Limpopo Lipadi Research

Defining the water balance of the Limpopo Lipadi Reserve for a resilient future

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Delft University of Technology

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by

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Abstract

The Limpopo Lipadi Reserve has the difficult task of restoring its natural ecosystems and protecting them from future challenges. The increasing occurrence of droughts due to climate change and the historical use of this land for cattle farming contribute to concerns about the future availability of water for animals, vegetation and staff, as well as the overall health of the soil. By establishing a water balance and investigating soil health, conclusions could be drawn about the current state of the Reserve's soil and water resources and recommendations made for future research. The parameters of the water balance were defined by combining the literature and the results of field experiments. A climate change model was applied to the water balance to assess how the Reserve will be affected by changes in precipitation and temperatures. Soil sampling was also undertaken at four characteristic sites in the Reserve to assess the impact of bush clearing on soil health and aquifer recharge through changes in physical, biological and hydraulic properties.

The results of the water balance and the different simulated scenarios show that: 1) the aquifers can currently be accounted as reliable when considered as a total available resource for the entire area of the Reserve; 2) when the bush clearing scenario was simulated, it was found that doubling the amount of clearing has a minor impact and only when 50 % of the reserve is cleared the impact becomes significant; 3) due to climate change and its impact on ecosystems, it was found that there will be an intensification of the hydrological cycle (wetter, hotter summer) with an increased seasonality. However, the results of this scenario indicated that there will be no drastic changes in the main pattern of water dynamics in the next 25 years and therefore no immediate threat to the available groundwater storage.

In carrying out the soil characterisation tests, it was noted that 8 different soil types were being studied, which would certainly include a wider range of values for soil properties. However, looking at the effects of bush clearing and considering the different types of soil, the results showed that there was indeed an outcome in the treated areas. For most of the studied sites, it was consistently found that bulk density had increased in the cleared areas, while porosity levels, soil moisture and organic matter decomposition rate had decreased. It was also discovered that as a side effect of bush clearing, insects such as termites were present, which played a role in some of the soil processes. Furthermore, no clear relationship with clearance status could be observed for hydraulic conductivity. These results were then used in a multi-criteria analysis to assess the health of the soils studied. This assessment showed that, overall and for the specific purpose of the research undertaken, all the soils analysed could be classified as 'healthy' to sustain the current environmental practices of the Reserve, even after clearing was performed.

Although the results presented in this report take into account the current status of the Reserve, it is noted that there may be differences when different time frames are considered. The results provide valuable insights based on the highlights found and, based on these, recommendations that will impact the future environmental management and land use practices of the Reserve are provided.

Further analysis is recommended to gain a complete understanding of the possible effects of bush clearing on water dynamics and to compare the results presented in this research. It must also be

borne in mind that there may be discrepancies in the results obtained due to lack of equipment and time constraints.

2
Introduction

Botswana is one of the world's 186 water-stressed countries, with an average annual rainfall of 481 mm and a total evapotranspiration (TET) of 468 mm per year [1]. In addition, water resources are unevenly distributed throughout the country, with most of the water in the north-west and the population concentrated in the eastern corridor [2]. The country's geographical location, semi-arid climate and high dependence on international and transboundary water [2] make it vulnerable to drought and water scarcity. This affects not only human water consumption, but also the country's flora and fauna. The Limpopo Lipadi Reserve (also referred to as "LLR" and "the Reserve" in this report), located in south-eastern Botswana, in the Tuli Block, has the challenging task of preventing, mitigating and overcoming water scarcity at a local level, so that it can continue to be a sanctuary for wildlife.

The Reserve has a rich history and its land underwent many changes over the years. Initially, it was utilized as a cattle farm owned by the Van Niekerk family and was also used to grow crops such as peanuts, maize, potatoes, cabbage, and orange trees. In 2002, South African promoters purchased the land and transformed it into a game reserve and wildlife sanctuary [3]. Decades of cattle ranching, of different land uses and of different management practices have impacted the surrounding ecosystems, and combined with the challenges of climate change, have encouraged widespread bush encroachment. This phenomenon consists of certain invasive species (i.e. Acacia Tortilis and Sickle bush) dominating vegetation areas to the detriment of other more nutritious species for animal consumption. To restore the Reserve to its full potential, bush clearing has been carried out in affected areas, by cutting or burning invasive species to make way for grass. However, little is known about the effects of this practice on soil health and aquifer recharge.

The climatic conditions of Botswana present challenges linked to water scarcity and its management in the context of a semi-arid climate and the reality of global climate change. In addition, the primary water source for the Reserve are the underground aquifers which allow for the presence of permanent waterholes for the animals and water availability for human consumption. Comprehensive data on aquifer dynamics is currently lacking in the context of the Reserve, increasing the risks of extracting groundwater at unregulated rates. Managing extraction rates as consciously as possible is therefore crucial, particularly in dry years like the present and upcoming years. This issue could potentially be further impacted by the ongoing bush clearing activity in the Reserve, while clearing vegetation may improve visibility and help with land management, its effects on soil health and water retention are largely unknown. In this context, the possible consequences of bush clearing of reducing the soil's ability to retain moisture, further straining the already suffering groundwater water supply will be researched.

Therefore, this report aims to answer the following research question: "How do the major water fluxes in the Limpopo Lipadi Reserve interact to form a comprehensive water balance, given the different soil characteristics, water retention capacities and land management practices?"

This research question gives rise to a number of sub-questions and hypotheses that are the guiding principles of this investigation project:

- ”How can the main water fluxes (precipitation, evaporation, groundwater abstraction, surface runoff) within the reserve be quantified?”
  This sub-question serves as a starting point, significant data regarding both natural fluxes like rainfall and evaporation, and human-driven factors like groundwater abstraction need to be collected and analyzed to be quantified and linked together.
- ”What is the impact of future climate change and bush clearing practices on the dynamics within the system?” This sub-question will provide a quantitative assessment of how bush clearing practices impact groundwater storage and will show the future effects of climate change on this resource within the reserve.
- ”What are the impacts of bush clearing on soil health, water retention capacity, and aquifer recharge?”
  This sub-question seeks to understand how soil composition influences water behavior through the first layers of the soil matrix, specifically, given the potential for bush clearing to alter its dynamics.
- ”What are the recharge rates of the boreholes within the reserve, and how can these rates be monitored effectively to support more sustainable and conscious groundwater extraction?”
  Providing the Reserve with a simple and reproducible method to assess the boreholes recharge rate will represent a starting point to increase the ability of consciously extracting groundwater. This is being done with the intention of reducing water waste and advancing the basic understanding of the dynamics of subsurface water.

Hypotheses

- It is expected that the major outgoing fluxes are evaporation and transpiration due to the high local temperatures. Runoff and human extraction are considered significant due to concerns raised by reserve management regarding the impact of these fluxes on water resources.
- Cleared areas are anticipated to experience increased runoff and reduced infiltration, leading to a negative impact on groundwater storage.
- Climate change is expected to enhance seasonality, increasing the strain on the available groundwater.
- It is expected that the soil has less organic matter in cleared areas.
- It is anticipated that the microbial activity will be higher in vegetated (uncleared) areas.
- By clearing the land, it is expected to have a higher bulk density and a reduction of the hydraulic conductivity due to the soil disturbance.
- Sandy soils in the reserve should have a higher water conductivity due to their permeability.
- Clay soils should have a better holding capacity and improve soil health where this type of soil is found.

This report aims to give an overview of the Reserve’s current situation and to focus on analysing and answering the proposed research question. This was done by reviewing relevant literature, conducting various field tests (i.e. constant head infiltration, double ring infiltrometer, slug test, water runoff test, and the teabag index), and processing and analysing the collected data to identify trends and draw conclusions. Ultimately, the objective is to provide the Reserve with valuable recommendations that will hopefully have an impact on its future management and land use practices, preventing the threat of water scarcity and soil degradation.

3
Theoretical Background

3.1. Site description

3.1.1. Geography

The Limpopo Lipadi Reserve is located in south-eastern Botswana, and is part of the Tuli block [4] [5]. It covers 20,712 hectares and was fenced in 2007. Its southern boundary, as well as the border between Botswana and South Africa, is formed by the Limpopo river. This river, together with Lipadi hill, situated within the Reserve, served as inspiration for the name Limpopo Lipadi [5].

The climate in Botswana can be described by two seasons, summer and winter, where fall and spring are not distinguishable in this climate. Summer lasts from November to March and winter from April to October. Winter is characterized by its dry days, with no precipitation for up to six months. The average temperature is relatively cool, ranging from 14 to 22°C. Summer is characterized by its hot rainy days, with temperatures often exceeding 35°C. Overall, the climate can be defined as arid to semi-arid, with annual rainfall of about 400 mm [6].

The climate varies throughout the country and, as mentioned above, from season to season, meaning that national and annual averages cannot accurately describe the influence of climate, specifically on the Limpopo Lipadi Reserve. More localized measurements are needed to determine the impact of climate on, for example, the vegetation, geology and hydrology of the Reserve [5].

These rainfall patterns result in an event-driven ecological system, meaning that a rain event can change the growth production of the vegetation in the Reserve. The newly available moisture for vegetation can transform a brown, dry landscape into a lush green one [5]. This change in vegetation growth can come quite drastically after the first rain event, as the water will become suddenly available for the vegetation. This influx of vegetative growth increases soil organic matter. At the same time, this vegetative cover and additional moisture availability will help stabilize the topsoil [7].

3.1.2. Geology

As mentioned above, the Reserve is located in the Tuli Basin. This basin covers part of South Africa, Zimbabwe and Botswana and surrounds part of the Limpopo River. This basin is known for its geology, defined by sedimentary and igneous rocks of the Karoo supergroup [8]. The Karoo Rocks, found throughout southern Africa, show the changing climate of the continent. From a glacial climate, to a more temperate and humid climate, to the hot semi-arid conditions that are known today [5]. The Reserve is located on the southern edge of the Tuli block and the specific sediment types of this region may differ from the general Karoo Supergroup.
In 2019 a consultancy created a preliminary geological report for the Reserve of which the geological formations are shown in figure 3.1.

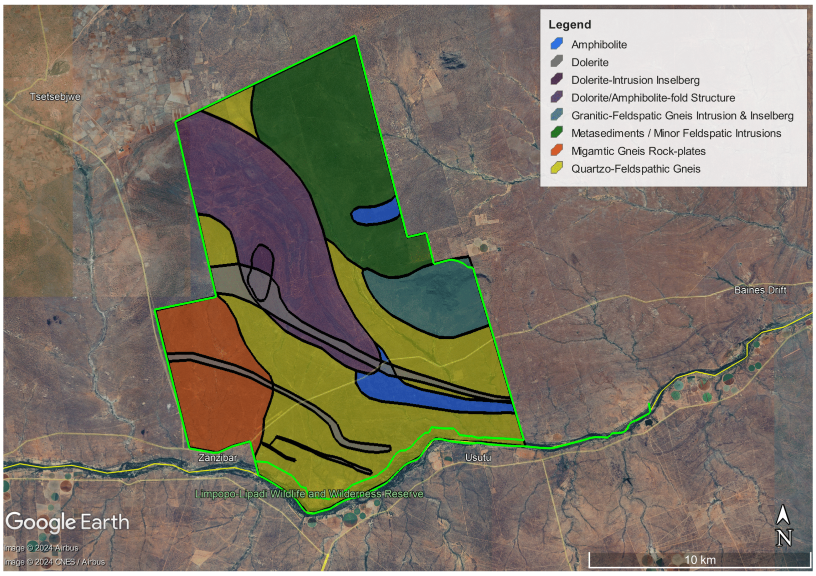


Figure 3.1: Preliminary geology report of the Limpopo Lipadi Reserve [5]

The most prominent lithologies in the Reserve are Archean gneisses and Archean metasediments. These lithologies have no primary permeability, with permeability being mainly due to secondary properties such as fracturing of the soil. This is particularly important for aquifer recharge. The main aquifers in the eastern part of Botswana, where the Reserve is located, can be identified as crystalline basement aquifers and, as mentioned above, infiltration is highly dependent on the weathering and fracturing of the bedrock [9] [10]. These aquifers are the nation's primary source of drinking water, and identifying characteristics of this bedrock is critical to understanding aquifer recharge.

In 2008 a soil survey was also completed, unfortunately the specifics of this soil survey could not be reviewed. The only information that remained are the identification of several top soils and surface horizons [5]. During this survey the main A-horizon was determined to be an orthic A-horizon, which was found across the entire Reserve. This horizon can be defined by the absence of a organic or humic topsoil. The main soil group that was found in the B-horizon are oxidic soils, meaning there is high concentration of iron oxides, giving the soil its red colour [7]. The main soil forms that were found are Hutton, Mispah, Clovelly, Glenrosa, Augrabies and Avalon [5].

3.1.3. Hydrology

The southern boundary of the Reserve is represented by the Limpopo River. However, this is not the only water course present, smaller seasonal drainage courses run throughout the study area as shown in figure 3.2. The hydrogeology of the area is mainly controlled by the geology, the surface water hydrology strongly influences the groundwater dynamics on the Reserve. Both the Limpopo River and the seasonal drainage courses impact the groundwater storage, being them dry for large portion of the year, rainfall and infiltration mechanisms are crucial in recharging the aquifer [5]. During the rainy season the aquifers get replenished the groundwater storage is therefore strongly dependent on the area receiving enough rainfall to sustain groundwater levels.

3.2. Description of the Limpopo Lipadi Reserve

3.2.1. Historical Land Management

Colonial Times

Due to the threat of the German Colony (South West Africa) in conjunction with the independent Boer Republic of the Transvaal, the British established the Bechuanaland Protectorate in 1885, covering what is now Botswana. This was done to prevent territorial gains by Germans and South African

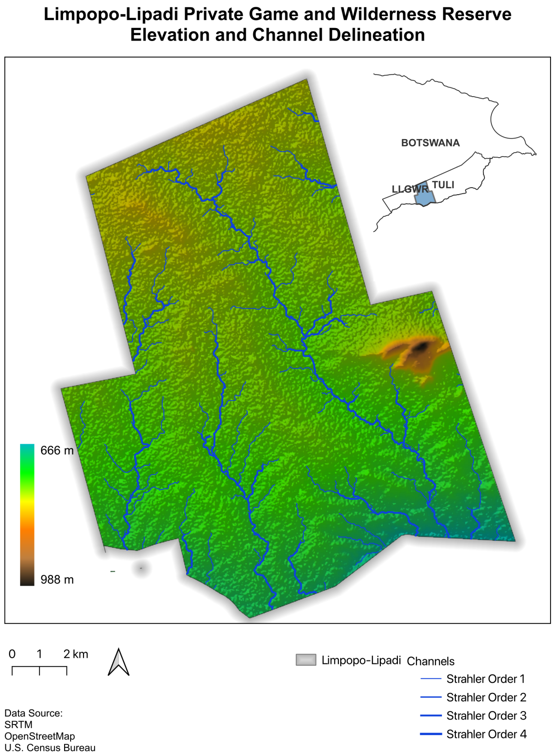


Figure 3.2: Limpopo Lipadi Reserve Elevation and Channel Delineation

citizens of Dutch, German or Huguenot descent, also known as Boers. The Bechuanaland Protectorate remained under British rule during this period, and the settlement of white people was limited and restricted to some areas [11].

The territory was divided into eight largely self-governing ”tribal” Reserves, and five farm blocks which included the Tuli Block, as freehold land for white settlers, while the remaining land was designated as Crown or state land. Currently, this division still exists within the country, with freehold land referring to land owned by a person or group of people who have elite control over its use and can be transferred from one owner to another without government approval, while tribal land refers to land claimed by the nation's various tribes and administered through the Tribal Arrive Act. Finally, state land refers to land owned and managed by the state for various purposes [12].

When the first farmers, mainly English and Afrikaner settlers, arrived in the region in the 20th century, they soon realized that the land was only suitable for livestock farming. As a result, and after realizing the opportunity to earn more money through tourism, the Tuli Block became a legendary hunting ground and trading route [13].

Farming

The land that now makes up the Reserve was traditionally used for cattle ranching. Historically, the property supported up to 3,000 head of cattle on 27,000 hectares, with the animals roaming freely and using various water points supplied by groundwater through boreholes and pumps, a system that is still in place today. In addition to cattle, crops such as peanuts, corn, potatoes, cabbage, and oranges were grown, although these efforts ceased around 2000 due to reduced rainfall. Cattle ranching continued on the Reserve until 2004. However, between 2002 and 2004, plans were made to purchase the farm and turn it into a private game Reserve, with a focus on wildlife conservation and the establishment of a sanctuary. In 2007, the land was fenced and used for both cattle ranching and commercial hunting.

Past agricultural activities and improper grazing practices have transformed the former Savannah landscapes into woodlands, dense forests, bush veld and thickets, affecting the vegetation found in the area, as well as causing significant soil erosion. This has led to a new vision and the need for a new land management plan.

3.2.2. Current Land Management

The Limpopo Lipadi Reserve has committed to ”active adaptive management with accompanying extensive habitat rehabilitation” [5]. Their goal is to return the land, which has been degraded by decades of exploitation and neglect, to a state of ”pristine wilderness” [5]. This approach involves detailed monitoring of vegetation and animals, intervention to balance animal feeding class ratios, and the use of science to inform decision making.

The Reserve aims to increase its potential vegetative carrying capacity for the grazing species in order to redistribute the animal grazing pressure. The goal is to create areas where palatable and nutritious species are abundant and accessible to grazer species. By this standard, an area densely populated with thorny bushes and unpalatable grasses is deemed problematic because it is of low nutritional potential for grazers and the thorns can cause infections in the animals' hooves.

The Reserve also aims to address localized overgrazing and bush encroachment to increase vegetative forage capacity through a water management program, bush thinning program, reseeding, animal stocking rates, increasing grasslands, and many other interventions. All of these issues are interrelated because water availability and land management practices affect the type of vegetation that can grow to feed the animals. Thus, any attempt to address this imbalance will have a major impact on the functioning of the Reserve as a whole.

A summary of the results of an Ecological Scoping Report and Survey conducted in 2019 found in [5] showed the poor condition of the Reserve due to a combination of factors: repeated droughts combined with a passive management strategy pushed the Reserve's flora and fauna to its limits, and immediate action was urgent. Thus, rehabilitation zones were identified as priority areas where the rehabilitation program has been implemented since 2019.

To better understand how these rehabilitation areas are selected, it is important to understand the type of vegetation present in the Reserve. The Reserve area is mainly comprised of sweet-veld mopane and mopane mixed bushveld vegetation which have been transformed into closed woodland and shrubland thickets. This change is largely due to livestock pressure and the recurrence of extreme weather events such as droughts. The vegetation found in the LLR can be characterized as part of an event-driven system, where organic matter (OM) production accelerates drastically with the onset of the rainy season due to short rainfall events.

Four major floristic units were identified in a floristic survey conducted in 2008: drainage line woodlands, mopane woodland, Vachellia Tortilis woodland and disturbed / over-grazed areas. Areas of past cultivated lands that were transformed into thorn tree shrubland savannah veld (i.e. disturbed / overgrazed areas) are the principal target of the rehabilitation programme. This habitat can be characterised by indicator species including D. Cinerea, V. Tortilis and C. Mopane open woodland (see Habitat 7 and 8 in Figure 3.3).

Habitats 7 and 8 share a similar vegetation profile, as these areas were disturbed by agricultural ploughing before they were added to the Reserve. The bushland and woodland then transformed to shrubland bushveld, making it harder for the plains game species to access the nutritious grass through the thickening and encroaching vegetation. They are characterised by shrubs of V. Tortilis, D. Cinerea and C. Mopane and a grazing capacity of 5 to 16 ha/LSU (Large Stock Unit) and a browse capacity of 8 to 15 ha/BU (Browser Unit) per annum. These values represent the ability of an area to sustain herbivore species without negatively impacting the local ecosystem.

Research into the factors involved in bush encroachment in Botswana's grazing areas reveals a debate about the anthropogenic responsibility in this phenomenon [14]. In bush encroached zones, cattle selectively graze herbaceous species which over time leads to encroaching species to dominate. The presence of cattle can also be linked to high soil nitrogen contents. Additionally, light or course grained soils in such areas have a lower moisture content which is favourable to woody plant growth. In contrast, a higher moisture content at the surface enhances grass growth. Compounding to the small amount of

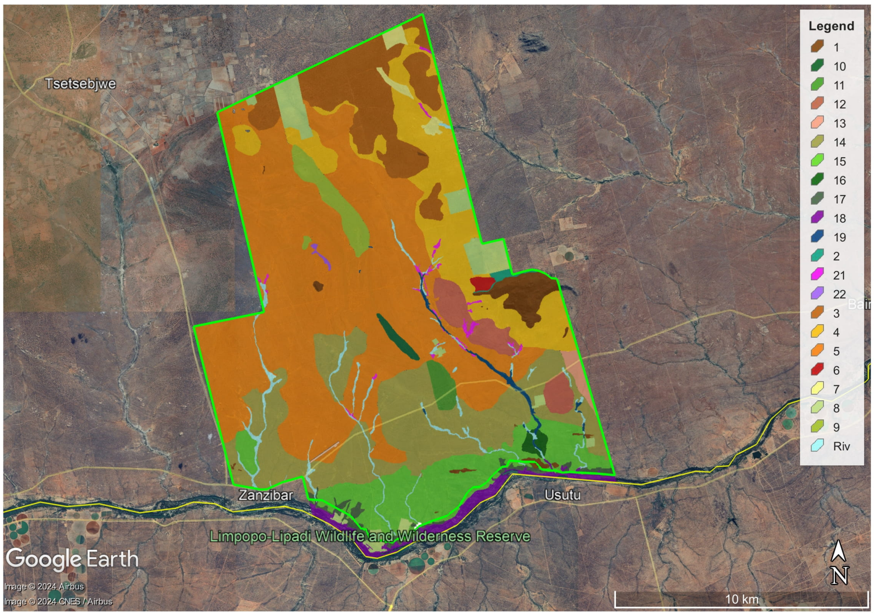


Figure 3.3: Map of the Vegetation Habitats in the LLR (from [5])

grass is a reduced frequency of fires as herbaceous species constitute the main fuel load.

To combat bush encroachment and improve animal nutrition opportunities, a bush clearing and re-seeding programme was first implemented in 2019 and is still in progress to this day. The programme consists in removing encroached bushes and re-seeding perennial climax grass species, though in practice re-seeding has only been implemented in minor parts of the cleared areas. The cut-off branches are left on site to decompose and provide cover for the new growth. The planted species are selected for their high nutritional value and palatability. The small shrubs are removed whilst the larger shrubs are left to create an open savannah environment with less than 100 trees per hectare area. The specifics of the rehabilitation strategy varies depending on the veld habitat and soil potential [5].

3.3. Impact of Climate Change

As a country, Botswana is highly vulnerable to climate variability and change due to its heavy reliance on rain-fed agriculture and natural resources, and its relatively low adaptive capacity. High levels of poverty, particularly in rural areas, further increase this vulnerability. The main challenges posed by climate change in Botswana revolve around the availability of water resources, changing rainfall patterns, and the increasing demands of a growing population.

Botswana's climate is characterized as arid to semi-arid, with highly variable rainfall patterns. As mentioned above, Botswana experiences only two seasons, summer (November to March) and winter (April to October). The rainy season lasts from approximately October to April, with large annual variations. Botswana's climate is determined by a number of natural phenomena. These include its proximity to the equator, its inland location and its flat topography. Botswana's high temperatures are related to its proximity to the equator, as it receives intense solar radiation throughout the year. The generally flat topography does not affect the weather patterns too much, allowing other weather systems mentioned later to dominate. However, local variations in elevation, such as in the eastern parts of the country (where the Limpopo Lipadi Reserve is located), can slightly affect rainfall distribution [6]. Moreover, the Hadley Cell plays a significant role in Botswana's climate by driving both the Subtropical High Pressure System and the Inter-Tropical Convergence Zone (ITCZ). The Hadley Cell is a large-scale atmospheric circulation pattern that operates between the equator and about 30° latitude in both hemispheres. The Subtropical High Pressure Belt, is a zone of high atmospheric pressure typically located around 30° latitude in both hemispheres. This belt is formed by descending air from the upper atmosphere due to Hadley cell circulation. This pressure system contributes to Botswana's arid to semi-arid climate by suppressing cloud formation and rainfall, resulting in dry conditions, especially outside the rainy season. The ITCZ is the region where trade winds from the northern and southern hemispheres meet. Warm, moist air rises in the ITCZ, resulting in frequent rainfall and thunderstorms. This zone is highly dynamic, shifting north and south with the seasons, following solar heating patterns. During the summer months (November to March), the Inter-Tropical Convergence Zone (ITCZ) brings moisture to the northern and eastern parts of Botswana, with progressively drier conditions towards the western regions. Mean annual rainfall varies across the country, from over 650 mm in the northeast to less than 250 mm in the southwest, with a national average of about 475 mm. Also, El Niño and La Niña have a significant impact on Botswana's climate. During El Niño years, the country often experiences reduced rainfall and increased drought. Conversely, La Niña years can bring more rainfall, although still with variability [15].

In recent decades, Botswana has experienced notable changes in its climate, particularly in temperature and precipitation patterns, partly related to the expansion of Hadley cells. According to [6], average temperatures have increased by 1.5°C since the 1970s, with increases of up to 2°C observed in the central and arid interior regions. The most significant warming has been observed in the November to March period. In addition, an increase in the frequency of warm days and nights and a decrease in cold days and nights have been observed throughout the region. This increase in temperature leads to higher evaporation rates and changes in rainfall patterns and may further increase the tension between agricultural, livestock and human water needs and alter groundwater quality. Within the Limpopo Lipadi Reserve, a shift in temperature could lead to further heat stress on the current ecosystem, including both animals and vegetation.

Precipitation trends remain very variable over both seasons and years. The changes in precipitation are expressed in the onset, duration, and intensity of rainfall events, with an increased frequency of dry spells [16]. These changes pose significant risks to water availability and the broader ecological and socio-economic systems in Botswana. Floods and droughts have always affected the population, however the magnitude, frequency, and impact has been observed to have increased. Increased periods of drought will affect the availability of water resources and will put increased stress on groundwater as a source. Groundwater is the main source of water within the Limpopo Lipadi Reserve, decrease in rainfall and increase in high intensity rainfall events can affect the water infiltration and thus the groundwater recharge negatively, which could lead to over abstraction of groundwater and eventually severe water shortages within the Reserve. In short, shifting climate conditions and especially shifting rainfall patterns could potentially negatively impact the ecosystems, wildlife, plant species, and natural habitats within the Limpopo Lipadi Reserve.

3.4. Bush encroachment and clearing

Bush encroachment refers to the expansion of native woody species in the savanna ecosystem. It is a threat to southern African soils that has been recognized since the end of the nineteenth century. Several factors have been identified as potential drivers of bush encroachment, including climate, animal pasturing, fire regimes, increased harvesting of woody species for fuel production and land use change for human settlement, among others. It has been shown that bush encroachment tends to be more rapid on small conservancies, moderate on commercial soils, and slower on communal lands and in natural environments where mega-herbivores are present, as is the case in the Reserve [17].

Previous research conducted for Botswana's land concludes that by 1995, approximately 6.8% or 37,000 km2 of the country's land area had been encroached upon [18]. This made the practice of bush clearing techniques, which consist of the removal and disposal of bushes and root systems to prevent their regrowth and prolong clearing cycles, urgent [19].

Unfortunately, the soils in the Limpopo Lipadi Reserve are not immune to this situation, mainly due to previous farming activities that have weakened the health of the soils. For this reason, different methods of bush clearing are practiced within the demarcated zones. In an interview with the Reserve's Research Manager, it was noted that all bush clearing methods are used in the Reserve to prevent further bush encroachment. The type of bush clearing method, i.e. manual or mechanical, is chosen based on the type of vegetation found at each site. Hand clearing is preferred when selective clearing is required, as mechanical clearing makes it difficult to select bushes. Chemicals are applied to the stem of the removed vegetation; the selected chemical does not affect animals or surrounding vegetation. The whole interview can be found in the Appendix E.

A review of the available literature on the effects of bush clearing on various soil properties revealed a lack of clear scientific consensus. While some articles emphasize the negative effects of this practice, others advocate its benefits. This highlights the need for soil health experiments to be conducted in situ on the Reserve, as the relevant scientific literature shows significant variation. The following paragraphs provide an overview of the various findings related to the effects of bush clearing in order to establish a baseline against which the results of the analysis of the soil characteristics of the Limpopo Lipadi Reserve can be compared.

A thesis investigating the effects of bush clearing on soil properties at the Cheetah Conservation Fund farm in Otjozondjupa, Namibia, demonstrates the detrimental effects of this activity [20]. The study was conducted in an area with a similar context to the Reserve, with a semi-arid climate, thorn bush savanna vegetation type and chromic cambisols. By experimentally detecting differences in physical, chemical and biological indicators in both cleared and uncleared sites, the theory of negative impacts of bush clearing was corroborated. The results showed that the cleared sites had a significantly higher nitrogen content than their uncleared counterparts due to the process of nitrogen fixation by leguminous trees. Once the trees were removed, this natural cycle was interrupted, resulting in a decrease in N content of the cleared sites. In addition, the study found that soil Organic Matter (OM) and macronutrient levels were depleted on cleared sites where the vegetative cover had been removed, coupled with the exposure of the topsoil to erosion during extreme rain events.

Also, the article *Changes in Soil Organic Matter Associated with Land Use of Arenosols from Southern Botswana* [21], provides valuable insights that complement the present research, as one of the sites analysed is the located on the Tuli Block, similarly to the Reserve. Although these types of soils are known for having a low amount of OM, also due to the clearing of the areas, a decrease in the content of free organic matter was suspected. The humic acid content was also higher in the cleared areas than in the uncleared areas. This parameter is important because it contributes significantly to soil fertility by improving its structure, nutrient holding capacity and water retention, which is particularly important in dry or arid regions. It also suggests that human activities cause both soil disturbance and changes in the nature of organic matter in the soil.

A study on semi-arid soils in Zimbabwe [**Campbell_clearing**] warns that while bush clearing may temporarily enhance grass growth, the long-term effects can harm soil health. Reduced canopy cover diminishes organic matter contributions, eventually lowering soil fertility and grass production. Trees and shrubs also aid in maintaining soil structure and moisture, important for aquifer recharge.

These unfavourable effects are also supported by an article focused on the side-effects of different bush clearing techniques [22]. The impacts of mechanical and manual bush clearing should not be underestimated as physical disturbance can alter habitat structure and thus promote the re-establishment of undesirable species and other perennial plant species. Thinning and clearing of vegetation species leads to rapid changes in competition between woody and herbaceous species. Furthermore, the authors emphasize the importance of being aware that focusing on controlling bush encroachment could lead to the rapid establishment of new problematic woody species.

In parallel with these findings, several sources confirm the benefits of bush clearing. The Namibian bush-clearing report [23] connects soil hydraulic behaviour to vegetation cover, explaining that shallow-rooted grasses compete with deep-rooted shrubs and trees for water. When the grass layer is sparse or cleared, water infiltrates deeper into the soil, favouring shrub growth. However, a dense grass layer after clearing can increase water runoff, as grass consumes the topsoil's moisture.

Another source that confirms the short-term benefits of bush clearing is [**SA_clearing**], which states that bush clearing is essential for the restoration of herbaceous vegetation. This source includes an evaluation of bush clearing performed at Makapaanstad, North West Province in South Africa. On cleared sites in this area, grass was found to be more abundant and total biomass production was lower. However, the report notes that vegetation restoration and its success is highly dependent on the bush clearing method used. Nevertheless, for this particular case and study site, it is stated that bush clearing is important for the restoration of herbaceous vegetation.

Bush clearing's impact on soil respiration has also been explored, revealing no significant differences between cleared and uncleared sites [24]. This is due to various processes in both areas, such as root biomass in uncleared sites and litter content in cleared areas. However, soil respiration was found to be more influenced by soil moisture than temperature or clearing methods, suggesting that seasonal and ecosystem variations are key to understanding soil respiration's link to bush clearing. Moreover, a study from Makapaanstad, South Africa, emphasizes short term benefits of bush clearing and states that it is essential for restoring herbaceous vegetation, noting increased grass abundance and lower biomass production in cleared areas. However, the success of vegetation restoration depends on the clearing method used [**SA_clearing**].

Finally, and from a more neutral point of view, another study discusses that bush clearing did not show significant differences in carbon content between cleared and uncleared areas. This was due to factors such as clay content, cation exchange capacity and rainfall rather than changes in soil physical properties. The naturally high fertility of the Tuli Block soils was found to be related to soil composition rather than land management practices [21]. Thus, the lack of a clear scientific consensus on the effects of bush clearing reinforces the importance of this study to observe the effects of this activity specifically in the LLR.

3.5. Stakeholder Analysis

Limpopo Lipadi aspires to establish itself as one of Southern Africa's premier wildlife and wilderness reserves, while prioritizing conservation, community engagement, and a unique visitor experience. Achieving this vision requires a comprehensive understanding of the diverse factors and stakeholders contributing to the Reserve's development and success. It is essential to understand the different levels of power and interest of the Reserve's stakeholders, in order to delimit the scope of this research and identify relevant sources of information. For Limpopo Lipadi, the following stakeholders have been identified,

- Limpopo Lipadi Reserve
- Shareholders/co-owners
- Landowners
- NGO donors
- Family and friends of shareholders
- Tourists
- Limpopo Lipadi staff
- Other Reserve staff
- Management
- Game Reserve Council
- Reserve committees
- Local communities
- Motse Initiative
- Anti-Poaching Unit (APU)
- Botswana Defense Force
- Department of Wildlife and National Parks (DWNP)
- Tuli Block region
- Vegetation
- Wildlife
- Botswana Government

For further information regarding each stakeholder, see Appendix A.

Figure 3.4 shows the division of the Limpopo Lipadi stakeholders, mentioned above, into internal and external stakeholders. Internal stakeholders are defined as individuals within an organization who are directly involved in decision processes [25], while external stakeholders are individuals outside of an organization who have vested interest in the service being offered [26].

The following stakeholders are considered to be internal within Limpopo Lipadi: Limpopo Lipadi staff, other Reserve staff, Limpopo Lipadi Investment Limited Board (LLBIL Board), Anti-Poaching unit (APU), Shareholders, shareholder committees, Game Reserve Council, management and landowners.

The remaining stakeholders are classified as external, they are the following: Tuli Block region, NGO donors, Botswana Defence Force (BDF), Motse Initiative, Department of Wildlife and National Parks (DWNP), wildlife, vegetation, family and friends of stakeholders, tourists, and local communities, Botswana Government.

Figure 3.4: Internal and external stakeholders of Limpopo Lipadi Reserve

Figure 3.5 includes a power-interest diagram for Limpopo Lipadi Reserve, showing the the power-interest relationship of the stakeholders mentioned above.

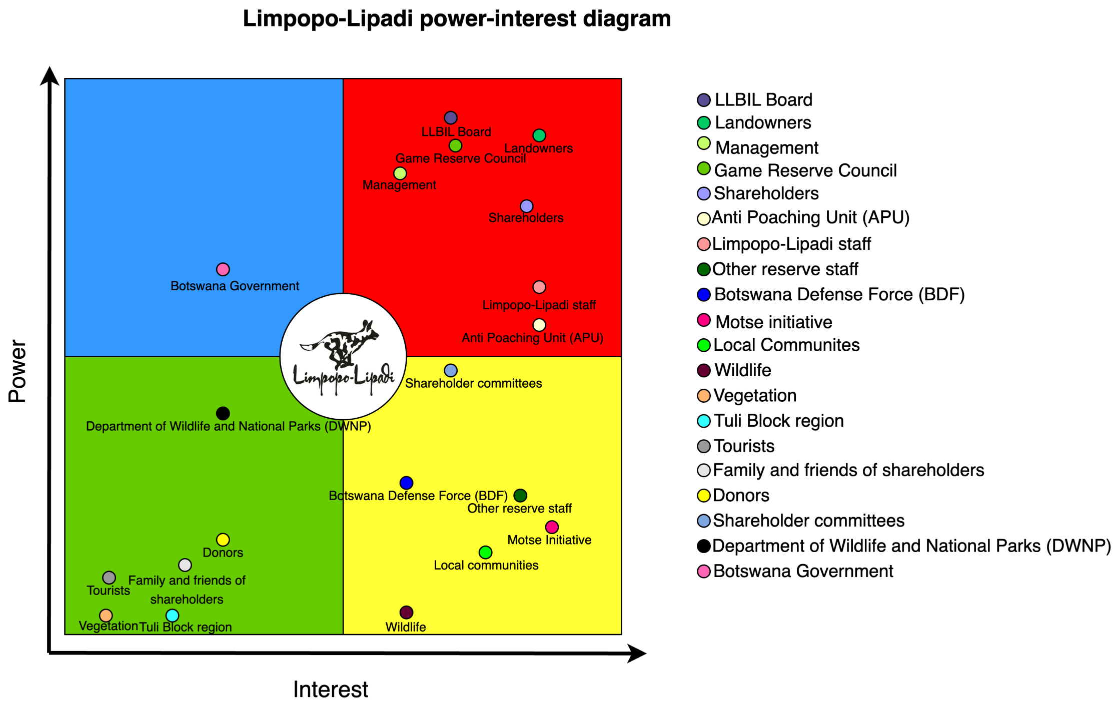


Figure 3.5: Limpopo Lipadi Reserve power-interest diagram

The following stakeholders are located within the *low interest and low power* section of the graph: Vegetation, Tuli Block region, tourists, friends and family of shareholders, NGO donors and the Department of Wildlife and National Parks (DWNP).

Measures to replenish *vegetation* within the borders of the Reserve are currently being implemented, with the vision of returning the area to its original state, before farming and other human activities began. It is considered that vegetation has low power, and relatively low interest.

As has been mentioned before, the focus of the *Tuli Block region* has shifted from farming to tourism opportunities. Both parties therefore have interest in the success of the Reserve. It is considered that the Tuli Block region has low power within the Reserve, and relatively low interest, but some interest nonetheless because of its tourism opportunities.

The power-relationship for *tourists* and *family and friends of shareholders* is considered to be similar, where both stakeholders have low power and relatively low interest in the Reserve. Family and friends of shareholders have a slightly higher interest, since they often have close connections to shareholders and are invited to explore the Reserve by them.

NGO donors have some power regarding where their donations contribute towards, and their reason for donating to the Reserve shows some interest in it, its their services and social contributions.

The Department of Wildlife and National Parks is charged with regulating and managing wildlife and national parks located in Botswana. Certain activities of the Reserve are controlled by regulations in the Wildlife Conservation and National Parks Act [5]. It can be assumed that this stakeholder has relatively high power, that is, if the Reserve is not following their guidelines, they will have to interfere. They have interest in some aspects of the Reserve (i.e. wildlife conservation matters), therefore it can be determined that they relatively low interest in the Reserve, as their interest only covers some of the Reserves services and activities.

The following stakeholders are located within the *high interest and low power* section of the diagram: wildlife, Motse Initiative, local communities, other Reserve staff, Limpopo Lipadi Reserve staff, and Botswana Defence Force.

The Limpopo Lipadi Reserve closely monitors *wildlife* found within the borders of the Reserve itself, and implements conservation measures if needed. It can be assumed that wildlife as a stakeholder has high interest in conservation efforts done by the Reserve, but low power.

The purpose of the *Motse Initiative* is to fund and oversee community outreach programs, that are requested by local community representatives [27]. It can be assumed that this stakeholder has high interest in the Reserve, meaning that with higher success of the Reserve, the higher the funds which will contribute to community outreach programs for surrounding communities. The initiative has relatively high power, as it has local representatives within the committee. These representatives are involved in decision making relating to the Reserves contribution to Motse Committee.

The Reserve offers employment opportunities for individuals coming from *local communities* and contributes to the area's economic growth. It can be assumed that surrounding communities have relatively high interest in the Reserve and its social contributions. The power of local communities can come in various forms, i.e. through Limpopo Lipadi staff, services of goods, local consultation, and more. It can therefore be assumed that they have relatively low power, since only a portion of the individuals living in these local communities contribute towards this power, but some power nonetheless.

Other Reserve staff, includes staff of the various private lodges within the Reserve. These stakeholders are smaller in number, compared to the staff of Limpopo Lipadi, and are less connected to the Reserve itself directly. It can be assumed that they have some interest in the Reserve, as it contributes to their employment and services offered. They have some power in the service they provide and their impact on the reserve, but as they are not directly employed by the Reserve, their power becomes less.

Botswana Defense Force (BDF) is employed by the Botswana government and compliments the Reserve's Anti Poaching Unit (APU). They are therefore considered to have lower interest and lower power than the APU. As they are contributing to the Reserves conservation measures, it can be assumed that they have interest in the Reserve and some power in their services, as they are the only armed force at the reserve.

The following stakeholders are located within the *high interest and high power* section of the diagram: Landowners, Limpopo Lipadi Botswana Investment Limited Board (LLBIL Board), Anti Poaching Unit, Shareholders, Management, Game Reserve Council, and Limpopo Lipadi staff.

Game Reserve Council is charged with developing, implementing and monitoring the Reserve Management plan. Within the council there are shareholders, landowners and Limpopo Lipadi management representatives. The council has high interest and high power within the Reserve, where their main goal is the success of the Reserve and they have the necessary tools to implement the Reserve Management Plan.

Within the Reserve, there are two *landowners*, the owners of private lands, Lubbesrust and Longwope. The lands have been incorporated into the Reserve, and representatives of the owned land have a seat within the Game Reserve Council. It can be assumed that *Landowners* have high interest in the Reserve and their services, and have high power.

The Game Reserve Council reports to the *Limpopo Lipadi Botswana Investment Limited Board (LLBIL Board)*. If everything goes to plan within the Reserve, the board should not have to interfere too much in the day to day management and other activities within the Reserve. It can therefore be assumed that the board has more or less the same interest in the Reserve as the Game Reserve Council, but slightly more power as they are higher in the Reserves power rank.

The Reserves *Anti Poaching Unit (APU)* contributes to various tasks and goals within the Reserve. Their main objective is to prevent poaching incidents, where rhinos are of the main concern. Without the APU, conservation measures of endangered species would very likely not be achieved. It can therefore be assumed that the APU has high power within the Reserve, and even higher interest. Both the Reserve and the APU benefit from each other, where the Reserve offers employment opportunities and the APU contributes to the Reserves conservation matters.

Without *shareholders*, the system that the Reserve operates on would collapse. Shareholders secure funding for the Reserve and in return, shareholders can experience the African bush on their own terms, and share the experience with family and friends. Additionally, shareholders often buy shares in the company because of their high interest in conservation matters. It can therefore be assumed that shareholders hold both high power and high interest in the Reserve and their operations. However, this can sometimes lead to conflicts of interest, as shareholders are often involved in the Reserve's management and decision-making.

The contribution of the *staff of Limpopo Lipadi* is vital for the success of the Reserve. Without staff members and their respective roles, the services and goals of the Reserve would not be achieved. It can therefore be assumed that this stakeholder has high power within the Reserve, and high interest as the Reserve provides employment opportunities for them.

One stakeholder is in the *low interest and high power* section of the diagram, the Botswana Government. As mentioned before, the Botswana Defence Force is employed by the Botswana government, where the force is assumed to have low power and high interest. The Depertment of Wildlife and National Parks (DWNP) is an department within the government and assumed to have relatively low power and interest. However, the Botswana Government as a whole can interfere and affect some of the Reserve's operations i.e permits, limitations, law and regulations. Therefore, along with the Defence Force and DWNP, the Botswana Government is considered to hold relatively high power but low interest overall.

The Reserve's stakeholders have been identified and their power, and interest in the Reserve's operations analyzed. This is essential for both the writers and readers of this report, as it provides additional context and insight into the Reserve. The stakeholder analysis tools, shown above, indicate that the identified stakeholders of Limpopo Lipadi vary significantly in their contributions to the Reserve and its activites. Each stakeholder is unique, and must be treated as so. Without these stakeholders and their contributions, the goals and vision of the Limpopo Lipadi Reserve could not be realized.

4 Problem Statement and Relevance

4.1. Relevance

Botswana is facing considerable challenges linked to water scarcity and its management in the context of a semi-arid climate and the reality of global climate change. The yearly rainfall is primarily concentrated during the summer season where it happens as sporadic and intense rainstorms causing the presence temporary streams. From mid-April to mid-October, the rest of the year, the climate is characterized by an extended dry spell.
In order to assure water availability throughout the year, the primary source for the Reserve are the underground aquifers which allow for the presence of permanent waterholes for the animals and water availability for human consumption.
Comprehensive data on aquifer dynamics is currently lacking, increasing the risks of extracting groundwater at unregulated rates in the context of the reserve. Managing extraction rates as consciously as possible is therefore crucial, particularly in dry years like the present and upcoming years.
During dry periods, such as the ones experienced by the Reserve and the ones expected in the future, excessive groundwater abstraction can ultimately cause a lowering of water tables, impacting both human use and the Reserve's ecosystems well being. This issue could be further impacted by the ongoing bush clearing activity in the Reserve, while clearing vegetation may improve visibility and help with land management, its effects on soil health and water retention are largely unknown. In this context, the possible consequences of bush clearing of reducing the soil's ability to retain moisture, further straining the already suffering groundwater water supply will be researched.
Given these challenges, by investigating the different soil types and their water retention capacities, the entities of the main water fluxes, as well as evaluating the impact of various land management practices, the research goal is to provide valuable insights into the water dynamics to allow for long-term preservation of the Reserve's water resources, ensuring that both human and ecological needs are met.

4.2. Research Question

The main focus of this research is to understand and link together the dynamics of the main water fluxes within the Limpopo Lipadi Reserve. Given the semi-arid conditions, expected to intensify due to global climate change, and the heavy reliance on groundwater, the soil characteristics and the current land management need to be taken into account when assessing the current water dynamics. This study aims to address the following primary research question:
"How do the key water fluxes in the Limpopo Lipadi Reserve interact to form a comprehensive water balance, considering varying soil characteristics, water retention capacities, and land management practices?".
Multiple sub-questions regarding specific areas of investigation have been identified as necessary to be able to comprehensively answer the main research question.

- "How can the main water fluxes (precipitation, evaporation, groundwater abstraction, surface

runoff) within the reserve be quantified?"
This sub-question serves as a starting point, significant data regarding both natural fluxes like rainfall and evaporation, and human-driven factors like groundwater abstraction need to be collected and analyzed to be quantified and linked together.

- "What are the impacts of bush clearing on soil health, water retention capacity, and aquifer recharge?"
This sub-question seeks to understand how soil composition influences water behavior through the first layers of the soil matrix, specifically, given the potential for bush clearing to alter its dynamics.
- "What are the recharge rates of the boreholes within the reserve, and how can these rates be monitored effectively to support more sustainable and conscious groundwater extraction?"
Providing the Reserve with a simple and reproducible method to assess the boreholes recharge rate will represent a starting point to increase the ability of consciously extracting groundwater. This is being done with the intention of reducing water waste and advancing the basic understanding of the dynamics of subsurface water.

The combination of all the research questions aims to develop a thorough understanding of how the main water fluxes in the Limpopo Lipadi Reserve interact. Specifically, the analysis will provide a clear overview of the flow patterns and their proportions. The key parameters which will be investigated to support the water balance are the influence of different soil characteristics, water retention capacities, and current land management practices, particularly bush clearing, on infiltration and groundwater recharge. The knowledge gathered and presented in this study intends to contribute to the development of more sustainable water management practices to ensure responsible use and preservation of water resources.

