolating much faster through the soil due to less adsorptive forces by hydrophilic organic matter acting on the water molecules and retaining the water (Schaetzl and Anderson, 2005). Furthermore, the soil water potential measured on the basalts was notably lower than the coarse-grained granitic burn plots. This finding is attributed to greater soil organic matter content measured on the basalts as well as the increased proportion of clays and finer particles inherent in basaltic soils. Stoof *et al.* (2010) noted that water-holding capacity, an indication of the amount of water which can be stored in the soil, and soil infiltration controls the fate of precipitation. Thus, the ability of the soil to retain moisture is a critical driver controlling the movement of soil water through the landscape. Since post-fire regeneration of burned vegetation is reliant on water, the capacity of the soil to retain moisture is particularly vital owing to the fact that most savanna fires occur after the dry season (Kennedy and Potgieter, 2003) when the veld is water-stressed. Thus, the re-establishment of plants is dependent on water retention capacities at low water contents. Indirectly, the ability of the soils to store water in the catchment controls the distribution of herbivores in the landscape as their movements are guided by palatable forage.

Vegetation characteristics such as grass biomass and basal cover were assessed in order to determine how they may influence soil hydraulic properties in a fire-prone savanna system. As hypothesized, the highest grass biomass was found on the fire-suppressed no burn plots in both the granitic and basaltic regions of KNP; as would be expected after many years of fire exclusion. Furthermore, basal cover was greatest on the fire-suppressed no burn plot on the basaltic N'wanetsi EBPs. These findings are likely due to decades of fire exclusion resulting in the accumulation of vegetation on the no burn plots. This increase in vegetation may control the distribution of water through the catchment.

5.2 Runoff and Sediment Yield Analyses

A reduction in vegetation cover is believed to be responsible for the increased runoff rates observed on the annual burn plots in the granitic region of Pretoriuskop. Reduced vegetation or surface cover will result in less rainfall interception and thus exposing the soil surface to direct raindrops known to compact soil surfaces and inhibit infiltration. More runoff was generated from the annual plots compared to the no burn plots at the 200 mm/h rainfall intensity 24 hours after the 157 mm/h intensity was applied. The effect of fire on the amount of runoff generated as well as the rate of runoff increases as rainfall intensity increases. This phenomenon was highlighted when the runoff rates (at 200 mm/h rainfall intensity) between the Numbi and Kambeni no burn plots were compared; the Numbi plot displayed a higher runoff rate than the Kambeni no burn plot. This finding is attributed to the fact that an accidental fire burned across the Numbi no burn plot in September 2012 which is believed to have been intense considering that fire has been excluded from the plot for decades and resulted in an accumulation of fuel (biomass). Besides a faster runoff rate, there was also an increase in the amount of runoff generated on the Numbi no burn plot due to the reduction in vegetation cover (Moody *et al*., 2009). Comparatively, the fire exclusion plot on Kambeni had more vegetation cover and surface litter which intercepted more rainfall and allowed for greater infiltration. In terms of the sediment analyses, it was found that the sediment loss from the fire exclusion plots was greater than the sediment loss from the annual plots. It is believed that this was due to the compacted soil measured on the annual burn plot.

5.3 Soil Water Balance

It was hypothesised that the no burn plots would render the highest cumulative ET since it had the greatest vegetation density or biomass (Bijker *et al.*, 2001 and Oliveira *et al.*, 2005). Analysis of the SEBAL data revealed that for the granitic Kambeni EBPs, the VFR displayed a higher cumulative aET value compared to the no burn and annual plots. Close analysis of the SEBAL raster images revealed that an accidental fire burned several hectares of vegetation surrounding the Pretoriuskop EBPs in October 2012. The SEBAL raster images, however, simultaneously suggested that all the EBPs in Pretoriuskop (granites) had burned in the runaway fire which was not the case. Since the EBPs are small experimental plots in relation to the extent of the burned area, it is suggested that aET may have been masked by the values obtained by the surrounding burned area.

It is believed that the VFR plot at Kambeni displayed a higher cumulative ET due to rapid regrowth and re-establishment of consumed vegetation stimulated after the accidental fire which increased the amount of transpiration. Additionally the evaporation contribution may have been elevated following the fire as a result of the soil being denuded and increasing the extent of bare soil exposed to the elements. These suggestions are in agreement with the findings of Sakalauskas *et al*. (2001) who observed higher net above-ground primary productivity (NAPP) in burned plots especially following the first year after a fire. They, too, attributed the increase in NAPP both the high vegetation regrowth and recovery after the fire as well as elevated evaporation from the bare soil. Furthermore the SEBAL data suggests that the cumulative ET from the no burn and annual EBPs was very similar. This finding is likely due to the fact that the annual plot did not burn as scheduled due to unfavourable conditions for two consecutive years, resulting in similar vegetative conditions between the two fire regime plots.

Surprisingly the SEBAL data for the other granitic EBPs, i.e. Numbi, revealed a higher cumulative ET amount for the no burn plot compared to the annual plot even though this string also burned during the accidental fire. It is possible that due to the establishment of numerous big trees on the no burn plot over the years, it was easy for these resilient trees to re-sprout and re-coppice after the fire. Thus, the difference in vegetation recovery between the annual and no burn plots would have resulted in different ET since the annual plot is covered predominantly by grasses and not trees like the no burn plot.

The basaltic N’wanetsi EBPs of Satara also displayed the expected result of higher ET within the fire exclusion no burn plot compared to the annual and VFR plots. This was attributed to the higher vegetation density within the fire exclusion plot compared to the VFR and annual plots. The Satara EBPs displayed a converse trend to that of N’wanetsi, with the annual EBP showing a greater cumulative ET compared to the no burn EBP. It is likely that due to the prescribed burn during August that year (roughly 3 months before modelling period), vegetation was at a recovering stage since it was the first rainy season since that annual burn. Naturally, transpiration rates would be higher than usual. In addition, as fire has denuded the area of vegetation and rendered the soil bare, evaporation from the soil would also be higher than on the denser no burn plot.

Therefore from the SEBAL data alone, comparison of the Pretoriuskop (granitic) and Satara (basaltic) EBPs suggest that fire frequency and seasonality influences ET from the basalts to a greater extent than compared to the granites. The strong correlation between rainfall and the subsequent aET highlighted the relationship between soil moisture and evapotranspiration. Since fire will impact transpiration potential from a landscape, it will very likely impact on the soil water balance and the distribution of water within the landscape too.

The results of instantaneous and cumulative evapotranspiration, as determined by the HYDRUS model under the specified conditions, revealed that in some cases the granitic (Pretoriuskop) and basaltic (Satara) EBPs displayed slightly different results compared to the SEBAL ET results. Modelling complex and dynamic environments such as savanna systems can be very challenging. Uncertainty in these modelling scenarios is inevitable due to the sensitivity of the model to various parameters such a soil texture. Abbott and Refsgaard (1996) discuss the aforementioned point and stated that although some extent of natural heterogeneity is exhibited in all natural systems we can never expect to account for all the underlying processes occurring within a natural system. In terms of this report it needs to be highlighted that additional uncertainties are expected since a model, i.e. SEBAL and the Penman-Monteith equation, was used to estimate relevant data which was fed into another model, i.e. HYDRUS. Therefore the limitations of the first model are transferred to the second model and subsequently the uncertainties involved should be acknowledged.

In terms of the granitic EBPs, the SEBAL and HYDRUS aET data revealed a consistent pattern at Numbi, with the no burn plot displaying a greater cumulative and instantaneous ET compared to the annual plot. This was attributed to similarities in the soil properties. Whereas the amount of aET determined by the model on the granitic Kambeni string was slightly different compared to the aET input from the SEBAL data. This discrepancy is thought to be due to the different soil properties used as input into the model as well as the set of conditions specified or implemented. The soil water balances for the granitic EBPs suggested the influence different soil processes between the varying fire regimes. The mass balance analysis alluded to higher ET and subsequently less drainage on the no burn plot compared to the annually-burned plot. Thus in terms of water availability and distribution within the landscape, the mass balance analysis suggests that for the modelling period a greater volume of water would have drained through into the groundwater from the Numbi annual plot to a greater extent compared to the no burn EBP. Yet, the overall change in water storage between the annual and no burn plots on the Numbi string was very similar which is believed to be due to similar soil hydraulic conductivities.

Analysis of the mass balance data revealed that for the Kambeni EBPs, the no burn plot displayed the greatest change in storage with a lower ET amount compared to the annual and VFR plots and a subsequently higher amount of free drainage out of the soil domain. The change in storage for the no burn plot was due to the relatively high conductivity of the soil in the wet range as well as the fact that the no burn plot remained wetter than the other two plots during the modelling period since less ET took place. Since hydraulic conductivity increases with increasing soil moisture due to a lower matric potential, more water was able to drain from the no burn plot during the modelling period. With regards to the availability of water in the landscape, a greater volume of water from the no burn plot would have recharged groundwater aquifers which in turn would contribute to sustaining nearby streams.