Filling the gaps in knowledge regarding the water resources within the reserve represents a challenge that can be addressed considering numerous approaches. Various methods could be valuable options to obtain information about aquifer dynamics and subsurface water behaviour, nonetheless, they are often costly and may require extensive water usage. This would not be ideal given the purpose of the investigation. In this study, a more practical and simple approach is applied, which implies closing a water balance over the Limpopo Lipadi Reserve. This method allows for a cohesive representation and quantification of all the primary water fluxes, linking them all together in a complete picture. The outcome of the water balance will show the changes in groundwater storage over time without having to interfere with the subsurface water dynamics. Therefore, the water balance is believed to serve as powerful tool to draw conclusions about water resources without the need for large-scale infrastructure or intrusive testing. This makes it ideal for addressing the concern on water scarcity and guiding the long-term water management plan for the Limpopo Lipadi Reserve.

5 Methodology

The main focus of this research is to understand and link together the dynamics of the main water fluxes within the Limpopo Lipadi Reserve, with a specific interest on how these water fluxes are affected by bush clearing.

To achieve this goal this report focuses on the design of a water balance. A water balance is a hydrological model that quantifies the inflows, outflows, and storage changes of water in a system. To build the model, historic data on inflows (precipitation and river inflow) and certain outflows (evapotranspiration, river outflow and human consumption) are needed. A number of parameters need to be determined to be able to quantify the fluxes within the model. During the fieldwork for this project, the values of these parameters were determined. The project's fieldwork phase was focused on evaluating soil properties in order to gain a basic understanding of the types of soils found in the Reserve. This allowed for a significant comparison of the other measured properties used to evaluate the impact of bush clearing on soil health and, ultimately, on the water balance.

5.1. Site selection

To determine the values of certain soil parameters needed for the water balance and to assess the the impact of bush clearing within the Limpopo Lipadi Reserve, field experiments were conducted on-site.

Due to the extensive area of the the Reserve, the diversity of land management practices and variations in soil characteristics, as well as the constraints of a limited time-frame, only a select number of sites and specific locations within each site could be chosen. Several factors were considered in determining the areas of interest, including the following:

- The last time the area was cleared;
- Clearing method (mechanical, hand-clearing and/or fire);
- Previous land management;
- Current land management;
- Present vegetation;
- North to south spread.

Clearing methods were first implemented within the boundaries of the Reserve in 2019. Several sites have since experienced significant vegetation regrowth, with some returning to conditions similar to those prior to clearing. With this in mind, sites where vegetation has grown back were chosen, as well as recently cleared sites. It should be noted that it was not analysed specifically how much of the vegetation had regrown at each site, but rather information gathered from the Reserve's Research Manager regarding how much time has passed since the area was cleared and if clearing methods were to be implemented again. See Appendix E.2 for an summary of the interview conducted with Botilo Thsimologo, the Research Manager of the Reserve.

To facilitate a comparative analysis of the impacts of various clearing methods, sites were selected based on the specific techniques employed: mechanical, hand-clearing, and/or fire. Sites were chosen based on which clearing method has been implemented, where the goal was to choose at least one site for each clearing method. The comparative analysis is limited due a combination of clearing methods for some areas. That is, for some sites both hand and mechanical clearing methods have been implemented, and not always clear where each method has been utilized.

As mentioned before, portions of land found within the Reserve were previously used for farming activities, leading to substantial changes in vegetation patterns and soil health. These affected areas are therefore of particular concern for the Reserve and have been prioritized for bush clearing efforts.

At each location, factors such as surrounding vegetation and visible animal impact were also taken into account. Surrounding vegetation can increase plant litter and thus influence soil composition, while animal impact, including trails and droppings, can affect soil compaction and overall composition. As can be assumed, surrounding vegetation and animal impact were often difficult to avoid when choosing each sample location. Therefore, for each location a 10x10 meter grid was defined and within each grid, vegetation and animal impact was documented through descriptions and video recordings, available for subsequent review and analysis. The analysis of surrounding vegetation and animal impact is limited due to subjective observations, subsequent of site analysis and variations in vegetation and animal impact between sites.

It was important to choose sites that were spread out from North of the Reserve to South, in order to determine certain parameters for the water balance. The experiments conducted at each site will be used to compute general parameters for the water balance, which reinforces the importance of selecting sites that are representative of the Reserve as a whole and thus assuming homogeneity. In reality, this homogeneity is not true, since soil characteristics, vegetation cover characteristics, and other important factors, are rather heterogeneously spread out across the Reserve. By taking the average of the values retrieved from locations spread out from north to south of the Reserve, more accurate generalized parameter can be determined, and used for the water balance.

A total of six locations were selected for each site: three where clearing methods had been applied and three adjacent areas where no clearing methods had been implemented. This design allows for an evaluation of the impacts of bush clearing methods on soil health and water infiltration, by comparing results from cleared and uncleared areas.

To ensure the safety of both students and the accompanying ranger, chosen locations were situated relatively close to accessible roads and the ranger's vehicle. This limits the selection of locations significantly, where locations deep within the bush could not be chosen. A criteria of distance between a set of locations, i.e. cleared location and adjacent non-cleared location, was set at minimum of 30m, up to a couple of kilometers.

As can be assumed, the vegetation spread for cleared and non-cleared areas differs greatly. For cleared areas, locations were chosen where vegetation cover was deemed as low, while for uncleared areas, locations were chosen where vegetation cover was deemed as high. For the latter, samples were taken in between bushes, but this was often hard to achieve because of the high width of the bushes and limited access to the soil.

5.2. Water Balance

As mentioned above, one of the main goals of this research is the design of a water balance. By quantifying the water flow components, the model helps identify how water is distributed, stored, and lost over time. The model will allow for a better understanding of water availability, which is essential for managing resources and planning for sustainable land and water use.

5.2.1. Model description

Conceptual Model

The model used in this report is a lumped conceptual model, which consists of a series of flow processes which will be simulated on historic data on a daily basis [28]. In this study, the Reserve is treated as a closed system, where inputs, for example precipitation and river inflow, and output, among which evaporation, transpiration and river outflow, are analyzed. By assuming no significant exchanges with external systems, the model accounts for water retention and loss, providing insights into the Reserve's hydrological dynamics under local climate conditions.

Each Flow process in the model consists of:

- A storage component (expressed in [mm])
- One or more fluxes, either in- or out-fluxes (expressed in [mm d^{-1}])
- One or more parameters that define the size of the storage component and/or the relation between storage and out-fluxes.

A schematc representation of the water balance model is shown below in figure 5.1. The model consists of four storage components, displayed here as buckets. The arrows represent fluxes and several of the used parameters are displayed.

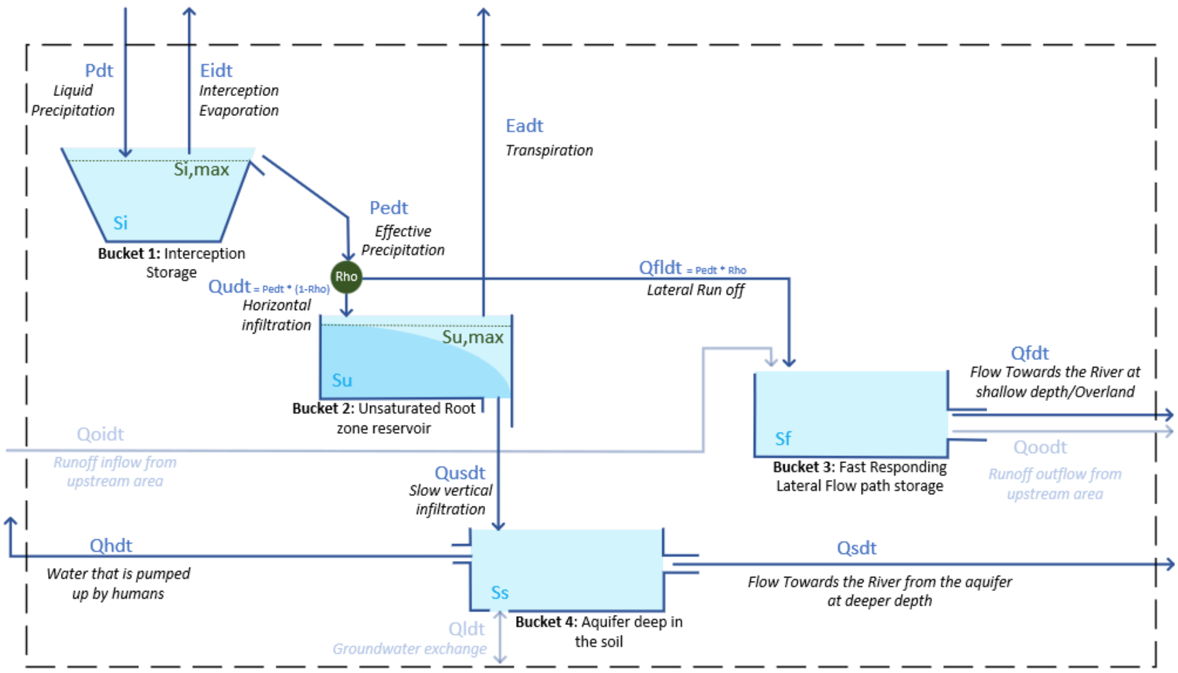


Figure 5.1: Schematisation of water balance model

Table 5.1 defines all the storage components, entering, exiting and internal fluxes, along with the parameters that have to be defined. A more detailed description of the required parameter values can be read in section B.3 of annex B, referred to in the third column of the table.

Parameter	Flow process	Description	Elaboration
Bucket 1			
Si	Storage	Interception Storage [mm]	B.1.1
Si,max	Parameter	Maximum Interception Storage [mm]	B.3.1
Pdt	Influx	Liquid percipitation [mm d-1]	B.2.1
Epdt	Influx	Potential Evaporation [mm d-1]	B.2.2
Eidt	Outflux	Interception Evaporation [mm d-1]	B.2.2
Pedt	Flux	effective Evaporation or otherwise refered to as through fall [mm d-1]	-
Bucket 2			
Rho	Parameter	Runoff coefficient [-]	B.3.2
Qfldt	Flux	Lateral fast flow towards the river [mm d-1]	-
Qudt	Flux	Water flow into Su [mm d-1]	-
Su	Storage	Unsaturated root zone storage [mm]	B.1.1
Su,max	Parameter	Maximum unsaturated root zone storage [mm]	B.3.3
Qusdt	Flux	Water infiltrating vertically towards groundwater storage [mm d-1]	B.2.5
Pmax	Parameter	Maximum recharge perculation rate [mm d-1]	B.3.5
Ep_upd	Flux	max(0, Epdt - Eidt)	-
Eadt	Outflux	Plant transpiration and soil evaporation [mm d-1]	B.2.2
Lp	parameter	relative soil moisture	B.3.4
Bucket 3			
Sf	Storage	Storage of lateral flow towards the river	B.1.1
Qfdt	Outflux	Lateral flow into the river	B.2.3
Kf	Parameter	Storage coefficient for Sf	B.4.1
Qoidt	Influx	Incoming runoff from upstream areas	B.2.4
Qoodt	Outflux	Outgoing runoff from upstream areas	B.2.4
Bucket 4			
Ss	Storage	the ground water aquifer storage	B.1.2
Qsdt	Outflux	flow from the storage Ss into the river	B.2.5
Ks	Parameter	Storage coefficient for Ss	B.4.2
Qhdt	Outflux	Human extraction	B.2.7
Qldt	Outflux	export/ import of groundwater	B.2.6

Table 5.1: List of parameters, fluxes, and their determination

Process description

Bucket 1 represents the interception storage Si, which receives liquid precipitation Pdt. Interception refers to the process by which liquid precipitation is captured by vegetation, buildings, or other surfaces before it reaches the ground. This intercepted water can evaporate directly back into the atmosphere Eidt or, after a certain threshold is exceeded Si,max [mm], fall on the ground. The water that cannot be stored by the interception storage and does fall on the ground is called the effective precipitation Pedt. The processes are schematised in figure 5.2.

Bucket 2 represents the storage of water in the unsaturated root zone Su. This storage zone has a maximum capacity Su,max [mm]. The Divider Rho [-] represents the Runoff Coefficient, which divides the flux Pedt into flux Qust, which is the portion of the precipitation Pedt which infiltrates and can temporarily be stored in Su and the portion of Pedt that drains away (Bucket 3). From Storage Su, the water can leave as either one of two fluxes. The first type, flux Eadt, consists of the direct soil evaporation Esdt and the plant transpiration Etdt. Eadt depends on how much solar energy is still available after the interception evaporation, how much water is available in storage Su and the relative soil moisture Lp [-]. The relative soil moisture Lp [-] represents the moisture content at which vegetation starts to experience water stress. The second type of flux is the slow percolation Qusdt, which depends on how much water is available in storage Su and the maximum percolation rate Pmax [mm d^{-1}]. The processes are schematised in figure 5.3

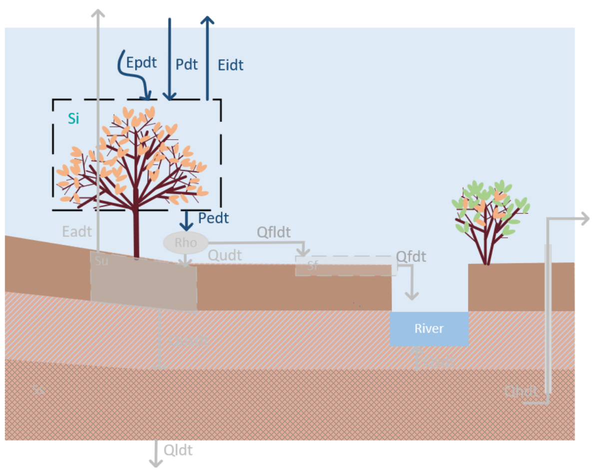


Figure 5.2: Bucket 1

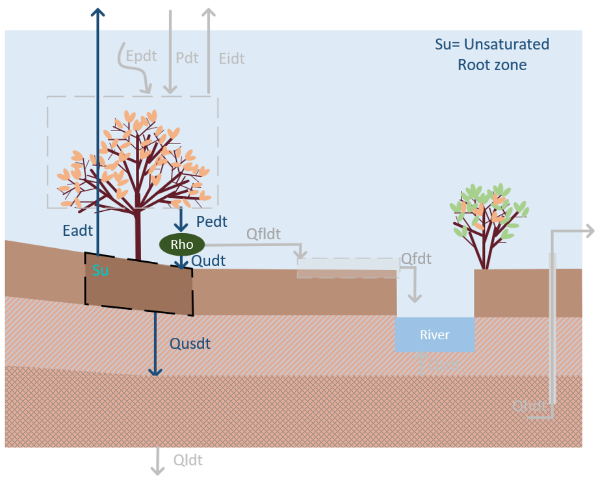


Figure 5.3: Bucket 2

Bucket 3 represents the fast responding lateral flow path component Sf. Flux Qfldt in an inflow, which is the water that surpasses the maximum storage capacity of Su,max [mm]. The storage of Sf depends on storage coefficient kf [d^{-1}] and released as preferential flow Qfdt to the stream. Qoidt rrespresents the inflowing lateral runoff from upstream areas. It is assumed that the same amount of water flows out again as lateral runoff again, represented with Qoodt. Qoodt and Qoidt thus cancel eachother out. These lateral fluxes are also often referred to as shallow subsurface flow. This preferential flow is water that is rapidly routed in a lateral direction through the macro-pores of the soil and reaches the river before it reaches the groundwater aquifer. These macro-pores can be created by , for example, animal activity such as canals dug by insects and other animals, canals formed by the roots of plants and trees, drying cracks and subsurface erosion features. The effect of the macro-pores depends on several factors such as size, topography and connectivity of the pores throughout the soil profile. The processes are schematised in figure 5.4

Bucket 4 represents the groundwater storage Ss. The flux entering this groundwater storage is the slow percolation Qusdt. The water outflow from this bucket is threefold. First, the groundwater is released to the river Qsdt. Water flow Qsdt is released according to a relationship with Ss and the storage coefficient Ks [d^{-1}]. Secondly, there is a water flow Qhdt, which represents the groundwater extracted by humans via boreholes. Groundwater is used for human consumption and is used to to create water ponds for animals in the Reserve. This water leaves the system either via evaporation or the sewage system. The third water flow that leaves the system is the groundwater that is exported (or imported) from groundwater systems outside the catchment boundaries as Qldt. Given that flow rates for Qldt are typically low and both inflow and outflow are assumed to be present, they are considered to cancel each other out, resulting in an effective Q_{ldt} of zero. The processes are schematised in figure 5.5

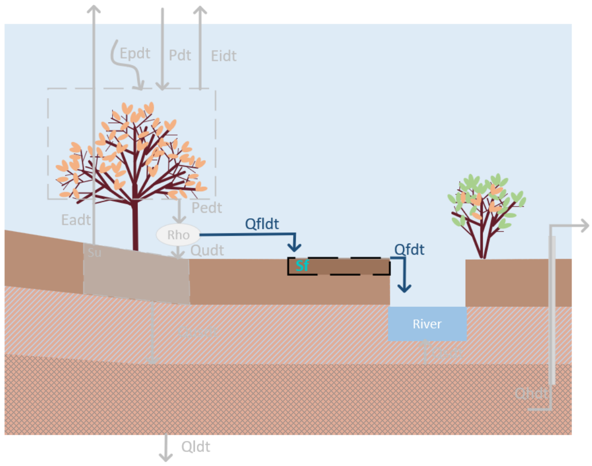


Figure 5.4: Bucket 3

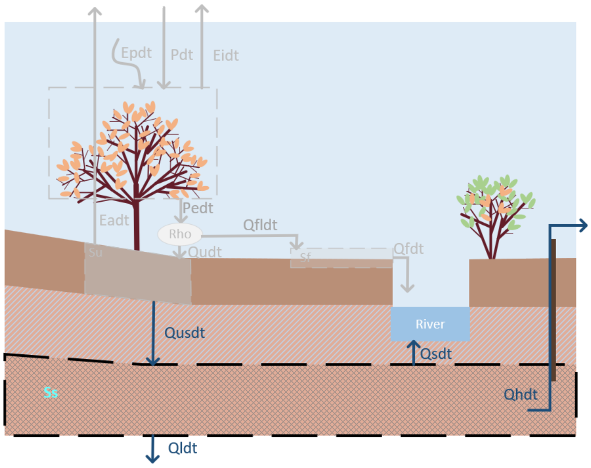


Figure 5.5: Bucket 4

5.2.2. Model Design

To design the model, a computer code written in Python was used. The model aims to take into account the main physical characteristics of the landscape as well as land management practices, specifically, bush clearing.

The model considers spatial variability over the area of interest by taking four raster files as input, each of them containing key information about the topography and land use. The input data include a digital elevation model (DEM), a raster image of the reserve, a slope file, a Height Above Nearest Drainage (HAND) file, and a land management classification file of the LLR.

The core concept of the applied technique is to make the model structure based on a small number of landscape classes, where topography and land management practices are the primary determinants. Parallel running lumped conceptual models are then used to represent these classes, they differ in structure based on the classes characteristics and will receive input parameters accordingly.

For the specific case of the LLR, the landscape classification resulted into six classes as follows: wetland cleared, plateau cleared, hillslope cleared, wetland uncleared, plateau uncleared, hillslope uncleared. The full code can be seen in F.

DEM

A digital elevation model allowed for the generation of two important files used for the landscape classification: the HAND file and the slope file. The elevation data was retrieved from the Shuttle Radar Topography Mission (SRTM) with a raster resolution of 30 meters.

HAND

The HAND model calculates the normalized elevation of the system with respect to the drainage system. The local drainage directions were determined and together with the DEM, the HAND file was created [29]. This was used in the water balance to determine the 'Wetland' and 'Plateau' classes, where the latter is described by a HAND of lower than 3 meters and the 'Wetland' is described as higher than 3 meters. This HAND distinction is an important factor to determine the water table and the associated parameters. The HAND of less than 3 meters indicates a surface water table and higher than 3 meters can indicate a shallow or deep water level, depending on the elevation and slope [29].

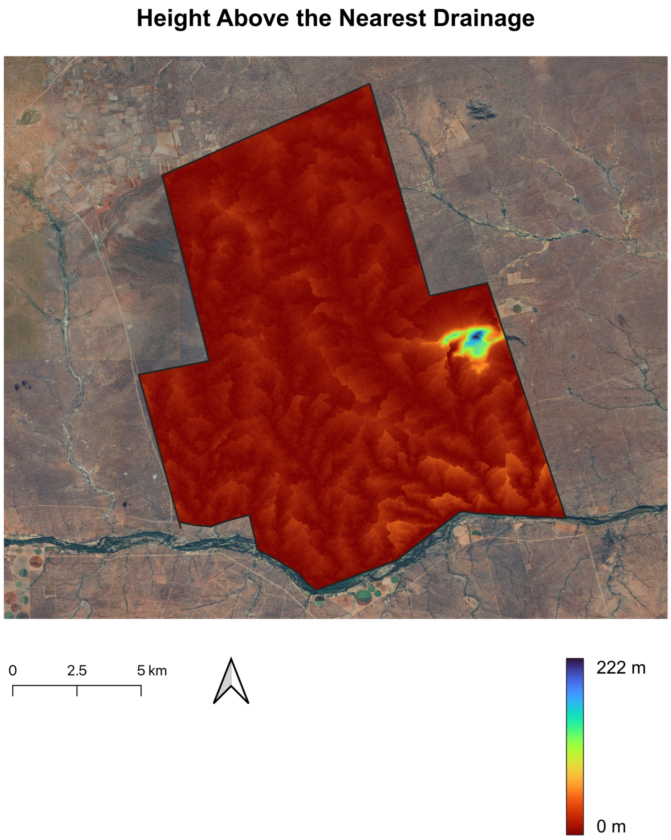


Figure 5.6: Map Height Above Nearest Drainage

Slope

A slope file was generated using the slope algorithm of the raster terrain analysis available on QGIS. The steepness of the surface was used to estimate different runoff coefficients over the Reserve, along with the vegetative state of the test area.

Land Management Classification

This study aims to quantify the impact of bush clearing and its effects on the water retention capacity of the soil as well as the soil health. In order to be able to take this factor into account, a classification based on land management practices was applied to divide the reserve into cleared and non-cleared areas. The classification was performed using the "Semi-Automatic Classification Plugin" (SCP) available on QGIS. Landsat data (satellite images used for the classification) were downloaded from the USGS Earth Explorer website [30]. By using the SCP, a training set was built in order to allow the algorithm to recognize a cleared and an uncleared area, assigning the colour red and green respectively. The classification was then used by the distributed conceptual model to treat each pixel as cleared or non cleared and use the right parameters accordingly. It is interesting to notice how the four site selected in this study as "cleared" are being correctly detected by the land classification procedure, validating the outcome of the algorithm.

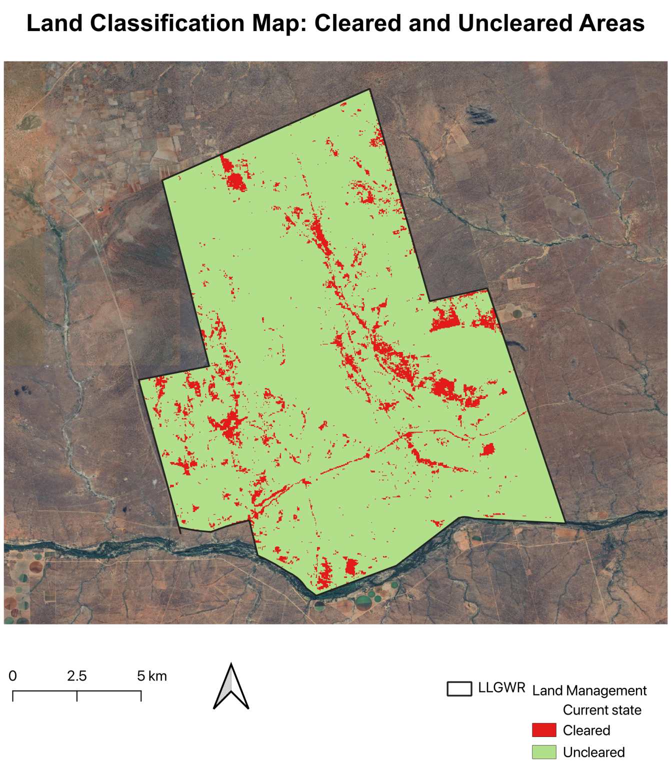


Figure 5.7: Land Management Classification

5.2.3. Closing the water balance

As the system, in this case the Limpopo Lipadi Reserve, is considered closed, the sum of all incoming and outgoing fluxes must be equal to zero, as water cannot be created or lost spontaneously within the system. This implies that over the entire analysis period, equation 5.1 should hold.

$$\text{Water Balance} = Q_{in} - Q_{out,liquid} - Q_{out,evap} = 0\,[\text{mm}] \tag{5.1}$$

In which:

$$Q_{in} = P \tag{5.2}$$

$$Q_{out,liquid} = Q_h + Q_l + Q_s + Q_f \tag{5.3}$$

$$Q_{out,evap} = E_i + E_a \tag{5.4}$$

5.2.4. Limitations of Model Design

There are several assumptions that have to be made in order to create this model, which will affect its accuracy. First of all, it assumes that the system is entirely closed, which would not hold true in natural environments. In real life, there would be interactions with the surroundings of the system. Also, the model ignores spatial variability in soil properties which can significantly affect water infiltration, runoff, and storage fluxes locally throughout the system. Lastly, the values for out-going fluxes and the values for several parameters would be determined based on estimations, assumptions and literature studies, and due to a lack of local discharge data it would be impossible to further calibrate the parameters. This leaves the model vulnerable to inaccuracies in predicting water fluxes, as it relies heavily on estimated values rather than real-time, site-specific measurements. Consequently, the model's results may not fully capture the dynamic and complex nature of water movement within the system, leading to potential errors in long-term water balance estimations.

5.2.5. Scenario-Based Modeling for Future Climate Projections

Once the water-balance model was successfully validated for the current scenario, two potential system changes were simulated to assess their impacts. These simulations include a potential future climate scenario and alterations in vegetation cover, allowing to evaluate the effects of these changes on the system's behavior.

Climate Change Scenario

To asses the impact of climate change on the dynamics of the water fluxes, the model was run for a data set simulating potential future precipitation and evapotranspiration data. Historic data was analysed to identify climate trends. These trends, combined with a climate data generator, were used to create a dataset that simulates future climate conditions. This dataset served as the basis for modelling potential future scenarios.
Future predictions of forcing data were generated from the Coupled Model Intercomparison Project Phase 5 (CMIP5), within this framework multiple modelling groups provide simulations of past, present and future climate. The mentioned models offer different climatic projections based on future greenhouse gas concentrations, the Representative Concentration Pathways (RCPs), representing different levels of radiative forcing. The most commonly available scenarios are RCP2.6, RCP4.5, RCP6.0 and RCP8.5 for which monthly averages of precipitation and evaporation are available.
In the context of this study, climate projections were used together with historical observations to simulate possible future climate scenarios, specifically, historical daily precipitation and evaporation datasets were manipulated with monthly coefficients in order to account for the expected changes in precipitation and evaporation due to climate change. The historic daily dataset from ERA5 was divided into two main sets, one study set (34 years) used to observe the ongoing trends in change and one validation set (10 years) used to quantify the ability of the method to represent future data.
The coefficients were computed by considering the predicted future precipitation and evaporation time series estimated from the CMIP5 considering the RCP45 climate scenario which predicts a 4.5 Watts per metre squared – $[W/m^2]$ – forcing increase relative to pre-industrial conditions [31].
From the mentioned dataset two time slots were selected, one referring to historical values (1999-2024) and one referring to future values (2025-2050). Over the two periods, the ratio between the monthly mean future precipitation and the monthly mean historical precipitation was computed. The same procedure was conducted using the study set from the daily precipitation and evaporation time series retrieved from ERA5.
In order to determine which model to use to predict future climatic patterns from the many models from CMIP5, the computed coefficients from all the available models for precipitation have been compared with each other and with the observed coefficients from the precipitation data from study set, this allowed for a sensitive selection of the climate model that performs better in simulating the local climate in the historical runs. The selected model was then also used to compute coefficients for the evaporation data.
Finally, the validation phase consisted in applying the monthly coefficients to the study set and comparing it with the validation set to see if the method was able to produce meaningful future daily forcing data. A t-test was conducted to check the hypothesis of there being a insignificant difference between the validation set and the modified study test, which would indicate good performance of the described method.
These coefficients were then applied to the full daily precipitation and evaporation datasets from ERA5, this enabled the consideration of climate change consequences without losing the daily variation of the available historical dataset.

Vegetation Cover Change Scenario

In order to estimate the effect of bush clearing on the water fluxes within the system, several scenarios were determined and were implemented in the model. As explained in section 5.2.2 the Reserve was divided into cleared and uncleared areas. To discover the impact of increased clearing on the water fluxes of the system, the percentages of the vegetation cover were changed to create three different scenarios. In the first scenario the amount of clearing is doubled with respect to the current clearing, which could be a realistic scenario in the future. In the second scenario the amount of clearing is taken as half of the reserve, to show a 'worst case scenario'. Lastly, a scenario of no clearing was taken to show the water fluxes of the system when the Reserve is at its most natural form. These scenarios were implemented by changing the input percentages of the six different subsystems. It was taken into account that the overall percentage for the three topographic subsystems, such as hillslope and plateau, were kept the same.

5.3. Soil Characteristics

As mentioned above, this research has a specific focus on the effects of bush clearing on the water dynamics and soil health properties of the soil. This specific interest can be seen in the water balance described above due to the separation between vegetated and cleared areas. In order to analyse the effects of bush clearance in more detail, a more extensive study of soil properties was conducted. It is essential to be able to distinguish the difference in soil type, its composition and texture in order to assess the difference in soil at each experimental site. In this way it will be possible to establish a clear relationship between soil type and the results of other water balance experiments.

A series of experiments were conducted to evaluate the soil samples characteristics: soil sampling and drying (for bulk density, moisture content and porosity); soil texture analysis and jar test (for soil texture classification); constant head test, double ring infiltrometer, and slug test (for hydraulic conductivity); Munsell colour analysis and loss-on-ignition protocol (for OM content), Teabag Index (TBI) (for soil organic activity). It is important to note that all the experiments were carried out using 'home equipment' due to lack of access to a soil laboratory. The methodology of each experiment is described in the following subsections.

5.3.1. Bulk Density, Moisture Content and Soil Porosity

Bulk density, moisture content, and soil porosity are fundamental soil characteristics that provide essential information about soil structure and water retention capacity. The method used to extract these samples is described in Annex B.5.3. The moisture content was determined by first weighing the samples, and after drying them weighing them again. The masses recorded after drying were used to determine the bulk density, based on the the known volume of the ring and the weight of the soil sample. The calculated bulk density and the known particle density for these types of soils, were used to determine the soil porosity. The methods used are described in more detail in Annex section B.5.4

5.3.2. Texture Analysis

Each of the samples used to determine the bulk density of the soil was later used to perform a texture analysis. By applying this method, described in detail in annex B.5.1 and using the bulk density determined before, the following characteristics were determined:

- Range of particle sizes which results in an estimation of the percentages of sand, silt and clay.
- The soils plasticity, stickiness, and granularity
- The soil air capacity, field capacity and plant-available field capacity.

It is important to note that for this analysis, the German soil classification parameters were used, as they provide more detailed information about the soils texture classes [32].

5.3.3. Jar Test

The jar test is a simple method of obtaining an estimate of the amount of clay, sand or silt in a soil sample. This method was used to check the accuracy of the texture analysis, mentioned above. It is expected that the results of the texture analysis and the jar test will be similar, thus confirming the accuracy of the texture analysis. To do this, random samples were selected from the previously analyzed soil samples to be retested with the jar test.

A portion of soil was mixed with water and powdered detergent in a glass jar. The mixture was shaken and then left to stand, after which the sediment layer was measured at various time intervals. The thickness of the different sediment layers measured at the time intervals gives the percentages of sand, silt, and clay. The complete procedure for this test can be found in the Appendix **??**.

5.3.4. Soil Hydraulic conductivity

Soil hydraulic conductivity is a key parameter in the creation of a water balance and it gives valuable insight into the soil properties. The hydraulic conductivity of a soil sample is dependent on multiple parameters, such as the type of vegetation, the soil texture, the level of compaction and the local geology. In order to better understand the role of these parameters on the ability of soil to transport water, it is useful to conduct tests at different depths and in different conditions. Thus, the double ring (DR) infiltrometer, the constant head infiltration test and the shallow hole inverse slug test were conducted throughout the selected sites.

Double Ring

The double ring infiltrometer test was conducted on two locations per site, one in the cleared section and one in the non-cleared section. The full set up and procedure can be found in appendix B. The data obtained from this test was then analysed on Python to find the hydraulic conductivity. The full Python script can be found in appendix B.5.5.

Constant head test (or Mariotte's bottle test)

The constant head test was conducted using a Mariotte's bottle on undisturbed samples collected in the field. Two undisturbed samples were collected per location for each site and taken to the main camp. The data was further analyzed by applying the constant head test formula, which was done with the use of Python. The full set-up, procedure and formulas are described in appendix B.5.5. The associated Pythons script can be found in appendix F.

Slug test

Similar to the double ring experiment, two slug tests were performed per site, one in the cleared section and one in the non-cleared section. Per location two holes were created using an auger. These holes were filled with water and a diver was inserted to measure the pressure. These results were analyzed on Python to determine the hydraulic conductivity. The full procedure can be found in appendix B.5.5, and the Python script can be found in appendix F.

Soil hydraulic conductivity and soil texture class

In order to evaluate if the results from the three different soil hydraulic conductivity tests were accurate and in line with the analysed soil textures, an evaluation was made by using values retrieved from table 13 from [33]. The values retrieved are applicable to the soils upper layer (1-30cm) and therefore applicable to the results of the three different experiments conducted.

The values from *Table 13* were interpolated with the dry bulk density results obtained for each sample to estimate the reference hydraulic conductivity for each location. These estimates, which are based on soil texture class and dry bulk density, were then compared to the results from the Slug test, Double Ring test, and Mariotte's bottle test.

5.3.5. Soil Organic Matter Content

Soil organic matter (OM) content is an important property useful in understanding the impact of bush clearing on soil health. Organic matter includes all organic material at any stage of decomposition, including animal dung, dead plants and animal carcasses, among others.

Munsell Soil Colour Analysis Conducting a soil colour analysis is an important step in identifying soil properties. To accomplish this, the Munsell colour Chart was used to qualitatively determine the hue (H), value (V) and chroma (C) of each soil sample. This standardized classification system is commonly used for field applications. After obtaining these colour parameters, inferences can be made about soil type and their chemical and biological processes. The relative abundance of organic carbon, iron or nitrogen are all correlated with HVC values, allowing for qualitative comparisons of soil at different locations and sites in the LLR. A more detailed description of the protocol can be found in Annex B.5.6, Table B.3.

It is important to be aware that when using the Munsell colour chart, it is possible to experience some discrepancies in the results. This is mainly due to human error and varying soil moisture conditions. Measures such as adding a 48 hour drying period, and assessing all the samples in the same lighting in one sitting were taken to minimize these discrepancies.

A correlation between soil colour and OM content is generally accepted in scientific articles, as the dark coloured particles darken the colour value of the sample. The FAO guidelines for soil description [34] include a method for estimating the soil OM content based on Munsell soil colour. For this estimation, only the value and chroma are considered in combination with soil texture and moisture content. Thus, the Munsell colour of the samples can be used to estimate the OM content.

Loss-On-Ignition Method The OM content of certain soil samples was also determined more accurately using the Loss-On-Ignition (LOI) method, which provides a quantitative rather than qualitative value. The samples used for this experiment were selected on the basis of their texture and clearing status: for each site, samples from the same characteristic texture were selected and an equal number of clear and uncleared locations were used, for a total of 12 analysed samples. The protocol consists in first drying the samples at 105°C and then increasing the temperature to 260°C until all the OM had burnt. The resulting mass loss was attributed to the organic matter contained in the soil. The detailed experimental protocol can be found in B.5.6.

5.3.6. Teabag Index (TBI) for Soil Organic Activity

The Tea Bag Index (TBI) can be used as a method to measure the decomposition rate k and stabilization factor S of plant litter, which serve as important indicators for evaluating and comparing carbon decomposition in different ecosystems and soil types around the world.

By burying the tea bags and tracking their weight loss over time, it is possible to assess the rate of decomposition of the plant material and observe changes in the organic matter, such as the ingrowth of finer roots or the presence of fungal biomass. Additionally, this method helps to better understand factors such as climate and soil respiration and carbon degradation [35].

This method uses commercially available tea bags (Lipton Green and Rooibos teas), making it simple and inexpensive, which is beneficial for educational use or in situations where specialised equipment and facilities are not available [35].The procedure followed in this research is described in Appendix B.5.7.

5.4. Soil Health Multi-Criteria Analysis

A multi-criteria matrix was developed to assess key parameters that indicate optimal soil characteristics for the identified soil types in the Reserve to ensure soil health. Different parameters were selected to evaluate the health of the soils studied. The following parameters were chosen for this specific multi-criteria analysis:

- Bulk density
- Porosity
- Plant available field capacity
- Field capacity
- Organic matter content

Each parameter was assigned a score between 0 and 1, with scores closer to 1 indicating results closer to an expected result. The ranges considered were estimated from the literature review, see table C.23 in Appendix C.9.1. A range was determined that included a lower and a higher value. The results for bulk density, porosity, plant available field capacity, field capacity and organic matter content were then compared with these ranges.

Based on this comparison, results were classified as ”within range”, ”x % higher” or ”x % lower”. If the results were within the expected range, the result was awarded a total of 1 point. If the result was out of range, points were subtracted proportionally, e.g. a result that was 2 % lower than the expected range received $1 - 2\%/100$ = 0.98 points.

The total score indicates whether the results obtained are within the expected range, thus providing an assessment of soil health. A low total score indicates that the results deviate from the expected characteristics for that particular soil type, and therefore, action should be taken.

It should be noted that for some parameters the expected range is relatively wide, making it more likely that the parameter will receive a high score. Another limitation of this proposed analysis is the ranges that have been established, as there may be discrepancies as to whether these ranges are appropriate for the specific climate and conditions of the area.

6
Results

The following chapter summarizes the obtained results. Elaborations on the here described results can be found in Annex C.

6.1. Site selection

Considering the factors discussed in section 5.1, as well as the information and guidance provided by the Reserve's Research Manager, the following sites were selected:

- Southern Plains
- Phofu drive
- Middle plains
- Northern plains

The four sites were selected based on the intensity of encroachment at each site. Prior to the Reserve's purchase of the land, the selected sites, with the exception of Phofu Drive, had been used for agriculture, which has left the area in poorer condition than the surrounding areas. The selected sites and their respective GPS coordinates are shown in Table C.1 in Appendix **??** .

Southern Plains has been cleared two times, in 2019 and 2024. The dominant species in the area is Vachellia Tortellis and the preferred clearing method for the area is hand clearing. Figure 6.1 shows the chosen area of Southern Plains, and the locations selected for this site

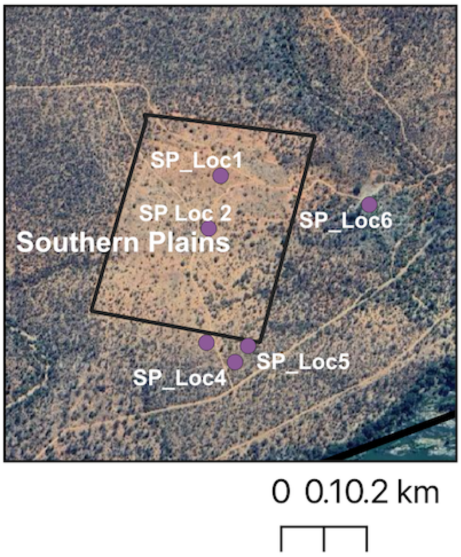


Figure 6.1: Southern Plains locations

Phofu Drive is the only site selected that has not previously been used for farming purposes. An experimental bush-clearing program has been implemented on Phofu Drive, clearing one hectare at a time. One hectare is cleared per day until the selected areas are cleared. The dominant species found on Phofu Drive are Mopane trees. The Reserve hopes that by clearing some of the mopane, the area will allow other species to grow and increase biodiversity. Both mechanical and manual clearing methods are being used in the area to allow for selective clearing. Figure 6.2 shows the area selected for Phofu Drive and the locations chosen for this site.

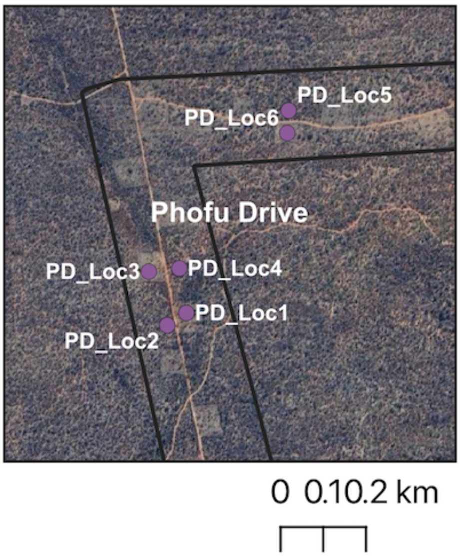


Figure 6.2: Phofu Drive locations

Middle Plains has the highest frequency of bush clearing compared to the other sites studied. Areas within this site have been cleared a total of three times since clearing began within the Reserve in 2019. The first clearing took place in 2022, then in 2023, and is currently underway again. The dominant species in the area is Sickle Bush, the rate of regrowth of this species is extremely high. The Reserve anticipates that the area will need to be cleared annually. Mechanical and manual clearing methods is implemented for Middle Plains. Figure 6.3 shows the selected area of the Middle Plains and the locations selected for this site.

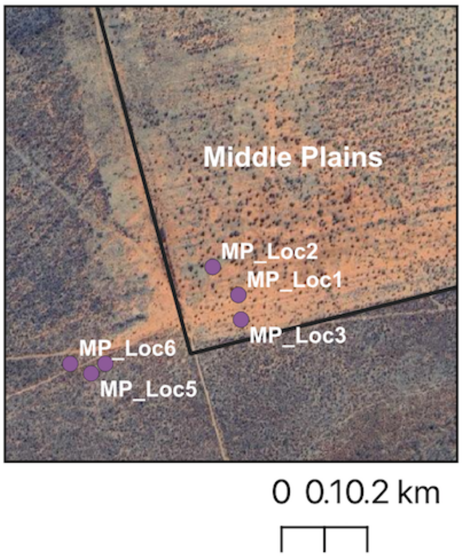


Figure 6.3: Middle Plains locations

Finally, Northern Plains was never fully cleared. Clearing of the area had to be stopped before completion due to change of contractor. The dominant species in the area is sickle bush and the preferred clearing method is a combination of hand and mechanical clearing. Figure 6.4 shows the selected area of the Northern Plains and the locations chosen for this site.

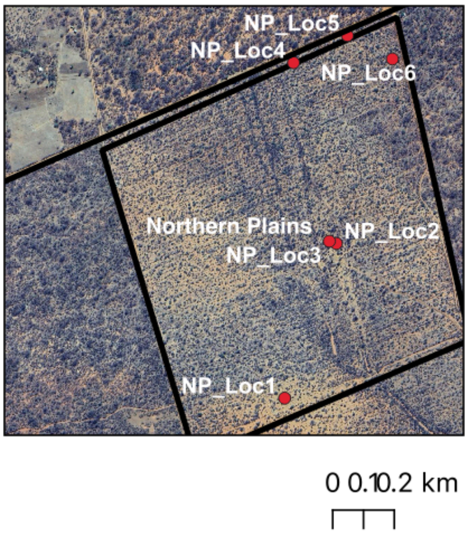


Figure 6.4: Northern plain locations

In order to get a broader perspective of the current state of the Reserve, it was important to select sites that spread from North to South, as described in section 5.1. This was achieved by selecting the Southern Plains and the Northern Plains and their respective locations as sites.

6.2. Water-balance

The water dynamics over the Limpopo Lipadi Reserve were quantified using a HBV distributed model, a conceptual hydrological model used in this case to assess the major water fluxes within the LLR based on multiple hydrological inputs and parameters.

6.2.1. Water-balance input

The division of the system into different categories, based on the existing landscape, is illustrated in Figure 6.5.

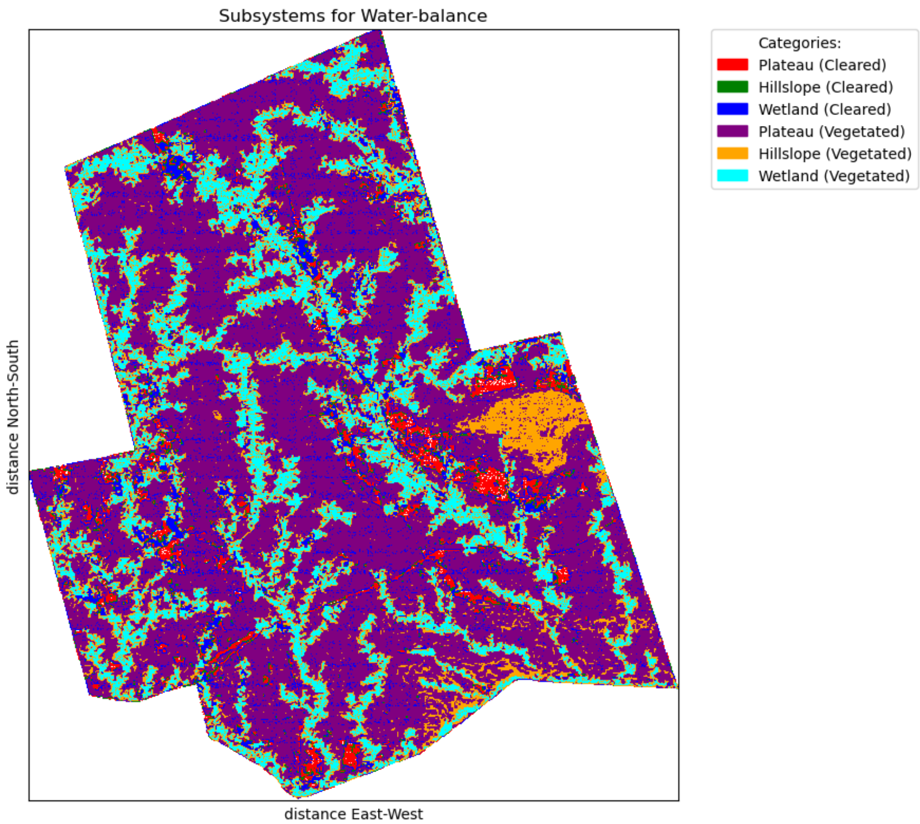


Figure 6.5: Subsytems determined based on landscape characteristics

According to the subsystem division, about 8% of the Reserve have sparse or no vegetation cover, meaning that these regions are free of vegetation. Either humans have cleared these areas, or they are naturally occurring as a result of various environmental processes. The remaining 92% is vegetated. Table 6.1 provides a quantitative explanation of Figure 6.5 above.

Landscape Type / Vegetation State	Vegetated (%)	Cleared (%)	Total Landscape Type (%)
Plateau	54	4	58
Hillslope	10	0	10
Wetland	28	4	32
Total	92	8	100

Table 6.1: Percentages of the subsystems present in the landscape.

The determined boundary flux data is described in more detail in Appendix C in section C.3. The parameters, based on fieldwork and literature estimates, for each subsystem can be found in Table 6.2. Further elaboration on the determination of the parameters is given in section C.4.

Subsection	Imax	LP	Sumax	Pmax	Kf	Ks
Cleared Plateau	0.5	0.07	34	27	0.25	0.0067
Cleared Hillslope	0.5	0.07	34	27	0.25	0.0067
Cleared Wetland	0.5	0.07	34	27	0.25	0.0067
Uncleared Plateau	5	0.07	340	27	0.25	0.0067
Uncleared Hillslope	5	0.07	340	27	0.25	0.0067
Uncleared Wetland	5	0.07	340	27	0.25	0.0067

Table 6.2: Parameters for each subsystem

It can be noted that the parameters change, due to the vegetated state of the section. These parameters are more specifically the interception storage and unsaturated root zone storage. The parameters related to the deeper soil layers, such as the percolation rate and groundwater storage coefficient, do not change as a result of these subsections.