The aET on the basaltic EBPs of N'wanetsi and Satara as calculated by the HYDRUS and SEBAL models revealed consistent patterns for the first half of the modelling periods. For example the instantaneous and cumulative ET for both the SEBAL and HYDRUS results revealed the same pattern for the N'wanetsi EBPs, with the no burn plot displaying higher values than the VFR and annual EBPs. Similarly for the Satara EBPs, both the HYDRUS and the SEBAL models suggested that the instantaneous and cumulative ET from the annual EBP was greater than that from the no burn plot. During the period around the 15th of March 2013, however, the ET pattern between the annual and no burn plots were dissimilar, i.e. the aET rate for the no burn plot was noticeably lower than that of the annual plot. After analysis of the SEBAL aET data it was discovered that poor pixel values resulted in this obscure pattern, likely attributed to cloud-cover or an error in the SEBAL algorithm, i.e. keeping in mind that actual evaporation adapted from the SEBAL model was applied as a boundary condition in the HYDRUS model.

Mass balance analysis of the Satara EBPs suggest that on both the N'wanetsi and Satara strings, the effect of fire management on the water balance is significant. It was discovered that the amount of ET from the no burn plot on N'wanetsi was the greatest and therefore the amount of free drainage and water stored within the plot was lower than that of the VFR and annual plots. On the other hand, the annual plot had the lowest amount of ET and therefore the highest amount of free drainage and soil water storage at the end of the modelling period. Therefore based on the HYDRUS calculations under the specified conditions, the model predicts that for the modelling period, the N'wanetsi annual plot rendered a depth of drainage approximately 1.17 times greater than the no burn plot and 1.07 times greater than the VFR plot. Additionally at the end of the modelling period, the annual plot had 1.60 and 1.13 times more water stored in the soil compared to the no burn and VFR plots, respectively. In terms of water availability within the landscape, this suggests that during the modelling period a greater volume of water would have drained and potentially recharged groundwater from the N'wanetsi annual plot.

The converse trend was observed on the Satara EBPs, with ET from the annual plot being greater than the ET from the no burn plot. Subsequently, the drainage from the no burn plot was higher than the drainage seeping from the annual plot. Therefore based on the HYDRUS calculations under the specified conditions, the model predicts that for the modelling period, the Satara no burn plot rendered a depth of drainage approximately 1.03 times greater than the annual plot. Additionally, the no burn plot had 1.50 times more water stored in the soil compared to the annual plot at the end of the modelling period. With regards to water availability within the landscape, this finding suggests that a greater volume of water would have percolated through the soil medium and possibly recharged groundwater from the Satara no burn plot compared to the annual plot. Additionally, considerably more water is available from within the soil of the no burn plot compared to the annual plot. This suggests that more water is stored in the soil of the no burn plot and therefore more water is available for plant growth and redistribution in the subsoil.

The overall key hydrological mechanisms stemming from fire impacts are represented in Figures 5.1 and 5.2. These are based on the assumption that the “burned soils” were burned by a hot fire less than 1.5 years prior (Figure 5.1) whereas the “unburned soils” has not been burned for at least the last two years (Figure 5.2). On frequently-burned soils (e.g. annually) where fires denude areas of vegetation cover, the soil surface is exposed to processes such as raindrop impact and splash which may result in sealing. In addition, there is an increase in herbivore densities on recently burned soils since these animals are attracted to improved forage and increased visibility against predators. The intensification of herbivore presence results in compacted soil due to frequent trampling. Thus there is an increased likelihood for soil compaction. This in turn has a negative effect on soil infiltration which leads to increased surface runoff. Additionally, based on the assumption that these processes are taking place during the wet season (i.e. after the onset of the first rains), compacted soils are moist and cemented to such a degree that sediment yield remains surprisingly low. However, the authors believe that there is a threshold involving rainfall intensity and rainfall duration which could dislodge compacted soil layers in extreme events, particularly when the soil is still relatively dry.

As the hot fire consumes and reduces the vegetation cover in the burned area, the intensity of the fire consumes soil organic matter concentrated in the upper layers of the soil surface. In addition, frequent burning will inhibit the accumulation of organic matter due to reduced vegetation cover. This has a cascading effect on the water retention capacity of the soil by negatively impacting the soil’s ability to retain moisture in a post-fire environment. The reduction in the water-holding capacity of the soil, coupled with low ET rates due to the fire decreasing vegetation cover, more water is ultimately available within the soil medium to percolate and recharge groundwater or contribute to streamflow in nearby channels. In one case, i.e. the Satara EBPs, it was found that ET was lowest on the no burn plot. This was attributed to more regrowth on the recently burned annual plot which would have increased transpiration as well as more evaporation from more bare soil exposed on the annual plot.

The inverse hydrological processes occur on unburned granitic and basaltic soils (Figure 5.2). To summarize, increased bioactivity by insects, microorganisms and plant roots as well as lower herbivore densities result in less soil compaction. This in turn allows for more infiltration and less runoff compared to frequently burned soils. However, there is an increase in sediment yield due to loose soil. Due to fire suppression, an increase in vegetation will result in an increase in organic matter content as well as ET. Since there is less water available in the soil to percolate and higher water-holding capacity, less water is freely available to recharge groundwater.

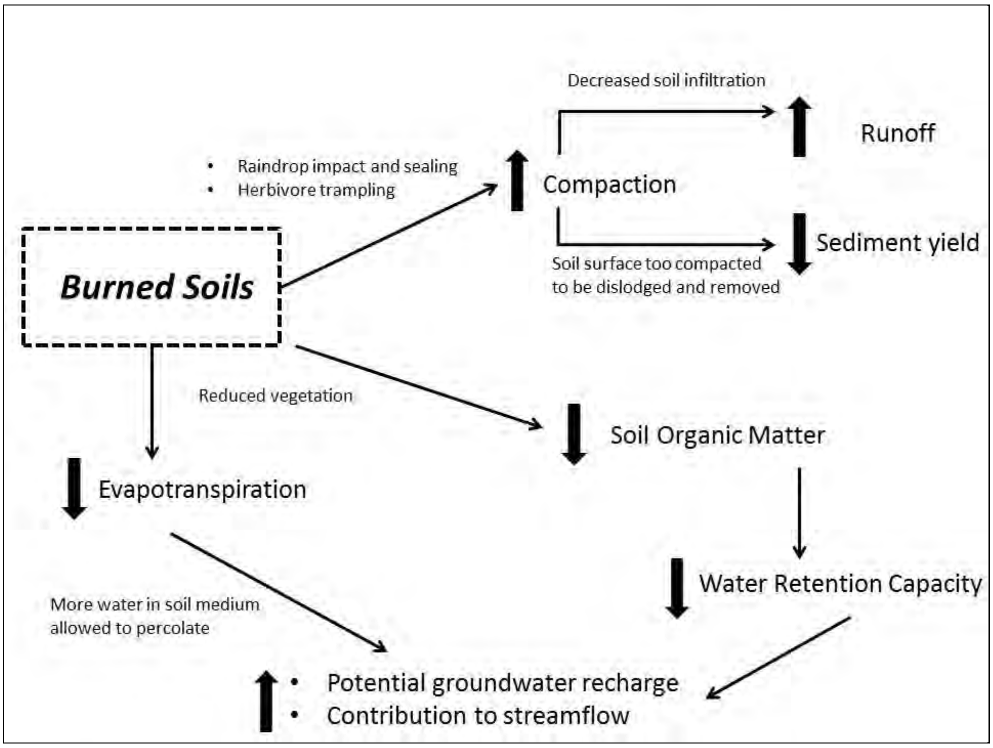

Figure 5.1 An illustration of the hydrological mechanisms on annually-burned granitic and basaltic soils