6.2.2. Water-balance: Current State

The water-balance model was simulated over a five-year period using daily input data. Figure 6.6 presents the cumulative totals of the fluxes and the final storage in each of the storage components, expressed in millimeters. This figure provides an indicative overview of the relative magnitudes of the boundary and internal fluxes, highlighting the dominant fluxes within the system.

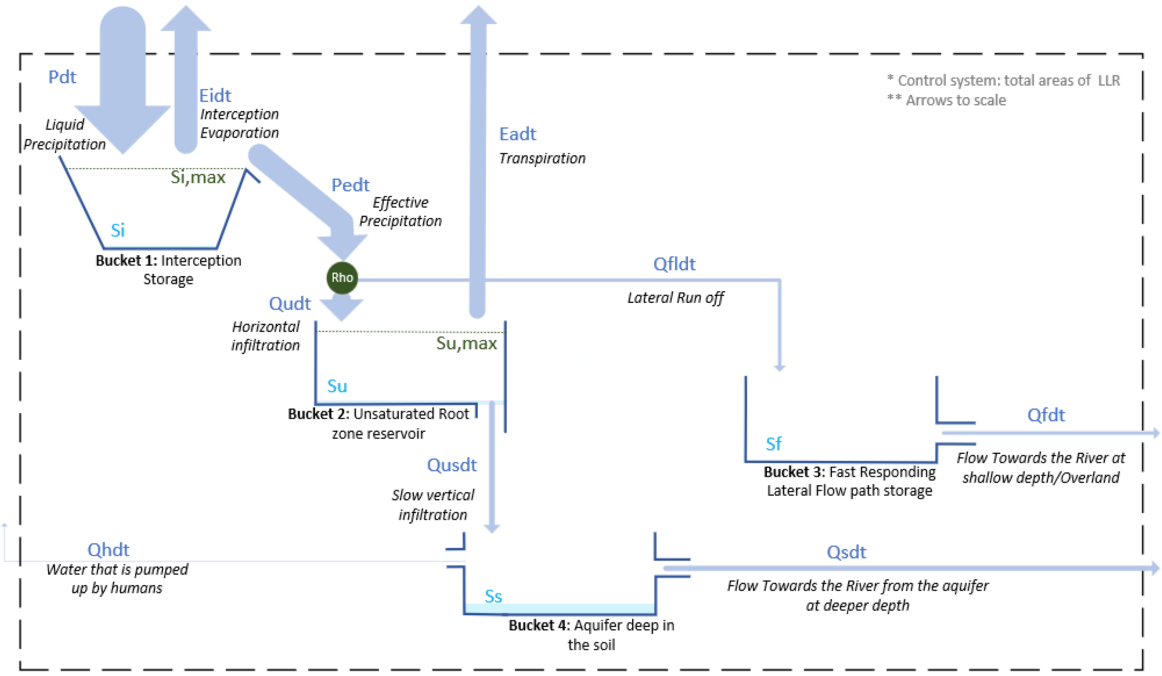


Figure 6.6: Representation of the cumulative fluxes in water-balance model.

Figure 6.6 shows that the main outgoing fluxes are evaporation and transpiration, while human extraction, although not necessarily minimal in local areas, is very small when averaged over the Reserve.

Figure 6.7 shows the stacked outgoing water fluxes from the system. These fluxes include the evapotranspiration (Ea), evaporation from the interception storage (Ei), overland runoff (Qf), flow towards the river from the aquifer (Qs) and lastly, the human extraction (Qh). The cyan blue line shows the precipitation, which is the only ingoing flux of the system. Groundwater exchange and Inflow of overland runoff are also incoming fluxes, however, they are assumed to cancel themselves out (the same quantity comes in and goes out on a daily basis) and are thus not considered in the water balance model. These values were resampled and summed per month over a five-year period, from 2019 to 2024. The year 2019 is the year the Reserve began its current land management practices, which include bush clearing. This figure shows whether outflows exceed inflows, which would lead to water scarcity in the long term. As a result of the dry season, precipitation is actually less than runoff for part of the year, but during the wet season, precipitation is equal to or greater than runoff. This can be better observed by zooming in on one year, which can be seen in Figure 6.8 below.

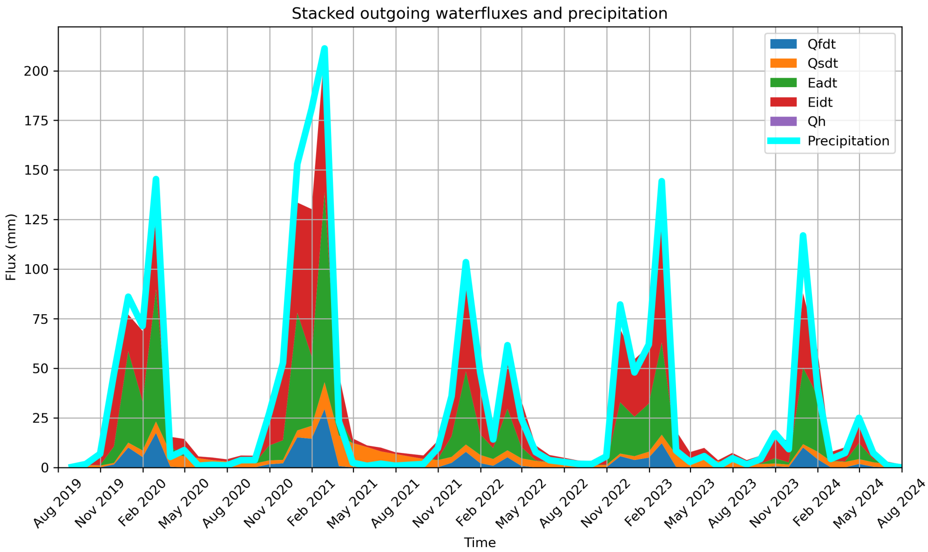


Figure 6.7: The Stacked inflows and the precipitation over a span of 5 years between 2019 and 2024

Figure 6.8 Shows the ingoing and outgoing fluxes for one year, from August 2023 until August 2024. This figure is included to illustrate in greater detail the differences between incoming and outgoing fluxes for a dry year, following two consecutive dry periods.

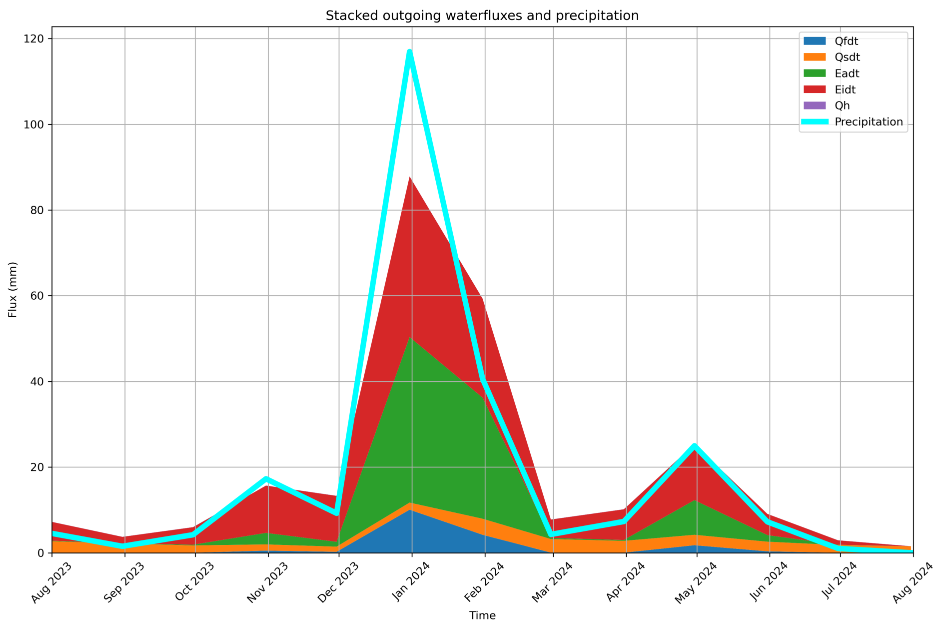


Figure 6.8: The Stacked inflows and the precipitation from August 2023 until August 2024

Given the LLR's strong reliance on the groundwater storage component as its primary source of fresh water, the aquifer known as Bucket 4, or storage component Ss, is seen to be the most crucial part of the water balance for the Reserve. Figure 6.9 shows the estimated storage values of the aquifer. It is evident that the groundwater storage has been fluctuating but not drying out over the past five years, enabling groundwater extraction at present rates without risk of damage. The peak in groundwater storage in 2021 results from a relatively wet period that year compared to the preceding and following years. The main point of interest shown by this graph is that there is no significant downwards trend in groundwater storage over the years. It is important to note that the numerical values in the water bucket model carry uncertainty due to the high heterogeneity within the Reserve and the simplified nature of the model. The primary insight from this graph lies in the observed trends, highlighting periods of aquifer recharge during wet seasons and draw down during dry seasons, showing that even in dry periods, the groundwater storage never decreases to zero.

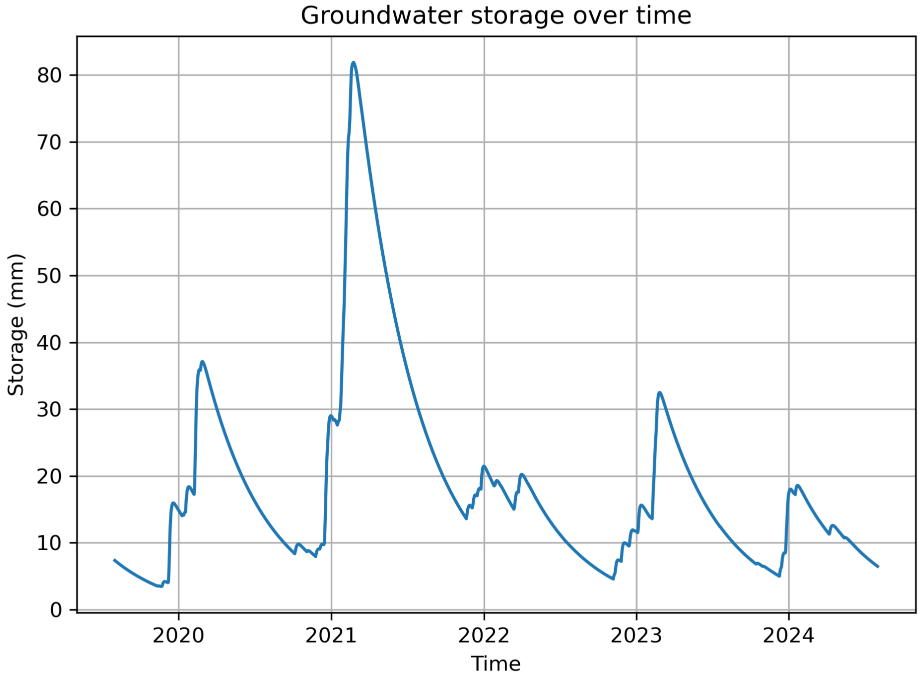


Figure 6.9: The modelled groundwater storage Ss

6.2.3. Water-balance: Increased cleared landscape

Three different scenarios with respect to the bush clearing were applied to the model to determine the effect of clearing on the water fluxes in the system. The results can be found in Table 6.3. It was made sure that the total percentage of Hillslope, Wetland and Plateau remained the same.

As mentioned before, the groundwater storage is one of the most important components of the model, thus observing the change in the groundwater storage due to the change in land cover can bring some valuable insights. Figure 6.10 shows the trend in groundwater storage over five years for each of the three scenarios together with the current situation.

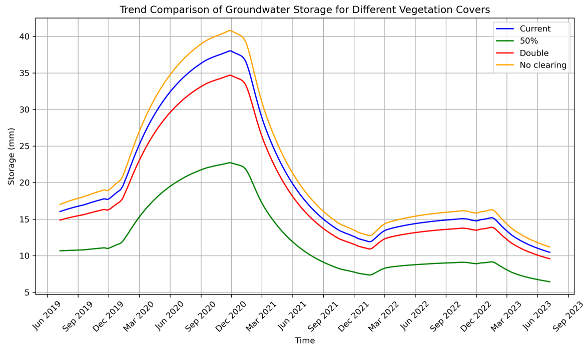


Figure 6.10: Trend comparison in groundwater storage for different vegetation covers

Figure 6.10 shows a higher groundwater storage with a decreased amount of clearing. The scenario where there is no clearing in the Reserve shows the highest storage, while the scenario where half of the Reserve is cleared shows the lowest groundwater storage. It is hard to quantify the amount of groundwater storage from this graph as it shows the trend, however it does show that there is a change in trend between the different scenarios. In the situation where half of the Reserve is cleared, the increase during the wet period of 2020-2021 is significantly lower than in the current situation, which would suggest that the groundwater storage does not replenish as quickly with increased clearing. However, the difference in the trend lines appears to be quite small for both the 'double clearing' and the 'no clearing' with respect to the current situation. Therefore, it is reasonable to conclude that in order to see a large change in the groundwater storage, the amount of clearing needs to be significantly higher, approximately 50% of the Reserve. However, it should be noted that even with 50% of the reserve cleared the groundwater storage does not appear to be draining.

Figure 6.11 shows a bar graph of three different fluxes, the runoff to the river, the evaporation of the interception reservoir (Eidt) and the evapotranspiration (Eadt). The last bar graph also shows the combined Ei and Ea. It should be emphasized that the years 2019 and 2024 provide only partial data, as the time series starts on the first of August 2019 and ends on the first of August 2024.

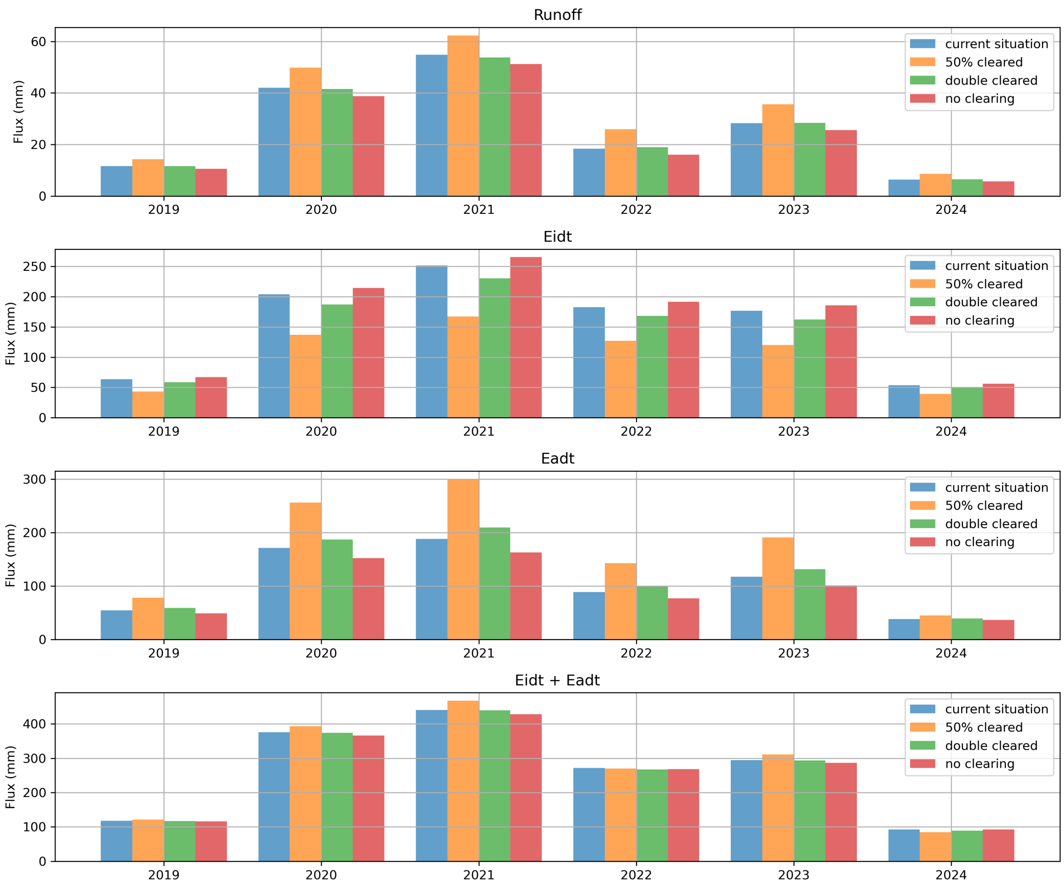


Figure 6.11: Bar graph of different fluxes over five years

It can be noted that the runoff increases with increased clearing, as the root zone is reduced and can therefore hold less water. Evaporation from the interception reservoir, however, decreases because the interception reservoir itself has decreased significantly. However, evapotranspiration increases with less cleared areas as more energy is available for soil evaporation. The final bar graph, 6.11, shows the combined interception evaporation and evapotranspiration. It can be noted that the overall sum does stay quite equal, even though the internal fluxes change in distribution. However, some change in evaporation can still be observed between the different clearing scenarios in 6.11, where the overall evaporation increases with increased clearing.
The scale of the y-axis should be noted, as the maximum flux for runoff is about 60 mm and the largest change can be estimated to be about 10 mm, but the maximum flux for total evaporation is close to 500 mm. The largest change can be estimated to be between 10-15 mm. Looking at the trend of the groundwater storage fluxes, the difference between the current situation and the scenario with 50% of the Reserve cleared can also be estimated at around 20 mm, which could thus be explained by the increased runoff and evaporation due to increased clearing.

Scenario	Hillslope cleared	Hillslope uncleared	Plateau cleared	Plateau uncleared	Wetland cleared	Wetland uncleared
Current percentages	0	10	4	54	4	28
Half of the Reserve cleared	4	6	25	33	21	11
Double the current amount of clearing	0	10	8	50	8	24
No clearing	0	10	0	58	0	32

Table 6.3: Landscape Scenarios (in %)

6.2.4. Water-balance: Climate Scenario

Different future climate prediction scenarios were taken into account in order to estimate the effects of climate change on the water balance. Scenario RCP4.5 was decided upon and incorporated into the analysis as it is a median range stabilization scenario [36] and is more likely to represent a realistic situation. For each of the 40 models that were available, monthly mean change coefficients were calculated as explained in Section 5.2.5. The model that best fit the historical trend was selected, which was GFDL-ESM2G. Figure 6.12 presents the selected model, alongside the historical trend and its corresponding uncertainty range for precipitation.

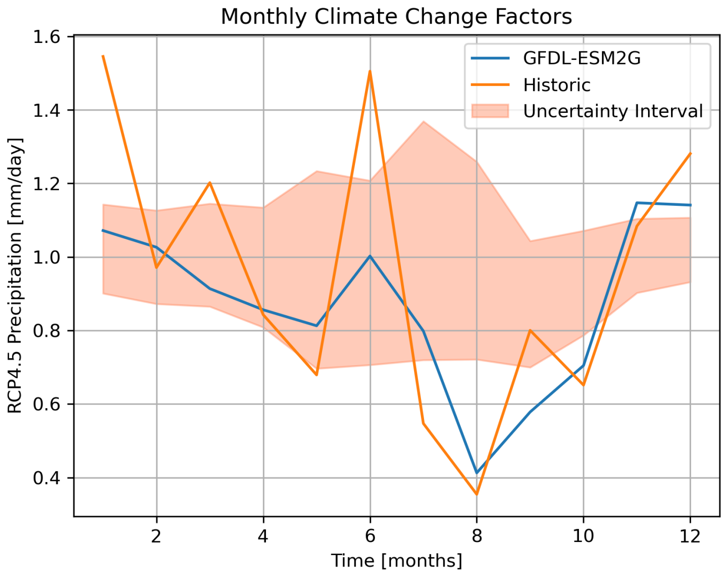


Figure 6.12: Monthly precipitation change coefficients according to scenario RCP45 from GFDL-ESM2G

The coefficients were applied on the daily historical study set for precipitation to test the ability of the method to produce future data, the validation was based on precipitation data. The manipulated study set (1979-2010) was therefore compared with the validation set (2010-2023) and a t-test was conducted to check for significant differences in the two sets, if no difference is detected it can be assumed that by manipulating historic data with carefully selected monthly coefficients it is possible to meaningfully reproduce future data.

The test outcome for precipitation showed a p-value greater than alpha value, suggesting no significant difference between manipulated study set and validation set. This allowed for a quantification of the ability of the method to produce future climate data based on historical daily data and monthly mean change coefficients.

Even though the statistical test suggested the difference was not significant, a percentage difference was computed to quantify the magnitude of change between the two sets. This resulted in a 10% difference, which represents the uncertainty behind the predicted future forcing data.

For evaporation, given the need to keep the model used to produce future data consistent, the GFDL-ESM2G RCP45 scenario was also used to calculate monthly change coefficients for this flux. As observable from Figure 6.13, model GFDL-ESM2G falls far out of the uncertainty interval, making the prediction process less reliable. This observation was also confirmed by running the above t-test. In this case, scenario RCP45 showed a p-value lower than the alpha value, indicating a significant difference between the manipulated study set and the validation set.

Prediction of future evaporation data is therefore highly uncertain, but the GFDL-ESM2G model was still used for consistency with precipitation.

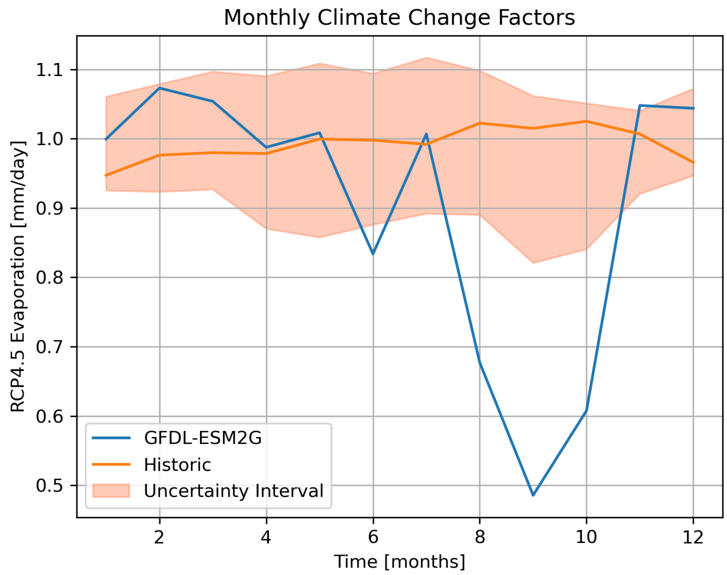


Figure 6.13: Monthly evaporation change coefficients according to scenario RCP45 from GFDL-ESM2G

Figure 6.14 shows the simulation considering the current situation below the simulation which considers the future climate scenario according to RCP45. Both simulations cover a five-year period: 2019–2024 for the current situation and 2045–2050 for the future scenario. A five-year period was chosen to allow meaningful comparison between the current situation, here the model reflects the Reserve since clearing began in 2019.

Comparing the two simulations, which show the monthly sum of the boundary fluxes over the five-year reference period, the difference between the historical data and the future prediction does not show a clear difference overall.

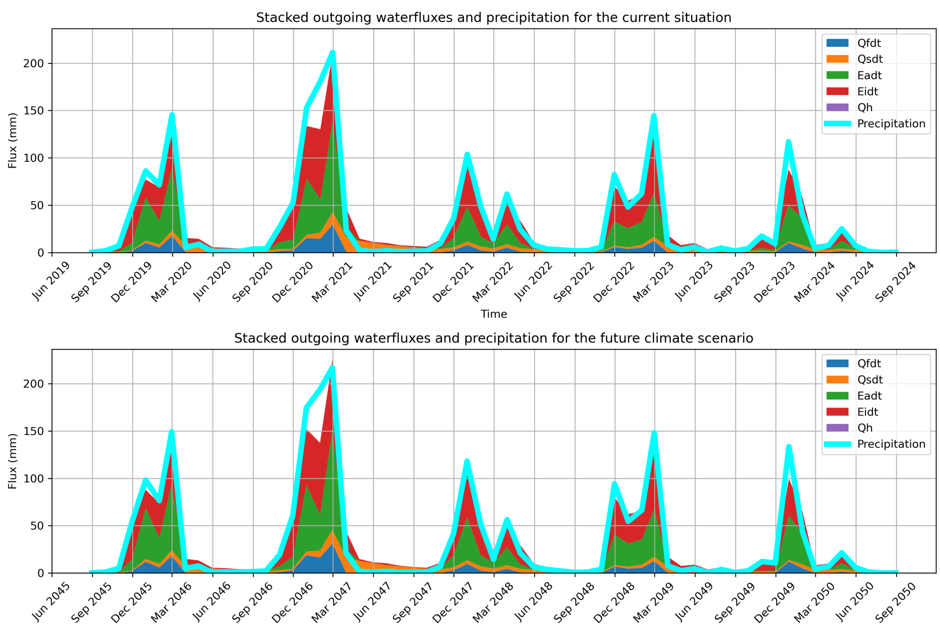


Figure 6.14: Fluxes simulation in current situation and according to RCP45

For better understanding of the small-scale changes in the water balance the two simulations were compared in figure 6.15, by subtracting the future scenario to the current situation and representing the stacked fluxes of the difference between the two. Negative values indicate higher fluxes in the future scenario compared to the current situation; conversely, when positive values appear in the graph, they indicate higher fluxes in the current situation compared to the RCP45 future prediction. As noticeable from the graph in Figure 6.15, the main differences between the two situations can be seen during the summer period. Precipitation and evaporation both show significant increases, as expected from the nature of the local climate patterns. The already existing division into dry and wet seasons appears to be exacerbated in the future with increased rainfall and temperatures in the wet season. Finally, the flow to the river at shallow depths shows greater increases than the flow to the river at deeper depths, indicating that water would follow the horizontal path at shallow depths more than the slow vertical infiltration path and consequent flow to the river at deeper depths from groundwater storage.

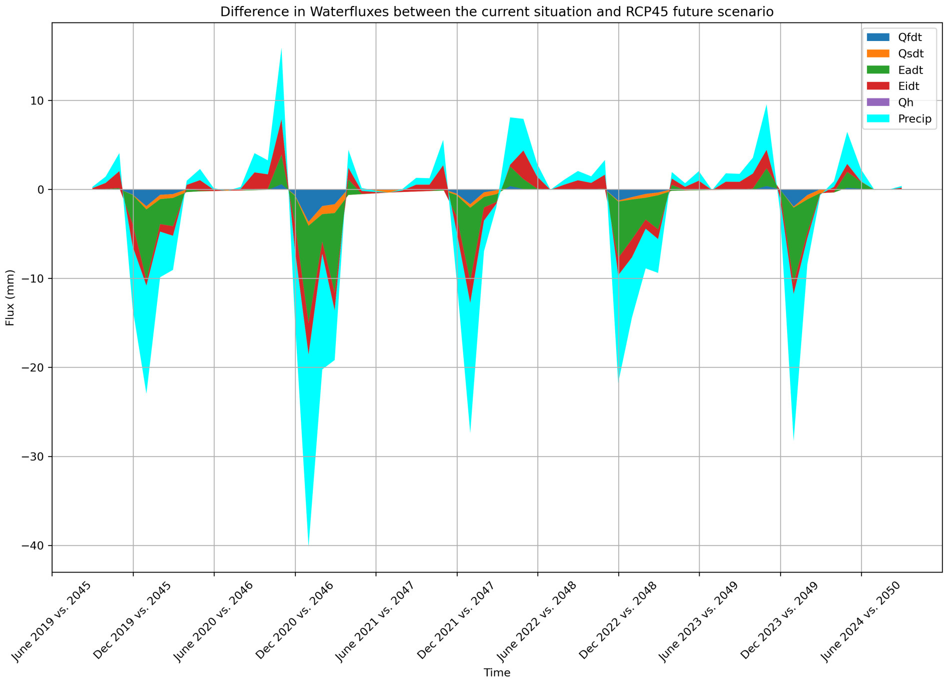


Figure 6.15: Comparison of model simulations with historical time series and climate scenario RCP45: fluxes quantity and distribution

6.3. Soil Characteristics

This next section contains the results of the soil characterisation experiments conducted in the four selected sites in the LLR. This information, when compared with expected values, is valuable in determining soil health in both cleared and uncleared sites, and in understanding the specific effect of bush clearing on hydraulic conductivity.

6.3.1. Soil Texture Classification

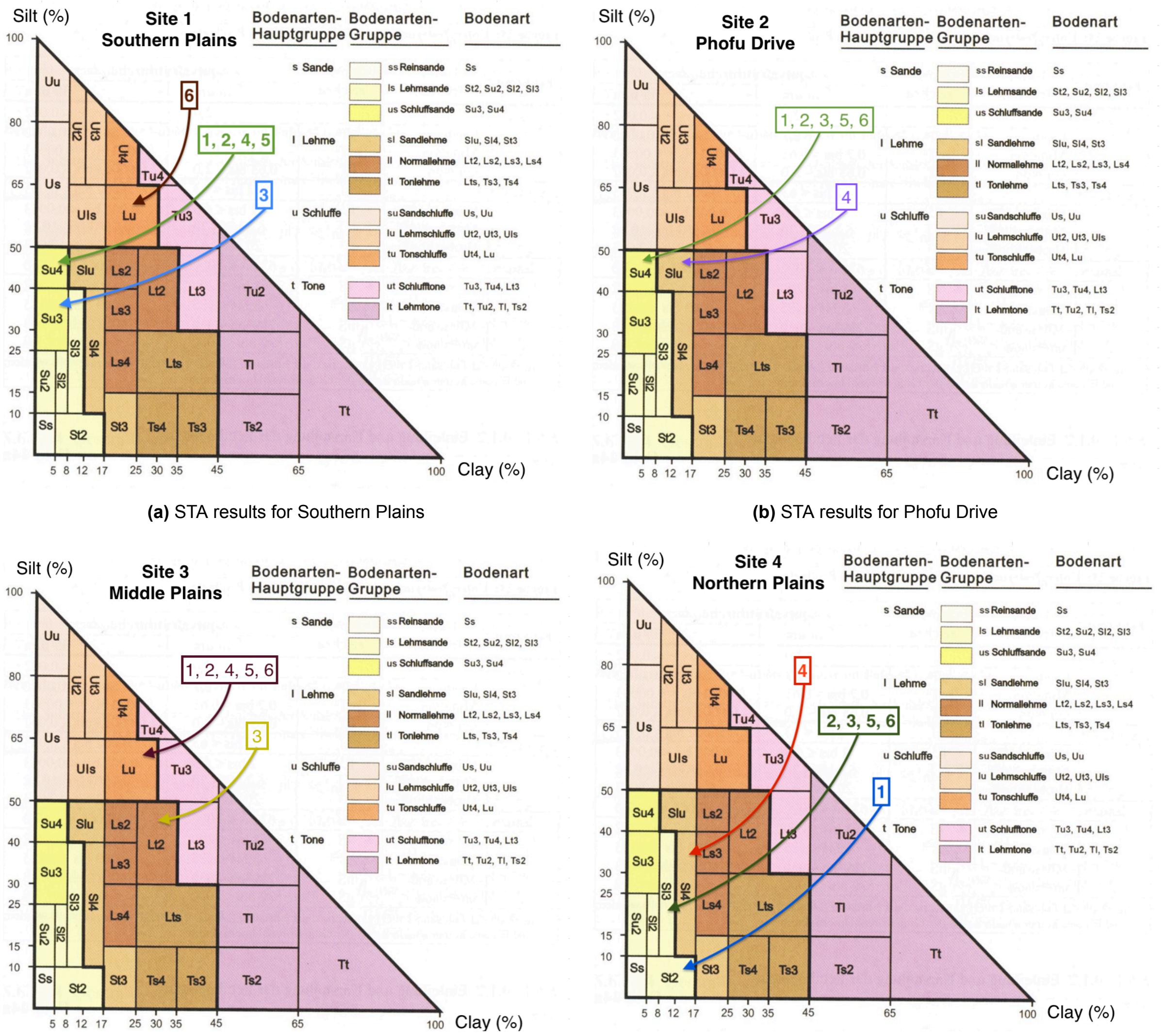
To determine the relative proportions of each class (sand, clay, silt) in each of the soils of the Reserve where the experiments were carried out, and thus classify them, two different methods were used: 1) the manual soil texture analysis (MSTA) followed by the German soil texture triangle (KA5), and; 2) the jar test followed by the international soil texture triangle.

The following subsections describe the results for each technique.

Manual Soil Texture Analysis (MSTA)

A manual soil texture analysis (MSTA) was carried out with the aim of analysing soil types found in the chosen study areas of the Reserve. This is important as texture of the soil is a crucial environmental factor, as it significantly influences processes such as soil degradation and water transport [32].

The soil texture class of each soil sample collected, at the 6 locations of the 4 sites, are shown in Figure 6.16a, Figure 6.16b, Figure 6.16c and Figure 6.16d, respectively.



(a) STA results for Southern Plains

(b) STA results for Phofu Drive

(c) STA results for Middle Plains

(d) STA results for Northern Plains

Figure 6.16: Soil texture analysis results [source for the triangle]

Figure 6.16a shows the soil texture classes analysed for Southern Plains (site 1). The prominent soil texture class for this site is Su4, with locations 1, 2 and 4 falling into this soil texture class. Su4 falls into the *sand* part of the KA5 triangle where the soil type is *silty sands* and the soil texture group is *very silty sand*. Other soil texture classes analysed for this site are Su3 for location 3 and Lu for location 6. Similar to soil texture class Su4, Su3 is defined as *sand* where the soil type is *silty sand* and the soil texture group is *medium silty sand*. For location 6, soil texture class Lu is defined as *silt* where the soil type is *clayey silt* and the soil texture group to which it belongs is *silty clay*. Table 6.4 summarizes the information discussed before and Table 6.5 gives the estimated mass-% of clay, silt, and sand for these soil texture classes and their permeability classes [37]. Table B.2 in Appendix C gives an overview of the permeability classes used and their corresponding soil textures.

Soil texture class	Locations	Soil class	Soil type	Soil texture group
Su4	1, 2, 4, 5	Sand	Silty sands	Very silty sand
Su3	3	Sand	Silty sand	Medium silty sand
Lu	6	Silt	Clayey silt	Silty Clay

Table 6.4: KA5 Triangle result summary for Southern Plains

Soil texture class	Clay	Silt	Sand	Permeability class
Su4	0-<8	40-<50	42-<60	1 - Fast and very fast
Su3	0-<8	25-<40	52-<75	1 - Fast and very fast
Lu	17-<30	50-<65	5-<33	3 - Moderate

Table 6.5: Mass-% of clay, silt and sand and permeability class for Southern Plains (site 1)

Figure 6.16b includes the MSTA results for Phofu Drive (Site 2). The main texture class is Su4, with locations 1, 2, 3, 5 and 6 falling into this soil texture class. As mentioned above, Su4 is *sand*, with *silty sand* as the defined soil type and *strongly silty sands* as the soil texture group. The remaining class is Slu, for location 4. Slu is defined as *loam*, soil type as *sandy loams* and the soil texture group as *loamy silty sand*. Table 6.6 summarizes the information discussed before and Table 6.7 provides the estimated mass-% of clay, silt, and sand for these soil texture classes [33] and their permeability classes [37].

Soil texture class	Locations	Soil class	Soil type	Soil texture group
Su4	1, 2, 3, 5, 6	Sand	Silty sands	Very silty sand
Slu	4	Loam	Sandy loams	Loamy silty sand

Table 6.6: KA5 Triangle result summary for Phofu Drive

Soil texture class	Clay	Silt	Sand	Permeability class
Su4	0-<8	40-<50	42-<60	1 - Fast and very fast
Slu	8-<17	40-<50	33-<52	2 - Moderate fast

Table 6.7: Mass-% of clay, silt and sand and permeability class for Phofu drive (site 2)

Figure 6.16c includes the MSTA results for Middle Plains (site 3). The prominent soil texture class for this site is Lu, with sites 1, 2, 4, 5 and 6 falling into this soil texture class. As mentioned above for Southern Plains, the soil texture class for Lu is *silts*, with the soil type *clayey silts* and the soil texture group *silty clay*. For location 3, the analysed soil texture class is Lt2. Soil texture class Lt2 is defined as *loam*, where the soil type is *normal clay* and the soil texture group is *slightly clayey sand*. Table 6.8 summarizes the information discussed before and Table 6.9 includes the mass-% of clay, silt and sand for the analysed soil texture classes for Middle Plains, along with the permeability class.

Soil texture class	Locations	Soil class	Soil type	Soil texture group
Lu	1, 2, 4, 5, 6	Silt	Clayey silt	Silty Clay
Lt2	3	Loam	Normal clay	Slightly clayey sand

Table 6.8: KA5 Triangle result summary for Middle Plains

Soil texture class	Clay	Silt	Sand	Permeability class
Lu	17-<30	50-<65	5-<33	3 - Moderate
Lt2	25-<35	30-<50	15-<45	4 - Moderate low

Table 6.9: Mass-% of clay, silt and sand and permeability class for Middle Plains (site 3)

Figure 6.16d includes the MSTA results for Northern Plains (site 4). The prominent soil texture class for this site is Sl3, with locations 2, 3, 5 and 6 falling into this soil texture class. Soil texture class Sl3 is defined as *sand*, with the soil type *loamy sands* and the soil texture group as *medium loamy sands*. The other soil texture classes analysed for this site is St2, for location 1, and Sl4, for location 4. Soil texture class St2 is defined as *sand*, where the soil type is *loamy sands* and the soil texture group is *slightly clayey sands*. The remaining soil texture class Sl4, is defined as *loam*, with the soil type as *sandy loams* and the soil texture group as *highly loamy sand.* Table 6.10 summarizes the information discussed before and Table 6.11 includes the mass-% of clay, silt and sand for the analyzed soil texture classes for Northern Plains, along with the permeability class.

Soil texture class	Locations	Soil class	Soil type	Soil texture group
Sl3	2, 3, 5, 6	Sand	Loamy sands	Medium loamy sands
St2	1	Sand	Loamy sands	Slightly clayey sand
Sl4	4	Laom	Sandy loams	Highly loamy sand

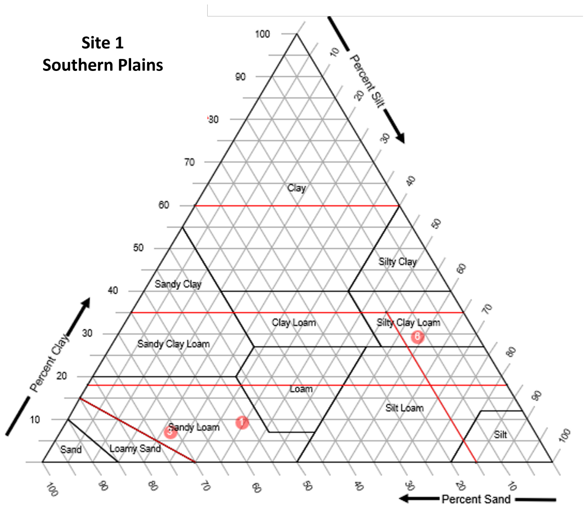
Table 6.10: KA5 Triangle result summary for Middle Plains

Soil texture class	Clay	Silt	Sand	Permeability class
St2	5-<17	0-<10	73-<95	2 - Moderate fast
Sl3	8-<12	10-<40	48-<82	2 - Moderate fast
Sl4	12-<17	10-<40	43-<78	2 - Moderate fast

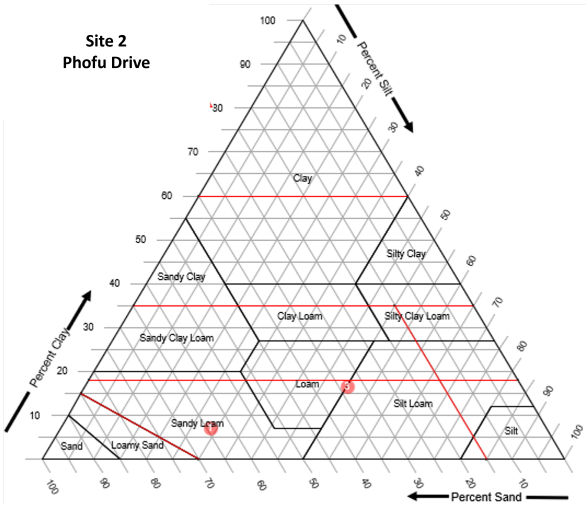
Table 6.11: Mass-% of clay, silt and sand for Northern Plains (site 4)

Jar test

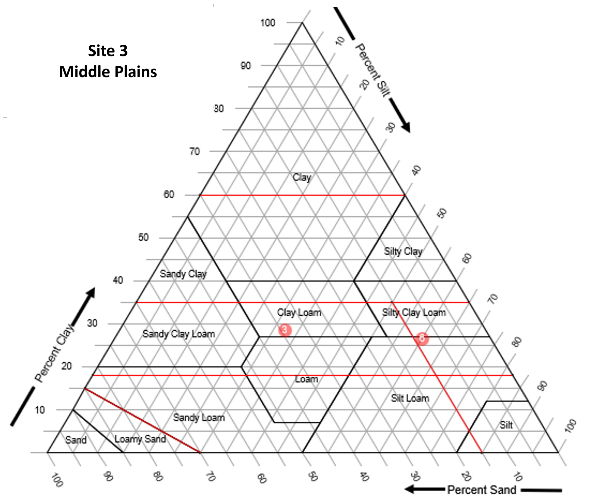
In the jar test, ten different samples were analysed to determine their texture class and compare these results with those obtained from the manual soil texture analysis (MSTA) method previously performed. Figure 6.17, shows these results; Figure 6.17a describes the soil textures found in Site 1, locations 1, 3 and 6; Figure 6.17b describes the soil textures found in Site 2, locations 1 and 3; Figure 6.17c describes the soil textures found in Site 3, locations 3 and 6 and; figure 6.17d describes the soil textures found in Site 4, locations 1, 3 and 4.



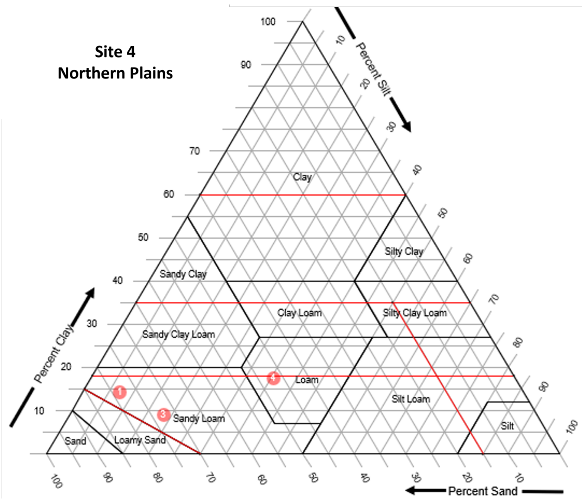
(a) Southern Plains Jar Test Results



(b) Phofu Drive Jar Test Results



(c) Middle Plains Jar Test Results



(d) Northern Plains Jar Test Results

Figure 6.17: Soil Texture Analysis Results from the Jar Test

Table C.5 found in the Appendix C.6 describes the calculated values of mass % of clay, sand, and silt observed in each sample. These values were used to determine the soil textures that can be found in each specific location.

Comparison of MSTA and Jar test

To provide consistent data, the results from the texture analysis and the jar test were compared. Table C.6 in the Appendix includes the results of the two soil texture analysis methods used. It shows the mass % of sand, silt and clay and texture classes per site and sample for each soil sample tested by the two methods. It is important to recall that the texture classes obtained from the manual soil texture analysis (MSTA) are based on those described in the KA5 triangle, while those obtained from the jar test are based on the International Soil Texture Triangle (IST Triangle).

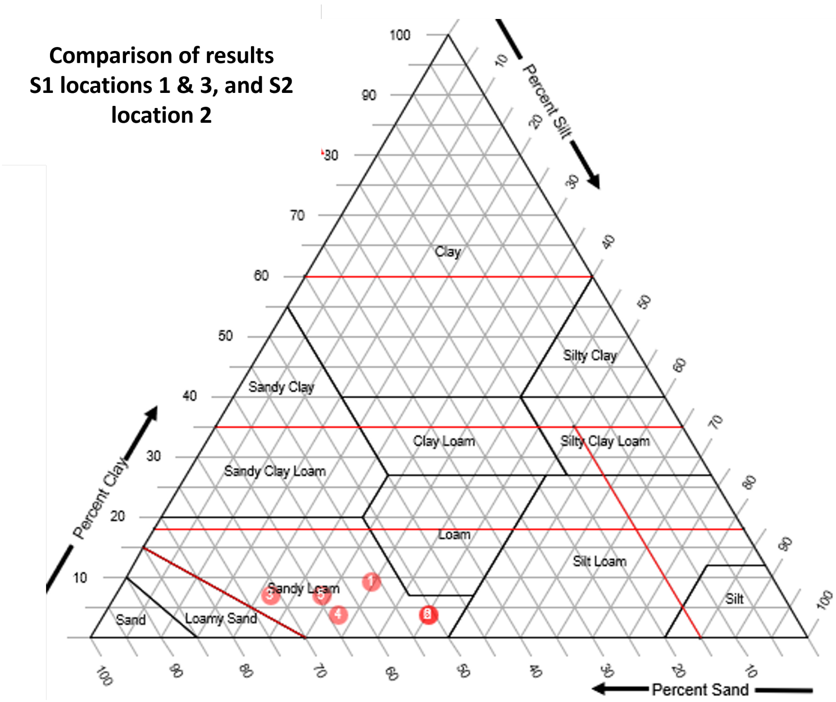


Figure 6.18: Soil Texture Analysis Results and Jar Test Results for Site 1 (Loc. 1 and 3) and Site 2 (Loc.2)

Figure 6.18 shows the soil texture determined by both texture analysis tests as a function of the mass % of sand, silt and clay for Site 1, locations 1 and 3, and Site 2, location 2. The exact information of each plotted point found on Figure 6.18 can be seen in Table C.7 in C.6.

6.3.2. Soil Bulk Density, Moisture Content and Porosity

Results for soil bulk density, moisture content and porosity were calculated for all 48 samples. Two samples were collected at each location, so the average of the resulting characteristics of both samples has been used to represent each sampling location in this section. Refer to Table C.3 in Appendix C, for the exact results of the dry bulk density, moisture content and soil porosity of each excavated sample. The results presented for the site-by-site comparison exclude certain data points due to the difference in vegetation habitat and differences in soil texture. Furthermore, the data presented in the comparison of results sorted by sand content exclude samples that did not belong in the characteristic texture class of each site. More details on the data selection can be found in Appendix C, Section C.6

Bulk Density

The dataset describing the bulk density in all four sites has a mean of 1.70 g/cm^3 and a standard deviation of 0.08 g/cm^3. The median bulk densities are of 1.70 g/cm^3 for sites 1 to 3 and 1.74 g/cm^3 for site 4 respectively. The cleared locations generally have a higher bulk density than the uncleared locations: 1.73 g/cm^3 compared to 1.70 g/cm^3, however this gap is relatively small when considering the standard deviation. This trend is confirmed for sites 2, 3 and 4, but site 1 shows a higher bulk density in uncleared locations (see Figure 6.19).

In order to compare bulk density by soil texture, only Su4 samples (for site 1 and 2), Lu (for site 3), Sl3 (for site 4) were taken into consideration (see Figure 6.19). Both Lu (19% sand) and Sl3 (51% sand) have a median bulk density of 1.70 g/cm^3 and Su4 (65% sand) one of 1.77 g/cm^3. When sorted by texture, all three textures considered have a higher mean bulk density when cleared, but put in perspective with the standard deviation, the significance of this gap is debatable. Additionally, the gap between cleared and uncleared median bulk densities increases with a decreasing sand content.