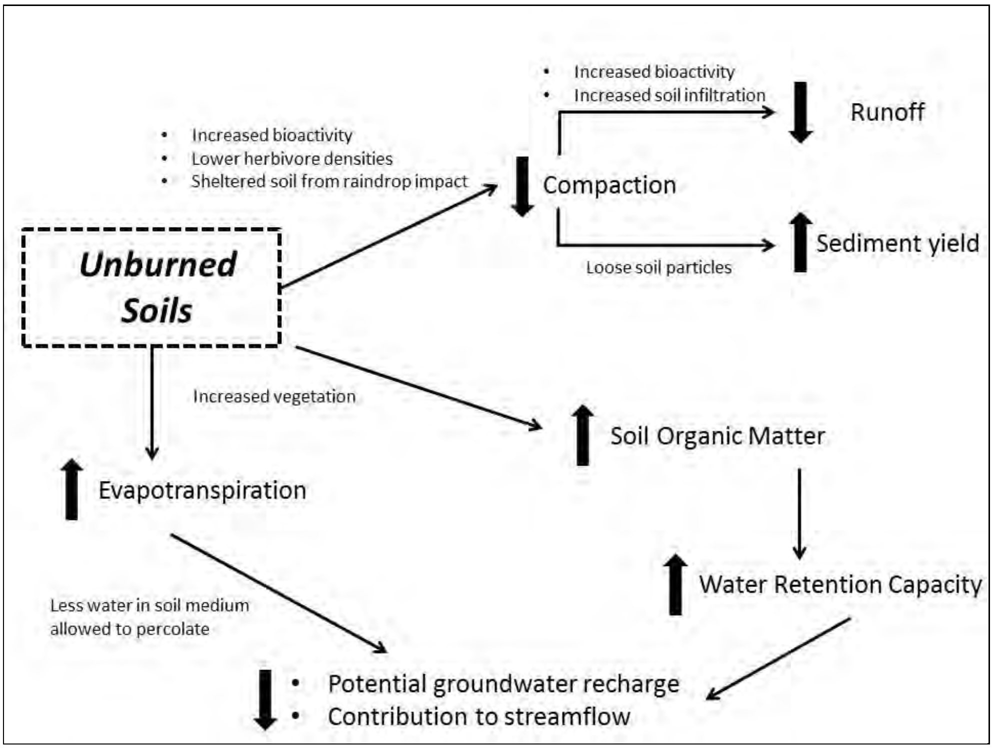

Figure 5.2 An illustration of the hydrological mechanisms on unburned African savanna soils

6. CONCLUSIONS

Fire effects are complex owing to many interrelated factors which all play a role in influencing each other. Soil hydrology is affected by both direct and indirect fire effects. Fire may either directly impact the soil by altering soil chemistry and inducing hydrophobicity or indirectly by changing environmental conditions at the soil surface. Therefore investigating and understanding the impact of fires in African savannas is vital considering that fire is a major driver in savanna ecosystem dynamics. This is of particular importance in KNP where fire is also applied as a management tool to control and manipulate vegetation structure and composition. Furthermore, the fact that information relating to the impact of fire on soil hydrology in African savannas is scarce, it provides additional incentive for research of this nature.

The effect of fire frequencies on soil hydraulic properties is negligible considering that it is actually the time following a fire which plays a significant role on soil hydrology in a savanna ecosystem. The effects of fire on soil infiltration rates were most prominent after a recent fire whereas plots where fires had burned more than two years prior had similar infiltration rates as unburned plots. These effects were primarily observed at the soil surface suggesting that savanna fires may lack the high intensities required and/or due to its rapid burning behaviour, does not have sufficient contact time to transfer heat beyond the soil surface. Furthermore data suggested that after two years following the fire, soil infiltration rates improved suggesting that soils are capable of recovery relatively soon. Re-sampling soil hydraulic properties on the VFR plot at Kambeni after two years will serve as further confirmation that soil infiltration rates will improve and increase again to pre-fire conditions.

The frequently-burned plots on the coarse-grained soils on Kambeni were the most compacted. On the clayey soils in the central basaltic region of KNP, it was high concentrations of herbivores which lead to soil compaction to depths of at least 4.5 cm. With the exclusion of herbivores, fires resulted in compacted soil surfaces due to bare soil exposed to processes such as raindrop impact and splash. Even though soils were compacted by both fire (indirectly) and herbivores (directly), this did not impact soil hydraulic properties significantly. In this case, the influence of soil compaction by fires and herbivores on soil hydrology is considered negligible. With the water-holding capacities of the soil influenced by above-ground biomass and organic matter, the effect of fire frequencies on the ability of the soils to retain moisture at low water contents is critical to understand seeing as it is one of the most important properties in a post-fire environment.

After performing rainfall simulations in order to compare the effect of historical fire regimes (annual versus no burning) on the runoff and sediment yield generated, it was discovered that long term fire management unequivocally affects the amount of runoff generated from the savannas of the KNP. The amount of runoff generated is strongly related to the rainfall intensity, with more runoff generated at higher rainfall intensities, i.e. 200 mm/h. Vegetation cover and soil properties were found to influence the onset of runoff generation. In terms of the sediment yield data, inconclusive results were obtained attributed to a poor sampling strategy induced from poorly designed equipment, i.e. the runoff plot, which limited sediment collection.

It is likely that long-term fire management practice, i.e. fire frequency, will affect the rate of ET losses from savannas in the KNP. Additionally, these fire regimes affect soil properties and soil water balances which ultimately control the distribution of water through the landscape. The impact of fire on soil water balances was found to be more obvious within the granitic Pretoriuskop area, characterised by sandy soils and higher rainfall, than compared to the basaltic Satara area, characterised by clayey soils and lower rainfall. Therefore at the catchment scale, fire frequency and intensity likely impact the availability of water within a catchment considerably within the Pretoriuskop area and to a lesser extent in the Satara area. A suitable fire management regime is critical in ensuring that the availability of water within a catchment is not negatively affected.

In light of climate change and problems associated with bush encroachment, it is critical for scientists and managers to understand how fires impact soils and their hydrology, especially in a fire-manipulated landscape such as KNP. Considering that KNP management policies are designed for large-scale areas, these results would need to be extrapolated and confirmed at a catchment scale. The findings gathered in this study provide the initial platform from which further large-scale studies may be initiated to compliment, support and improve these results.

Below is a breakdown of how this study's hypotheses (H) correlated to actual results (R).

H_1: It was hypothesised that the annual burn plot will have the slowest K_{unsat} and K_{sat} due to frequent fires.

R_1: Results suggested that it is not necessarily fire frequency impeding soil infiltration but rather the time following a fire. These negative impacts dissipate over time.

H_2: The soil on the annual burn plot will be the most compacted due to frequent burning.

R_2: It was confirmed that the annual burn plot had the most compacted soils. However, it was discovered that it was actually the effect of herbivore trampling which lead to increased soil compaction.

H_3: Soil organic matter will be greatest on the no burn plot due to many (> 50) years of fire exclusion.

R_3: This was found to be true only on the basaltic burn plots (N'wanetsi). It is believed that this may be due to the extreme differences in above-ground biomass between the annual and no burn plots. The lack of vegetation on the annual burn plot on N'wanetsi has even limited prescribed burning on this plot due to insufficient fuel load.

H_4: Soil water potential will be greatest on the no burn plot since fire exclusion would have allowed for an increase in the organic matter content which is hydrophilic and thus also increases soil water retention.

R_4: Results have confirmed that water potential and soil water retention was greatest on the no burn plot where fire has been excluded.

H_5: Due to the suppression of fire, the no burn plot will have the highest grass biomass and percentage basal cover. This in turn will lead to more evapotranspiration from the unburned plots.

R_5: It was confirmed that the no burn plot had increased grass biomass. However, basal cover was only significantly greater on the basaltic plots on N’wanetsi which is likely attributed to the similarity in vegetation types between N’wanetsi and the grasslands where the methodology was developed. With regards to evapotranspiration, results suggested that the annually-burned plots had decreased evapotranspiration rates due to a reduction in vegetation cover. However it was discovered that soon after a fire (e.g. the next growing season), evapotranspiration rates can increase dramatically due to a sudden increase in transpiration by recovering vegetation as well as increased evaporation from exposed soil surfaces.

H_6: More runoff and sediment yield will be generated on the annually-burned plots.

R_6: Results verified that the annually-burned soils generated more runoff. However, this did not correspond with an increase in sediment yield. It is believed that there was no increase in sediment yield because these runoff simulations were conducted well into the wet season where soils are already moist and because these soil surfaces may be too compacted to be dislodged.

7. RECOMMENDATIONS

This study has yielded some very interesting findings and has improved the understanding of fire effects on soil hydrology in savanna systems. This study provides valuable insight into how factors such as fire, soil, water, vegetation and herbivores interact in the African savanna landscape. However, as with any research, outcomes are not absolute and there are aspects of uncertainty which have been identified during the study, possibly influencing interpretations.

Since soils are so diverse and may change over short distances due to its heterogeneity, the primary concern involves the experimental design of the EBPs. On the granites, the EBP strings were positioned on hillslope crests in order to minimise soil variation (Biggs *et al*., 2003) and the study by Venter and Govender (2012) concluded that the majority of the plots are representative of the surrounding landscapes except for a few outliers. Even though the plots where this research was focused on both the granites and basalts were identified as suitable plots for comparative studies, it is still recommended that a particle size analysis be used to determine the soil texture across these plots. This will reduce the uncertainty regarding whether differences in soil hydraulic properties are truly due to the burning regime or due to different soil textures.

Unfortunately before the EBP experiment was initiated, pre-conditions of the veld are unknown. Had such baseline data been available, it would have been interesting to identify how the soil hydraulic properties could have been altered after more than 50 years of fire treatments. Furthermore, there have been many cases where scheduled burning did not occur owing to insufficient fuel load due to herbivory or droughts, or too much moisture in the veld thus preventing the ideal conditions to support the prescribed fire.

Furthermore, it is urged that this initial study be taken forward by investigating the effect of fire intensities on soil hydrology as well and not just focus on fire frequency. Patterns identified in this study along with suggestions by many other studies (e.g. Scholes and Walker; 1993; DeBano and Neary, 2005; Mataix-Solera *et al.*, 2011) proposed that the intensities of fire play a major role in how the soil is affected, and especially how deep and how long these effects may linger. To facilitate this research, it is recommended that the impact of ash on soil infiltration rates also be assessed. Cerda and Robichaud (2009) recognized that there are many post-fire studies which usually neglect the temporary effect of ash aiding soil infiltration.

It is recommended that the impact of herbivores on soil compaction in the granitic areas of KNP also be investigated in order to compliment the findings stemming from the herbivore exclosures in the basalts. It is possible that the extent of soil compaction by herbivores might be different between the two geologies considering that the grain sizes of the sediment differs, there is more finer-material on the basaltic soils, and that herbivore densities are generally greater on the basalts.

It was noted that in the basaltic region of KNP, the formula used to calculate basal cover (Hardy and Tainton, 1993) was applicable and provided realistic results while it miscalculated trends on the Kambeni EBPs in the granites. Since Hardy and Tainton (1993) conducted their study in a South African grassland, it is likely that their formula would rather be suitable to the *Sclerocarya birrea caffra/ Acacia nigrescens* Savanna in Satara due to the high proportion of grasses which is similar to the grasslands Hardy and Tainton (1993) used. Meanwhile, the Kambeni EBPs in the higher rainfall, granitic region of KNP are classified as the Lowveld Sour Bushveld which has more woody vegetation than the Satara section. It is recommended that this formula only be used in similar landscapes as the original study site or that an alternative method of evaluating basal cover and consequently the area of bare soil be applied.

Even though the equipment used to determine runoff and its setup are unwieldy, it is suggested that more sites are replicated in order to increase data confidence. This may also allow for more simulations as a greater variety of rainfall intensities. Furthermore, duplicating this experiment on the other dominant geology in KNP will prove very useful as well. It is also advised that sediment yield samples are collected regularly during the rainfall simulation experiments.

Recommendations for further research would involve the implementation of more hydrological instrumentation within the specific EBP strings to improve the accuracy and confidence in future soil water balance modelling. These include the installation of rain gauges, soil moisture sensors and conducting detailed soil surveys. Although these studies are not based around the impacts of fires, it may be useful for future studies to complement their soil moisture research with reference made to studies by Vischel *et al.* (2007), Vischel *et al.* (2008), and Sinclair and Pegram (2010).

Once our understanding has been enriched as to the effects of both fire frequency and fire intensity, it would be ideal to up-scale this type of study to larger areas similar to the Supersites in KNP (Smit *et al*., 2013). Stoof *et al.* (2011) recognized the scarcity in pyro-hydrology research at catchment scales and attempted to investigate this fire-water relationship by burning an entire catchment. Their study highlights the need for catchment-scale fire experiments considering that the fire effects observed at plot scale may be diluted by the heterogeneity and variation inherent in larger areas such as catchments. This would reduce the uncertainties of extrapolating from a small plot scale to a catchment scale. Thus, by increasing the scale of this study, results will be more applicable to management policies since these policies are designed for implementation at a large scale. Furthermore, future research could make use of a hydropedological model whereby dominant hydrological processes may be inferred based on the soil type (Van Tol *et al*., 2013). Unfortunately for this study, the soil types did not match.

Since fire is implemented as a management tool, KNP management could benefit from this study by integrating its fire policy with its water in the landscape policy. In order to ensure that catchment hydrological properties are not adversely affected by unsuitable burning regimes which may result in increased water repellency, decreased infiltration rates and decreased water retention capacities, it is advised that management actively ensures that the veld does not burn as often as every two years. Soil properties require a minimum of two years to return to pre-fire conditions on both the granitic and basaltic regions of the park. Since management utilises a Strategic Adaptive Management (SAM) approach with clear objectives which undergoes regular reviews, policies should be modified in order to take these findings into account when making fire management decisions. A co-operative relationship between science and management is necessary to ensure a steady transfer of knowledge between the two sectors to facilitate SAM.

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9. APPENDICES

Appendix A: Alpha values required for K_{sat} calculations

Table 9.1 The alpha (α) values used based on soil texture and structure (Elrick *et al*., 1989; Elrick and Reynolds, 1992; Reynolds, 1993c)

α* (cm^{-1})	**Soil Texture/ Structure Category**
0.01	Compacted and structureless clays (clay liners)
0.04	Unstructured fine-textured soil (clays)
0.12	Most structured soils with medium and fine sands (first choice for most soils)
0.36	Coarse sands and highly structured soils with large cracks and macropores
0	The Gardner Solution (Reynolds and Elrick, 1985). Pressure and gravity contributions negligible

Appendix B: SEBAL analysis and data correction

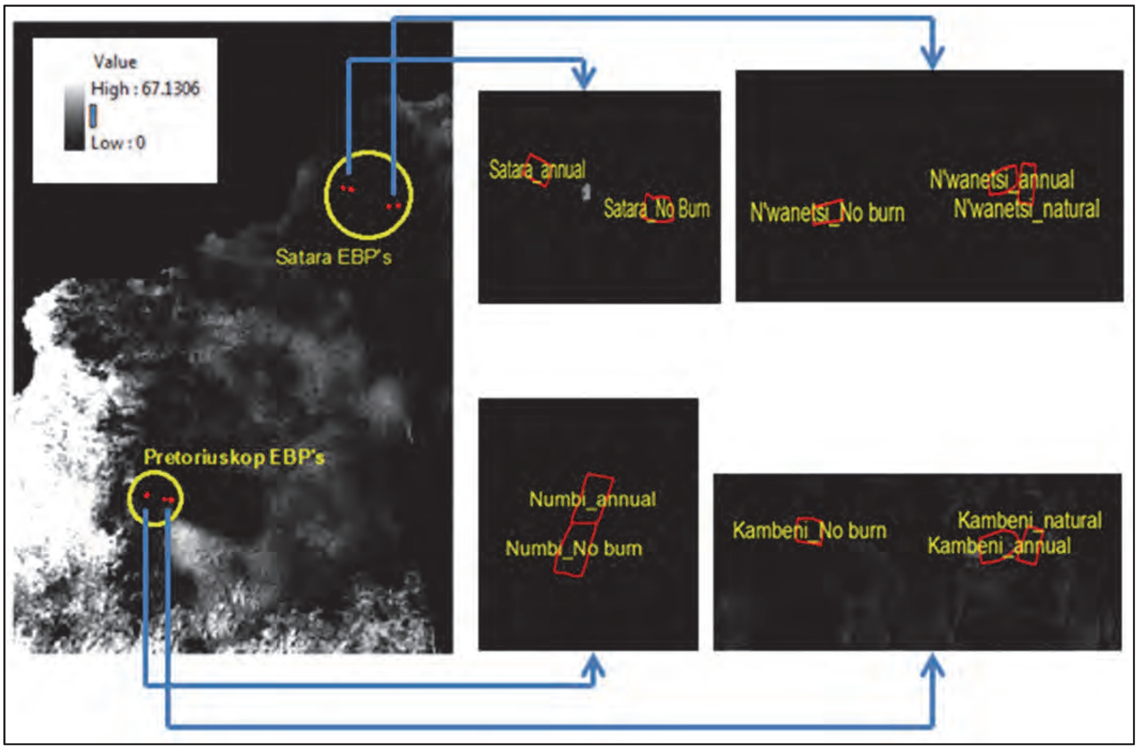

Figure 9.1 Actual evapotranspiration raster from the beginning of the modelling period (10/10/2012 – Week 1) showing fire scar from an accidental runaway fire

Table 9.2 Example of errors in SEBAL data for the N’wanetsi EBPs of Satara

Date	2013/01/02	2013/01/09	2013/01/16	2013/01/23	2013/01/30	2013/02/06	2013/02/13
N'wanetsi Annual	9.7024	9.3571	0.0000	0.0000	0.0000	20.0862	22.5517
N'wanetsi Natural	11.8451	11.3944	0.0282	0.0282	0.1127	21.7925	24.2453
N'wanetsi No Burn	17.5208	17.3229	8.0417	10.6771	16.0521	25.1290	27.5323

Table 9.3 Example of errors in SEBAL data for the Kambeni EBPs of Pretoriuskop

Date	2013/02/27	2013/03/06	2013/03/13	2013/03/20	2013/03/27	2013/04/03	2013/04/10
Kambeni Annual	36.1818	30.0000	0.0000	0.0000	0.0000	15.6220	16.7561
Kambeni Natural	35.6563	29.5200	0.0000	0.0000	0.0000	15.0645	16.0323
Kambeni No Burn	34.7636	29.0000	0.0000	0.0000	0.0000	13.9180	15.0984