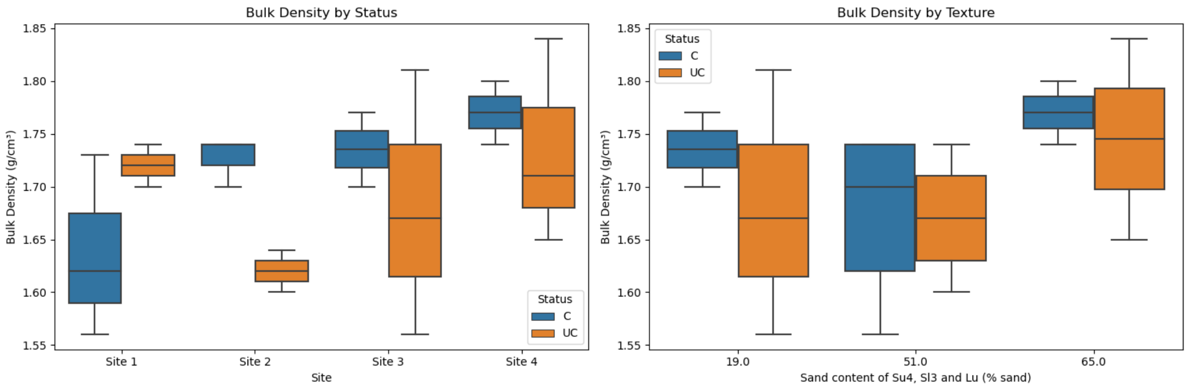


Figure 6.19: Soil Bulk Density According to Site and Texture

Moisture Content

The moisture contents recorded have a mean of 0.27% and a standard deviation of 0.24%, with values ranging from 0.04% to 0.79%. The median soil moisture content varies from site to site, and is equal to 0.08%, 0.25%, 0.49% and 0.06% for sites 1 to 4 respectively. Though cleared locations have an overall higher moisture content, as their mean moisture content is of 0.20% compared to 0.16% for uncleared locations, this trend cannot be confirmed in Sites 2, 3 and 4. The moisture contents of soil when sorted by sand content decreases with increasing sand content, at 0.49%, 0.25% and 0.07% for Lu, Sl3 and Su4 samples respectively.

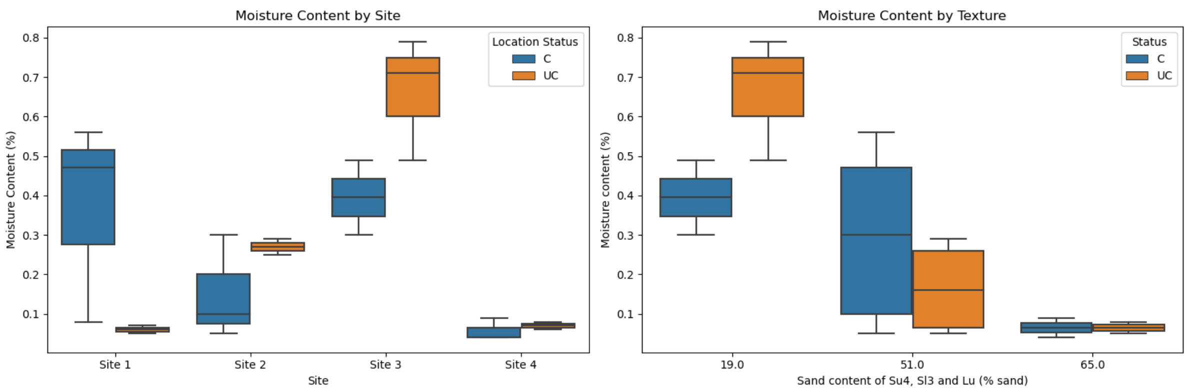


Figure 6.20: Soil Moisture Content According to Site and Texture

Porosity

The porosity of the soil samples analysed ranges from 29% to 47%, with a mean of 35% and a standard deviation of 4%. The median porosity is very similar at each site, at 35%, 35%, 34% and 33% at sites 1 to 4 respectively. However, the response to bush clearing differs significantly: whilst sites 2 to 4 all see a decrease in their porosity after clearing, site 1 has a higher porosity in cleared locations. The median porosity across all cleared locations is of 34%, yet in site 1 cleared locations have a median porosity of 38%. When observing the variation in porosity depending on soil sand content, it appears that the median porosity is lower in cleared sites for all soil types considered (Su4, Lu, Sl3). With decreasing soil sand content, a bigger difference in median porosity between cleared and uncleared samples can be observed; from 0% difference for Su4, to 1% for Sl3 and 3% difference for Lu.

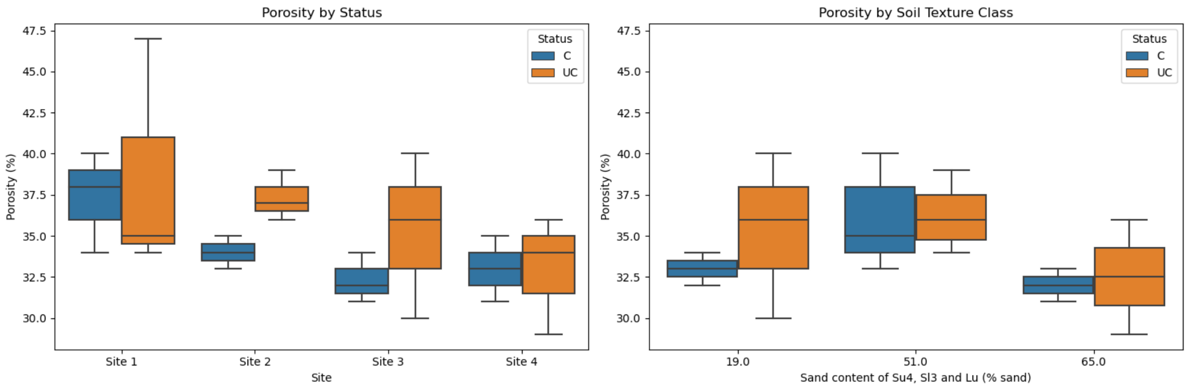


Figure 6.21: Soil Porosity by Site and Texture

6.3.3. Hydraulic conductivity

Three different tests were conducted to determine the hydraulic conductivity (Ksat) of the topsoil layer in cleared and uncleared locations of the Reserve. Each test was conducted at a different depth while remaining in the top layer of the soil (0-30 cm).

Constant Head Infiltration Test

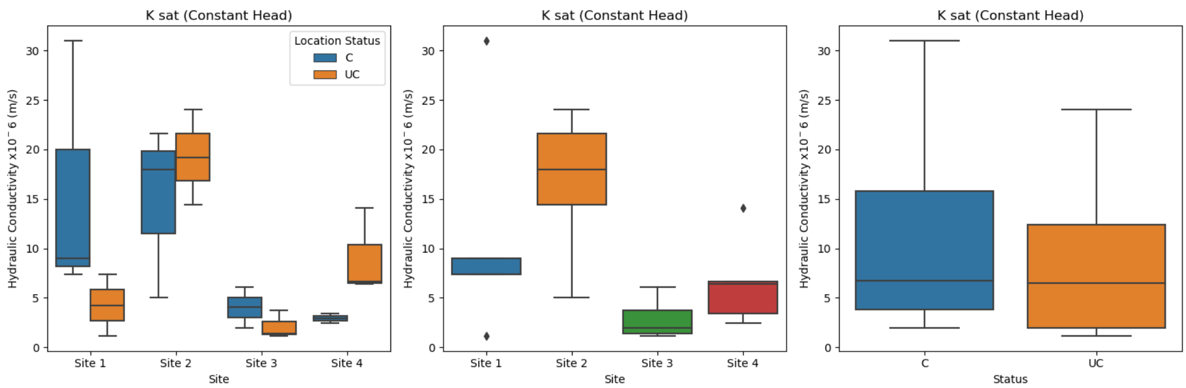


Figure 6.22: Hydraulic Conductivity Results (Constants Head Test)

Undisturbed soil samples were collected from 24 locations and tested at the main camp using a Mariotte's bottle. The results are displayed below in table C.8 in Appendix C and in Figure 6.22.

The constant head infiltration test with a Mariotte's bottle was carried out on most of the samples: two per site (48 samples in total). The average of these two samples at each location was taken to represent the hydraulic conductivity at that site. This dataset has a mean hydraulic conductivity of 9.3x10^{-6} m/s. The values for cleared and uncleared locations are of 6.8x10^{-6} m/s and 6.5x10^{-6} m/s respectively. Looking at the variation in hydraulic conductivity within each site, sites 1 and 3 have a higher hydraulic conductivity when cleared, and vice versa for sites 2 and 4. Overall, the highest median Ksat was recorded for samples from Site 2 (Phofu Drive). When considering the effect of soil texture on hydraulic conductivity, Sl3 and Lu soils have a higher median Ksat on cleared sites, whereas Su4 has a lower Ksat on cleared locations. Furthermore, the gap between the median values for cleared and uncleared sites varies with the sand content of the samples: from 2.6x10^{-6} m/s for Lu to 7.1x10^{-6} m/s for Sl3 and 3.6x10^{-6} m/s for Su4.

Slug test

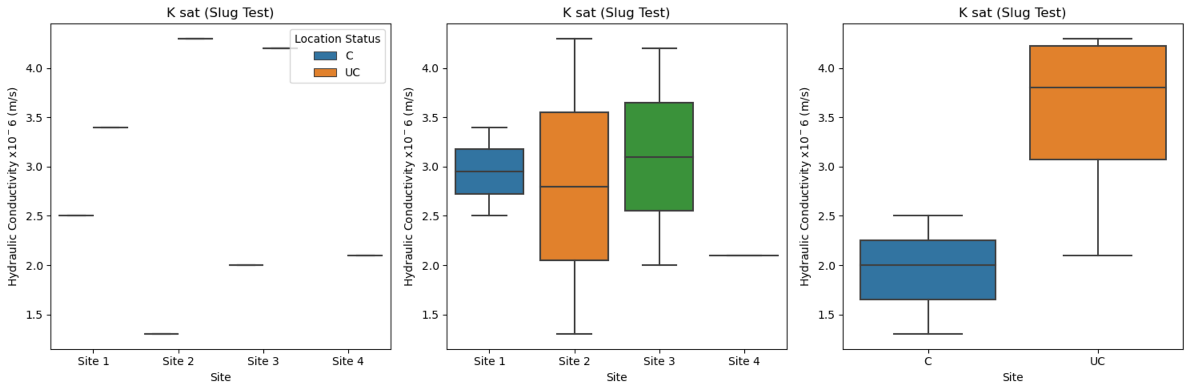


Figure 6.23: Slug Test Results

A total of eight shallow boreholes, each 30 cm deep, were drilled at eight locations to perform inverse slug tests and to obtain an indication of the hydraulic conductivity of the topsoil. Specifically, two locations were selected at each site, one representative of the cleared areas and one representative of the uncleared areas.

The computed values are displayed in table C.9 in Appendix C. The slug tests show generally lower Ksat for cleared locations (2.0x10^{-6} m/s) compared to the uncleared locations (3.8x10^{-6} m/s). This observation is confirmed in sites 1, 2, 3. The results of Ksat obtained from the slug tests sorted by texture show lower median values for cleared sites in Lu and Sl3 samples.

The data are presented in figure 6.23 to better illustrate the differences in hydraulic conductivity between cleared and uncleared areas.

Double Ring Infiltrometer

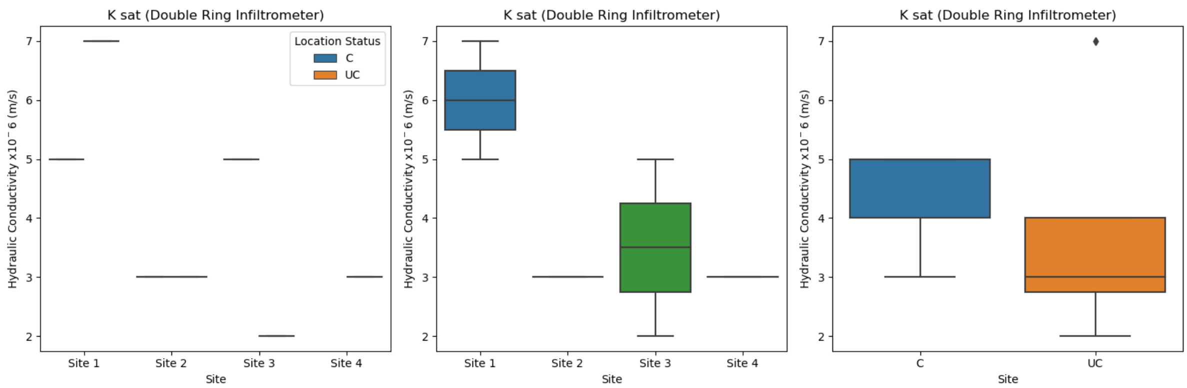


Figure 6.24: Double Ring Infiltrometer Results

A Double Ring Infiltrometer test was carried out on the same four study sites, in this case eight sites were selected to provide an indication of the hydraulic conductivity of the topsoil. As with the slug test, two locations were selected at each site, one representative of the cleared areas and one representative of the uncleared areas.

The computed values are displayed in tables C.10 and C.11, in Annex C.14 . Table C.10 shows the infiltration rate at each site according to the Double Ring Infiltrometer and C.11 shows the Ksat values at each site according to the same test.

According to this test, cleared sites have a higher Ksat (5.0x10^{-6} m/s) than uncleared sites (3.0x10^{-6} m/s). However, considering the different results for the distinct soil textures Su4, Sl3 and Lu, no clear trend between sand content and Ksat can be established.

Soil hydraulic conductivity and soil texture class

The accuracy of the Ksat values obtained from the Slug test, Double Ring Infiltrometer test and Mariotte's Bottle were evaluated by comparing them to literature reference values based on soil texture and dry bulk density.

Table C.12 shows the deviation of the two values i.e. calculated Ksat and Ksat retrieved from Table 13 in Teil and Teil [33]. This was done for each site and location where the Double Ring Infiltrometer and Slug Test were conducted. The average deviation is 7120,1% for the Slug test, 1525,5% for the Double Ring Infiltrometer test, and 122.1% for the Mariotte's bottle test. Table C.12 includes a summary of the results gathered by comparing the Ksat results of the three different tests conducted with reference Ksat value based on dry bulk density and the analyzed soil texture class.

Site-Location	Slug test	Double ring	Mariottes bottle
S1-L1	5376,2%	1018,1%	97,1%
S1-L4	9453,2%	1863,8%	73,2%
S2-L1	3928,8%	802,5%	457,8%
S2-L6	8641,6%	607,8%	184,6%
S3-L1	21500,0%	4884,6%	105,2%
S3-L4	2194,5%	1529,4%	34,4%
S4-L1	1891,2%	1039,7%	60.71
S4-L2	3975,2%	-457,8%	24,2%
Average deviation	**7120,1%**	**1525,5%**	**102,76%**

Table 6.12: Comparison of soil hydraulic conductivity and hydraulic conductivity based on soil texture class and dry bulk density

Refer to Tables C.12, C.13, C.14 and C.15 in Appendix C for more details on the values discussed here above.

6.3.4. Organic Matter Content

The Munsell color analysis resulted in hues ranging from 5 YR to 10 YR. Their values ranged between 3 and 5, and their chromas were spread from 4 to 8. The detailed Munsell color results can be seen in B.5.6. The OM contents derived from the colour analysis of the samples are shown in 6.25 and 6.26. The Munsell colours for each of the samples collected were determined and their respective HVC values were converted to an OM content using table B.3 in combination with the soil texture analysis results. The box plot in 6.25 shows a side-by-side comparison of the OM content of cleared and uncleared locations. The median OM content for the uncleared sites is of 8.5% and that of the cleared site is of 12%.

In site 1, the median OM content in cleared sites is 7.5% and that of uncleared locations is 5%. In site 2, 3 and 4, the median values of cleared and uncleared locations are the same, at 12%, 12% and 5% respectively.

The OM content of a selection of 12 samples was also determined using an "at-home" loss-on-ignition (LOI) protocol for greater accuracy. This resulted in OM contents ranging from 0.36% to 0.81%, as seen in Figures 6.25 and 6.26. The median OM content for cleared sites is of 0.66% and 0.48% for uncleared sites. The drying process took 2 hours and 39 minutes and was declared complete when the mass had stabilized. Burning was stopped after 9 hours, when the mass no longer decreased. The complete data can be found in C.20 of B.

Both protocols give results that show the same trend of decreasing OM content with increasing sand content. They also show a similar trend with sites 2 and 3 having an overall slightly higher median OM content than sites 1 and 4 (cleared and uncleared sites combined).

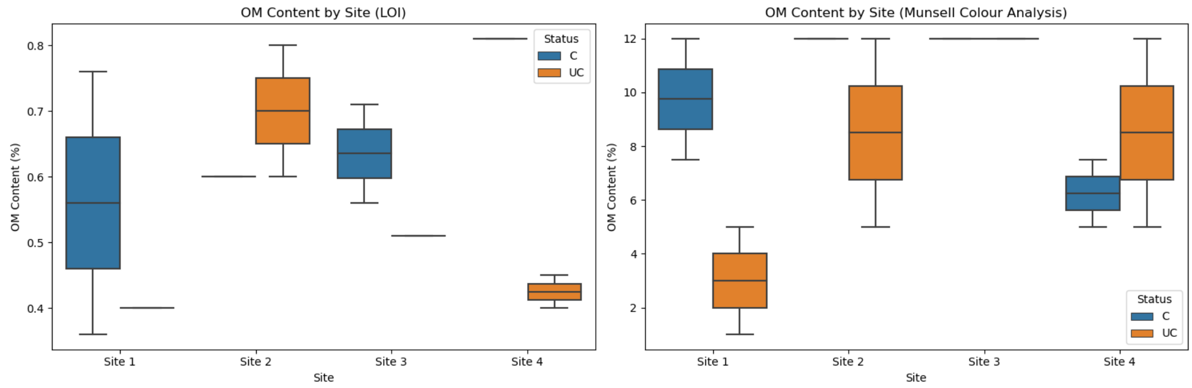


Figure 6.25: OM Content by Site and Status for LOI and Munsell Colour Analysis Results

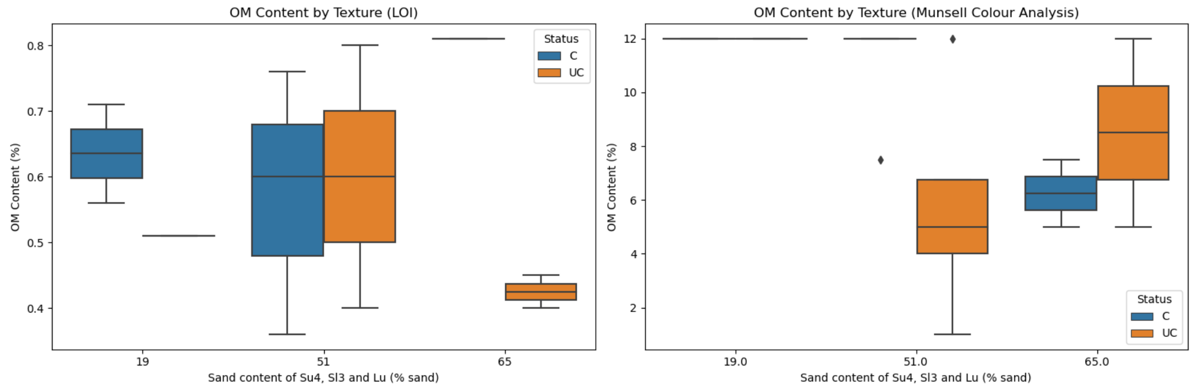


Figure 6.26: OM Content by Soil Texture for LOI and Munsell Colour Analysis Results

6.3.5. Teabag Index (TBI) for Soil Organic Activity

As mentioned before, by using the Tea Bag Index, it is possible to determine the decay rate and stabilization factor at each location where the teabag samples were buried.

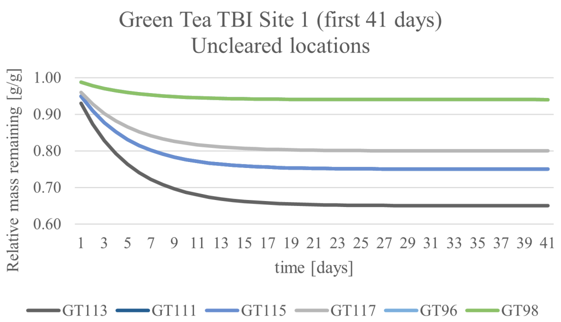
This test was conducted at four different sites in the Reserve and at six different locations per site. A total of 48 pairs of *Rooibos* and *Green Lipton* tea bags were buried at a depth of 10 cm to allow contact with the active layer of soil and at a distance of 15 cm from each other. All samples were exhumed from their locations after 41 days. Table C.1 describes the details of all the burials.

Various parameters were calculated to better understand the stabilization factor S of the Green tea bags and the decomposition rate k constant of both classes of tea. These parameters were compiled in Table 6.13

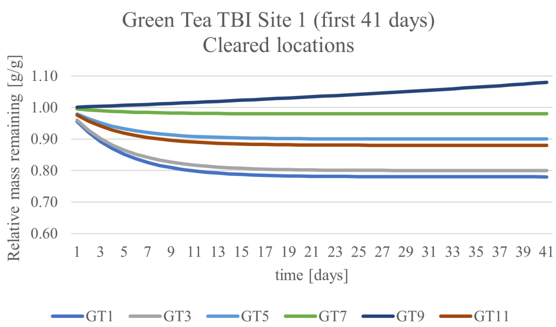
Parameter	Value
Green tea stabilization factor S [-]	0.792
Average decomposable fraction Rooibos a_r[-]	0.115
Average decomposable fraction Green tea a_g [-]	0.175

Table 6.13: Tea Bag Index Parameters

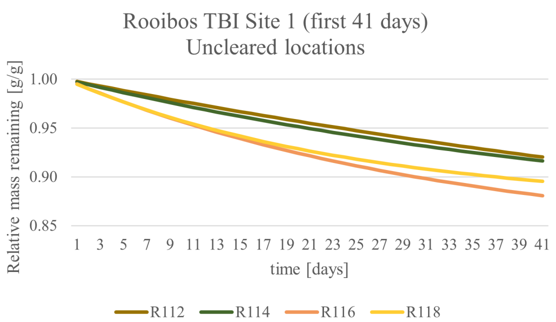
The same parameters were calculated for Sites 1 and 2 and are shown in Table C.21 and Table C.22 in Annex E respectively.



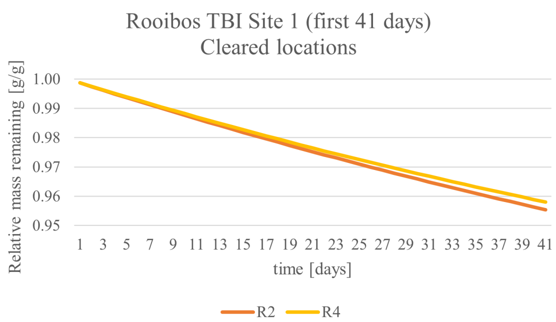
(a) Green tea mass loss over time in uncleared locations



(b) Green tea mass loss over time in cleared locations



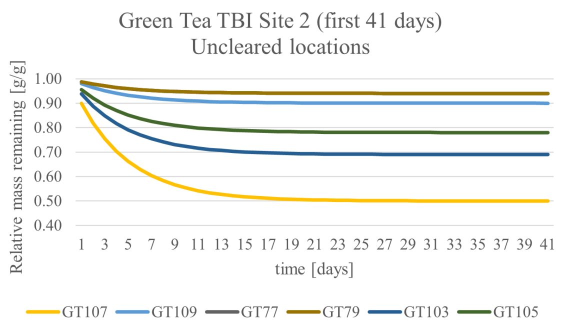
(c) Rooibos tea mass loss over time in uncleared locations



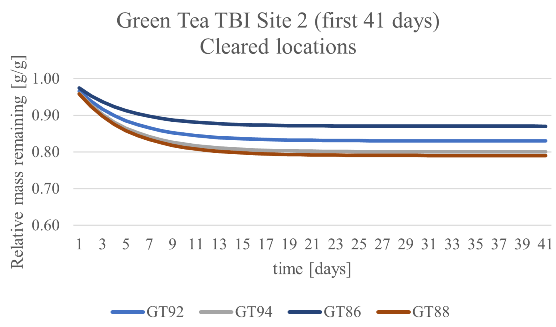
(d) Rooibos tea mass loss over time in cleared locations

Figure 6.27: Tea mass loss over time in cleared and uncleared locations on Southern Plains

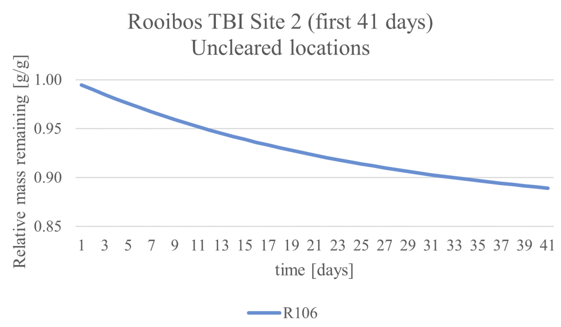
Figure 6.27 shows the graphs of mass loss over time (41 days) for both Rooibos and Green teas in cleared and uncleared locations of Site 1. As in the same case for Site 1, Figure 6.28 shows the mass loss over time of both teas in cleared and vegetated locations from Site 2.



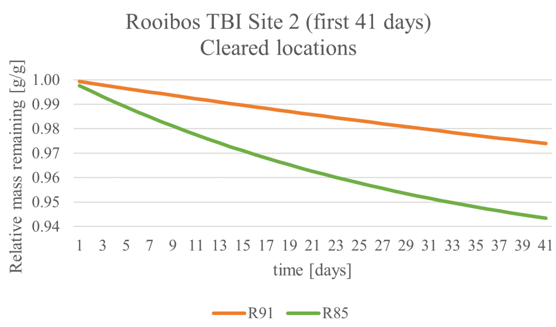
(a) Green tea mass loss over time in uncleared locations



(b) Green tea mass loss over time in cleared locations



(c) Rooibos tea mass loss over time in uncleared locations



(d) Rooibos tea mass loss over time in cleared locations

Figure 6.28: Tea mass loss over time in cleared and uncleared locations on Phofu Drive

The mean TBI values (k and S) for both classes of tea observed at Sites 1 and 2 are shown in Tables 6.14 and 6.15. Green tea is defined as (GT), while Rooibos tea is defined as (RT).

Parameter	GT Cleared	GT Vegetated	RT Cleared	RT Vegetated
Mean decomposition rate k	0.184	0.225	0.117	0.024
Mean stabilization factor S	0.854	0.768	0.904	0.848

Table 6.14: Mean TBI values in cleared and vegetated sites of the Southern Plains

Parameter	GT Cleared	GT Vegetated	RT Cleared	RT Vegetated
Mean decomposition rate k	0.225	0.225	0.018	0.038
Mean stabilization factor S	0.789	0.753	0.862	0.900

Table 6.15: Mean TBI values in cleared and vegetated sites of Phofu Drive

6.3.6. Soil Health Multi-criteria Analysis

The key parameters selected for the multi-criteria analysis of soil health are: bulk density, porosity, plant available field capacity, field capacity and organic matter.

Table 6.16 summarizes the results of the multi-criteria analysis for the four sites and their respective locations. Refer to Tables C.25, C.27, C.29 and C.31 in Appendix C for further details on the matrix results. Additional information on the coefficients for each soil parameter can be found in Tables C.26, C.28, C.30 and C.32. Each site can achieve a maximum score of 36 points based on five criteria factors, each contributing 0-1 points, with a highest available score of 6 points per each location per site. It should be noted that these values are relative to the scope of this research and if a wider comparison is required, further soil health evaluation should be considered.

Tables C.23 and C.24 summarize the range values used for comparison, forming a fundamental basis for the multi-criteria matrix and its results.

Location	Site 1	Site 2	Site 3	Site 4
1	5.68	5.36	5.73	5.78
2	5.23	5.30	5.56	5.96
3	5.69	5.72	5.60	5.88
4	5.87	5.63	5.76	5.43
5	5.30	5.22	5.22	5.82
6	5,30	4,51	5,67	5,82
TOTAL	33.58	31.74	33.55	34.70

Table 6.16: Location and Site Data Summary

Table 6.17 shows the results of the multi-criteria matrix for the four sites and their cleared and vegetated locations, with a maximum achievable score of 18 points for vegetated/cleared locations of each site.

Status	Site 1	Site 2	Site 3	Site 4
Cleared	16,60	16,30	16,56	17,49
Vegetated	16,98	15,43	16,99	17,21

Table 6.17: Multi-criteria matrix for cleared and vegetated sites

7 Discussion

7.1. Site selection

The selection of sites, i.e. Southern Plains, Middle Plains, Phofu Drive and Northern Plains, is considered appropriate for the scope of this project as past activities in these areas have had a significant impact on the surrounding environment. These specific sites will need to be closely monitored by the Reserve in the future to assess the positive or negative impacts of bush clearing on the Reserves environment and its effect on water availability. It should be noted that for the chosen locations within each site, it is assumed that farming activities were implemented at the specific chosen location in the past, but not confirmed.

After carrying out the various field experiments at each site, and further analysis of the experiments, it was realized that some sites could have been chosen more carefully. As mentioned in Section 5.1, locations within each site were selected once the team had arrived at each site and some constraints influenced these decisions. Following the subsequent evaluation of each location selected, it is felt that sites could have been selected with greater consideration of the factors mentioned in Section 5.1.

As can be seen in Figure 6.1 in Section 6.1, location 6 is some distance away from locations 1-5, and no trend was found from the retrieved and processed data. It was therefore not possible to compare the results of the field experiments for this location with those of the neighbouring locations. The soil samples taken from this location were also very different in colour and texture from other samples taken from Southern Plains. After further investigation of the surrounding vegetation and geology of Southern Plains, it was determined that the vegetation for location 6 was different from the other five previous locations. This can be seen in Figure C.1 in AppendixC.1.

As has been discussed before, the goal was to choose a total of 6 locations, where 2 locations are adjacent to each other. It can be observed in Figure 6.3 in Section 6.1 that locations 1-3 are situated relatively close to each other and the same can be observed for locations 4-6. The proximity of these locations triggers the differences that might exist between sites, and therefore only 2 sets of neighbouring sites were considered, rather than 3 as originally planned. This can also be seen in figures 6.1 and 6.4 in section 6.1. This has made it difficult to assess the impact of bush clearance on these specific locations.

When the team arrived in the Northern Plains, it was unclear where the clearing methods had been implemented and it was difficult to decide where to conduct field experiments in relation to cleared areas and adjacent uncleared areas. This problem was later discussed with the Reserve's research manager, who explained that clearing on the Northern Plains had been suspended due to a change of clearing contractor. As a result, this area has sections that are either fully cleared, partially cleared or not cleared at all. This explains why the team had a hard time navigating where clearing had been performed and choose locations based on that. Although this information was later known, it was impossible to change the selected sites as the tea bags had already been buried in the selected locations. By observing the selected sites on a map of the Reserve and analysing the video descriptions of the surrounding vegetation, it could be assumed that sites 1-3 are uncleared and the remaining sites are cleared. It should be noted, however, that these are conclusions based on visual inspection and are not confirmed.

Given the size of the Reserve, the limited time frame, the varying land management practices and the different methods of bush clearing, it was hard to select sites and their respective locations, which take into account the factors mentioned in section 5.1. However, the sites and locations chosen for this research were chosen because they were well distributed, allowing the impact of bush clearing to be assessed in different locations and providing valuable results for this project.

7.2. Water balance

This section describes an analysis of the bucket model used in this report, examining both the input and output components of the model. The model input section, Section 7.2.1, that influence the accuracy of the model, including boundary fluxes and essential parameters. The Model Output section, section 7.2.2, discusses the current scenario and projections for different land cover and climate change scenarios, providing insight into the application of the model under different environmental conditions.

7.2.1. Model Input

This section examines the driving elements for the bucket model, focusing on boundary fluxes and parameter selection.

Boundary fluxes

The bucket model used to model the water balance requires the input of several boundary fluxes. First, the uncertainty of the precipitation and evapotranspiration data was analysed. In order to assess the uncertainty intervals behind the input fluxes of precipitation and evaporation, a comparison of the ERA5 time series with other sources was made. The precipitation datasets from ERA5, CFSR, CHIRPS, NOAA and TRMM [38] were compared, the uncertainty interval behind precipitation data can be seen in figure 7.1. TThe same comparison was made for evaporation, for which fewer data sets were available in the study area. Evaporation datasets from ERA5, GLDAS and NOAA [38] were compared, showing a high uncertainty interval as observable from figure 7.2. Uncertainty was assessed over a time period for which all of the aforementioned datasets were available, resulting in a 20-year period from 2000 to 2020. Overall, this analysis shows that while the uncertainty for precipitation data is relatively small, the much larger uncertainty range for evaporation data underlines the need for careful consideration when interpreting water balance results. The lack of reliable evaporation data suggests that it may be beneficial to focus on improving local evaporation data collection for future research; however, due to current limitations, it was decided to continue with the ERA5 dataset for this study.

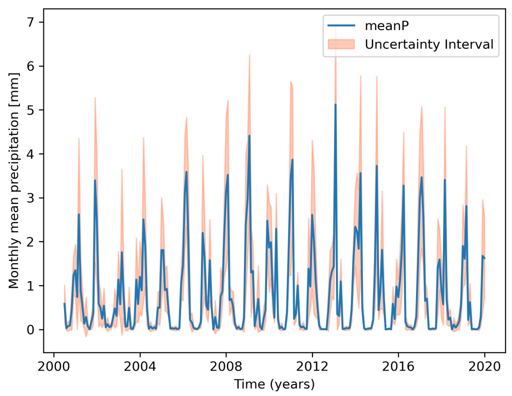


Figure 7.1: Uncertainty Interval Precipitation

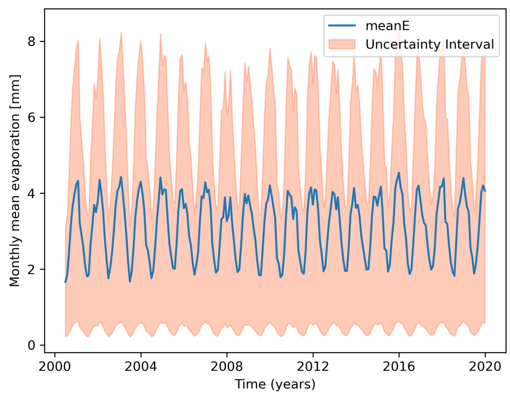


Figure 7.2: Uncertainty Interval Evapotranspiration

An estimate of the human withdrawal was made based on human consumption rates and water losses from water points. Quantifying this uncertainty is difficult due to the lack of reliable data sources. However, this flux is estimated to be quite small compared to other fluxes within the model, resulting in a small impact on the overall water distribution. For future research, it is recommended that flow meters be installed at major boreholes to monitor discharge over time, which would improve the accuracy of estimates of human groundwater abstraction.

The remaining boundary fluxes result from internal processes within the model and carry significant uncertainty as they are derived from several parameters, each with its own inherent uncertainty. The uncertainty of the lateral Runoff (Qf) and flow from the aquifers towards river (Qs) can be minimised by comparing the sum of these fluxes with the discharge of the streams flowing from the Reserve to the river. However, such discharge data were not available, which means that the parameters used in the model cannot be calibrated, leaving these outflow fluxes vulnerable to high uncertainties of an unknown magnitude.

Parameters

The parameters identified in this study control the main fluxes and determine the model results. Imax and Sumax are found to be different for cleared and uncleared sections within the Reserve, which is understandable given their direct relationship with vegetation. The parameter Rho differs on a daily basis, as it depends on the ratio between Su and Sumax, but also on the landscape present, as it was found that runoff is five times higher in hilly areas. The other parameters, Lp, Pmax, Kf and Ks, were estimated to be the same for each category.

Each parameter value in the model has been determined through field experiments, literature research, or both. Field experiments provide direct measurements under real-world conditions but result in variability due to environmental variations, seasonal differences, and heterogeneity of local conditions. This variability introduces uncertainty, as field measurements represent only a snapshot and may not fully capture the complexity across different times or locations within the Reserve. In this report, the impact of of spatial differences were minimized by taking numerous measurements, spread out over the Reserve and averaging the results. However, variability could be reduced further by increasing the number of samples and collecting them throughout the season to account for temporal variability.

Each parameter value in the model has been determined by field experiments, literature review or both. Field experiments provide direct measurements under real-world conditions, but result in variability due to environmental changes, seasonal differences and heterogeneity of local conditions. This variability introduces uncertainty because field measurements are only a snapshot in time and may not fully capture the complexity at different times or locations within the Reserve. In this report, the impact of spatial variation has been minimised by taking numerous measurements across the Reserve and averaging the results. However, variability could be further reduced by increasing the number of samples and collecting them throughout the season to account for temporal variability.

As mentioned above, the availability of local discharge data would have allowed the parameters to be calibrated, the model to be optimised and uncertainties to be minimised. However, local discharge data are not recorded and therefore the parameters remain uncalibrated, leaving a high vulnerability to uncertainty. This vulnerability can be mitigated in future research if local discharges are recorded at times when the rivers within the Reserve are not dry, or if a comprehensive analysis of the Limpopo River discharge is undertaken. A discharge analysis of the Limpopo River would involve detailed measurements of river discharge at several points upstream and downstream of the Reserve to determine the flow into or out of the river. By establishing a comprehensive discharge analysis, preferably across different seasons over an extended period of time, it would be possible to identify periods when the river is recharging (contributing water to the local aquifer within the Reserve) and periods when it is draining (drawing water from the Reserve's aquifers). Such measurements would allow the model parameters to be calibrated by comparing the modelled and actual boundary fluxes.

7.2.2. Model Output

This section examines the conclusions that can be drawn from the water balance results presented in the previous chapter.

Current Scenario

The five-year (2019-2024) water balance model results indicate that the primary outflow fluxes are evaporation and transpiration. This is in line with expectations in this semi-arid climate. Although lateral runoff and groundwater discharge to the river are also significant, they contribute much less than the evaporative fluxes. Human abstraction, when averaged across the Reserve, is negligible compared to these other flows, but it is important to note that it can have a significant impact locally. Water for human consumption is primarily abstracted at two sites where locally large volumes are abstracted, potentially affecting the local water balance. Further analysis would be required to assess these localised effects, where human abstraction may no longer be negligible. The main conclusion from running the model is that groundwater storage fluctuates from year to year, but never falls below 5 mm at any time during the five years the model is run. Even after three relatively dry years, the groundwater seems to be able to recover with the relatively low rainfall. This means that in the current situation the recharge of the aquifer is able to keep up with the abstraction and losses. It is important to recognise the uncertainty behind the figures presented. The values shown in each graph represent the results of a bucket model, which simplifies real-world conditions and relies on parameters and input boundary fluxes which have inherent uncertainties, as described in the previous sections. The model results should be interpreted with caution, recognising that variability in each input contributes to the overall uncertainty in the results. Further analysis or additional data could help to refine these inputs and reduce the uncertainty in the model outcomes.

Different Land cover Scenarios

The three different land cover scenarios that were implemented in the model were, double the amount of current clearing, half of the Reserve cleared, and no clearing. These scenarios were chosen to show the impact of clearing on the distribution of the water fluxes as well as the impact on the groundwater storage. In the future, the Reserve might want to increase the amount of bush clearing due to bush encroachment and it is important to understand the impact of clearing on water flows.

The situation where half of the Reserve is cleared is quite an extreme scenario and is used to demonstrate a 'worst case scenario' of bush clearing. This scenario does indeed show a decrease in groundwater storage. In the situation where half of the Reserve is cleared, the increase during the wet period of 2020-2021 is significantly lower than in the current situation, which would suggest that the groundwater storage does not replenish as quickly with increased clearing. The water fluxes in the system are distributed differently due to the increased clearing, as can be seen in Figure 6.11. The runoff and evaporation have both increased in this scenario regarding the current situation. This could explain the decrease in groundwater storage as the amount of water available for infiltration is reduced.

A more realistic scenario is the situation where the amount of clearing will be doubled. The trend in groundwater storage shows a similar case to the previous scenario, where the amount of storage is reduced compared to the current situation. However, when looking at Figure 6.11 one can note that the amount of runoff does not necessarily increase with this change in land cover. This can specifically be observed in 2020 and 2021. The Eidt also decreases in this scenario, meaning even more throughfall reaches the soil than in the current situation, expecting an increase in runoff. This runoff could increase due to the implementation of the rho factor, which increases the runoff in a sloped area. As can be seen from the table 6.3, the percentage of 'hillslope uncleared' is 0, which is the percentage entered for the different land cover scenarios. However, the percentage determined by the distributed model is slightly higher than the 0 percent used as input for the current scenario. This difference was assumed to be insignificant, but as the rho is multiplied by 5 in the hillslope subsystem, this could result in lower runoff if this subsystem is not taken into account. This could possibly explain the lower runoff for the double clearing scenario compared to the current situation.

The final scenario considered is the situation where there is no clearing. This would be the more natural situation for water storage, but due to the encroaching bushes on the Reserve after a long history of farming, this seems unattainable in the near future. This scenario shows that without clearing, the amount of groundwater storage is increased compared to the current situation. In particular, in a year with peak rainfall, as shown in the rainy season of 2020-2021, groundwater storage is higher. The bar chart shows a similar trend to the other scenarios, but in the opposite direction, with less runoff and less evaporation. Most importantly, none of the three scenarios in this model drained the groundwater storage completely.

The bar chart with the three different fluxes shows how the distribution within the system changes, with an overall increase in runoff and evaporation as clearing increases. This could explain the decrease in groundwater storage, as less water is available for infiltration. An important point to emphasise is

the similarity in the amount of runoff between the current situation and the double clearing scenario. This could be due to the way the fluxes are modelled, especially the hillslope subsystem. However, it still shows no significant rise in runoff when the amount of clearing is slightly increased. The biggest outgoing flux in the system is the evaporation, which does increase with more clearing.
It should be taken into account that the percentage of clearing determined for this Reserve was done by using satellite images and a supervised learning algorithm. As described in section 5.2.2 this algorithm was trained to recognize cleared and uncleared areas. As it is possible that not all cleared areas were detected by this algorithm, the percentage of clearing may have been underestimated for this model. Figure 5.7 in section 5.2.2 shows the determined cleared and uncleared sites, it includes the four different sites that were studied in the research. However, sometimes not all of the cleared area was classified as 'cleared', which could lead to uncertainties in the implementation of the model. Due to these and other uncertainties, the results of these different situations should serve as an indication. Increasing bush clearing still impacts the distribution of the fluxes and potentially in the long run, could impact the groundwater storage.

Climate Change Scenario
The results of the comparison between the current situation simulation and the RCP45 climate prediction simulation show changes in water fluxes, which are present but generally modest. Seasonal differences are evident, with more pronounced changes in the summer months. This seasonal increase in precipitation and evaporation suggests a potential intensification of the hydrological cycle, leading to wetter and hotter summers and thus more extreme water availability. During the non-summer months, the differences in water fluxes are insignificant, showing less change between the two simulations. This supports the hypothesis of increased seasonality. Although these changes are observable and significant, they do not suggest drastic changes in the main hydrological pattern, while they show an intensification of the existing climatic pattern of the study area.
The difference plot in Figure 6.15 shows changes in the distribution of water fluxes. The shallow flow towards the river (Qfdt) varies between -0mm to +5mm whereas deeper groundwater flow towards the river (Qsdt) shows generally smaller changes, indicating a tendency of the excess precipitation to travel horizontally rather then infiltrate deeper into the groundwater system. This could be related to the increased intensity of rainfall during the summer months, which would result in more rain falling over the Reserve in a limited period of time, increasing the tendency for shallow runoff compared to deeper infiltration mechanisms. However, the observed changes suggest that the magnitude of the shift towards more shallow horizontal flow is small and that the predicted future climate scenario does not pose an immediate threat to the available groundwater storage.
The mentioned minor changes might still have long-term effects, particularly if they are coupled by additional environmental stresses like changes in land management practices.
It is important to recognise the uncertainty behind the results presented and discussed in this analysis. The values presented are the result of model outputs with inherent uncertainties. Firstly, the prediction of the future climate scenario is already uncertain due to the process used to define it, more on this can be found in section 5.2.5. In addition, the fluxes modelled are based on a number of simplifying assumptions that increase the uncertainty of the analysis. This should be taken into account when drawing conclusions on the impact of future climate scenarios on hydrological fluxes and water availability.

7.3. Soil Characteristics

7.3.1. Soil Texture Classification

Manual Soil Texture Analysis (MSTA)

Soil texture is an important environmental factor as it directly affects key soil processes such as moisture retention, drainage and nutrient availability, also it should be noted that different textures have different characteristics. Texture also plays a critical role in determining how susceptible the soil is to erosion and how well it supports plant growth. As a result, soil texture is a critical factor in soil conservation and agricultural management, influencing the productivity and long-term sustainability of the land [39].

The first part of the analysis of the different soil textures consisted of the collection of 48 samples from 24 locations. The soil texture classification allowed for the identification of certain locations that were not representative of their respective site and were therefore not included in the discussion. These include site 1 location 6, site 2 location 4, site 3 location 3 and site 4 location 1.

As mentioned in the results of this test, the dominant soil texture class (STC) found for Southern Plains (site 1) is Su4, observed at locations 1, 2 and 4; for location 3, the observed STC is Su3 and for location 6 it is Lu. The clay, silt and sand composition of soil texture classes Su4 and Su3 are similar, as can be seen in Table 6.5, while the composition for the analysed STC of location 6 of site 1 differs from the previously mentioned classes. A possible reason for this change may be due to the presence of a micro-ecosystem within the delimited zone, as can be observed in Figure C.1 in Appendix C.1. These results confirm that for relatively short distances between locations, soil texture classes and its properties can change substantially. The permeability class for Su3 and Su4 is *fast or very fast*, while for Lu it is defined as *moderate*.

In summary, Site 1 (Southern Plains) and Site 2 (Phofu Drive) should exhibit high topsoil permeability, while Northern Plains should show moderate permeability. Middle Plains has the lowest probability of high permeability, ranging from moderate to low. This correlates with the results of the Constant Head Infiltration Test, shown in Figure 6.22, where Site 2 (Phofu Drive) has the highest Ksat value, followed by site 1 (Southern Plains), Site 4 (Northern Plains), and Site 3 (Middle Plains).

The characteristics of the different soil texture classes can be seen in 6.19, 6.20 and 6.21. Sites with a higher clay content (Lu) have a lower median bulk density than those with a higher sand content (Su4, Su3). In addition, it was found that the moisture content increased in sites with higher sand content, while the porosity values decreased with higher sand content and increased with higher clay content. This further validates the results of the manual soil texture analysis, as Su4 and Su3 were expected to fall into the *fast and very fast* permeability class, while Lu falls into the *moderate* permeability class.

These variations are still within the expected soil textures and have similar mass-% of clay, silt and sand compared to the dominant texture class. It should be noted that the soil texture class does not change with ongoing bush clearing, but key properties such as bulk density, moisture and porosity may change.

Jar Test
As mentioned above, the jar test was performed on 10 samples of the collected soil samples. In order to confirm the results of the soil texture analysis and its evaluation by the German KA5 triangle, decided to analyse those samples whose texture stood out from all the others because it was different from the predominant soil texture at each site. In this case, these samples were: Site 1 Location 3 which from the texture analysis was found to be medium silty sand (Su3); Site 1 Location 6 which from the texture analysis was found to be silty clay (Lu); Site 2 Location 4 which from the texture analysis was found to be silty loamy sand (Slu); Site 3 Location 3, which from the texture analysis was found to be a light clay loam (Lt2); Site 4 Location 1, which from the texture analysis was found to be a light clay sand (St2); and; Site 4 Location 4, which from the texture analysis was found to be a heavy clay sand (Sl4). The other 4 samples analysed by this method were randomly selected. These included: Site 1 Location 1 and Site 2 Location 2, which were found to be very silty sand (Su4) by texture analysis; Site 3 Location 6, which was found to be silty clay (Lu) by texture analysis, and; Site 4 Location 3, which was found to be medium loamy sand (Sl3) by texture analysis.

The procedure was followed exactly as described in the Appendix B.5.2. After calculating the percentages of sand, silt and clay, the results could be plotted on the International Soil Texture Triangle. It should be noted that it was decided to plot the results obtained from this test on the International Soil Texture Triangle in order to compare the two tools and to identify their limitations in terms of precision and misclassification of soils due to oversimplification of the relationship between soil particles, without fully addressing how particle size distribution within these categories affects soil behaviour.

The results of the analysed samples are presented in C.7, where it is visible that there is a predominant soil texture class, which in this case was Sandy loam. This type of class can be found in the soil samples from site 1 (locations 1 and 3), site 2 (location 2) and site 4 (locations 1 and 3). However, other types of textures were identified by conducting this test. The percentages that were calculated were then compared with the percentages dictated by the German KA5 triangle to confirm that the results and the content of clay, sand and silt corresponded accurately and thus there was a similarity in the definition of the texture class.

Comparison of MSTA and Jar test

The results shown in the table C.6 describe the different texture classes into which each of the analysed samples could be classified, depending on their mass % content of clay, silt and sand.

As can be seen, 7 of the 10 samples analysed (Site 1 location 6; Site 2 location 4; Site 3 locations 3 and 6, and; Site 4 locations 1, 3 and 4) fall within the same ranges of mass % content of the three different particle types, so regardless of which soil texture triangle they were evaluated in, either the international or the German KA5, both would give the same result. The other 3 samples compared (Site 1 locations 1 and 3, and Site 2 location 2) show some variations in the ranges of results obtained. When judged by the jar test and the international soil texture triangle, and later compared to the limits established by the German KA5 triangle: Site 1 location 1 appeared to have less silt (5.6%) and more clay (1.4%); Site 1 location 3 appeared to have less silt (3.6%), and; Site 2 location 2 appeared to have more sand (4.3%) and less silt (11.4%).

These discrepancies can be due to several factors that influenced the results of the jar test, either in terms of measurements, lighting, size of the sample analysed, or on the other hand, to some discrepancies in the evaluation when performing the soil texture analysis step by step, since this methodology tends to be quite subjective. However, these differences are not significant, since for the last three results compared (Site 1, locations 1 and 3, and Site 2, location 2), when plotting the values obtained from the jar test and the mean of the ranges established by the German KA5 triangle in the International Soil Texture Triangle, both results indicate the same soil texture type. This can be observed in Figure 6.18.

7.3.2. Bulk Density, Moisture Content and Soil Porosity

Bulk Density

Initially, it was postulated that bush clearing was associated with an increase in bulk density due to the use of heavy machinery with a compaction effect combined with a reduction in vegetation cover. The results of the bulk density analysis appear to support this theory, as a trend towards increased bulk densities in cleared locations was observed at sites 2, 3 and 4. Whilst no trend could be identified between soil clay content and bulk density, it appears that an increasing amount of sand results in a smaller gap between cleared and uncleared bulk densities.

Southern Plains (Site 1) differs from the other sites in that it has a higher mean bulk density in the uncleared locations. This difference cannot be related to differences in clearing methods, as Phofu Drive was cleared by the same method (hand clearing and fire) but does not show the same anomalies. Thus, the soil texture class in the Southern Plains seems to be the possible explanation. Site 1 consists mainly of Su4 (with a relatively high sand content) and as discussed above, a higher sand content can have a higher bulk density due to the size of the particles.

The bulk density results for the 48 excavated samples are all within the expected range for their respective soil textures and compaction levels (see Table C.4 in Annex **??**). This, however, does not mean that bush clearing has no impact, but rather that at the time of the measurements, the differences observed have not yet exceeded the bounds of what is expected of each soil sample.

This increase in bulk density should be closely monitored as it has a compounding effect on soil properties such as water infiltration, microbial activity and soil respiration, to name but a few. For example, if bulk density increases beyond acceptable limits, this could in turn affect the soil's ability to perform its key functions of supporting bush vegetation and conducting water to aquifers.

Moisture Content

It was initially thought that the moisture content of cleared land would be lower than that of uncleared land. According to this hypothesis, the vegetation cover would play a major role in retaining moisture in the topsoil layer through its root system. The measured moisture contents show a clear trend at Phofu Drive, Middle Plains and Northern Plains; at these sites, cleared locations consistently have lower moisture contents than their uncleared counterparts.

Furthermore, the texture analysis shows that increasing sand content leads to lower soil moisture contents and a smaller difference between cleared and uncleared sites. This could explain why Southern Plains, which consists mainly of Su4 (65% sand), responds differently to bush clearing than the other sites, with higher moisture contents in cleared locations. In contrast, site 3 has the largest difference in mean moisture content between cleared and uncleared sites (0.30%) and is also the site with the highest clay content.

Thus, the results of the moisture analysis seem to confirm the initial hypotheses that bush clearing reduces soil moisture and that this effect is exacerbated by high soil clay content. An expected range of values for the moisture content of each soil type could not be defined due to the high variability of results for topsoil moisture depending on the time of sampling (day, year) and the sampling method. The topsoil moisture content is expected to change throughout the day and the seasons due to variations in temperature and rainfall. In addition, it is important to note that some steps in the methodology may have resulted in some moisture not being accounted for (some water may have evaporated during sample collection and transport, and some moisture may have remained after air drying).

Soil Porosity
Soil porosity is influenced by factors such as soil texture and organic matter content. Looking at the results obtained, the porosity ranges are aligned with what in theory would be expected in semi-arid soils.

It was expected that soils with a higher mass % content of sand, such as Su4 and Sl3 found in Phofu Drive and Northern Plains respectively, would have lower porosity levels. On the other hand, those classified as having a higher silt content, such as Lu found in the Middle Plains, could maintain slightly higher porosity levels due to better soil aggregation. Furthermore, as can be seen from the results, there is a decrease in soil porosity when the land is cleared, regardless of the type of soil being treated. This could be a sign of soil compaction, which affects the water holding capacity of the soil and could also affect microbial activity. It should be noted that under normal conditions compaction occurs on the Reserve's soils due to the free passage of large and small animals, people and vehicles, but in some of the sites (Sites 3 and 4) special machinery (tractors) is used for clearing, which naturally increases soil compaction and therefore decreases porosity.

For water retention purposes and future land management practices in the Reserve, it would be important to consider soils with a higher clay content, as the particles are smaller and therefore less porous and better able to retain more water. However, these types of soils were not identified in this study and further research would therefore be required.

7.3.3. Soil Hydraulic conductivity

The initial purpose of the hydraulic conductivity tests was to estimate the Ksat value for each chosen location. However, after obtaining the results, the high correlation between Ksat values for the three different tests was considered to be too high. It was therefore decided to not use these values for the water balance, as the difference between the three tests is substantial, of a factor of 1 or 2 between tests.

In the Constant Head Infiltration test, site 1 (Southern Plains) and site 4 (Northern Plains) showed the most significant differences between cleared and vegetated areas, while site 2 (Phofu Drive) and site 3 (Middle Plains) showed minor differences. Site 2 had the highest hydraulic conductivity, followed by sites 1, 4, and 3. Tables 6.5, 6.7, 6.9 and 6.11 confirm that these values align with the expected permeability classes. However, the test did not show a clear distinction between Ksat results for cleared and vegetated areas.

The Slug test results differed from the Constant Head test but showed some correlation with expected permeability, with site 2 having the highest values. However, site 3 deviated from expectations, yielding the second-highest results. Additionally, the slug test showed a significant distinction between cleared and vegetated area.

For the Double Ring Infiltrometer (DRI) test, site 1 had the highest hydraulic conductivity, followed by sites 3, 4, and 2. Differences between cleared and vegetated areas were present but less significant than when compared with the values obtained in the slug test.

The tests were expected to correlate with site conditions (cleared vs. vegetated), but results varied across the tests. The Slug test had the greatest differences, followed by the Double Ring Infiltrometer test and Constant Head Infiltration test.

As discussed before in this report, three different tests were conducted to determine topsoil hydraulic conductivity, but results varied significantly due to lack of professional equipment and influencing factors. Ksat values from the tests were compared with those based on soil texture and dry bulk density to validate the results. Refer to tables C.12, C.13, C.14 and C.15 in Appendix C for more details on the results. Among the three tests, the Constant Head Infiltration test had the lowest average deviation from the reference values, while the slug test had the highest, followed by the DRI. Table C.12 shows high average deviation across the tests: 7120.1% for the slug test, 1525.5% for the DRI, and 102.8% for the Constant Head Infiltration test. The variations can be attributed to factors like soil saturation and test uncertainties.

Bulk density plays an important role in the results shown in Table C.12, as the expected range is based on the bulk density of the sample. The bulk density of the soil varies between the three tests. The samples used for the constant head infiltration test, were quite compacted and had a bulk density similar to the one obtained in the results. In the Double Ring Infiltrometer test, the bulk density is not affected by the equipment used as the buckets are only buried in the top 0-5cm of soil.

The results obtained are also highly dependent on the saturation level of the soil. For the slug test, the saturation level varies between the three trials conducted in the same hole. In the first trial, the unsaturated hole was filled up with water for the first time. In some of this holes it was found that when pouring the water, tiny holes made by insects (i.e. spiders) were uncovered. This could indeed affect the infiltration rate and therefore the results obtained from this test. In order to limit this variation, the experiment was repeated 3 times per hole and it was found that the saturation level had changed significantly.

For the Constant Head Infiltration Test, the test was performed in a more controlled setting and thus there were less factors that could influence the results. As discussed before, the sample was excavated on site and transported to the camp for further testing. Factors that could explain the variation in the constant head infiltration test are changes in soil compaction during excavation of the soil sample, incorrect placement of the filter and tape which could result in leakage, and the fact that the constant head drop over a time interval must be assessed by visual inspection.

The testing depth could also affect the results of the three tests. For the Constant Head Infiltration test, soil was excavated at 10 cm, the slug test at an average depth of 30 cm, and the Double Ring Infiltrometer test involved burying buckets 3–5 cm deep. These varying depths likely contributed to some differences in the test results between the three tests.

In summary, while the hydraulic conductivity results vary between tests, they still allow for evaluating result quality. The Constant Head Infiltration test provides the most reliable results when compared to expected values and observed permeability classes.

7.3.4. Organic Matter Content

The dominant soil type in the Reserve is Luvisols [40]. These soils are characterized by dark brown to brown colours (7.5 YR 3/2 to 7.5 YR 4/4) [41]. Their structure is formed by humus accumulation in the top layer, and a clay migration to the bottom layer.

When initially considering the OM content of all cleared locations compared to all uncleared locations, there appears to be a clear difference between both management strategies. The median OM content of cleared locations is 14% higher than in uncleared locations. As a higher OM content is desirable, this would initially indicate that the soils at cleared locations are healthier.

However, looking at individual sites, this conclusion is less obvious. All sites except for Southern Plains have the same median OM content. In Site 1, the cleared location have a 15% higher median OM content than the uncleared locations. Thus, no significant conclusion can be drawn from the Munsell color analysis on the scale of the Reserve, but rather on the local scale. The selected sites vary in soil type, vegetation and clearing method. In Southern Plains, Vachellia Tortilis is the dominating encroaching species which is cleared by hand in combination with fire. This site was in the past a cattle kraal (i.e. a livestock enclosure) and its vegetation is typical of an area that was used in livestock farming. Thus the more contrasting OM contents in Site 1 could be explained by the historical land use and the clearing method.

An empirical comparison of the values calculated can also be taken into consideration. The OM contents for sites 1 to 4 range from 2% to 12%, 5% to 12%, 12%, and 2.5% to 12% respectively. These values are all within the same range, though they are higher and more dispersed than the 7.3-6.5% [42] range found in scientific literature. These differences can be explained by the methodology used for determining soil OM. The source cited above used high precision laboratory equipment to calculate soil C, whereas the values recorded in the Reserve were estimated based on soil color. However, these values were confirmed in an earlier soil study carried out for the Reserve, which found that the generally sparse vegetation cover and the rapid decomposition of organic material in the characteristic dry climate had affected the organic matter content of the soil.

The LOI test was conducted on a selection of 12 samples due to technical limitations (the high energy consumption of the process and limited space in the oven lead to a maximum of 12 samples being tested). Thus, for each site, three samples of the dominant soil texture were selected: Su4 for sites 1 and 2, Lu for site 3, Sl3 for site 4. Additionally, the same number of cleared and uncleared samples were selected for comparison purposes.

The results of this experiment were drastically different in magnitude from those obtained from the Munsell colour analysis. The LOI protocol was defined to be as close as possible to protocols found in scientific literature, however the temperature limit of the oven used may have lead to some of the OM not burning completely. Despite the difference in magnitude between the two experimental protocols, similar trends in the data could be observed: in both sets of results, sites 2 and 3 have high OM contents and small difference between cleared and uncleared sites. Furthermore, a big contrast between the median OM contents in cleared and uncleared samples in site 1 and 4 could be observed. Thus the LOI method was beneficial in obtaining more accurate OM values and the similar data trends found in both methods confirm the validity of the observations made.

Furthermore, comparing OM content based on soil texture for cleared and uncleared sites only reveals variation for the SL texture class, for which cleared locations have a median OM content of 7.5% compared to 5% for uncleared sites.

Although these results have been obtained by carrying out all the experiments described in the most careful way, it is important to mention that there is a possibility of inaccuracy compared to those that could have been obtained if all the necessary laboratory equipment had been available. Also, more measurements could have been made, such as carbon content, micro- and macro-nutrient concentration, soil respiration activity, pH and humic acidity, which would have led to more specific and solid conclusions.

7.3.5. Tea Bag Index (TBI) for Soil Organic Activity

The first batch of tea bags to be recovered were those from Site 1 (Southern Plains) and Site 2 (Phofu Drive). These were exhumed after 42 and 41 days of burial respectively. Most of the tea bags still had the label on, but there were also some where the label had lost its colour so that the number on it was no longer visible, or the label came off easily from the tea bag when touching it, or even some in which the label was missing. It is also important to note that while most of the burials retained their original depth, the first burial of Site 1 (Southern Plains) was less deep. This could be due to windblown or other weathering processes.

Overall, the tea bags collected from these sites retained their dimensions and were in good physical condition. These bags appeared to be dry, so 'cleaning' them to remove any attached soil or organic matter was fairly straightforward. The decomposition of some of them was visible to the naked eye, as the outside of the bag had changed colour slightly, and it looked as if the tea contents were mouldy, which was a good sign as this is an indicator of fungal growth and thus decay. In some of the locations of Phofu Drive, there was evidence of heavy termite infestation. Some of the tea bags had holes in them and the tea content had disappeared. These samples were removed from the site to see if any mass could be recovered, but unfortunately this was not possible. The recovered tea bags were left to air-dry for two days before their analysis. Some pictures of this process can be seen in Figure Figure C.11 found in Annex C.9.1.

When the samples from Site 3 (Middle Plains) and Site 4 (Northern Plains) were excavated 44 and 43 days after burial respectively, it was interesting to note that most of the samples had remained intact. Some of them had lost their labels or the colour on them, so the sample number was no longer visible. Compared to the other 2 sites, the tea bags in these sites looked dry and without any signs of disturbance or growing mould. It was also very interesting to note that there were some zebra and kudu footprints in the burial at location 5 from site 4, but this did not affect the condition of the samples. Unfortunately, none of these tea bags could be used in the analysis as they were badly damaged during the drying process and could not be recovered without causing discrepancies in the actual results.

Looking at the results of the samples exhumed from all the sites and analysing the rate of decomposition of tea bags recovered from sites 1 and 2, it is quite compelling to see that the Green tea bags showed a more pronounced process while the Rooibos tea mass only lost some of its mass. This was evidenced by the presence of a black mould in the Green tea leaves, caused by the combination of organic matter, soil moisture and microbial activity. A picture of this can be found in Figure **??**. In contrast, no fungus of any kind was visible in the Rooibos tea bags. In addition, Rooibos tea, due to the complex compounds in its composition, was found to be more difficult to degrade by microbiological activity, which was even harder in this type of soil due to the already limited activity. This finding is supported by the fact that Green tea contains high quality organic matter with a low C:N ratio, whereas Rooibos tea contains low quality organic matter with a high C:N ratio [43]. These variations are often discussed in the literature, as this experiment shows that the combination of temperature and moisture can explain 50–70% of the variation in decomposition [35], and that this process is regulated mainly by the composition of the organic litter found in a specific site. Additionally, it was surprising to note that only the Rooibos tea bags were damaged by the termites, which had an impact on the longevity and retrieval of these samples.

To calculate the decomposition rate, which describes the rate at which the weight of the tea decreases over time, and the stabilization factor, which provides an estimate of how much easily decomposable material remains intact and has not yet decomposed, only data from fully recovered tea bags from Sites 1 and 2 were used, excluding those that had been damaged by termites or other factors, as their mass value could affect the results. When analysing the results of the Green tea bags recovered from Southern plains, and as it can be seen in 6.27 and read from C.21, there was a higher decomposition rate in the locations which had not been cleared. This is consistent with the hypothesis that vegetation increases microbial activity. The stabilization factor for these tea bags is also lower in the uncleared sites. On the other hand, when looking at the results for the Rooibos tea, the decomposition rate was higher in the cleared sites, which may be due to the presence of termites, which interact with the litter decomposition by accelerating it. From the results obtained for Phofu drive, it was interesting to note that the decomposition rate of Green tea was the same for both cleared and vegetated locations. However, by analysing the stabilisation factor, it can be concluded that there is a better chance of organic matter decomposing in the vegetated locations. Regarding the Rooibos tea in this Site, it was observed that the decomposition rate is very low in both cleared and uncleared sites. Some of the reasons for these values could be due to the composition of the tea itself, the low presence of termites, or other factors such as soil moisture and temperature. It is possible to note that Green tea bags are more susceptible to degradation than Rooibos tea bags, regardless of location, due to their more easily broken down composition. This is also confirmed by most of the TBI experiments carried out around the world [35].

These results for the rate of decomposition were not expected, as they indicate that the decomposition of organic matter was rapid, which is unusual in semi-arid soils such as those in which we conducted the test. What may have caused them is the time frame in which the results were collected and analysed. However, when looking at the global TBI references derived from Keuskamp [44] and at some of the results from people who have experimented in similar conditions to the study sites, the results are consistent. It is visible a rapid rate of decomposition in the first 30-40 days and then a stabilization. Possibly, the reason why their TBI values appear to be lower is because they have a different time frame, as they often leave the tea bags buried for at least 90 days.

Based on these results, it is reasonable to conclude that the rate of decomposition of organic matter in the Reserve's soils is favoured by physical and biological factors. However, it could be expected that if it had been possible to leave the tea bags in the soil for a longer period (at least 90 days), more convincing results would have been obtained. Losses could also be reduced by burying more tea bags and using the right equipment for proper drying.

7.3.6. Soil Health Multi-criteria Analysis

The FAO defines soil health as the continued ability of soil to function as a dynamic living system that supports biological productivity, maintains air and water quality, and promotes the health of plants, animals and people within natural and managed ecosystems [45].

By using the proposed multi-criteria matrix, it is expected that soil health can be assessed. It should be noted that the parameters have been chosen from an integral point of view in order to provide a good assessment. The parameters describe ranges of values according to the different soil types found in the Reserve and whether or not clearing has taken place. Although more parameters could be assessed for a more in-depth evaluation, the parameters in this matrix are based on comparable results from the literature and the field experiments carried out. It is intended that the physical properties of the soil will be assessed by checking values for bulk density and porosity; the hydraulic properties by checking values for water holding capacity, hydraulic conductivity and field capacity; while the biological properties will be assessed by checking values for soil organic matter.

The highest possible score per site, including all locations, is 36, which indicates that all the measured values for a given soil texture are in agreement with the reference values, and therefore, the analysed soil can be classified as 'healthy'. As can be seen in Table 6.16 the total score of each of the four sites is within the same range, of 31.5-33.8, with Northern Plains scoring the lowest and Southern Plains scoring the highest. As mentioned before, the maximum score for the multi-criteria matrix is 36 points, where Southern Plains is missing 2.28 points, Phofu Drive is missing 4.26 points, Middle Plains 2.45 points and Northern Plains 5.11 points in total. In addition, the values displayed in Table 6.17 show that there is no significant difference between cleared and vegetated areas for each site. Therefore, the studied soils could be categorized as 'healthy'.

By assessing these properties it is possible to gain an insight into the condition of the soil being evaluated. However, it is important to remember that the definition of a healthy soil is very subjective, depending on the specific purpose of the soil. In this case, the main objective of soils is to provide the best conditions to enhance water retention, given the intrinsic soil texture and characteristics, and to provide the conditions to sustain a vital living system.

Moreover, this proposed matrix can be used as a reference to evaluate soil health, but if more accurate values are required, it is recommended that the correct laboratory sampling and testing be carried out.

8 Conclusion

This project aims to address the research question *How do the major water fluxes in the Limpopo Lipadi Reserve interact to form a comprehensive water balance, given the different soil characteristics, water retention capacities and land management practices?* Through the various experiments conducted at the four selected sites in the Limpopo Lipadi Reserve and the analysis of the data obtained, it was possible to define how the major water fluxes interact to form a water balance model. This water balance takes into account the different intrinsic soil characteristics which, through various factors such as texture, past land management practices and current clearing techniques, can affect the water retention capacity of the Reserve.

The main water fluxes within the Reserve have been identified using the water balance. The largest fluxes include interception evaporation and evapotranspiration. Human extraction was found to be negligible when considering the Reserve as a whole. However, looking at the extraction rates at a more local scale could give a different result, where human extraction could exceed the groundwater recharge rate. Nevertheless, the pumping tests showed a relatively high recharge rate from the borehole in the Reserve, which indicates that there is enough water to replenish large withdraws quickly. It should be noted that only three boreholes were tested and the recharge rate may vary along the length of the Reserve.

By studying the different soil types at the selected sites, it was possible to understand how soil composition influences the different soil properties and water dynamics, particularly in the first layers of the matrix, and what factors and activities of the Reserve team could potentially influence this. This was demonstrated by the land-cover change scenario, which shows a decrease in groundwater storage when the amount of clearing is increased, due to increased runoff and evaporation. However, a significant reduction in groundwater storage is only observed in the scenario where half of the Reserve has been cleared. There are still many gaps and limitations in attempts to define the effects of bush clearing on soil health, water retention capacity and aquifer recharge. Although current results indicate an increase in bulk density and a decrease in porosity, microbial activity and moisture in cleared sites, these observations suggest that there is not yet a threatening effect. Nevertheless, it is important to note that further research should be carried out in coming years to gain a more complete picture of the long-term effects and to address the uncertainties surrounding clearing practices on these specific soils.

To assess the impact of climate change on the water fluxes of the Reserve, a climate scenario of RCP4.5 was applied to the water balance. The climate scenario shows small changes in the various water fluxes and mainly a tendency to increase the existing hydrological patterns, so it does not show a significant impact on groundwater storage for the next 25 years. However, an increase in seasonality due to climate change may have an impact in the future and should not be disregarded.

In summary, the data obtained indicated that the way in which the Reserve is currently managed, regarding water management and bush clearing, may not have a significant impact on water availability and soil health. Nevertheless, it should be noted that the results presented in this report are representative of only a small section of the total area of the Reserve, making it difficult to draw general conclusions. Also, it is possible that time constraints and lack of professional equipment may have caused some discrepancies between the results discussed in this report and those that could have been obtained under different conditions and with the use of appropriate equipment. However, within the scope of this study all the tests were carried out with the utmost care and the data obtained were analysed thoroughly in order to provide an accurate picture of the current status of the Reserve.

9 Future Recommendations

9.1. Recommendations

In recent years, the Limpopo Lipadi Reserve has been working on intensive environmental management practices that support their conservation goals without compromising their social responsibility and business objectives. The results of this research have provided some valuable insights into the impacts of current water management and bush clearing practices and the factors that need to be considered in future land management strategy. The following text provides recommendations for the Reserve to continue the research initiated by this project and to apply the findings. Recommendations for research on water management practices are outlined first, followed by recommendations on soil health and bush clearing.

To gain a clearer understanding of the local water system and the impact of water management practices in the Reserve, several future studies are recommended. The first recommendation is to continue and improve local data collection methods. For the past year, local rainfall data has been collected within the Reserve using manual rain gauges. In recent weeks, digital weather stations have been installed at various scattered locations within the Reserve, which will improve the collection of rainfall data for the future. Similar measures could be taken with regard to the collection of data on local incoming solar radiation and the flow of the Limpopo River and the small streams within the Reserve that flow into the river when not dry. The collection of these data will allow a better understanding of the general water system and enable accurate modelling of water flows within the Reserve. All the data should be continuously and stored to start a rigorous data collection protocol.

Secondly, a number of measures can be taken to gain a better understanding of the characteristics of the aquifer. Firstly, it is important to gather information on the geological profile across the entire Reserve. Knowing the different geological layers and their main characteristics, such as type and thickness, can greatly improve the understanding of groundwater dynamics and allow for better groundwater modelling. Once this information has been gathered, it is recommended that the aquifers are explored, for example by conducting pumping tests. The recommendations regarding the explicit execution of the pump tests can be read in appendix D. Conducting these pump tests will provide maximum yield values for each well and a better understanding of the local water storage capacity. Mapping the old, currently inactive boreholes and tracking the newly drilled boreholes and determining their status (dry, full or still storing water) will help to ensure that these pumping tests are carried out correctly. Finally, the regular recording of water levels in the boreholes will contribute to a better understanding of the aquifers. However, it is mainly interesting to know the stable groundwater levels over time, and our studies have shown that the currently installed pumps cause drawdown when the pump is running or has recently been running. It is therefore recommended that these measurements be continued at times when the pumps have been off for at least a few hours, such as at night for the solar-powered boreholes.

Thirdly, a future study regarding the optimization of the water infrastructure within the Reserve could be beneficial. Improving the infrastructure could lead to a reduction in water losses and a reduction in water shortages, both in water holes and in water used for human consumption. The current practice of the reserve to make the waterholes small and a bit deeper is an good example of the optimization of the infrastructure as is minimizes the loss of water due to evaporation, which is the biggest source of water loss within the reserve. This optimisation of infrastructure should be accompanied by a programme to improve awareness of water use and loss. Although water scarcity is not severe at present, awareness of water use remains crucial to maintain the ecosystem and prepare for possible future scenarios where less water is available. Implementing a water conservation awareness programme for both locals and visitors to the Reserve would reinforce the importance of sustainable water practices and help to conserve this valuable resource in the long term.

From a soil health perspective, it would first be useful to list and identify the different soil types found in the Reserve, and to delineate the areas in which they occur. This is important in order to make informed decisions about land management and restoration practices, as the experimental results indicate the important role of soil texture in its response to bush clearing. Although the clearing of areas is necessary and has been promoted by the various consultants hired by the Reserve, it is also necessary to confirm that the current method is appropriate to the soil type and current vegetation, bearing in mind that although it may be effective in the short term, it may also have some long-term effects. The second recommendation is therefore linked to the need to be aware of these side effects, and the possibility of addressing any undesirable impact should be clearly stated. If the Reserve decides to expand the cleared areas, it is strongly recommended that close attention is paid to soil texture. For example, clearing clay rich soils may result in a greater deterioration of soil health than on sandy soils. Nevertheless, it should be emphasised that the results presented in this report are only preliminary and the response of the topsoil layer may evolve over the years following clearance.

Thirdly, it is recommended that soil health experiments, including tea bag index, bulk density, soil hydraulic conductivity and organic matter content, be continued. These experiments should be conducted on a larger scale, focusing on the same sites: Southern Plains, Phofu Drive, Middle Plains, Northern Plains, as reference data has been obtained. If the Reserve decides to implement clearing methods in other areas within the Reserve boundary, soil texture and invasive species should be key considerations in site selection. For the teabag index, it is recommended that the methodology described in Section 5.3.6 be followed, and that the teabags be buried for a total of 90 days. In order to assess the impact of bush clearing on soil health and water availability, it is recommended that the following bush clearing data are consistently collected: date of clearing; clearing method (e.g. controlled burning, mechanical or hand clearing); GPS locations; target species cleared; undesirable species; rate of regrowth. As well as to monitor the cleared area for regrowth and any visible adverse soil effects. If regrowth is observed, then the proposed experiments should be repeated several times to assess soil changes.

Finally and as discussed earlier, the lack of professional equipment may have affected the experimental results presented in this report. If the Reserve continues to investigate the effects of bush clearing on soil health and water availability, investment in appropriate equipment is highly recommended. The following equipment should be considered: Professional drying oven, for the drying of teabags and soil (OM content analysis); Soil rings for bulk density and soil hydraulic conductivity analysis; Double Ring Infiltrometer test equipment, inner and outer galvanised steel ring and driving cap with centering pins; and divers.

The team hopes this report will help the Reserve assess the long-term effects of bush clearing on soil health and water availability.

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A

Stakeholder definitions

In this appendix a more detailed description of all the relevant stakeholders can be found. This information was obtained in an interview with the general manager of the Reserve.

Limpopo Lipadi Game Reserve
The Limpopo Lipadi Private Game and Wilderness Reserve consists of *Owned Properties* and *Adjacent Land*, consisting of a total of 20,712 ha of land, situated in the Tuli Block of Botswana. The purpose of the Reserve is to carry on the activities of a game Reserve and all other related activites[5].

Owned properties are properties owned by the company, Limpopo Lipadi Botswana Investments Limited (LLBIL), and are often referred to as "*freehold properties*". The total area of freehold properties is 17,287 ha and form a part of the Game Reserve [5].

Adjacent land is defined as the properties which are adjacent to *owned properties*. The total area of *'Adjacent Land'* is 3,425 ha, and has been incorporated into the Game Reserve [5].

Owned land
Lubbesrust is an defined as an *adjacent land* to the Reserve, where the total area is 856 ha. The land is incorporated into the Game Reserve, where shareholders have traversing rights [5].

Longwope Longwope consists of Longwope Farm House and Lipadi Hill. The total land of the area is 2.569 ha, and has been incorporated into the Game Reserve ('*Ajdacent land'*) [5]).

Longwope Farm House consists of a total of 3 buildings and 4 camp sites. Currently, there are 3 staff members employed for Longwope Farm House.

The total land area used for Lipadi Hill is 20ha, where a total of 3 staff members are currently employed.

Limpopo Lipadi Botswana Investments Limited (LLBIL)
To become a co-owner of the Reserve, an investment must be made in the public registered company in Botswana, Limpopo Lipadi Botswana Investments Limited (LLBIL) [46]. The company has an authorized share capital of 5000 ordinary shares, where a total of 100 shareholders are currently were subscribed in the Company [5].

Shareholders
A portion of the shareholders, approximately 15%, are directly involved in decision making of the Reserve. The role of a shareholder within the Reserve is to provide funding, provide representatives for the Game Reserve Council and various committees and experience what the Reserve has to offer.

Shareholders provide funding for the Reserve, either through investments in the Company, through operational levies (Opex), through which shareholders make an annual contribution to the running costs of the Reserve, or user levies [5].

Shareholders can utilize several communal and private lodges located on the Reserve and experience the African bush on their terms, with friend and famliy, during their stay at the Reserve.

The Company has different classes of shareholders; Gold, Diamond, and Platinum. Diamond and platinum shareholders have specific and exclusive rights at the Reserve. This includes using a designated area of land within the Reserve, which allows Gold and Diamond shareholders to construct residential properties on the sites [5].

Private lodges
The following lodges are privately owned and within the borders of the Reserve; Logwope Farm House, Lipadi Hills, Lubbesrust, Leopard River Lodges (Charlies), Bruns, Island Lodge Kgaroba, Morobusi, Kubu Lodge, Tlou Lodge, Salida Lodge, Mashatu River Lodge, Makaeny Lodge and Matala Lodge.

The occupancy rate of private lodges ranges from 3-40 %, where higher occupancy rates are due to a combination of commercial use of the lodges and private use. Private lodges either have their own permanent staff or utilize Limpopo Lipadi staff for maintenance of the lodges.

Limpopo Lipadi Botswana Investment Limited Board
In Limpopo Lipadi Botswana Investment Limited Board there are three appointed members and three elected members. Currently, all members are shareholders but this is not always the case.

NGO Donors
Funding collected from NGO Donors is directed towards conservation matters, such as Motse Committee and/or wildlife conservation. The donors decide where the money they donate goes towards.

Friends and family of shareholders
Friends and family of shareholders can be invited to the Reserve by their respective shareholder, where they are offered to share the unique opportunity of experiencing the African Bush.

One of the Reserves core values and main principles is to “Offer quality tourism and animal viewing experiences to the Company’s shareholders and other visitors;”

Tourists
Commercial stays at private lodges are offered to tourists, but this service is limited to some of the private lodges.

One of the Reserves core values and main principles is to “Offer quality tourism and animal viewing experiences to the Company’s shareholders and other visitors;” [5].

Limpopo Lipadi staff
Currently, the Reserve employs approximately 90 individuals. The vast majority of the Reserve’s employees come from surrounding towns and villages, located close to the Reserve [5].

The Reserve offers accommodation for all staff members, with a total of two staff villages. One village is located within the Reserve and the other just a few kilometers away from the Reserves borders.

Other Reserve staff
A total of 22 other Reserve staff members are currently employed for private lodges within the Reserve. The following private lodges employ staff for their private lodges, where the number of staff members is shown within brackets: Lubbesrust (5), Lonwope Farm House (3), Lipadi Hills (3), Matala Lodge (5), and Salida Lodge (6).

Management
The following managing roles are within the management team of Limpopo Lipadi; general manager, research manager, human resource manager, financial manager, lost prevention manager and lodge manager. As can be seen from their respective job titles, the role of the managers within the Reserve vary, but their main objective is to carry out activities within the Reserve and to implement the Research Management Plan.

Game Reserve Council
The Game Reserve Council consists of a total of 7 members, where members are shareholders/LLBIL representatives (5) and Landowners (2). [5]. The general manager and research manager of the Reserve are also a part of the council, but they do not have a vote.

The Council is charged with developing, implementing and monitoring the Reserve Management Plan and must report to the Board of Directors [5].

Board of directors
Within the board, there are a total of 12 seats, but currently only 5 out of 12 board seats are assigned. The role of the Reserves Board of Directors is to provide oversight and interfere, but only if needed.

Local communities
One of the Reserve's core values and founding principles is to uplift local communities, either through employment opportunities and/or community-based projects [5].

Two villages are located close to the Reserve. The first one being Tsetsebjwe, located at a approximately 20 km distance from the Reserve and the latter one is Mathathane, located approximately 30 km away from the Reserve.

Motse Committee
Motse Committee is a Botswana-registered cooperation. The committee works in the education and healthcare sector [3]. Through Motse Committee, several projects have been completed with local labor and materials, and by providing employment opportunities for people from surrounding towns and villages [27] .

Anti Poaching Unit (APU)
The anti-poaching personnel are employed by the Reserve and are responsible for all anti-poaching operations [5]. Currently, there are 26 APU personnel employed by the Reserve.

The appointed role of the Anti-Poaching Unit is to secure the whole Reserve for general anti-poaching, where the main focus is preventing poaching incidents of rhinos. This is achieved either through patrols or rhino walks, and fortunately, no poaching incidents have been recorded since 2017 [5].

Additionally, the APU partakes in anti-fire initiatives, contributing to burning blocks and maintenance. The unit also monitors the Reserves fences daily, and report if there are any breaches, whether the voltage intensity of the fences is correct and if maintenance is needed or not.

Botswana Defence Force
There is a permanent Botswana Defence Force (BDF) presence on the Reserve, employed by the government. The task of the BDF is to provide additional security and to assist in anti-poaching operations, if needed [5].

B

Methodology: procedure description

In this appendix, the in-depth methodology of the different experiments and measurements conducted is presented.

B.1. Water Balance: Initial Storage Values

B.1.1. Su, Si, Sf

Each of the four buckets must be given an initial storage value. The model was initiated at the end of a dry period (August), allowing the assumption that the initial storage for interception (Si), the unsaturated root zone (Su), and lateral runoff (Sf) to all be equal to zero.

B.1.2. Ss

The storage in the groundwater aquifer (Ss) cannot be assumed to be zero after a long period of no precipitation, thus this value was estimated. The precipitation and evaporation data for a 45 year period was used to determine a baseline for the storage in the aquifer. The HBV model was run with this dataset and the groundwater storage was plotted over time. The dataset was decomposed into a trend, the seasonality and the residuals, where the trend was taken as a baseline. The average of the trend was determined and was used as the initial value for the groundwater storage.

B.2. Water Balance: Boundary Fluxes

The model requires all fluxes that cross the boundaries of the system to be defined, which are defined as the boundary fluxes.

B.2.1. Precipitation (P)

The precipitation is an inflowing flux. The precipitation data used in this report is sourced from ERA5, a global atmospheric reanalysis dataset providing historic weather information. The data contains daily precipitation values, measured in millimeters. To tailor the data spatially, the ERA5 dataset was clipped using a shape-file outlining the specific region of interest, ensuring that only the relevant spatial data is used for the model's input. It is nonetheless important to notice that the ERA5 has a resolution of 9.6 km.

B.2.2. Evaporation (Ei + Ea)

The evaporative outflow is comprised of interception evaporation (Ei) and evapotranspiration (Ea), with the latter including both soil evaporation and plant transpiration. To ensure temporal and unit consistency with the precipitation data, ERA5 was also used to source evaporation data. However, since ERA5 provides only total evapotranspiration values, it was assumed that these values encapsulate both Ei and Ea. The specific contributions of each source to the total evaporation were dependent on the availability of water within the system.

B.2.3. Runoff (Qf)

The Boundary flow Qf, which is the overland/ top soil layer lateral runoff, is completely dependent on the runoff coefficient (Rho) and the Storage coefficient (Kf). This flow contributes to the river discharge. In most water balance models, discharge data is typically used to validate whether the sum of all inflows into the river matches the actual recorded discharge. However, due to the unavailability of reliable discharge data in this case, such validation was not possible. Consequently, the outgoing flow was determined solely based on internal processes within the model.

B.2.4. Inflowing and Out-flowing Runoff from the surrounding area (Qoi & Qoo)

In the model used within this project, it is assumed that the incoming lateral (or overland) runoff (Qoi) from surrounding areas is balanced by an equal outgoing runoff flux (Qoo). This suggests that any water entering the system from surrounding areas as surface runoff exits at an equivalent rate, resulting in no net contribution or loss to the model's overall water balance. This is assumed because the south boarder of the Reserve lies along the river, and thus, lies along a drainage line, towards which all runoff drains. This assumption simplifies the model by focusing on internal fluxes without accounting for excess lateral contributions or deficits from surrounding land areas.

B.2.5. Groundwater discharge (Qs)

The boundary flow Qs represents the flow from the groundwater aquifer towards the river. This flow depends on the groundwater storage coefficient (Ks), which can be determined using a master recession curve. This process is described in greater detail in B.4.2.

B.2.6. Groundwater exchange (Ql)

The Boundary flow Qldt, which is the exchange of groundwater with surrounding systems represents groundwater coming in and out from surrounding groundwater aquifers. Within the scope of this project it is assumed that the incoming and outgoing fluxes cancel each other out. And thus, they can be neglected in the design of the bucket model.

B.2.7. Groundwater extraction (Qh)

The flow Qh represents the water extracted by humans. This includes both water that is used by humans, such as water for the shower and toilets, as well as water pumped up for the watering holes. The water consumption for human use was estimated using monitored extraction data from each lodge within the Reserve, for which monthly values are available. The water extraction for the boreholes within the Reserve, which are meant for the animals to drink from, were determined by estimating the consumption of the animals in addition to losses due to open water evaporation.
The evaporation was determined by using the Penmann equation

$$E_o = \frac{\frac{sR_n}{\rho\lambda} + \frac{C_p\rho_a}{\rho\lambda}\frac{e_s - e_a}{r_a}}{s + \gamma} \tag{B.1}$$

where:

E_o : Open water evaporation [mm/d]
s : Slope of the saturation vapour pressure-temperature curve [kPa/$^{\circ}$C]
R_n : Net radiation on the earth's surface [J d^{-1} m-2]
ρ : density of water (kg/m^{-3})
λ : Latent heat of vaporization [J/kg]
ρ_a : density of air (kg/m^{-3})
C_p : Specific heat of air at constant pressure (J kg^{-1} K^{-1})
e_s : Saturation vapour pressure for the air at 2m height [kPa]
e_a : actual vapour pressure in the air at 2m height [kPa]
r_a : aerodynamic resistance [d/m]
γ : Psychrometer constant [kPa/$^{\circ}$C] = [0.066 kPa/$^{\circ}$C]

Data that was needed for this equation, such as downward shortwave radiation, wind speed and mean temperature, were taken from the climate engine [38]. The consumption of animals was also taken into account. An estimation of the amount of different animals were known from aerial counts and camera trap surveys. The amount of water intake per animal was taken from literature and from conversation with the Reserve's rangers. With these numbers an estimation of daily water consumption of the animals was determined. A daily dataset was created comprising the three different fluxes.

B.3. Water Balance: Parameters

Given the complexity of the interactions of water with the environment, a large number of parameters must be implemented in the water balance conceptual model in order to account for all the relevant fluxes. The sections below describe the determination of these parameters.

B.3.1. Maximum Interception Storage (Si,max)

The maximum interception storage was determined through literature. Research has been conducted in a similar area, namely the northern Limpopo basin in Zimbabwe, where a equivalent lumped conceptual model was created [47]. The literature values have been then manipulated in order to account for the different level of vegetation cover. In order to do so, a factor based on field observation was applied to downscale the Si,max in the cleared areas compared to the uncleared ones.

B.3.2. Runoff Coefficient (Rho)

The runoff coefficient (Rho) is a key parameter relating the amount of runoff to the amount of precipitation received. The determination of this parameter is achieved by integrating the results of the texture analysis, which provided the field capacity, with an experimental setup specifically designed to define the effect of the present slope on the coefficient.
Based on the texture analysis, the runoff coefficient Rho was determined using formula B.2.

$$Rho = (\frac{S_u}{S_u max})^{\beta} \tag{B.2}$$

where:

Rho : Runoff coefficient [-])
S_u : Storage of water in the unsaturated root zone [mm/day]
$S_u max$: Maximum Capacity of the storage in the unsaturated root zone [mm]
β : The shape parameter, assumed to be equal to 1 [-]

The runoff coefficient determined based on the texture analysis is then altered based on the effect of the slope. The runoff coefficient experimental setup is composed of three main fluxes: precipitation, infiltration and runoff. To determine the design precipitation event used in the experiment, historical precipitation data was retrieved from the AgERA5 dataset and generated using Copernicus Climate Change Service information (2024). This precipitation data is in the precision of daily values, which is not specific enough to directly determine a hourly design precipitation rate. Therefore, additional details were considered in order to replicate a single precipitation event. The study region's precipitation pattern demonstrates the frequency of brief, heavy rainfall events that last between one and two hours. This information allowed to assume the totality of the precipitated daily water to be concentrated in a single, short precipitation event, resulting in a 'worst-case-scenario' design precipitation event of 30 mm/h.

The experimental setup, shown in figure B.1 consists of a watering system capable of delivering water at a rate of 30 mm/h concentrated in a one square meter controlled environment. The system is made of five plastic bottles each perforated at different spots along the height and circumference, the bottles are placed at the four corners and in the middle of the experimental area. Specifically, one bottle presents holes along the entire circumference and at three different heights, whereas the remaining four bottles only present holes on one quarter of the total circumference at three different heights. The holes distribution is designed and tested to allow for a homogeneous and complete coverage of the one square meter surface area.

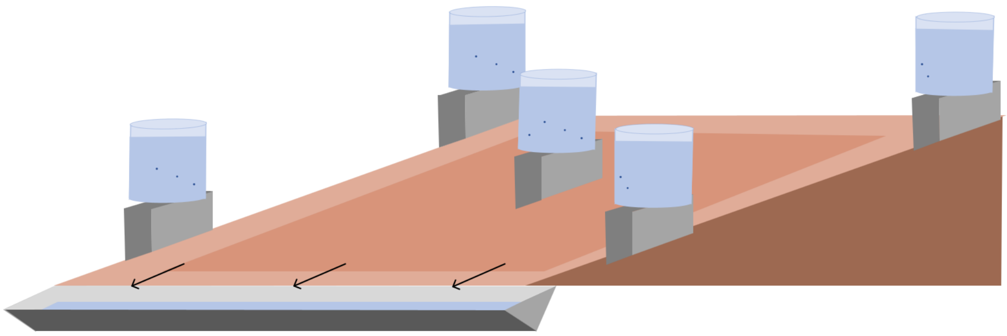

Figure B.1: Set up for Runoff experiment

The chosen experimental area was characterized by a slight elevation difference which allowed for simplified runoff collection. This elevation difference would either be classified as greater or smaller than 5%. The runoff water was collected downstream of the sloped area through the excavation of a ditch, covered in plastic. The test on site was performed over 30 minutes, all bottles were initially filled completely, this initial pressure present in the bottles would allow the holes to deliver water to the furthest point possible. Over time, the water level in the bottle would decrease and so would the pressure inside the bottle, reducing the range of impact of the water flowing from the holes. The bottles were periodically refilled during the test with a calibrated bottle, after each refill the amount of water poured was noted down. Refilling the bottles over time allowed the pressure inside them to change, varying the range of the water reaching the ground from the bottles increasing the watering uniformity.

During the test some of the water reaching the ground infiltrated, some of it ran off towards the impermeable ditch. After thirty minutes the bottles were refilled one last time and immediately removed from the experimental setup, the water present in the ditch was transferred into another bottle. Due to the inevitable presence of soil and other small objects inside the ditch during the experiment, the water collected inside the bottle after the experiment had to be filtered before it could be finally weighed. Having noted down the amount of water poured into the five bottles during the experiment and knowing the amount of water collected in the impermeable ditch it was possible to conclude the divide between infiltrated water and runoff during the design precipitation event.

Coefficients were measured at different sloped areas, the values from areas with slope >5% and slope

<5% were then compared to be able to manipulate the runoff coefficient computed with the texture analysis in order to take the topography into account.

This method is vulnerable to a set of assumptions. First of all, the uniformity of water distribution from the bottles, despite efforts to mitigate uneven pressure, may not perfectly replicate natural rainfall conditions. Secondly, only one precipitation event was used, the 30 mm/h event, and variations in rain events might affect the runoff coefficient as well. Thirdly, initial conditions of the soil, affected by for example the time between previous and present rainfall event, also has an impact. Moreover, the slight elevation difference in the experimental area also assumes that runoff collection was efficient, but variations in slope, soil type, and surface roughness in the natural environment could affect real runoff behaviour. Lastly, slight amounts of water might be lost during the transfer from the ditch to the bottle which is weighted.

B.3.3. Maximum Unsaturated Root Zone Storage (Su,max)

The Maximum unsaturated root zone storage is defined as the difference between field capacity and the wilting point. To determine the field capacity and wilting point, an texture analysis is conducted on soil samples collected at the chosen sites. This texture analysis is described in more detail in section B.5.1. The texture type, together with the bulk density were used to determine the Air Capacity (AC), Field Capacity (FC) and the Plant-Available Field Capacity (PAFC). The FC was noted down as the Sumax, in volume percent. This volume percent then had to be converted into mm per m^2. This was done by estimating the depth of the root zone for the uncleared and cleared areas.

B.3.4. Relative Soil Moisture (Lp)

Similarly to Sumax, the LP was determined through the soil texture analysis. As the LP could be described as the relative soil moisture content at which point the vegetation starts to experience water stress, the PAFC was subtracted from the FC to find the permanent wilting point, representing LP. This was kept in a volume percent.