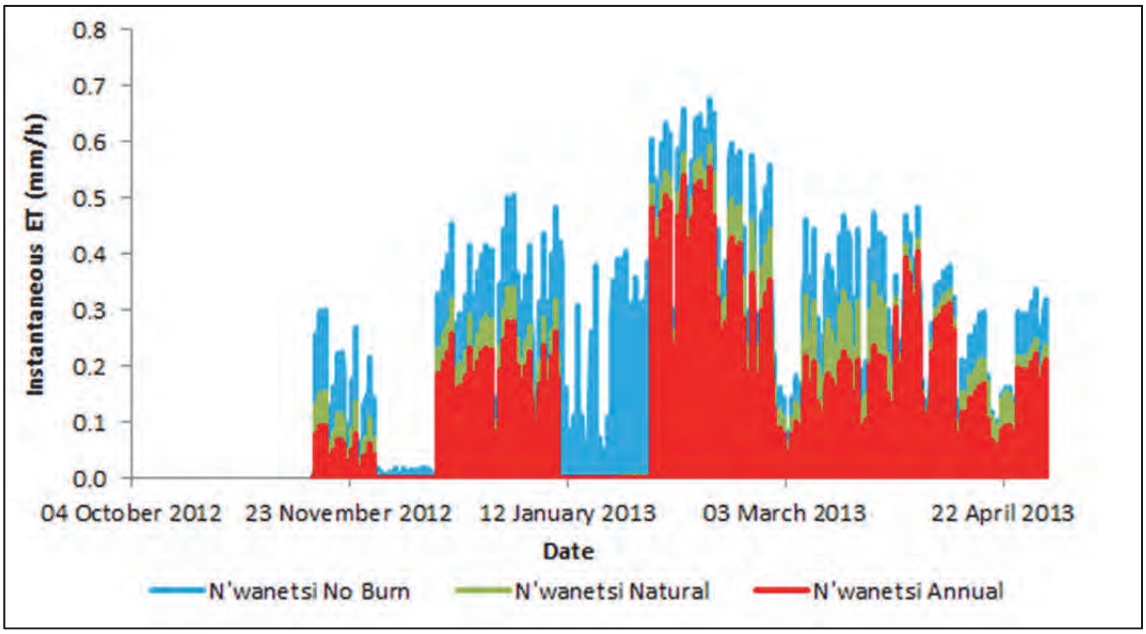

Figure 9.2 N’wanetsi aET before correction

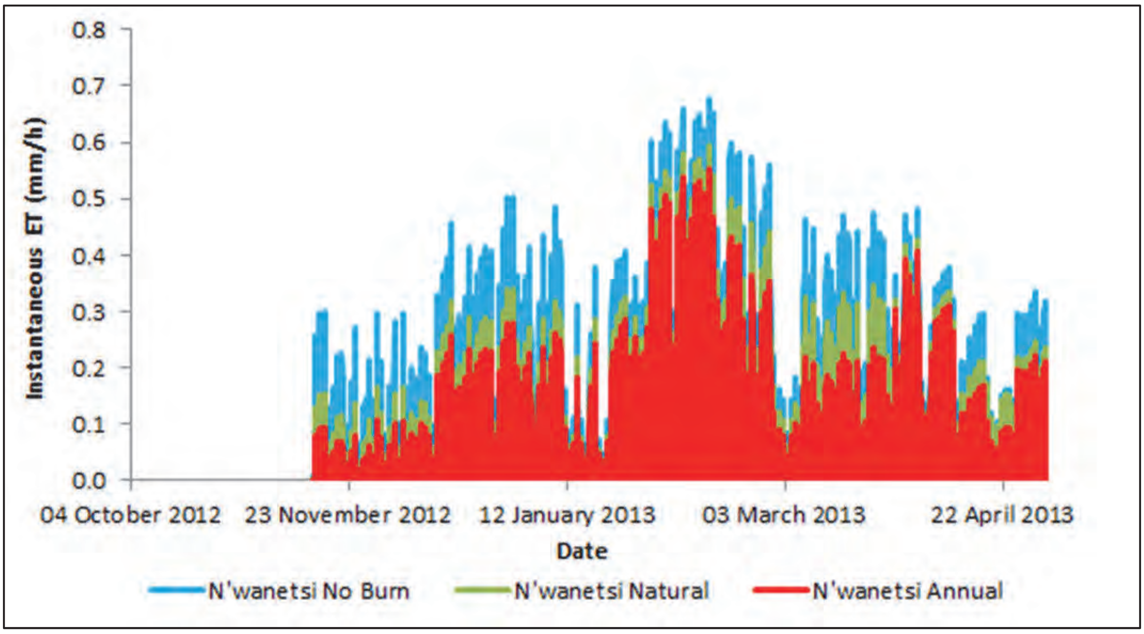

Figure 9.3 N’wanetsi aET after correction

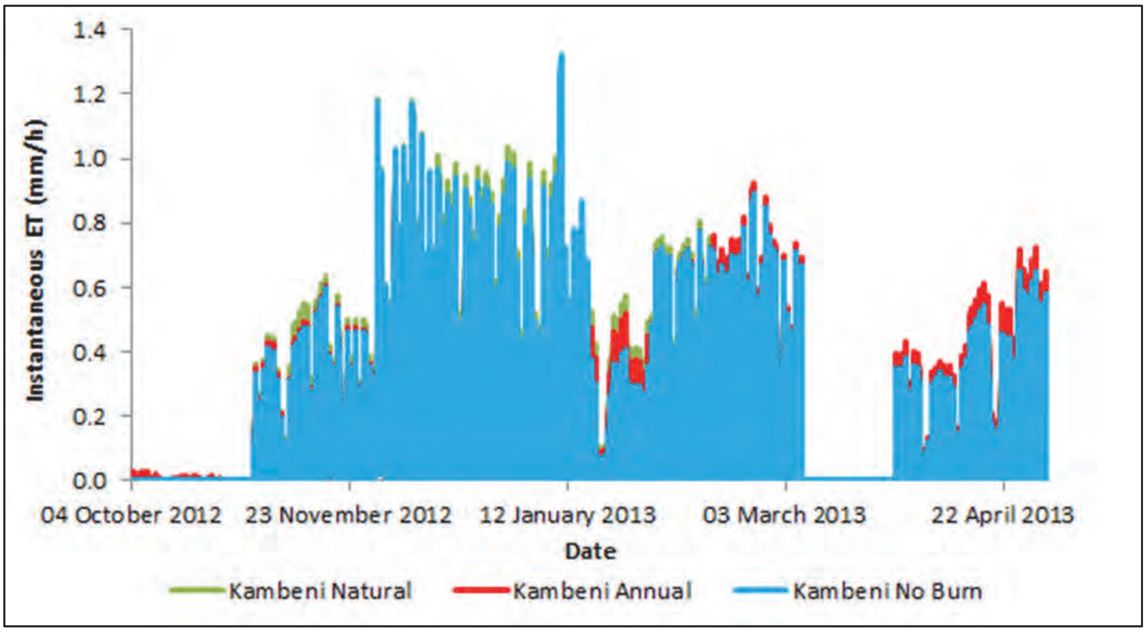

Figure 9.4 Kambeni aET before correction

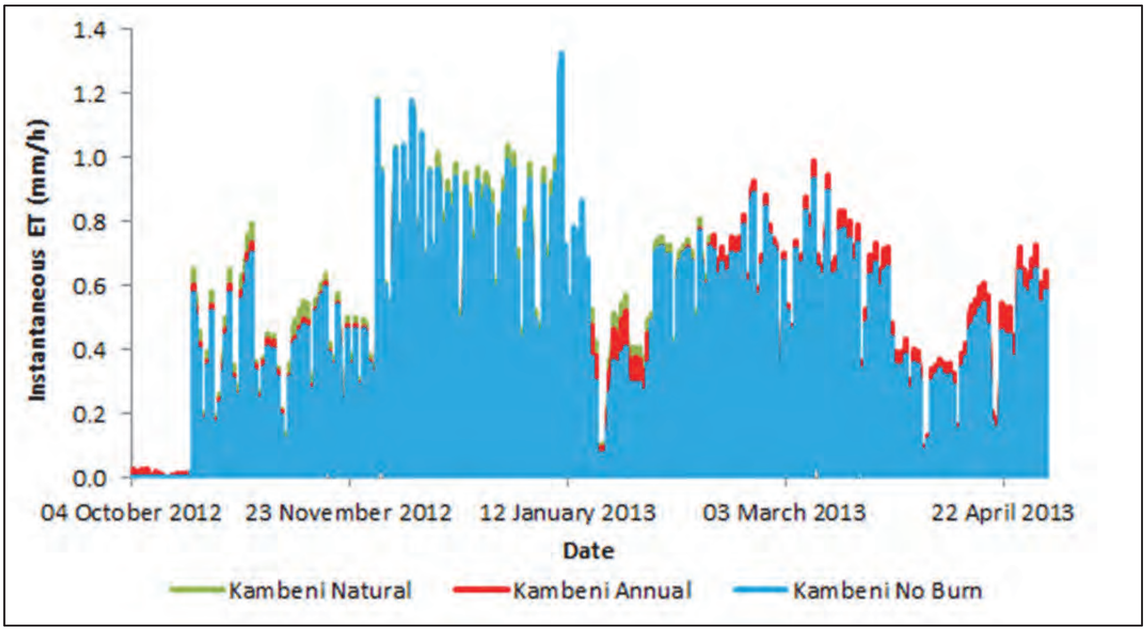

Figure 9.5 Kambeni aET after correction

Appendix C: Additional information relating to the SEBAL and HYDRUS modelling

(i) Justification of evapotranspiration partitioning

Sutanto *et al*. (2012) and Lauenroth and Bradford (2006) state that quantifying the partitioning of evapotranspiration is extremely challenging, mainly due to two reasons (1) the partitioning of evapotranspiration into transpiration and evaporation is strongly dependent on above ground biomass, seasonality, soil texture and precipitation. (2) Distinguishing between evaporation and transpiration fluxes is very difficult.

- In general, however, using a grass-covered lysimeter simulating summer conditions, Sutanto *et al*. (2012) found a partitioning of 86.7% and 13.3% for transpiration and evaporation respectively using an isotope analysis method, and alternatively discovered a partitioning of 69.7% and 30.3% for transpiration and evaporation respectively using a modelling technique (HYDRUS 1D).
- Lauenroth and Bradford (2006) found the average fraction of transpiration from a semi-arid grassland, situated 30 km south of Cheyenne, Wyoming, USA to range from 40-75% depending on the season, soil type and above ground biomass.
- Yepez *et al*. (2003) estimated a transpiration fraction of 85% and a soil evaporation fraction of 15% within a heavily vegetated semi-arid savanna in Arizona, USA, with dense deep rooted woody vegetation.

Therefore since the partitioning values obtained using a K_d value of 0.8 fell within the general ranges supported by the literature and identifying the complexity in determining such fluxes, this partitioning fraction was implemented (with visual analysis of the EBPs suggesting a relatively high vegetation cover in general). Additionally for simplicity it was assumed that the rooting depth was equal to the depth of the soil (Domain i.e. 1000 mm), with the maximum rooting intensity applied to the upper 300 mm of the soil and the rooting distribution focused in the vertical direction, i.e. a limited horizontal rooting distribution. Again this assumption was consistently applied throughout.

(ii) Setting-up EBP domains

The area of each EBP was obtained from GIS data analysed with ArcGIS 9. The area was used to calculate plot dimensions (for simplicity the area was assumed to be square, X = Y). These dimensions (X and Y vectors) along with a selected soil depth (Z vector) were converted into millimeters and input into HYDRUS to create each EBP domain (Figure 9.6). The VFR X, Y domains, however, were created slightly differently, since they are not demarcated like the EBPs. In this case the GPS points of the soil samples taken in the VFR area were used to create polygons (shape files) in ArcGIS 9 that were traced around the sample points. The area was then similarly calculated using the calculate geometry function in ArcGIS 9 and subsequently the X and Y dimensions were determined and entered into HYDRUS as the domains for the VFR.