B.3.5. Maximum Recharge Percolation Rate (Pmax)

To estimate a Pmax value, the saturated hydraulic conductivity is determined based on pump tests. The procedure used for these pump tests are described in D. The pumping tests included a recovery phase, which is used to determine the transmissivity which in turn can been used to determine the hydraulic conductivity. The analysis of the recovery phase is based on the Theis theory, and applies only for confined aquifers. When the boreholes were drilled in the Reserve, the water rose to above the local groundwater table, thus indicating the presence of a pressurized layer which characterizes the boreholes as confined. In a confined aquifer, water is trapped between impermeable layers, creating pressure within the aquifer. This characteristic pressure is a key feature distinguishing confined aquifers from unconfined aquifers, where water levels in boreholes typically align with the local groundwater table.

To estimate the Transmissivity (T), a plot is generated showing with on the x-axis t over t-prime, where t is the time since pumping started and t-prime is the time since pumping stopped. The y-axis displays the residual drawdown. The residual drawdown is the difference between the water level in stable condition and the water level at time t. Then, a line was fitted through this data and the transmissivity was determined using the formula B.3.

$$\Delta s' = \frac{2.3Q}{4\pi T} \tag{B.3}$$

where:

$\Delta s'$: change in residual draw down (slope of the fitted regression line) [-]

Q : Pumping rate [m^3/s]

T : Transmisivity m^2/s

By multiplying the transmissivity with the depth of the aquifer the hydraulic conductivity was found.

B.4. Water Balance: Storage coefficients

B.4.1. Storage Coefficient Lateral Flow (Kf)

The storage coefficient for lateral flow Kf was determined through literature, using the same source described in B.3.1.

B.4.2. Groundwater Storage Coefficient (Ks)

A Master Recession Curve analysis was conducted to estimate the groundwater storage coefficient Ks. For this purpose, discharge data were retrieved from the measuring station BEITBRUG D/S, measuring discharge from the Limpopo river in the nearest location available to the Limpopo-Lipadi Reserve [48]. In order to select a groundwater storage coefficient, the individual dry period recessions were identified and overlaid on each other and the lower limit curve was selected as the master recession curve (MRC). Finally, the MRC was displayed in a semi-log plot and the slope was extrapolated, the slope value representing the groundwater storage coefficient Ks [d-1].

B.5. Soil Characteristics

B.5.1. Texture analysis

The samples used for this analysis were the same as those used to determine the bulk density of the soil. For this test, 50 grams of each soil sample was used. All visible lumps, branches and stones were removed. This portion of the soil was then moistened, taking care not to allow any free water. The soil was then rolled into a ball and flattened with the thumb.

To assess the plasticity of the soil, the sample was rolled again and checked to see if it could be rolled between the hands to half the diameter of a pencil. The sample was then given a rating in one of five categories for this property. Once the plasticity category was determined, the stickiness of the soil was assessed. This was done by selecting one of the five categories available for this property, noting that not all are available in each plasticity category. Once the stickiness category was determined, the granularity of the soil and other characteristics such as shear surfaces were determined by looking at the attributes described by each category. It was then possible to determine values for air capacity, field capacity, and plant-available field capacity for different soil texture classes. Finally, each soil texture was identified in the German KA5 triangle which is shown in figure B.2, and is very similar to the FAO triangle.

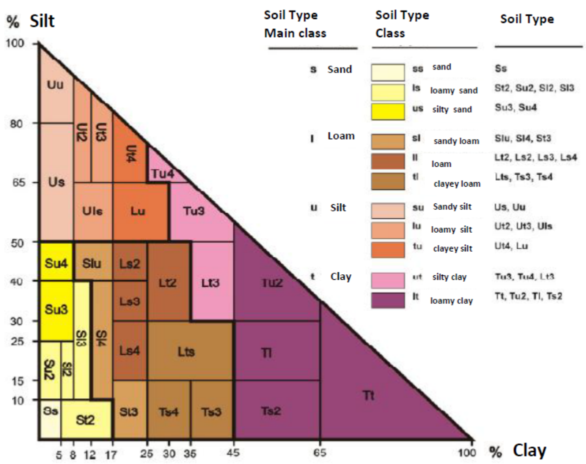

Figure B.2: German KA5 triangle (from [49])

The categories used for the analysis are in accordance with the German soil texture classification and can be found in Table B.1.

The classification of soil plasticity, stickiness, and other characteristics relies on subjective judgments that can vary between observers and their experience, and can lead to misclassification of soil texture. This method has other limitations, mainly due to environmental factors and their temporal variability, disturbance of the samples due to mass loss and excessive water content, and the overlap of different

Step 1 Plasticity	Step 2 Stickiness	Step 3 Granularity and other features	Soil texture class
0 = cannot be rolled, crumbles upon trial	0 = no stickiness, sample crumbles immediately	Without visible fine substance	Ss
		Very little fine substance	Su2
		Clear fine substance that also adheres to the finger grooves	Su3
		Lots of fine substance that strongly adheres to the finger grooves	Su4
	1 = very little stickiness, sample crumbles very easily	Clear fine substance that also adheres to the finger grooves	Su3
		Lots of fine substance that strongly adheres to the finger grooves	Su4
1 = cannot be rolled, sample cracks and breaks at more than half a pencil's diameter	0 = no stickiness, sample crumbles immediately	Clear fine substance that also adheres to the finger grooves	Su3
		Lots of fine substance that strongly adheres to the finger grooves	Su4
		Sand grains visible, velvety-floury fine substance dominates	Us
		Sand grains hardly visible, almost only velvety-floury fine substance	Uu
	1 = very little stickiness, sample crumbles very easily	Very little fine substance	Sl2
		Sand grains visible, velvety-floury fine substance dominates	Us
		Sand grains hardly visible, almost only velvety-floury fine substance	Uu
	2 = little stickiness, sample crumbles easily	Very little fine substance	St2
		Fine substance dominates	Uls
2 = difficult to roll, as sample has a strong tendency to crack and break	0 = no stickiness, sample breaks immediately	Clear fine substance that also adheres to the finger grooves	Su3
		Lots of fine substance that strongly adheres to the finger grooves	Su4
	1 = very little stickiness, sample breaks very easily	Clear fine substance that also adheres to the finger grooves	Su3
		Lots of fine substance that strongly adheres to the finger grooves	Su4
		Very little fine substance	Sl2
		Sand grains hardly visible, almost only velvety-floury fine substance, dull shear surfaces	Ut2
	2 = little stickiness, sample breaks easily	Very little fine substance	St2
		Fine substance dominates	Uls
		Sand grains hardly visible, almost only velvety-floury fine substance, dull shear surfaces	Ut3
3 = can be rolled, sample cracks or breaks only lightly	1 = very little stickiness, sample breaks very easily	Lots of clearly floury fine substance	Slu
	2 = little stickiness, sample breaks easily	Little to moderate fine substance	Sl3
		Very little fine substance	St2
		Lots of clearly floury fine substance	Slu
		Moderate to lots of fine substance, weakly glittering shear surfaces	Sl4
		Fine substance dominates	Uls
	3 = medium stickiness, sample breaks only little	Sand grains clearly visible, moderate amount of very sticky fine substance	St3
		Sand grains clearly visible, moderate fine substance, weakly glittering shear surfaces	Ls4
		Sand grains clearly visible, lots of fine substance, glittering shear surfaces	Ls3
		Sand grains clearly visible, lots of lightly floury fine substance	Ls2
		Sand grains hardly visible, lots of fine substance, dull to weakly glittering shear surfaces	Lu
		Sand grains not visible, only weakly floury fine substance, dull to glittering shear surfaces	Ut4
	4 = strong stickiness, sample hardly breaks	Sand grains hardly visible, lots of fine substance, dull to weakly glittering shear surfaces	Lu
4 = easy to roll, sample does not crack or break	3 = medium stickiness, sample breaks only little	Sand grains hardly visible, lots of fine substance, dull to weakly glittering shear surfaces	Lu
	4 = strong stickiness, sample hardly breaks	Sand grains well visible, lots of fine substance, lightly rough and weakly glittering shear surfaces	Lt2
		Sand grains well visible, lots of fine substance, very strongly glittering shear surfaces	Lts
		Sand grains hardly visible, lots of fine substance, dull to weakly glittering shear surfaces	Lu
		Sand grains well vsisble, lots of fine substance, rough and glittering shear surfaces	Ts4
		Sand grains not visible, only fine substance, rough and weakly glittering shear surfaces	Tu4
	5 = very strong stickiness, sample does not break	Sand grains well visible, lots of fine substance, very strongly glittering shear surfaces	Lts
5 = very easy to roll to also less than galf of a pencil's diameter	4 = strong stickiness, sample hardly breaks	Sand grains well visible, lots of fine substance, very strongly glittering shear surfaces	Lts
		Sand grains not visible,only fine substance, lightly rough, glittering shear surfaces	Tu3
	5 = very strong stickiness, sample does not break	Sand grains well visible, lots of fine substance, very strongly glittering shear surfaces	Lts
		Sand grains well visible, lots of fine substance, lightly rough and glittering shear surfaces	Ts3
		Sand grains poorly visible, lots of fine substance, lighly rough and glittering shear surfaces	Lt3
		Little sand grains visible, lots of fine substance, strongly glittering shear surfaces	Ts2
		Very little sand grains visible, lots of fine substance, glittering shear surfaces	Tl
		Sand grains not visible, only fine substance, lightly rough, glittering shear surfaces	Tu3
		Sand grains not visible, only fine substance, rough, glittering shear surfaces	Tu2
		Sand grains not visible, only fine substance, smooth and glittering shear surfaces	Tt

Table B.1: The categories used for the texture analysis

particle sizes, which makes it difficult to distinguish between fine sand and silt. This introduces an element of inconsistency compared to standardized laboratory-based methods. Determining soil properties in a laboratory would have been more accurate, but a laboratory was not available during this project. However, in order to reduce the possible uncertainty of the results, some of those obtained by this test were later compared with those obtained by the jar test.

To get an indication of the permeability class of each soil texture class, the following permeability classes were used for analysis. The permeability classes are 6 in total, ranging from *fast and very fast*, to *very slow*. Table B.2 includes the permeability classes used for the analysis of analyzed soil texture classes for each site and locations.

Permeability class	Texture
1 (fast and very fast)	Sand
2 (moderate fast)	Loamy sand, sandy loam
3 (moderate)	Loam, silty loam
4 (moderate low)	Sandy clay loam, clay loam
5 (slow)	Silty clay loam, sand clay
6 (very slow)	Silty clay, clay

Table B.2: Permeability class according to texture of the soil[37]

B.5.2. Jar Test

In order to determine the content of clay, silt and sand, a jar test was conducted. To do this, 45 grams of loose, rock-free soil had to be placed in a glass jar. Then 2 teaspoons of powdered detergent were added to the mixture, along with 150 millilitres of water. After this mixture was made, the jar was sealed with a lid and shaken vigorously for three minutes. The mixture was left undisturbed for 24 hours.

After 24 hours, the total depth of soil that had settled to the bottom of the jar was checked. Later, the jar was shaken again for three minutes, this time by swirling and turning it upside down, and then left standing for 40 seconds. The depth of the settled soil was then measured, as this value indicates the sand layer. After 30 minutes, the depth of the settled soil was measured again. To find the thickness of the silt layer, the depth of the sand layer was subtracted from this new measurement. The particles still suspended in the fluid were considered to represent the clay fraction [50]. To calculate this, the combined value for the depths of the sand and silt layers was subtracted from the total soil depth previously measured. Finally, it was necessary to convert the measurements into percentages to determine the content of clay, sand and silt, and thus the texture classes of each of the soil samples using the German KA5 triangle, shown in Figure B.2. The results of this test were compared with the results of the texture analysis.

However, it is important to note that results obtained by this method may have some limitations as they tend to underestimate the true clay content of the soil due to a few key factors that are difficult to control without specific laboratory equipment. For example, particle settling time, organic matter interference, or inadequate mixing.

B.5.3. Sample Collection

Two undisturbed and two disturbed soil samples were collected at each site. Just below the topsoil, a flat plateau was created using a pickaxe, on which the soil rings were placed. The rings were gently hammered into the soil until they were completely filled, while ensuring that its contents were not further compacted. The lid was placed on top of the rings and a wide spatula was used to lift them. The samples were then turned over and after removing the spatula, it was confirmed that no losses had occurred. For undisturbed samples, the lid was then placed on the ring to ensure that the soil remained undisturbed, and the full soil ring was placed in a plastic bag. For disturbed samples, the soil was removed from the ring and placed in an airtight plastic bag. All the samples were transported back to base camp for analysis.

This sample collection method is susceptible to various external factors that may compromise the integrity of the samples. Hammering the sample rings into the soil can lead to compaction of the top layer, resulting in a distorted and compacted sample. Additionally, for disturbed samples, losses may occur during the multiple transfers between containers, potentially affecting the accuracy of the collected material.

B.5.4. Bulk density, soil moisture content and porosity

The following method was used to determine the bulk density, soil moisture content and the porosity.

As noted above, two disturbed samples were collected per site. Soil was transferred to plastic containers and weighed using a precision balance to determine the weight of wet soil. Samples were air dried in the sun for a minimum of 48 hours. Based on preliminary testing with wet soil samples, 48 hours in 30°C+ weather was considered acceptable to obtain soil moisture content. The main challenges with this method were that the wind could pick up some of the soil, wildlife could disturb the samples, or moisture in the air could affect the sample. Therefore, the samples were placed in a protected box to minimize wildlife disturbance, in an area protected from the wind, and during periods when the temperature was above 30°C during the day. The box contained ventilation holes to provide sufficient air for evaporation. After drying, the samples were reweighed to obtain the weight of dry soil and then the soil moisture content was determined. The soil moisture content can be expressed as a percentage of the dry soil using the following formula:

$$\theta_g = \frac{m_w}{m_s} * 100$$

where:

θ_g : Gravimetric moisture content (%)
m_w : Mass of water (g)
m_s : Mass of dry soil (g)

The weight of the dry soil was also used to calculate the dry bulk density, using formula B.4.

$$\rho_b = \frac{m_s}{v_t} \tag{B.4}$$

where:

ρ_b : Dry bulk density (g cm^{-3})
m_s : Mass of dry soil (g)
v_t : Total volume cm^3

The total volume of the sample is known to be 100 cm^3, as this is the volume of the soil ring. The total mass of the soil, including the water, can also be used in the same formula, to determine the bulk density, ρ.

The value for the dry bulk density was used to determine the soil porosity, for which the soil particle density was also needed. During the texture analysis, which is explained in greater detail in B.5.1, different soil types were determined, together with their sand, silt and clay composition. The soil particle density was taken from literature, where an article related the soil composition to the particle density [51]. Formula B.5 was used to calculate the soil porosity.

$$\epsilon = 1 - \frac{\rho_b}{\rho_s} \tag{B.5}$$

where:

ϵ : Total soil porosity
ρ_b : Dry bulk density (g cm^{-3})
ρ_s : Particle density (g cm^{-3})

The calculation of bulk density, soil porosity and moisture content is exposed to several sources of error. As mentioned before, the hammering of the rings into the soil could affect the integrity of the sample, for example due to compaction or slight soil losses and thus affect the bulk density. The precision of the scale is 0.01 g, which should also be taken into consideration. Finally, the drying process may have incurred some losses despite the mitigation measures, due to the variability of the weather conditions during the air-drying process. The large number of samples analysed (46 in total), however, contributes to increasing the statistical significance of these observations and minimises the impact of the errors described earlier.

B.5.5. Hydraulic Conductivity

Double ring infiltrometer

The double ring infiltrometer was set up on two locations per site, one in the cleared section and one in the non-cleared section. This infiltrometer was created by cutting out the bottom of two buckets of different diameters, respectively 19 cm and 25 cm. The bucket with the smaller diameter was placed inside the larger bucket during the in-field experiment creating an inner and an outer ring, which can be seen in figure B.3.

The inner and outer rings both need to be inserted into the soil at a depth of approximately two cm and then filled at the same time up to a certain point. Inside both rings a marker was placed to denote a length of 10 cm from the bottom of the bucket. Two separate bottles were prepared by marking every 50 or 100 ml, creating a measuring cylinder.
To start the experiment both rings were filled up to the marker at the same time, the amount of water that was added was noted down as ‘initial fill volume’. This was done by denoting the starting volume of water inside the measuring cylinder and the final volume after pouring. After the rings were filled up the timer was started. After a time interval of two minutes, the rings were refilled up until the marker and the initial and end volume of each measuring cylinder was noted down. This was done for the same

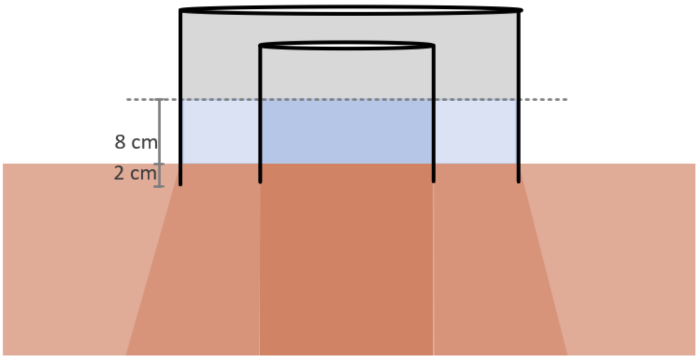

Figure B.3: Set up for Double Ring Infiltrometer

two minutes time interval until the water volume that was poured each interval stabilized, after which the time interval could be changed to five minutes, depending on the speed of the infiltration. After 1.5 hours, the final fill was noted down.
The data that was collected was further analysed in Python, the full script can be seen in appendix F. The amount of water that was added in each ring per time interval was calculated, together with the area of each ring. Using formula B.6, an infiltration rate value [mm/m^2/hour] for each time interval was determined.

$$r = \frac{V}{At} \tag{B.6}$$

where:

r : Infiltration rate (L/m^2/h)
V : Volume (L)
A : Cross-sectional area of the ring (m^2)
t : Time interval (h)

The infiltration rate decreases over time eventually reaching a constant value. This relationship can be described by the Horton decay function [52]. The decay function used is described in formula B.7.

$$f_p = f_c + (f_o - f_c) * e^{-kt} \tag{B.7}$$

where:

f_p : Infiltration capacity at any given time (mm/h)
f_c : Final infiltration capacity at saturation (mm/h)
f_o : Initial infiltration capacity (mm/h)
t : Time from beginning of the experiment (h)
k : exponential decay constant

By fitting the curve and thus determining the constant value approached over time, an hydraulic conductivity rate can be determined for each experiment.

This in-situ experiment is susceptible to several sources of error. Firstly, the measuring cylinders were self made. The marks on the bottle were created by weighing 50 grams of water and denoting the water level on the bottle. This introduces several sources of error, such as the weighing of the water on a scale with a 0.01 precision, as well as denoting this water level on the plastic bottle. The second measuring cylinder already contained markings every 100 mL. Reading the water level of these measuring cylinders also introduces a source of error due to parallax.

Constant head test

A Mariotte's bottle was created to perform a constant head test on the undisturbed samples to determine the hydraulic conductivity. The bottle was filled with water and closed off with a stopper such that it was vacuum sealed. Two flexible plastic tubes protrude from the stopper, where one tube is longer and situated slightly lower inside the bottle than the other. The longer tube will be referred to as the water tube and the shorter one as the air tube. A measuring tape was attached to the outside, to measure the decreasing water level. The full set up can be seen in figure B.4.

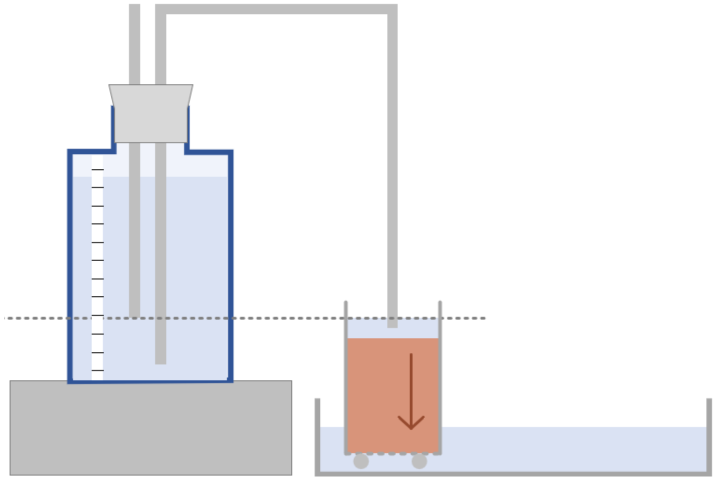

Figure B.4: Set up for Mariotte bottle setup

The undisturbed sample had to be fully saturated before the constant head test could start. A filter was placed on the bottom of the sample and extra tape was added to the top of the sample to create a higher cylinder. A small layer of water settles on top of the soil sample during the experiment and the extra tape ensures this is possible. To saturate the sample, it was placed underneath the Mariotte's bottle in a container with water, on top of an iron mesh to allow free flow of water through the sample. The test was ready to start when a shiny film could be seen on top of the sample, ensuring total saturation. The longer tube was placed slightly above the soil sample; the air tube was hanging on the side, which can be seen in figure B.4. Air was blown through the air tube and subsequently water would flow through the long tube onto the sample. The bottom of the air tube is at the same height as the water on top of the sample. As the water infiltrates into the sample, the water level on top of the sample goes down. To maintain the same water level, water gets pushed through the tube onto the sample and the water level inside the bottle goes down. The time it takes for the water level to decrease five mm was noted down.
The hydraulic conductivity was finally estimated by applying the constant head test as follows.

$$K = \frac{QL}{Aht}$$

where:

Q : Volume of water collected (m^3)
L : Length of the sample (m)
A : Cross-sectional area of the sample (m^2)
h : Head difference across the sample (m)
t : Time over which the water is collected (s)

Per sample the hydraulic conductivity was determined as above, together with the uncertainty. In order to estimate the uncertainty on the final k value, the different uncertainties on the measures were propagated through the formulas applied to get the final value. Per location two samples were collected and the mean k value was determined. These were plotted in a boxplot graph, together with their uncertainty intervals. The hydraulic conductivity for the clear area and the non-cleared areas were also plotted in a box-plot graph. This method is susceptible to error due to the potential compaction of the collected samples, which would result in lower hydraulic conductivity values. The presence of large rocks or other structures in the soil can significantly affect hydraulic conductivity. However, the inclusion of such structures in a sample does not necessarily represent the composition of the entire soil profile. To mitigate this issue, two samples were collected from each location to minimize error and improve representativeness. Additionally, measuring the decrease in water level in the bottle using a ruler placed alongside introduces potential for human error, as the readings may not always be precise.

Slug test

Two slug tests were performed per site, one in a cleared area, one in a non-cleared area. These test were conducted at the same location as the double ring infiltrometer. Using an auger, two holes were dug, each with a depth of around 30 to 35 cm. The exact depth, the diameter and other characteristics, such as if the bedrock was hit, or if there were any holes on the side, were noted down. Two divers were started, to measure the pressure and temperature every 15 seconds. The hole was filled with water and the diver was lowered into the hole. After the water had infiltrated the diver was taken out and cleaned if necessary. This was repeated two more times. The data on the diver was read and exported. To determine the draw down of the water level the measured pressure was converted to a height by subtracting the atmospheric pressure. The head change over time was used to obtain the hydraulic conductivity, with the use of formula B.8.

$$K_{\text{sat}} = 1.15r\frac{\log[Z(t_1) + \frac{1}{2}r] - \log[z(t_2) + \frac{1}{2}r]}{t_2 - t_1} \tag{B.8}$$

with:

r : Radius of the bore hole [L]
$Z(t_1)$: Head at time t_1 [L]
$z(t_2)$: Head at time t_2 [L]

These calculations were performed on Python and the full python script can be found in appendix F. This method can be affected by the presents of macro-pores along the side of the holes, which might not be representative for the entire profile of the soil.

B.5.6. Organic Matter Content

The organic matter content of the soil samples collected throughout the Reserve were estimated with two methods: the Munsell colour analysis and the loss-on-ignition (LOI) method. The latter protocol was used to confirm the results or the trends that may have been observed in the former. However, due to a lack of laboratory equipment, this analysis was only used for a qualitative site-by-site comparison rather than to obtain quantitative results.

Munsell Colour Analysis The soil colour classification was established using the second edition of the Munsell Colour Chart [53]. The method for identifying the colour of a soil sample consists in finding the three attributes of colour, i.e. hue, value and chroma (see B.5).

Hue is the dominant spectral light of a sample; red (R), yellow (Y), green (G), blue (B) or purple (P)). Complement colours are made of different hue combinations fit in between the dominant hues: yellow-red (YR), green-yellow (GY), blue-green (BG), purple-blue (PB) and red-purple (RP). Each colour is attributed a number from 0 to 10, with 10 being the purest form of the dominant hue. Value represents the lightness of each colour and is quantified on a scale from 0 to 10, or from absolute black to absolute white. Chroma is the relative purity of the spectral colour, with 0 corresponding to neutral greys and ranging up to 20 as the soil colour becomes more vivid (though this value is never reached in soils). The combination of hue, value and chroma attributes is denoted as follows: first the hue (for example 2.5R), followed by the value (e.g. 5), a dash and the chroma (e.g. 2). This would results in the 2.5R 5/2 soil colour.

It is important that all observations are made under the same lighting conditions, avoiding direct sunlight and keeping the sample as close as possible to the colour chip. The dry sample is obtained from the 48-hour air-drying process described in section B.5.4.

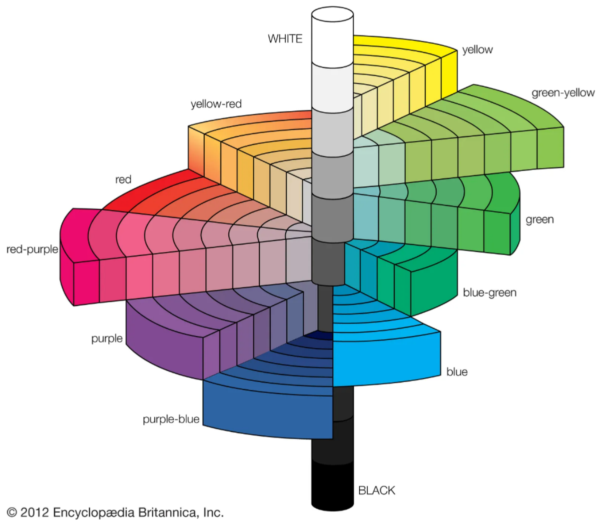

Figure B.5: Munsell Colour System (from [54])

The organic matter content of the soil samples collected in the four sites of the Reserve was estimated based on Table B.3. Depending on the soil texture, previously determined in section B.5.1, the OM content of the samples was estimated after the soils were dried for bulk density calculation (see B.5.4).

Colour	Munsell Value	S	LS, SL, L	SiL, Si, SiCL, CL, SCL, SC, SiC, C
Light grey	7	<0.3	<0.5	<0.6
Light grey	6.5	0.3-0.6	0.5-0.8	0.6-1.2
Grey	6	0.6-1	0.8-1.2	1.2-2
Grey	5.5	1-1.5	1.2-2	2-3
Grey	5	1.5-2	2-4	3-4
Dark grey	4.5	2-3	4-6	4-6
Dark grey	4	3-5	6-9	6-9
Black grey	3.5	5-8	9-15	9-15
Black grey	3	8-12	>15	>15
Black	2.5	>12		
Black	2			

Table B.3: Soil colour classification based on Munsell Colour Chart values for dried soils given in %, adapted from [34]

Despite the rigorous protocol for soil colour identification, this process is limited by the subjectivity of colour perception and the variability of lighting and moisture content. In the scope of this analysis, the colours of soil samples were used to compare soil properties to each other, thus qualitative observations were sufficient to draw meaningful conclusions about the OM and ferric pigment contents.

Loss On Ignition Method A selection of 12 samples was made for the loss on ignition (LOI) method to validate the OM contents estimated with the colour analysis. For each site, three samples were selected with the dominant soil texture of the site. The same number of cleared and uncleared samples were chosen in total. The first step of this method consists in drying the soil samples in an oven at 105°C for an initial period of one hour, after which the weight of the samples was measured every 30 minutes until their mass had stabilized. Once the dry mass was obtained, the samples were burnt in an oven at 265°C for an initial period of 6 hours, after which their mass was measured at 1 hour increments until they had turned black in colour and their mass had stabilized. The difference of the "ignited" mass and the dry mass gives the organic matter content. This experimental protocol was adapted from scientific sources [**LOI_method**] to the technical limitations of the Reserve (i.e. oven temperature limited to 260°C).

B.5.7. Teabag Index (TBI) for Soil Organic Activity

This analysis was carried out at four different sites in the Reserve and at six different locations per site to measure the decomposition rate k and stabilisation factor S of plant litter. A total of 48 pairs of rooibos and green Lipton tea bags were buried. The procedure used is described below.

Tea bag initial conditions:

1. Use a bag of Lipton green tea and one of Lipton rooibos tea per dupe. Consider to bury more than one replicate per site.
2. Measure the initial weight of each tea bag (air-dried, not oven-dried) and subtract the weight of an empty bag, the string and label.
3. Using a permanent black marker, enumerate the teabags in the label.

Preparing the samples:

1. At each location, dig four holes 5 cm in diameter and 10 cm deep, making sure they are at least 15 cm apart.
2. Bury each tea bag in a separate hole, keeping all labels visible. Mark each burial location.
3. Record the date of burial, coordinates, and a description of the marker used and the conditions of the location.
4. Repeat this process 6 times per site. A total of 24 bags per site have been buried.

Retrieval of samples:

1. At each location, exhume the tea bags after 42 days. Place them in plastic bags for their further manipulation.
2. Record date of the exhumation.
3. Remove any dry soil particles and air dry for two days.
4. Remove the remaining tea from the bag and weigh its mass in grams.
5. Calculate the decomposition rate k and the stabilization factor S and plot the data.

Tea Bag Index calculation:

1. Express the remaining dry mass as a ratio to the original dry mass using the unit g/g.
2. In g gDM-1 report the amount of mass lost.
3. To calculate the stabilization factor, S, from the green tea data, use the following formula, where S is the ratio of the stabilized to the total hydrolysed fraction of the green tea. This factor reflects the long-term stability of carbon in the soil based on how much of the carbon in the green tea is resistant to decomposition over time.
$$S = 1 - \frac{a_g}{H_g}$$

where:

S : Stabilisation factor
a_g : loss of mass of Green Tea (at time of exhumation) (g gDM$^-1$)
H_g : hydrolysable fraction of Green Tea (g gDM$^-1$)

4. Quantify the decomposable fraction of rooibos tea a_r by using the following formula:

$$a_r = H_r(1 - S)$$

where:

S : Stabilisation factor
H_r : the hydrolysable fraction of rooibos tea

5. Find the rate constant k for both green and rooibos teas by using the exponential decay function:

$$M(t) = ae^(kt) + (1 - a)$$

where:

$M(t)$: mass of tea after burial time (t)
a : breakdown (labile)
$1 - a$: recalcitrant fraction of both tea and rooibos teas)
k : rate constant fitted from the decomposition curve for each of the two teas

It is key to note that there may be some limitations to this method, such as a poor relationship between the organic matter present in the ecosystem studied and that represented by the teabags, the influence of environmental factors cannot be easily accounted for, the presence of soil fauna (e.g. ants and other native insects) cannot be easily assessed, sensitivity to burial depth, and a short-term measurement that may not capture long-term decomposition dynamics. Random errors may also occur in the calculation of values, mainly due to scale errors during sample preparation and exhumation, and due to variations in soil moisture and temperature.

C

Results

This appendix contains detailed experimental results described in Chapter 6.

C.1. Site Selection

Table C.1 includes the selected sites and locations, their respective GPS coordinates and whether the area has been cleared or not.

Site	Location number	GPS Coordinates	Bush Clearance
Southern plains	1	S-22.5764, E28.523119	Yes
Southern plains	2	S-22.57760, E28.52285	Yes
Southern plains	3	S-22.580195, E28.5228	Yes
Southern plains	4	S-22.58063, E28.52344	No
Southern plains	5	S-22.58027, E28.52374	No
Southern plains	6	S-22.57705, E28.52650	No
Phofu drive	1	S-22.55638, E28.52959	Yes
Phofu drive	2	S-22.55666, E28.52915	No
Phofu drive	3	S-22.555510, E28.528740	Yes
Phofu drive	4	S-22.555436, E28.529436	No
Phofu drive	5	S-22.552361, E28.531894	Yes
Phofu drive	6	S-22.55185, E28.531922	No
Middle plains	1	S-22.487191, E28.556320	Yes
Middle plains	2	S-22.486555, E28.555738	Yes
Middle plains	3	S-22.487752, E28.556380	Yes
Middle plains	4	S-22.488752, E28.553303	No
Middle plains	5	S-22.488974, E28.552979	No
Middle plains	6	S-22.488755, E28.552504	No
Northern plains	1	S-22.43026, E28.47847	No
Northern plains	2	S-22.42537, E28.48010	No
Northern plains	3	S-22.42530, E28.47988	No
Northern plains	4	S-22.41966, E28.47875	Yes
Northern plains	5	S-22.41966, E28.47875	Yes
Northern plains	6	S-22.41954, E28.48187	Yes

Table C.1: Selected sites and locations

Figure C.1 clearly shows the change in vegetation between locations 1-5 and location 6 for Site 1, Southern Plains.

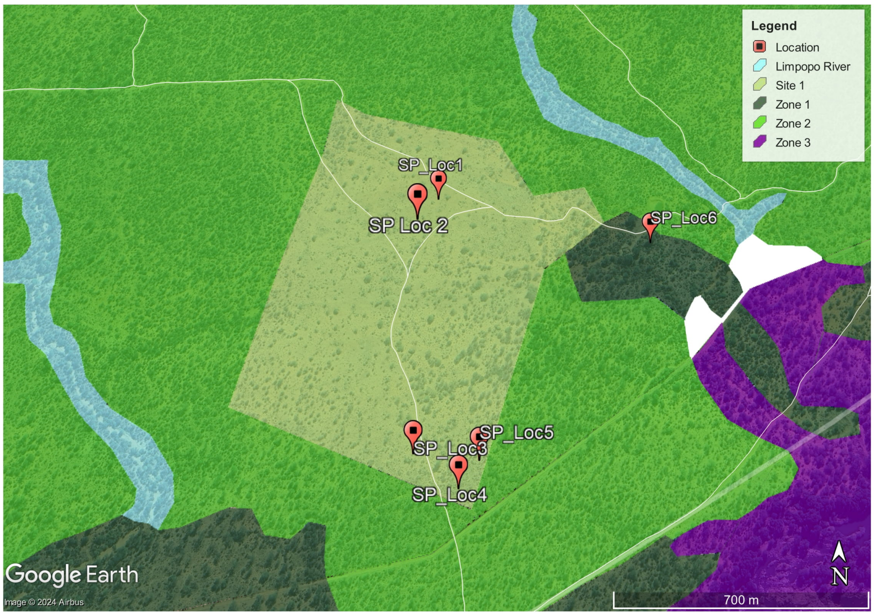

Figure C.1: Vegetation cover of Southern Plains

C.2. Water Balance: Initial values

As mentioned in B.1 most of the initial values for the water balance have been set to zero, since the time series of the input data start after a dry year. The value for the initial storage in the aquifer was found after applying a seasonal decomposition to find the trend of the groundwater storage. The trend was plotted over 45 years and it was noted that this stayed relatively stable. The average was determined, and was implemented as the initial value for Ss, which was found to be 7.5 mm.

C.3. Water Balance: Input Boundary Fluxes

The main idea behind the model is to account for all the fluxes entering, leaving and being stored in the system, in the following section the relevant fluxes are described.

C.3.1. Precipitation (P)

Precipitation is the only input water flux in the water balance. Its seasonality and intensity highly influence the water availability throughout the year. The precipitation data used were retrieved from "Global Weather for Agriculture - AgERA5" [38]. The typical climatic patterns of the area are easily observable from the forcing data used as input for the model in figure C.2. Precipitation is concentrated in the wet season spanning from October to April, leaving the rest of the year without any consistent precipitation events.

C.3.2. Evaporation (Ei and Ea)

Evaporation represents an essential flux in this region given the semi-arid climatic conditions that characterize it. This flux also follows seasonal patterns, it is enhances during the hot months of summer and reaches its minimum during the winter. It is important to notice the alignment of summer with the wet season which causes the periods of high evaporation to coincide with the rainy season as observable from figure C.2.

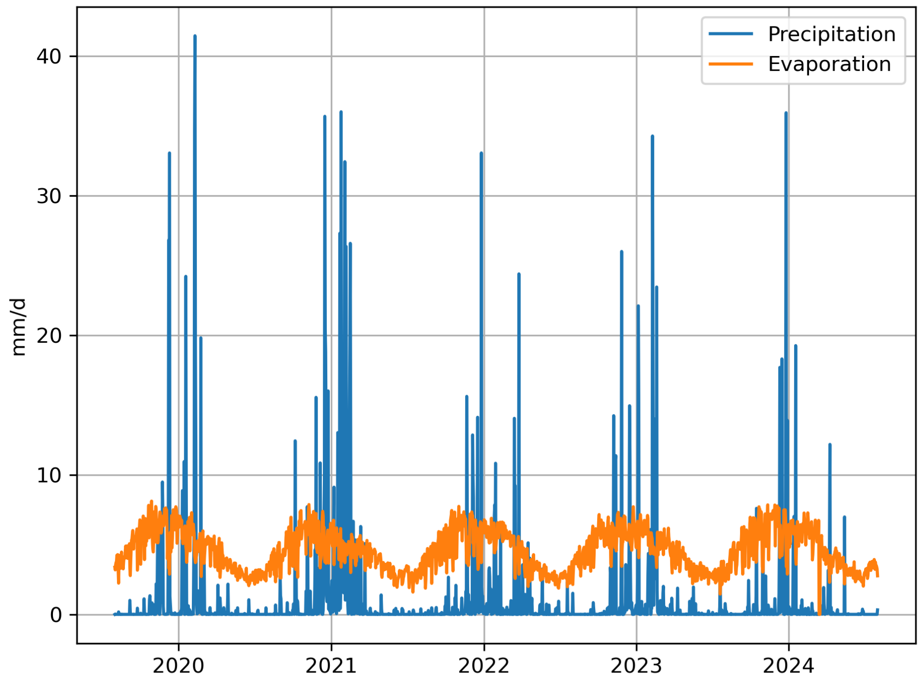

Figure C.2: Precipitation and Evaporation

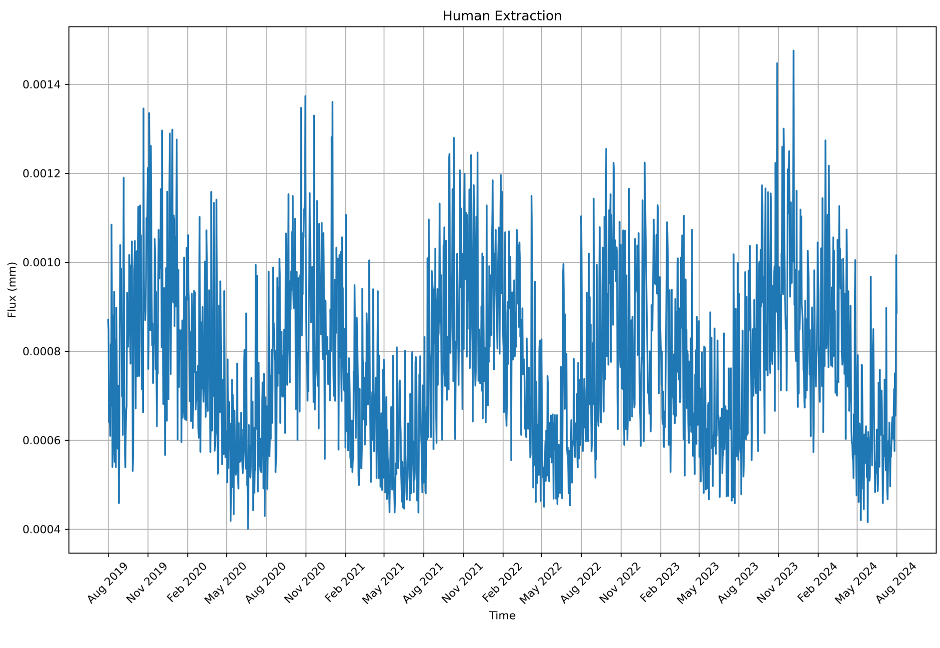

Figure C.3: Human consumption

C.3.3. Human Extraction (Qh)

The amount of water extracted by humans was estimated through three different fluxes. The human consumption, the animal consumption and the open water evaporation from the watering holes.
As mentioned previously, the water usage in the tourist lodges were monitored per month and an average was taken to obtain daily values. This amount was multiplied by a factor to account for the water use in the staff villages, where the water consumption was not known. Most of the lodges have pools, but are only occupied part of the year, while the staff village is occupied all year around, but uses

less water per occupant, thus a factor of three was chosen.
It was known that there were around 16 working boreholes that supplied water to the watering holes. The area of these watering holes were determined by taking the average of all the watering holes in the Reserve, this was estimated to be 4425 m^2. The evaporation per day was determined using the Penmann equation and the amount of water consumed by the animals was estimated to be 25 m^3 per day. The evaporation and the daily animal use were added together to form a daily dataset.
The human and animal consumption and the evaporation were converted to mm d^{-1}, by dividing the water use in m^3 by the area of the Reserve. This dataset has been plotted over time and can be seen in figure C.3. This was used as input for the Qh parameter.

C.4. Input Parameters

C.4.1. Interception Storage (Si,max)

The value for Si,max has been obtained through literature as mentioned in section B.3. The different parameters were determined with a multiple regression model. The parameter for the interception storage was found to be 5 mm per day, and this was taken as Si,max in the present model. However, the maximum interception storage will change regarding the vegetative cover. From field observations it had become clear that the amount of vegetation in the cleared areas was around 90% less than in the uncleared areas, thus the parameter for the cleared areas was taken as 10% of the parameter of the cleared areas. As mentioned above, the Si,max of 5 mm d^{-1} was taken for the uncleared areas and thus an Si,max of 0.5 mm d^{-1} for the cleared areas was used.

C.4.2. Run off Coefficient (Rho)

The runoff coefficient is determined by the current storage in the unsaturated root zone (Su) and the maximum storage in the unsaturated root zone (Sumax). By dividing the Su with the Sumax, the rho will fall anywhere between 0 and 1. To account for any initial runoff, the minimum of rho is set to either 0.1 or is equal to the effective precipitation (Pedt) if this is lower than 0.1.
The effect of a slope on the runoff was also incorporated by up scaling the coefficient with a factor of 5. This number was determined through the runoff coefficient experiment described in (REF). This experiment was conducted on 5 sites, 3 of which had a slope greater than 10% and the other two sites had a slope of 5% or less. The collected runoff showed that there was 5 times more runoff in the sloped areas than the non-sloped areas, thus a factor of 5 was chosen to increase the Rho in the hillslope subsystem.

C.4.3. LP and Sumax

The Air Capacity, Field Capacity and Plant-Available Field-Capacity was determined through the soil texture analysis, which is described in greater detail in section 6.3.1. These parameters were in turn used, together with the bulk density, to determine two parameters needed for the water balance, namely the relative soil moisture (LP) and maximum storage capacity for the unsaturated root zone (SuMax). These can be seen in table C.2. The parameters are divided between uncleared and cleared for each site, where the average was taken.

Cleared or Uncleared	LP vol.-%	Sumax vol.-%
Site 1: Southern Plains		
Cleared	7	20
Uncleared	7	20
Site 2: Phofu Drive		
Cleared	7	20
Uncleared	7	20
Site 3: Middle Plains		
Cleared	19	15
Uncleared	19	15.5
Site 4: Northern Plains		
Cleared	10	14
Uncleared	10	13

Table C.2: LP and SUMAX for each site

An average was taken for the LP for the different sites and it was found to be 11 vol .%, thus the input for the water balance will be 0.11 [-] for LP. This parameter is used as a constraint for plant transpiration. No transpiration will occur when the soil moisture is below a fraction, in this case 0.11, of the Sumax. To determine the Sumax, an average was also taken, Sumax was determined to be 17 vol. %. The model takes the parameter in millimetres and thus depends on the depth of the unsaturated root zone. The vegetative cover in the uncleared areas is much more prominent than in the cleared areas. The uncleared section have grasses and shrubs as well as trees, thus the depth of the root zone was taken to be rather deep, namely a depth of 2 m. For one square meter, the Sumax would be 340 mm. The cleared areas have significantly less vegetation, either having bare soil or several shrubs. The depth of the root zone for the cleared areas is thus assumed to be around 20 cm, for which the Sumax is 34 mm per m^2.

C.4.4. Maximum Percolation Recharge Rate (Pmax)

The Pmax was determined from the results of the pumping tests. The pump test was conducted at Motlhalatau private lodge, currently used for gardening purposes. The borehole at Motlhalatau private lodge is located in the south of the Reserve, around 100 m away from a rain-fed river that was dry at the time of the experiments. A pump with a capacity of 15 l/min pumped for around 23 hours, after the pump was switched off, the measurements continued for an other 6 hours, showing an almost complete recovery. During the conducted pump test, the flow rate changed slightly, and thus it was decided to determine the saturated hydraulic conductivity based on the recovery rather than the pump test itself.

The recovery data was transformed to display the t over t-prime on the x-axis and the residual drawdown on the y-axis, resulting in the graph shown in figure C.4. A line was fitted using linear regression which resulted in a slope of 2.5 [-]. Formula B.3 was rewritten to calculate the Transmissivity using the known pumping rate and the found slope of the fitted line, resulting in a Transmissivity of 1.6 e-05 [m^2/s]. An estimation was made regarding the thickness of the aquifer layer of 50 meters, resulting in an hydraulic conductivity of 27 mm/day. This hydraulic conductivity is used as an estimation for the maximum percolation rate Pmax.

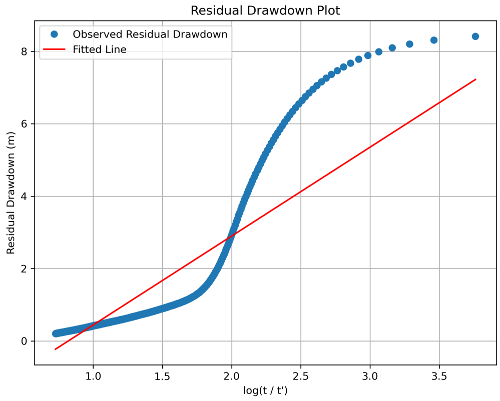

Figure C.4: Residual Drawdown with fitted line

C.4.5. Storage Coefficient for Lateral flow (Kf)

The Kf parameter represents a delay factor for the discharge from saturated soil or from the overland flow towards the river. The value for Ks was determined from literature [47] as 0.25 [d-1] and is assumed as constant over the whole study area.

C.4.6. Groundwater Storage Coefficient (Ks)

The groundwater storage coefficient was determined conducting a master recession curve analysis. The final value for Ks computed and used as input for the model is 0.067 [d-1].
The results of the analysis are displayed below. Figure C.5 shows the hydrograph of the Limpopo river from the nearest available station, with specific discharge (mm/h) plotted against time over a five year period from 2019 to 2024. The plot shows different peaks representing strong precipitation events, after which, the recession periods where discharge decreases are highlighted in light blue. The individual recession periods were overlaid and are displayed in figure C.6, the lowest of all the dry period recession limbs was selected and is shown in figure C.7, this represents the master recession curve (MRC). Finally, as shown in figure C.8, a line was fitted to the MRC, its slope represents the groundwater storage coefficient Ks used in the model.