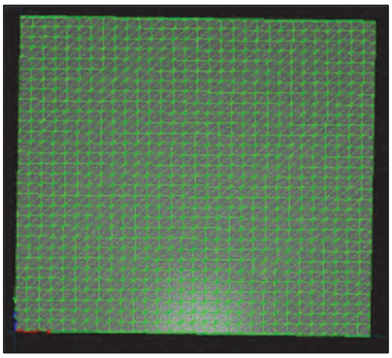

Figure 9.6 Example of the Kambeni no burn EBP domain as set-up in HYDRUS

Appendix D: SEBAL data and model setup

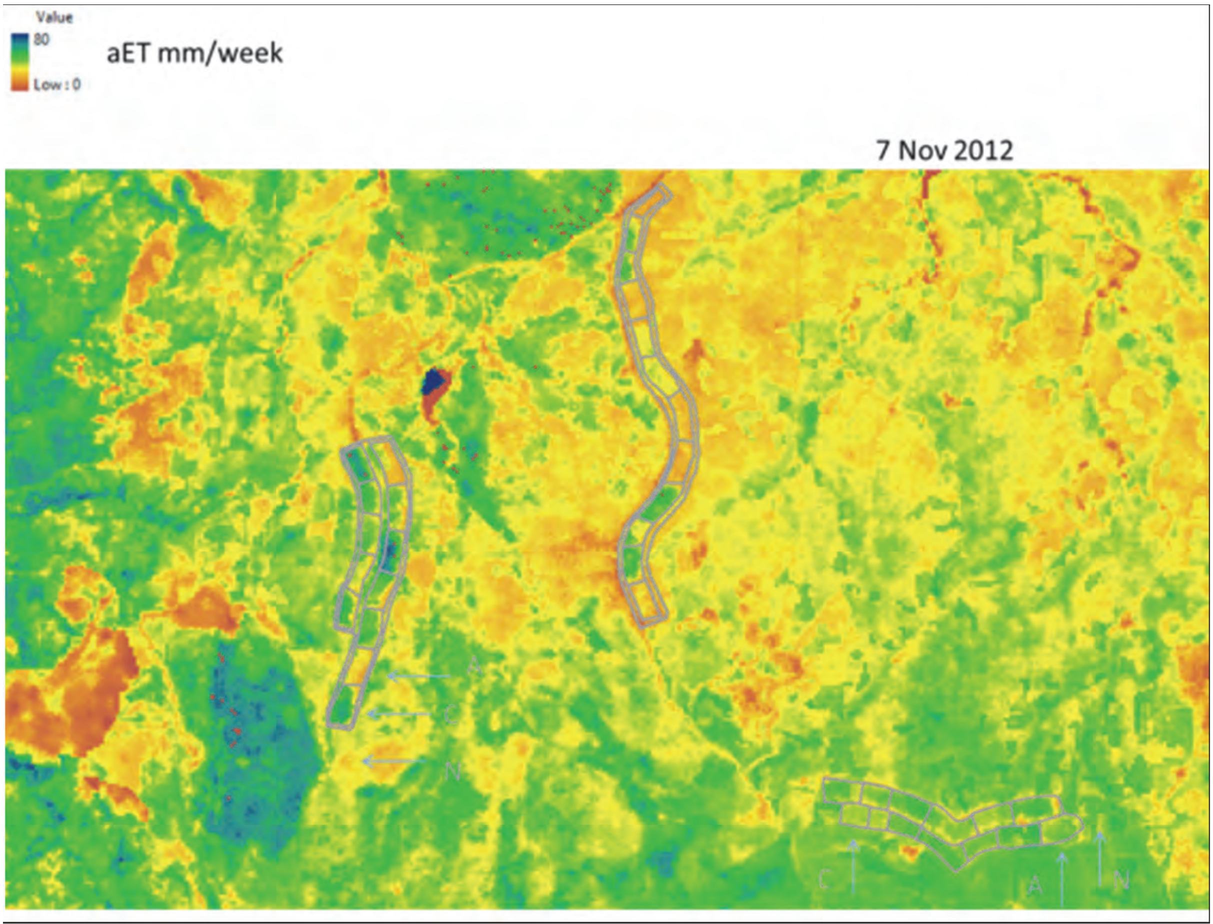

Figure 9.7 SEBAL data available for 7 November 2012

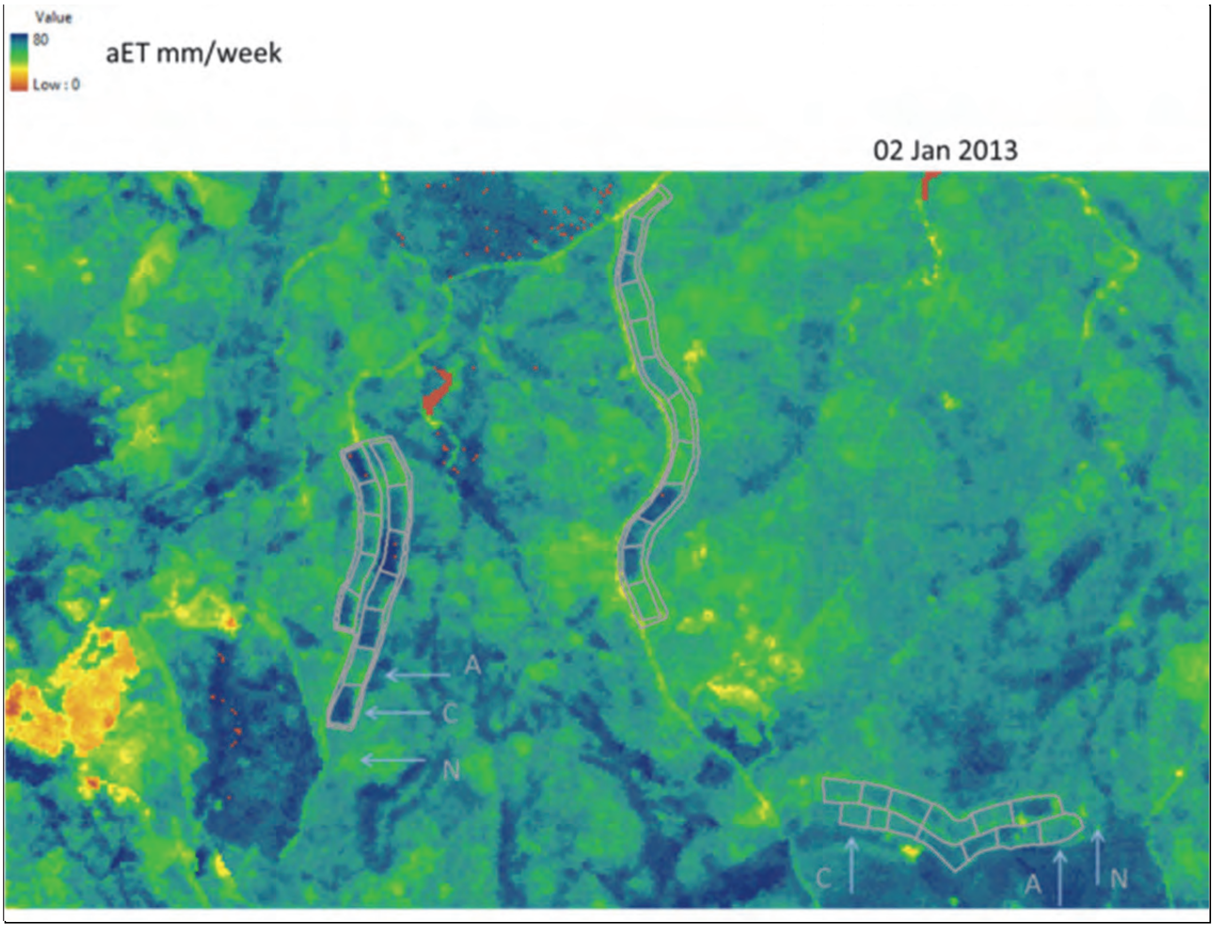

Figure 9.8 SEBAL data available for 2 January 2013

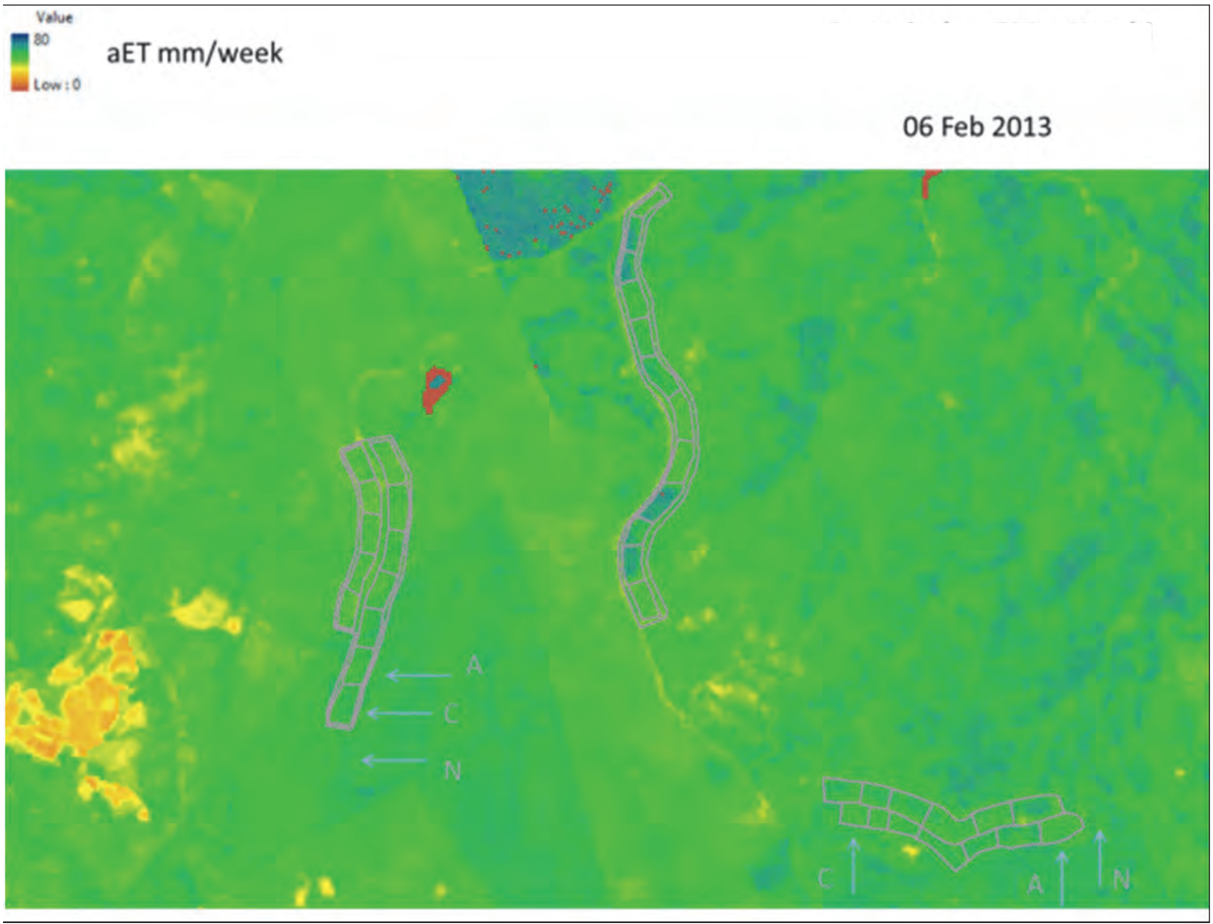

Figure 9.9 SEBAL data available for 6 February 2013

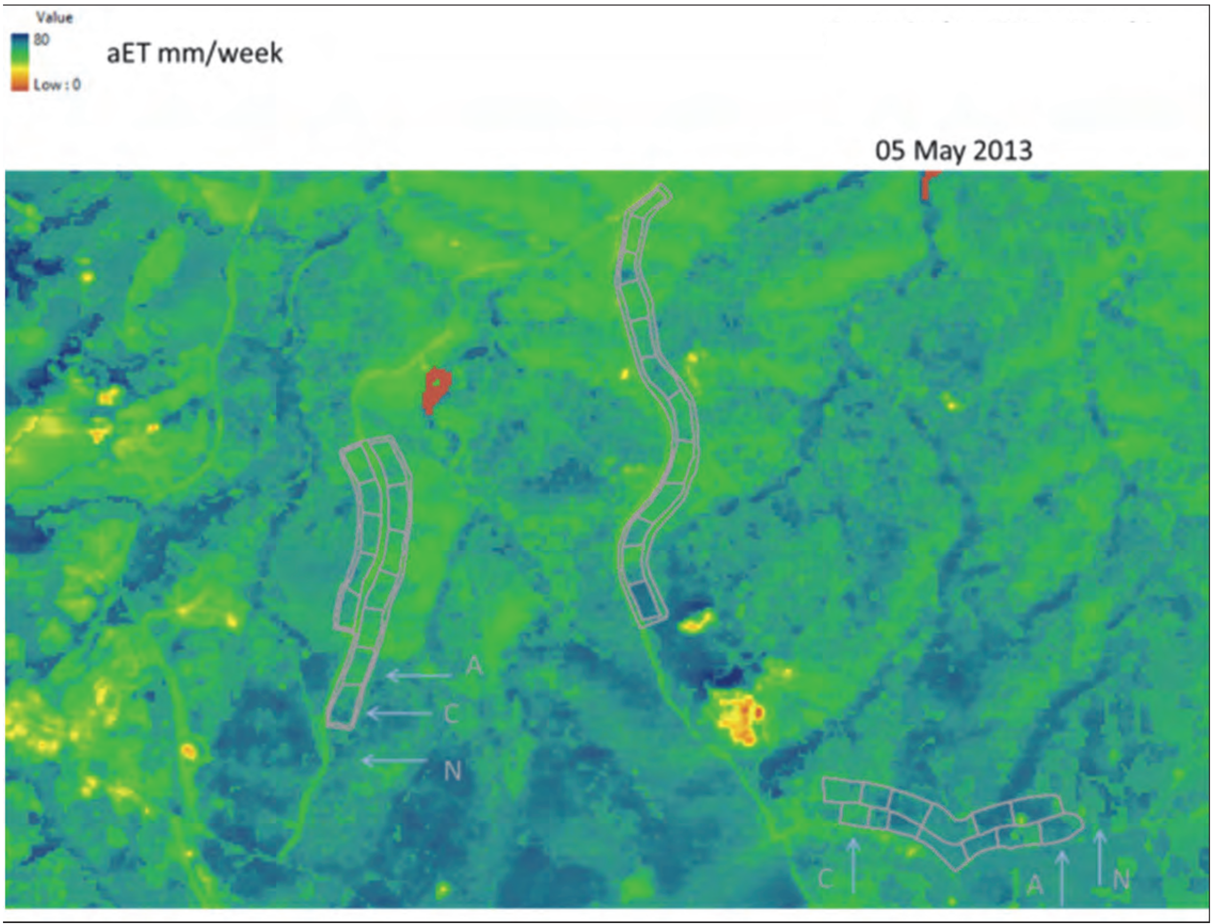

Figure 9.10 SEBAL data collected on 5 May 2013

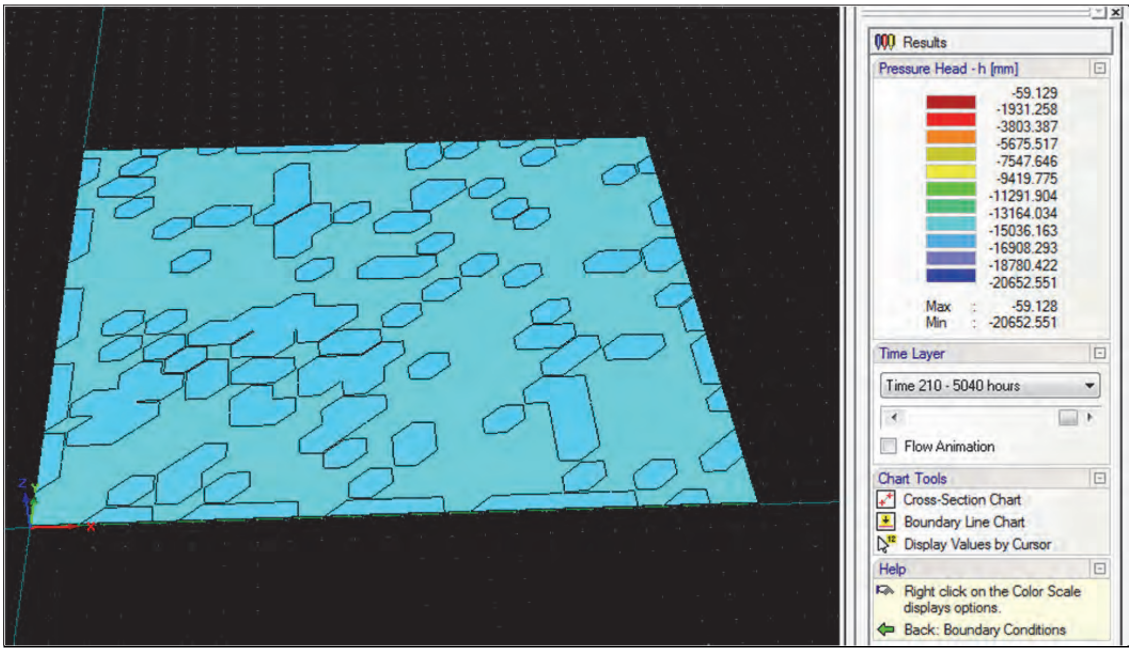

Figure 9.11 Pressure head on Kambeni no burn plot at the end of the modelling period (time 5040 hours)

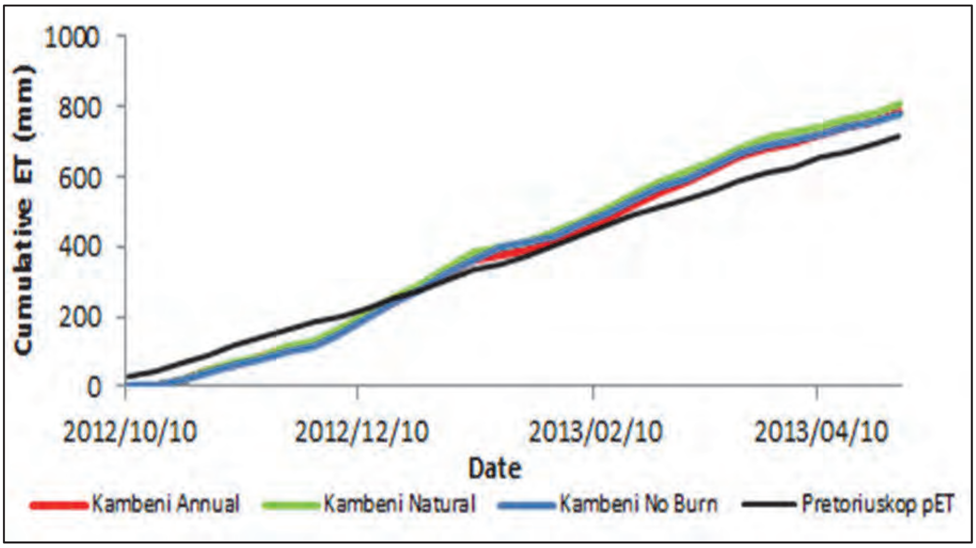

Figure 9.12 The outcome of using the SEBAL data and the model

Appendix E: Results for each statistical test conducted at Numbi, Kambeni and N'wanetsi EBPs

Table 9.4 Statistical results for each variable measured at the Numbi EBPs on the granites

		Distribution	Statistical Test	Test Value	P-value	Significance
K_{unsat}	5 mm	Not normal	Mann-Whitney U	143	0.191	No
	30 mm	Not normal	Mann-Whitney U	125	0.254	No
K_{sat}	2-3 cm	Not normal	Mann-Whitney U	61	0.000	Yes
	5-7 cm	Not normal	Mann-Whitney U	124	0.068	No
Soil Compaction	1st Strike	Not normal	Mann-Whitney U	496	0.000	Yes
	2nd Strike	Not normal	Mann-Whitney U	452.5	0.000	Yes
	3rd Strike	Not normal	Mann-Whitney U	446	0.000	Yes
	10th Strike	Not normal	Mann-Whitney U	680	0.000	Yes

Table 9.5 Statistical results for each variable measured at the granitic Kambeni EBPs

Variable		Distribution	Statistical Test	Test Value	P-value	Significance	Post-hoc Test
K_{unsat}	5 mm	Not normal	Kruskal-Wallis	10.830	0.005	Yes	Multiple Comparisons
	30 mm	Not normal	Kruskal-Wallis	9.183	0.010	Yes	Multiple Comparisons
K_{sat}	2-3 cm	Not normal	Kruskal-Wallis	1.512	0.470	No	Not required
	5-7 cm	Not normal	Kruskal-Wallis	0.914	0.633	No	Not required
Soil Compaction	1st Strike	Not normal	Kruskal-Wallis	49.055	0.000	Yes	Multiple Comparisons
	2nd Strike	Not normal	Kruskal-Wallis	37.705	0.000	Yes	Multiple Comparisons
	3rd Strike	Not normal	Kruskal-Wallis	24.407	0.000	Yes	Multiple Comparisons
	10th Strike	Not normal	Kruskal-Wallis	19.770	0.000	Yes	Multiple Comparisons
Soil Organic Matter		Not normal	Kruskal-Wallis	1.260	0.533	No	Not required
Soil Water Potential		Not normal	Kruskal-Wallis	0.902	0.637	No	Not required
Grass Biomass		Not normal	Kruskal-Wallis	157.1	0.000	Yes	Multiple Comparisons

Table 9.6 Statistical results for each variable measured at the basaltic N'wanetsi EBPs

Variable		**Distribution**	**Statistical Test**	**Test Value**	**P-value**	**Significance**	**Post-hoc Test**
K_{unsat}	5 mm	Not normal	Kruskal-Wallis	1.463	0.481	No	Not required
	30 mm	Not normal	Kruskal-Wallis	2.468	0.291	No	Not required
K_{sat}	2-3 cm	Not normal	Kruskal-Wallis	5.791	0.055	No	Not required
	5-7 cm	Not normal	Kruskal-Wallis	4.431	0.109	No	Not required
Soil Compaction	1st Strike	Not normal	Kruskal-Wallis	75.598	0.000	Yes	Multiple Comparisons
	2nd Strike	Not normal	Kruskal-Wallis	87.989	0.000	Yes	Multiple Comparisons
	3rd Strike	Not normal	Kruskal-Wallis	89.020	0.000	Yes	Multiple Comparisons
	10th Strike	Not normal	Kruskal-Wallis	56.688	0.000	Yes	Multiple Comparisons
Inside vs. Outside Herbivore Exclosures (Annual Plot)		Not normal	Mann-Whitney U	137.500	0.000	Yes	Not necessary
Inside Herbivore Exclosures (Annual and No Burn Plot)		Not normal	Mann-Whitney U	28	0.000	Yes	Not necessary
Soil Organic Matter		Not normal	Kruskal-Wallis	29.337	0.000	Yes	Multiple Comparisons
Soil Water Potential		Not normal	Kruskal-Wallis	1.800	0.407	No	Not required
Grass Biomass		Not normal	Kruskal-Wallis	176.041	0.000	Yes	Multiple Comparisons