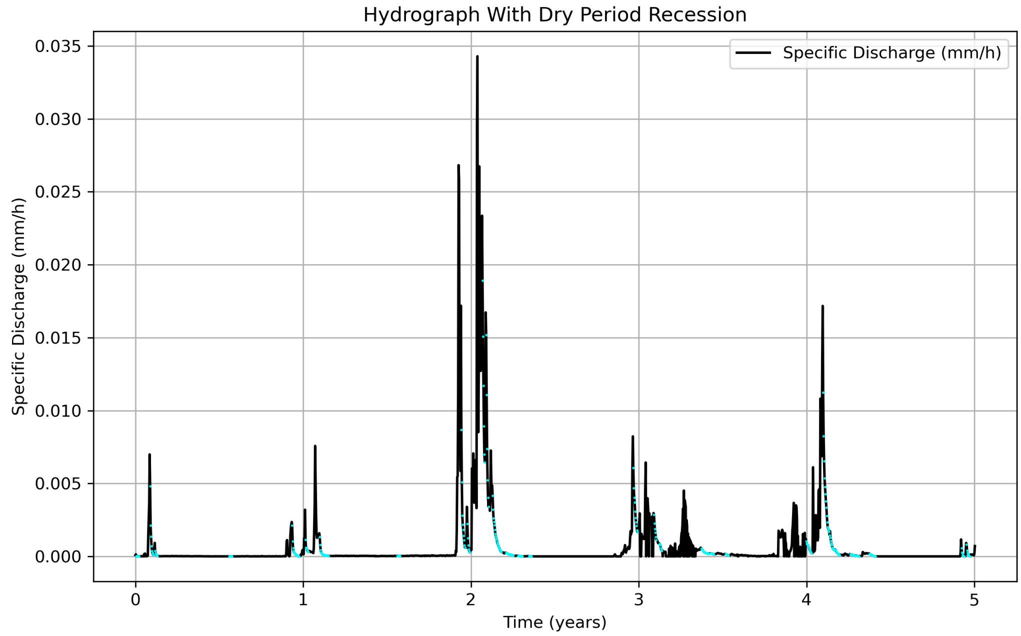

Figure C.5: Hydrograph with Individual Dry Period Recessions

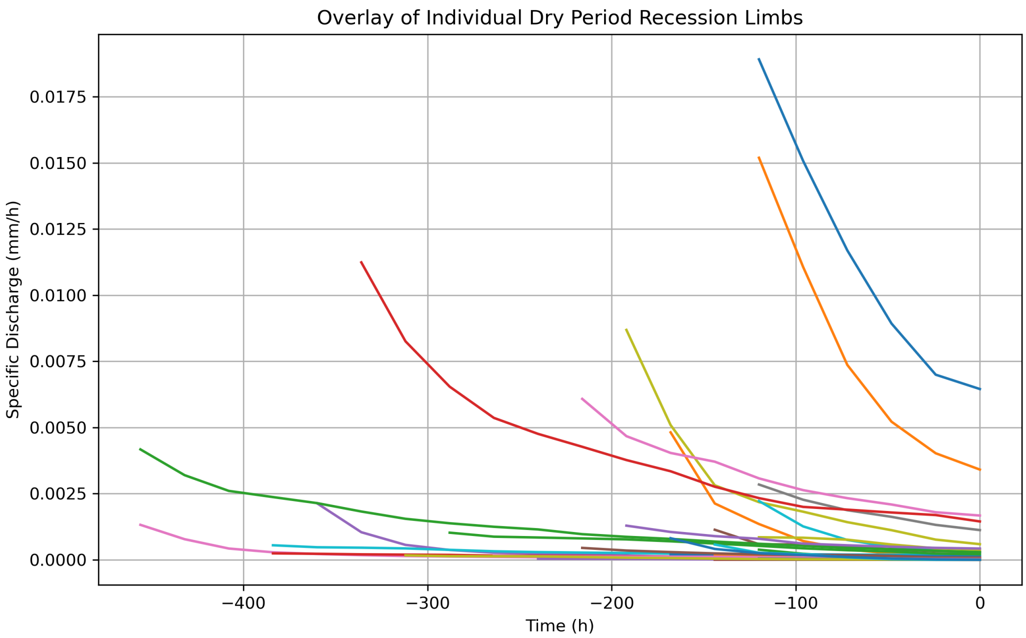

Figure C.6: Overlay of Individual Dry Period Recessions Limbs

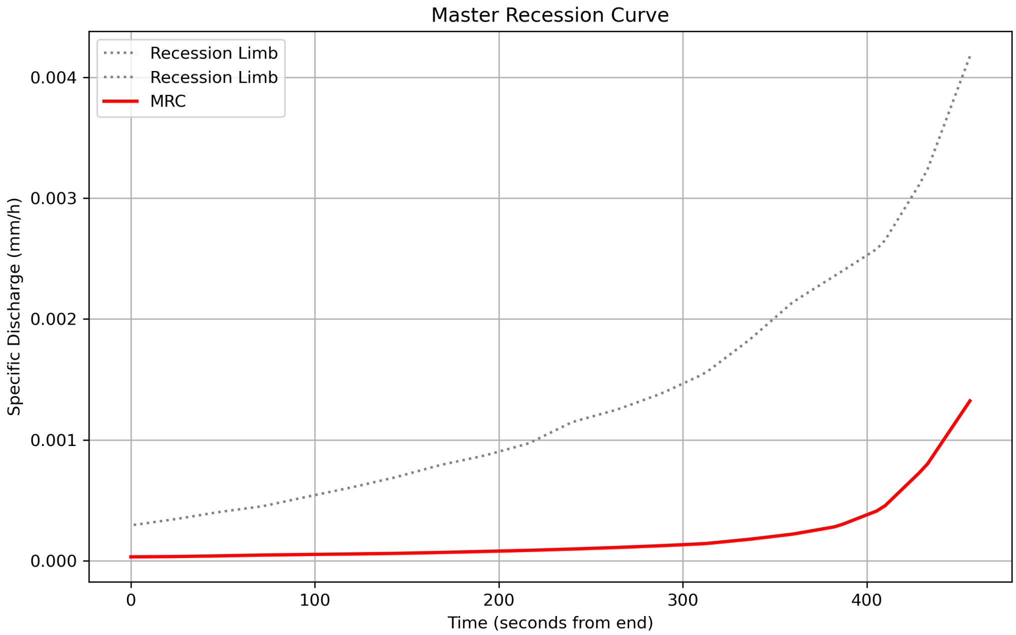

Figure C.7: Master Recession Curve

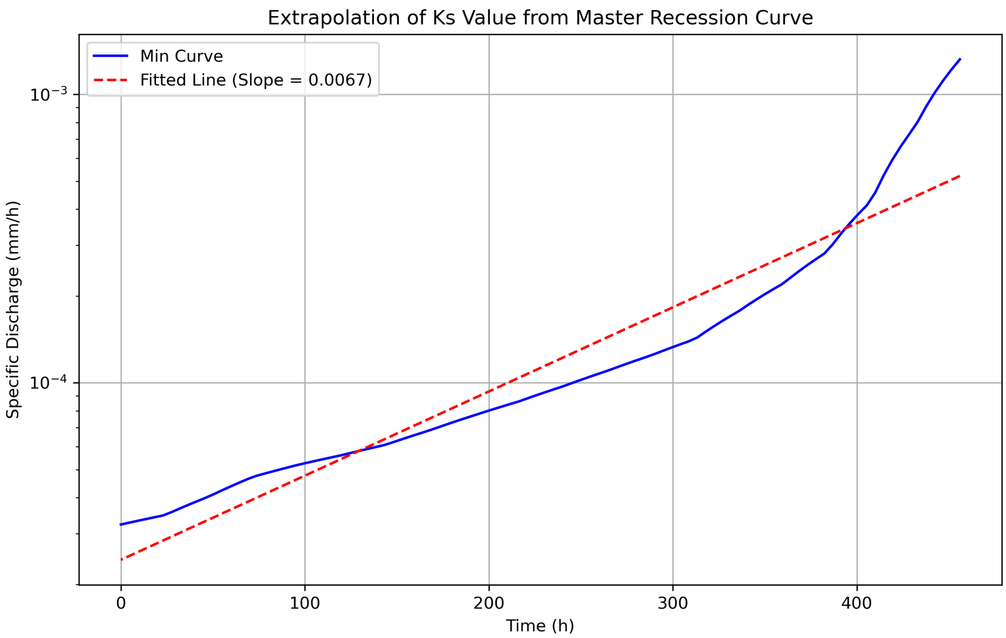

Figure C.8: Extrapolation of Ks Value from Master Recession Curve

C.5. Soil Characteristics

C.5.1. Bulk Density, Soil Moisture and Soil Porosity

In table C.3 the different soil characteristics can be found. These include the bulk density, moisture content and the soil porosity. For each site two samples were taken and thus two values for the different characteristics were determined, the values in the above table are the average of the two.

Location	**Dry Bulk Density [g/cm^3]**	**Moisture content [$\%$]**	**Soil Porosity** [-]
Site 1: Southern Plains			
1	1.62	0.47	0.38
2	1.56	0.56	0.40
3	1.73	0.08	0.34
4	1.74	0.07	0.34
5	1.70	0.05	0.35
6	1.37	2.24	0.47
Site 2: Phofu Drive			
1	1.74	0.05	0.34
2	1.64	0.29	0.37
3	1.74	0.10	0.33
4	1.66	0.09	0.36
5	1.70	0.30	0.35
6	1.60	0.25	0.39
Site 3: Middle Plains			
1	1.70	0.49	0.34
2	1.67	0.49	0.36
3	1.75	0.43	0.31
4	1.56	0.71	0.40
5	1.77	0.30	0.32
6	1.81	0.79	0.30
Site 4: Northern Plains			
1	1.71	0.04	0.35
2	1.65	0.05	0.36
3	1.80	0.04	0.31
4	1.71	0.06	0.34
5	1.74	0.09	0.33
6	1.84	0.08	0.29

Table C.3: Soil Characteristics for each location

The ranges shown in Table C.4 here below are based on values found in Table 2, page 10 in Teil and Teil [33]. The compaction of the samples excavated is not known, so the range includes values from L1 (Low density) to L5 (High density).

Soil texture Class	Dry Bulk Density Range [g/cm^3]
Su4	1,14 - 1,94
Su3	1,15 - 1,95
Lu	1,03 - 1,81
Lt2	1,01 - 1,83
St2	1,14 - 1,94
Sl3	1,13 - 1,93
Sl4	1,1 - 1,9
Slu	1,09 - 1,89

Table C.4: Ranges used for the evaluation of DBD results

C.6. Soil Texture Classification

Table C.5 includes the estimation of Mass% of sand, silt and clay and textures per site and sample for the Jar test analysis.

Site	Location	%Sand	%Silt	%Clay	Soil texture class
1	1	56.25	34.38	9.38	Sandy loam
1	3	71.43	21.43	7.14	Sandy loam
1	6	11.76	58.82	29.41	Silty clay loam
2	2	64.29	28.57	7.14	Sandy loam
2	4	33.33	50	16.67	Silt loam
3	3	39.29	32.14	28.57	Clay loam
3	6	13.33	60	26.67	Silty clay loam/ Silt loam
4	1	78.57	7.14	14.29	Sandy loam
4	3	72.73	18.18	9.09	Sandy loam
4	4	47.06	35.29	17.65	Loam

Table C.5: Mass% of sand, silt and clay and textures per site and sample

Table C.6 includes a comparison of results retrieved from the manual soil texture analysis and the jar test.

Comparison of MSTA and Jar test

Site	Location	Method	%Sand	%Silt	%Clay	Soil texture class
1	1	Soil Texture Analysis	42-<60	40-<50	0-<8	Very silty sand (Su4)
1	1	Jar Test	56.25	34.38	9.38	Sandy loam
1	3	Soil Texture Analysis	52- <75	25-<40	0-<8	Medium silty sand (Su3)
1	3	Jar Test	71.43	21.43	7.14	Sandy loam
1	6	Soil Texture Analysis	5-<33	50-<65	17-<30	Silty clay (Lu)
1	6	Jar Test	11.76	58.82	29.41	Silty clay loam
2	2	Soil Texture Analysis	42-<60	40-<50	0-<8	Very silty sand (Su4)
2	2	Jar Test	64.29	28.57	7.14	Sandy loam
2	4	Soil Texture Analysis	33-<52	33-<52	8-<17	Silty-loamy sand (Slu)
2	4	Jar Test	33.33	50	16.67	Silt loam
3	3	Soil Texture Analysis	15-<45	30-<50	25-<35	Slightly clayey loam (Lt2)
3	3	Jar Test	39.29	32.14	28.57	Clay loam
3	6	Soil Texture Analysis	5-<33	50-<65	17-<30	Silty clay (Lu)
3	6	Jar Test	13.33	60	26.67	Silty clay loam/ Silt loam
4	1	Soil Texture Analysis	73-<95	0-<10	5-<17	Slightly clayey sand (St2)
4	1	Jar Test	78.57	7.14	14.29	Sandy loam
4	3	Soil Texture Analysis	48-<82	10-<40	8-<12	Medium loamy sand (Sl3)
4	3	Jar Test	72.73	18.18	9.09	Sandy loam
4	4	Soil Texture Analysis	43-<78	10-<40	12-<17	Strong clayey sand (Sl4)
4	4	Jar Test	47.06	35.29	17.65	Loam

Table C.6: Mass % of sand, silt and clay and textures per site, sample and method

Table C.7 includes the Mass% of sand, silt, and clay and analysed textures for the Manual soil texture analysis and the jar test.

Site	Location	Evaluation	Point number	%Sand	%Silt	%Clay	Soil texture class
1	1	Jar test- IST Triangle	1	56.3	34.4	9.4	SANDY LOAM
1	1	Soil texture analysis- KA5 Triangle	2	51.0	45.0	4.0	SANDY LOAM
1	3	Jar test- IST Triangle	3	71.4	21.4	7.1	SANDY LOAM
1	3	Soil texture analysis- KA5 Triangle	4	63.5	32.5	4.0	SANDY LOAM
2	2	Jar test- IST Triangle	5	64.3	28.6	7.1	SANDY LOAM
2	2	Soil texture analysis-KA5 Triangle	6	51.0	45.0	4.0	SANDY LOAM

Table C.7: Mass % of sand, silt, and clay and textures per site, sample

Data Selection The results of the soil texture analysis reveal that certain locations stand out for being in a significantly different soil class from the rest of the samples at the same site, namely site 2 location 4, site 3 location 3 and site 4 location 1. Thus, the corresponding data points were excluded from the data sets for bulk density, moisture content and porosity for further analysis. Additionally, it was observed after the sample for site 1 location 6 had been collected that it was located in a different vegetation habitat, so it was also excluded from the analysis.

When comparing the results for the soil characteristics described above by their sand content, only Su4, Sl3 and Lu samples were taken into consideration. This was decided as other soil texture classes were observed in fewer locations and the lack of data would prevent any significant trend from being observed. The specific data points that were excluded for this analysis, in addition to the outliers already removed, are from site 1 location 3 and site 4 location 4.

C.7. Soil Hydraulic conductivity

Table C.8 presents the Ksat values [m/s] and their corresponding uncertainty [m/s] from the Constant Head test, conducted at each site and location.

Location	Hydraulic Conductivity [m/s]	Uncertainty [m/s]
Site 1: Southern Plains		
1	9.0e-06	4.8e-06
2	3.1e-05	1.8e-05
3	7.4e-06	3.7e-06
4	1.14e-06	5.7e-06
5	7.4e-06	3.7e-06
6	1.2e-05	5.9e-06
Site 2: Phofu Drive		
1	1.8e-05	1.2e-05
2	2.2e-05	1.3e-05
3	5.0e-06	2.5e-06
4	5.6e-06	2.8e-06
5	2.1e-05	1.3e-05
6	1.4e-05	7.3e-06
Site 3: Middle Plains		
1	1.9e-06	1.1e-06
2	3.8e-06	1.9e-05
3	2.96e-06	1.4e-06
4	1.2e-06	3.2e-06
5	6.1e-06	3.3e-06
6	1.4e-06	7.2e-07
Site 4: Northern Plains		
1	2.96e-06	1.4e-06
2	6.4e-06	3.4e-06
3	3.4e-06	1.7e-06
4	1.41e-05	7.1e-06
5	2.45e-06	1.2e-06
6	3.27e-06	1.7e-06

Table C.8: Hydraulic Conductivity from the Mariotte bottle test

Table C.9 presents the Ksat values [m/s] from the Slug test conducted at selected sites and locations.

Location	Hydraulic Conductivity [m/s]
Site 1: Southern Plains	
S1-L1	2.5e-04
S1-L4	3.4e-04
Site 2: Phofu Drive	
S2-L1	1.3e-04
S2-L6	4.3e-04
Site 3: Middle Plains	
S3-L1	2.0e-04
S3-L4	4.2e-05
Site 4: Northern Plains	
S4-L1	1.5e-04
S4-L2	2.1e-04

Table C.9: Hydraulic conductivity of unsaturated topsoil

Table C.10 presents the infiltration rate [mm/m²/h] from the Shallow Hole Inverse Slug test conducted at selected sites and locations.

Location	Infiltration Rate [mm/m²/h]
Site 1: Southern Plains	
Cleared	180
Uncleared	252
Site 2: Phofu Drive	
Cleared	109
Uncleared	123
Site 3: Middle Plains	
Cleared	20
Uncleared	68
Site 4: Northern Plains	
Cleared	143
Uncleared	104

Table C.10: Infiltration rates at each site according to the Double Ring Infiltrometer

Table C.11 presents the Ksat values [m/s] from the Double Ring Infiltrometer, conducted at selected sites and locations.

Location	Hydraulic Conductivity [m/s]
Site 1: Southern Plains	
Cleared	5e-05
Uncleared	7e-05
Site 2: Phofu Drive	
Cleared	3e-05
Uncleared	3e-05
Site 3: Middle Plains	
Cleared	5e-05
Uncleared	2e-05
Site 4: Northern Plains	
Cleared	4e-05
Uncleared	3e-05

Table C.11: Hydraulic Conductivity with Double Ring Infiltrometer

C.8. Soil hydraulic conductivity and soil texture class

Table C.12 includes a summary of the the results gathered by comparing the Ksat results of the three different tests conducted with reference Ksat value based on dry bulk density and the analyzed soil texture class.

Site-Location	Slug test	Double ring	Mariottes bottle
S1-L1	5376,2%	1018,1%	97,1%
S1-L4	9453,2%	1863,8%	73,2%
S2-L1	3928,8%	802,5%	457,8%
S2-L6	8641,6%	607,8%	184,6%
S3-L1	21500,0%	4884,6%	105,2%
S3-L4	2194,5%	1529,4%	34,4%
S4-L1	1891,2%	1039,7%	60.71
S4-L2	3975,2%	-457,8%	24,2%
Average deviation	**7120,1%**	**1525,5%**	**102,76%**

Table C.12: Comparison of soil hydraulic conductivity and hydraulic conductivity based on soil texture class and dry bulk density

Tables C.13, C.15 and C.14 include further information regarding the values summarized in Table C.12

here above.

Site-Location	Slug test Ksat [m/s]	Ksat (relation to DBD) [m/s]	Deviation (%)
S1-L1	2.50E-04	4.57E-06	5376.15% higher
S1-L4	3.40E-04	3.60E-06	9453.17% higher
S2-L1	1.30E-04	3.20E-06	3928.84% higher
S2-L6	4.30E-04	4.90E-06	8641.65% higher
S3-L1	2.00E-04	9.30E-07	21500.00% higher
S3-L4	4.20E-05	1.80E-06	2194.53% higher
S4-L1	1.50E-04	7.50E-06	1891.17% higher
S4-L2	2.10E-04	5.20E-06	3975.24% higher

Table C.13: Slug Test and texture class comparison of soil hydraulic conductivity

Site	Double Ring Ksat [m/s]	Ksat (relation to DBD) [m/s]	Deviation (%)
S1-L1	5.00E-05	4.50E-06	1018.07% higher
S1-L4	7.00E-05	3.60E-06	1863.77% higher
S2-L1	3.00E-05	3.30E-06	802.54% higher
S2-L6	3.00E-05	4.20E-06	607.78% higher
S3-L1	5.00E-05	1.00E-06	4884.62% higher
S3-L4	2.00E-05	1.20E-06	1529.42% higher
S4-L1	4.00E-05	3.50E-06	1039.72% higher
S4-L2	3.00E-05	5.40E-06	457.80% higher

Table C.14: Double Ring and texture class comparison of soil hydraulic conductivity

Location	Hydraulic Conductivity [m/s]	Ksat (relation to DBD) [m/s]	Deviation [%]
S1-L1	9,00E-06	4,6E-06	97,14% higher
S1-L2	3,10E-05	5,7E-06	444,25% higher
S1-L3	7,40E-06	4,6E-06	60,81% higher
S1-L4	1,14E-06	4,3E-06	73,2% lower
S1-L5	7,40E-06	2,8E-06	166,4% higher
S1-L6	1,20E-05	3,8E-06	219,02% higher
S2-L1	1,80E-05	3,2E-06	457,84% higher
S2-L2	2,40E-05	4,9E-06	387,91% higher
S2-L3	5,03E-06	3,3E-06	53,69% higher
S2-L4	5,60E-06	2,9E-06	94,59% higher
S2-L5	2,16E-05	3,5E-06	522,08% higher
S2-L6	1,44E-05	4,9E-06	192,74% higher
S3-L1	1,96E-06	9,3E-07	111,68% higher
S3-L2	3,78E-06	9,3E-07	308,24% higher
S3-L3	2,96E-06	1,2E-06	155,74% higher
S3-L4	1,20E-06	1,8E-06	34,44% lower
S3-L5	6,10E-06	9,3E-07	558,8% higher
S3-L6	1,40E-06	9,3E-07	51,2% higher
S4-L1	2,96E-06	7,5E-06	60,71% lower
S4-L2	6,40E-06	5,2E-06	24,2% higher
S4-L3	3,40E-06	3,4E-06	1,41% lower
S4-L4	1,41E-05	3,5E-06	306,08% higher
S4-L5	2,45E-06	4,0E-06	38,96% lower
S4-L6	6,63E-06	3,0E-06	117,89% higher

Table C.15: Double Ring Infiltrometer results and texture class comparison of soil hydraulic conductivity

C.9. Organic Matter Content

Tables C.16, C.17, C.18 and C.19 include the Munsell colour results for sites 1-4.

Location	Sample	Code	Munsell Color	OM Content (%)
1A Dry	1	5 YR 3/6	Dark-reddish brown	12
1B Dry	3	5 YR 3/6	Dark-reddish brown	12
2A Dry	5	5 YR 3/6	Dark-reddish brown	12
2B Dry	7	5 YR 4/8	Reddish-brown	3
3A Dry	15	7.5 YR 4/6	Brown	5
3B Dry	13	7.5 YR 4/6	Brown	5
4A Dry	18	7.5 YR 5/8	Bright brown	1
4B Dry	19	7.5 YR 5/8	Bright brown	1
5A Dry	21	7.5 YR 4/6	Brown	5
5B Dry	23	7.5 YR 4/6	Brown	5
6A Dry	86	10 YR 5/3	Dull reddish brown	5
6B Dry	85	10 YR 5/3	Dull reddish brown	5

Table C.16: Site 1 (Southern Plains) Munsell Colour Results

Location	Sample	Code	Munsell Color	OM Content (%)
1A Dry	25	5 YR 3/4	Dark-reddish brown	12
1B Dry	27	5 YR 3/4	Dark-reddish brown	12
2A Dry	29	5 YR 3/4	Dark-reddish brown	12
2B Dry	31	5 YR 3/6	Dark-reddish brown	12
3A Dry	33	5 YR 3/6	Dark-reddish brown	12
3B Dry	35	5 YR 3/6	Dark-reddish brown	12
4A Dry	37	5 YR 3/4	Dark-reddish brown	12
4B Dry	39	5 YR 3/4	Dark-reddish brown	12
5A Dry	45	5 YR 3/6	Dark-reddish brown	12
5B Dry	47	5 YR 3/6	Dark-reddish brown	12
6A Dry	41	5 YR 4/6	Reddish-brown	5
6B Dry	43	5 YR 4/6	Reddish-brown	5

Table C.17: Site 2 (Phofu) Munsell Colour Results

Location	Sample	Code	Munsell Color	OM Content (%)
1A Dry	51	5 YR 3/6	Dark-reddish brown	12
1B Dry	52	5 YR 3/6	Dark-reddish brown	12
2A Dry	53	5 YR 3/6	Dark-reddish brown	12
2B Dry	55	5 YR 3/6	Dark-reddish brown	12
3A Dry	57	5 YR 3/6	Dark-reddish brown	12
3B Dry	59	5 YR 3/6	Dark-reddish brown	12
4A Dry	65	5 YR 3/4	Dark-reddish brown	12
4B Dry	67	5 YR 3/4	Dark-reddish brown	12
5A Dry	73	5 YR 3/4	Dark-reddish brown	12
5B Dry	75	5 YR 3/4	Dark-reddish brown	12
6A Dry	95	5 YR 3/4	Dark-reddish brown	12
6B Dry	71	5 YR 3/4	Dark-reddish brown	12

Table C.18: Site 3 (Middle Plains) Munsell Colour Results

Location	Sample	Code	Munsell Color	OM Content (%)
1A Dry	9	7.5 YR 4/4	Brown	2.5
1B Dry	10	7.5 YR 4/4	Brown	2.5
2A Dry	11	7.5 YR 4/4	Brown	5
2B Dry	12	7.5 YR 4/4	Brown	5
3A Dry	103	7.5 YR 4/3	Brown	7.5
3B Dry	104	7.5 YR 4/3	Brown	7.5
4A Dry	115	7.5 YR 4/4	Brown	5
4B Dry	116	7.5 YR 4/4	Brown	5
5A Dry	112	7.5 YR 4/4	Brown	5
5B Dry	113	7.5 YR 4/4	Brown	5
6A Dry	109	5 YR 3/6	Dark-reddish brown	12
6B Dry	108	5 YR 3/6	Dark-reddish brown	12

Table C.19: Site 4 (Northern Plains) Munsell Colour Results

Table C.20 includes OM results for a total of 12 selected samples, gathered by using the LOI method.

Location	**S1 L1**	**S1 L2**	**S1 L4**	**S2 L1**	**S2 L2**	**S2 L6**	**S3 L1**	**S3 L2**	**S3 L4**	**S4 L2**	**S4 L3**	**L4 L6**
Sample	1	5	18	25	29	41	51	53	65	11	104	108
Texture	Su4	Su4	Su4	Su4	Su4	Su4	Lu	Lu	Lu	Sl3	Sl3	Sl3
Status	C	C	UC	C	UN	UN	C	C	UN	UN	UN	C
Initial Mass (g)	20.70	19.88	20.24	20.09	20.09	20.00	20.00	20.05	20.00	20.04	20.00	20.00
Dry Mass	19.59	19.66	20.05	19.87	19.86	19.82	19.80	19.80	19.79	19.87	19.89	19.84
Burnt Mass (g)	19.52	19.51	20.03	19.74	19.72	19.72	19.67	19.67	19.66	19.79	19.82	19.68
Moisture (%)	5.36	1.11	0.64	1.14	1.05	0.80	1.10	1.20	1.20	0.80	0.50	0.80
OM (%)	0.36	0.76	0.40	0.60	0.80	0.60	0.56	0.71	0.51	0.45	0.40	0.81

Table C.20: OM Content of 12 Soil Samples with LOI Method

C.9.1. Teabag Index (TBI) for Soil Organic Activity

Tables C.21 and C.22 include the TeaBag Index Parameters for Site 1 and Site 2.

Parameter	Value
Green tea stabilization factor S [-]	0.812
Average decomposable fraction Rooibos a_r[-]	0.104
Average decomposable fraction Green tea a_g [-]	0.158
Average decomposition rate k constant Green tea [/day]	0.205
Average decomposition rate k constant Rooibos [/day]	0.019

Table C.21: Tea Bag Index Parameters Site 1 (Southern Plains)

Parameter	Value
Green tea stabilization factor S [-]	0.768
Average decomposable fraction Rooibos a_r[-]	0.128
Average decomposable fraction Green tea a_g [-]	0.195
Average decomposition rate k constant Green tea [/day]	0.225
Average decomposition rate k constant Rooibos [/day]	0.025

Table C.22: Tea Bag Index Parameters Site 2 (Phofu Drive)

Figure C.9 shows a graph of mass loss over time for both rooibos and green teas. This relates to the tea bags recovered from Site 1 (Southern Plains) and the mass remaining at the time of excavation, which in this case was 41 days.

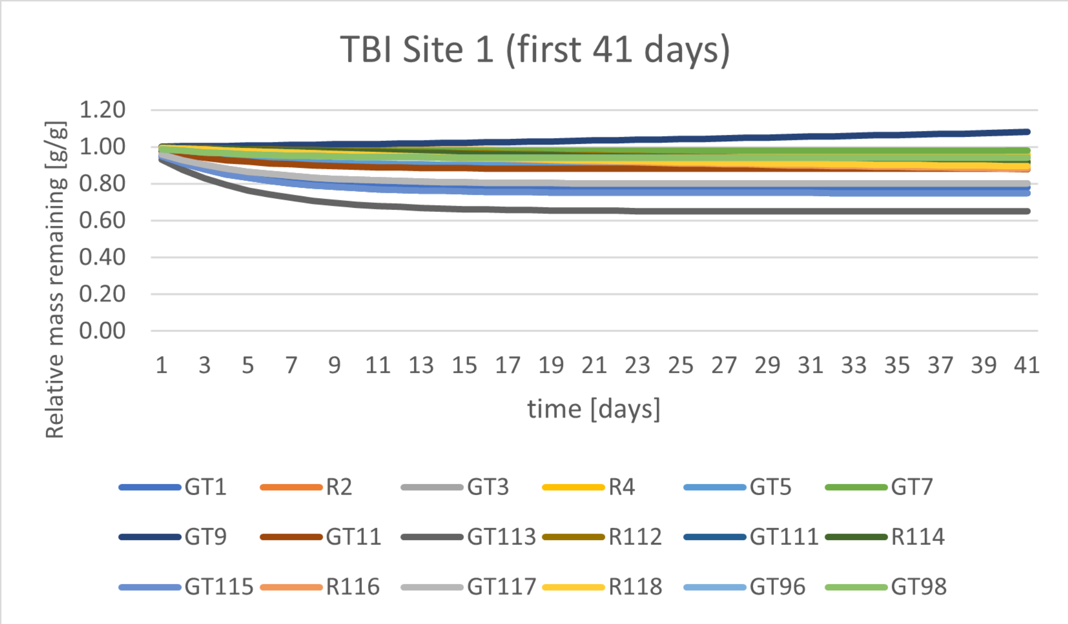

Figure C.9: Tea mass loss over time at Southern Plains (Site 1)

The graph of mass loss over time (41 days) and the remaining mass after exhumation for both kinds of teas observed in Site 2 (Phofu Drive) can be seen in Figure C.10

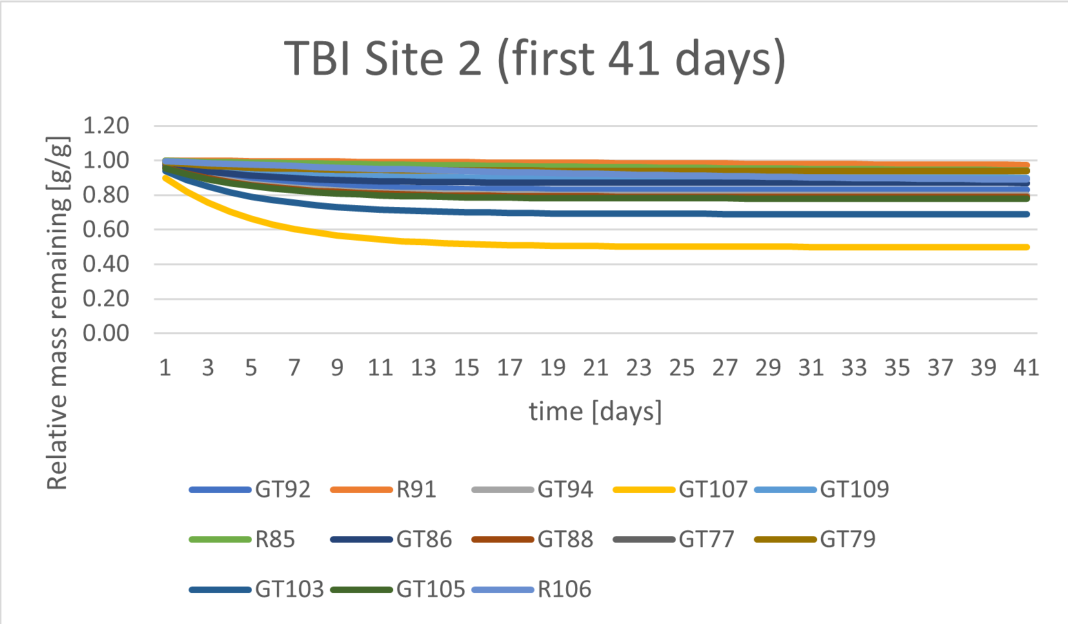

Figure C.10: Tea mass loss over time at Southern Plains (Site 1)

Figure C.11 includes photographs taken when excavating and analyzing the teabags.

(a) Exhumation of teabags

(b) Termite presence in sample spot

(c) Termite presence in sample spot

(d) Unrecoverable teabag

(e) Mouldy tea

(f) Holes in teabag

Figure C.11: Exhumation process and recovery of teabags

Multicriteria analysis

Table C.23 includes the chosen ranges used for the analysed soil properties of the multi-criteria matrix. The ranges retrieved from Teil and Teil [33].

Parameter	Su4	Su3	Lu	Lt2	St2	Sl3	Sl4	Slu
Bulk Density [g/cm^3]	1.14-1.94	1.15-1.95	1.03-1.81	1.01-1.7	1.14-1.94	1.13-19.93	1.1-1.9	1.09-1.89
Porosity [-]	0.25-0.36	0.25-0.32	0.35-0.39	0.33-0.41	0.29-0.35	0.35-0.4	0.3-0.34	0.3-0.34
Plant available field capacity [-]	0.18-0.2	0.15-0.18	0.15-0.17	0.1-0.12	0.09-0.11	0.12-0.20	0.12-0.20	0.14-0.18
Field Capacity [-]	0.25-0.27	0.22-0.25	0.3-0.34	0.28-0.31	0.17-0.19	0.24-0.29	0.24-0.29	0.25-0.27
OM [%]	0-1%	0-1%	0-1%	0-1%	0-1%	0-1%	0-1%	0-1%

Table C.23: Ranges for chosen soil Properties

Table C.24 includes the expected hydraulic conductivity (Ksat) value for each site and location. The values are based on the analysed soil texture class and dry bulk density of the excavated soil sample.

Site-location	Ksat [m/s]	Site-location	Ksat [m/s]	Site-location	Ksat [m/s]	Site-location	Ksat [m/s]
S1-L1	4.6E-06	**S2-L1**	3.2E-06	**S3-L1**	9.3E-07	**S4-L1**	7.5E-06
S1-L2	5.7E-06	**S2-L2**	4.9E-06	**S3-L2**	9.3E-07	**S4-L2**	5.2E-06
S1-L3	3.2E-06	**S2-L3**	3.3E-06	**S3-L3**	1.2E-06	**S4-L3**	3.4E-06
S1-L4	3.6E-06	**S2-L4**	2.9E-06	**S3-L4**	1.8E-06	**S4-L4**	3.5E-06
S1-L5	3.5E-06	**S2-L5**	3.5E-06	**S3-L5**	9.3E-07	**S4-L5**	4.0E-06
S1-L6	3.7E-06	**S2-L6**	4.9E-06	**S3-L6**	9.3E-07	**S4-L6**	3.0E-06

Table C.24: Range for hydraulic conductivity based on soil texture class and dry bulk density

Table C.25 includes the results of the multi-criteria matrix conducted for site 1, Southern Plains. Table C.26 includes whether the results are within the expected range, and if not, how much the value deviates from the range (% higher/lower).

Southern Plains		**Site–Location**					
Parameter	**Coefficient**	**S1-L1**	**S1-L2**	**S1-L3**	**S1-L4**	**S1-L5**	**S1-L6**
Bulk Density	0-1	1	1	1	1	1	1
Porosity	0-1	0.94	0.89	1.00	1.00	1.00	0.79
Plant Available Field Capacity	0-1	0.95	0.93	0.97	1.00	1.00	1.00
Field Capacity	0-1	0.88	0.86	1.00	0.94	0.92	0.73
OM (Organic Matter)	0-1	1.00	1.00	1.00	1.00	1.00	1.00
Cleared	C/UC	C	C	C	UC	UC	UC
Soil texture class		Su4	Su4	Su3	Su4	Su4	Lu
Total Grade	0-6	5.68	5.23	5.84	5.87	5.81	5.30

Table C.25: Southern Plains MCA results

Property	S1 L1	S1 L2	S1 L3	S1 L4	S1 L5	S1 L6
Hydraulic conductivity	97.14% higher	444.25% higher	134.56% higher	67.97% lower	113.12% higher	227.65% higher
Porosity	5.56% higher	11.11% higher	Within range	Within range	Within range	20.51% higher
Field capacity	12% higher	14% higher	Within range	6% higher	8% higher	26.67% higher
OM	Within range	Within range	N/A	Within range	N/A	N/A
Plant available Field Capacity	5% higher	7.5% higher	2.78% lower	Within range	Within range	Within range

Table C.26: Determination of coefficients for Southern Plains

Table C.27 includes the results of the multi-criteria matrix conducted for site 2, Phofu drive. Table C.28 includes whether the results are within the expected range, and if not, how much the value deviates from the range (% higher/lower).

Phofu Drive		Site–Location					
Parameter	**Coefficient**	**S2-L1**	**S2-L2**	**S2-L3**	**S2-L4**	**S2-L5**	**S2-L6**
Bulk Density	0-1	0	0	0	0	0	1
Porosity	0-1	1.00	0.97	1.00	0.94	1.00	0.92
Plant Available Field Capacity	0-1	1.00	0.95	1.00	1.00	1.00	0.95
Hydraulic Conductivity	0-1	0.54	0.65	0.95	0.91	0.50	0.82
Field Capacity	0-1	0.82	0.73	0.77	0.78	0.73	0.82
OM (Organic Matter)	0-1	1.00	1.00	1.00	1.00	1.00	1.00
Cleared	C/UC	C	UC	C	UC	C	UC
Soil texture class		Su4	Su4	Su4	Slu	Su4	Su4
Total Grade	0-6	4.36	4.30	4.72	4.63	4.22	4.51

Table C.27: Phofu Drive MCA results

Property	**S2 L1**	**S2 L2**	**S2 L3**	**S2 L4**	**S2 L5**	**S2 L6**
Hydraulic conductivity	457.84% higher	347.25% higher	52.77% higher	94.59% higher	504.8% higher	184.61% higher
Porosity	Within range	2.78% higher	Within range	5.88% higher	Within range	8.33% higher
Field capacity	18% higher	27.27% higher	22.73% higher	22% higher	27.27% higher	18% higher
OM	Within range	Within range	N/A	N/A	N/A	Within range
Plant available Field Capacity	Within range	5% higher	Within range	Within range	Within range	5% higher

Table C.28: Determination of coefficients for Phofu Drive

Table C.29 includes the results of the multi-criteria matrix conducted for site 3, Middle Plains. Table C.30 includes whether the results are within the expected range, and if not, how much the value deviates from the range (% higher/lower).

Middle Plains		Site–Location					
Parameter	**Coefficient**	**S3-L1**	**S3-L2**	**S3-L3**	**S3-L4**	**S3-L5**	**S3-L6**
Bulk Density	0-1	1	1	1	1	1	1
Porosity	0-1	0.97	1.00	0.94	0.97	0.91	0.86
Plant Available Field Capacity	0-1	1.00	1.00	1.00	1.00	1.00	1.00
Hydraulic Conductivity	0-1	0.89	0.69	0.77	0.97	0.44	0.95
Field Capacity	0-1	0.87	0.87	0.89	0.82	0.87	0.87
OM (Organic Matter)	0-1	1.00	1.00	1.00	1.00	1.00	1.00
Cleared	C/UC	C	UC	C	UC	C	UC
Soil texture class		Lu	Lu	Lt2	Lu	Lu	Lu
Total Grade	0-6	5.73	5.56	5.60	5.76	5.22	5.67

Table C.29: Middle Plains MCA results

Property	**S3 L1**	**S3 L2**	**S3 L3**	**S3 L4**	**S3 L5**	**S3 L6**
Hydraulic conductivity	105.2% higher	310.4% higher		34.44% lower	558.8% higher	51.2% higher
Porosity	2.86% lower	Within range	6.06% lower	2.56% higher	8.57% lower	14.29% lower
Field capacity	13.33% higher	13.33% higher	10.71% higher	18.33% higher	13.33% higher	13.33% higher
OM	Within range	Within range	N/A	Within range	N/A	N/A
Plant available Field Capacity	Within range	Within range	Within range	Within range	Within range	Within range

Table C.30: Determination of coefficients for Middle Plains

Table C.31 includes the results of the multi-criteria matrix conducted for site 4, Northern Plains. Table C.32 includes whether the results are within the expected range, and if not, how much the value deviates from the range (% higher/lower).

Northern Planes		Site–Location					
Parameter	**Coefficient**	**S4-L1**	**S4-L2**	**S4-L3**	**S4-L4**	**S4-L5**	**S4-L6**
Bulk Density	0-1	1.00	1.00	1.00	1.00	1.00	1.00
Porosity	0-1	1.00	1.00	0.89	0.94	0.94	0.83
Plant Available Field Capacity	0-1	0.98	1.00	1.00	0.87	1.00	1.00
Hydraulic Conductivity	0-1	0,94	0,98	1,00	0,69	0,96	0,99
Field Capacity	0-1	0.87	0.98	1.00	0.93	0.92	1.00
OM (Organic Matter)	0-1	1.00	1.00	1.00	1.00	1.00	1.00
Cleared	C/UC	C	UC	C	UC	C	UC
Soil texture class		St2	Sl3	Sl3	Sl4	Sl3	Sl3
Total Grade	0-6	5,78	5,96	5,88	5,43	5,82	5,82

Table C.31: Northern Plains MCA results

Property	**S4 L1**	**S4 L2**	**S4 L3**	**S4 L4**	**S4 L5**	**S4 L6**
Hydraulic conductivity	60.71% lower	24.20% higher	1.41% lower	306.08% higher	38.96% lower	7.47% higher
Porosity	Within range	Within range	11.43% lower	6.25% higher	5.71% lower	17.14% lower
Field capacity	13.24% higher	2.08% higher	Within range	6.82% higher	8.33% higher	Within range
OM	N/A	Within range	Within range	N/A	N/A	Within range
Plant available Field Capacity	2.27% higher	Within range	Within range	13.33% lower	Within range	Within range

Table C.32: Determination of coefficients for Northern Plains

D

Pumping test

Within this project, a pumping test was conducted to determine the saturated hydraulic conductivity, which is used to estimate parameter Pmax. However, apart from this project the Limpopo Lipadi Reserve expressed an specific interest into conducting pumping tests for all boreholes in the reserve to analyse their water management practices. They requested research into the requirements of the test before conducting these tests in the future.

This annex first outlines the pumping tests conducted to estimate the maximum percolation rate, P_{max}. It then provides an overview of the potential of conducting additional pumping tests in the future.

D.1. Pumping tests Conducted during this Project

D.1.1. Method

Limpopo Lipadi has a wide range of different types of boreholes pumping from aquifers with different characteristics. The main difference are the boreholes that use fuel pumps (mainly for human consumption), and the boreholes with a pump driven by solar radiation (mainly for waterholes). Pumping tests can be done at both types of boreholes, but small changes have to be made in the procedure between the tests. Lastly, there are several old boreholes that are not currently in use, that could function as observation wells, however, the locations of these boreholes are often unknown.
Since there was no external pump available, it was decided to use the pumps that are currently installed in each borehole. It was decided to find boreholes that fit the requirements for doing these tests, and conduct a short duration pumping test at the maximum capacity of the installed pump. A short-duration test was chosen because long-term assessments require observation wells.

And thus it was decided to find boreholes that fit the following requirements:

- the pump can be shut off safely for 24 hours without this affecting people or animals in the reserve directly.
- The pump is hybrid, which allows for a generator or the pump to be linked to the electricity grid.
- The pump set-up allows for the installation of the flow meter.
- The water that is pumped up during the test can be stored in a way that does not affect the test directly.
- The opening of the borehole at the top is open, allowing the water level meter and the diver to be lowered down.

D.1.2. Findings at boreholes that were analysed during this project

Several boreholes were analysed to determine if they comply with the requirements mentioned above. Not all boreholes were analysed due to lack of time. The first criterion considered was whether the pump had a hybrid controller which means it can be powered by a generator or powered by the grid. Afterward, the other criteria were checked on site. The findings for each of the Boreholes is summarized in the following table:

Borehole	**Pump**	**Can be shut off**	**Flowmeter can be installed**	**Water storage**	**Borehole cover**
Northern House borehole	capacity: 5 m3/hour, powered by the grid & pumpdepth: 59 m	yes, only supplies waterhole right now	Directly after the pump	in waterhole	Open
Borehole at Motlhalatau private Lodge	capacity: 0.9 m3/hour, powered by the grid & pump depth: 46 m	yes, not in use for human consumption yet	Only at the outlet side	released in the garden +100 m way from borehole	Open
Mogorosi	capacity: 3 m3/hour, hybrid pump & pumpdepth: 20 m	Yes, only supplies waterhole	yes, directly after the pump	in waterhole	Open
Max pan	capacity: unknown, hybrid pump	yes, only supplies waterhole	Yes, directly after the pump	in waterhole	Open
Borehole at APU	capacity: Unkown, hybrid pump	Supplies APU with water, so preferably not	yes, at outlet side	in 2 large tanks, but that is too little storage space	Open
The Borehole at the outside staff village	capacity: unkown, powered by generator	Supplies staff village with water, so preferably not	unkown	two tanks, with insufficient storage	unkown
Mbuzi	pump capacity: >3 m3/hour, only solar	Yes, only supplies waterhole right now	yes, directly after the pump	in waterhole	Open
Pieties dam	capacity: unkown, hybrid pump	Yes, only supplies waterhole right now	No, no space to install flowmeter at pump or at the outlet	in waterhole	Open
Ten Tanks	capacity: +- 10 m3/hour, powered by generator	Not easily, supplies lodges with water	yes, at outlet	in ten tanks and in waterhole when tanks are full	Closed, diver could not be lowered
Service borehole near the office	capacity: 6 m3/hour, powered by the grid & pumpdepth: 16 m	yes, is off most of the time	yes, at outlet	in tanks for irrigation at Central, with overflow in gardens	Open

Table D.1: Water Supply Sources

These findings resulted in the selection of Northern House, Max pan, the borehole at Motlhalatau private lodge, Mogorosi and the service pump near the office as the most suitable. The tests were executed according to the protocol described in section D.2.5.

D.1.3. Results conducted Pumping tests

Northern House

At northern house, a short one hour pumping test was conducted, which showed a substantial initial draw down. Within minutes, the water was drawn down about 3 meters and thus drawing it down below the diver. It was then concluded that, due to the limitations of the diver used for this project (max 10 meters underwater), measuring the draw down continuously over the entire test would be impossible. As soon as the pump was shut down, the borehole recovered back to almost its original state within minutes, suggesting a robust aquifer. Similar behaviour was expected at Max pan borehole given its proximity. And thus, no further tests were conducted at these two locations. Further testing can be conducted with more robust equipment.

Mogorosi

At Mogorosi, a generator was installed to allow for an constant flow rate. The pump pumped constantly over the entire test at its maximum capacity of 3 m^3/hour. However, at this pump rate only an initial draw down of 0.5 meters was measured within the first minutes. Then the water level remained constant after this initial drop of 0.5 meters.
Mogorosi is a natural spring, which indicates that the groundwater table in this area is high. We suspect that the limited draw down can be explained by the limited pumping capacity and the fact that the unlined borehole into which the water is pumped is only 27 meters away from the borehole. Which might result in a loop between pumped water and re-infiltration and water being drawn towards the pump.

Due to the fact that with the current equipment it was not possible to stress this aquifer, and because the borehole is so close to the unlined waterhole, no conclusions were made regarding the hydraulic conductivity of the aquifer. The minimal draw down and the rapid recovery of the water level within minutes after prolonged pumping suggest that the aquifer is robust and not stressed even at the maximum pump rate of the installed pump.

The data measured by the diver is displayed in figure D.1. This figure shows an sudden increase in pressure, which is the moment the diver is lowered into the water. As soon as the pump starts pumping a drop of around 0.5 meters can be seen, after which the pressure stabilises. The pump stopped for a period of time, due to the generator running our of fuel, which can be seen as the instant recovery. As the pump is restarted, the pressure drops again and stabilises almost instantly. The last drop in pressure is the moment the diver is taken out of the borehole.

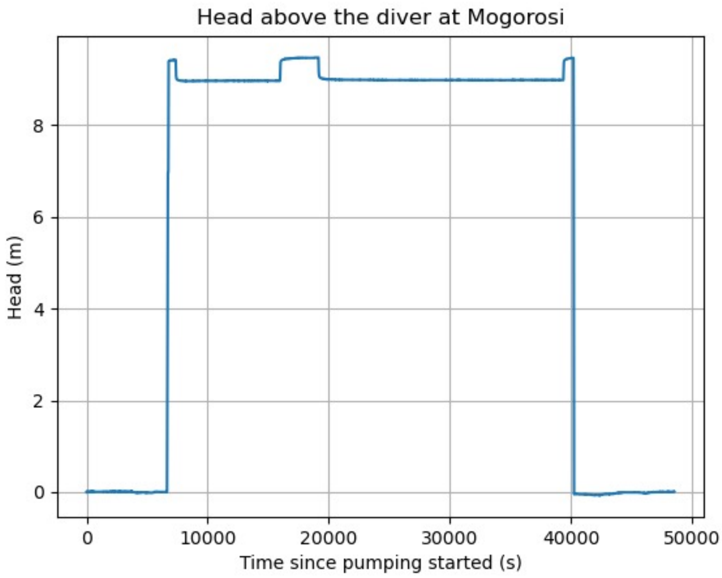

Figure D.1: Pressure measured during Pumping test at Mogorosi Borehole

The borehole at Motlhalatau private lodge
The Pumping capacity of the pump in this borehole was limited. Within the first 2 hours, the water levels were drawn down from an initial depth of 5.5 meters (after full stabilization) to around 11.5 meters. At a depth of around 11 meters, with a draw down of around 6 meters from initial level, the water level stabilized and remained constant. However, the pumping flow rate decreased over time. Going down from an initial value of 19 l/minute which remained for the first half hour, then remaining around 14 l/min for the next few hours and then reaching 12 l/min at the end of the 24 hour test. After the pump was switched off, the borehole recovered for approximately 90 percent within in the two hours after the pump was switched off. The borehole continued to recover slowly over the next 7 hours, but was approaching its initial state as can be seen in figure D.2. The primary point of interest in this test was the decreasing flow rate, which could not be explained, as the pump was connected to the power grid and the head above the pump was remained stable after the first few hours.

Figure D.2 shows the recovery phase of the pumping test conducted at this location. The recovery phase of this conducted pumping test was used to determine the local saturated hydraulic conductivity. The analysis of the recovery phase is based on the Theis theory, and applies only for confined aquifers.

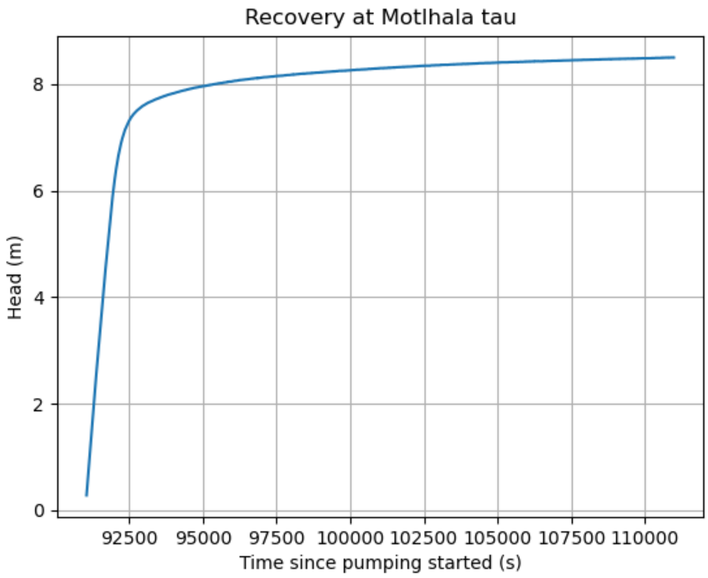

Figure D.2: Pressure measured during the recovery phase of the pumping test conducted at Motlhalatau Lodge.

To estimate the Transmissivity (T), a plot is generated shown in figure D.3 showing with on the x-axis t over t-prime, where t is the time since pumping started and t-prime is the time since pumping stopped. The y-axis displays the residual drawdown. The residual drawdown is the difference between the water level in stable condition and the water level at time t. Then, a line was fitted through this data, and the transmissivity was determined to be 1.6×10^{-5} m/s, which corresponds to a hydraulic conductivity of 28 mm/day. The primary uncertainty in this method is the estimated thickness of the aquifer layer, assumed to be 50 meters. Additional research is needed to obtain more accurate measurements.

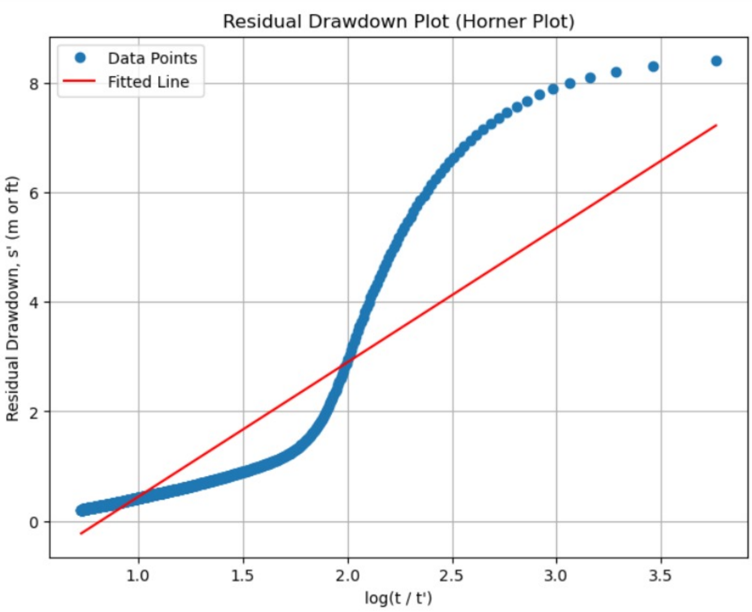

Figure D.3: Residual Drawdown of the pumping test conducted at Motlhalatau Lodge.

Service Borehole near the Office

The Pumping capacity of the pump in this borehole was high compared to the other locations. The test began at 08:40 with an initial water level of 5 meters. Over the first 30 minutes, the water levels dropped from 5 meters to 5.8 meters. During the total pumping time of around 8 hours, the water level decreased to 9.5 meters, which equals to a total draw down of 4.5 meters. Between 14:00 and 15:00, the flow rate began to decrease, dropping from a constant 78 L/min during the first 5 hours to a final rate of 58 L/min. This decrease in flow could potentially be attributed to the change in head above the pump, which was measured to be quite drastic by the diver. However, this was not conclusively determined to be the cause of this decrease in flow rate. The recovery phase for this borehole is shown in figure D.5. After approximately 6 hours, the borehole had recovered approximately 90 percent. The borehole was fully recovered after around 30 hours of no pumping. The main point of interest for this test was the decreasing flow rate which could not be conclusively explained.

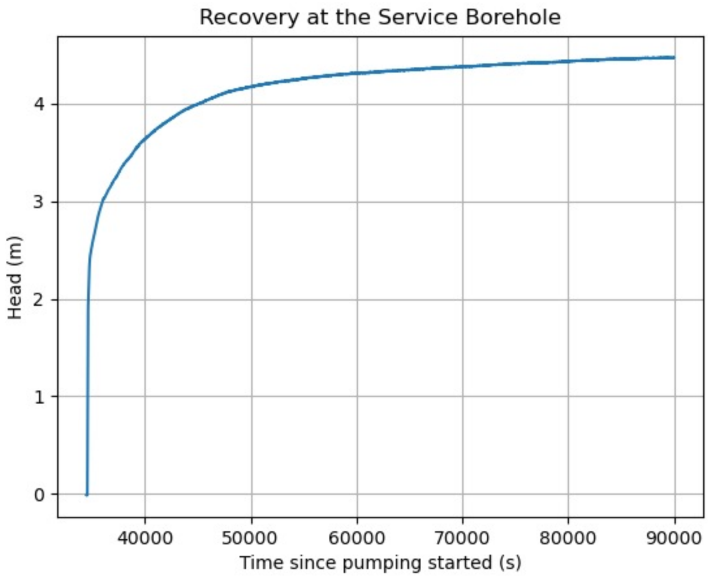

Figure D.4: Pressure measured during the recovery phase of the pumping test conducted at the Service Borehole

For this recovery phase a similar plot was made to determine the hydraulic conductivity. The fit for this graph appears to be quite good; however, the hydraulic conductivity calculated (using the estimated aquifer thickness of 50 meters) does not align with values found in the literature. As a result, this hydraulic conductivity is considered unreliable. Factors such as the unknown aquifer thickness or the proximity to the nearby river may have contributed to these inconsistent results. It was thus determined not to continue with these results until further research has been done.

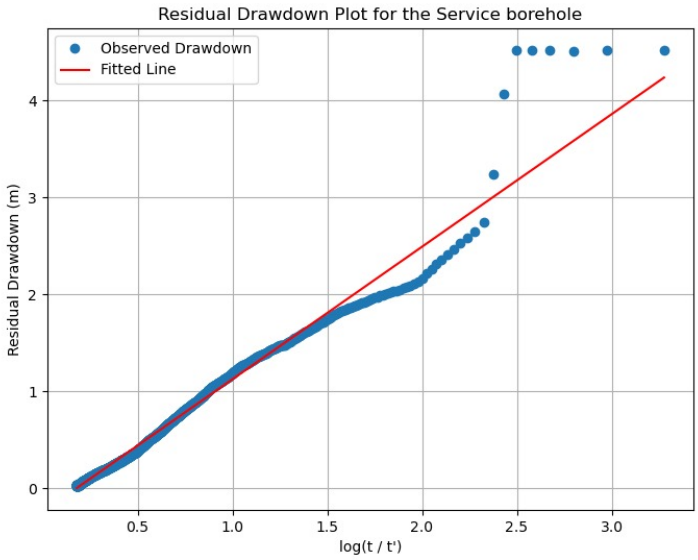

Figure D.5: Residual Drawdown of the pumping test conducted at the Service Borehole.

D.1.4. Conclusions regarding conducted pumping tests

The equipment required to properly conduct the pumping test were not available. Specifically, not having a external pump, an accurate water level measurement tool and, a diver that could be lowered deeper into the water column. With the equipment available and within the limited time-frame, the team was able to conclude that the drawdown of the pumps did not approach the installed pumps, and the pumps at Mogorosi and Motlhalatau do not stress the aquifers. However, the fluctuating flow rate at the Service Borehole made it impossible to determine if the aquifer was being stressed over time.

The relatively fast recovery at all boreholes suggests that, even at the end of prolonged dry period after three dry years, there is no current shortage of water in the aquifers tested. However, the installation depth of the pump at the Service Borehole, at only 16 meters, should be investigated further, as the powerful pump used for fire hydrants did not function optimally showing a decreasing pump rate. The data gathered at the private borehole at Motlhalatau lodge was used to determine the maximum Percolation rate (Pmax), since this test yielded the best results given the limited equipment. The analysis of the data used to estimate Pmax, used in the waterbalance.

In addition to these findings, conducting these tests provided valuable insight into the equipment needed for the Reserve in the future, to conduct proper pumping tests within the Reserve.

D.2. Recommendations for Future Testing

This section is written as per request of the LLR research board and is written in informal style to improve readability for the Reserve's purposes. These recommendations can be used to prepare for future research regarding the aquifer properties.

D.2.1. Water management at Limpopo Lipadi

During the time the team stayed at Limpopo Lipadi Reserve, we were informed that there is a specific interest in conducting pumping tests within the reserve. Not all equipment needed was available to our team during our project and our team lacked the time to prepare the procedure in great detail. This is why it was decided to focus mainly on analysing the possibilities of conducting these tests in the future and to make a clear recommendation for future water related research. With the help of several individuals within the Reserve, an analysis was conducted to determine whether it is recommended to do pumping tests within the Reserve, and if there is a need to do these tests, what resources are necessary.

To get an initial idea of the current water management practices within the Reserve, our team talked to several people from the maintenance team of the Reserve. From our initial conversation we have come to understand that the water management practices are mainly based on experience, rather than scientifically substantiated. The years of experience of the people working in this reserve is a valuable contribution to the management practices and has been successful so far. So far, there has never been an instance of water shortage and individuals managing the water and drilling of the boreholes work with limited materials that are available here in the region. The history of the reserve suggests that at one point in time, not more then 2 or 3 decades ago, the water extraction levels were much higher, due to this region being a high density cattle farm. Based on this information, it is reasoned that if there were no water shortages at this historic extraction rate, that was much higher compared to current extraction rates, we should not experience any shortages now or in the near future. This logic appears to be valid for the time being, as there seems to be sufficient water available to pump at high rates without depleting supplies below the pump levels at any point.

Each borehole has its own unique set up. Different pumps are utilized, mainly based on which pump is available at the time of installation. Different power sources are used, such as generators, electricity from the grid and solar energy. The depth at which the pump is installed, is based on experience and availability of materials. The rate at which the pump pumps, is based on the pumping capacity of the pump that is installed and the power supply used to power it. The distance between the borehole and the location of the waterhole/tank, to which it supplies water, varies strongly over the reserve. Lastly, all pumps and valves are operated manually based on how full the tanks and waterholes are. As the tanks and waterholes are not constantly monitored, instances occur where tanks or holes deplete or overflow. Mainly, overflowing seems to be happening regularly at the Reserve. Lastly, there are multiple boreholes that are currently not in use and are spread out over the reserve. These boreholes have either run dry, or still contain water. The locations and the total amount of these boreholes are unknown.

As of right now, it can be concluded that the management is fairly successful, in the sense that there are no major incidents of water shortage or significant floods. However, we believe that due to climate change and potential changes in landscape and (local) changes in water demand within the reserve, it can will be beneficial to further analyse the water availability within the reserve and yields of the boreholes in use. An option to analyse the aquifers present is by conducting the pumping tests, which is in line with the interest of the shareholders.

D.2.2. Introduction Pumping test

Limpopo Lipadi strongly relies on groundwater. An aquifer is a natural underground layer of permeable rock, sand, or gravel that stores water, providing a source for wells. A pumping test is a method used to determine the hydraulic properties of an ground water aquifer by pumping water from a borehole at a known constant rate while continuously measuring the water level in the borehole.

During the test, water levels in the borehole are monitored to measure how the aquifer responds to the pumping. This test provides important data, such as the aquifer's transmissivity (how easily water moves through the aquifer) and the draw-down (the reduction in water level in response to pumping), which are critical for understanding groundwater availability and management.

To do a pumping test safely, a strict protocol has to be followed. Pumping for too long and/or at an pumping rate that is to high can damage the aquifer or the borehole set up. If a pumping test is conducted for too long or at a rate that is too high, it can lead to too much draw-down, which might cause the water table to drop too much, emptying the aquifer locally and harming its long-term water supply. It can also cause the collapse of the well or borehole. Lastly, it can damage the pump, as the water level gets too close to where the pump is installed in the borehole, or causes poor-quality water from surrounding areas to be sucked towards the well at which you are pumping, contaminating the aquifer for future use. **Due to these risks, these tests should be conducted by either experts or a student team with knowledge of hydrology and supervised remotely by an expert.**

D.2.3. Potential Results

A short duration pumping test (6-12 hours) conducted at a pumping rate which stresses the aquifer (which can be determined based on a step test) can give an indication of the hydraulic conductivity of the aquifer. This gives an indication of what the maximum rate is, at which water can be pulled out from the aquifer and into the borehole.

A long duration pumping test (48-72 hours) conducted at a pumping rate which stresses the aquifer and with an observation well can give the hydraulic conductivity of the aquifer, and give an indication if the aquifer is confined or unconfined, which boundary conditions are at play and can give an indication of the size of the aquifer. A confined aquifer is an aquifer trapped between impermeable layers, creating pressure that can cause water to rise above the aquifer when a borehole is made. An unconfined aquifer, is open to the surface, allowing water levels to fluctuate according to the fallen precipitation. For this purpose, a minimum of 1 well, preferably more then one, within a range of around 500 meters near the borehole at which the pumping test is done is required to function as observation well.

D.2.4. Requirements & Equipment

The following requirements must be met to conduct a pumping test:

- The depth at which the pump is installed needs to be known.
- To conduct the test, the borehole has to stabilize prior to conducting the test. This means that the pump has to be shut down 24 hours prior to conducting the test. The water supply will be shut down, which might impact the users of the borehole.
- During the tests, the pump will most likely be pumping at a higher rate then normal, and this volume of water has to be accounted for. It was to be determined where this pumped up water is going to be stored.
- The water that will be pumped up has to be stored in a tank that does not leak, an well lined waterhole, or be released on the ground as far away from the borehole as possible. If the water is released on the ground too close to the borehole, it might create a loop of infiltration and pumping, which has a negative effect on the results.
- The top of the borehole can not be completely closed. It has to allow for a water level meter and a diver to go in.
- Natural surface water bodies in the surrounding area (rivers, waterholes that are not lined, springs, etc.) need to be identified prior to testing. The distance from the surface water body to the borehole needs to be known.
- At least one observation well (a borehole within a range of 50-500 meters away from the borehole which is going to be pumped) is required, to determine the additional aquifer properties, such as indication of size and boundary conditions, gathered by doing long duration test with observation wells. Multiple observation wells is even better.

The following equipment is needed to conduct the pumping test:

- A pump with high maximum capacity which can run at different rates, chosen by the person using the pump. Once a certain rate is chosen, the pump should pump constantly. Contact a hydrologist to determine the appropriate pump.
- Pipes and connection parts necessary to install the pump.
- A generator or a different power supply that can supply the pump with consistent energy.
- A large tank or a pipeline that can pump water into a lined waterhole or far away from the pumping site.
- Flow meter that can be installed. The meter must be installed in the pipe that comes out of the borehole pump (precision for liters). Preferably one that logs the rate at certain intervals.

- Water level meter (as precise as possible) that can be lowered into narrow boreholes, without getting stuck on the sides of the borehole or the pump.
- Multiple divers that measure the pressure head. It has to be able to be submerged at least 50 meters underwater. Including the diver reader and software to extract the data from the diver.
- Materials required to lower the diver down into a borehole. This includes a cable/strong rope of at least 50 meters for each diver. Also pieces pvc piping that exceed 50 meters in total, or a 50 meter flexible tube.
- Stopwatch or a charged phone with a timer.

D.2.5. Procedure

Procedure 1: Calibration Test

Calibration Test can be done on the first day of testing.

1. Measure the water level in the borehole (H0) and the total borehole depth (BD). See Figure D.7 (if BD is +50m (the bottom can not be reached), write down 50+ m) and read section D.2.5.
2. Take out the currently installed pump and place the pumping test pump. Make sure to note the depth at which the pump is installed (PD) (i.e. the depth in the borehole from which the pump extracts water). See Figure D.7.
3. Install the flow meter and reset the flow meter to zero.
4. Start the pump and raise the flow rate gradually, noting down the rate over time.
5. While gradually raising the flow rate, monitor the water level in the borehole continuously by measuring the water level in the manner described in section D.2.5. Once the water level reaches the point were it is 5 meters above the pump, stop the pump.
6. Note down the rate at which the test was stopped (Qcalibration*), this pumping rate will be used to set up the Step test, the next procudure, properly.
7. After this calibration test, turn off the pump to allow for a full recovery before the next procedure can start. The pump should be shut off for at least 24 hours, to allow the aquifer to return to its natural stable state. See figure D.7 to see what is meant with stable conditions.

Procedure 2: Step Test

To determine the rate at which the constant pumping test can be done, a step-test has to be conducted. This test can be done on day 2 of the pumping test. After the rate is determined and the aquifer has fully recovered, the constant pumping test can be performed.

1. The 24 hours before the start of the step test, the pump has to have been completely turned off to allow the aquifer to return to its natural stable state. See Figure D.7
   .
2. Reinstall the flow meter, that is if it was removed after the calibration test. Reset the flow meter to zero.
3. Reinstall the pumping test pump, that is if it was removed after the calibration test. Make sure to once again know the depth at which the pump is installed (PD) (i.e. the depth in the borehole from which the pump extracts water) by pulling the pump and measuring the depth. See Figure D.7.
4. Check if the storage space/waterhole is empty enough to store large quantities of water.
5. Start pumping at the pumping rate of 0.25 x Qcalibration. Measure and record the water level in the well at frequent intervals following the procedures described in section D.2.5 and record the flowrate as described in D.2.5.

6. Make sure that the drawdown does not come within 5 meters of the depth at which the pump is installed (PD). If it reaches the 5 meter mark, stop pumping.
7. Continue until the drawdown stabilizes or approaches semi-stable conditions, with a minimum time of 30 minutes. Even if it stabilizes after 15 minutes, continue for at least 30 minutes. If the draw down continues to decrease, stop when the water level comes within 5 meters of the depth at which the pump is installed (PD) or after pumping for 2 hours at this rate.
8. Repeat steps 5 - 9 for each increasing pumping rates. Each increase is seen as a 'Step'. The rate for each step is shown in the Table D.3.

Step	Pumprate
step 1	0.25 x Qcalibration
step 2	0.5 x Qcalibration
step 3	0.75 x Qcalibration
step 4	1 x Qcalibration
step 5	1.25 x Qcalibration

Table D.2: Pumping rates at each step

9. Once the pumping is done, shut off the pump again if the constant pumping test is performed the following day.
10. The goal of this test is to determine the rate at which the constant pumping test will be done (Qconstant). This rate is the rate at which the aquifer is stressed to is maximum, without drawing the water level so far down that it comes within 5 meters of the pump. When conducting the contant pumping test, described below, at this rate the borehole should show a steady drawdown without excessive rapid declines.

Procedure 3: Constant Pumping test
During the Step Test the pumping rate is determined (Qconstant). This Rate will be used to constantly pump water over a span of 6 to 72 hours (depending on the type of test conducted). A longer tests allows for more precise result, with regards to the determined hydraulic conductivity. The length of the test depends on several factors such as:

- The time available by the people conducting the test
- Their ability to work overnight
- The storage capacity available (there can only be as much water pumped as can be held in storage)
- Draw down limitations. That is, during the Constant test, the water level can once again not go down below 5 meters above the pump.

Once the total time of the test (6-72 hours) is determined based on the criteria mentioned above the following steps can be followed continuously over the total duration of the experiment. This procedure can be followed on day 3 of the pumping test.

1. 24 hours before the start of constant pumping test, the pump should be turned off, to allow the aquifer to return to its natural stable state. See Figure D.7 to see what is meant with stable conditions. Observation wells used during the test have to be shut down as well. (If no pumping has occurred between the end of the step test and the start of this test, 12-16 hours could also be considered to be sufficient. Check to see if the water level has returned to the same level as the stable state before turning on the pump to conduct the step test.

2. After the pumps has been switched off for at least 24 hours, measure the water level in the boreholes (H0) again. Figure D.7 illustrates what is meant with HO. This is the stable waterlevel for each borehole.

3. Familiarise yourself again with the depth at which the pump is installed (PD). See Figure D.7. Calculate how much water is above the pump by calculating the difference at which the pump is installed and the stable water level depth (PD - HO).
4. Check if the storage space/waterhole is empty enough to store water.
5. Place the divers in the observation wells. Make sure to know the depth at which the diver is placed and note this depth down for each well. Make sure no pumping will occur at these wells for the duration of the test.
6. Place the diver in the pumping borehole. Make sure the diver is placed securely 4 meters above the pump.
7. Start pumping at the determined constant rate (Qconstant, determined in the step test). Measure and record the water level in the well at frequent intervals, as described in Section **??**. Write down the time and the measured water level on the water level sheet.
8. If the water level is measured to approach the 5 meters above the pump mark, measure more often and if necessary, stop the test when the water level reaches the point at which it is only 5 meters above the pump.
9. At the same time as measuring the water levels, measure the flow, using the flow meter as described in section D.2.5. Write the values down on the flow rate sheet.
10. After the full duration of the test, stop the pump.
11. Leave the divers in the pumping well and the observation wells for another 24 hours to observe how the boreholes recover. The divers can be left in the borehole without supervision. This step can only be done if the pump has a non return valve. If there is no non-return valve, skip this step.
12. Retrieve all divers once 24 hours have passed.
13. Draw down values over time, written on the water level measurement sheet can be transferred to an excel sheet or other digital interface. This will function to check if the diver functions well.
14. The analysis of the draw down over time can be done using different methods, such as for example the Theis Method.

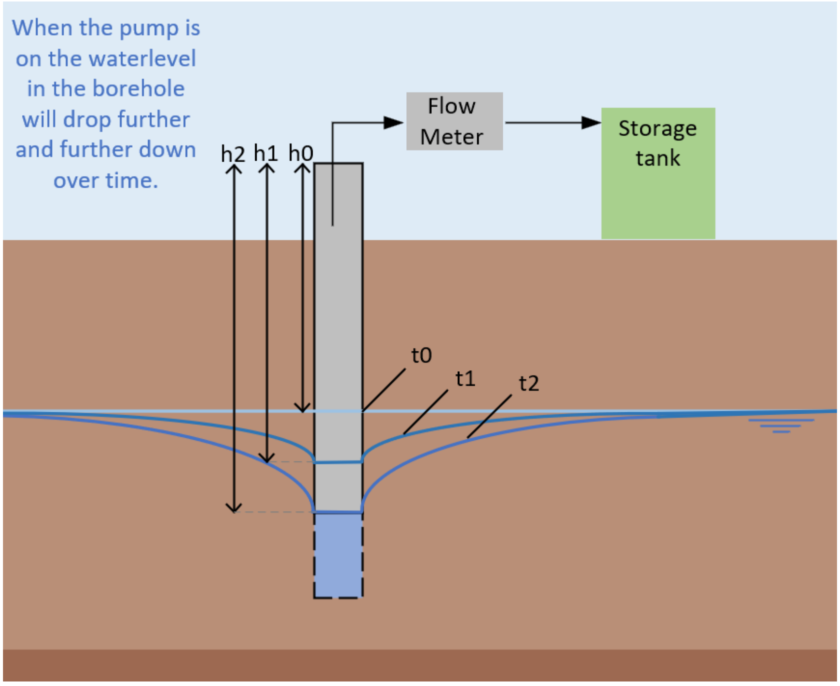

Figure D.6: Set up for Phases 1 and 2

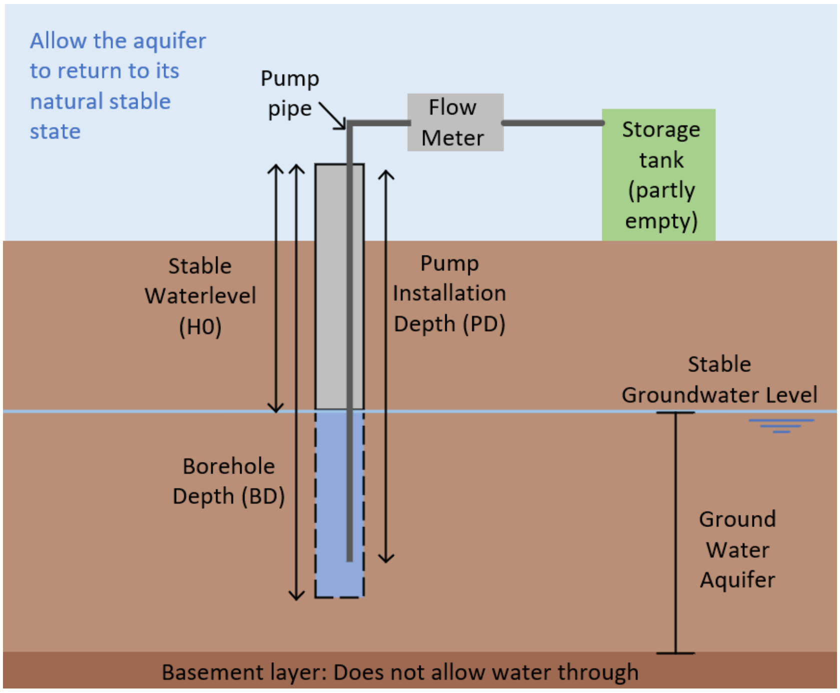

Figure D.7: Set up for Phases 1 and 2

Flow rate measurement

Determination of the flow rate depends on the device that is used. When a flow meter that counts the number of liters that have passed the flow meter is used, the flow can be determined by taking a 1 minute video and analysing the video to determine the difference between the value at the end and at the start of the video. This will result in the rate in liters/minute, which can be converted to m3/hour, or other unit at use.

For the Calibration test, the flow rates should be measured continuously every 5 minutes. Since the rate is gradually changing, it is important to continuously check if the expected pumping flow rate is the same as the flow measured by the flow meter.

The flow rates during the step test should be measured every 5 minutes during the first 30 minutes and every 10 minutes for the remainder of the time, restarting this procedure for every step in pumping rate taken.

For the Constant pumping test the following protocol can be followed:

time since start	intervals
0 - 30 minutes	every 5 minutes
30 - 120 minutes	every 10 minutes
120- end of test	every 1 hour

Table D.3: Flow Rate measurements constant pumping test

Water level measurements

The way to determine the water level depends on the device that is used. The water level should be determined from the rim of the borehole down into the borehole. Consistency in procedure is important. When using a weighted plopper, the waterlevel is measured by lowering the plopper down into the borehol until the plopper hits the water surface. The length of the string to which the plopper lowered is then measured after pulling the plopper back up.

For the Calibration test the flow rates should be measured continuously every 2 minutes and note down the measured water level for each measurement. Measuring this often is needed since the rate is constantly changing and thus, the rate of drawdown will change as well. Since the rate is gradually changing, it is important to continuously check if the expected pumping flow rate is the same as the flow measured by the flow meter.

The flow rates during the step test should be measured according to the following the intervals described below in table D.4 for every step in pumping rate. This means that once the pumping rate is increased, you restart the frequencies and start measuring every 2 minutes again.

time since start	intervals
0 - 10 minutes	every 2 minutes
10 - 60 minutes	every 5 minutes
60 - 120 minutes	every 10 minutes

Table D.4: Water level measurements Step Test

Assuming that the Step test was conducted properly and a diver is used during the constant pumping test, the measuring of the water level is mainly performed to ensure that the water level does not draw down below the threshold of 5 meters above the pump. These measurements should be taken at the frequencies described in table D.2.5. When the water level does approach this threshold, then the water level should be checked at a higher frequency to make sure the threshold is not surpassed. However, noting down the measured values if of importance to check the accuracy of the diver and can be used if the data from the diver is lost.

time since start	intervals
0 - 30 minutes	every 5 minutes
30 - 120 minutes	every 30 minutes
120 - end of test	every 60 minutes

Table D.5: Water level measurements Step Test

D.2.6. Future Recommendations

For future recommendations regarding pumping tests, it is essential to consult an expert, such as Maddy Tracy (contact of Dave Pearce), to review the procedure and provide advise on suitable equipment. The experts guidance should focus primarily on identifying the appropriate external pump that fits the boreholes within the reserve (20 cm diameter, with casing that does not go all the way down) and provide the correct flow rate range. Several divers, fit for pumping tests, under the conditions within the reserve, should be purchased. Proper equipment should either be acquired or rented for this purpose, prior to the research teams arrival. The equipment could also be brought to the Reserve by the student team, due to the lack of equipment available in this region.

To do pumping tests at all actively used boreholes currently, the old inactive boreholes that are in close proximity to the boreholes that are tested (within 500 meters) should be mapped. If the boreholes are filled up, they could be flushed clean, to provide observation wells.

To analyze the data gathered from the pumping tests, a better understanding of the local geology is essential. It's important to have a clear understanding of the various geological layers, including the specific location of the aquifer within these layers and the thickness of the aquifer layer. This information will enable more accurate conclusions.

Finally, the gain and necessity of conducting pumping tests should be evaluated before proceeding. These tests will provide valuable insights into hydraulic conductivity, which is crucial for further research in this area, but it needs to be specified if there is a interest in conducting further research. Long-duration pumping tests can help estimate the size of the underground aquifer, but it's important to note that this size can fluctuate over time, influenced by seasonal changes and variations between dry and wet years. A single test will offer limited information. It's essential to identify the specific hydraulic properties of interest for the reserve. If the goal is to monitor water levels in the boreholes and determine the changes over time, a different protocol may be more suitable.

In summary, there are many different aspects that can be studied within the Reserve with respect to water management. Before a future project can start, it should be specified what the exact goals are with regards to water management research. If it is determined that the information gathered by conducting pumping test is essential, then the protocol described in this report, and the recommendations made above should be considered.

E

Interviews

In this appendix, interviews conducted to better understand the Limpopo Lipadi Reserve and its current challenges are fully reported.

E.1. Interviewing Limpopo Lipadi's General Manager: Malcolm Campbell

1. **How involved are the shareholders in the Reserve decisions?**
   Direct, any major initiative (positive and negative impact) is put to vote. Important role in the budget and representation of the Council. 15% is involved in the whole process.

2. **How is this participation organized?**
   Shareholders shouldn't be very involved in all decision-making processes; not all of them are experts. There shouldn't be an imbalance of time spent.
3. **Does the anti-poaching team do any other work in the Reserve besides anti-poaching?**
   Protect the rhinos, secure the whole reserve for general anti-poaching (important as its a big problem). Also do anti-fire initiatives, fat burning: burning blocks + maintenance team. Check the fences daily (breaches - fix or call maintenance and check if animals are leaving; monitor voltages at a certain 7000 volts). Patrols (vehicles and foot), rhino walks.
4. **Would you consider the Tuli Block region a stakeholder?**
   The Tuli Block is considered a stakeholder because in recent years it has made a shift from farming activities to tourism, which is beneficial to the reserve.
5. **How do shareholders contribute financially?**
   Purchase of shares, OPEX, CAPEX, user levies (they come and pay for they stay and kilometers driven).
6. **Are shareholders the only source of funding? If not, what are the other sources of funding for the reserve?**
   No, we also have NGO donors who focus their funding on conservation issues. They decide where the money is spent. An associated NGO and other people who contribute to the Motse Committee (budget: OPEX + shareholders + other contributors).
7. **According to the environmental report you received in 2020, what is the most important issue for the reserve? Have you had a chance to implement any of the proposed actions? Which are feasible and which are not?**
   The most important issue is to sell shares and increase the number of shareholder visits (increase revenue from visits and reduce OPEX). As far as the environment is concerned, the main issue that is being addressed is the one of the two wells where the diesel is spilling all over the site and seeping into the ground. They will investigate where to replace and clean the area, for now they

have covered the space with sand. The proposed actions are feasible. However, some will have to be postponed due to various factors.

8. **Is it possible to get support from the government or other stakeholders?**
   Not really. The government only pays for the National Guard employees, but the equipment and infrastructure are owned by LLGR, and the facilities are off the grid.
9. **Are there any tourists visiting the reserve or are only friends/family members of the shareholders allowed in the reserve?**
   Yes, tourists can visit the reserve.
10. **Are there any rules about shareholder involvement in management, in case it ever creates a conflict of interest/what do you do to prevent it?**
    Malcolm Campbell is the first shareholder to be directly involved, out of necessity, but it creates a conflict of interest. However, his decisions must be justified and taken in the role of management.
11. **What is the role of the board of directors and how many seats are on the board?**
    Their role should be supervisory, but it is not. It is quite executive, because unfortunately the management has been very corrupt. Some of the directors have been involved in malicious activities and things have not been done properly. There are 12 board members and an agreement is in place with an internal entity to have 2 appointed directors and no more than 5 permanent directors.
12. **Is this true: "There are currently 26 APU personnel employed by the reserve, supplemented by 6 gate security personnel"?**
    No, it is not accurate. We have 28 members of the APU, and security 10 full gates. They have the dedicated activity of checking the fence, there should be a combination APU + Maintenance + BDU. However, currently only APU + Maintenance work together.
13. **What are the main management issues you are currently facing?**
    Compliance; Financial structure, it's complex when it shouldn't be; Discipline, employee habits
14. **What groups are involved in making important decisions?**
    The management team, but very often pushed up to the board. The board should not be involved in many details.
15. **What is the main vision for the coming year?**
    Get the reserve management plan back on track: predators (needs permits), panels, etc. Outside shareholders are not working with the reserve, all permits take a lot of time.
16. **How will the population of the reserve change in the coming years?**
    Within a period of 5 years, it is expected that there will be a better balance between predators and prey, and that there will be an increase in species and varieties.
17. **How does the reserve see its future in terms of water and energy use? And what plans are in place to deal with a potential water crisis?**
    Regarding energy, it would be nice to have a hydrogen plant to cover the energy needs of the reserve. We would like to find new sources of clean energy. Currently Botswana depends on South Africa for supplies, sometimes there is not enough to meet the demand. In terms of water, we actually have pretty good rainfall on average, so the water balance should be okay. However, water use should be better managed (e.g. repair of small leaks). Water consumption has been measured for the private areas and the office complex. There is no record of the water pumped into the boreholes, there are no meters to measure it.
18. **How often is the management plan be reviewed or renewed? Are external organizations/-consultants consulted?**
    It is reviewed and adjusted annually with input from directors and advisors. And yes, an external consultant is contacted.
19. **Regarding the new boreholes... is there a plan for where they will be made?**
    In the short term, the idea is to have a new one close to the fence. In the Northern part of the reserve as it gives security to the rhinos. The Game Reserve Council is who will decide on the locations.

E.2. Interviewing Limpopo-Lipadi's Research manager: Botilo Tshimologo

Bush clearing

1. **Is there a specific reason why we are focusing on these 4 zones of the reserve?**
   The 4 zones are chosen based on the intensity of encroachment and the species of encroachment in each site. The reserve plans to clear these areas specifically. These areas, excluding Phofu drive, previously had farming there, they were used for crop farming. Because of farming, the area is in worse shape compared to other locations. You could talk to Piti if you want to get more information regarding the farming locations and what kind of farming was performed at each location. *Dominant species according to sites:*
   Southern Plain: Vachellia tortilis (dominates where kraal were located for cattle)
   Middle plains: Dichrostachys cinerea (Sickle Bush)
   Phofu drive: Mopane
   Northern plains: Dichrostachys cinerea (Sickle Bush) and Vachellia tortilis

2. **For each location, what is the chosen bush clearing method, date of first clearing and of the latest clearing?**
   Southern Plains:
   Bush clearing method: hand clearing and fire
   Frequency: 2019, and now in 2024
   Date of the first clearing and of the latest clearing: Bush clearing started in 2019, controlled use of fire started after soon after bush clearing started. Done once and then not again for a while, and now they are starting again
   Phofu Drive
   Bush clearing method: hand clearing and fire
   Frequency: in 2020, and then not again
   Date of the first clearing and of the latest clearing: Open up the mopane, kind of experimental, hectare by hectare, do 1 hectare per day until they are done, last cleared in 2020, over time they took the Mopane for firewood. It has also been exposed to fire. The area is not regrowing fast, which is the goal. Mopane is not eaten by many animals, primarily by elephants.
   Middle Plains
   Bush clearing method: Bob-cat, later by hand, and fire
   Frequency: redone the most frequently, last in 2022, and in 2023 and then again now in 2024. Quite a big area, Sickle bush is very aggressive when it regrows again. Possible that it will have to be cleared every year.
   Date of the first clearing and of the latest clearing: 2022, 2023, 2024.
   Northern Plains
   *Bush clearing method:*Machinery and hand cleearing, + history of crop production
   Frequency: Only once, and then it was stopped aruptly before work had finished. The reserve plans to do it again soon.
   *Date of the first clearing and of the latest clearing:*Clearing was stopped because of a dispute with the contractor, the contractor wanted to take away the cut branch while the reserve wanted to leave the branches at the location where they were cut.
   Additional information:

   - Fire is not used as a clearing method but rather as a opening method and clearing frequency is not the same for each area.

   - Method of bush clearing is determined by the vegetation growing in each location. You have to select the species that are cleared, machinery makes this difficult, makes selective clearing difficult. Avoiding to cut down big trees.

   - How to cut the bushes properly: cut the stem and apply a chemical, if not it could contribute to regrowth in the following year. The chemical is only used on the stem, and it does not affect animals and surrounding vegetation.

- When one type of bush is starting to grow at a certain location, they dominate the area.

3. **What are the benefits/drawbacks of each method and how is the method selected for a specific site (for example: fewer bush fires, altering natural environment…)**
Drawbacks are the fast regrowing after being cleared, i.e. sickle bush grows back quickly
For Phofu drive an experimental method is being implemented; observing how well the mopane will grow back. Mopane is a very dominant species, and dominates the undergrowth, by clearing them they hope to get more diversity. I would say that the clearing method used for Phofu Drive was very successful and I would want to implement this method possibly for other areas. But this is determined by other factors as well, such as grass growing and soil composition, for clearer visibility, it will be recommended.
Reseeding in the cleared area: reseeding has only been implemented near the stream. There are some management gaps that could explain this, the areas are well drained in terms of water. I do not have a lot of information about reseeding in these areas. The rhinos love the river section, where there are tall trees.

4. **What is the current management approach to bush clearing? (Do they try to slow down/accelerate clearing? Why? Is it a priority to continue bush clearing?)**
Yes, the reserve plans to expand bush clearing activities to other areas.

5. **Who does the clearing? (Would there be an opportunity to interview someone?)**
The reserve hires contractors for the clearing. The same contractors are not hired everytime, sometimes they do not do it properly. A new contractor started last month, 28ha have been covered so far, the current contractoris currently redoing areas at middle plains.
Only one contractor per time, the reserve evaluats if the contractor does a good job.
The reserve tells the contractor what should be cleared and how, and the contractor should follow the reserves plan.
The reserve chooses to do brush packing i.e. leave the removed bushes where they were removed to decompose.

6. **Have any incidents ever occurred due to bush clearing activities? For instance, losing control of fire, vegetation never recovering or growing back in unplanned way, animals harmed or driven away?**
Last uncontrolled fire was back in 2022, far away from the selected sites. It was not related to any clearing activities, it was an accidental fire.
Have not had a species recolonisation yet, it is usually just the species that were already there and were the target of the previous clearing.

7. **Would you consider the bush clearing activities conducted thus far in the reserve successful? And what parameters indicate this success rate?**
Yes, in terms of how the vegetation grows back, the grass cover, and how the animals prefer the space. So far the reserve has not had any proper scientific study to assess the impact. There is some research that there is positive impact of bush clearing and fire, the study is done annually, and additonally there audit that is done annually for the reserve but this is included in a confidential report for the reserve.
For Middle Plains, animals like Wildebeast like cleared areas in that location. For them, the cleared area is safer in open plains, where they can spot their predator.

8. **Is there a specialist or consultant who verifies that the clearing method is correct?**
I (Botilo) am in charge of that, I go back to the cleared area to check if the contractor is removing the right species, if they are cutting the stem properly, and if they are applying the right chemicals. Additionally, I observe the amount of hectares removed, every week.

The reserve is also interested in the carbon sequestration; a short study has been performed to check this. There is very little moisture and very little activity of termites. This idea comes from the carbon credit idea.

9. **Have you ever tested to see if there are any negative effects on soil properties that may interfere with the soil remediation mission?**
   No, not yet.

10. **For how many years are you expected to do the land clearing?**
    The reserve is going to try to implement bush-clearing in areas where encroachment is high and dominant.

11. **In what year did bush-clearing measures begin at the reserve?**
    In the year 2019.
    Boreholes

12. **Regarding the new boreholes... is there any plan on where to make them? If yes, has it been checked by a specialist?**
    There is a plan to find new boreholes, or drill new boreholes, because the reserve wants to have water availability as much as they possibly can, for the animals. There is no plan to close other boreholes, the reserve wants to increase the number of boreholes.
    No specialist has been appointed, but it will be done in the future.
    There is not really concern of overextraction of boreholes, but there is some concern for the boreholes used by the reserve, for human consumption. The reserve wants to conserve waater as much as they possibly can.
    The reserve wants to focus on making smaller boreholes instead of bigger ones. Smaller shallow ponds are more prone to algae, which is of some concern at the moment, the blue green algae is the only algae of concern. The green alage is not of too much concern, since it is not toxic.
    Specific research in the reserve:

13. **Is it possible to get any rain data. The management report shows a graph of monthly precipitation data from 2012-2018.**
    I (Botilo) ordered some weather station and should be arriving today (24092024). There should be some monthly rain data, from 2020 (covid), 2023-2024 as well.
    Rain gauges: located at gate 3, gate 2, northern gate and the APU
    The APU checks the rain gauges them when there is rain, they check it in the morning

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Python code scripts

The Python code used for this study is available on GitHub, the link to the repository can be found below.

Link to repository: `https://github.com/camicocozza/MDP_CODE.git`

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Collaboration

Collaboration within our team

The strength of this MDP group was the diversity in backgrounds and skills. This meant that if one team member ever had difficulties with one task, another could step in. Our group is comprised of students from various backgrounds: mechanical, civil and environmental engineering. Furthermore, we come from different cultures: Mexico, Iceland, Italy, France and the Netherlands. These differences were a valuable asset in the completion of this project, as we could approach problems from different perspectives and sometimes find unconventional solutions. For example, we built an experimental set up to fake rain to overcome the lack of rain in the Reserve during our stay. In our current studies, three students study Water Resource Engineering with a speciality in Hydrology and three students study Waste and Resources Engineering (two specialized in Waste Processing Technologies, one in Reactive Waste and Resources). This was particularly useful in addressing our problem statement linking both groundwater resources and soil health.

The task division for this project followed each of our technical specialities: Iris, Camilla and Leanne focused on creating the water balance and assessing the aquifer parameters whilst Valeria, Salvör and Tjasa worked on soil health and its impact on water resources. Seeing this project as an opportunity to broaden our skill set, we seized every opportunity to learn from one another. This happened naturally, as soil and water are intrinsically linked the knowledge gained from a soil experiment could usually contribute water experiments, and visa versa.

Collaboration with the Limpopo Lipadi Reserve

The objective of a project of this nature is first and foremost to help the ”client” with a specific environmental engineering challenge. Thus, the delivery of relevant and useful results to the Reserve was a priority throughout our work. Our group had a unique position, as we were the first students to come to Limpopo Lipadi to conduct research. As the Reserve expressed their ambition to receive more groups like ours in the future, our work set a precedent for the next and it was extremely important that we establish a good working relationship between LLR and TU Delft. To ensure that we were on the right track, we consistently communicated our plans with our supervisor, Botilo, and the Reserve General Manager, Malcom. This led to some changes in our initial project outline, for instance we conducted pumping tests that were not included in the project proposal.

Before undertaking experiments, we were mindful of their impact on the ecosystem and of our skills. Tests that could easily be conducted in the Netherlands due to the abundance of water were reconsidered and redesigned to be safely conducted in the Reserve. We had the opportunity to share our progress and evaluate our work with a mid term presentation we delivered to both our local supervisor and our TU Delft supervisors. We also contributed to the Reserve's information day, during which the Reserve updates the shareholders on their progress in the past year and future plans.

Finally, we had the opportunity to meet some fantastic people who kindly shared their knowledge of the Reserve, helped us with conducting our experiments and made us feel at home during our stay.